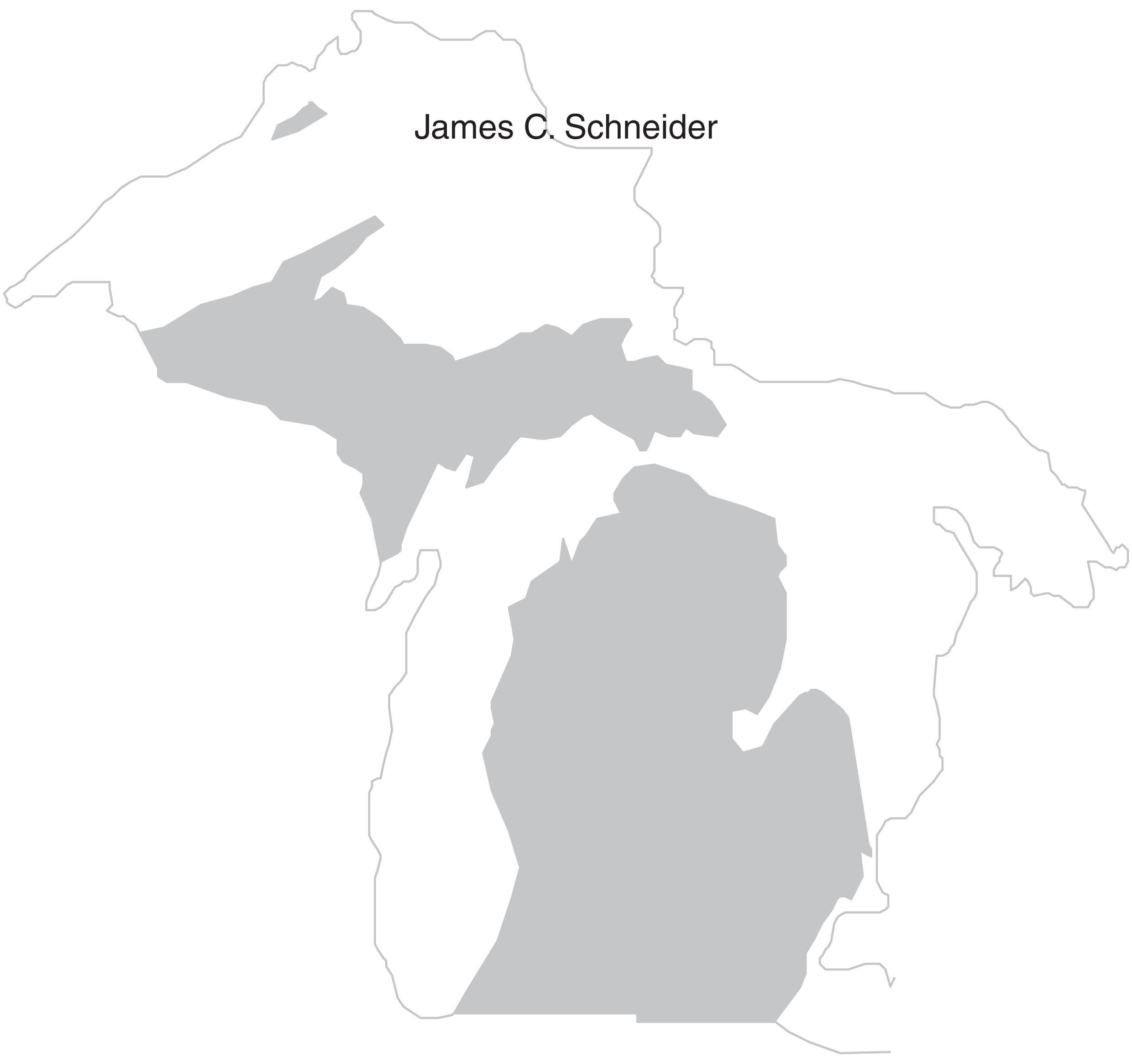
STATE OF MICHIGAN
DEPARTMENT OF NATURAL RESOURCES

Number 2061 April, 2002

Fish as Indicators of Lake Habitat Quality and a Proposed Application

James C. Schneider



www.dnr.state.mi.us

FISHERIES DIVISION
RESEARCH REPORT

MICHIGAN DEPARTMENT OF NATURAL RESOURCES
FISHERIES DIVISION

Fisheries Research Report 2061
April 2002

Fish as Indicators of Lake Habitat Quality and a Proposed Application

James C. Schneider

Printed under authority of Michigan Department of Natural Resources
Total number of copies printed 200 — Total cost $470.12 — Cost per copy $2.35

Michigan Department of Natural Resources
Fisheries Research Report 2061, 2002

Fish as Indicators of Lake Habitat Quality and a Proposed Application

James C. Schneider

Michigan Department of Natural Resources
Institute for Fisheries Research
212 Museums Annex Building
Ann Arbor, Michigan 48109-1084

Abstract–The potential application of the Index of Biological Integrity (IBI) approach to classifying Michigan lakes was considered. This report reviews practical problems with IBI metrics as indicators of fish community health and discusses the types of perturbations occurring in lakes. Species actually present in a particular lake result from regional, local accessibility, chemical, macrohabitat, and microhabitat filters. Also reviewed are distribution and relative abundance patterns of species common to Michigan lakes and life history attributes useful for predicting their sensitivity. Many species should have value as indicators based on their general life history characteristics. A tentative scheme for scoring 11 fish metric indices is presented that minimally requires a good list of all fish species present in a lake plus additional information. Fish scoring results should be considered with other indices of lake condition. Additional fieldwork is needed to validate the utility of certain fishes as habitat indicators.

Introduction

Presence, absence, and relative abundance of fishes strongly depend on habitat suitability. Conversely, but to a less predictable extent, fish may serve as indicators of habitat quality. This is an important issue and a potential tool for agencies charged with environmental protection.

The purpose of this report is to review and integrate concepts useful for understanding fish as indicators of habitat for Michigan lakes. Six steps are presented. First, principles of the Index of Biological Integrity (IBI) and problems with their application to lakes are reviewed. Second, the discussion is broadened to review types of lake perturbations. Third, several types of filters that determine the distribution patterns of fishes are considered. Fourth, species most likely to be sensitive to various types of perturbations are identified based on an extensive review of life history and laboratory information. Fifth, an application of these concepts is proposed that uses a scoring system to rate habitat quality. Sixth, a preliminary test of the proposed scoring system is made.

The Index of Biological Integrity

The IBI is a popular, ecology-based approach to providing simple, integrated measures of environmental health and change that ultimately can be used to enforce environmental protection laws (Karr 1981). IBIs may be based on fish, invertebrates, or multiple levels of aquatic ecosystems.

Typically, they are developed for an ecoregion or a geographical region. Generally, other types of landscape classifications have not been very useful for predicting freshwater biota or for separating natural from human influences, and local factors are believed to be the more important (Hawkins et al. 2000). Diatoms in streams may be a useful exception (Pan et al. 2000).

IBIs based on fish ecology have been usefully applied to warmwater stream problems in Ohio (Karr 1981), and the IBI approach has been extended to streams and rivers in other areas with lesser success. The most current question is: can the IBI approach be used to assess lake conditions (Jennings et. al. 1999; Schultz et al. 1999; Thoma 1999; Whittier 1999)? To date, applications for lakes have met with less success than applications for streams.

The IBI approach attempts to infer environmental change in streams and lakes when more direct and reliable approaches cannot be used. More direct and reliable approaches include "before-after" comparison, where historical background information on water quality or biota is available for comparison to current conditions. Such information could be based on direct sampling prior to a recent perturbation, paleolimnological study, or reliable historical accounts. Another more direct and reliable approach is "upstream-downstream" in which a questionable section of stream or lake is compared to a hydrologically similar (and potentially biologically similar) but non-impacted section higher up the same drainage basin.

An IBI requires a base of reference. The choice of the most appropriate base lies on a continuum from "pristine" (usually pre-European settlement and climax landscapes) to "good" (i.e., minimally affected by mankind) to "as good as can be expected for a developed area." In the purest sense, pristine conditions no longer exist anywhere since airborne pollutants circle the globe and rain on even remote lands and waters. The good condition is quite rare in the Midwest because very few lakes and streams retain completely undeveloped watersheds and most have been potentially altered by exotic organisms, fish exploitation, or stocking. The third reference base is the most pragmatic and acknowledges that the standard bar cannot be set so high that there is no practical method of restoring an altered lake or stream to its best possible condition. In extensively altered regions lacking suitable reference waters, it is hoped that an IBI can serve as a surrogate standard.

IBI elements and their interpretation

The main metrics (ingredients) in fish IBIs typically include:

- total number of species;
- ratio of native to non-native species;
- sensitive species;
- community structure, usually expressed as ratios of generalist species, insectivorous species, and piscivores;
- incidence of deformities and diseases.

These and other metrics deemed suitable to the region or fauna are scored (usually on a scale of 1-5), then summed or averaged to give a single index number. The significance of that number is then interpreted against a reference base selected by the analyst.

Metrics 1-4 above are usually based on species presence-absence information, and thereby ignore the entire dimension of relative abundance. Consequently, intensive sampling with a variety of gear types is required to obtain a complete species list for the lake or stream of concern, and there is never complete assurance that rare species have indeed been discovered. Another difficulty is that strays (such as a riverine-dwelling smallmouth bass [see Table 1 for all scientific names] sampled while wandering through a lake) receive the same importance as an abundant true lake resident (such as lake trout or bluegill).

The total number of species present in a lake is related to lake size and connectivity as well as lake quality. Large, well-connected lakes tend to have more species than small, isolated lakes (Magnuson et al. 1998; Matuszek et al. 1990). Generally, large lakes provide a greater diversity of habitat, including greater depth and wave-swept, rocky shoals as well as quiet bays. Also, large lakes simply have more living space available and are more likely to support the critical number of individuals needed to sustain a reproducing population.

IBI metrics 1-3 are based on the premise that high numbers of native species and low numbers of exotic species indicate the unaltered condition. The presence of exotic species is clearly an indication of change, but prior to European settlement many waters contained fewer native species than presently. In addition, for Michigan streams, warm waters generally contain more native species than the most pristine cold waters (Wehrly et al. 1999). Lyons et al. (1996) also acknowledged this dilemma while attempting to construct a fish IBI for Wisconsin streams. In Michigan lakes, fish faunas have become progressively more diverse through natural dispersal mechanisms since the last glaciation. As late as 30 years ago, some isolated lakes contained no fish even though they contained suitable habitat. Over the last 150 years, numerous species have been so widely stocked by fish managers (and others) that it is almost impossible to verify the pristine status of any accessible and potentially manageable body of water. By now, it is more likely that the absence of a sport species from a lake indicates the lack of suitable habitats for a complete life cycle than lack of opportunity for colonization through natural mechanisms. Many valuable species (e.g., rainbow and brown trout) were exotics intentionally introduced into Michigan, and other species (e.g., brook trout and walleye) were native but have been distributed more widely.

Another difficulty with applying IBI metrics 3 and 4 is that lakes seem to have fewer species that are sensitive to perturbations than streams. Many lake species are generalists that are not closely linked to habitat characteristics (such as substrate) and actively move across habitats. Consequently, they may be caught out of their preferred habitat and their distribution may vary daily or seasonally. Elimination of a preferred habitat may simply cause utilization of a less preferred habitat rather than extirpation of the species from the lake.

Metric 5 has been eliminated from some IBIs because situations where water quality is poor enough to cause deformities, diseases, and parasites are very rare. Also, sometimes these unpleasantries are not related to water quality at all.

During the construction of IBI metrics, an initial step is to attempt to classify species according to their sensitivity to human influences. Such classification attempts suffer from a lack of good information on habitat needs, and especially on the reactions of species to environmental change. In addition, the types of perturbation to which a species is sensitive are usually not clearly defined. Whittier and Hughes (1998) have made a good start at partitioning environmental stressors according to five types: introduced species, phosphorus, turbidity, and watershed and shoreline disturbances. However, a more comprehensive approach would define the types of environmental variables each species is sensitive to and recognize that some changes can be natural as well as human induced. This is the approach I will follow.

