BEFORE THE ILLINOIS POLLUTION CONTROL BOARD

IN THE MATTER OF:	)	
	)	
PROPOSED AMENDMENTS TO	)	R 04-25
DISSOLVED OXYGEN STANTARD	)	
35 Ill. Adm. Code 302.206	)	
	)	

NOTICE OF FILING

See attached Service List

PLEASE TAKE NOTICE that on Wednesday, August 3, 2005, we filed the attached Testimony of David L. Thomas, PhD. with the Clerk of the Illinois Pollution Control Board, a copy of which is herewith served upon you.

Respectfully submitted,

ILLINOIS DEPARTMENT OF
NATURAL RESOURCES

By: [signature]
One of Its Attorneys

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CERTIFICATE OF SERVICE

The undersigned certifies that a copy of the foregoing Testimony was filed by hand deliver to the Clerk of the Illinois Pollution Control Board and served upon the parties to whom said Notice is directed by first class mail, postage prepaid, by depositing in the U.S. Mail at One Natural Resources, Springfield, Illinois on Wednesday, August 3, 2005.

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TESTIMONY

David L. Thomas, PhD
Chief, Illinois Natural History Survey
August 3, 2005

My name is David L. Thomas, and I am Chief of the Illinois Natural History Survey, a Division of the Department of Natural Resources (Department). I received my Masters degree in Ecology from the University of Illinois in 1967, where I worked on the Percina darters of the Kaskaskia River for my thesis. I completed my PhD from Cornell in 1971 in Ecology and Systemmatics, and my thesis was on the drums (Sciaenidae) of the upper Delaware Bay and lower Delaware River. I also taught the laboratories for Ichthyology and Advanced Ichthyology while at Cornell, and was curator of the Cornell fish collection.

This testimony is presented on behalf of the Illinois DNR and based on my experience as a trained ichthyologist, on my more than 35 years of evaluating the effects of various environmental parameters on aquatic biota, and my first-hand knowledge and experience on Illinois fishes. I have regularly measured DO as part of the physical/chemical parameters measured during field collections, and have experience evaluating the effects of this parameter on aquatic resources in Illinois. I interact with our Ichthyologist at the Survey on a regular basis, and have made numerous collections with him over the last 5 years. I deal with a variety of issues with our fisheries staff, particularly regarding invasive species. I have also conducted field work with DNR fisheries staff, and assisted in their basin surveys.

The present DO standard requires that at no time shall concentrations decline below 5 mg/L and for at least 16 hours each day they must remain above 6 mg/L. The IAWA, based on testimony and recommendations of Drs. Garvey and Whiles, recommended the following changes to the DO standard:

A 1-day minimum* of 5.0 mg/L spring through summer (i.e., March 1 through June 30)

A 7-day mean** of 6.0 mg/L spring through early summer (i.e. March 1 through June 30)

A 1-day minimum of 3.5 mg/L the remainder of the year (i.e., July 1 through February 28 or 29)

A 7-day mean minimum*** of 4.0 mg/L the remainder of the year (i.e., July 1 through February 28 or 29)

** 1-day minimum is the lowest measured value of DO during a 24-hour calendar day*

*** 7-day mean DO is the average of the daily mean DO values from the current and previous 6 calendar days.*

**** 7-day mean minimum is the arithmetic average of the daily minimum DO values from the current and previous 6 calendar days.*

The DNR believes that while we should recognize that some rivers and streams could maintain present aquatic populations under a revised standard like that proposed by the IAWA, there are many streams and rivers in Illinois that would not be able to maintain present aquatic populations. If one statewide standard is going to be put into place, it needs to be high enough to protect sensitive species. The IAWA proposal does not accomplish this level of protection. We believe the present standard should be maintained until it can be demonstrated that the biota in particular water bodies will not be negatively affected by a lower standard.

Since the second hearing on this matter, conducted on August 12, 2004, the Department has been actively participating in status conference calls and stakeholder meetings addressing the merits of the rulemaking proposal. Though the stake holders meetings did not result in an agreed upon regulatory proposal, it helped the DNR understand the state of knowledge in Illinois as it relates to dissolved oxygen and aquatic life needs.

The DO standard in Illinois needs to account for the natural DO levels in the water body in question and the presence or absence of DO sensitive species. Initially, the opposite approach was attempted, that is, to designate streams that needed greater protection than proposed by the IAWA, however, our level of knowledge of all streams and the species that they contain is not sufficiently developed to come up with a complete list. Without a complete list of streams needing to maintain at least the present standard, implementation of a lower standard could prove to be detrimental to sensitive aquatic species. Justification for needing greater protection (than those proposed by the IAWA) of some of our aquatic resources are presented below.

There are a significant number of rivers and streams in Illinois that contain fish species considered to be oxygen sensitive (see Table 1). This list represents 25 fish species that are sensitive to low DO based on life history and distribution data for Illinois (Smith,1979) and Wisconsin (Becker, 1983). These species were considered good indicators for waters that contain DO sensitive aquatic biota. Other species could be added to this list as indicated below.

A list of 30 "DO" tributaries and 10 "DO" major rivers is contained in Table 2. These were selected based on the presence of at least 5 DO sensitive indicator fish species for major river mainstems, and 4 DO sensitive indicator species for tributary streams, and represents the kinds of streams that would need greater protection than the proposal from IAWA. All streams are perennial according to 7Q10 flow maps from the Illinois State Water Survey. Rankin recently (2004) provided data for Ohio that showed that Exceptional Warmwater Habitat streams (described below) maintained fairly high DO levels and could have 10 or more sensitive species. Those streams with mean DO values between 6-7 mg/l rarely had more than 5 intolerant species.

The Ohio EPA (1996) made a good rationale for why some warmwater streams needed a greater level of protection, and higher DO standards, than other warmwater streams. This document developed a rationale for designation of DO criteria for Exceptional Warmwater Habitat (EWH), and their standard for these streams was a 6.0 mg/l daily average and a 5 mg/l minimum. EWH designation was reserved for waters which support "unusual and exceptional" assemblages of aquatic organisms which are characterized by a high diversity of species, particularly those which are highly intolerant and/or rare, threatened, endangered, or special status (i.e., declining species). These waters were characterized by Index of Biotic Integrity (IBI) values above 46. In a summary of individual Ohio streams and rivers (page 17), they state the following: "The results of the comparison of continuously measured D.O. and EWH attainment in six steams and rivers of varying sizes shows that the latter can be compatible with minimum D.O. values less than 6 mg/l. However, values less that 5 mg/l were either infrequent, did not frequently correlate with full EWH use attainment, or were measured only under extreme low flow conditions. Thus, the analysis would appear to support a minimum EWH D.O. standard less that 6 mg/l, but not less than 5 mg/l."

Illinois has many streams that meet the Ohio standard for Exceptional Warmwater Habitat, and we list 40 of these as "DO sensitive streams" based on the presence of DO sensitive species. Eighteen of the streams selected had IBI scores with an average weighted score of 50. Only two of these streams had an IBI under 46 (one with a value of 40 and one with a value of 43). There were 29 other streams on the larger list provided that had IBI values of over 46, and on closer examination these too might be considered for greater protection.

There are other fishes found in Illinois, other than those listed in Table 1, that are found in "higher" DO waters. Rankin (2004) produced a table of various fishes and the weighted mean DO values at which they were captured. I went through the list and noted all fish species that I was sure also occurred in Illinois that were found at DO levels greater than Smallmouth bass (which was found at a weighted mean DO of 6.61 mg/l). This list is included as Table 3, and includes four species (Black Redhorse, Blacknose Dace, Northern Hog Sucker and Rosyface Shiner) listed as DO sensitive in Table 1. One of the species on this list, the Slenderhead darter, was a species that I had worked on for my master's theses at University of Illinois. I found in tests I conducted that this species had a higher rate of respiration, and was found in higher oxygen waters, than the Blacksided darter, another species that I studied. In Ohio the weighted mean DO value for all collections of Slenderhead darter was 6.7 mg/l, whereas it was 5.6 mg/l for Blacksided darter.

The Department has given strong consideration to the Ohio data for this testimony because they are on the same latitude as much of Illinois, and have many of the same Ohio River drainage fishes as are found in Illinois. Ohio EPA has developed one of the better databases that we have found on field measurements of DO with individual fish collections. The Ohio data corroborates our field observations in Illinois, and fish that are DO sensitive in Ohio, will be DO sensitive in Illinois and across their range.

The IAWA recommended an end date for the sensitive season (spawning and early development of fish) of June 30 statewide. This date will not be protective of many species that spawn up through late June, or are summer spawners. Table 4 is a summary of Illinois fishes that spawn primarily in the summer. This list does not include late spring spawners such as Smallmouth bass which may spawn into late June. It also does not include the Channel catfish, although Simon and Wallus (2003) stated that yolk-sac larvae and early juveniles were collected mid-May through August with peaks in June and July in the Tennessee and lower Ohio rivers. Six of the "summer" spawners in Table 4 are also listed in Table 3 as being found in Ohio in higher oxygen waters - Emerald shiner, Ironcolor shiner, Bigmouth shiner, Weed shiner, River redhorse, and Stonecat. One of these species, the Bigmouth shiner, was studied by a student (Clinton Kowalik) at University of Illinois that I helped advise. He found that peak gonad development occurred on June 26 and small young (under 20mm) were collected in July.

Ohio EPA (1996) stated that while 5mg/l (their recommended minimum for Exceptional Warmwater Habitat) is more stringent than that proposed by U.S. EPA (1986) for adults and juveniles, it is necessary to protect younger life stages. They go on to state that "the EWH D.O. criterion that we propose lies between the U.S. EPA recommended warmwater and coldwater levels (non-embryonic life stages only) of protection which also seems reasonable given that some of the sensitive warmwater species that comprise the assemblages representative of EWH may well approach the sensitivity of salmonids". With the information provided, it is evident the standard, as proposed, will not be protective for all the waters of the state.

The Ohio EPA document addresses an issue that we have struggled with in Illinois, and that is that there is a group of fishes that fall in DO sensitivity between cold-water and the more typical warm-water fauna. The Ohio Exceptional Warmwater Habitat category recognizes that a number of species found in their biologically diverse warm water streams require very good water quality including well oxygenated waters. We recognize that Illinois also has waters that could be considered as needing extra protection because they contain diverse fish populations, threatened and endangered species, and many DO sensitive species. If one statewide standard is going to be put in place, then it needs to be high enough to protect these sensitive species. The IAWA proposal does not accomplish that and should not be adopted.

The Ohio EPA document cites FWPCA (1968) as stating that "In some cases, good populations of warmwater fish, including game and pan fishes, occur in waters in which dissolved oxygen may be as low as 4 mg/l for short periods...(and)...Five and 4 mg/l are close to the borderline of oxygen concentrations that are tolerable for extended periods. For a good population of game and pan fishes the concentration should be considerably more than this."

In light of the above statements it seems particularly important that we provide greater protection for warm water streams that have high biotic integrity, good game and pan fishes, and oxygen sensitive fishes.

The focus of this testimony has been on fishes, but there are a number of mussels and other invertebrates that are also sensitive to low DO (see Rankin 2004). In addition, we have a number of state threatened and endangered species in Illinois, and for many we know little about their oxygen requirements. All of the above indicates that we should maintain our present standard, unless we can show for particular water bodies that a lower standard will not negatively affect aquatic species in that system.

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Table 1: Species of fish found in Illinois that require higher dissolved oxygen levels

Common Name
American brook lamprey
Banded sculpin
Bigeye chub
Bigeye shiner
Black redhorse
Blacknose dace
Brook stickleback
Fourhorn sculpin
Ironcolor shiner
Least brook lamprey
Longnose dace
Mottled sculpin
Ninespine stickleback
Northern brook lamprey
Northern hog sucker
Northern pike
Ozark minnow
River redhorse
Rock bass
Rosyface shiner
Slimy sculpin
Southern redbelly dace
Spoonhead sculpin
Threespine stickleback
Weed shiner

Table 2 - TESTIMONY OF DAVID L. THOMAS, AUGUST 2005

IB-BASIN	CATCHMENT_NAME OR MAINSTEM	PROPOSED DO WATERS	DO MAJOR RIVER	DO TRIBUTARY	HIGH DO FISH INDICATOR SPECIES	NUMBER OF HIGH DO FISH INDICATOR SPECIES	IBI
ABASH RIVER MS	WABASH RIVER MS	X	X		X	6	53
ERMILION (SOUTH) RVR	LITTLE VERMILION (SOUTH) RIVER	X		X	X	6	54
ERMILION (SOUTH) RVR	VERMILION (SOUTH) RIVER MS	X	X		X	5	48
ERMILION (SOUTH) RVR	SALT FORK	X		X	X	5	51
ERMILION (SOUTH) RVR	MIDDLE FORK	X		X	X	4	50
ACKINAW RIVER	MACKINAW RIVER MS	X	X		X	7	56
ACKINAW RIVER	LITTLE MACKINAW RIVER	X		X	X	6	
G BUREAU CREEK	BIG BUREAU CREEK (MS)	X	X		X	6	50
ERMILION (NORTH) RVR	VERMILION (NORTH) RIVER MS	X	X		X	5	48
OX RIVER	FOX RIVER MS	X	X		X	7	40
OX RIVER	INDIAN CREEK	X		X	X	4	
OX RIVER	BIG ROCK CREEK	X		X	X	4	
OX RIVER	NIPPERSINK CREEK	X		X	X	4	
NGAMON RIVER	KICKAPOO CREEK	X		X	X	4	
NKAKEE RIVER	KANKAKEE RIVER MS	X	X		X	10	50
NKAKEE RIVER	FORKED CREEK	X		X	X	4	46
NKAKEE RIVER	HORSE CREEK	X		X	X	4	50
NKAKEE RIVER	ROCK CREEK	X		X	X	4	50
OQUOIS RIVER	IROQUOIS RIVER MS	X	X		X	5	
OQUOIS RIVER	BEAVER CREEK	X		X	X	4	
OQUOIS RIVER	SUGAR CREEK	X		X	X	5	
PPLE RIVER	APPLE RIVER MS	X	X		X	5	
PPLE RIVER	FURNACE CREEK	X		X	X	6	
PPLE RIVER	SOUTH FORK	X		X	X	6	
PPLE RIVER	CLEAR CREEK	X		X	X	5	
OCK RIVER	GREEN RIVER	X		X	X	5	
OCK RIVER	FRANKLIN CREEK	X		X	X	6	
OCK RIVER	LEAF RIVER	X		X	X	5	50
OCK RIVER	KYTE RIVER	X		X	X	4	43
OCK RIVER	STILLMAN CREEK	X		X	X	6	
OCK RIVER	KISHWAUKEE RIVER	X		X	X	7	56
OCK RIVER	KILLBUCK CREEK	X		X	X	7	
OCK RIVER	PISCASAW CREEK	X		X	X	5	51
OCK RIVER	COON CREEK	X		X	X	5	
OCK RIVER	RUSH CREEK	X		X	X	5	56
OCK RIVER	SOUTH BRANCH-EAST KISHWAUKEE	X		X	X	6	
OCK RIVER	NORTH BRANCH-KISHWAUKEE RVR	X		X	X	4	
OCK RIVER	PINE CREEK	X		X	X	4	
OCK RIVER	SUGAR RIVER	X		X	X	4	51
OCK RIVER	ROCK RIVER MS	X	X		X	5	
		TOTALS BY CATEGORY =		40	10	30	

Table 3: The weighted mean DO for various fishes collected in Ohio streams. Fish listed are ones that occur in Illinois, and were found at DO levels equivalent to or higher than for Smallmouth Bass*

Weighted DO Means (Mg/l) for Ohio Streams	
Smallmouth Bass	6.61
Central Stoneroller	6.62
Black Crappie	6.63
Golden Redhorse	6.70
Slenderhead Darter	6.71
Silver Redhorse	6.72
Silverjaw Minnow	6.81
Hornyhead Chub	6.82
Emerald Shiner	6.83
Black Redhorse	6.93
Shorthead Redhorse	6.96
Blacknose Dace	6.96
Northern Hog Sucker	7.02
Rosyface Shiner	7.18
Bigmouth Shiner	7.22
Stonecat Madtom	7.41
River Chub	7.49

*Rankin, E.T. 2004. [Draft] Notes on Associations between Dissolved Oxygen and Fish and Macroinvertebrate Assemblages in Wadeable Ohio Streams.

