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[Article]

Turbidity Tolerances of Great Lakes Coastal Wetland Fishes

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Abstract.—Despite recent interest in assessing the condition of fish assemblages in Great Lakes coastal wetlands and a concern for increasing turbidity as a major stressor pathway influencing these ecosystems, there is little information on fish tolerance or intolerance to turbidity on which to base wetland assessment metrics. Existing studies have borrowed tolerance designations from the stream literature, but they have not confirmed that the designations apply to Great Lakes wetlands or that designations based on tolerance to degradation in general apply to turbidity in particular. We used a published graphical method to determine turbidity tolerances of Great Lakes fishes based on their pattern of occurrence and relative abundance across coastal wetlands spanning a turbidity gradient. Fish composition data were obtained from fyke-net and electrofishing surveys of 75 wetlands along the U.S. shoreline of the Laurentian Great Lakes, representing a turbidity range of approximately 0–110 nephelometric turbidity units (NTU). Turbidity levels of 10, 25, and 50 NTU (corresponding to the thresholds in use for state water quality criteria) were used to separate fish into tolerance classes. We found that the turbidity tolerances of many species in Great Lakes wetlands differed from the published tolerances to general degradation in streams. Also, the tolerance levels for many species were unclear owing to the species' infrequent occurrence. Although many of the wetlands sampled had quite low turbidity, a large proportion of the fish species were tolerant or moderately tolerant to turbidity and very few were intolerant, suggesting that enumerating intolerant species may not be a useful metric or that the metric should be expanded to include moderately intolerant species. Our study lays the foundation for additional turbidity indicator development efforts for Great Lakes coastal wetlands.

Coastal wetlands play an important role in supporting fishes in the Laurentian Great Lakes (Jude and Pappas 1992; Whillans 1992; Wei et al. 2004), and there is considerable interest in developing tools for assessing ecological conditions in these increasingly impacted and degraded ecosystems (e.g., Environment Canada and USEPA 2003; Lawson 2004). Decreasing water clarity, as measured by turbidity, is one major pathway via which anthropogenic nutrient and sediment loading affect fishes in coastal wetlands. An altered light regime has implications for visual foragers and predator–prey interactions as well as impacts on the reproductive and foraging habitat structure provided by submerged aquatic vegetation (Brazner and Beals 1997; Crosbie and Chow-Fraser 1999; Lougheed et al. 2001; Jude et al. 2005). Inclusion of metrics assessing fish responses to turbidity would therefore be a desirable part of broader fish condition assessments in the Great Lakes.

Metrics reflecting fish tolerance or intolerance to anthropogenic stressors are often included in indices of biotic integrity (IBIs). In their original IBI, Karr et al. (1986) proposed metrics based on the number of intolerant species and the relative abundance of particular tolerant taxa; recent IBIs generally replace the latter with a metric based on the abundance of individuals of all tolerant species (Miller et al. 1988; Barbour et al. 1999; Karr and Chu 1999). Species tolerance designations for a particular IBI formulation

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are typically derived by combining data and inferences from a number of sources, including other IBIs, natural history descriptions, threatened and endangered species lists, and analogies to related species, without specifying the factors to which the species is tolerant or intolerant beyond a general degradation of its environment. Such extrapolated tolerance designations may be inaccurate because fish may differ in sensitivity to different types of stressors (e.g., eutrophication, thermal stress, and habitat degradation); the stressor regime may vary by region and water body type; or species responses, even to the same stressors, may depend on the water body type or portion of the geographic range inhabited (Karr et al. 1986; Whittier and Hughes 1998). The vast majority of published IBIs concern fish in wadeable streams, and the applicability of those tolerance designations or stressor regimes to the same species in wetlands and lakes is largely untested. Concern with these issues led Whittier and Hughes (1998) to develop an approach for determining fish tolerance designations using data on their distribution across the actual water body type and stressor gradient of interest.

Only a handful of studies have proposed fish IBIs for Great Lakes wetlands or littoral areas, and their approach with regard to tolerance metrics varies widely. Some do not include tolerance metrics (Uzarski et al. 2005), some have adopted general fish tolerance metrics and classifications from the stream literature (Thoma 1999), and some provide insufficient information to evaluate the source and rationale for tolerance designations (Wilcox et al. 2002). Minns et al. (1994) chose turbidity intolerance in particular as a metric for their nearshore IBI because turbidity was a stressor of concern and because their primary reference text (Scott and Crossman 1973) identified fish species requiring clear water. However, Minns et al. (1994) considered only turbidity intolerance, not tolerance, and worked with a relatively species-poor data set, so their study provides little information to support further IBI development. Grabas et al. (2004) rejected turbidity intolerance as an IBI metric for Lake Ontario wetlands based on lack of relationship to anthropogenic disturbance, but they too classified fish based only on the stream literature (G. Grabas, Canadian Wildlife Service, personal communication).

Our primary objective in this study is to develop appropriate turbidity tolerance classifications for fishes of Great Lakes coastal wetlands so that metrics relevant to water clarity degradation can be included in fish assemblage assessments. Turbidity impacts are of direct concern for Great Lakes fishes (Whillians 1992; Minns et al. 1994; Crosbie and Chow-Fraser 1999; Jude et al. 2005), and general tolerance measures may be insufficiently sensitive because Great Lakes wetland fishes are adapted to a rather wide range in other conditions (e.g., dissolved oxygen, temperature; Jude and Pappas 1992). We derive turbidity tolerance designations by applying the method of Whittier and Hughes (1998) to a data set of fish catches from coastal wetlands across the U.S. Great Lakes. We base tolerance categories on turbidity thresholds commonly used in water quality criteria but also discuss possible alternative approaches. Turbidity tolerance designations specific to Great Lakes fish species are not currently available, so this work supports future indicator development efforts.

Methods

Data sets.—We began this analysis by using fish and turbidity data collected over the summers of 2002–2004 as part of a larger multi-investigator project with the goal of developing indicators and stressor–response relationships for Great Lakes coastal wetlands. Two independent crews (Great Lakes Environmental Indicator Project [GLEI] and U.S. Environmental Protection Agency [USEPA]) used two different gear types to sample fish, with deliberate partial overlap among the wetlands sampled by each gear type. Sites were distributed across the wetland types (riverine, protected; Keough et al. 1999), ecological provinces (Laurentian mixed forest, eastern broadleaf forest; Keys et al. 1995), and range of anthropogenic impacts found along the U.S. shoreline of the Great Lakes by means of a stratified random sampling design (Danz et al. 2005). Because relatively few sites sampled by the GLEI and USEPA crews had high turbidity, we decided to include data from additional wetlands sampled in an earlier (1990s) study of fish assemblage patterns along the turbidity gradient in Lake Michigan's Green Bay (Brazner 1997; Brazner and Beals 1997). The GLEI and USEPA crews also sampled wetlands in Green Bay, but turbidity there had declined substantially from the early 1990s, owing in part to effects of the zebra mussel *Dreissena polymorpha*.

The USEPA crews sampled 58 wetlands over 2002–2004, visiting some sites in more than 1 year. Fish were collected by daytime electrofishing (15-ft [4.6-m], flat-bottomed boat; 5,000-W generator; 1-m Wisconsin ring with stainless steel droppers; 6–8-A DC, depending on conductivity). Five to seven sampling stations were distributed around the wetland to represent the range of habitat types present (e.g., backbays, channels, and open areas). At each station, the crews electrofished for 10 min, covering approximately 100 m of shoreline and all the vegetation zones present (emergent, submerged and floating, and open water). Turbidity was measured at each station on surface water collected from the 0.5-m depth contour with a Hydrolab multiprobe (nephelometric turbidity units [NTU]; stated accuracy $\pm 1\%$) that was calibrated before each sampling trip.