A More Comprehensive Approach for Evaluating Lakes

Lake Perturbation Types

We need to review the types of perturbations we are looking for before we can make a judgement of a species' sensitivity to them. Types of perturbations include acidification, eutrophication, macrophyte and algae modifications, chemical pollution, edge modifications and water level control, fish species introductions, and proactive fish management.

1. Acidification causes physiologically stressful pH levels. It is usually more acute in early spring when acidic snow melts. Early life stages are typically more vulnerable than adult stages. Acidification of lakes is both a natural process and one caused by airborn pollutants.
2. Eutrophication causes a variety of habitat changes due to an increase in overall biological productivity. In a chain reaction, increased phosphorus or nitrogen loading cause increases in algae and macrophyte production, decreases in dissolved oxygen content of deeper water during summer and winter, and increases in turbidity and siltation. In addition, there are shifts in species, such as toward tolerant blue-green algae and benthos, which affect higher levels of the food chains including fishes. Sources of eutrophication can be natural (e.g., runoff from fertile soils in the watershed or goose droppings) or anthropogenic (e.g., runoff from septic tanks or fertilized lawns).
3. Macrophyte and algae modifications can alter habitats and food chains. Both chemical and mechanical (harvesting machine) control methods are used by lake residents. Control efforts alter total abundance of macrophytes for varying lengths of time, and often cause shifts in plant species and increases in algae abundance. A variety of fishes use macrophytes for shelter at some life stage, and many fishes eat associated invertebrates. Algae control, a more temporary change, is often initiated by riparians when obnoxious bluegreen algae blooms are stimulated by eutrophication or macrophyte control. Changes in macrophytes and algae are often anthropogenic, but sometimes are due to natural processes such range extension (e.g., Eurasian milfoil), weather effects, disease outbreaks, and species succession.
4. Chemical pollution (exclusive of perturbations 1-3) poisons components of lake ecosystems. Examples include pesticides, herbicides, and household and industrial wastes that are directly or indirectly added to lakes or their tributary streams. Salts from water softening or highway de-icing are useful tracers of potential anthropogenic influences on lakes (Schultz et al. 1999). However, NaCl is not very toxic. Such chemical contamination is much more likely to occur in reservoirs with large watersheds than in isolated lakes. This type of perturbation is rarely known to affect Michigan inland lake fish populations and will not be considered further in this report.
5. Edge modifications and water level control can alter or eliminate both aquatic and wetland habitats. Within the water proper, the emergent vegetation zone is affected most. Examples of edge modifications are breakwalls, filling of wetlands, removal of woody debris, and general "cleaning up" of frontage. Edges are also modified by stabilizing water levels. Northern pike spawning habitat and the edge habitat used by certain minnows are vulnerable. Such activities also affect habitat for amphibians and reptiles and may impede their movements. Edge modifications are usually anthropomorphic but in some lakes may be caused by natural water level fluctuations. Water level control structures (dams) have an additional effect because they impede fish migrations between the lake and its outlet stream.
6. Fish species introductions can modify predation and competition interactions. Introductions may affect growth, survival, reproductive rates and, ultimately, the risk of extirpation of existing species. Introductions into a lake occasionally result from natural range expansion, but are more often due to intentional fish stocking, incidental fish stocking (releases from bait buckets), or unintentional human activities (access via canals or ship ballast).

7. Proactive fish management activities favor sport and food species, and modify food chains and predation and competition interactions. In addition to fish stocking, examples include aggressive species control programs and fishing laws that may favor sporting predators and, intentionally or not, may reduce or eliminate other species or certain sizes of fishes.

Filters

Patterns in the distribution and relative abundance of fish in Michigan can be thought of as resulting from successive filtering from the available species pool of those species best adapted to the available habitats at each site. Filters are of six basic types: regional, local accessibility, physiological, macrohabitat, microhabitat, and reproductive.

1. Regional filters reflect the fact that only a subset of the worldwide and North American pool of fish species naturally occurs in Michigan. This is primarily due to historic patterns of colonization, and limitations of climate and favorable habitat. Even smaller subsets of the Michigan species pool are likely to be found within a given watershed. Watersheds in southern Michigan are potentially more diverse due to the natural distribution patterns of certain warmwater species. However, some other species are restricted to northern watersheds. The general distribution patterns of each lake species in Michigan, based on the recent computerized fish distribution list (Michigan Fish Atlas Maps 2000), are summarized in Table 1. Note that species have been arranged by cold, cool, and warm groups based on information presented later in Table 2. Additional distribution data should be added as it becomes available, then used to compute the probability of occurrence of each species within a watershed and within a lake. This will allow for more realistic expectations of which species should be present or absent in a given lake and aid in interpreting if the lake is indeed stressed.
2. Local accessibility filters reflect that colonization (and re-colonization) of a particular lake within a watershed depends on opportunity. Lakes with permanent and unrestricted connections to others are more accessible to the regional species pool than land-locked lakes. However, widespread stocking (intentional or unintentional) of sport and bait species has by-passed the accessibility filter for most waters. Consequently, the local accessibility filter is most relevant for species unrelated to fishing.
3. Physiological filters strain out species according to their physiological tolerances. The survival and relative success of Michigan species are primarily constrained by filters for pH, temperature, and dissolved oxygen (DO) concentration.
   - The pH of Michigan lakes varies from approximately 4 to 9. The acidic end of that range limits fish distribution and success in a significant number of lakes, especially in the Upper Peninsula (Schneider 1986). A summary of species tolerances compiled from the literature is given in Table 2. These tolerances should be interpreted as approximate guidelines for lake suitability. Confounding factors include elevated levels of aluminum and other toxins are often associated with low pH, early life stages are generally more sensitive than adults, and pH tends to be lowest in the spring of the year due to acid snow melt.
   - The temperature of Michigan lakes varies from 0^{o}C to approximately 24^{o}C. A lake's temperature is primarily influenced by air temperature and by depth, and for a few lakes and reservoirs, by significant inputs from cold tributary streams or groundwater. Low temperatures very rarely affect fish survival in lakes, but survival of coldwater species is restricted by summer maximum surface temperatures even in northern deep lakes. A species' growth is constrained, seasonally, by the volume of water within its growth preferenda. Thermal habitats for coolwater and warmwater species are available in virtually every lake, but with the exception of spring ponds, are lacking for coldwater species in unstratified lakes. Thermal preferences and tolerances are summarized in Tables 1 and 2. Thermal data, and secondary considerations, such as how other authors have classified species and breadth of north-south distribution pattern, were used to assign species into coldwater, coolwater, and warmwater groups. The boundaries of the three

groups were not clear-cut, especially between coolwater and warmwater, and the placement of several species (e.g., mottled sculpin, and johnny and Iowa darters) could be debated. However, this thermal classification has no significant bearing on analyses described later in the text.

- The dissolved oxygen (DO) concentration of lake water can vary from 0 to 14.6 ppm depending on the balance between temperature, aeration, photosynthesis, and respiration. Low values of DO commonly limit survival and may, to some extent, limit growth. Minimal DO levels for overall suitable summer habitat are approximately 3.0 ppm for coldwater and coolwater species and 2.5 ppm for warmwater species (Table 2). During winter, when metabolism is low, fish can tolerate much lower DO. Sensitivity to winterkill varies considerably by species (Table 2). Consequently, winterkill prone lakes and ponds have fish assemblages skewed toward the most DO tolerant species: central mudminnow, blackchin shiner, blacknose shiner, golden shiner, black bullhead, brown bullhead, yellow bullhead, bowfin, yellow perch, and northern pike. The predominance of those species can often be used as an indicator of a recent winterkill.

There have been previous successful attempts to quantitatively relate fish to thermal and DO characteristics of lakes. For Minnesota lakes, Stefan et al. (1995) incorporated temperature and DO criteria to compute volume and area of habitat seasonally available for coldwater, coolwater, and warmwater fish. However, this was based on guilds, and the authors suggest it may not work as well for individual species. For the Great Lakes, Magnuson et al. (1990) used only thermal criteria to estimate volume of coldwater, coolwater, and warmwater habitat. These modeling approaches have strong appeal, and their application to individual species should be more vigorously pursued. Earlier, Schneider (1975) suggested computing the volume of warm and cold habitats per lake as a measure of potentially available fish habitat. This could be expressed as the ratio of epilimnion volume (or thermocline plus hypolimnion volume) to total lake volume. More generally, Schneider (1975) related the distribution and relative abundance of major species in Michigan lakes to an oxygen-thermal classification on one axis and growing-degree days on the other axis. That oxygen-thermal classification scheme recognized six lake types. Four types were stratified lakes, based on midsummer data, grading from well oxygenated at the bottom to poorly oxygenated in the thermocline. Types five and six were unstratified and winterkill lakes, respectively.

4. Macrohabitat filters strain out species according to broad habitat preferences. Preferred habitat (indicated by larger populations) may be streams, reservoirs, lakes, and ponds/bogs. Some species have strong preferences along this flow gradient, others only weak or no apparent preferences. Table 1 summarizes generalized abundance of fishes by lake type based on fish distribution patterns. Within lakes, choices of habitat zone include shoreline edge, littoral, and offshore in the horizontal dimension; and benthic, midwater, and surface in the vertical dimension. Some species may use combinations of these depending on life stage and season. Table 3 summarizes my interpretations of preferences based on life history accounts and personal experiences.

5. Microhabitat filters are finer scale habitat characteristics that may influence a species' success. I evaluated the importance of water clarity, vegetation, substrate, and diet to each species based on life history accounts (Table 3).

6. Spawning and nursery requirements act as filters on a species' reproductive success. They may be significantly different from the general needs of juveniles and adults. One difficulty in evaluating spawning habitat suitability of a lake is that population success may be more due to spawning success in tributaries than to the quality of spawning habitat within the lake proper. For example, lake and reservoir populations of walleye, white sucker, pearl dace, and common shiner are often sustained by spawning in tributary rivers or streams. I assume in the following analysis that reproductive success is most likely for species that are (a) least substrate selective (mud and sand are more common in lakes than rubble), (b) least vulnerable to smothering of their eggs by silt, and (c) least vulnerable to predation on their eggs or fry. Consequently, species with buoyant eggs (e.g., yellow perch), short hatching times (summer temperatures), and which build nests and care for young (e.g.,

centrachids and bullheads) should have an advantage during eutrophication of lakes. In Table 4, I summarize relevant reproductive characteristics and judge the vulnerability of eggs and fry of each species to predation, siltation, submergent vegetation loss, edge modification, and stabilization of water levels.

Evaluating species sensitivity

The information in Tables 1-4 was used to predict the relative sensitivity of each species to 11 types of perturbations (Table 5).

Expected responses to winterkill and increasing acidity or temperature were straight forward based on field or laboratory data. Note temperature responses can be negative or positive depending on species and temperature range. For responses to eutrophication perturbations, I attempted to divide what are often combined effects into five components: decreases in summer DO, and increases in productivity, turbidity, siltation, and macrophytes. Sometimes these occur independently, affect different life stages, and can have either negative or positive effects depending on the species. Increasing productivity alone was thought of as a positive influence on a species' abundance unless it conceivably altered food chains and competitive outcomes. The independent effect of increasing turbidity was presumed to be negative for fish species highly dependent on sight feeding and potentially positive for species with other adaptations. Siltation, which can come from higher plant productivity or erosion of shorelines and uplands, was assumed to be a negative for substrate-dependent fish and benthic invertebrate food chains. Macrophytes tend to increase with eutrophication initially, then to decrease when shaded-out by algae or they become the target of control efforts by humans. Some fish species are adapted to plant habitats. The perturbations of edge loss and water level stabilization are partially correlated. However, loss of natural edge habitat to grass lawns, riprap, and bulkheads can occur with or without an alteration of the floodplain caused by water level stabilization. The eleventh type of perturbation reflects the ability of species to persist in the face of increasing predation or competition from other species. Useful examples include certain minnows that seem to thrive only in bogs and other waters lacking larger fishes, and certain sunfishes that seem to be weak competitors in the presence of other sunfishes.