Table 4. Summary of the fishes of Illinois thought to spawn through summer (based in part on Smith 1979. The Fishes of Illinois)

Table 1. List of summertime (June –August) fish spawners in Illinois.	
Scaphirhynchus albus Pallid shiner	*Lythrurus fumeus* Ribbon shiner
Dorosoma cepedianum Gizzard shad	*Lythrurus umbratilis* Redfin shiner
Notemigonus crysoleucas Golden shiner	*Pimephales notatus* Bluntnose minnow
Macrhybopsis hyostoma Shoal chub	*Pimephales promelas* Fathead minnow
Platygobio gracilis Flathead chub	*Pimephales vigilax* Bullhead minnow
Phenacobius mirabilis Suckermouth minnow	*Carpiodes carpio* River carpsucker
Notropis atherinoides Emerald shiner	*Carpiodes velifer* Highfin carpsucker
Notropis blennius River shiner	*Moxostoma carinatum* River redhorse
Notropis boops Bigeye shiner	*Noturus flavus* Stonecat
Notropis buchanani Ghost shiner	*Fundulus olivaceus* Spotted topminnow
Notropis chalybaeus Ironcolor shiner	*Gambusia affinis* Western mosquitofish
Notropis dorsalis Bigmouth shiner	*Labidesthes sicculus* Brook silverside
Notropis heterodon Blackchin shiner	*Menidia beryllina* Inland silverside
Notropis shumardi Silverband shiner	*Lepomis cyanellus* Green sunfish
Notropis stramineus Sand shiner	*Lepomis gibbosus* Pumpkinseed
Notropis texanus Weed shiner	*Lepomis gulosus* Warmouth
Opsopoeodus emiliae Pugnose minnow	*Lepomis humilis* Orangespotted sunfish
Cyprinella lutrensis Red shiner	*Lepomis miniatus* Redspotted sunfish
Cyprinella spiloptera Spotfin shiner	*Ammocrypta clara* Western sand darter
Cyprinella whipplei Steelcolor shiner	

REFERENCES

FISHES
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Water Quality Criteria

Report of the
National Technical Advisory Committee
to the
Secretary of the Interior

APRIL 1, 1968

WASHINGTON, D.C.

FEDERAL WATER POLLUTION CONTROL ADMINISTRATION

Recommendation for Cold Waters: Because of the large number of trout and salmon waters which have been destroyed, or made marginal or nonproductive, the remaining trout and salmon waters must be protected if this resource is to be preserved:

(1) Inland trout streams, headwaters of salmon streams, trout and salmon lakes and reservoirs, and the hypolimnion of lakes and reservoirs containing salmonids should not be warmed. No heated effluents should be discharged in the vicinity of spawning areas.

For other types and reaches of cold-water streams, reservoirs, and lakes, the following restrictions are recommended.

(2) During any month of the year, heat should not be added to a stream in excess of the amount that will raise the temperature of the water more than 5 F (based on the minimum expected flow for that month). In lakes and reservoirs, the temperature of the epilimnion should not be raised more than 3 F by the addition of heat of artificial origin.

(3) The normal daily and seasonal temperature fluctuations that existed before the addition of heat due to other than natural causes should be maintained.

(4) The recommended maximum temperatures that are not to be exceeded for various species of cold water fish are given in table III–1.

NOTE.—For streams, total added heat (in BTU's) might be specified as an allowable increase in temperature of the minimum daily flow expected for the month or period in question. This would allow addition of a constant amount of heat throughout the period. Approached in this way for all periods of the year, seasonal variation would be maintained. For lakes the situation is more complex and cannot be specified in simple terms.

TABLE III–1

[Provisional maximum temperatures recommended as compatible with the well-being of various species of fish and their associated biota]

93 F: Growth of catfish, gar, white or yellow bass, spotted bass, buffalo, carpsucker, threadfin shad, and gizzard shad.
90 F: Growth of largemouth bass, drum, bluegill, and crappie.
84 F: Growth of pike, perch, walleye, smallmouth bass, and sauger.
80 F: Spawning and egg development of catfish, buffalo, threadfin shad, and gizzard shad.
75 F: Spawning and egg development of largemouth bass, white, yellow, and spotted bass.
68 F: Growth or migration routes of salmonids and for egg development of perch and smallmouth bass.
55 F: Spawning and egg development of salmon and trout (other than lake trout).
48 F: Spawning and egg development of lake trout, walleye, northern pike, sauger, and Atlantic salmon.

Note.—Recommended temperatures for other species, not listed above, may be established if and when necessary information becomes available.

Dissolved oxygen

Oxygen requirements of aquatic life have been extensively studied. Excellent survey papers are presented by Doudoroff (1957), Doudoroff and Shumway (1967), Doudoroff and Warren (1962), Ellis (1937), and Fry (1960). Much of the work on temperature requirements also considers oxygen and those bibliographies are equally valuable.

Most of the research concerning oxygen requirements for freshwater organisms deals with fish, but since fish depend upon other aquatic species for food and would not remain in an area with an inadequate food supply, it seems reasonable to assume that a requirement for fish would serve also for the rest of the community. The fish themselves can be grouped into three categories according to their temperature and oxygen requirements: (1) the cold-water fish (e.g., salmon and trout), (2) the warm-water game and pan fish (e.g., bass and sunfish), and (3) the warm-water "coarse" fish (e.g., carp and buffalo). The cold-water fish seem to require higher oxygen concentrations than the warm-water varieties. The reason is not known, but it may be related to the fact that, for half saturation, trout hemoglobin requires an oxygen partial pressure three or four times that required by carp hemoglobin under similar circumstances. Warm-water game and pan fish seem to require a higher concentration than the "coarse" fish, probably because the former are more active and predatory.

Relatively little of the research on the oxygen requirements of fish in any of these three categories is applicable to the problem of establishing oxygen criteria because the endpoints have usually been too crude. It is useless in the present context to know how long an animal can resist death by asphyxiation at low dissolved oxygen concentrations; we must know instead the oxygen concentration that will permit an aquatic population to thrive. We need data on the oxygen requirements for egg development, for newly hatched larvae, for normal growth and activity, and for completing all stages of the reproductive cycle. It is only recently that experimental work has been undertaken on the effects of oxygen concentration on these more subtle endpoints. As yet, only a few species have been studied.

One of the first signs that a fish is being affected by a reduction of dissolved oxygen (DO) concentration is an increase in the rate at which it ventilates its gills, a process accomplished in part by an increase in the frequency of the opercular movements. The half dozen or so species (chiefly warm-water game and pan fish) that have been reported so far show a significant increase in frequency as the DO concentration is reduced from 6 to 5 mg/l (at about 72 F) and a greater increase from 5 to 4 mg/l. If the opercular rate is taken as the criterion by which the adequacy of an oxygen concentration is to be judged, then such evidence as we have indicates 6 mg/l as the required dissolved oxygen concentration. Several field studies have shown, however, that good and diversified fish populations can occur in waters in which the dissolved oxygen concentration is between 6 and 5 mg/l in the summer, suggesting that a minimum of 6 mg/l is probably more stringent than necessary for warm-water fishes. Because the oxygen content of a body of water does not remain constant, it follows that if the dissolved oxygen is never less than 5 mg/l it must be higher part of the time. In some cases, good populations of warm-water fish, including game and pan fishes, occur in waters in which the dissolved oxygen may be as low as 4 mg/l for short periods. Three mg/l is much too low, however, if normal growth and activity are to be maintained. It has been reported that the growth of young fish is slowed markedly if the oxygen concentration falls to 3 mg/l for part of the day, even if it rises as high as 18 mg/l at other times. It is for such reasons as this that oxygen criteria cannot be based on averages. Five and 4 mg/l are close to the borderline of oxygen concentrations that are tolerable for extended periods. For a good population of game and pan fishes, the concentration should be considerably more than this.

The requirements of the different stages in the life cycles of aquatic organisms must be taken into account. An oxygen concentration that can be tolerated by an adult animal, with fully developed respiratory apparatus, less intense metabolic requirements, and the ability to move away from adverse conditions, could easily be too low for eggs and larval stages. The eggs are especially vulnerable to oxygen lack because they have to depend upon oxygen diffusing into them at a rate sufficient to maintain the developing embryos. Hatching, too, is a critical time; recently hatched young need relatively more oxygen than adults, but until they become able to swim for themselves (unless they are in flowing water) they must depend upon the oxygen supply in the limited zone around them. These problems are not as great among species that tend their eggs and young, suspend their eggs from plants, or have pelagic eggs, as they are for salmonids. Salmonids bury their eggs in the gravel of the stream away from the main flow of the water thereby requiring a relatively high oxygen concentration in the water that does reach them.

Recommendation: In view of the above considerations and with the proviso that future research may make revision necessary, the following environmental conditions are considered essential for maintaining n tive populations of fish and other aquatic life:

(1) For a diversified warm-water biota, includir game fish, daily DO concentration should be abo 5 mg/l, assuming that there are normal seasonal ar daily variations above this concentration. Under e treme conditions, however, and with the same stipul tion for seasonal and daily fluctuations, the DO ma range between 5 mg/l and 4 mg/l for short periods time, provided that the water quality is favorable all other respects. In stratified eutrophic and dystroph lakes, the DO requirements may not apply to tl hypolimnion. In shallow unstratified lakes, they shou apply to the entire circulating water mass.

These requirements should apply to all waters e cept administratively established mixing zones. In lake such mixing zones must be restricted so as to limit tl effect on the biota. In streams, there must be no block to migration and there must be adequate and sa passageways for migrating forms. These zones of pa sage must be extensive enough so that the majority plankton and other drifting organisms are protecte (see section on zones of passage).

(2) For the cold water biota, it is desirable that D concentrations be at or near saturation. This is esp cially important in spawning areas where DO leve must not be below 7 mg/l at any time. For good grow and the general well-being of trout, salmon, and oth species of the biota, DO concentrations should not below 6 mg/l. Under extreme conditions they m range between 6 and 5 mg/l for short periods provide that the water quality is favorable and normal dai and seasonal fluctuations occur. In large streams th have some stratification or that serve principally as m gratory routes, DO levels may be as low as 5 mg/l f periods up to 6 hours, but should never be below mg/l at any time or place.

(3) DO levels in the hypolimnion of oligotroph small inland lakes and in large lakes should not lowered below 6 mg/l at any time due to the additi of oxygen-demanding wastes or other materials.

Carbon dioxide

An excess of "free" carbon dioxide (as disti guished from that present as carbonate and bica bonate) may have adverse effects on aquatic ar mals. These effects range from avoidance reactio and changes in respiratory movements at low co centrations, through interference with gas e change at higher concentrations, to narcosis a death if the concentration is increased further. Tl respiratory effects seem the most likely to be concern in the present connection.

Since the carbon dioxide resulting from met bolic processes leaves the organisms by diffusio an increase in external CO_2 concentration w make it more difficult for it to diffuse out of tl organism. Thus, it begins to accumulate internall The consequences of this internal accumulati are best known for fish, but presumably the prin ples are the same for other organisms. As the C accumulates, it depresses the blood pH, and tl

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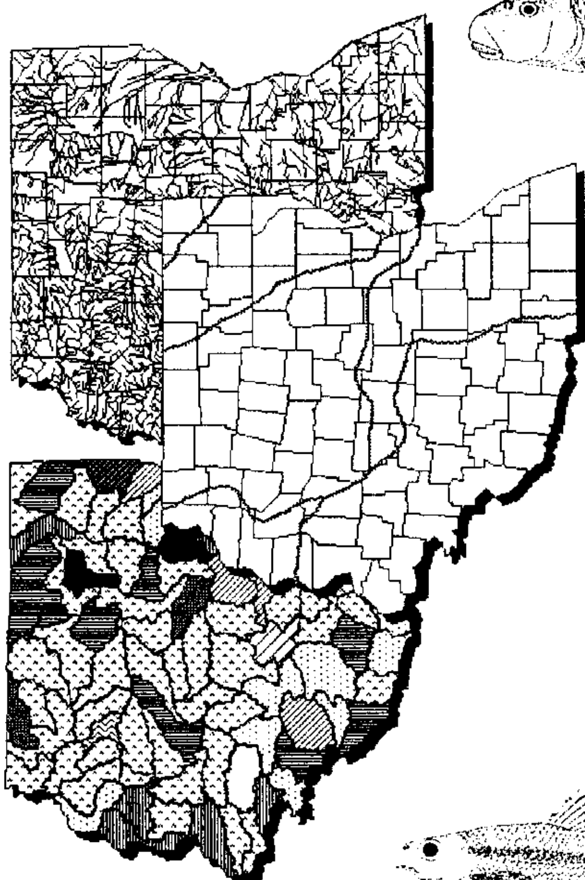

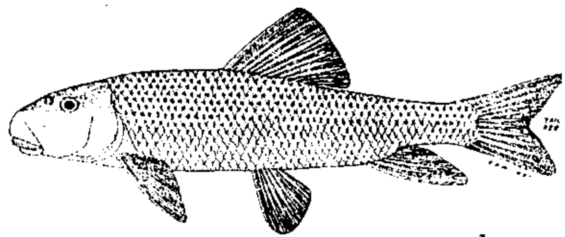

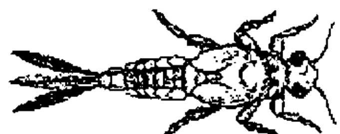

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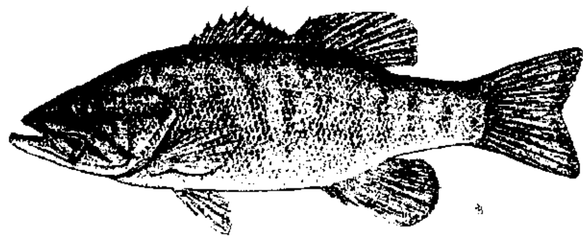

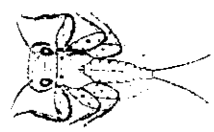

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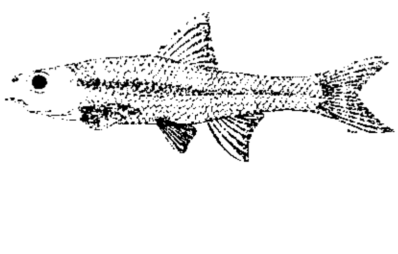

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State of Ohio Environmental Protection Agency
Division of Surface Water
Monitoring & Assessment Section
1685 Westbelt Drive
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NOTICE TO USERS

Ohio EPA incorporated biological criteria into the Ohio Water Quality Standards (WQS; Ohio Administrative Code 3745-1) regulations in February 1990 (effective May 1990). These criteria consist of numeric values for the Index of Biotic Integrity (IBI) and Modified Index of Well-Being (MIwb), both of which are based on fish assemblage data, and the Invertebrate Community Index (ICI), which is based on macroinvertebrate assemblage data. Criteria for each index are specified for each of Ohio's five ecoregions (as described by Omernik 1987), and are further organized by organism group, index, site type, and aquatic life use designation. These criteria, along with the existing chemical and whole effluent toxicity evaluation methods and criteria, figure prominently in the monitoring and assessment of Ohio's surface water resources.

The following Ohio EPA documents support the use of biological criteria by outlining the rationale for using biological information, the methods by which the biocriteria were derived and calculated, the field methods by which sampling must be conducted, and the process for evaluating results:

Ohio Environmental Protection Agency. 1987a. Biological criteria for the protection of aquatic life: Volume I. The role of biological data in water quality assessment. Division of Water Qual. Monit. & Assess., Surface Water Section, Columbus, Ohio.

Ohio Environmental Protection Agency. 1987b. Biological criteria for the protection of aquatic life: Volume II. Users manual for biological field assessment of Ohio surface waters. Division of Water Qual. Monit. & Assess., Surface Water Section, Columbus, Ohio.

Ohio Environmental Protection Agency. 1989b. Addendum to Biological criteria for the protection of aquatic life: Volume II. Users manual for biological field assessment of Ohio surface waters. Division of Water Qual. Plan. & Assess., Ecological Assessment Section, Columbus, Ohio.

Ohio Environmental Protection Agency. 1989c. Biological criteria for the protection of aquatic life: Volume III. Standardized biological field sampling and laboratory methods for assessing fish and macroinvertebrate communities. Division of Water Quality Plan. & Assess., Ecol. Assess. Sect., Columbus, Ohio.

Ohio Environmental Protection Agency. 1990. The use of biological criteria in the Ohio EPA surface water monitoring and assessment program. Division of Water Qual. Plan. & Assess., Ecol. Assess. Sect., Columbus, Ohio.

Rankin, E.T. 1989. The qualitative habitat evaluation index (QHEI): rationale,methods, and application. Division of Water Qual. Plan. & Assess., Ecol. Assess. Sect., Columbus, Ohio.

Since the publication of the preceding guidance documents new publications by Ohio EPA have become available. The following publications should also be consulted as they represent the latest information and analyses used by Ohio EPA to implement the biological criteria.

DeShon, J.D. 1995. Development and application of the invertebrate community index (ICI), pp. 217-243. in W.S. Davis and T. Simon (eds.). Biological Assessment and Criteria: Tools for Risk-based Planning and Decision Making. Lewis Publishers, Boca Raton, FL.

Rankin, E. T. 1995. The use of habitat assessments in water resource management programs, pp. 181-208. in W. Davis and T. Simon (eds.). Biological Assessment and Criteria: Tools for Water Resource Planning and Decision Making. Lewis Publishers, Boca Raton, FL.