The GLEI crews sampled fish by fyke-netting (four pairs of nets per wetland set parallel to depth contours in lead-to-lead fashion, 15-m connecting leads, 3-m wings). One pair of large (12-mm mesh, 0.9-m $\times$ 1.2-m front opening) and one pair of small (4-mm mesh, 0.45-m $\times$ 0.9-m front opening) nets were set in each of the two dominant shoreline types near the 1-m (large nets) and 0.5-m (small nets) depth contours for 24–48 h per wetland. The GLEI fyke-net data were matched with turbidity data collected by USEPA or by a GLEI water quality crew, which made readings on surface water from at least two submerged vegetation and two open-water stations per wetland with a Turner Designs AquaFluor meter (NTU units; stated minimum detection level 0.5 NTU) whose calibration was checked every 10 samples. This study uses only the 34 GLEI wetlands for which contemporaneous turbidity and fyke-net data were available, some of which were sampled in more than 1 year.

The Green Bay study also sampled fish by fyke-netting (two 4-mm mesh, 1.1-m $\times$ 1.4-m front-opening nets per wetland, set as for the GLEI study). Turbidity was measured on surface water collected at the 0.5-m depth contour with a La Motte model TTM turbidity test kit (Jackson turbidity units [JTU]). According to USEPA (1983), JTU and NTU are directly comparable, and we have expressed the units accordingly for this analysis. Additional sampling details are available in Brazner (1997) and Brazner and Beals (1997). Data from 11 wetlands in Lake Michigan's Green Bay, each sampled in the summers of both 1990 and 1991, are included in this analysis.

For all three data sets, the fish captured were enumerated to species (using Becker 1983 as the primary reference), measured, and released. Data for the various stations sampled in each wetland with each gear type and visit year were combined by simple addition and summarized as relative abundance (proportion of total catch) for each species. Turbidity data were summarized by computing the mean across stations within each wetland and year sampled. Four turbidity points were identified as outliers and deleted before the wetland averages were computed; three had values greater than two standard deviations above their wetland mean and magnitudes greater than 240 NTU, and a fourth point at 104 NTU had been flagged by the field crew as suspect.

Deriving turbidity tolerance designations.—Our analysis relied on a method developed by Whittier and Hughes (1998) for deriving fish tolerances from data sets of fish composition across the water body type and stressor gradients of interest. Although many factors can influence species composition at any given place and time, this method identifies patterns of species presence or absence and abundance that are consistent with the effects of a particular stressor, such as abrupt shifts in relative abundance or from presence to absence above some threshold stressor level (see Whittier and Hughes 1998 for examples).

The first step in the Whittier and Hughes method is to rank sites in order of increasing stressor levels and use relevant a priori classifications together with breakpoints in the distribution of sites to draw reference levels demarking tolerance categories. Because turbidity can change over time, we used wetland-years (geographic location $\times$ year sampled) as the basis for our analysis. We ranked wetland-years according to their mean turbidity and assigned consecutive ranks to ties. We drew reference lines at turbidity levels of 10, 25, and 50 NTU in accordance with existing water quality standards and because there appear to be breakpoints in the distribution of turbidity values at about 25 and 50 NTU. Upper allowable turbidity limits of 10 NTU for systems supporting coldwater fisheries, 25 NTU for lakes and reservoirs, and 50 NTU for freshwater in general are in common use among states with numeric turbidity standards (USEPA 1988). There are no standards specifically for Great Lakes waters, and we are aware of only one state (Minnesota; MPCA 2004) that has a turbidity standard for wetlands, namely, 50 NTU.

The next step in the Whittier and Hughes method is to create a plot of stressor level versus site rank for each fish species, coding the data points to reflect the relative abundance at each site (no data point if the species is absent, increasing point size with increasing relative abundance). The tolerance category for each species is then inferred from its distribution across the stressor gradient. Species are designated intolerant (occurring only at low levels of the stressor), moderately intolerant (present at low to moderate stressor levels), moderately tolerant (occurring across the stressor range but more abundant at lower stressor levels), or tolerant (present and abundant at high stressor levels) with respect to the reference levels determined in the first step. A species need not be abundant or common to be classified (i.e., it can be absent from many sites) as long as there are sufficient data points to describe its distribution.

We designated fish as intolerant if they had at least five occurrences but only at wetland-years with low turbidity (at most, one occurrence at >10 NTU; Table 1). Species found at several sites with average turbidity between 10 NTU and 25 NTU were designated as moderately intolerant. Species found at several sites

TABLE 1.—Criteria used for designating the turbidity tolerance of fishes based on their occurrence and relative abundance pattern across the turbidity gradient. No tolerance designations were made for species found at fewer than five sites and only at turbidity less than 10 nephelometric turbidity units (NTU), since this occurrence pattern could be due to chance alone.

Tolerance designation	Pattern of occurrence and abundance
Species found at five or more sites	
Intolerant (I)	At most one occurrence at turbidity >10 NTU
Moderately intolerant (MI)	Multiple occurrences at turbidity >10 NTU
	At most one occurrence at turbidity >25 NTU
Moderately tolerant (MT)	Multiple occurrences at turbidity >25 NTU
	Shift from present to absent or reduced relative abundance above 50 NTU turbidity
Tolerant (M)	Occurring across the turbidity gradient
	No decline in relative abundance above 50 NTU
Species found at fewer than five sites	
Distribution suggests at least MT	At least one occurrence at turbidity >25 NTU
Distribution suggests *not* I	At least one occurrence at turbidity >10 NTU

with turbidity greater than 25 NTU were designated as either moderately tolerant or tolerant, depending on the pattern of presence or absence and relative abundance. If the species was present across the turbidity gradient and showed no decrease in relative abundance above 50 NTU, we designated it as tolerant, whereas we designated it as only moderately tolerant if its abundance declined at higher turbidity or if it rarely occurred above 50 NTU turbidity. By these criteria, species that were never abundant could nevertheless be turbidity tolerant if they were found across the turbidity gradient. This differs from Whittier and Hughes (1998), who required that a species be dominant in high-turbidity sites to be designated tolerant. Species found at fewer than 5 wetland-years were considered to have insufficient data to be classified, but their presence in wetlands with turbidity greater than 10 or 25 NTU was noted as suggesting some turbidity tolerance (Table 1). Tolerance designations were not made for fish identified only to genus.

To have the largest possible sample size, our primary analysis combined data from fyke-net and electrofishing gear, each of which was applied across the turbidity gradient (101 wetland-years sampled with fyke-net, electrofishing gear, or both). However, to investigate possible effects on fish tolerance classifications arising from gear biases, we also made classifications for each gear type separately. This secondary analysis used 58 wetland-years of fyke-net data and 62 wetland-years of electrofishing data.