The coldwater group, as is well known, is relatively sensitive to temperature, DO, and related eutrophication effects in Michigan (Table 5). Extremely high productivity generally favors white sucker, white crappie, black bullhead, and common carp. Turbidity benefits mostly the same species, but the white sucker is quite plastic and thrives in clear waters as well. Silt has a negative effect on all species but less so for yellow perch and nest builders which are less dependent on substrate quality. Species most dependent on macrophytes are pugnose shiner (very limited distribution), pugnose minnow, least darter, lake chubsucker, and tadpole madtom. Species most sensitive to edge modification are expected to include banded killifish, grass pickerel, and northern pike. On the other hand, the sand shiner is likely to benefit from creation of sandy beaches by humans. Water level stabilization should have a large (but not always catastrophic) effect on northern pike reproduction.

In addition to rankings of sensitivity for each of the 11 perturbations, the last column in Table 5 contains a brief characterization of a species' value as an indicator. The most potentially useful, indicated in bold type, are expected to be losses of lake herring (to decreasing thermocline DO), pugnose shiner and least darter (to decreasing clarity and macrophytes), lake chubsucker (to decreasing macrophytes), and blacknose and blackchin shiners (to declines in natural edge and clarity). The most sensitive indicators of acidification are blacknose shiner, common shiner, mimic shiner, fathead minnow, bluntnose minnow, and logperch.

Species sensitivities derived from this analysis were compared to species tolerance/intolerance rankings reported elsewhere (Table 6). Additional comparisons, including more streams, may be found in Whittier and Hughes (1998). The basis for such rankings were not carefully explained by other authors, but probably reflected a general tolerance to man-induced eutrophication and siltation based on life history accounts or unpublished field observations. There is general agreement for species ranked by multiple authors, with the exceptions of lake chubsucker, grass pickerel, golden shiner, bluntnose minnow, and fathead minnow. I feel the first two species have potential value as indicators of macrophyte loss, which is only an indirect correlate of eutrophication. The golden shiner may prefer macrophytes (perhaps as shelter from predators) but seems less habitat-dependent and in my judgement is not a reliable indicator of human disturbance. The bluntnose minnow and the fathead minnow have been classified as tolerant by most observers, but analyses of lakes in Wisconsin (Jennings et al. 1999) and in the northeast (Whittier and Hughes 1998) suggested they are intolerant or moderately intolerant. In Michigan, these minnows seem to be relatively tolerant but rigorous analysis is lacking.

A Proposed Application to Assess Habitat Quality

Lake fish data may be used to evaluate habitat quality and, more traditionally, fishery quality and potential from a management perspective. The first step in evaluating the quality of a lake's habitat is to collect as many fish species as possible, then estimate relative abundance of each species by number and weight, stratified by gear. Information on size distributions and growth rates should also be collected to evaluate sport fishing status and potential. Possible interpretations of fish survey data from a fisheries management perspective are discussed elsewhere (Schneider 2000b).

To evaluate habitat change for a lake, the best method is to compare "before-after" survey data whenever "before" data are available. Look for trends in presence and relative abundance of sensitive species (Tables 5 and 6). When "before" data are not available, the 11 metrics proposed below may be used to infer the effects of perturbations from "after" data. The metrics may also be used to evaluate "before" or "after" status. Scores are ranked as indicated.

Metrics of habitat quality

1. Native fish fauna: Deductions for non-native species.
    - Count number of self-sustaining, exotic, and generally undesirable species (listed below). The fish fauna of the lake in question almost certainly cannot be reverted to its pristine status. Subtract 1 point per species from the pristine score of 5.
    - Count any Michigan species, not native to the lake, originating from intentional stocking, but now self-reproducing. The origin of species for a given lake may be difficult to determine because many species, in addition to those listed below, were widely distributed during 140 years of intensive fish management. This lake cannot be reversed either. Subtract 1 additional point per species.
    - Count any species, not native to the lake, maintained solely by periodic stocking. This lake could be moved back toward pristine fish assemblages by cessation of stocking. Subtract ½ additional point for any counted.
    - The minimal score is 1.

Generally undesirable exotics:	*Some commonly stocked species*:
Alewife	Salmonid spp
Rainbow smelt	Trout spp
Common carp	Lake whitefish
Goldfish	Bass spp
Sea lamprey	Muskellunge
Goby spp	Northern pike
Ruffe	Walleye
	Yellow perch
	Bluegill
	Redear sunfish
	Channel catfish
	Flathead catfish
	Fathead minnow
	Golden shiner

Score* ⑤ ○ ④ ○ ③ ○ ② ○ ①

*5 = pristine; 1 = poor

2. Winterkill: Intolerant species ratio (table below).
   - Calculate the percentage: intolerant / (intolerant + tolerant), based on species listed below, either by number of species present or by weight of fish caught. Score percentage as indicated below. Key species are bluegill and largemouth bass, which are widespread and usually comprise >50% of fish community biomass in Lower Peninsula lakes (Schneider 1981) and are moderately vulnerable to winterkill. Note that lakes with limited accessibility to the regional species pool may have, by chance, a subnormal fauna lacking intolerants. Note also that lakes completely dominated by yellow perch and northern pike may or may not be prone to winterkill. Direct evidence of winterkill is always preferred.

Winterkill tolerant:	*Winterkill intolerant*:
All bullheads	All trouts
Pumpkinseed	Lake whitefish
Yellow perch	Burbot
Bowfin	Lake herring
Goldfish	Mottled sculpin
Central mudminnow	Rock bass
Golden shiner	Walleye
Blacknose shiner	Smallmouth bass
Blackchin shiner	Banded killifish
Iowa darter	Largemouth bass
	Bluegill
	Redear sunfish
	Longear sunfish
	Spottail shiner
	Sand shiner

% by species	**>40**	**30-40**	**20-29**	**1-19**	**0**
Score*	⑤	④	③	②	①

*5 = no; 1 = severe

3. Acidity: Presence of indicator species (listed below).
   - Score 1 if no fish are present and lake is known to be acidic (pH<4).
   - Score 2 if only acid-tolerants are present (pH 4-5).
   - Score 3 if acid-tolerants and other species are present (pH>5).
   - Score 5 if any intolerants are present (pH>5.5).

Acid tolerant:	*Acid intolerant*:
Brook trout	Logperch
Yellow perch	Blacknose shiner
Lake chub	Common shiner
Finescale dace	Mimic shiner
Brook stickleback	Fathead minnow
Bluegill	Bluntnose minnow
Pumpkinseed	
Central mudminnow	

Score* ⑤ ③ ② ①

*5 = good; 1 = severe

4. Thermocline/hypolimnion dissolved oxygen: Presence of indicator species (listed below).
   - Score 5 for presence of lake trout (high requirement).
   - Score 4 for presence of any species with medium requirement.
   - Score 3 for absence of medium indicators and Winterkill metric score = 5.
   - Score 2 if Winterkill metric score = 2 to 4.
   - Score 1 if Winterkill metric score = 1.

Note: These indicator species do not necessarily occur in all lakes with high DO; stocking is also a factor. Lake herring occur in both stratified well-oxygenated lakes and unstratified lakes that are cool, northern, and large.

High requirement:	*Medium requirement*:
Lake trout	Burbot
	Lake whitefish
	Brook trout
	Brown trout
	Rainbow trout
	Lake herring
	Alewife
	Rainbow smelt

Score* ⑤ ④ ③ ② ①

*5 = good; 1 = severe

5. Productivity/enrichment: Relative abundance (catch by number or weight) of indicator species (listed below).

- Copy scores of 4 or 5 for thermocline/hypolimnion DO metric (Metric 4.).
- Otherwise, use ratio below that provides the lowest score (if species present).
- Otherwise, score 4.

Note: Secchi disk transparency, chlorophyll a, or oxygen deficits in relation to basin morphometry are more reliable indicators of productivity.

Ratio by number or weight:	*Percent:*				
Black/yellow bullheads			<10	10-89	>90
All bullhead/total weight			<15	15-69	>70
White/black crappie				0-89	>90
Black crappie/total		<5	5-19	20-69	>70
Common carp weight/total weight			<5	5-69	>70
Score*	5	4	3	2	1

*5 = low; 1 = high

6. Turbidity: Indicator species (listed below).

- Copy scores of 1 or 2 from Productivity/enrichment metric (Metric 5).
- Score 3 if no intolerants present.
- Score 4 if any intolerants present.

Turbidity intolerant:	*Turbidity tolerant:*
All trout	White crappie
Burbot	Black bullhead
Pugnose shiner	Common carp
Banded killifish	
Iowa darter	
Least darter	
Blacknose shiner	
Common shiner	

Score* 4 3 2 1

*4 = good; 1 = severe

7. Silt: presence of indicator species (listed below).
    - Copy scores of 1 or 2 from Productivity/enrichment metric (Metric 5.).
    - Score 4 for presence of any intolerants.
    - Score 3 if otherwise.

Silt intolerant:		*Silt tolerant*:
All trout	Northern pike	Black bullhead
Lake whitefish	Muskellunge	
Burbot	Trout-perch	
Lake herring	Blacknose shiner	
Walleye		

Score* ④ ③ ② ①

*4 = good; 1 = severe

8. Macrophytes: Presence and abundance of indicator species (listed below) supplemented with bluegill growth data.

    Bluegill growth is evaluated by comparing the observed average length at age to the Michigan average (Schneider et al. 2000); negative growth deviations >25 mm are considered to be stunted. The best warmwater lake condition is an intermediate abundance of macrophytes (areal coverage of approximately 33% — Schneider 2000a); therefore, a score of 5, in the center of the abundance scale, is considered to be optimal. Simple presence of strongly or mildly dependent species is an indicator of plant presence but not a reliable indicator of lake-wide plant abundance; a small patch of vegetation in a relatively barren lake may harbor a few closely dependent species.

    - Score 1 (too high) if plants are known to be abundant and stunted bluegill comprise >78% of the total fish weight or Winterkill metric = 1 or 2 (Metric 2.).
    - Score 5 if either bluegill, largemouth bass, or northern pike are common or abundant and bluegill growth ≥ Michigan average.
    - Score 3 if ≥4 dependents.
    - Score 2 if 1-3 dependents.
    - Score 1 (too low) if no dependent species are present.

Macrophyte strongly dependent:	*Macrophyte mildly dependent*:	
Pugnose shiner	Northern pike	Longear sunfish
Pugnose minnow	Bluegill	Yellow bullhead
Least darter	Largemouth bass	Bowfin
Grass pickerel	Muskellunge	Lognose gar
Spotted gar	Brassy minnow	
Lake chubsucker	Iowa darter	
Tadpole madtom	Warmouth	

Score* ⑤ ③ ② ①

*5 = good; 1 = too high or too low

9. Edge modification: Presence of indicator species (listed below) and altered shoreline.

- Score 5 if <10% alteration or ^{3}4 intolerants.
- Score 4 if 2 or 3 intolerants and ≥10% alteration.
- Score 3 if 1 intolerant.
- Score 2 if 0 intolerants and 50-80% alteration.
- Score 1 for presence of 0 intolerants and 80-100% alteration.

Edge modification intolerant:	*Edge modification tolerant*:
Northern pike	Sand shiner
Banded killifish	
Grass pickerel	
Blacknose shiner	
Blackchin shiner	
Blackstripe topminnow	

Score* 5 4 3 2 1

*5 = good; 1 = severe

10. Level stabilization: Presence of dam and indicator species (northern pike).

- Score 1 if no northern pike present and water level controlled.
- Score 2 if northern pike sparse and water level controlled.
- Score 3 if northern pike sparse or common.
- Score 4 if northern pike abundant.
- Score 5 if no water level control.

Score* 5 4 3 2 1

*5 = good; 1 = severe

11. Predation/competition tolerance: Prominence of indicator species (listed below).

A high abundance of these species indicates a fish assemblage lacking the usual dominants, but does not necessarily indicate an unnatural condition for certain macrohabitats.

- Score 3 if intolerant bog/brook minnows are abundant (usually natural cause).
- Score 2 if "weak" sunfish exceed other sunfish (sometimes disturbed habitats).
- Score 5 if otherwise.