Yoder, C.O. and E.T. Rankin. 1995. Biological criteria program development and implementation in Ohio, pp. 109-144. in W. Davis and T. Simon (eds.). Biological Assessment and Criteria: Tools for Water Resource Planning and Decision Making. Lewis Publishers, Boca Raton, FL.

Yoder, C.O. and E.T. Rankin. 1995. Biological response signatures and the area of degradation value: new tools for interpreting multimetric data, pp. 263-286. in W. Davis and T. Simon (eds.). Biological Assessment and Criteria: Tools for Water Resource Planning and Decision Making. Lewis Publishers, Boca Raton, FL.

Yoder, C.O. 1995. Policy issues and management applications for biological criteria, pp. 327-344. in W. Davis and T. Simon (eds.). Biological Assessment and Criteria: Tools for Water Resource Planning and Decision Making. Lewis Publishers, Boca Raton, FL.

Yoder, C.O. and E.T. Rankin. 1995. The role of biological criteria in water quality monitoring, assessment, and regulation. Environmental Regulation in Ohio: How to Cope With the Regulatory Jungle. Inst. of Business Law, Santa Monica, CA. 54 pp.

These documents and this report can be obtained by writing to:

Ohio EPA, Division of Surface Water
Monitoring and Assessment Section
1685 Westbelt Drive
Columbus, Ohio 43228-3809
(614) 728-3377

Several of the major water quality criteria compendia (*e.g.*, U.S. EPA 1986) were also examined during the course of this study. The information contained in this literature strongly suggests that the proposed revision to the EWH D.O. criterion is both protective and appropriate. Based on the information presented by U.S. EPA (1986) there is also justification for bringing the Cold Water Habitat (CWH) D.O. criterion (presently 6 mg/l minimum only) into line with the two-number average/minimum hierarchy of the Ohio WQS. In practical terms the proposed two-number criteria for EWH and CWH are consistent with the hierarchy of D.O. criteria between the WWH, MWH, and LRW use designations. The adoption of a 6 mg/l daily average, 5 mg/l minimum two-number D.O. criterion for EWH and a 7 mg/l daily average, 6 mg/l minimum two-number D.O. criterion for CWH is supported by the scientific evidence (both field and laboratory) examined by this study.

Summary and Conclusions

The principal objective of this study is to present a rationale for revising the existing 6 mg/l minimum dissolved oxygen (D.O.) criterion for the Exceptional Warmwater Habitat (EWH) use designation. The need for a revised EWH D.O. criterion has been recognized by Ohio EPA for more than a decade. D.O. criteria have traditionally been expressed as a period average (usually daily) along with a minimum below which D.O. values should not fall. The need for both is evident in the literature on the effects of D.O. on aquatic life. Such a two-number criterion is exemplified by the current Warmwater Habitat (WWH), Modified Warmwater Habitat (MWH), and Limited Resource Water (LRW) D.O. criteria, an approach which is recognized as appropriate by U.S. EPA (1986). Unlike these criteria, the existing EWH and Coldwater Habitat (CWH) D.O. criteria were adopted in 1978 as minimum only values. One reason cited by Ohio EPA for needing a two-number D.O. criterion, the daily average value in particular, was a more meaningful target for steady-state D.O. modeling efforts. The very nature of D.O. regimes in warmwater rivers and streams also substantiates the need for a two-number criterion. D.O. concentrations are subject to natural, diel changes which are influenced by the daily cycles of algal photosynthesis and respiration. The magnitude of change between the minimum and maximum D.O. during any 24-hour period is dependent on several factors including flow, ambient temperature, solar insolation, and the abundance and activity of photosynthetic algae and/or higher aquatic plants. In the warmwater rivers and streams of Ohio and the midwest U.S. a diel swing of as much as 3-5 mg/l may be considered "typical" during normal summer low flow and ambient temperature conditions. Thus, the relationship of the dynamic D.O. regime to an average value over a 24-hour period is as important as the minimum.

The need for a revised EWH D.O. criterion is also indicated by the frequent and widespread observation of full attainment of the EWH biological criteria where D.O. values less than the current 6.0 mg/l (minimum) criterion have been measured. The results of comparing continuously measured D.O. data and EWH use attainment in six streams and rivers of varying size shows that the latter is compatible with D.O. values less than 6 mg/l. However, values less than 5 mg/l were either infrequent, did not correlate with full EWH use attainment, or were measured only under extreme low flow conditions. The results of this analysis tends to support a minimum EWH D.O. criterion of less than 6 mg/l, but not less than 5 mg/l.

Justification and Rationale for Revisions to the Dissolved Oxygen Criteria in the Ohio Water Quality Standards

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Introduction

The Ohio Water Quality Standards (WQS; Ohio Administrative Code 3745-1) consist of designated uses and chemical, physical, and biological criteria designed to represent measurable properties of the environment that are consistent with the goals specified by each use designation. Use designations consist of two broad groups, aquatic life and non-aquatic life uses. In applications of the Ohio WQS to the management of water resource issues in Ohio's rivers and streams, the aquatic life use criteria frequently result in the most stringent protection and restoration requirements. The five major aquatic life uses which have broad application throughout Ohio are currently defined in the Ohio WQS. A brief description of each follows:

1) *Warmwater Habitat (WWH)* - this use designation defines the "typical" warmwater assemblage of aquatic organisms for Ohio rivers and streams and represents the principal restoration target for water resource management efforts.

2) *Exceptional Warmwater Habitat (EWH)* - this use designation is reserved for waters which support "unusual and exceptional" assemblages of aquatic organisms which are characterized by a high diversity of species, particularly those which are highly intolerant and/or rare, threatened, endangered, or special status (*i.e.,* declining species); this designation usually represents a protection target for water resource management efforts.

3) *Coldwater Habitat (CWH)* - this use is intended for waters which support assemblages of cold water organisms and/or those which are stocked with salmonids with the intent of providing a put-and-take fishery on a year round basis which is further sanctioned by the Ohio DNR, Division of Wildlife; this use should not be confused with the Seasonal Salmonid Habitat (SSH) use which applies to the Lake Erie tributaries which support periodic "runs" of salmonids during the spring, summer, and/or fall.

4) *Modified Warmwater Habitat (MWH)* - this use applies to streams and rivers which have been subjected to extensive, maintained, and essentially permanent hydromodifications such that the biocriteria for the WWH use are not attainable; the representative aquatic assemblages are generally composed of species which are tolerant to low dissolved oxygen, silt, nutrient enrichment, and poor quality habitat.

5) *Limited Resource Water (LRW)* - this use applies to streams (usually <3 $mi.^2$ drainage area) which have been irretrievably altered to the extent that no appreciable assemblage of aquatic life can be supported; such streams generally occur in extensively urbanized areas and/or completely lack water during normally recurring dry weather periods; other waters subjected to acidic runoff from past surface mining activities may also be designated LRW.

Chemical, physical, and/or biological criteria are generally assigned to each use designation in accordance with the broad goals defined by each. As such the system of use designations employed in the Ohio WQS constitutes a "tiered" approach in that varying and graduated levels of protection are provided by each. This hierarchy is especially apparent for parameters such as dissolved oxygen, ammonia-nitrogen, temperature, and the biological criteria. For other parameters such as heavy metals, the technology to construct an equally graduated set of criteria has been lacking, thus the same criteria may apply to two or more different use designations.

Dissolved Oxygen Criteria

Dissolved oxygen (D.O.) is one of the most important parameters in the protection and management of aquatic ecosystems since all of the higher life forms (*i.e.*, vertebrates. macroinvertebrates [including Unionidae]) are dependent on minimum levels of oxygen not only for survival, but critical life cycle functions such as growth, maintenance, and reproduction. As such, the D.O. criteria for each of the beneficial aquatic life uses[1] have been established in light of these protection end points. The D.O. criteria for the MWH and LRW use designations (Ohio EPA 1987a) are designed to maintain generally tolerant and lower value aquatic assemblages and for the prevention of nuisance conditions (*e.g.*, anoxia, odors, fish kills). The current D.O. criteria for each aquatic life use designation is listed in Table 1. The principal objective of this analysis is to present a rationale for revising the D.O. criterion for the Exceptional Warmwater Habitat (EWH) use designation. However, the lack of a daily average D.O. criterion for the Cold Water Habitat (CWH) use designation was also examined.

The Need for A Revised EWH D.O. Criterion

The need for a revised D.O. criterion for the EWH use designation has been sporadically recognized and considered by Ohio EPA for more than a decade. Dissolved oxygen (D.O.) criteria have traditionally been expressed as a period average (usually daily) along with a minimum below which D.O. values should not fall. This is exemplified by the current WWH, MWH, and LRW D.O. criteria (Table 1), an approach which is also recognized as appropriate by U.S. EPA (1986). The current WWH D.O. criterion was originally adopted in the 1985 revisions

[1] A beneficial use meets either the interim fishable/swimmable or biological integrity goals specified by the Clean Water Act (Section 101[1][2]). In the Ohio WQS, the following aquatic life uses are considered beneficial: EWH, WWH, and CWH.

Table 1. Current dissolved oxygen (D.O.) criteria for the major aquatic life use designations as presently codified in the Ohio Water Quality Standards (WQS; Ohio Administrative Code 3745-1).

Use Designation	Daily Average (mg/l)	Minimum (mg/l)	Protection Endpoint
Coldwater Habitat	-	6.0[a]	Coldwater organisms; periodic stocking of salmonids (maintenance, growth).
Exceptional Warmwater	-	6.0[a]	Highly sensitive aquatic organisms; growth and reproduction of recreationally and commercially important species; maintenance of populations of imperiled species.
Warmwater Habitat	5.0	4.0	Maintenance of typically representative warmwater aquatic organisms and recreationally important species.
Modified Warmwater	4.0	3.0	Maintenance of moderately and generally tolerant species which are common in highly modified stream habitats.
Limited Resource Water	3.0	2.0	Prevention of nuisance conditions (odors, anoxia, acute toxicity).

[a] the present criterion is expressed as a minimum value only - no average is specified.

to the Ohio WQS and emanated from the original introduction of tiered aquatic life uses in the 1978 WQS revisions. The current MWH and LRW criteria were adopted in the May 1990 revisions to the Ohio WQS. The existing EWH and CWH D.O. criteria were adopted in 1978 as minimum only values.

The need for a "two-number" D.O. criterion for each designated aquatic life use was recognized when Ohio EPA initiated the adoption of two-number criteria for most of the heavy metals and other toxic constituents for which a sufficient database existed (IOC by Dick Robertson dated August 8, 1983). The principal reason cited was that a two-number criterion, the daily average value in particular, would result in a more meaningful target for the steady-state D.O. modeling efforts which were widely employed by Ohio EPA in the early and mid 1980s. The present policy employed for water quality modeling is to target a daily average criterion value under an assumed set of critical, steady-state stream flow and discharge conditions. In the case of the existing D.O. criteria for EWH and CWH, a default value 0.5 mg/l above the daily minimum criterion is used as the target for steady-state modeling efforts. However, an average criterion is best suited for the steady-state modeling techniques which are commonly employed in the wasteload allocation process.

In addition to the aforementioned practical reasons for a two-number criterion for D.O., the very nature of D.O. regimes is more amenable to this type of approach. D.O. concentrations are subject to natural, diel changes which are influenced by the daily cycles of algal photosynthesis and respiration. The highest D.O. values in a 24-hour period occur during the daylight hours (usually in the late afternoon) and the lowest values occur in the early morning, pre-dawn hours. This naturally occurring cycle is sometimes referred to as the "diel D.O. swing". The extent or size of the "swing" between the minimum and maximum D.O. concentration recorded during a 24-hour period is dependent on several factors including stream or river flow, ambient temperature, solar insolation, and the relative abundance and activity of photosynthetic algal and/or higher aquatic plants. In Ohio's warmwater rivers and streams, a diel swing of as much as 2-4 mg/l may be considered "typical" during normal summer low flow and ambient temperature conditions. Variations outside of this range likely signify increased nutrient enrichment and the potential for negative effects to aquatic life, particularly for the most sensitive assemblages (*i.e.*, those representative of EWH). However, the relationship of the dynamic D.O. regime to an average value over a 24-hour period is also important. Thus, in using ambient D.O. data to analyze the causes of aquatic life use impairment, it is also important to consider the average in relation to minimum and maximum values *and* the width of the diel variation.

The need for a revised D.O. criterion for the EWH use designation is also evident in the repeated observation of full attainment of the EWH biological criteria when D.O. values less than the current 6.0 mg/l (minimum) criterion have occurred. Several examples from the Ohio EPA biological and water quality assessment database were used to illustrate this point.

Rationale for the Current EWH D.O. Criterion

In attempting to determine the origin of the current 6 mg/l minimum criterion, several sources were consulted. The Ohio EPA WQS files contained little explicit information about the origins of the 6 mg/l criterion and much of the documentation found pertained to justifications for the 5 mg/l average/4 mg/l minimum criterion for the WWH designation. There were references to the CWH and EWH D.O. criteria needing to be more stringent than WWH ". . . in order to give protection to more sensitive fish species" (IOC by Bob Monsarrat dated February 8, 1978). Ohio has had a 6 mg/l criterion (applied to specific rivers and streams) since 1967 (Ohio Water Poll. Contr. Bd. Resolutions), but the origins and level of protection specified remain unclear.

Some of the contemporary water quality criteria compendia of that time period allude to the range of D.O. between 5 mg/l and 6 mg/l as being a critical threshold for sensitive fish species, especially coldwater species (FWPCA 1968). This same study also established a hierarchy of decreasing sensitivity from coldwater fish (*e.g.*, salmon, trout) to warmwater game and pan fish (*e.g.*, bass, sunfish) to warmwater "coarse" fish (*e.g.*, carp, buffalo). While some of these categorizations do not necessarily parallel a species sensitivity (*i.e.*, "coarse" fish, several of which are actually sensitive species) the hierarchy remains an appropriate way to categorize levels of protection consistent with that specified by the Ohio EPA aquatic life uses (*e.g.*, CWH>EWH>WWH>MWH>LRW). Thus, a hierarchical set of D.O. criteria consistent with the hierarchy of the designated aquatic life uses seems appropriate.

None of this, however, sheds much more than indirect light on the origins of the EWH 6 mg/l minimum D.O. criterion. The FWPCA (1968) summary on D.O. was one of the documents available to Ohio EPA to support the development of the 1978 WQS which is where the EWH D.O. minimum of 6 mg/l first appeared. This study indicates that one of the first signs of stress on fish from declining D.O. concentrations is increased respiration (*i.e.*, gill movement) and that this becomes evident for the "half-dozen or so warmwater game and pan fish" as D.O. is reduced from 6 mg/l to 5 mg/l and the effects are further exacerbated from 5 mg/l to 4 mg/l. However, the FWPCA (1968) report also stated the following:

> "Several field studies have shown that good and diversified fish populations can occur in waters in which the dissolved oxygen concentration is between 6 and 5 mg/l in the summer, *suggesting that a minimum of 6 mg/l is probably more stringent than necessary for warmwater fishes* (italics added). Because the oxygen content of a body of water does not remain constant, it follows that if the dissolved oxygen is never less than 5 mg/l it must be higher part of the time. In some cases, good populations of warmwater fish, including game and pan fishes, occur in waters in which the dissolved oxygen may be as

low as 4 mg/l for short periods . . . (and) . . . Five and 4 mg/l are close to the borderline of oxygen concentrations that are tolerable for extended periods. For a good population of game and pan fishes the concentration should be considerably more than this."

The recommendations forthcoming from the FWPCA (1968) were 5 mg/l for a diversified warmwater biota assuming that there are normal seasonal and daily variations above this concentration. The D.O. could range between 5 and 4 mg/l for "short periods of time" provided other water quality conditions are favorable. However, the growth of young fish was markedly impaired if the D.O. dropped to 3 mg/l even for a part of the day when maximum values as high as 18 mg/l occurred. This is one of the reasons cited for needing a daily minimum criterion in addition to an average.

Based on an examination of Ohio EPA files and conversations with some of the key staff who developed the 1978 WQS (R. Shank, pers. comm.) the origin of the 6 mg/l minimum criterion was based on assuring the protection of a set of ecological values that were higher than "typical" (*i.e.*, WWH). Given that the tools and techniques now available to discriminate between the WWH and EWH uses were lacking, it is not surprising that a clear justification for the 6 mg/l criterion cannot be found. In one sense, the 6 mg/l minimum was largely a best professional judgement decision employing a generous margin of safety given the resource value implied by EWH. Thus, the proposed minor adjustment to the original 6 mg/l minimum criterion seems justified given the existence of new information resulting from the availability of improved assessment tools (*i.e.*, multimetric biological indices, biological criteria, etc.) and databases 18 years hence.