Results

The data set from the three studies combined covers 75 different wetlands (Figure 1) sampled on 101 site visits. Most wetlands were visited in only 1 year, but 15 were sampled in 2 years, 4 were visited in 3 years, and 1 was visited in 4 years. Wetland size ranged from approximately 3 ha to more than 100 ha inundated area (as digitized from U.S. Geological Survey digital orthophotographs), and the wetlands were predominately of the riverine and barrier-protected type (Keough et al. 1999), although a few sheltered embayment wetlands were included. Average turbidity ranged from 0 to 112 NTU (Figure 2). Of the 101 wetland-years, 50 (50%) had average turbidity less than 10 NTU, 25 (25%) had turbidity between 10 and 25 NTU, 10 (10%) had turbidity between 25 and 50 NTU, and 16 (16%) had turbidity greater than 50 NTU. A total of 43 wetland-year combinations were sampled only by electrofishing, 39 only with fyke nets, and 19 with both. Both fyke-net and electrofishing efforts were distributed across the turbidity gradient, although only wetlands with relatively low turbidity were sampled with both types of gear in the same year (Figure 3). Wetlands with average turbidity greater than 50 NTU occurred only in Lakes Erie and Michigan, but sites with low turbidity occurred in all five Great Lakes (Figure 3). All five Green Bay sites sampled in 1990–1991 and again in 2002–2004 had substantially higher turbidity in the earlier time period (Figure 3).

We found a total of 88 species of fish. Of these, 20 (23%) were classified as turbidity tolerant (Table 2) based on their distribution across wetland-years from the fyke-net and electrofishing data combined. Ten of the tolerant species were abundant at high turbidity (e.g., yellow perch, Figure 4), and another 10 were never abundant at any site but occurred across the turbidity gradient (e.g., channel catfish, Figure 4). Nineteen species (22%) were classified as moderately tolerant (Table 2); these were found in some wetland-year combinations with greater than 25 NTU average turbidity but occurred less frequently (e.g., round goby) or in lower abundances (e.g., bluegill) at more turbid sites (Figure 4). Thirteen species (15%) were classified

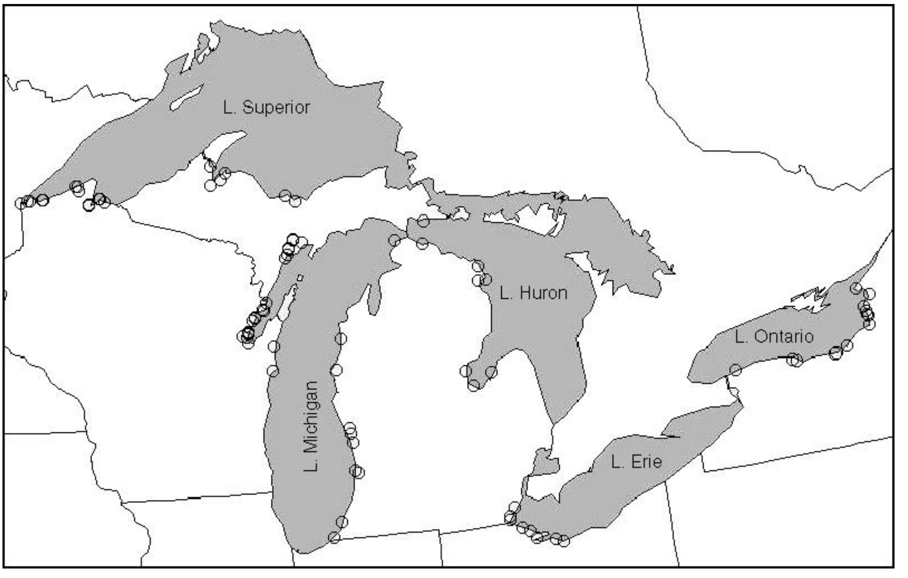

FIGURE 1.—Map of the Great Lakes showing the 75 coastal wetlands sampled on 101 site visits in 1990–1991 and 2002–2004.

as moderately intolerant, occurring in wetlands with up to 25 NTU average turbidity (Table 2; Figure 4). Only two species (2%), blackchin shiner and brook stickleback, were classified as intolerant based on having been found primarily in sites with less than 10 NTU turbidity (Figure 4).

Thirty-four species (39%) were found too infrequently (<5 wetland-years) to establish a turbidity tolerance; of these, distributions for 6 suggested at least

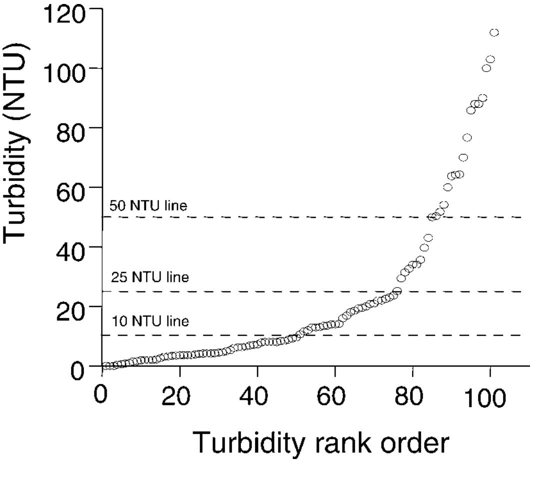

FIGURE 2.—Plot of average turbidity versus turbidity rank for the 101 wetland-years. Reference lines demark turbidity levels of 10, 25, and 50 nephelometric turbidity units (NTU). Each data point represents one wetland × year sampled combination.

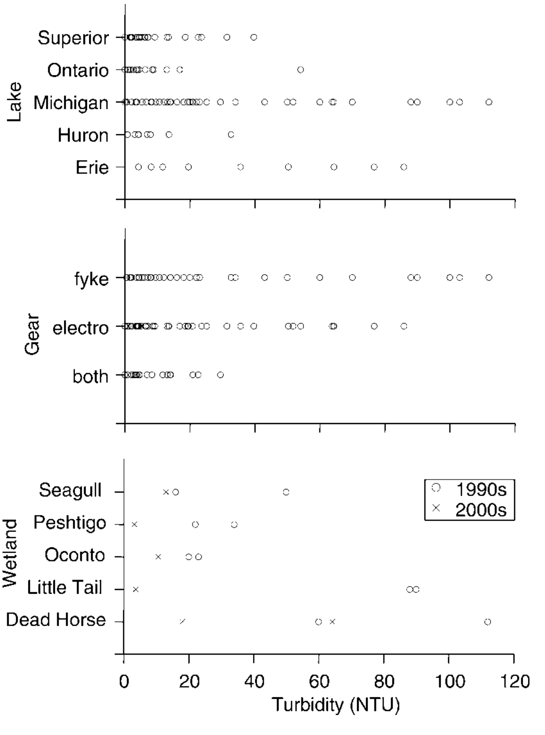

FIGURE 3.—Distribution of sites across the turbidity gradient relative to the lake in which the wetland is located and the gear types used; and turbidity levels in Green Bay wetlands during 1990–1991 compared with those during 2002–2004. Each data point represents one wetland × year sampled combination.

TABLE 2.—Percent of the 101 wetland-years in which each sampled species was found, the lakes in which it was found (Erie [E], Huron [H], Michigan [M], Ontario [O], or Superior [S]), the highest average turbidity at which it was found, and each species designated tolerance to (1) turbidity in Great Lakes wetlands (this study), (2) turbidity in New England lakes (Whittier and Hughes 1998), and (3) general anthropogenic disturbance in U.S. streams (Barbour et al. 1999). This study and that of Whittier and Hughes used the following categories: T (tolerant), MT (moderately tolerant), MI (moderately intolerant), and I (intolerant); Barbour et al. used T, I, and M (intermediate). Parentheses in the Barbour et al. designations denote exceptions applicable to the Great Lakes region, namely, those due to Lyons (1992; Wisconsin streams) or Halliwell et al. (1999; northeastern United States). Parentheses around lake abbreviations indicate that a species was not found there in this study but that its published range includes that lake.