Intolerant bog/brook minnows:	*Weak competitors*:
N. redbelly dace	Green sunfish
Finescale dace	Longear sunfish
Pearl dace	
Brassy minnow	
Brook stickleback	
Fathead minnow	

Score* 5 3 2

*5 = good; 2 = severe

Score Card

The scoring for each perturbation type can be condensed on a summary score card (below), then evaluated either individually, or summed or averaged in various meaningful ways. Low scores can be thought of as impairments to ideal fish habitat, but can be either natural or anthropomorphic in origin. If all 11 scores are simply summed, the perfect score is 53 (the maximum score for metrics 6 and 7 is 4, not 5). Perfection would be a deep, oligotrophic, non-acidic lake with moderate densities of macrophytes, which was unaffected by species introductions, low DO, eutrophication, or modifications of edge and water levels. However, the pristine condition of most Michigan lakes is relatively shallow, mesotrophic, and without DO in the colder waters. The best possible total score for these lakes is 50. Many other lakes (and ponds) are naturally so shallow and productive they are vulnerable to winterkill irrespective of human influences; at best they could score 31. The lowest possible total score is 12.

Lake Name: ______________________ Sampling Date: ______________________

	Score									
Metric	5		4		3		2		1	
1. Native fish fauna	○	○	○	○	○	○	○	○	○	_____
2. Winterkill	○		○		○		○		○	_____
3. Acidity	○				○		○		○	_____
4. Thermocline/hypolimnion DO	○		○		○		○		○	_____
5. Productivity/enrichment	○		○		○		○		○	_____
6. Turbidity			○		○		○		○	_____
7. Silt			○		○		○		○	_____
8. Macrophytes	○				○		○		○	_____
9. Edge modification	○		○		○		○		○	_____
10. Level stabilization	○		○		○		○		○	_____
11. Predation/competition	○				○		○			_____
									Total Score	_____

Among the 11 metrics, winterkill, acidity, and intolerant bog minnows are very serious because low scores eli minate nearly all sport fishing potential and override the effects of other perturbations. Only if each of these three have scores of 4 or more is it meaningful to evaluate the other metrics for eutrophication or other anthropomorphic effects.

The metrics for fish fauna, edge modification, and level stabilization together clearly indicate anthropomorphic activities. Low scores on all three indicate human activities and high scores indicate a relatively pristine condition. Note that other anthropomorphic effects (such as acid rain, nutrient loading, or macrophyte alteration) may show up in other metrics. By now, most Michigan lakes with recreational value have been modified to some degree.

Differences in basin morphometry account for many of the differences among pristine Michigan lakes and affect the interpretation of impairment. To interpret if the metric scores for Winterkill or Thermocline/hypolimnion DO represent unnatural values for a particular lake, consider the ratio of epilimnion volume to total lake volume. This ratio integrates the important morphometric components of lake depth (basin shape) and area (wind fetch influences thermocline depth). Stratification and DO characteristics of a lake can be predicted from equations (Hondzo and Stefan 1996; Stefan et al.

1996). In addition, Schneider (1975) compiled empirical data for 300 Michigan lakes that can guide expectations (Table 7).

These volume ratios indicate that lakes with similarly small epilimnions (32 to 37%) can vary widely in oxygen-thermal type (1-4). This is attributed to the progressively higher productivity of lakes in Types 3 and 4 that strips more DO from the water column. More useful here are the upper ranges of epilimnion ratios (63 to 99%); these indicate relatively low productivity and basic morphological constraints. Thus, Type 1 lakes (which can support highly DO sensitive lake trout and burbot, score 5) have epilimnions as large as 63% of the total volume. Therefore, any lake with >63% epilimnion cannot be expected to score as high as 5. Lakes capable of supporting coldwater fish with medium DO requirements are Types 1-3, and any epilimnion >85% cannot be expected to score 4 or more. Another way of expressing this is any lake with a mean depth >24 feet has trout potential unless it is unusually productive. Cooler northern lakes are less constrained (Schneider 1975). Winterkill lakes (Type 6 and score 1) are relatively shallow and productive but were not statistically described by depth or volume proportions.

Some test examples

A first draft of the scoring system was subjectively evaluated with data from 40 Michigan lakes. A rigorous analysis was inappropriate because the data were incomplete and may have been outdated. The evaluation lakes were diverse, including the 20 largest Michigan lakes (data summarized by Laarman 1976); private lakes (J. C. Schneider unpublished); and Upper Peninsula softwater lakes, relatively pristine warmwater lakes, and winterkill lakes (MDNR files). Subsequently, slight modifications were made in the scoring system that were incorporated in the second draft and presented above. The system performed well overall compared to intuitive expectations. It identified extreme scores well, but seemed to be less definitive in the midrange scores.

An example of the scoring process for Green Lake, Oakland County, is as follows:

Metric 1. Native fish fauna—Score 3.5 (5 - 1.5) because of the presence of common carp and stocked, non-reproducing walleye.

Metric 2. Winterkill—Score 5 because the ratio is >40%. Intolerants (lake herring, rock bass, walleye, largemouth bass, bluegill, longear sunfish, and sand shiner) divided by the sum of tolerants (pumpkinseed, yellow perch, blacknose shiner, and blackchin shiner) plus intolerants (the seven above) = 8/11 = 73%.

Metric 3. Acidity—Score 5 because of the presence of intolerant blacknose shiner and bluntnose minnow.

Metric 4. Thermocline/hypolimnion DO—Score 4 because of the presence of lake herring.

Metric 5. Productivity/enrichment—Score 4 (copy Metric 4).

Metric 6. Turbidity—Score 4 because of the presence of blacknose shiner.

Metric 7. Silt—Score 4 because of the presence of intolerants (lake herring, walleye, northern pike, and blacknose shiner).

Metric 8. Macrophytes—Score 3 because the bluegill growth deviation is –12 mm and ≥4 dependents are present (northern pike, bluegill, largemouth bass, longear sunfish, longnose gar).

Metric 9. Edge modification—Score 4 because 3 intolerants are present (northern pike, blacknose shiner, and blackchin shiner). (Note: this seems a bit high because very little natural shoreline remains.)

Metric 10. Level stabilization—Score 3 because northern pike are common.

Metric 11. Predation/competition—Score 5 because the indicator species are not unusually abundant.

The total score for Green Lake is 44.5, short of the perfect score of 53, but quite good for a lake in an urban setting. A good score is made possible by the lake's relatively great depth, and associated high DO in the thermocline, which create suitable habitat for the sensitive lake herring.

Lake Name: Green Lake, Oakland Co. Sampling Date: May 2000

Metric	Score 5		4		3		2		1	
1. Native fish fauna	○	○	○	X	○	○	○	○	○	3.5
2. Winterkill	X		○		○		○		○	5
3. Acidity	X				○		○		○	5
4. Thermocline/hypolimnion DO	○		X		○		○		○	4
5. Productivity/enrichment	○		X		○		○		○	4
6. Turbidity			X		○		○		○	4
7. Silt			X		○		○		○	4
8. Macrophytes	○				X		○		○	3
9. Edge modification	○		X		○		○		○	4
10. Level stabilization	○		○		X		○		○	3
11. Predation/competition	X				○		○			5
									Total Score:	44.5

Limitations

A major limitation of the method is that complete information on fish diversity, including minnows and other small species, is required in addition to samples of the larger sport fish. Many of the small species are useful indicators of lake quality. Such complete data on fish species presence and abundance have not been systematically collected from Michigan lakes for several decades. However, plans for future MDNR sampling will correct this deficiency. A minor limitation of the method is that metrics for Fish fauna, Macrophytes, Edge modification, and Level stabilization require supplemental information (in addition to traditional fish surveys) to better identify extreme scores. The final judgement of the condition of a lake should take into account natural limitations due to morphometry and indicators of water quality in addition to fish assemblages.

The system proposed here needs to be further validated and calibrated with survey data from more Michigan lakes. Most importantly, the predicted and assumed sensitivities of various species of fish to perturbations and habitat conditions need to be validated by field studies.

Acknowledgements

W. C. Latta, E. Rutherford, P. Seelbach, and K. Wehrly provided helpful reviews. This analysis and report were funded by the Michigan Department of Natural Resources through Federal Aid in Sport Fish Restoration, Project F-35-R, Study 668.

Table 1.–Synopsis of fish distribution in Michigan by area and, generally, relative abundance by lake type[1]. Species that rarely occur in standing water are excluded.

Species	Michigan distribution[2]	Lake types				
		Large >1300 ha	Small <1300 ha	Bogs/ ponds	Reser-voirs	Typical oxygen-thermal type[3]
Cold Species						
Lake trout *Salvelinus namaycush*	N, spotty	c	s			1, 2
Brook trout *Salvelinus fontinalis*	mostly stocked	s	c	c	c	1, 2
Brown trout *Salmo trutta*	mostly stocked	c	c		c	1, 2, 3,
Rainbow trout *Oncorhynchus mykiss*	mostly stocked	c	c		s	1, 2, 3
Lake whitefish *Coregonus clupeaformis*	N, spotty	c	s			1, 2, 3, 5
Burbot *Lota lota*	N, spotty	c			s	1
Lake herring *Coregonus artedi*	wide	c	c			1, 2, 3
Rainbow smelt *Osmerus mordax*	spotty	c	s			1, 2, 3
Mottled sculpin *Cottus bairdi*	N, spotty	c	s		c	1, 2, 3
Cool Species						
Smallmouth bass *Micropterus dolomieu*	wide	c	a		a	2, 3, 5
Walleye *Stizostedion vitreum*	wide	a	c		a	3, 4, 5
Rock bass *Ambloplites rupestris*	wide	c	c		c	2, 3, 5
White sucker *Catostomus commersoni*	wide	a	a		a	2, 3, 5
Yellow perch *Perca flavescens*	wide	a	a	s	c	2, 3, 4, 5, 6
Northern pike *Esox lucius*	wide	c	c		c	3, 4, 5, 6
Muskellunge *Esox masquinongy*	spotty	s	s			4, 5
Alewife *Alosa pseudoharengus*	GL fringe, spotty	c	s			1, 2, 3
Logperch *Percina caprodes*	wide	c	s			2, 3, 5
Trout-perch *Percopsis omiscomaycus*	GL fringe, N-LP, Ontonogon R.	a	s			1, 2-5?
Lake chub *Couesius plumbeus*	GL fringe, spotty	s				1, 2
Emerald shiner *Notropis atherinoides*	spotty, exc W-UP	a				1, 2

Table 1.–Continued.

Species	Michigan distribution[2]	Lake types: Large >1300 ha	Small <1300 ha	Bogs/ ponds	Reser- voirs	Typical oxygen-thermal type[3]
N. redbelly dace *Phoxinus eos*	wide exc S-LP, W-C			a		4, 5, 6
Finescale dace *Phoxinus neogaeus*	UP, N-LP exc W-C-LP	s	s	a		4, 5, 6?
Pearl dace *Margariscus margarita*	N		s	c	s	4, 6
Pugnose shiner *Notropis anogenus*	LP		s			3, 4, 5
Brook stickleback *Eucalia inconstans*	wide?			c		6
Banded killifish *Fundulus diaphanus*	wide exc N-UP		s	s		3, 4, 5
Brassy minnow *Hybognathus hankinsoni*	N of 43^{o}N latitude		s	a		4, 5
Johnny darter *Etheostoma nigrum*	wide	s	c		c	3, 4, 5
Iowa darter *Etheostoma exile*	wide	s	c	s	s	3, 4, 5
Least darter *Etheostoma microperca*	wide exc W-UP		s			3, 4, 5?
Warm Species						
Bluegill *Lepomis macrochirus*	wide	c	a	s	c	3, 4, 5
Largemouth bass *Micropterus salmoides*	wide	s	a		c	3, 4, 5
Pumpkinseed *Lepomis gibbosus*	wide	s	a	s	s	3, 4, 5, 6
Black crappie *Pomoxis nigromaculatus*	W-UP, S-LP, N-E-LP	s	a		a	3, 4, 5
White crappie *Pomoxis annularis*	spotty LP		c		a	4
Warmouth *Lepomis gulosus*	S-LP, W-C		c			4, 5
Redear sunfish *Lepomis microlophus*	S-LP from stocking					
Green sunfish *Lepomis cyanellus*	S-C-LP		c		c	4, 5, 6
Longear sunfish *Lepomis megalotis*	LP		s		c	4, 5
Grass pickerel *Esox americanus*	S-LP		c	s	s	4, 5, 6
Channel catfish *Ictalurus puntatus*	LP, often stocked		s		a	4, 5
Yellow bullhead *Ameiurus natalis*	S of Straits	s	c		s	3, 4, 5

Table 1.–Continued.