Rationale for A Revised EWH D.O. Criterion

Part of the rationale for a revised EWH D.O. criterion is based largely on the observation of full attainment of the EWH biological criteria under D.O. regimes which include minimum daily values less than 6 mg/l. Other information including the U.S. EPA *Ambient Water Quality Criteria for Dissolved Oxygen* (U.S. EPA 1986) was also examined to verify the efficacy of this criterion revision.

Analysis of the Statewide Database

One approach used to determine the appropriateness of the proposed EWH D.O. criterion was to examine the Ohio EPA statewide database for D.O. and biological community performance indicators (*i.e.*, Index of Biotic Integrity, Invertebrate Community Index). This was accomplished by plotting various expressions of D.O. levels (raw values, means, percentiles) in Ohio rivers and streams against the biological indices which comprise the Ohio EPA biological criteria (Ohio EPA 1987b, 1989a,b). After examining a number of different statewide comparisons, three stood out as offering both meaningful and representative information.

Raw D.O. values (instantaneous measurements) from the statewide database spanning the period of 1981-1992 were plotted against the Index of Biotic Integrity (IBI) values recorded at linked locations (*i.e.*, the D.O. value was deemed representative of the biological sampling location). The resultant scatterplot (Figure 1, upper tier) reveals a cluster of data points which we term a "wedge" of data points. The left surface of the wedge represents a boundary between which IBI values representative of a given level of biological community performance at a given D.O. concentration have been observed to occur. A 95% line of best fit was drawn across the left surface boundary with 5% of the data points falling to the left of the line (Figure 1). The 95% line corresponds to the lowest D.O. value at which a given level of biological community performance as measured by the IBI has regularly occurred - coincidences of D.O. and IBI values to the left of this line are by comparison rare. Thus, any proposed "new" criterion for D.O. can be evaluated for precedence against this historically and spatially robust database. As such this represents a "one-sided" analysis in that a proposed criterion can be evaluated to determine if it is under-protective moreso than evaluating if it is over-protective.

Shaded areas representing the boundaries of "representative" numerical biological criteria for the respective EWH, WWH, and MWH aquatic life uses were superimposed on the scatterplot to determine the D.O. levels at which attainment or non-attainment of these criteria have been observed. The existing 4 mg/l minimum D.O. criterion for the WWH use and the proposed 5 mg/l minimum for the EWH use were also superimposed to determine the D.O. concentrations at which IBI values consistent with the attainment of each use designation occurred. The results indicate that IBI values consistent with the EWH use designation at D.O. concentrations as low as 5 mg/l have precedence with some sporadic occurrences less than 5 mg/l (Figure 1, upper tier). A similar plot of median D.O. values (Figure 1, lower tier) shows that EWH attainment with median D.O. values as low as 6 mg/l also has precedence. Figure 1a is a box-and-whisker plot analysis by narrative biological performance ranges (*i.e.*, exceptional, good, fair, poor, and very poor) of the IBI showing the median, 10th, 25th, 75th, and 90th percentiles, and outliers for 10th percentile D.O. values. This analysis shows that the proposed 5 mg/l minimum corresponds to exceptional performance at the 10th percentile of D.O. values. The majority of the D.O. data in Figure 1 are comprised of daytime readings meaning that potentially lower readings, which would occur in the early morning hours, are not well represented. Thus, minimum daily values lower than those in Figures 1 and 1a probably occurred at the sites where full attainment of the EWH use was observed. As such, Figures 1 and 1a represent conservative analyses in that the data points do not necessarily represent all of the daily minimum values which likely occurred. While these analyses *alone* are not entirely conclusive regarding the efficacy of the proposed 6 mg/l average/5 mg/l minimum EWH D.O. criterion, the occurrence of daytime D.O. values less than the present 6 mg/l minimum criterion with full attainment of the EWH use is certainly not unprecedented in a historically, spatially, and observationally (n=14,992) robust database.

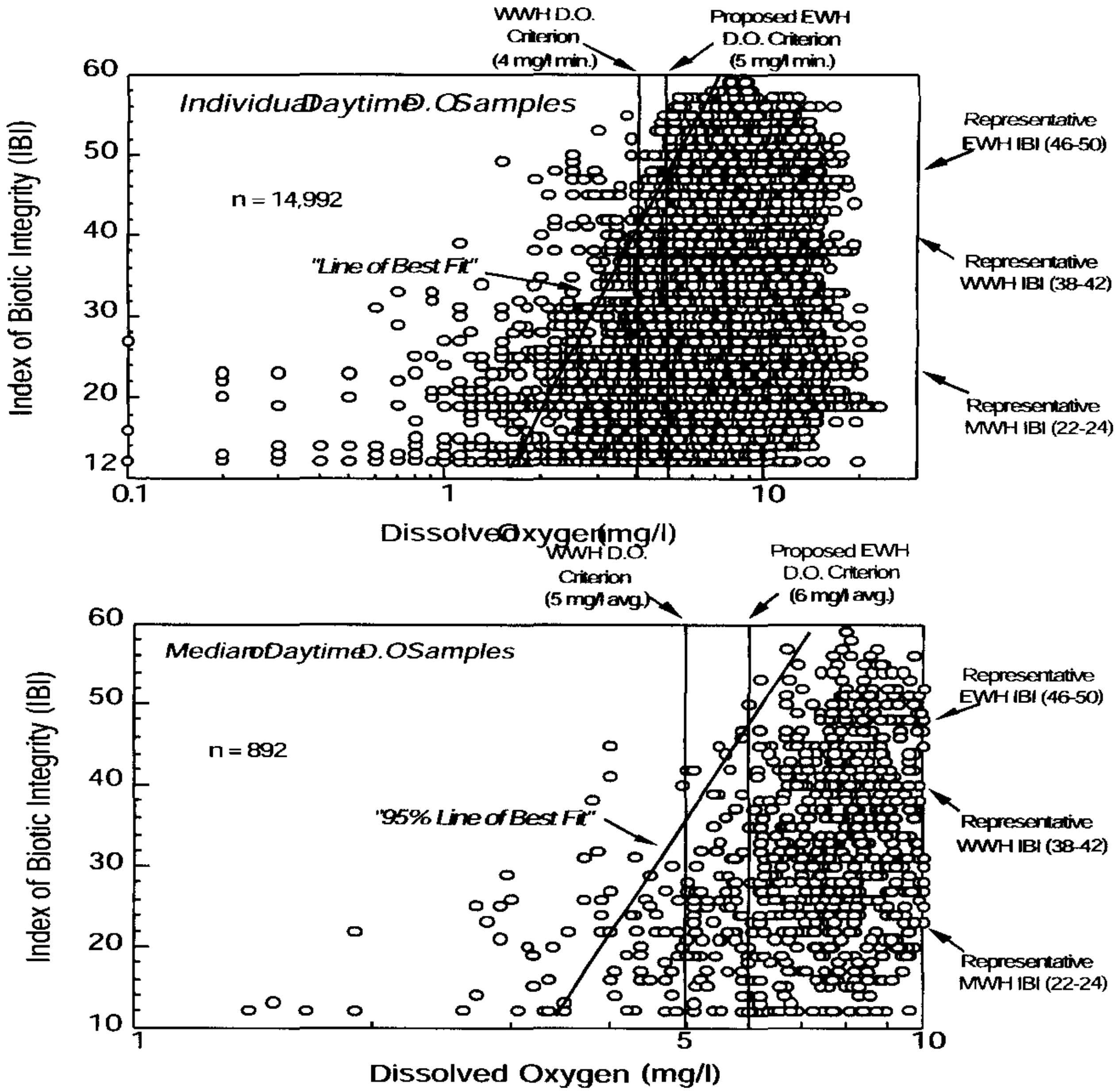

Figure 1. Relationship between the Index of Biotic Integrity (IBI) and individual (upper) and median (lower) dissolved oxygen (D.O.) concentrations at sampling sites in rivers and streams throughout Ohio based on daytime D.O. readings and biological sampling conducted between 1979 and 1992.

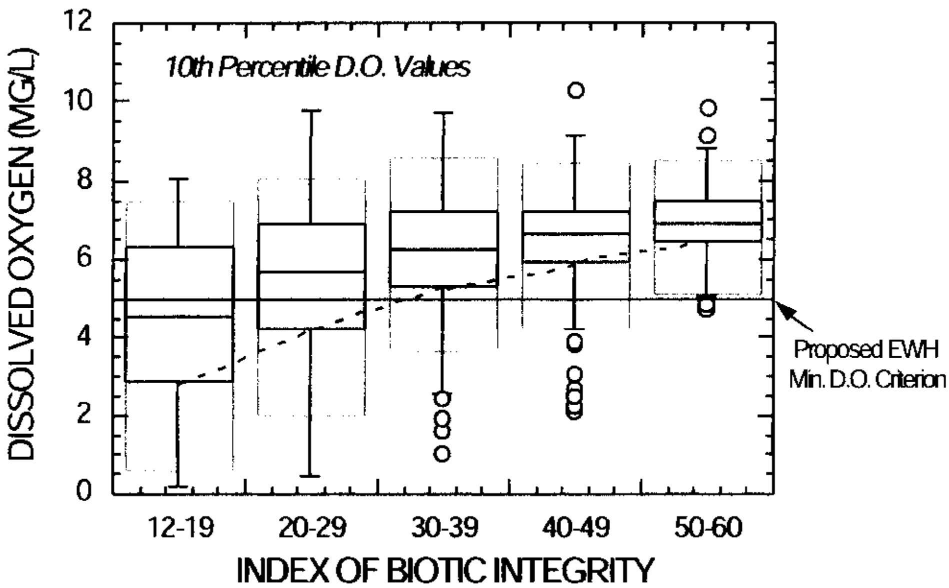

Figure 1a. Box-and-whisker plot of 10th percentile daytime D.O. values arranged by narrative biological performance categories based on the Index of Biotic of Integrity (IBI) and the Ohio EPA statewide D.O. database.

Observations in Individual Rivers and Streams

Another analysis undertaken in this study was an examination of the occurrence of attainment of the EWH biocriteria in designated (or recommended) EWH streams and rivers with an adequate continuous D.O. database. This analysis provides a comparison of the IBI and Invertebrate Community Index (ICI; DeShon 1995; Ohio EPA 1987a, 1989) with the D.O. results obtained using Datasonde continuous monitors. Information from six streams and rivers either presently designated as EWH (or where the biological data indicates a redesignation to EWH is appropriate) was examined. These represent a cross-section of different stream and river sizes as well. Full attainment of the EWH use designation over an extended length of river or stream and/or over multiple years under D.O. levels which are periodically below the present 6 mg/l minimum D.O. criterion represents additional evidence that the criterion should be revised.

Scippo Creek

Scippo Creek is a small tributary of the Scioto River located within the Eastern Corn Belt Plains (ECBP) ecoregion (Omernik and Gallant 1988) and drains 52 square miles of land area. Land use is predominantly row crop agriculture and one major point source (PPG Industries) discharges to the mainstem. Based on results obtained through monitoring conducted in 1992 and 1993, Scippo Creek is being recommended for redesignation as EWH. Both the IBI and ICI attain the EWH biological criteria at nearly all sites sampled, thus meeting the Ohio EPA requirement that the ability to attain EWH be demonstrated (Figure 2; Ohio EPA 1987b). Continuous D.O. readings taken in August 1993 indicate that minimum values below 6 mg/l occurred at most sites. No values below 5 mg/l were observed.

Big Darby Creek

Big Darby Creek is a major tributary of the Scioto River located within the Eastern Corn Belt Plains (ECBP) ecoregion (Omernik and Gallant 1988) and drains approximately 560 square miles of land area. Land use is predominantly row crop agriculture, but several small point sources (mostly WWTPs) discharge to the mainstem and tributaries. The existing use designation of the mainstem is EWH with the exception of the extreme headwaters which are designated as WWH. Big Darby Creek has long been recognized for supporting an unusually diverse and unique assemblage of aquatic life and is a nationally designated Scenic River and one of The Nature Conservancy's "Last Great Places". Biological performance as measured by the IBI and ICI indicate that the biological criteria for the EWH are largely met with the exception of localized reaches of impairment (Figure 3). The latest contiguous set of data (1992) indicates the strongest showing of full attainment and show the highest biological index scores to occur in the lower 40-50 miles of the mainstem. Several sets of continuous D.O. data have been collected between 1988 and 1992. The D.O. data collected in August 1992 covers the longest reach, but represents an elevated flow year (Figure 4). The D.O. data collected in 1988 represents the opposite extreme as critically low flows occurred during an extended drought period. The D.O. results

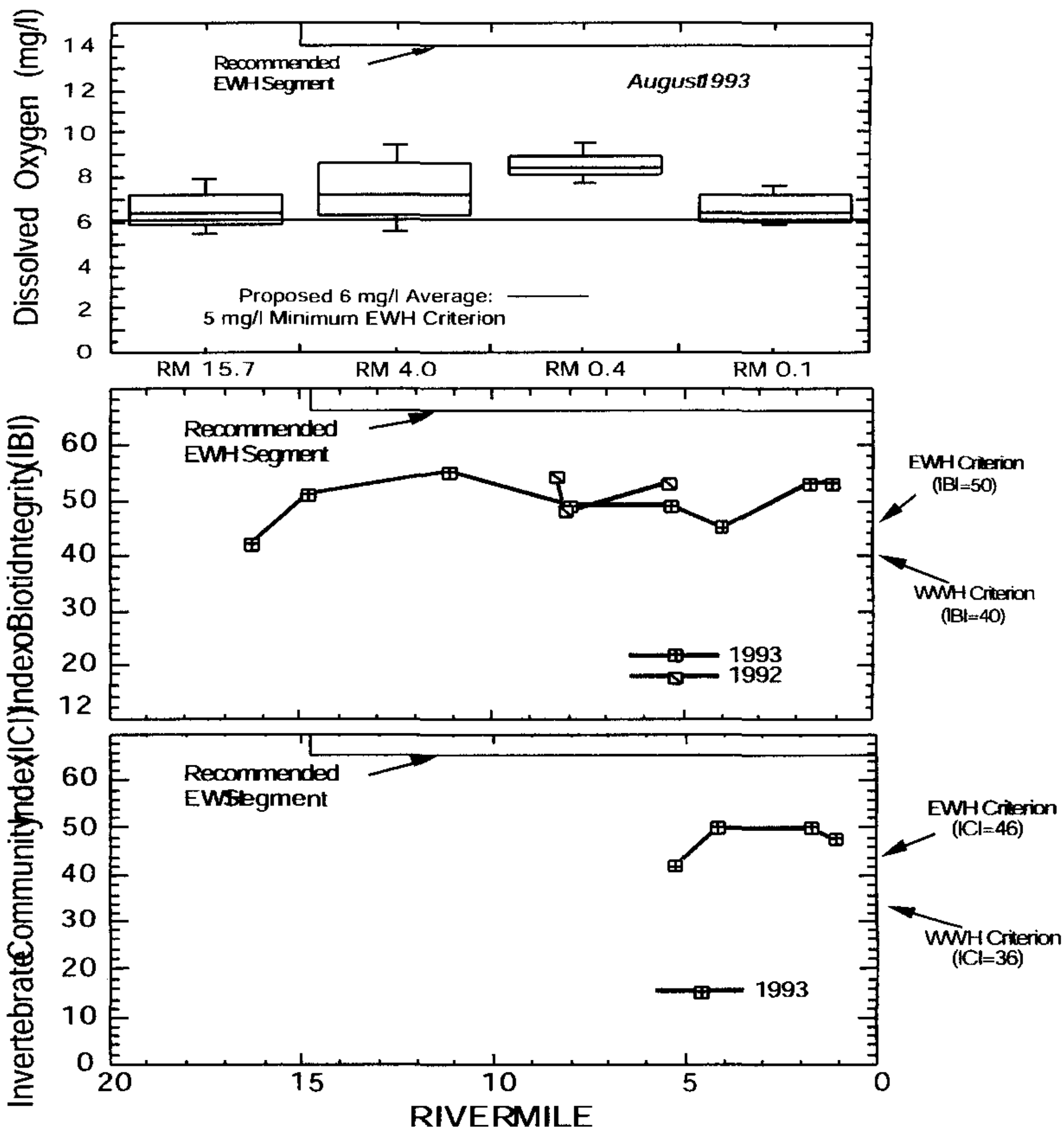

Figure 2. Biological and D.O. monitoring results from Scippo Creek during 1992 and 1993; D.O. (upper) as measured by Datasonde continuous monitors in August 1993 and the Index of Biotic Integrity (IBI; middle) and Invertebrate Community Index (ICI; lower).