Species	Percent of wetland years	Lakes in which found	Highest average turbidity (NTU)	Tolerance designation		
				This study	Whittier and Hughes (1998)	Barbour et al. (1999)
Tolerant—present and abundant at high turbidity						
Alewife *Alosa pseudoharengus*	36	E, H, M, O, S	112	T	MT	M
Gizzard shad *Dorosoma cepedianum*	32	E, H, M, O	112	T		M (T)
Goldfish *Carassius auratus*	17	E, H, M, O	86	T		T
Common carp *Cyprinus carpio*	71	E, H, M, O, S	103	T	T	T
Emerald shiner *Notropis atherinoides*	34	E, H, M, O, S	112	T		M
Common shiner *Luxilus cornutus*	40	E, H, M, O, S	112	T	MI	M
Spottail shiner *Notropis hudsonius*	53	E, H, M, O, S	112	T	I	M (I)
Spotfin shiner *Cyprinella spiloptera*	25	E, H, M, O	112	T		
White bass *Morone chrysops*	17	E, H, M, (O), (S)	112	T		M (T)
Yellow perch *Perca flavescens*	100	E, H, M, O, S	112	T	MT	M
Tolerant—never abundant but present across turbidity gradient						
Bowfin *Amia calva*	46	E, H, M, O	86	T		M (T)
Longnose gar *Lepisosteus osseus*	18	E, H, M, O	86	T		M
Quillback *Carpiodes cyprinus*	5	E, (H), M, (O)	86	T		M (T)
Golden redhorse *Moxostoma erythrurum*	7	E, (H), M, (O)	64	T		M (I)
Yellow bullhead *Ameiurus natalis*	15	E, H, M, O, S	77	T	MT	T
Channel catfish *Ictalurus punctatus*	11	E, H, M, (O), (S)	64	T		M
Brook silverside *Labidesthes sicculus*	17	E, H, M, O	86	T		M (I)
Green sunfish *Lepomis cyanellus*	23	E, H, M, (O), (S)	77	T		T (M)
White perch *Morone americana*	19	E, H, M, O, S	77	T	T	M
Freshwater drum *Aplodinotus grunniens*	18	E, (H), M, (O), (S)	86	T		M
Moderately tolerant—absent or declining abundance at more turbid sites						
Northern pike *Esox lucius*	54	E, H, M, O, S	54	MT	MI	M (I)
Golden shiner *Notemigonus crysoleucas*	51	E, H, M, O, S	88	MT	T	T
Sand shiner *Notropis stramineus*	15	(E), H, M, O, S	52	MT		M
Bluntnose minnow *Pimephales notatus*	65	E, H, M, O, S	112	MT	MI	T
Fathead minnow *Pimephales promelas*	22	E, H, M, O, S	77	MT	I	T
White sucker *Catostomus commersonii*	65	E, H, M, O, S	112	MT	MT	T
Black bullhead *Ameiurus melas*	27	E, H, M, O, S	112	MT		M
Brown bullhead *Ameiurus nebulosus*	63	E, H, M, O, S	100	MT	MT	T (M)
Banded killifish *Fundulus diaphanus*	40	E, H, M, O	70	MT	MI	T (M)
Rock bass *Ambloplites rupestris*	71	E, H, M, O, S	86	MT	I	M (I)
Pumpkinseed *Lepomis gibbosus*	78	E, H, M, O, S	77	MT	T	M
Bluegill *Lepomis macrochirus*	66	E, H, M, O, S	100	MT	T	M (T)
Smallmouth bass *Micropterus dolomieu*	47	E, H, M, O, S	103	MT	MI	M (I)
Largemouth bass *Micropterus salmoides*	58	E, H, M, O, S	86	MT	MT	M (T)
Black crappie *Pomoxis nigromaculatus*	32	E, H, M, O, S	64	MT	T	M
Johnny darter *Etheostoma nigrum*	49	(E), H, M, O, S	60	MT		M
Logperch *Percina caprodes*	18	E, (H), M, O, S	86	MT		M
Walleye *Sander vitreus*	23	(E), (H), M, (O), S	112	MT		M
Round goby *Neogobius melanostomus*	13	E, H, M, (O), (S)	36	MT		
Moderately intolerant—mostly at <25 NTU turbidity						
Central mudminnow *Umbra limi*	26	(E), H, M, O, S	24	MI		T
Grass pickerel *Esox americanus*	7	(E), M, O	21	MI		M
Hornyhead chub *Nocomis biguttatus*	5	(E), (H), M, (O), S	31	MI		I (M)
Blacknose shiner *Notropis heterolepis*	24	(E), (H), M, O, S	31	MI	MI	I
Mimic shiner *Notropis volucellus*	7	(E), H, M, (O), S	23	MI		I (M)
Creek chub *Semotilus atromaculatus*	7	(E), (H), M, (O), S	23	MI	MI	T
Silver redhorse *Moxostoma anisurum*	6	(E), H, M, (O), S	31	MI		M
Shorthead redhorse *Moxostoma macrolepidotum*	12	(E), (H), M, O, S	24	MI		M
Tadpole madtom *Noturus gyrinus*	9	E, H, M, O, S	24	MI		M
Trout-perch *Percopsis omiscomaycus*	5	(E), (H), (M), O, S	31	MI		M
Threespine stickleback *Gasterosteus aculeatus*	7	(E), (O), S	13	MI		M

TABLE 2.—Continued.

Species	Percent of wetland years	Lakes in which found	Highest average turbidity (NTU)	Tolerance designation: This study	Tolerance designation: Whittier and Hughes (1998)	Tolerance designation: Barbour et al. (1999)
Warmouth *Lepomis gulosus*	5	(E), H, M, O	21	MI		M
Ruffe *Gymnocephalus cernuus*	11	(M), S	24	MI		M
Intolerant—mostly at <10 NTU turbidity						
Blackchin shiner *Notropis heterodon*	12	(E), H, M, O, S	23	I		I
Brook stickleback *Culaea inconstans*	10	(E), (H), M, (O), (S)	10	I		M (I)
Little data—distribution suggests at least moderately tolerant						
Muskellunge *Esox masquinongy*	3	(E), (H), (M), (O), S	>25			M (I)
Longnose dace *Rhinichthys cataractae*	2	(E), (H), M, (O), S	>50			I (M)
River carpsucker *Carpiodes carpio*	2	(E), H, M	>25			M
Bigmouth buffalo *Ictiobus cyprinellus*	4	E, (M), (O)	>50			M
Spotted sucker *Minytrema melanops*	4	E, M	>50			M (I)
Orangespotted sunfish *Lepomis humilis*	4	E	>50			M
Little data—distribution suggests *not* intolerant						
Chestnut lamprey *Ichthyomyzon castaneus*	1	(M), S	>10			M (I)
Shortnose gar *Lepisosteus platostomus*	4	M	>10			M
Rainbow trout *Oncorhynchus mykiss*	3	(E), (H), (M), (O), S	>10			M (I)
Stonecat *Noturus flavus*	2	(E), (H), (M), O, S	>10			I (M)
Longnose sucker *Catostomus catostomus*	1	(E), (H), (M), (O), S	>10		I	M (I)
Pirate perch *Aphredoderus sayanus*	2	(E), (H), M, O	>10			M
Burbot *Lota lota*	2	(E), (H), M, (O), S	>10		MI	M
Yellow bass *Morone mississippiensis*	1	M	>10			M
Redear sunfish *Lepomis microlophus*	2	(E), M	>10			M
White crappie *Pomoxis annularis*	4	E, (H), M, (O)	>10			M (T)
Insufficient data to determine turbidity tolerance						
Spotted gar *Lepisosteus oculatus*	2	(E), M, O	?			M (I)
Brown trout *Salmo trutta*	1	(E), (H), (M), (O), S	?			M (I)
Brook trout *Salvelinus fontinalis*	1	(E), (H), (M), (O), S	?		MI	M (I)
Brassy minnow *Hybognathus hankinsoni*	4	(E), H, M, O, (S)	?			M
Bridle shiner *Notropis bifrenatus*	1	O	?		MI	I
Northern redbelly dace *Phoxinus eos*	4	(E), (H), M, (O), S	?		I	M
Finescale dace *Phoxinus neogaeus*	1	H, (M), (O), (S)	?		I	M
Eastern blacknose dace *Rhinichthys atratulus*	2	(E), (H), (M), (O), S	?		MI	T
Creek chubsucker *Erimyzon oblongus*	1	(E), (M), O	?		M	M (I)
River redhorse *Moxostoma carinatum*	1	(E), M	?			I
Greater redhorse *Moxostoma valenciennesi*	1	(E), (H), M, (O), (S)	?			I
Ninespine stickleback *Pungitius pungitius*	1	(H), M, (O), (S)	?			M
Mottled sculpin *Cottus bairdii*	2	(E), (H), (M), (O), S	?			I (M)
Slimy sculpin *Cottus cognatus*	3	(E), H, (M), (O), S	?		I	M (I)
Longear sunfish *Lepomis megalotis*	1	(E), M	?			I
Iowa darter *Etheostoma exile*	2	(E), H, (M), (O), S	?			M (I)
Least darter *Etheostoma microperca*	1	(E), (H), (M), (O), S	?			M (I)
Blackside darter *Percina maculata*	2	(E), H, M, (O)	?			M