Species	Michigan distribution[2]	Lake types: Large >1300 ha	Small <1300 ha	Bogs/ ponds	Reser- voirs	Typical oxygen-thermal type[3]
Brown bullhead *Ameiurus nebulosus*	wide exc W-UP	s	c		c	3, 4, 5, 6
Black bullhead *Ameiurus melas*	wide	s	c	c	a	4, 5, 6
Bowfin *Amia calva*	lower	s	c		s	4, 5, 6
Longnose gar *Lepisosteus osseus*	LP	s	c		s	3, 4, 5
Spotted gar *Lepisosteus oculatus*	S-W-LP	s	c		s	3, 4, 5
Common carp *Cyprinus carpio*	wide	s	c		a	4, 5, 6
Goldfish *Carassius auratus*	S-LP		s	c	c	4, 5, 6
Gizzard shad *Dorosoma cepedianum*	Near GL, S of Straits	s	s		s	4, 5
Lake chubsucker *Erimyzon sucetta*	S-LP, rare N-LP		c			4, 5
Spottail shiner *Notropis hudsonius*	wide, most near GL	a	c		s	3, 4, 5
Blacknose shiner *Notropis heterolepis*	wide	s	c	s		3, 4, 5
Blackchin shiner *Notropis heterodon*	wide exc W-UP	s	c	s		3, 4, 5
Common shiner *Luxilus cornutus*	wide		c	c	s	5, 6
Striped shiner *Luxulis chrysocephalus*	S-LP		s			
Golden shiner *Notemigonus crysoleucas*	wide	s	c	s	s	4, 5, 6
Mimic shiner *Notropis volucellus*	wide exc W-UP	c	c		c	4, 5
Sand shiner *Notropus stamineus*	wide exc C-UP	c	c		s	4?
Spotfin shiner *Cyprinella spilopterus*	S of 45°N	s	s		c	3, 4, 5
Pugnose minnow *Opsopoeodus emiliae*	S-E-LP		s			4, 5?
Fathead minnow *Pimephales promelas*	wide		s	a	s	4, 6
Bluntnose minnow *Pimephales notatus*	wide	c	c	s	c	3, 4, 5, 6
Blackstripe topminnow *Fundulus notatus*	S-LP, rare N-LP		c		c	3, 4, 5

Table 1.–Continued.

Species	Michigan distribution[2]	Lake types: Large >1300 ha	Small <1300 ha	Bogs/ ponds	Reser- voirs	Typical oxygen-thermal type[3]
Central mudminnow *Umbra limi*	wide	s	s	a	s	4, 6
Brook silverside *Labidesthes sicculus*	S-LP		c		c	3, 4, 5
Tadpole madtom *Noturus gyrinus*	LP		s			

[1]Relative abundance (by species, across lake types, in waters with favorable habitat): a = abundant; c = common; and s = sparse. Based on general descriptions of habitat preference for the species by Hubbs and Lagler (1964), Scott and Crossman (1973), Trautman (1981), and Becker (1983), and on MDNR collections.

[2]Width of distribution and/or frequency based on Michigan Fish Atlas Maps (2000). C = central, E = eastern, N = northern, S = southern, W = western; LP = Lower Peninsula, UP = Upper Peninsula; GL = Great Lakes; wide = widespread and common; spotty = scattered locations; exc = except, and ? = uncertain.

[3]Limnological lake types with the best habitat and where the species is most likely to be abundant. Schneider's (1975) lake types based on midsummer temperature-dissolved oxygen profiles or fish kills: 1 = stratifies with 2+ ppm DO from surface to bottom; 2 = stratifies with DO<2ppm in hypolimnion; 3 = stratifies with DO>2 ppm in lower thermocline; 4 = stratifies with DO<2 ppm in top of thermocline; 5 = unstratified; 6 = winterkill prone, and ? = uncertain.

Table 2.–Temperature preferences and tolerances, and dissolved oxygen (DO) and pH tolerances, for fish species based on published references.

	Temperature (°C)			Lowest pH	
Species	Maximum[1]	Preferred or good growth[2]	Minimum DO[3] (ppm)	Critical[4]	MI,WI,ONT observed[5]
Cold Species	**23.4**	**9.0-18.5[e]**	**>3.0**		
Lake trout		10[m,b],11[p],12-16[w]		4.4-6.8	5.5[x]
Brook trout	22.3	13-16[w],14[e],16[p]		4.5-5.0	4.4[x]
Brown trout	24.1	12-16[w],18[e]		4.5-5.5	5.5[x]
Rainbow trout	24.0	12-17[w],18[e],11[p]		5.5-6.0	5.4[x]
Lake whitefish		12[m],13[p],14-17[w]		<4.4	
Burbot		15-18[w],17[p]		5.2-6.0	6.0[y]
Lake herring		18[w],16[p]		4.4-4.7	5.5[x], 6.2[y]
Rainbow smelt		11-16[w],6-13[b]			
Mottled sculpin	24.3	17[w,p]			5.5[y]
Cool Species	**30.4**	**16.3-28.2**	**>3.0**		
Smallmouth bass	29.5	28-31[w], 28[e], 21-27[b]		4.4-6.0	4.0[x], 5.6[y]
Walleye	29.0	20[m], 22[e], 20-23[w]		5.2-6.0	6.0[x], 5.5[y]
Rock bass	29.3	26-29[w], 27[e], 29[p]		4.2-5.2	5.5[x], 5.6[y]
White sucker	27.3	24[w], 26[e],16[p]		4.2-5.2	5.2[x], 4.9[y]
Yellow perch	29.1	23[m], 27[e], 17-27[w], 21[p]	0.3-0.4	4.2-4.8	4.0[x], 4.4[y]
Northern pike	28.0	20-21[w,p], 13-23[b]	0.3-0.4	4.2-5.2	4.0[x], 5.5[y]
Muskellunge		22-27[w], 17[b], 25[p]			5.6[y]
Alewife		11-25[w], 19[k]			
Logperch					6.3[y]
Trout-perch		15-18[w]		5.2-5.5	6.2[y]
Lake chub				4.5-4.7	4.7[z]
Emerald shiner	31.6	24-29[w], 25[b], 23[p]			
N. redbelly dace		25[w]			5.5[x], 5.3[y], 5.0[z]
Finescale dace					4.7[z]
Pearl dace		16[p]			5.5[x], 4.7[z]
Pugnose shiner		*15-18[w]*			
Brook stickleback					4.0[x], 5.4[y], 4.7[z]
Banded killifish		24[p]		<5.1	
Brassy minnow					
Johnny darter	26.5	24[w], 23[p]		5.0-5.9	5.5[x], 6.2[y]
Iowa darter			<0.2	4.8-5.9	5.5[x], 6.2[y], 5.1[z]
Least darter					
Warm Species	**>30.4**	**19.7-32.3**	**>2.5**		
Bluegill	36	30[w,e], 31[p]	0.6	<4.2	4.4[x], 4.5[y]
Largemouth bass	31.7	28[m], 29[e], 25-30[w,b]	0.6	4.4-5.2	5.4[x], 4.6[y]
Pumpkinseed	29.1	25-31[w]	0.3-0.4	<4.2-5.2	4.0[x], 4.9[y]
Black crappie	30.6	22-28[w], 27-28[e]	0.3-0.4		5.3[x], 5.8[y]
White crappie	31.3	*19-25[w]*			
Warmouth	34		0.3-0.4		
Redear sunfish					
Green sunfish	31.7	28[w], 31[e]			5.2[x]
Longear sunfish	34				
Grass pickerel		26[w,b]	0.3-0.4		
Channel catfish	31.6	30[e]			

Table 2.–Continued.

	Temperature (°C)			Lowest pH	
Species	Maximum[1]	Preferred or good growth[2]	Minimum DO[3] (ppm)	Critical[4]	MI,WI,ONT observed[5]
Warm Species (continued)					
Yellow bullhead		28[w]	0.2-0.3		5.5[x], 4.9[y]
Brown bullhead	29.5	25-28[w], 28[e], 30[p]	0.2-0.3	4.5-5.2	5.0[x]
Black bullhead	34				5.0[x], 4.5[y]
Bowfin		30[w]	<0.2		
Longnose gar	31.5	26[w], 31[k]			
Spotted gar		*15-17*[w]			
Common carp	31.4	25-32[w], 31[e], 29[p]			
Goldfish		25-28[w]			
Gizzard shad	34	28-31[w,e], 23-24[b]			
Lake chubsucker			0.3-0.4		
Spottail shiner					
Blacknose shiner			<0.2		5.5[x], 6.5[y], 5.8[z]
Blackchin shiner			<0.2		
Common shiner	29.2	22.2[s]		<5.7	5.5[x], 6.2[y], 5.4[z]
Striped shiner					
Golden shiner	30.8	22-29[w], 21[p], 24[e]	0.2-0.3	4.8-5.2	5.4[x], 5.2[y], 4.7[z]
Mimic shiner					6.2[y]
Sand shiner	31.8				
Spotfin shiner		29[w]			
Pugnose minnow					
Fathead minnow	34	26-29[w], 27[p]			5.8[x], 6.7[y], 5.5[z]
Bluntnose minnow	30.1	27[w], 28[p]		5.7-6.0	5.8[x], 6.2[y], 5.6[z]
Blackstripe topminnow			<0.5		
Central mudminnow		29[p]			4.5[x], 4.0[y]
Brook silverside		25[k]	<0.5		
Tadpole madtom			<0.2		

[1]95th percentile of maximum weekly temperatures at sites of occurrence in US (Eaton et al. 1995; Eaton and Shiller 1996).

[2]Temperature preference or best growth (rounded to 1°C) as compiled by: [b]Becker (1983); [e]Eaton et al. (1995); [k]Minns, King, and Portt (1993); [m]Magnuson, Meisner, and Hill (1990); [p]Portt, Minns, and King (1988); [s]Barila et al. (1982); and [w]Wismer and Christie (1987). Values in italics are inconsistent with other sources.

[3]Approximate lowest dissolved oxygen species can tolerate in winter (Cooper and Washburn 1949). Ranges for species groups (shown in bold) were used by Stefan et al. (1996) as year-around minimum requirements.

[4]Critical pH is the approximate pH at which population decline has been observed in acidified waters (Haines 1981). Shown for banded killifish is the pH avoided (Peterson et al. 1989).

[5]Lowest known pH for Michigan lakes where the species was collected. Sources: [x](Schneider 1986); Wisconsin [y](Rahel and Magnuson 1983); and Ontario [z](Matuszek et al. 1990).