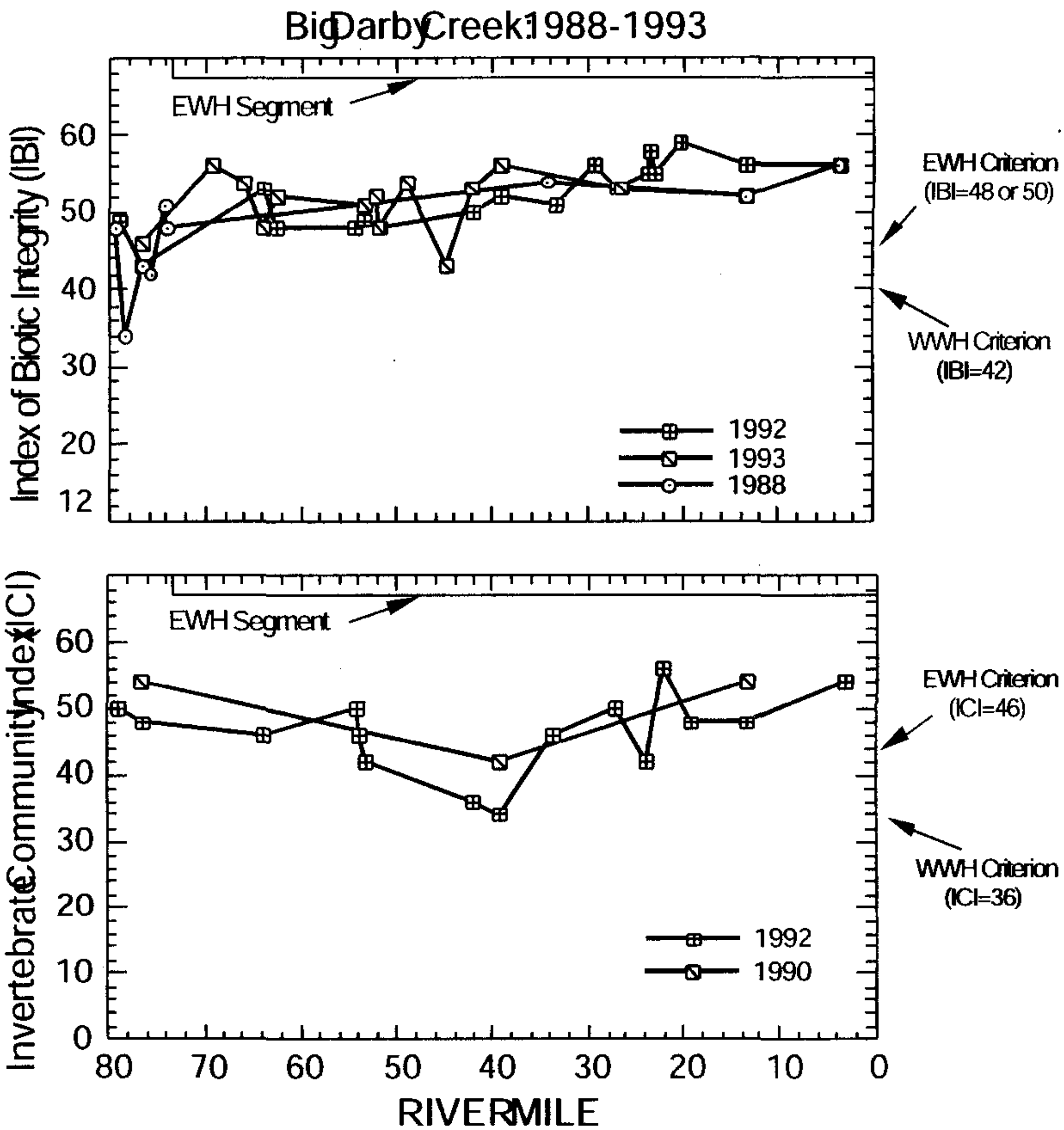

Figure 3. Index of Biotic Integrity (IBI; upper) and Invertebrate Community Index (ICI; lower) results for the mainstem of Big Darby Creek during 1988, 1990, 1992, and 1993.

indicate that values less than the existing 6 mg/l EWH D.O. criterion have occurred in the lower mainstem while biological performance consistent with the EWH use designation also occurred (Figures 3 and 4). The site at RM 13.36 showed extremely low D.O. values during the extended low flow period in 1988 with minimum values less than 3 mg/l and a 25th percentile value of 4 mg/l (Figure 4). Long-term monitoring with macroinvertebrates at this same site shows ICI values well above the EWH biological criteria with similar values persisting in 1990 and 1992 (Figure 4). IBI values were also well above the EWH criteria at this same site in 1988 with similarly high values extending into 1990 and 1992.

Upper Great Miami River
The Great Miami River is a major tributary of the Ohio River located within the Eastern Corn Belt Plains (ECBP) ecoregion (Omernik and Gallant 1988). Our focus here is with the upper mainstem which drains approximately 1150 square miles of land area. Land use is predominantly row crop agriculture, but several major point sources (mostly WWTPs) discharge to the mainstem. The existing use designation of the mainstem is WWH, but the results obtained in 1994 strongly suggest a redesignation to EWH is in order. IBI and ICI values along most of the mainstem between RM 85 and 140 were above the EWH biological criteria (Figure 5). Minimum D.O. values less than 6 mg/l were measured at three sites, two of which were either close to or at biological sampling locations which met the EWH biological criteria (Figure 5). Values less than 5 mg/l occurred at only one site which was in a localized impoundment on the mainstem which will remain designated WWH.

Little Miami River
The Little Miami River is a major tributary of the Ohio River located within the Eastern Corn Belt Plains (ECBP) and Interior Plateau ecoregions (Omernik and Gallant 1988) and drains approximately 1760 square miles of land area. Land use is predominantly row crop agriculture, but numerous major point sources (mostly WWTPs) discharge to the mainstem. The volume of municipal WWTP effluent is the largest of any EWH designated river in Ohio (50 million gallons/day) and is projected to increase. Full attainment of the EWH biological criteria occurs in two disjunct reaches and the cumulative distance in full attainment increased substantially between 1983 and 1993 (Figure 6). Three other reaches including the lower mainstem (downstream from RM 20), a reach between RM 50 and 65, and the headwaters upstream from RM 80-85 were in partial attainment due primarily to organic enrichment from municipal WWTP discharges and combined sewer overflows (lower reach only; Ohio EPA 1995). Biological performance along most of the mainstem has improved significantly since 1983, reflecting loading reductions from point sources. Reaches of full EWH attainment were correlated with D.O. values less than the current 6 mg/l criterion, but very few values were found to be less than 5 mg/l (Figure 6). Because most of the WWTPs are submitting expansion plans, the Little Miami River is a case in point as to the appropriate D.O. target for wasteload allocation purposes. The

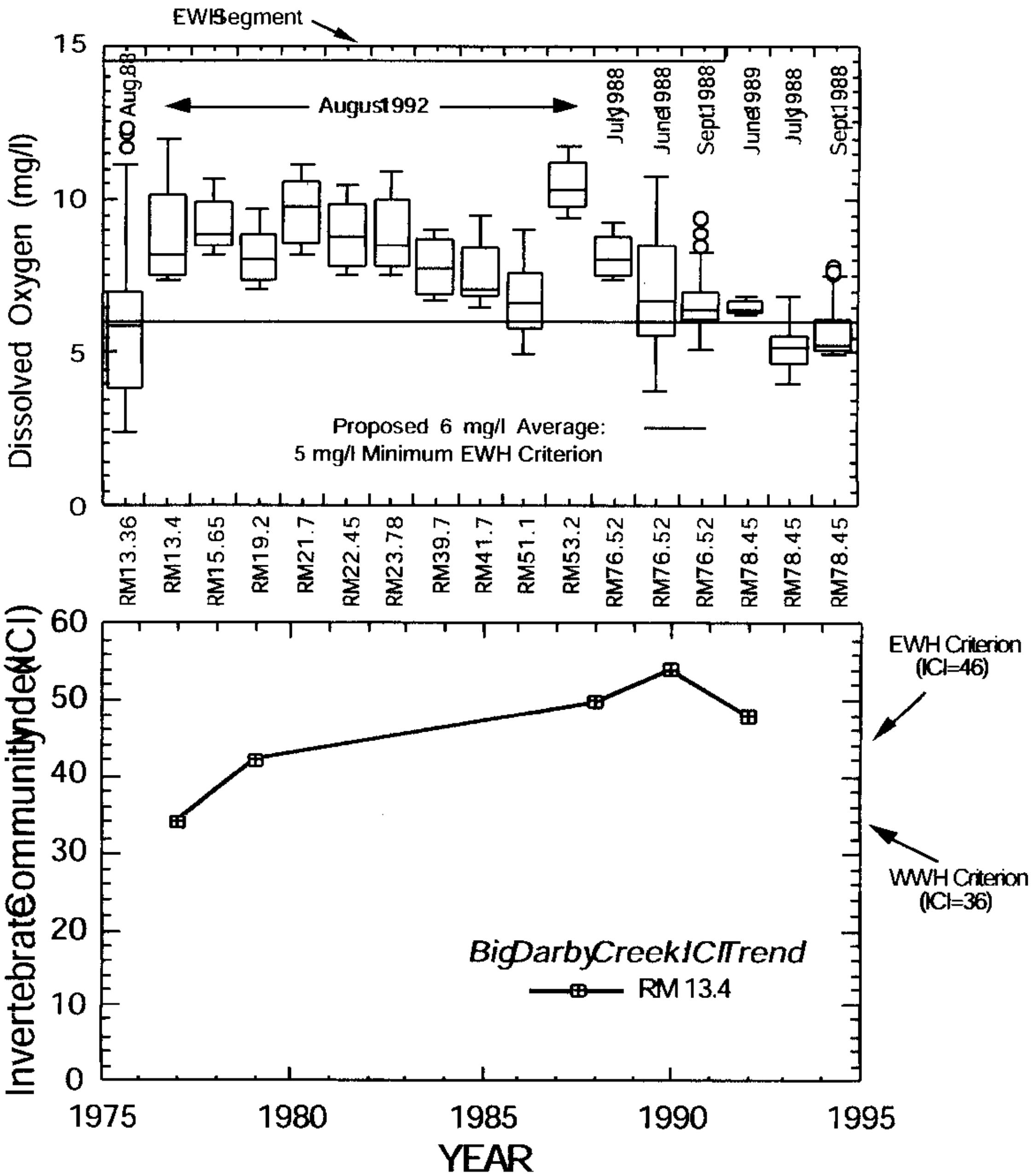

Figure 4. D.O. results (upper) obtained with Datasonde continuous monitors during the summer months of 1988 and 1992 from the mainstem of Big Darby Creek and Invertebrate Community Index (ICI; lower) results obtained at a long-term fixed monitoring location (RM 13.4) between 1976 and 1992.

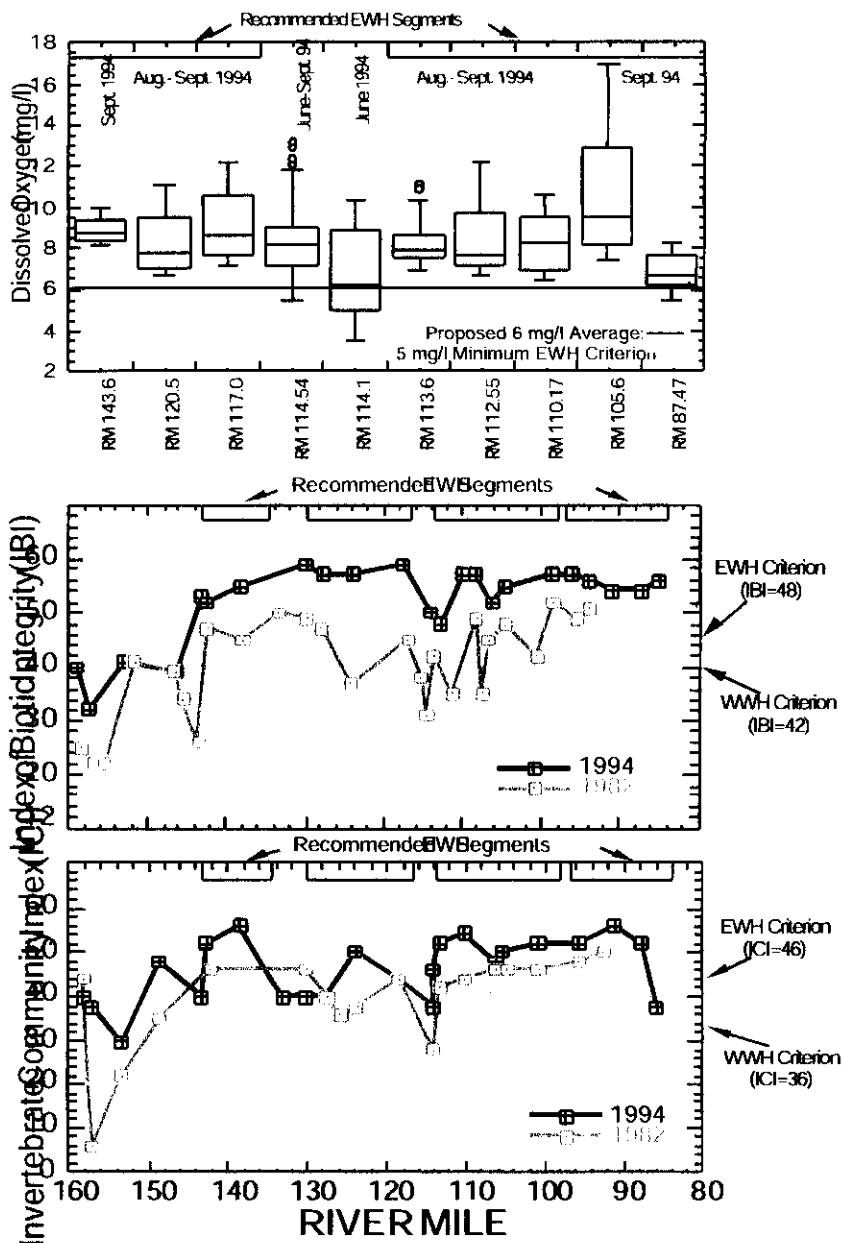

Figure 5. Biological and D.O. monitoring results from the upper Great Miami River during 1982 and 1994; D.O. (upper) as measured by Datasonde continuous monitors during June-September 1994 and the Index of Biotic Integrity (IBI; middle) and Invertebrate Community Index (ICI; lower) based on results obtained in 1982 and 1994.

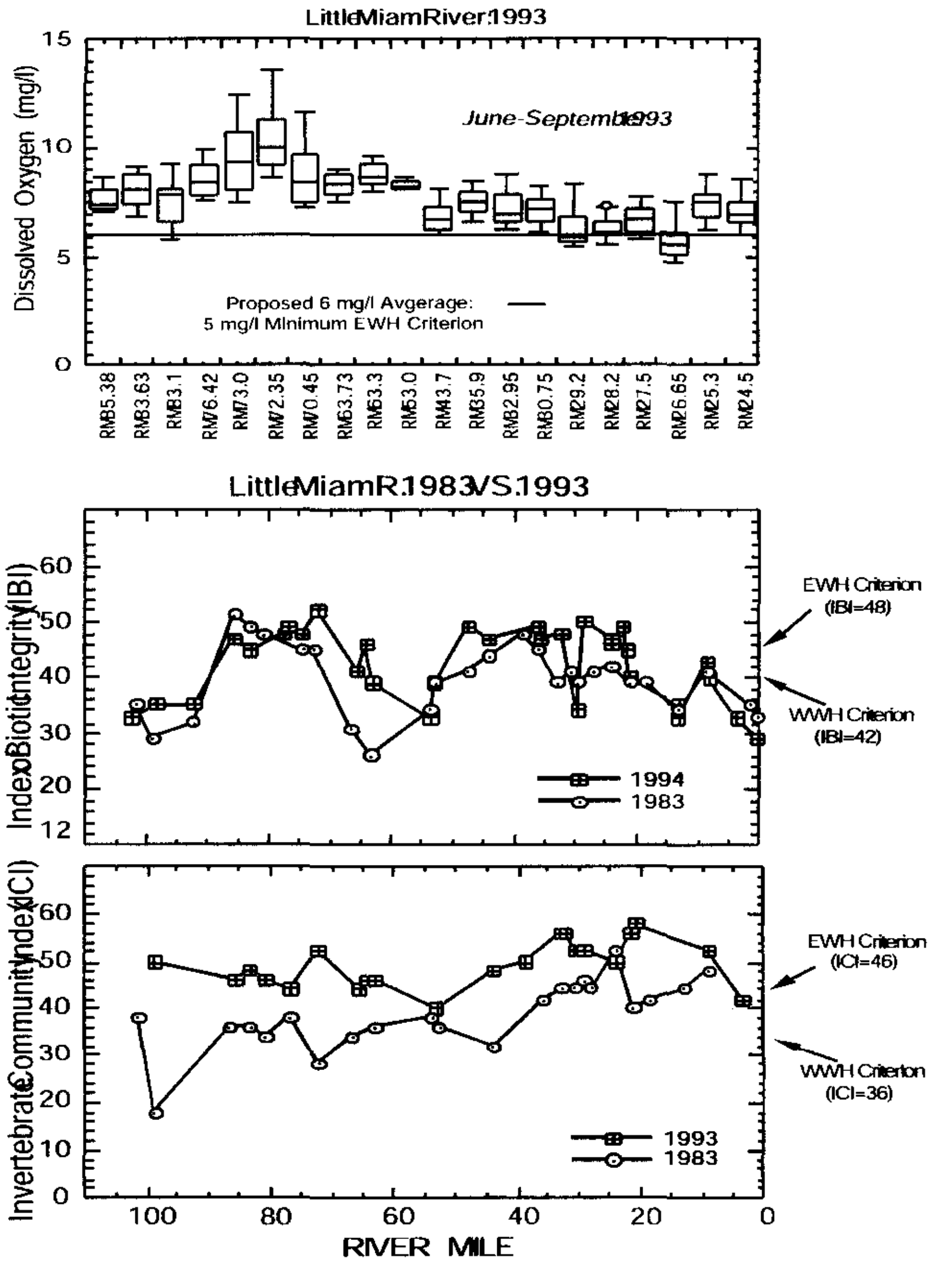

Figure 6. Biological and D.O. monitoring results from the Little Miami River during 1983 and 1993; D.O. (upper) as measured by Datasonde continuous monitors during June-September 1993 and the Index of Biotic Integrity (IBI; middle) and Invertebrate Community Index (ICI; lower) based on results obtained in 1983 and 1993. The entire mainstem to RM 3.0 is designated EWH.

problems associated with the WWTP impacts included excessive nutrient concentrations (mostly total phosphorus) and the influence of this on diel D.O. patterns. The available information suggests that protecting for the proposed 6 mg/l average/5 mg/l minimum EWH D.O. criterion would be appropriate for maintaining and further restoring the EWH use designation.