moderate tolerance (occurrences at >25 and >50 NTU; Table 2), and another 10 were found in sites with turbidity greater than 10 NTU, suggesting they were at least not intolerant (Table 2). Eighteen uncommon species were found only in sites with average turbidity less than 10 NTU, but given that 50% of the wetland-years fell into this category, this could be due to chance alone and should not be interpreted as evidence of turbidity intolerance.

One possible confounding factor for determining turbidity tolerances would be lack of overlap between species ranges and the gradient of interest. Only wetlands in Lakes Michigan and Erie had mean turbidity greater than 50 NTU (Figure 3), so if a species did not occur in either of these lakes, we could not find it to be turbidity tolerant by our criteria. To investigate this possibility, we used range maps and descriptions in Underhill (1986) and Page and Burr (1991) to examine the distribution pattern of each species. We found that all species for which we had five or more occurrences were present in either Lake Michigan or Lake Erie or both (Table 2), so overlap between species ranges and the turbidity gradient should not have had much influence on our results. One species (bridle shiner) had a range that excluded both Lake Michigan and Lake Erie, but it was so

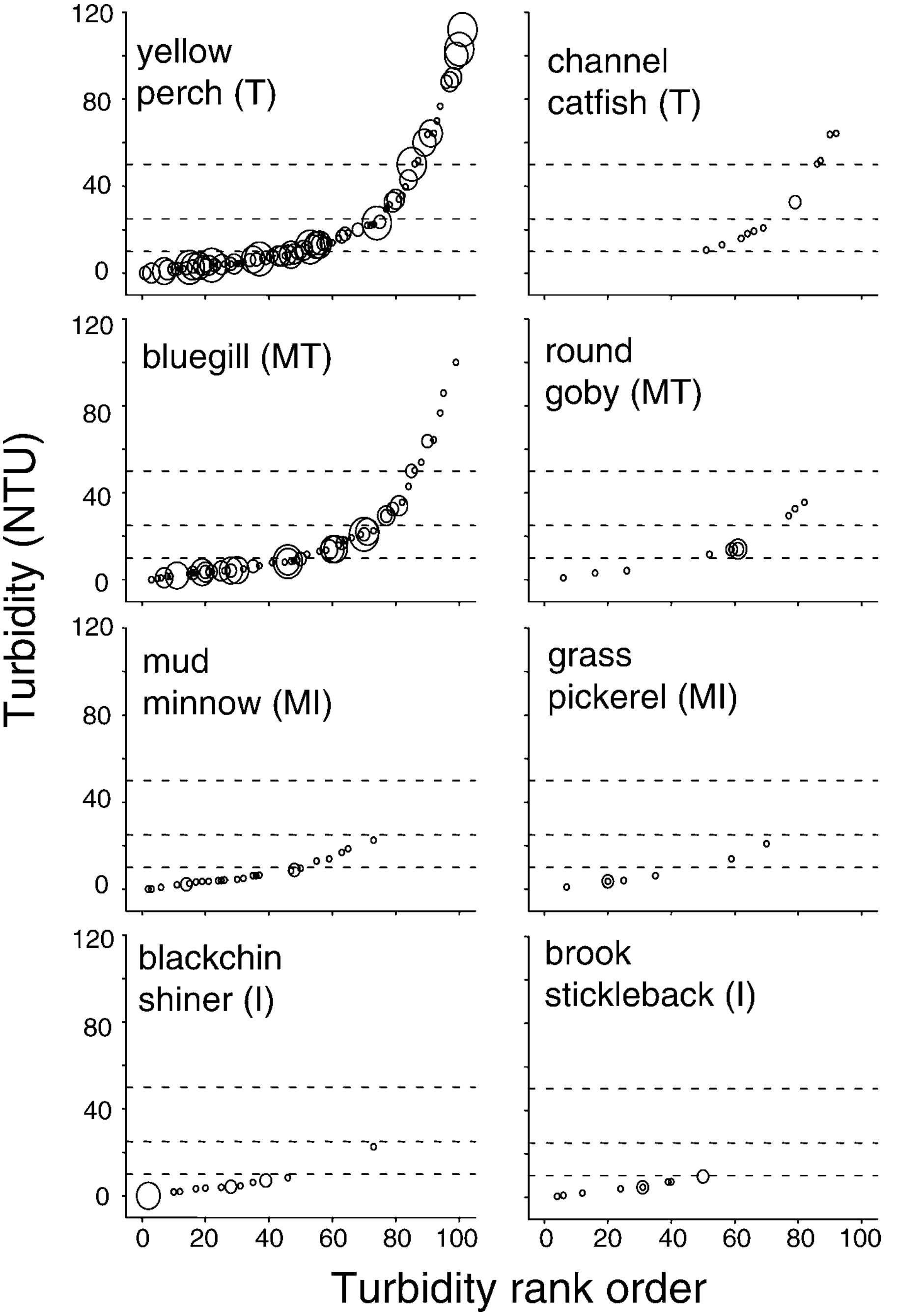

FIGURE 4.—Examples of fish species illustrative of four classes of turbidity response (tolerant [T], moderately tolerant [MT], moderately intolerant [MI], and intolerant [I]), as determined from species' presence or absence and relative abundance pattern across the turbidity gradient. One common species and one relatively uncommon species are illustrated for each tolerance level. The circles show the wetland-years during which each species was present, and increasing symbol size indicates increasing relative abundance (<1%, 1–5%, 5–15%, 15–30%, 20–60%, and >60%). The reference lines demark turbidity levels of 10, 25, and 50 nephelometric turbidity units (NTU).

uncommon that we could not designate its turbidity tolerance anyway (Table 2).