Table 3.–Ranks (1=most preferred; 4=least preferred) of summer habitat preferences and diets of adult/juvenile fishes in Michigan lakes.[a]

	Location			Depth			Water clarity					Vegetation			Substrate[b]				Diet													
Species	Edge	Littoral zone	Offshore	Surface	Midwater	Bottom	Very clear	Clear	Slightly turbid	Turbid	Brown	Much	Some	Sparse/unimportant	Rocky	Gravel/sand	Soft	Silt	Detritus	Algae	Macrophyte	Phytoplankton	Zooplankton	Terrestrial	Emerging insects	Epibenthos	Benthos	Mollusca	Crayfish	Fish	Higher vertebrates	Scavenger
Cold Species																																
Lake trout			1		1	2	1	2						1	1	2											2			1		
Brown trout		2	1	3	1	2	2	1						1									3	3	2	2	2		2	1		
Rainbow trout		2	1	2	1		2	1						1									1	2	2	3	2		3	3		
Lake whitefish			1		2	1	2	1	3					1	2	1	3						3				1	2		3		
Burbot			1		2	1	1	2						1	2	1	3										2			1		
Lake herring			1		1		2	1						1									1		3		3			3		
Rainbow smelt			1		1		2	1						1									1		3		3			2		
Mottled sculpin		1	2			1		1						1		1							2			1			3			
Cool Species																																
Smallmouth bass		1	3	3	2	1	1	1	2				2	1	1	2											2		1	1		
Walleye		1	1		2	1		3	1	2	2		2	2	1	2	3										2		2	1		
Rock bass		1	3		1	2	2	1	2				1	2	1	2											1		2	1		
White sucker		3	1			1	2	2	2	2			2	1		1	1		2				3				1					
Yellow perch		1	1		2	1	3	1	2	3	2	2	1	3	3	1	2	3					2			2	1		3	1		
Northern pike		1	3	3	1			1	2			1	2																	1	2	
Muskellunge		1	3	2	1			1	2			1	2	3																1	2	
Alewife			1		1			1	2					1								2	1		3							
Logperch		1	3			1		1	3					1	1	2											1					
Trout-perch			1			1		1	1					1		1							2				1					
Lake chub		1	3		2	1		1	2	3			2	1		1					3		3				1					
Emerald shiner		2	1	1	2	3		1	2					1						3			2	2	3		1			4		
N. redbelly dace		1	3		1	2		2			2	2		2			2	1	2	1	2		2	2			2			4		
Finescale dace		1	2		1	2		2			1		2	2		2	2	2		2				2			1	2		4		
Pearl dace		1			1			1	3		2			1						3	3		2	3			1					
Pugnose shiner		1			1		1	2				1								1		2	1									
Brook stickleback		1			1			1	2		1		1										1			2	2					
Banded killifish	1	2		1	2	3	1					2	1	2									1		2		1					

Table 3.–Continued.

Species	Location			Depth			Water clarity					Vegetation			Substrate[b]				Diet													
	Edge	Littoral zone	Offshore	Surface	Midwater	Bottom	Very clear	Clear	Slightly turbid	Turbid	Brown	Much	Some	Sparse/unimportant	Rocky	Gravel/sand	Soft	Silt	Detritus	Algae	Macrophyte	Phytoplankton	Zooplankton	Terrestrial	Emerging insects	Epibenthos	Benthos	Mollusca	Crayfish	Fish	Higher vertebrates	Scavenger
Cool Species (continued)																																
Brassy minnow		1			1	2		2	2		1		2	1		2	2	1		1		2	2				3					
Johnny darter		1	3			1		1	2	2		3	2	2	2	1	2	3					2				1					
Iowa darter		1				1		1	3				1			1	2						2				1					
Least darter	2	1				1		1				1	3			2	1						2				1					
Warm Species																																
Bluegill		1	1	2	1	2		1	1	3	3	1	1							3	3		1	3	2	2	1			4		
Largemouth bass		1	3	2	1	3		2	2	3		1	1											3	3	4	4		2	1	2	
Pumpkinseed		1			2	1	3	1	2			2	1			2	1						2			2	1	1		3		
Black crappie		2	1	2	1			1	1	2		2	1										1		2		3			1		
White crappie		3	1		1				2	1			2	1									2							1		
Warmouth		1			2	1		2	1	2		1	2				1						3	3		3	1	3		3		
Redear sunfish		1	3			1		1					1			2	1										2	1		4		
Green sunfish	3	1		3	1	3		2	2	2		2	1	2		2	1								4	2	1			3		
Longear sunfish	2	1		2	1	3		1	2			2	1			1	2							3			1					
Grass pickerel	2	1			1			1	2			1	2			2	1										2		3	1		
Channel catfish		2	2		1	3		2	1	2			2	1			2										2		2	1		
Yellow bullhead		1	2			1		1	3			1	2				1	2		3	4		3				1	3	3	3	3	2
Brown bullhead		1	2			1		2	1			2	1				1	2		3	4		3				1	3	3	3	3	2
Black bullhead		1	3			1		3	2	1		2	1	3			2	1		3	4		3				1	3	4	3	2	1
Bowfin		1	2		1	2		1	2			1	2				1										2		2	1		
Longnose gar		1	2	1	2			1	2			2	1	3																1	3	
Spotted gar		1		1	2			1	2			1	2																	1	3	
Common carp		1	2		3	1		3	2	1		2	1	3		2	1	3	3	3	3		3				1	2	4	4		
Goldfish		1		3	2	1		3	2	1		1				3	1	2		1	2	2	1			2	1	3				
Gizzard shad			1	2	1			3	1	2			3	1						3		2	1				3					
Lake chubsucker		1			3	1		1	3			1	3	0			1			1			3			4	2	2				
Spottail shiner		1	2		1			2	1	2			2	1						3			1				2					

Table 3.–Continued.

Species	Location			Depth			Water clarity					Vegetation			Substrate[b]				Diet													
	Edge	Littoral zone	Offshore	Surface	Midwater	Bottom	Very clear	Clear	Slightly turbid	Turbid	Brown	Much	Some	Sparse/unimportant	Rocky	Gravel/sand	Soft	Silt	Detritus	Algae	Macrophyte	Phytoplankton	Zooplankton	Terrestrial	Emerging insects	Epibenthos	Benthos	Mollusca	Crayfish	Fish	Higher vertebrates	Scavenger
Warm Species (continued)																																
Blacknose shiner	1	2			2	1		1				2	1			1	2			3			1				1					
Blackchin shiner	1	2		2	1			1	2				1			1	2						1	2			2					
Common shiner		1		2	1	3		1	2				2	2					3	1	3				2	4	1			4		
Striped shiner		1			1			1												1	3						1					
Golden shiner		1	3	2	1			1	2			1	2							2	3		1			2	2					
Mimic shiner	2	1		2	1	2		1	2				1			1	2			3		3	2		1	2	2					
Sand shiner		1		2	1	2		1	2	2			2	1		2			2	3			1		2		1					
Spotfin shiner	2	1	3	2	1	3		3	2	1			2	1		1					3					2	1					
Pugnose minnow		2			2	2		2	2			1				3	1			3			2				3					
Fathead minnow		1	3		2	1		3	2	3	2	2	1	3						1			2				3			4		
Bluntnose minnow	2	1			2	1	2	2	2	3		2	1	2		2	2	2	2	1				3	3	3	2			4		
Blackstripe topminnow	2	1		1	3			2	2			2	2			1	2		3					2	4	2	1					
Central mudminnow		1			2	1		2			2	3	3	1			2	1		3			1				1	2				
Brook silverside		1	2	1	3			1	1					1						2			1	1	1		1			4		
Tadpole madtom		2	2			1		1				1	2			2	2										1	2				

[a]Primary references: Hubbs and Lagler (1964), Scott and Crossman (1973), Schneider (1975), Trautman (1981), Becker (1983), Portt et al. (1988), Casselman and Lewis (1996).

[b]Unimportant to surface or midwater, littoral or offshore species except when related to spawning (Table 4).

Table 4.–Synopsis of reproductive characteristics and likely vulnerabilities for fish species in lakes.[1]

	Nesting substrate										Method		Care		Incubation			Reproduction may be vulnerable to:				
Species	Bouyant egg/fry	Rock	Gravel	Sand	roots/mud	Submerged plants	Edge plants	Algae	Flood vegetation	Special	Broadcast	Nest	None	Guard nest	Long	Med	Short	Predation	Ssilt/eutrophy	Sumergent loss	Edge loss	Stable level
Cold Species																						
Lake trout		x									x		x		x			med	high	low	low	low
Brook trout			x^2									x	x		x			low	high	low	low	low
Brown trout			x^2									x	x		x			low	high	low	low	low
Rainbow trout			x^2									x	x			x		low	high	low	low	low
Lake whitefish			x								x		x		x			high	high	low	low	low
Burbot	x		x								x		x		x			high	low	low	low	low
Lake herring	x					x					x		x		x			high	low	low	low	low
Rainbow smelt				x							x		x			x		med	high	low	low	low
Mottled sculpin		x										x		x			x	low	med	low	low	low
Cool Species																						
Smallmouth bass			x									x		x			x	low	med	low	low	low
Walleye		1	2								x		x		x			high	high	low	low	low
Rock bass			x									x		x			x	low	med	low	low	low
White sucker		1	2								x	x	x		x			high	med	low	low	low
Yellow perch	ribbons					x					x		x			x		low	low	med	low	low
Northern pike									x		x		x			x		high	high	low	high	high
Muskellunge					x	x					x		x			x		high	high	med	low	low
Logperch			x	x							x		x			x		high	med	low	low	low
Trout-perch			x	x							x		x		x			high	high	low	low	low
Lake chub		x	x	x							x		x			x		high	med	low	low	low
Emerald shiner	x			x							x		x				x	high	low	low	low	low
N. redbelly dace								x			x		x				x	med	med	low	low	low
Finescale dace										branches	x		x			x		med	low	low	low	low
Pearl dace				x	usually streams						x		x	area			x	med	low?	low	low	low
Pugnose shiner					x?																	
Brook stickleback							x			woven		x		x			x	low	low	low	high	low

Table 4.–Continued.

Species	Nesting substrate										Method		Care		Incubation			Reproduction may be vulnerable to:				
	Bouyant egg/fry	Rock	Gravel	Sand	roots/mud	Submerged plants	Edge plants	Algae	Flood vegetation	Special	Broadcast	Nest	None	Guard nest	Long	Med	Short	Predation	Ssilt/eutrophy	Sumergent loss	Edge loss	Stable level
Cool Species (continued)																						
Brassy minnow							x		x		x		x				x	med	med	low	med	med
Johnny darter										crevice		x		x			x	low	low	low	low	low
Iowa darter					x		x					x	area		x			low	med	med	med	low
Least darter			x		x		x						some				x	low	med	med	high	low
Warm Species																						
Bluegill			1	2	3							x		x			x	low	low	low	low	low
Largemouth bass				1	2							x		x			x	low	low	low	low	low
Pumpkinseed			1	2	3							x		x			x	low	low	low	low	low
Black crappie					x							x		x			x	low	low	med	low	low
White crappie					x							x		x			x	low	low	low	low	low
Warmouth					x							x		x			x	low	low	med	low	low
Redear sunfish				x	x							x		x			x	low	low	low	low	low
Green sunfish			x	x								x		x			x	low	low	low	low	low
Longear sunfish			x									x		x			x	low	med	low	low	low
Grass pickerel									x		x		x			x		high	high	med	high	high
Channel catfish										crevice		x		x			x	low	med	low	low	low
Yellow bullhead										dig hole		x		x			x	low	low	low	low	low
Brown bullhead										dig hole		x		x			x	low	low	low	low	low
Black bullhead				x	x							x		x			x	low	low	low	low	low
Bowfin					x							x		x			x	low	low	med	low	low
Longnose gar						1			2		x		x				x	low	med	med	med	med
Spotted gar						x					x		x				x	low	med	high	low	low
Common carp						1	2		3		x		x				x	med	med	med	med	med
Goldfish							x	x			x		x				x	med	med	med	med	low
Gizzard shad	x										x		x				x	low	low	low	low	low
Lake chubsucker						x	x				x		x			x		med	med	high	med	low
Spottail shiner				x							x		x				x	med	med	low	low	low
Blacknose shiner				x							x		x				x	med	med	med	med	low

Table 4.–Continued.

Species	Nesting substrate										Method		Care		Incubation			Reproduction may be vulnerable to:				
	Bouyant egg/fry	Rock	Gravel	Sand	roots/mud	Submerged plants	Edge plants	Algae	Flood vegetation	Special	Broadcast	Nest	None	Guard nest	Long	Med	Short	Predation	Ssilt/eutrophy	Sumergent loss	Edge loss	Stable level
Warm Species (continued)																						
Banded killifish				x			x				x		x				x	med	med	low	med	low
Blackchin shiner							x?				x		x				x	med	med	med	high	low
Common shiner			x									x	x				x	low	med	low	low	low
Striped shiner			x									x	x				x	low	med	low	low	low
Golden shiner		old beds				x					x		x				x	med	med	high	low	low
Mimic shiner						x?					x		x				x	high?	med	high?	low	low
Sand shiner				x	+veg						x		x				x	med	med	med	low	low
Spotfin shiner										crevice		x		x			x	med	low	low	low	low
Pugnose minnow							?														high?	
Fathead minnow										crevice		x		x			x	low	low	low	low	low
Bluntnose minnow										crevice		x		x			x	low	low	low	low	low
Blackstripe topminnow							x				x		x				x	low	med	med	high	low
Central mudminnow							x				single		x			x		med	low	low	med	low
Brook silverside						x	x				x		x				x	med	low	med	med	low
Tadpole madtom										crevice		x	some				x	low	low	low	low	low

[1]X or 1 = preferred, 2 or 3 = acceptable, ? = uncertain. Primary references: Hubbs and Lagler (1964), Scott and Crossman (1973), Becker (1983), Portt et al. (1988). Extensive compilations of other reproductive characteristics are in Portt et al. (1988) and Winemiller and Rose (1992).