Walhonding River

The Walhonding River is a major tributary of the Muskingum River located within the Western Allegheny Plateau (WAP) ecoregion (Omernik and Gallant 1988) and drains approximately 2250 square miles of land area. Land use is predominantly row crop agriculture, but point sources discharge to the upper sections of several major tributaries which feed the Walhonding. The existing use designation of the mainstem is EWH and the biological results easily reaffirm this (Figure 7). Continuous D.O. data collected during three different years show some minimum values less than 6 mg/l, but above 5 mg/l (Figure 7). The Walhonding is probably the largest river in Ohio with no direct point source discharges and only a few scattered concentrations of such in the upper parts of the watershed.

Scioto River

The Scioto River is a major tributary of the Ohio River located within the Eastern Corn Belt Plains (ECBP) ecoregion (Omernik and Gallant 1988). Our focus here is with the central mainstem which drains approximately 3200 square miles of land area making it the largest river among the six examples. Land use in the upper watershed is predominantly row crop agriculture, but two major point sources (both WWTPs) and several smaller sources (WWTPs, industries) discharge to the mainstem. The existing use designation of the mainstem is WWH, but results obtained since the mid and late 1980s strongly suggest a redesignation to EWH for an approximately eight mile long reach of the lower central mainstem. IBI and ICI values in the reach between RM 106.1 and 97.9 indicate full attainment of the EWH biological criteria at most locations (Figure 8). Continuous D.O. data collected in 1988 shows values less than 6 mg/l and even 5 mg/l during an extended drought. Daytime grab samples during other years also show minimum values less than 6 mg/l at sites which attain the EWH biocriteria. Long-term results for the ICI and IBI both show values approaching and exceeding EWH biological criteria as early as 1986 and generally persisting through 1992 (Figure 9).

Summary of Individual Streams and Rivers

The results of the comparison of continuously measured D.O. and EWH use attainment in six streams and rivers of varying sizes shows that the latter can be compatible with minimum D.O. values less than 6 mg/l. However, values less than 5 mg/l were either infrequent, did not frequently correlate with full EWH use attainment, or were measured only under extreme low flow conditions. Thus, this analysis would appear to support a minimum EWH D.O. criterion less than 6 mg/l, but not less than 5 mg/l.

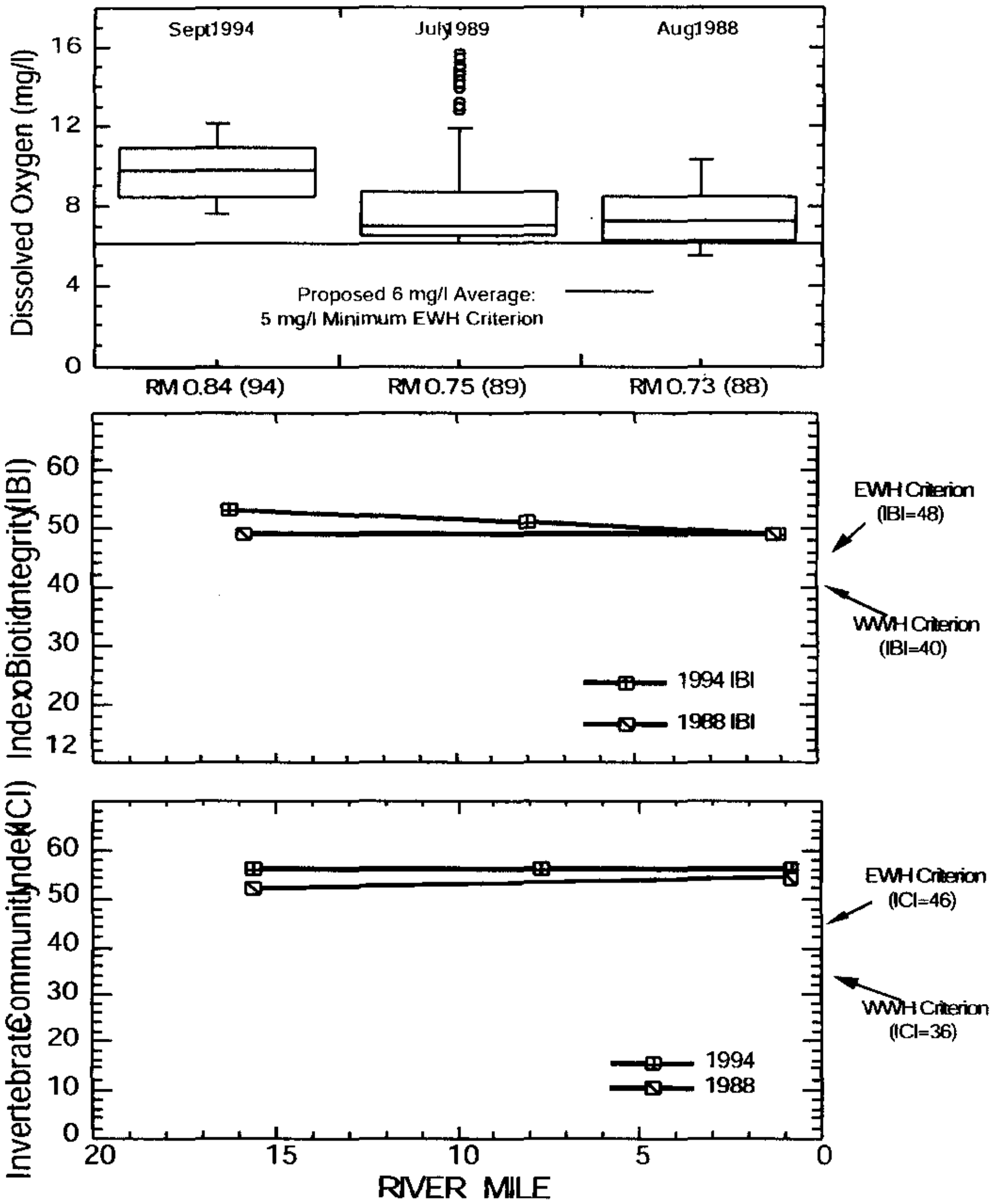

Figure 7. Biological and D.O. monitoring results from the Walhonding River during 1983-1994; D.O. (upper) as measured by Datasonde continuous monitors during August 1988, July 1989, and September 1994 and the Index of Biotic Integrity (IBI; middle) and Invertebrate Community Index (ICI; lower) based on results obtained in 1983, 1988, and 1994. The Walhonding River is designated EWH.

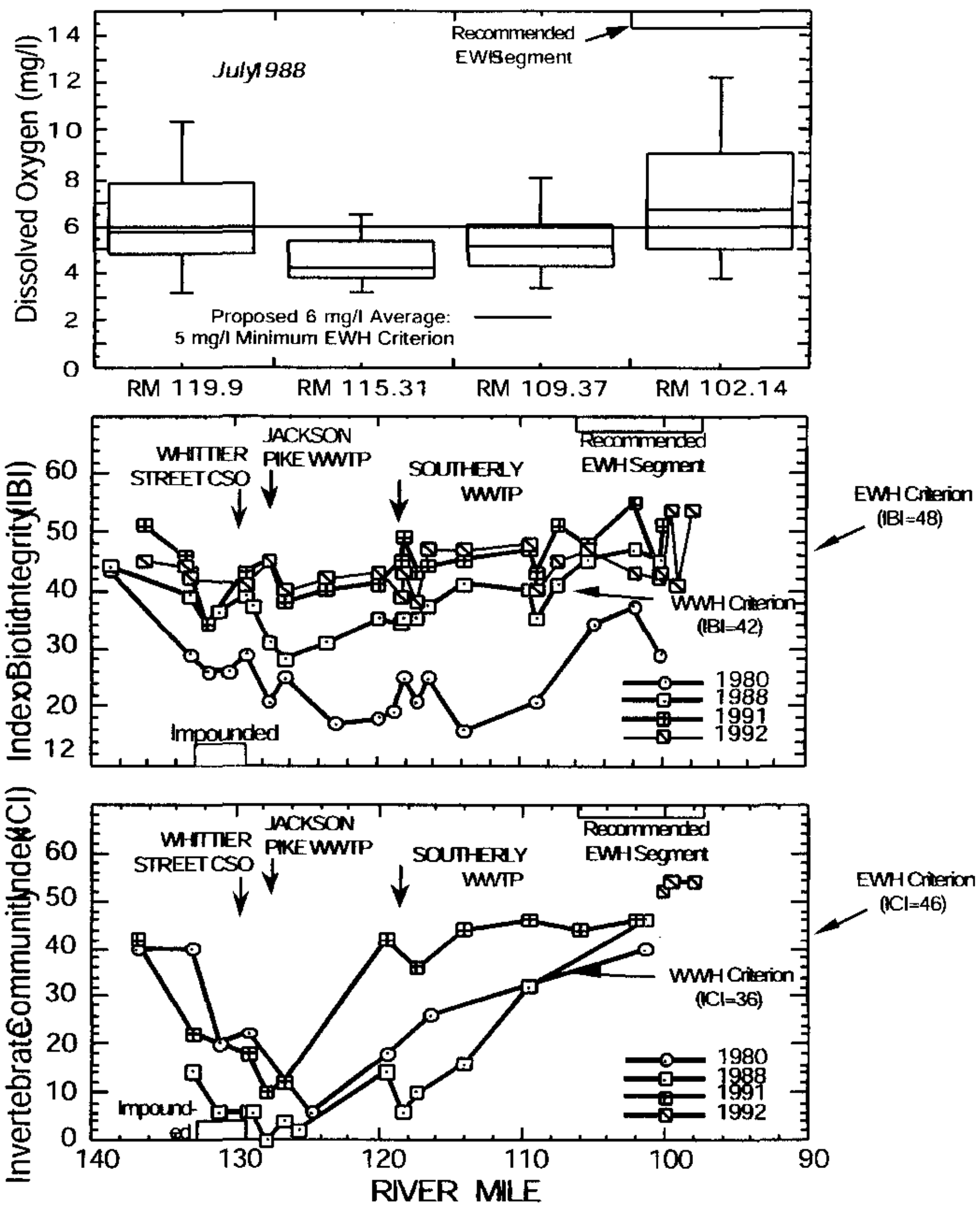

Figure 8. Results of continuous D.O. Monitoring in 1988 (upper) compared to Index of Biotic Integrity (IBI; middle) and Invertebrate Community Index (ICI; lower) results for the central Scioto River mainstem during 1980, 1988, 1991, and 1992.

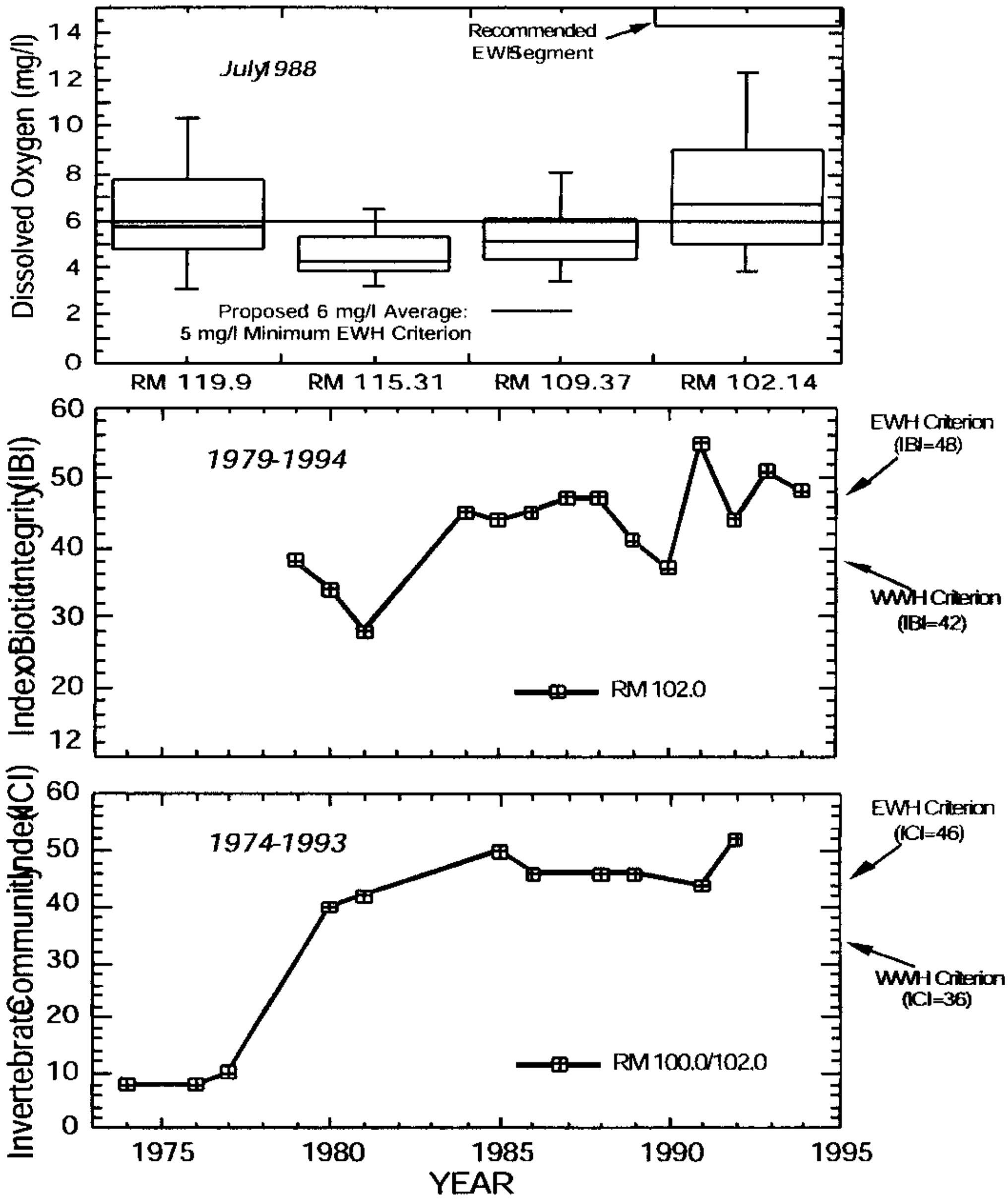

Figure 9. Comparison of D.O. (upper) concentrations in the Scioto River as measured by Datasonde continuous monitors during July 1988 and the Index of Biotic Integrity (IBI; middle) and Invertebrate Community Index (ICI; lower) based on results obtained at fixed locations (RM 100.0 and 102.0) during 1974-1994.