A second factor that could confound species turbidity tolerance classifications would be differences in vulnerability to the different sampling gear types. We examined this possibility by also deriving tolerance classifications for the electrofishing and the fyke-net data separately. We found discrepancies between tolerance classifications from the separate gear types compared with results from both gear types combined for 19 of the 54 species present at greater than 5 wetland-years (Table 3). Most were cases where the tolerance classification for one gear type was lower than that for both gear types combined because the species was not found by that gear at enough high-turbidity sites. For example, a number of large-bodied species (bowfin, longnose gar, channel catfish, white perch, northern pike) were not caught in fyke nets in turbid wetlands, although they were caught in fyke nets at lower turbidity sites (Table 3). In a small number of cases, the tolerance classification for one gear was higher than for both combined. These cases were for species that were never caught except in low numbers in that gear at any sites, so declines in relative abundance above 50 NTU turbidity that were evident in the combined data were not visible in that gear alone. There were 12 species for which tolerance designations could not be made for one or both gear types owing to insufficient occurrences (Table 3).

Discussion

Our study is the first to derive turbidity tolerance estimates for fishes specifically in Great Lakes coastal wetlands. The range of turbidity over which this evaluation was made (0–112 NTU, Figure 2) using data from U.S. shoreline coastal wetlands is comparable to the range reported across the Great Lakes in other recent studies that include Canadian-side data (e.g., Crosbie and Chow-Fraser 1999; McNair and Chow-Fraser 2003; Grabas et al. 2004; Uzarski et al. 2005). The graphical method of Whittier and Hughes (1998) could be readily applied to our data set, although we caught quite a few species with insufficient frequency to establish tolerance designations.

Fully 23% of the species in our study were classified as turbidity tolerant and only two (~2%) were turbidity intolerant. Our turbidity tolerance distributions clearly do not adhere to the suggestion of Karr et al. (1986) that the most sensitive category ought to contain 5–10% of the species. Given the large number of sites at which average turbidity was less than 10 NTU (Figure 2), it was certainly possible for a species to occur numerous times yet be found only in low-turbidity wetlands, so the absence of turbidity-intolerant species seems to be ecologically significant. Fishes inhabiting wetlands are generally adapted to a wide variety of water quality conditions (Jude and Pappas 1992), and the distribution of species among turbidity-tolerance classes appears to reflect this.

Almost all the species commonly of interest to anglers (yellow perch, largemouth and smallmouth bass, bluegill, pumpkinseed, black crappie, walleye, and northern pike) were present across the turbidity gradient, suggesting that degradation of coastal wetlands via increased turbidity does not directly exclude the fish species of most public concern. However, the abundance of these species might be reduced at high turbidity as a result of degradation of spawning and nursery habitat from the shading of submerged vegetation (e.g., Lougheed et al. 2001; McNair and Chow-Fraser 2003), reduced feeding success brought about by impaired visibility and light-mediated shifts from benthic-epiphytic to planktonic food web pathways (Sierszen et al. 2006), or the accumulation of fine sediments that degrade spawning substrates for nest-building species (Waters 1995). Such impacts would not necessarily alter species presence or absence patterns, but might instead shift relative abundances. Decreases in abundance at high turbidity were the reason why most of these species were rated moderately tolerant rather than tolerant (e.g., bluegill; Figure 4).

Fish species differ in their vulnerability to various types of sampling gear depending on such factors as body size, visual acuity, swimming style, and preferred position in the water column. Accordingly, the fish composition from fyke-net catches will differ somewhat from the composition from electrofishing catches (Barthelmes and Doering 1996; Fago 1998) independent of turbidity or other differences among wetlands. A number of fish species were not well represented in one or the other type of gear (Table 3), although both were applied across the turbidity gradient (Figure 3). Most commonly, the result was that data were insufficient to classify tolerance for one gear type or that the assigned tolerance classification for one gear type was lower than that for both combined. More rarely, the assigned tolerance designation for one gear type was higher than that for both combined because declines in relative abundance at high turbidity could not be observed if the gear never caught more than a few individuals of the species at any site. Combining data sets from complementary gear types (e.g., active versus passive, day versus night) as we did appears to increase the likelihood that shifts in presence/absence or relative abundance consistent with a turbidity response threshold are identified for a broad range of species. However, this would be true only if each gear

TABLE 3.—Turbidity tolerance designations determined from electrofishing and fyke-net data combined (as in Table 2) compared with designations for the separate gear types and description of the discrepancies present.

Species	Gear type: Both	Fyke net	Electrofishing	Nature of discrepancy
Tolerant according to data from both gear types combined				
Alewife	T	T	T	
Gizzard shad	T	T	T	
Goldfish	T	MT	T	Fyke net: no occurrences at >50 NTU
Common carp	T	T	T	
Emerald shiner	T	T	T	
Common shiner	T	T	MT	Electrofishing: decline in abundance at >50 NTU
Spottail shiner	T	T	T	
Spotfin shiner	T	T	T	
White bass	T	T	T	
Yellow perch	T	T	T	
Bowfin	T	MT	T	Fyke net: no occurrence at >50 NTU
Longnose gar	T	MI	T	Fyke net: no occurrence at >25 NTU
Quillback	T		T	Fyke net: insufficient data
Golden redhorse	T		T	Fyke net: insufficient data
Yellow bullhead	T	MT	T	Fyke net: only 1 occurrence at >50 NTU
Channel catfish	T	MT	T	Fyke net: no occurrences at >50 NTU
Brook silverside	T		T	Fyke net: insufficient data
Green sunfish	T	MT	T	Fyke net: only 1 occurrence at >50
White perch	T	MI	T	Fyke net: only 1 occurence at >25 NTU
Freshwater drum	T		T	Fyke net: insufficient data
Moderately tolerant according to data from both gear types combined				
Northern pike	MT	MI	MT	Fyke net: only 1 occurrence at >50 NTU
Golden shiner	MT	T	MT	Fyke net: no decline in abundance at >50 NTU
Sand shiner	MT	I	MT	Fyke net: only 1 occurrence at >10 NTU
Bluntnose minnow	MT	MT	MT	
Fathead minnow	MT	MI	MT	Fyke net: no occurrences at >25 NTU
White sucker	MT	MT	T	Electrofishing: no decline in abundance at >50 NTU
Black bullhead	MT	MT		Electrofishing: insufficient data
Brown bullhead	MT	T	MT	Fyke net: no decline in abundance at >50 NTU
Banded killifish	MT	MT	MT	
Rock bass	MT	MT	MT	
Pumpkinseed	MT	MT	MT	
Bluegill	MT	MT	MT	
Smallmouth bass	MT	MT	MT	
Largemouth bass	MT	MT	T	Electrofishing: no decline in abundance at >50 NTU
Black crappie	MT	MT	MT	
Johnny darter	MT	MT	MI	Electrofishing: only 1 occurrence at >25 NTU
Logperch	MT	MI	MT	Fyke net: no occurrences at >25 NTU
Walleye	MT	MT	MT	
Round goby	MT	MT	MT	
Moderately intolerant according to data from both gear types combined				
Central mudminnow	MI	I	MI	Fyke net: no occurrence at >10 NTU
Grass pickerel	MI		MI	Fyke net: insufficient data
Hornyhead chub	MI			Either gear alone: insufficient data
Blacknose shiner	MI	MI	MI	
Mimic shiner	MI	MI	MI	
Creek chub	MI	MI	MI	
Silver redhorse	MI		MI	Fyke net: insufficient data
Shorthead redhorse	MI		MI	Fyke net: insufficient data
Tadpole madtom	MI	MI	MI	
Trout-perch	MI			Either gear alone: insufficient data
Threespine stickleback	MI	I	MI	Fyke net: no occurrences at >10 NTU
Warmouth	MI	MI		Electtrofishing: insufficient data
Ruffe	MI		MI	Fyke net: insufficient data
Intolerant according to data from both gear types combined				
Blackchin shiner	I	I	I	
Brook stickleback	I	I	I	

type were deployed across the stressor gradient; otherwise, apparent thresholds in species composition due to gear biases might confound actual thresholds of response to the stressor.