[2]With groundwater.

Table 5.–Tentative tabulation, by species, of relative sensitivity to lake perturbation types and utility as indicator (based on Tables 1-4). Perturbation types include those always with negative effects (winterkill, increased acidity, competition, and predation) and those that may have either positive or negative effects (all others listed).[1]

				Etrophication								
Species	Winter kill	Acid. inc.[2]	Temp. inc.	Sum.DO dec.	Product. inc.	Turbid. inc.	Silt inc.	Macroph. inc.	Edge dec.	Level stabilization	Comp./ Pred.[3]	Indicator for:
Cold Species												**cold, oligotrophy**
Lake trout	**v. high**	med	--	**v. high**	--	--	--	sl	sl	sl	med	**-hypolimnion DO**
Brook trout	**v. high**	**low**	--	**v. high**	-	-	--	sl	sl	sl	med	**-thermocline DO**
Brown trout	**v. high**	med	--	**high**	-	-	--	sl	sl	sl	low	**-thermocline DO**
Rainbow trout	**v. high**	med	--	**high**	-	-	--	sl	sl	sl	med	**-thermocline DO**
Lake whitefish	**v. high**	low	-	**high**	sl	-	--	sl	sl	sl	med	coolness
Burbot	**v. high**	**high**	-	**high**	-	--	--	sl	sl	sl	low	cool/cold
Lake herring	**v. high**	med	-	**high**	-	-	--	-	sl	sl	med	**-eutrophication**
Rainbow smelt	high		-	**high**	sl	-	-	sl	sl	sl	med	exotic
Mottled sculpin	high	med	-	low	sl	-	-	-	sl	sl	low	+rubble
Cool Species												**cool, mostly clear**
Smallmouth bass	high	med	sl	med	-	-	-	sl	sl	sl	low	gravel spawning
Walleye	high	med	sl	med	-	+	--	sl	sl	sl	**high**	gravel/rubble spawning
Rock bass	high	med	sl	med	-	-	-	sl	sl	sl	low	+clarity
White sucker	med	med	sl	low	++	sl	-	sl	sl	sl	med	tolerant
Yellow perch	v. low	low	sl	med	sl	-	sl	sl	sl	sl	low	tolerant reproduction
Northern pike	low	med	-	med	+	-	--	+	--	--	**high**	+spawning marsh
Muskellunge	med?	med	-	med	+	-	--	+	sl	-	**high**	-pike, low tolerance
Alewife	high		sl	high	+	-	-	sl	sl	sl	med	exotic
Logperch		high	sl	low	+	-	-	-	sl	sl	**high**	
Trout-perch	high?	med	-	high	+	-	--	sl	sl	sl	med	cool, large
Lake chub	high?	low	sl	med	+	-	-	-	sl	sl	med	cool
Emerald shiner	high?		sl	low	+	-	-	sl	sl	sl	**high**	large lakes
N. redbelly dace	low?	med	-	low	+	-	sl	sl	sl	sl	**high**[f]	+bog,silt,-competition
Finescale dace	low	low	-	low	+	-	sl	sl	sl	sl	**high**	+bog,silt,-competition
Pearl dace	med	low	-	low	+	-	sl	--	sl	sl	**high**[f]	+bog,silt,-competition
Pugnose shiner	low?		sl	low	+	--	-	++	sl	sl	**high**	**+weeds**
Brook stickleback	low?	low	sl	low	+	-	sl	sl	sl	sl	**high**	-competition
Banded killifish	med		+	low	sl	--	-	sl	--	sl	med	+clarity, edge
Brassy minnow	low?		-	low	+	-	sl	+	sl	sl	**high**	+bog,silt,-comp.

Table 5.–Continued.

Species	Winter kill	Acid. inc.[2]	Temp. inc.	Eutrophication: Sum.DO dec.	Eutrophication: Product. inc.	Eutrophication: Turbid. inc.	Silt inc.	Macroph. inc.	Edge dec.	Level stabilization	Comp./ Pred.[3]	Indicator for:
Cool Species (continued)												**cool, mostly clear**
Johnny darter	low	med	sl	low	sl	-	sl	sl	sl	sl	low	tolerant
Iowa darter	v. low	med	sl	low	sl	--	-	+	-	sl	med	-turbidity
Least darter			+	low	sl	--	-	++	-	sl	med	**+clarity, weeds**
Warm Species												**warm, productive**
Bluegill	med	low	sl	med	sl	sl	sl	+	sl	sl	low	
Largemouth bass	med	med	sl	low	sl	-	sl	+	sl	sl	low	
Pumpkinseed	low	low	sl	low	-	sl	sl	sl	sl	sl	low	+snails, relatively clear
Black crappie	low	med	sl	med	+	+	sl	sl	sl	sl	low	+plankton productivity
White crappie	low		+	low	++	++	sl	sl	sl	sl	low	+eutrophication
Warmouth	low		+	low	sl	sl	sl	+	sl	sl	med	+weeds
Redear sunfish	med		+	low	sl	-	-	sl	sl	sl	med	+marl, snails
Green sunfish	low	med	+	low	+	++	sl	sl	-	sl	high	+disturbed
Longear sunfish	med		+	low	sl	-	-	+	-	sl	high	
Grass pickerel	low	low?	+	low	sl	-	+	++	--	-	med	+weed, edge, clear
Channel catfish	low?		+	low	+	+	sl	sl	sl	sl	low	rather tolerant
Yellow bullhead	v. low	med	sl	low	sl	-	sl	+	sl	sl	low	+weeds, clarity
Brown bullhead	v. low	med	sl	low	+	+	sl	sl	sl	sl	low	tolerant
Black bullhead	v. low	med	+	low	++	++	+	sl	sl	sl	low	+very tolerant
Bowfin	v. low		+	low	sl	-	sl	+	sl	sl	low	-turbidity
Longnose gar	low		+	low	sl	-	-	+	-	-	low	+weeds,edge
Spotted gar	low		+	low	sl	-	-	++	-	sl	low	+weeds
Common carp	low		+	low	++	++	-	sl	-	-	v.low	tolerant eutrophication, pollutants
Goldfish	v. low		+	low	+	sl	-	+	-	sl	high	+disturbed
Gizzard shad	med		+	low	+	+	sl	sl	sl	sl	low	+productivity
Lake chubsucker	low		+	low	-	-	-	++	-	sl	med	**+weeds**
Spottail shiner	high		sl	low	+	-	-	sl	sl	sl	med	-pH
Blacknose shiner	v. low	high	sl	low	-	--	--	sl	--	sl	med	**-edge, turbidity,pH**
Blackchin shiner	v. low		sl	low	-	-	-	sl	--	sl	med	**-edge, turbidity**
Common shiner	low	high	sl	low	sl	--	-	sl	-	sl	high[f]	-turbidity, pH
Striped shiner	low		sl	low	sl	-	-	sl	-	sl	high	
Golden shiner	v. low	med	sl	low	sl	-	-	+	sl	sl	med	+weeds

Table 5.–Continued.

Species	Winter kill	Acid. inc.[2]	Temp. inc.	Eutrophication: Sum.DO dec.	Eutrophication: Product. inc.	Eutrophication: Turbid. inc.	Silt inc.	Macroph. inc.	Edge dec.	Level stabilization	Comp./ Pred.[3]	Indicator for:
Warm Species (continued)												**warm, productive**
Mimic shiner	low	high	sl	low	+	+	-	+	-	sl	med	+eutrophication, -pH
Sand shiner	med		sl	low	sl	+	-	-	+	sl	med	tolerant beaches
Spotfin shiner	low		+	low	+	+	sl	--	-	sl	med	rather tolerant
Pugnose minnow	low		+	low	-	-		++	-	sl	med	-weed loss
Fathead minnow	low	high	sl	low	+	+	sl	sl	sl	sl	high	tolerant;exc low pH,competition
Bluntnose minnow	low	high	sl	low	sl	sl	sl	sl	-	sl	low[f]	tolerant, exc low pH
Blackstripe topminnow	low		+	low	-	sl	-	+	--	sl	med	
Central mudminnow	v. low	low	sl	low	sl	sl	sl	sl	-	sl	med	+severe, silt
Brook silverside	low		+	low	sl	sl	sl	-	-	sl	med	
Tadpole madtom	v. low		+	low	-	-	-	++	sl	sl	low	+weeds

[1]Perturbation types: Acid. = acidity, Comp./Pred. = competition or predation, dec. = decrease, inc. = increase, Macroph = macrophytes, Product. = productivity, Sum. DO = summer dissolved oxygen content, Temp. = temperature, and Turbid. = turbidity. Sensitivity classifications: low = low; med = medium; high = high; v. = very; and ? = uncertain. Effect classifications: sl = slight, **-** = negative, **--** = strongly negative, + = positive, and ++ = strongly positive. Blank = no opinion, and **bold** = most useful.

[2]Relative sensitivity to declining pH based on Table 2. Approximately, effects at: low = 4-5, medium = 5-6, and high = >6

[3]Relative sensitivity to competition or predation from other species. Species which tend to dominate communities are ranked low, and species seem to be abundant only when uninhibited by competition or predation are ranked high. [f]Indicates tolerance to introduced predators per Findlay et al. (2000).

Table 6.–Ranking of sensitivity to anthropogenic effects: I = intolerant, T = tolerant, M = intermediate tolerance, and blanks indicate no opinion or intermediate tolerance. Other abbreviations: agri. = agriculture, DO = dissolved oxygen, poll. = pollution, turb. = turbibity, veg. = macrophytes, and wkill = winterkill.

Species	This analysis	MI rivers[a]	WI lakes[b]	Inshore L. Erie[c]	Great Lakes[d]	Northeast Lakes[e]	FL Lakes[f]	Comments by: Trautman (1981)	Comments by: Becker (1983)
Cold Species									
Lake trout	I	I	I			MI			
Brook trout	I	I				MI			
Brown trout	I	I				M			
Rainbow trout	I	I				MI			
Lake whitefish	I	I							
Burbot	I								
Lake herring	I	I							
Rainbow smelt						M			
Mottled sculpin	I	I	I						
Cool Species									
Smallmouth bass	I	I		I		M			
Walleye	I								
Rock bass	I	I	I		I turb.	M			
White sucker	T	T	T	T		MT		T: turb.,silt, poll., DO	and pH
Yellow perch						MT		I: turb., silt, low veg.	T: DO
Northern pike						M			
Muskellunge	I	I	I						
Alewife	I					M			
Logperch									
Trout-perch	I								
Lake chub									
Emerald shiner									
N. redbelly dace									
Finescale dace									
Pearl dace		I							
Pugnose shiner	I	I		I					
Brook stickleback									
Banded killifish	I	I		I		M		I: clay, silt	

Table 6.–Continued.