Synthesis of Information

The information presented thus far from the Ohio EPA database consists mostly of field observations with the goal of evaluating the efficacy of a 6 mg/l average/5 mg/l minimum two-number EWH D.O. criterion. These observations (Figures 1-9) tend to support changing the current 6 mg/l minimum EWH D.O. criterion to the proposed two-number criterion. Not only have there been observations of EWH use attainment with minimum D.O. values less than 6 mg/l, the evidence also suggests the relative absence of this occurrence when instantaneous D.O. levels drop below 5 mg/l and median levels drop below 6 mg/l (see Figures 1 and 1a). These results also seem to correlate with the findings of Ellis (1937) and Coble (1982) who both found that fish communities characterized by a high diversity and a significant proportion of sport species (*e.g.*, percids, bass, sunfish) occurred at sites *averaging* greater than 5 mg/l. The latter study by Coble (1982) is particularly supportive as it focused on what are sometimes referred to as "cool water" fish assemblages. In distinguishing between EWH and WWH communities in Ohio, the qualitative association of "cool water" fish species with EWH is one way of describing some of the species which are the significant biological attributes of this use designation. In a review of these field studies U.S. EPA (1986) concluded ". . . that *increases in dissolved oxygen concentrations above 5 mg/l do not produce noteworthy improvements in the composition, abundance, or condition of non-salmonid fish populations* (italics added), but that sites with dissolved oxygen concentrations below 5 mg/l have fish assemblages with increasingly poorer population characteristics". While these studies essentially pre-dated the development of multimetric indices such as the IBI, the qualitative characteristics of the fish populations which are described by each are consistent with some of the key differences between the WWH and EWH uses which are discriminated and quantified by multimetric indices such as the IBI and ICI.

The most recent and comprehensive compendium of the effects of D.O. on fish and other aquatic organisms is the U.S. EPA *Ambient Water Quality Criteria for Dissolved Oxygen* (U.S. EPA 1986). This document included the findings and conclusions of some noteworthy reviews such as Davis (1975) and Doudoroff and Shumway (1967, 1970), the latter being cited by the water quality criteria compendia of that time (*e.g.*, National Academy of Sciences/Engineering 1973). While the U.S. EPA (1986) study only distinguished between warmwater and coldwater criteria, it did refer to varying degrees of protection within each category (*e.g.*, degrees of fish production impairment). One analysis correlated the percent survival of embryonic and larval stages of warmwater fish with mean D.O. which showed complete survival of eight species when the *mean* D.O. was greater than 6 mg/l (Figure 10). It was further noted that the minima in the laboratory experiments averaged about 0.3 mg/l less than the mean. The U.S. EPA (1986) recommendations for D.O. criteria specified three temporal thresholds for early life stages and other life stages including adults. For warmwater applications this consisted of the criteria listed in Table 2. Based on the thresholds developed by U.S. EPA (1986) a 6 mg/l average/5 mg/l

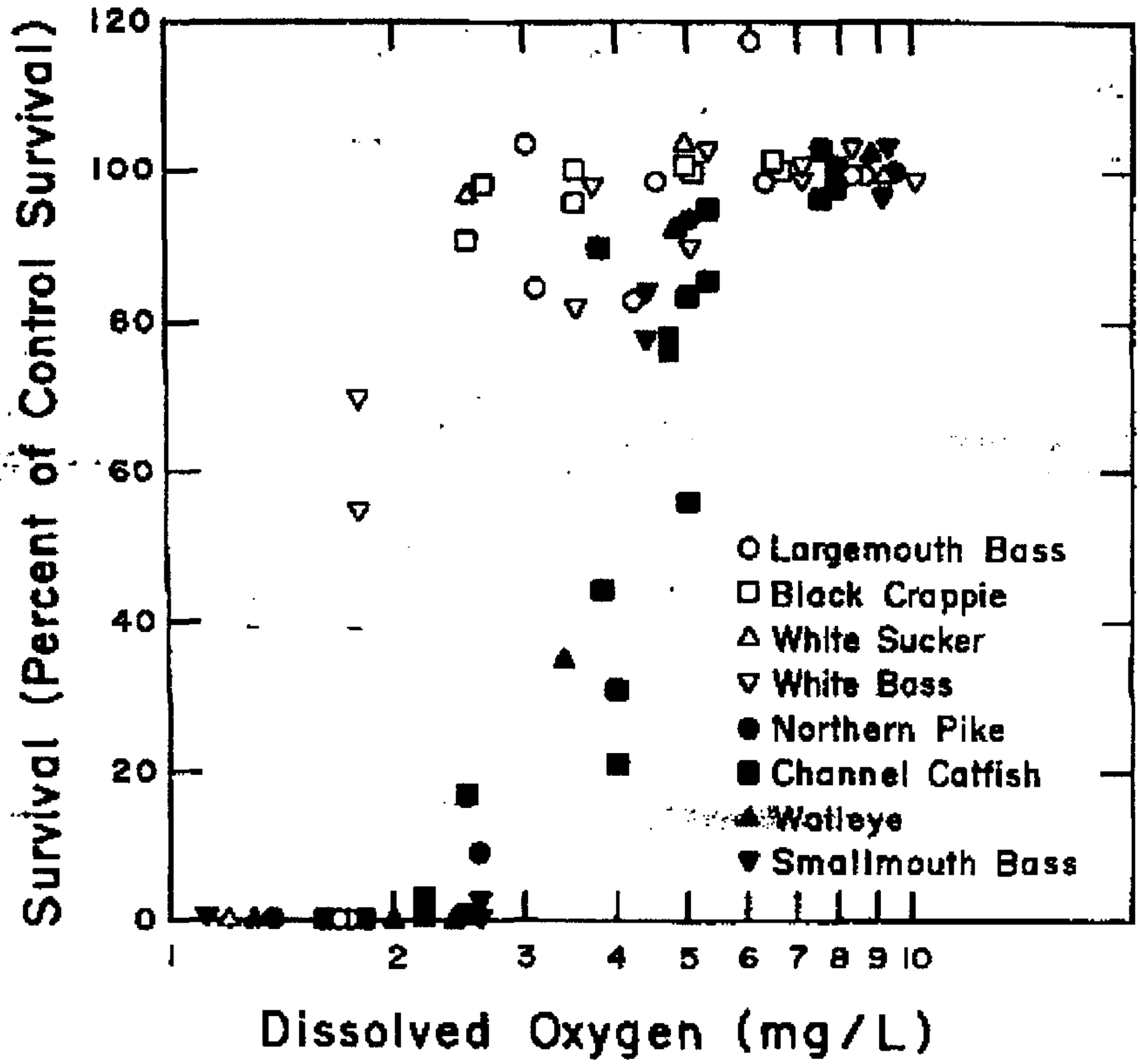

Figure 11. The effect of continuous exposure to various mean dissolved oxygen concentrations on survival of embryonic and larval stages of eight species of non-salmonid fish. Minima recorded in these tests averaged about 0.3 mg/l below the mean concentrations (reproduced from *Ambient Water Quality Criteria for Dissolved Oxygen,* U.S. EPA 1986)

Table 2. Water quality criteria for ambient dissolved oxygen concentrations to protect warmwater aquatic life as proposed by U.S. EPA (1986).

Life Stages	30-Day Mean	7-Day Mean	7-Day Mean Minimum	1-Day Minimum[a]
Early Life Stages (embryos, larvae, juveniles <30 days)	NA	6.0	NA	5.0
Other Life Stages (juveniles, adults)	5.5	NA	4.0	3.0

[a] instantaneous minimum.

minimum EWH D.O. criterion appears to be protective of all life stages. While a 5 mg/l minimum is more stringent than that proposed by U.S. EPA (1986) for adults and juveniles, it is necessary to protect younger life stages. It also seems a reasonable minimum given that EWH criteria should be more protective than those for WWH. The EWH D.O. criterion that we propose lies between the U.S. EPA recommended warmwater and coldwater levels (non-embryonic life stages only) of protection which also seems reasonable given that some of the sensitive warmwater species that comprise the assemblages representative of EWH may well approach the sensitivity of salmonids.

The adoption of a 6 mg/l average/5 mg/l minimum two-number D.O. criterion for EWH seems supported by the scientific evidence (both field and laboratory) examined by this study. In practical terms the proposed two-number criterion is also consistent with the hierarchy of D.O. criteria between the WWH, MWH, and LRW use designations. Based on the information presented by U.S. EPA (1986) there is also justification for bringing the Coldwater Habitat (CWH) D.O. criterion (presently 6 mg/l minimum) into line with the two-number average/minimum hierarchy of the other use designations. The addition of a 7 mg/l average seems to be supported by the U.S. EPA (1986) study which specifies a 6.5 mg/l 30-day mean for life stages other than embryos and larvae which are not at issue in Ohio's CWH designated streams. These life stages are not applicable protection end points for CWH in Ohio as this use is focused on maintaining adult and juvenile salmonids on a put-and-take basis, thus a 7 mg/l average/6 mg/l minimum criterion should be protective of the CWH use designation.

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Notes on Associations Between Dissolved Oxygen
and Fish and Macroinvertebrate Assemblages
in Wadeable Ohio Streams

DRAFT
Nov 12, 2004

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Introduction

Dissolved oxygen (DO) is perhaps the most important chemical constituent limiting to aquatic life in streams across the U.S. streams because of its obvious importance for respiration. Most flowing waters have sufficient dissolved oxygen to support natural populations of aquatic life and certain habitats with low natural levels of dissolved oxygen during some portion of a year have species adapted to obtain dissolved oxygen from other sources (gulping of atmospheric oxygen in the mudminnow, grass pickerel in certain wetland conditions). Most state water quality standards have developed dissolved oxygen requirement based on the U.S. EPA (1986) criteria derivation guidelines using the most sensitive species (to low DO) that inhabit these waters based on a relatively abundant literature related to DO requirements. Ohio has incorporated field data associating biological condition indices, such as the Index of Biotic Integrity (IBI) and the Invertebrate Community Index (ICI), with ambient dissolved oxygen measurements to adjust dissolved oxygen criteria by aquatic life use and, in some cases, ecoregion differences (Appendix 1).

Data

This fact sheet discusses two types of ambient dissolved oxygen data collect from Ohio streams. The largest database is composed of daytime grab samples (GRB) collected during intensive watershed surveys. Biological and chemical data were matched on a case by case where the exact location denoted by a river mile (RM) differed slightly. This can occur because water chemistry data is a point sample, macroinvertebrates sites are a combination of a point (artificial substrates) and short reach (natural substrates) and fish are sampled along a 150-500m transect. Chemical and biological data were linked if chemical data were deemed to be representative of the chemical conditions to which the biology was exposed and when no significant source of pollutants or dilution entered between sampling locations (e.g., tributary, discharge). Data also had to be collected during the same year and during the same summer period (June 15-October 15).

The second type of data was collected by Ohio EPA using Datasonde continuous monitoring samplers (CNT) that record parameters such as DO, temperature and pH every 15 minutes; these were typically set for 48 hours. This data, which we obtained from Ohio EPA, was collected between 1988 and 1994 and should encompass or include time periods where dissolved oxygen levels had both very high and very low values. There were fewer linked macroinvertebrate sites than fish sites with the continuous data so we focused on the GRB data when examining macroinvertebrate responses. The GRB database was extremely large so we used one subset that matched the continuous monitoring sites, a second subset from the Eastern Corn Belt Plains and Huron Erie Lake Plains ecoregions from 1994-2001 for fish, and the statewide data for the macroinvertebrates where there were somewhat fewer data points.

Day Time Grab Data (GRB) vs. Continuous (CNT) DO Data

Although CNT dissolved oxygen data collection is fairly widespread, it is often not collected at the same sites as biological, habitat, and other grab water chemistry data. GRB sample data are important because they have been used to determine whether ambient data meet or exceed water chemistry criteria in State Water Quality Standards (WQS). GRB samples in the Ohio EPA database are composed of approximately 6-8 samples during a summer period (mean 6.6, median 6.0) typically collected during daytime hours. Samples were processed in the Ohio EPA laboratory according to U.S. EPA approved methods. Datasonde samplers were generally set for 48 hours, but were occasionally set for long periods. Each Datasonde set averaged 94 samples (e.g., DO measures) with a median of 52 samples per set.

We compared GRB vs. CNT data from the same stations to explore how they compared in characterizing a station's DO regime. Figure 1 illustrates a scatter plot of minimum values from CNT samples vs. minimum values of GRB samples at these stations collected during the same summer period, but likely on different days. Although there is scatter these values are positively correlated (R^2=0.26). Quadrant A on Figure 1 illustrates situations where minimum GRB samples are > 4 mg/l (Ohio Warmwater Habitat [WWH] minimum criteria value), but CNT values are less than 4. Less frequent are values in quadrant B where CNT values are > 4, but GRB samples are less than 4 mg/l. These are concentrated above 3 mg/l (Figure 1). This pattern can also be illustrated with cumulative frequency

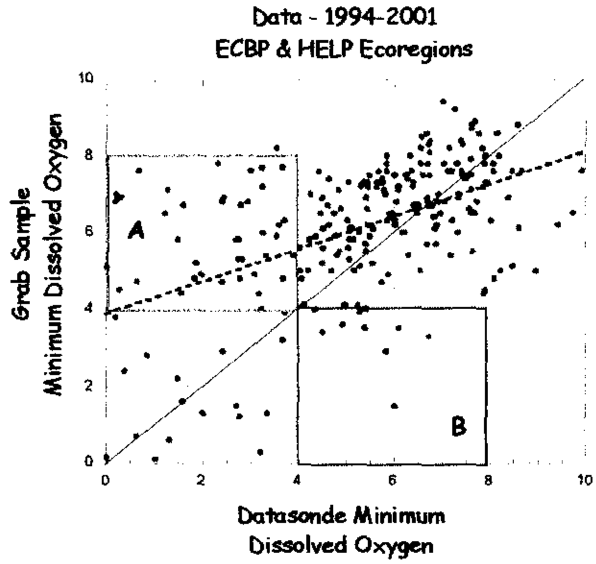


Figure 1. Plot of Datasonde continuous dissolved oxygen data vs. grab sample data for minimum dissolved oxygen data. Quadrant A has CNT values < 4m but GRB values > 4 while quadrant B has GRB values < 4m but CNT values > 4. Dashed line is a regression line and the solid line is a predicted line if data were perfectly matched.

plots that illustrate the percentage distribution values of dissolved oxygen for minimum values (Figure 2, right) and for 10th percentile values (Figure 2, left). These graphs contain the same information as Figure 1, but make it easier to estimate the overall differences between the methods. For example, the CNT sampling identified about 15% more values < 4 mg/l than did the GRB sampling. This is expected, but identifying the magnitude of difference can be important when applying GRB data for deriving field based targets.

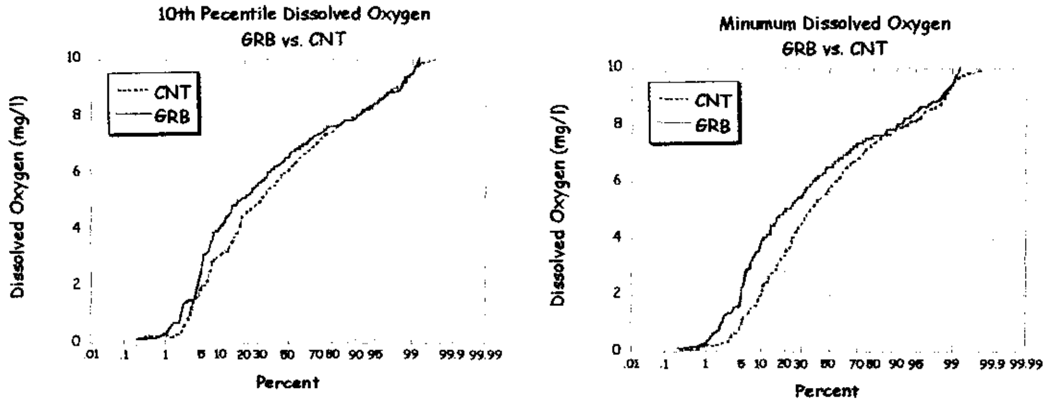


Figure 2. Cumulative frequency plot of 10th percentile (top) and minimum (bottom) dissolved oxygen values from CNT (dashed) and GRB (solid) samples

Associations Between Biological Indicators and Ambient Dissolved Oxygen

Although there is some variability related to multiple stressors that influence the relationship of DO to aquatic communities in Ohio, there is still a clear threshold relationship between biological indicators of aquatic condition and ambient dissolved oxygen. Figure 3 illustrates scatter plots of dissolved oxygen (GRB data) at sites in the ECBP and HELP ecoregions vs. IBI scores (top) and statewide data and ICI scores (bottom). The relationship between the GRB and CNT data indicates that diurnal data would push the threshold relationships to the left slightly if this were based on CNT data. There are sites that evidently support Exceptional Warmwater Habitat (EWH) or WWH IBI and ICI scores (~50 and 40, respectively) with individual DO concentrations below the minimum criteria established in Ohio for these uses (EWH=5 mg/l min; WWH=4 mg/l min). The grab sample data represent a snap shot of the actual DO regime. The furthest outlier on Figure 3 (top) where the IBI scores are greater than 40 is a DO of 1.6 mg/l. This was found in the headwaters of the Olentangy River. This area has had a history or relative severe impacts with nearby stations in 1979 with IBI scores below 20. Much of this has been abated and IBI scores in these areas are now in WWH ranges in the 40s. There were several DO sensitive species in this community (e.g., rainbow darter) although perhaps at lower abundances than expected. In addition, certain microhabitats such as riffles could have slightly higher DO regimes than pool areas where the DO sample was likely collected. In the macroinvertebrate data there is an extreme value in the Stillwater River with a DO of 1.3 mg/l that had an ICI of 40 in 1982. This was considered an impairment at that time and the data collected in 1990 had DO values above 6 mg/l and the ICI rebounded to a score of 50. We suggest that extreme examples or outliers should not be used to derive or support lowed DO criteria especially based on grab samples. Grab samples on average however are likely protective or conservative estimates because CNT identifies about 15% more low values than GRB samples do (Figure 2). Biological signatures (e.g., presence or absence of DO sensitive species or taxa) can be useful however, in determining whether an exceedance of the dissolved oxygen criteria is biological significant and should be identified as an area that needs some restoration (e.g., placed on a TMDL list).