Species Designations Compared to Other Studies

In general, we found species to be more tolerant of turbidity in wetlands than extrapolation from general tolerance designations based on stream studies (e.g., Barbour et al. 1999) or turbidity tolerance designations from the lake study of Whittier and Hughes (1998) would lead one to expect (Figure 5). In particular, many of the species we classified as turbidity tolerant were only of moderate general tolerance in other studies (Table 2). Substantial differences in ratings for some species emphasize that turbidity and general tolerances are not necessarily equivalent. For example, the brook silverside is fragile in aquaria and holding tank settings and considered somewhat intolerant in general (Barbour et al. 1999), but it is quite tolerant of turbidity according to our data (Table 2). Conversely, the central mudminnow is considered generally tolerant (Barbour et al. 1999) owing to its ability to survive hypoxia and a wide range of temperatures (Becker 1983), but Becker described it as less common in turbid water, which is consistent with our rating of moderate turbidity intolerance (Figure 4). The creek chub is reportedly tolerant of considerable pollution (Becker 1983; Barbour et al. 1999), but we found it to be moderately intolerant of turbidity, as did Whittier and Hughes (Table 2). This could be a habitat effect (preference for streams) because creek chub were found commonly and in high numbers in quite muddy streams in a study of Lake Superior tributaries (Brazner et al. 2004).

Turbidity tolerance categories for species found in both our wetlands and Whittier and Hughes' New England lakes (1998) were generally consistent but with some notable exceptions. Whittier and Hughes (1998) classified the spottail shiner as intolerant of turbidity and the common shiner as moderately intolerant of turbidity, but Becker (1983) described both as inhabiting a range of water clarity and we classified both as tolerant. Whittier and Hughes (1998) classified the fathead minnow as intolerant of turbidity, although it is tolerant to disturbance in general (Barbour et al. 1999), and we classified it as moderately turbidity tolerant. Distributions for rock bass, smallmouth bass, bluntnose minnow, and northern pike led us to designate them as moderately turbidity tolerant, in contrast to Whittier and Hughes (1998), who rated them as moderately intolerant or intolerant (Table 2). The species that we classified as moderately turbidity tolerant but that Barbour et al. (1999) or Whittier and Hughes (1998) had designated as tolerant (Table 2) were ones that occurred across the gradient but with declines in abundance at higher turbidity (e.g., golden shiner, pumpkinseed, bluegill).

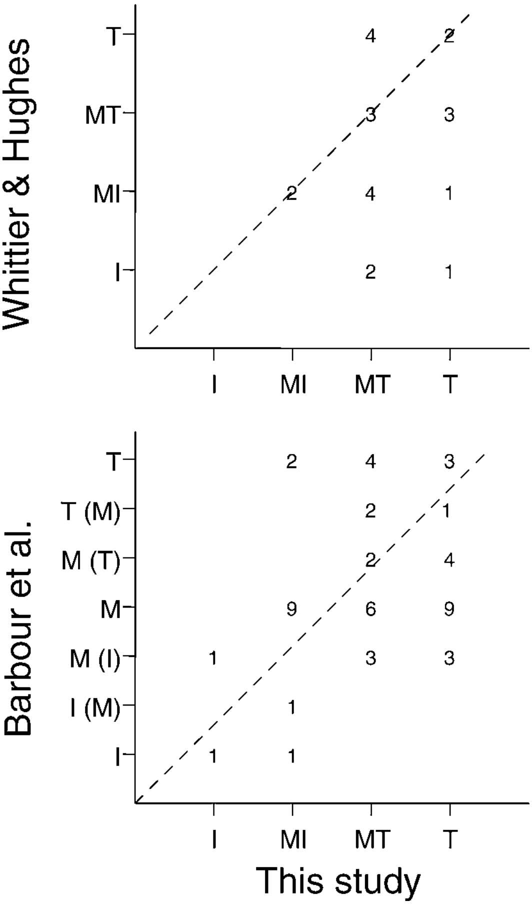

FIGURE 5.—Comparison between tolerance designations from our study (turbidity in Great Lakes coastal wetlands) and the designations of Whittier and Hughes (1998; turbidity in New England lakes) and Barbour et al. (1999; general disturbance in streams). The tolerance designation codes are as in Table 2. The numerals indicate the number of species in each combination (e.g., there were 4 species at T in our study and at M(T) in Barbour et al. 1999). The diagonal lines show equivalent tolerance categories.

The two species that we classified as turbidity intolerant, blackchin shiner and brook stickleback, had also been designated as intolerant or possibly so by Barbour et al. (1999; Table 2). However, none of the four species that Minns et al. (1994) used to assess turbidity intolerance in coastal wetlands were intolerant in our study. In fact, two of their intolerant species (spottail shiner and brook silverside) were turbidity tolerant in our study, one (rock bass) was moderately tolerant, and one (blacknose shiner) was only moderately intolerant of turbidity.

The species for which we have fewer than five occurrences but whose distribution suggested some tolerance to turbidity (Table 2) also tended to be of moderate general tolerance (Barbour et al. 1999). However, the species that by chance we caught only in low-turbidity wetlands varied widely in their published tolerance designations (Table 2). The blacknose dace is one example of a species that other studies have found to be common and *not* intolerant (Table 2) but that we probably caught only rarely because it is primarily a stream resident. Other species for which our low catches likely reflect their preference for streams include rainbow trout, brown trout, brook trout, brassy minnow, longnose dace, river redhorse, greater redhorse, and blackside darter (Table 2). Such occasional wetland visitors could be excluded from metrics for coastal wetlands owing to the low probability of finding them. On the other hand, the trouts are species for which turbidity is a known concern (e.g., Lloyd 1987), so perhaps they do contribute valuable information to a wetland assessment when present.

Issues Surrounding Classification Reference Levels

Assigning turbidity-tolerance designations using the Whittier and Hughes (1998) method hinges on the selection of reference levels because reference lines could be adjusted to produce a different distribution of species among categories. In the absence of more detailed information, we drew reference lines following existing water quality criteria (i.e., 10, 25, and 50 NTU), which also correspond to breakpoints in the data at about 25 and 50 NTU (Figure 2). Using a higher reference line than 10 NTU would permit more species to be designated as turbidity intolerant, and some might argue that applying a standard generally used for coldwater streams to coastal wetlands is inappropriate. However, some coastal wetlands in the northern Great Lakes do support coldwater species (e.g., blacknose dace, sculpin, and salmonids). Furthermore, about half of the wetlands in our study had average turbidity less than 10 NTU and might warrant protection standards keeping them that way, even if few of the fish inhabiting them required water that clear. Since there clearly is interest in using turbidity as a condition by which to evaluate water bodies (USEPA 1988), we see value in indexing fish categories to turbidity levels that already have some regulatory support when that is ecologically appropriate.