Species	This analysis	MI rivers[a]	WI lakes[b]	Inshore L. Erie[c]	Great Lakes[d]	Northeast Lakes[e]	FL Lakes[f]	Comments by: Trautman (1981)	Becker (1983)
Cool Species (continued)									
Brassy minnow									I: predation
Johnny darter	T	T						T: silt, poll.	T: turb., silt
Iowa darter	I	I	I					I: silt	Fairly T: turb., DO
Least darter	I	I	I						
Warm Species									
Bluegill						T	M		
Largemouth bass						T	M		
Pumpkinseed						T			
Black crappie	T					T	M	I: high turb., veg. loss	
White crappie	T							T: turb., silt, temp.	
Warmouth							M		
Redear sunfish							M		
Green sunfish	T		T	T				T: silt, turb.	
Longear sunfish								I: turb.	
Grass pickerel	I							I: turb	I: pike
Channel catfish						M	M		
Yellow bullhead		T	T	T		MT			T: wkill
Brown bullhead	T			T		T	T		
Black bullhead	T							T: poll., heat	T: poll., agri., wkill
Bowfin		T					M	I: silt, veg. loss	
Longnose gar							M		
Spotted gar								I: veg. loss	
Common carp	T	T	T	T		T		T: bottom, turb.	Negative to *Chara*
Goldfish	T	T		T		M			
Gizzard shad	T					M	M		
Lake chubsucker	I						M	I: turb., silt, veg. loss	T: wkill
Spottail shiner		I	I		I turb.	MI			
Blacknose shiner	I	I	I	I	I turb.			I: turb.	I: turb., silt, veg. loss
Blackchin shiner	I	I	I						
Common shiner	I					M			

Table 6.–Continued.

Species	This analysis	MI rivers[a]	WI lakes[b]	Inshore L. Erie[c]	Great Lakes[d]	Northeast Lakes[e]	FL Lakes[f]	Comments by: Trautman (1981)	Comments by: Becker (1983)
Warm Species (continued)									
Striped shiner									
Golden shiner		T	T	T		T	M	I: turb.	
Mimic shiner	T			I					
Sand shiner	T							T: organics, mining	
Spotfin shiner	T								T: silt, turb., poll
Pugnose minnow	I	I	I	I				I: turb.	
Fathead minnow	T	T	I	T		I		T: turb.	
Bluntnose minnow	T	T	I	T		M		T: turb., poll., other spp	T
Blackstripe topminnow								More T than killifish	Relatively T
Central mudminnow	T	T	T	T					T: heat, stagnant
Brook silverside					I turb		M		
Tadpole madtom	I					MI			

[a]Creal et al. (1998); [b]Jennings et al. (1999); [c]Thoma (1999); [d]Minns et al. (1994); [e]Whittier (1999) and Whittier and Hughes (1998); and [f]Schultz et al. (1999).

Table 7.–Relationship between oxygen-thermal types and two morphometric characteristics of Michigan lakes (Schneider 1975). See footnote to Table 1 for more complete description of types.

Oxygen-thermal type	Mean depth (m)	Epilimnion volume/total volume (%)
1 (high DO hypolimnion)	4.8 to 33.8	37 to 63
2 (some DO hypolimnion)	3.7 to 10.7	32 to 68
3 (high DO thermocline)	2.6 to 11.5	36 to 85
4 (low DO thermocline)	1.1 to 7.1	36 to 99
5 (unstratified)	0.9 to 7.2	100
6 (winterkill)	low	high

References

Barila, T. Y., J. R. Stauffer, and C. H. Hocutt. 1982. Temperature preference and avoidance response of the common shiner, *Notropis cornutus* (Mitchill). Archive fur Hydrobiologie 96: 112-119.

Becker, G. C. 1983. Fishes of Wisconsin. The University of Wisconsin Press, Madison.

Cassleman, J. M., and C. A. Lewis. 1996. Habitat requirements of northern pike (*Esox lucius*). Canadian Journal of Fisheries and Aquatic Sciences 53 (Supplement 1): 161-174.

Cooper, G. P., and G. N. Washburn. 1949. Relation of dissolved oxygen to winter mortality of fish in Michigan lakes. Transactions of the American Fisheries Society 74:23-33.

Creal, W., S. Hanshue, S. Kosek, M. Oemke, and M. Walterhouse. 1998. GLEAS Procedure 51, Metric Scoring and Interpretation. Chapter 25B *in* J. C. Schneider, editor. 2000. Manual of fisheries survey methods II: with periodic updates. Michigan Department of Natural Resources, Fisheries Special Report 25, Ann Arbor.

Eaton, J. G., J. H. McCormack, B. E. Goodno, D. G. O'Brien, H. G. Stefany, M. Hondzo, and R. M. Scheller. 1995. A field information-based system for estimating fish temperature tolerances. Fisheries 20:10-18.

Eaton, J. G., and R. M. Scheller. 1996. Effects of climate warming on fish thermal habitat in streams of the United States. Limnology and Oceanography 41:1109-1115.

Findlay, C. S., D. G. Bert, and L. Zheng. 2000. Effect of introduced piscivores on native minnow communities in Adirondack lakes. Canadian Journal of Fisheries and Aquatic Sciences 57: 570-580.

Hawkins, C. P., R. N. Norris, J. Gerritsen, R.M. Hughes, S. K. Jackson, R. K. Jackson, and R. J. Stevenson. 2000. Evaluation of the use of landscape classifications for the prediction of freshwater biota: synthesis and recommendations. Journal of North American Benthological Society 19:541-546.

Haines, T. A. 1981. Acidic precipitation and its consequences for aquatic ecosystems: A review. Transactions of the American Fisheries Society 110:669-707.

Hondzo, M., and H. G. Stefan. 1996. Dependence of water quality and fish habitat on lake morphometry and meteorology. Journal of Water Resources Planning and Management, September/October 1996:364-373.

Hubbs, C. L., and K. F. Lagler. 1964. Fishes of the Great Lakes region. Cranbrook Institute of Science, Bulletin 26, Bloomfield Hills, Michigan.

Jennings, M. J., J. Lyons, E. E. Emmons, G. R. Hatzenbeler, M. A. Bozek, T. D. Simonson, T. D. Beard, Jr., and D. Fago. 1999. Toward the development of an index of biological integrity for inland lakes in Wisconsin. Pages 541-562 *in* T. P. Simon, editor. Assessing the sustainability and biological integrity of water resources using fish communities. CRC Press, Boca Raton, Florida.

Karr, J. R. 1981. Assessment of biological integrity using fish communities. Fisheries 6(6):21-27.

Laarman, P. W. 1976. The sport fisheries of the twenty largest inland lakes in Michigan. Michigan Department of Natural Resources, Fisheries Research Report 1976, Ann Arbor.

Lyons, J., L. Wang, and T. D. Simpson. 1996. Development and validation of an index of biological integrity for coldwater streams in Wisconsin. North American Journal of Fisheries Management 16:241-256.

Magnuson, J. J., J. D. Meisner, and D. K. Hill. 1990. Potential changes in the thermal habitat of Great Lakes fish after global climate warming. Transactions of the American Fisheries Society 119:254-264.

Magnuson, J. J., W. A. Tonn, A. Banerjee, J. Toivonen, O. Sacbchez, and M. Rask. 1998. Isolation vs. extinction in the assembly of fishes in small northern lakes. Ecology 79:2941-2956.

Matuszek, J. E., J Goodier, and D. L. Wales. 1990. The occurrence of cyprinidae and other small fish species in relation to pH in Ontario lakes. Transactions of the American Fisheries Society 119: 850-861.

Michigan Fish Atlas Maps. 2000. Michigan Department of Natural Resources Spatial Data Library. http://intranet/spacialdatalibrary/Fish_Map.htm.

Minns, C. K., V. W. Cairns, G. Randall, and J. E. Moore. 1994. An index of biological integrity (IBI) for fish assemblages in the littoral zone of the Great Lakes' areas of concern. Canadian Journal of Fisheries and Aquatic Sciences 51:1804-1822.

Minns, C. K., S. W, King and C. B. Portt. 1993. Morphological and ecological characteristics of 25 fishes occurring in Great Lakes' areas of concern. Department of Fisheries and Oceans, Great Lakes Laboratory for Fisheries and Aquatic Sciences, Canadian Manuscript Report of Fisheries and Aquatic Sciences 2209, Burlington, Ontario.

Pan, Y., R. J. Stevenson, B. H. Hill, and A. T. Herlihy. 2000. Ecoregions and benthic diatom assemblages in Mid-Atlantic Highland streams, USA. Journal of the North American Benthological Society 19: 518-540.

Portt, C. B., C. K. Minns, and S. W. King. 1988. Morphological and ecological characteristics of common fishes in Ontario lakes. Department of Fisheries and Oceans, Great Lakes Laboratory for Fisheries and Aquatic Sciences, Canadian Manuscript Report of Fisheries and Aquatic Sciences 1991, Burlington, Ontario.

Rahel, F. J., and J. J. Magnuson. 1983. Low pH and the absence of fish species in naturally acidic Wisconsin lakes: Inferences for cultural acidification. Canadian Journal of Fisheries and Aquatic Sciences 40:3-9.

Schneider, J. C. 1975. Typology and fisheries potential of Michigan lakes. Michigan Academician 8(1):59-84.

Schneider, J. C. 1981. Fish communities in Michigan lakes. Michigan Department of Natural Resources, Fisheries Research Report 1890, Ann Arbor.

Schneider, J. C. 1986. "Acid rain": Significance to Michigan lakes and their fisheries. Michigan Academician 18(1):7-15.

Schneider, J. C. 2000a. Evaluation of the effect of the herbicide Sonar on sport fish in Michigan lakes. Michigan Department of Natural Resources, Fisheries Technical Report 2000-2, Ann Arbor.

Schneider, J. C. 2000b. Interpreting fish population and community indices. Chapter 21 *in* J. C. Schneider, editor. 2000. Manual of fisheries survey methods II: with periodic updates. Michigan Department of Natural Resources, Fisheries Special Report 25, Ann Arbor.

Schneider, J. C., P. W. Laarman, and H. Gowing. 2000. Age and growth methods and state averages. Chapter 9 *in* J. C. Schneider, editor. 2000. Manual of fisheries survey methods II: with periodic updates. Michigan Department of Natural Resources, Fisheries Special Report 25, Ann Arbor.

Schultz, E. E., M. V. Hoyer, and D. E. Canfield, Jr. 1999. An index of biological integrity: A test with limnological and fish data from sixty Florida lakes. Transactions of the American Fisheries Society 128:564-577.

Scott, W. B., and E. J. Crossman. 1973. Freshwater fishes of Canada. Fisheries Research Board of Canada Bulletin 184.

Stefan, H. G., M. Hondzo, X. Fang, J. G. Eaton, and J. H. McCormick. 1995. Predicted effects of global climate change on fishes in Minnesota lakes. Pages 57-72 *in* R. J. Beamish, editor. Climate change and northern fish populations. Canadian Special Publication Fisheries and Aquatic Sciences 121.

Stefan, H. G., M. Hondzo, X. Fang, J. G. Eaton, and J. H. McCormick. 1996. Simulated long-term temperature and dissolved oxygen characteristics of lakes in the north-central United States and associated fish habitat limits. Limnology and Oceanography 41:1124-1135.

Thoma, R. F. 1999. Biological monitoring and an index of biological integrity for Lake Erie's nearshore waters. Pages 417-462 *in* T. P. Simon, editor. Assessing the sustainability and biological integrity of water resources using fish communities. CRC Press, Boca Raton, Florida.

Trautman, M. B. 1981. The fishes of Ohio. Ohio State University Press, Columbus.

Wehrly, K. E., M. J. Wiley, and P. W. Seelbach. 1999. A thermal habitat classification for lower Michigan rivers. Michigan Department of Natural Resources, Fisheries Research Report 2038, Ann Arbor.

Whittier, T. R. 1999. Development of IBI metrics for lakes in southern New England. Pages 563-582 *in* T. P. Simon, editor. Assessing the sustainability and biological integrity of water resources using fish communities. CRC Press, Boca Raton, Florida.

Whittier, T. R., and R. M. Hughes. 1998. Evaluation of fish species tolerances to environmental stressors in lakes in the northeastern United States. North American Journal of Fisheries Management 18: 236-252.

Winemiller, K. O., and K. Rose. 1992. Patterns of life history diversification in North American fishes: Implications for population regulation. Canadian Journal of Fisheries and Aquatic Sciences 49: 2196-2218.

Wismer, D. A., and A. E. Christie. 1987. Temperature relationships of Great Lakes fishes: A data compilation. Great Lakes Fishery Commission, Special Publication 87-3, Ann Arbor.

Paul W. Webb, Editor
Edward S. Rutherford, Reviewer
Deborah L. MacConnell and Ellen S. Grove, Desktop Publishing
Alan D. Sutton, Graphics

Approved by Paul W. Seelbach