More precise characterization of turbidity levels of concern would be desirable in setting reference lines, but data on turbidity effects are actually quite limited. There exists a large body of literature on the impacts of sediments on fishes (summarized in Waters 1995), but it focuses on lotic rather than lentic waters, on deposited rather than suspended sediments, and primarily on salmonids. Newcombe and MacDonald (1991) and Newcombe and Jensen (1996) reviewed studies on suspended sediments, but they summarized data as the product of exposure concentration and duration, appropriate for the massive and acute impacts of most concern to them but less applicable to the modest but chronic impacts affecting coastal wetlands. Also, findings expressed as concentrations of suspended sediment translate only imperfectly to turbidity, which is also affected by factors such as growth of planktonic algae. A review by Lloyd (1987) of the much smaller set of studies that evaluated turbidity per se suggests that most effects on fishes involve increases of more than 25 NTU, consistent with our reference line at that level, although some studies found behavioral changes in response to turbidity increases of as low as 5 NTU.

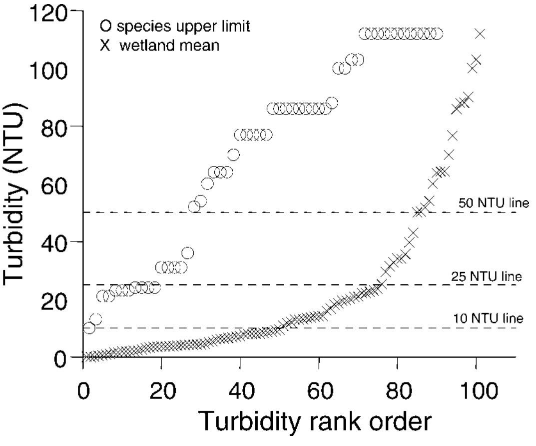

FIGURE 6.—Comparison of the highest turbidity at which each species was found with the wetland-year turbidity distribution. Only species found at 5 or more wetland-years are plotted. Reference lines demark turbidity levels of 10, 25, and 50 nephelometric turbidity units (NTU).

One alternative to setting turbidity reference lines a priori is to look for thresholds suggested by the distribution of the species themselves. In Figure 6, we have plotted the highest turbidity at which each fish species was found (column 4 from Table 2) compared with the distribution of all sites along the turbidity gradient. This figure lends support for a tolerance category division around 25 NTU, as a number of species were not found at turbidity higher than 20–30 NTU. In contrast, there is no evidence for a threshold around 10 NTU, either because coastal wetlands support few turbidity-intolerant species or because these species have a higher tolerance for turbidity in coastal wetlands than in other water body types. A threshold in the vicinity of 85 NTU turbidity is also suggested, but the apparent threshold near 110 NTU just reflects the species complement of the most turbid site (Figure 6). If occurrence above 85 NTU was used as the definition of "tolerant," most species listed as "present and abundant at high turbidity" would remain classified as turbidity tolerant, but most of the species listed as "never abundant but present across the turbidity gradient" would be downgraded to moderate tolerance, while many species listed as "declining abundance at more turbid sites" would be upgraded from moderately tolerant to tolerant.

Looking for thresholds in this manner ignores the relative abundance information that we used to distinguish among species that were moderately tolerant as opposed to tolerant. A future study might wish to evaluate whether a technique such as piecewise regression with relative abundance data or logistic regression with presence/absence data could be used to formalize identification of thresholds at which individual fish species respond to turbidity. But regardless of whether graphical (i.e., Whittier and Hughes 1998) or statistical methods are used to examine fish distributions, some sort of judgment about which levels appropriately divide a continuum of fish responses into tolerance categories is necessary. Existing turbidity water quality criteria provide a useful starting point, which future studies may wish to refine. Data from additional sites with high turbidity would also be desirable to increase our understanding of the upper limits of fish turbidity tolerances.

Related to the issue of tolerance category divisions, we note that Whittier and Hughes (1998) drew turbidity reference lines much lower than ours in their analysis of New England lakes (>4 NTU = highly turbid, <1.6 NTU = clear). However, their water samples were taken from the pelagic center of the lakes rather than from the shallow littoral stations where we took our water samples. Based on studies reviewed by Lloyd (1987), it seems unlikely that fish would differentiate between waters with turbidity of 2 versus 4 NTU. This is not to say that the Whittier and Hughes results were not statistically significant but to suggest that fish were actually responding to conditions in the littoral zone correlated with the pelagic turbidity values reported.

Application of Turbidity Metrics in Fish Assessments

Tolerance designations in many IBI studies use only three categories: intolerant (I), tolerant (T), and an implicit intermediate rating (M) for all other species. We used four categories, replacing the catch-all "M" with MI and MT for moderately intolerant and moderately tolerant, as Whittier and Hughes (1998) had done (they added a fifth "M" category when aggregating tolerances across stressor types). The MI and MT categories from our study could be collapsed back into an intermediate M category for future applications, but the low numbers of turbidity-intolerant species in wetlands suggest that the MI category should be combined with the I category, if a turbidity-intolerant metric for wetlands is desired. Our findings also suggest a reason why Grabas et al. (2004) found turbidity intolerance not to be correlated with disturbance in Lake Ontario wetlands: there are very few turbidity-intolerant species in coastal wetlands in the first place, and their designations were based on general tolerance borrowed from the stream literature.

We did not assign tolerance designations to fish that could be identified only to genus, such as young-of-year (age-0) sunfish, which are difficult to distinguish in the first month or two after hatch. Options for constructing an IBI in such cases include omitting those fish or assigning genus-level tolerance designation based on the likely component species. Since the two most common *Lepomis* species (bluegill, pumpkinseed) were moderately turbidity tolerant while the less common green sunfish was tolerant, unidentified age-0 sunfish could reasonably be imputed as of moderate turbidity tolerance. Likewise, age-0 bullheads can be hard to identify but can be assumed to be at least moderately turbidity tolerant since brown and black bullheads were moderately tolerant while the less common yellow bullhead was tolerant (Table 2).

The considerable spatial variability in water quality within some wetlands makes it possible for fish to appear to be turbidity tolerant (present in wetlands with high average turbidity) yet actually to be avoiding turbid locations. Spatially explicit sampling schemes are required to detect this, but our criterion of designating species only moderately tolerant if abundances declined at high turbidity helps guard against erroneous designations. Wetland water quality is also temporally variable, and turbidity in some wetlands might briefly be quite high following stream runoff events or wind- and wave-driven sediment resuspension (Bedford 1992; Chow-Fraser 1999). During such events, fish probably would temporarily tolerate turbidity levels that they would not tolerate in the long run or that would cause them to find refuge in adjacent waters, so fish are probably indicative of typical rather than unusual water quality conditions.

We envision that turbidity metrics based on the tolerance or intolerance designations developed in this study would form part of broader multimetric (e.g., IBI) or multivariate assessments of fish communities in coastal wetlands. Our data provide only a snapshot of turbidity conditions, and additional data for highly turbid sites and for uncommon species would help refine turbidity tolerance designations. We can also envision refinement of methods for making divisions among turbidity tolerance categories beyond simple use of thresholds established in water quality regulations. However, the turbidity tolerance designations we have put forth are based on actual fish composition from Great Lakes coastal wetlands and represent a considerable improvement over borrowing tolerance designations from the stream literature. Our data are as comprehensive and geographically extensive as any currently published for Great Lakes wetlands, and our study lays the foundation for further development of fish-based indicators of Great Lakes wetland condition.

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