Figures 4 and 5 illustrate the distributions of 10th percentile or minimum dissolved oxygen values for GRB samples (Figures 4 and 5) and CNT samples (Figure 4). These graphs are another method of illustrating the relationship between IBI or ICI and dissolved oxygen. The more frequent low values collected in CNT vs. GRB samples are reflected in the lower ranges of the open boxes which represent 10th percentile values across all stations. The CNT sampling picks up the diurnal swings that the GRB samples miss, although the grab samples cover more periods of time across a summer sampling period (when low DO values are more likely due to high temperatures, algal activity, and increase organic production). The biological data integrate stressor influences across multiple time periods (e.g., weeks to years), and the absence of low DO in either the CNT or GRB data can miss events or underestimate the severity of the DO influences. Biological signatures of low DO from impaired assemblages can compensate for the lack of "exceedences" of DO criteria and in fact the identification of DO as a cause of impairment in the Ohio 305(b) report (Ohio EPA 2000) is often accomplished without a specific chemical exceedence.

Figures 6a-f provides some insight into species sensitivity or tolerance to dissolved oxygen stress. These are plots of catch per unit effort (relative number per 300m) of individual species counts from electrofishing surveys paired with individual dissolved oxygen values for wadeable streams (< 200 sq mi). Each species count can be repeated for each GRB at a station. The DO tolerant species (carp, Figure 6f and creek chub, Figure 6e) provide a good illustration of the range of dissolved oxygen values distributed throughout this database which comprises the entire range of possible DO values. Moderately sensitive species (e.g., sand shiner and golden redhorse) are not found or found at reduced abundance at sites with less than 3-4 mg/l of dissolved oxygen. Two highly sensitive species, black redhorse and variegate darter are rarely (black redhorse), if ever (variegate darter) found at dissolved oxygen concentrations less than 5 mg/l. These types are data are important in helping establishing or verifying the appropriate minimum criteria for a given aquatic life use in Ohio. There is a continuum of sensitivity to ambient concentrations of dissolved oxygen across species and taxa that occur across Ohio. The presence of such sensitive species could be used to help identify reaches or watersheds that might be especially sensitive to factors that influence dissolved oxygen such as nutrient enrichment, habitat degradation and sedimentation. As has been outlined by us and others, these "nonpoint" stressors should typically be dealt with in combination and not separately as is often done in TMDL efforts.

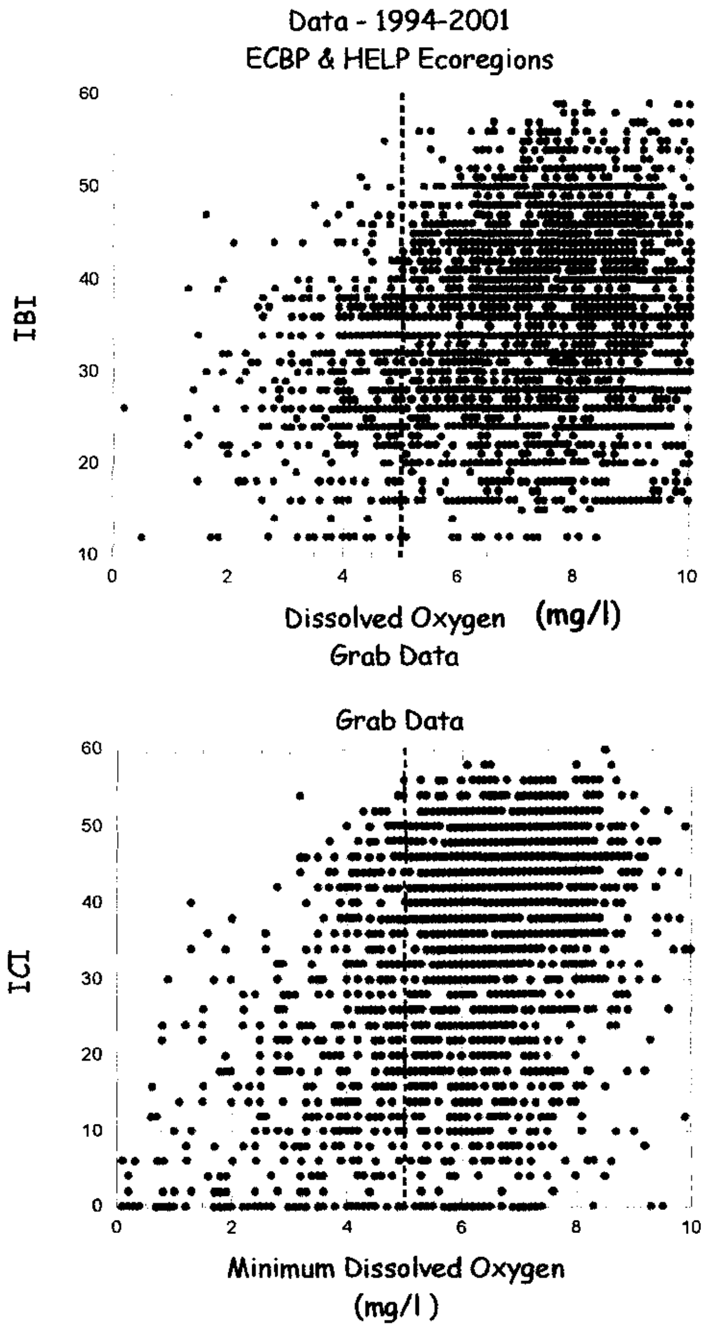


Figure 3. IBI (top) and ICI (bottom) vs. minimum dissolved oxygen (individual grab samples) at stations in the ECBP and EOLP ecoregion from 1994-2001 (top) and statewide data from 1978-2000 (bottom) Dashed line represents Ohio's warmwater criteria for average concentration of dissolved oxygen. Solid line is an 95th percentile threshold line drawn by eye.

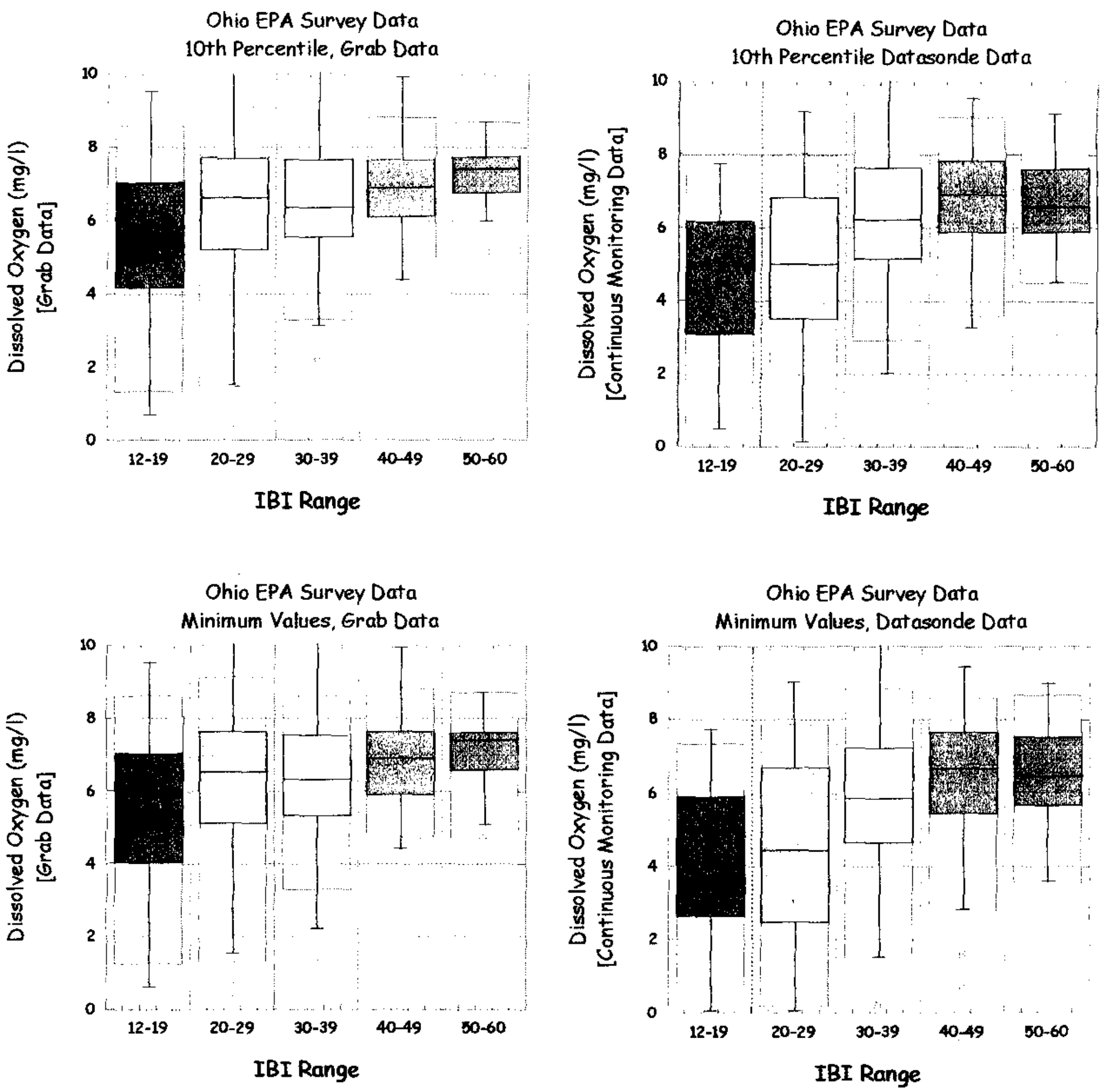
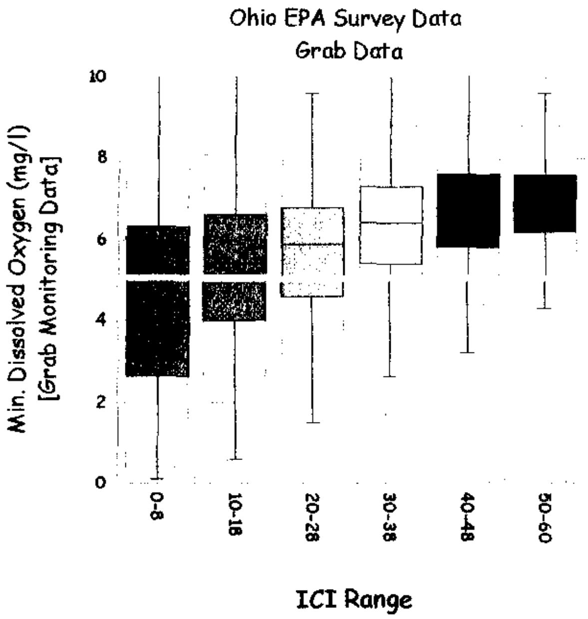


Figure 4. Box plots of 10^{th} percentile (top) and minimum (bottom) dissolved oxygen concentrations by IBI ranges for GRB samples (left) and for Datasonde continuous monitor data (right) at sites where both data types were collected between 1988 and 1994 by Ohio EPA.



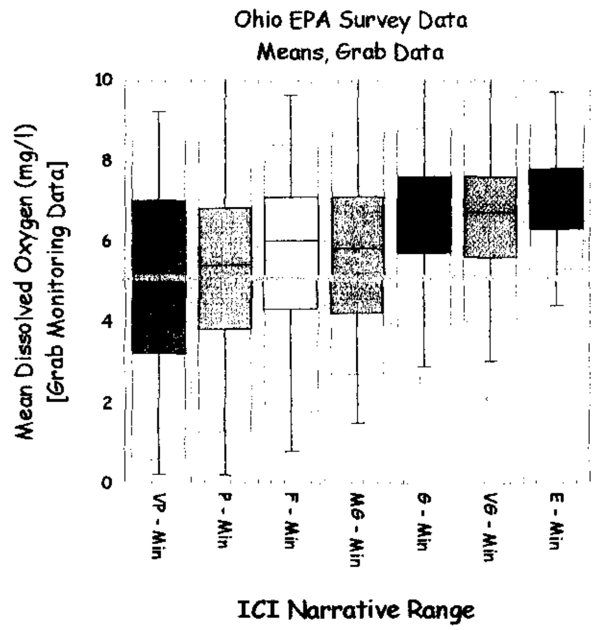


Figure 5. Box plots of minimum dissolved oxygen concentrations by ICI ranges (top and narrative ICI equivalents (bottom)) for GRB samples collected in Ohio from 1978-2000. Red line represents Ohio's warmwater criteria for average concentration of dissolved oxygen.

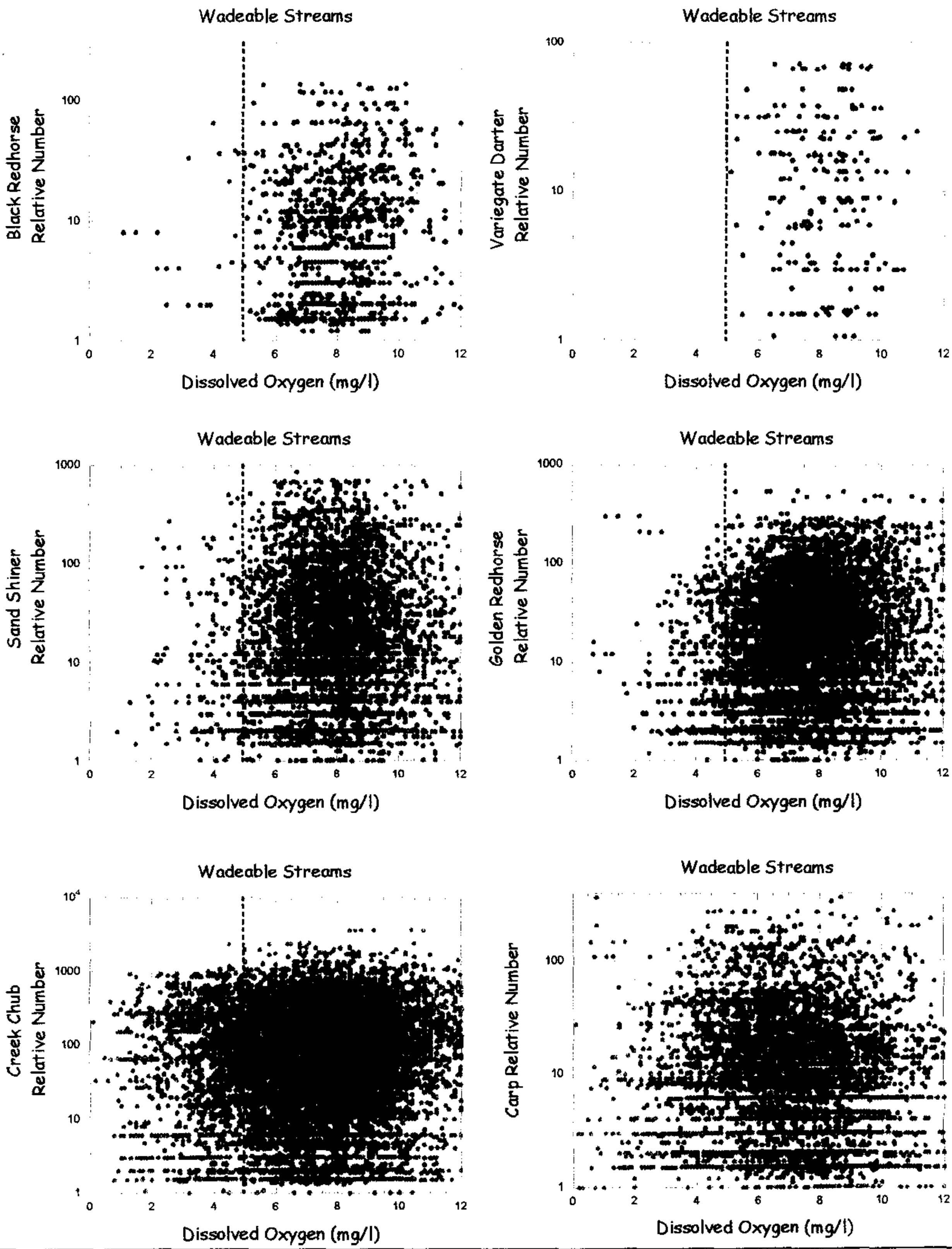
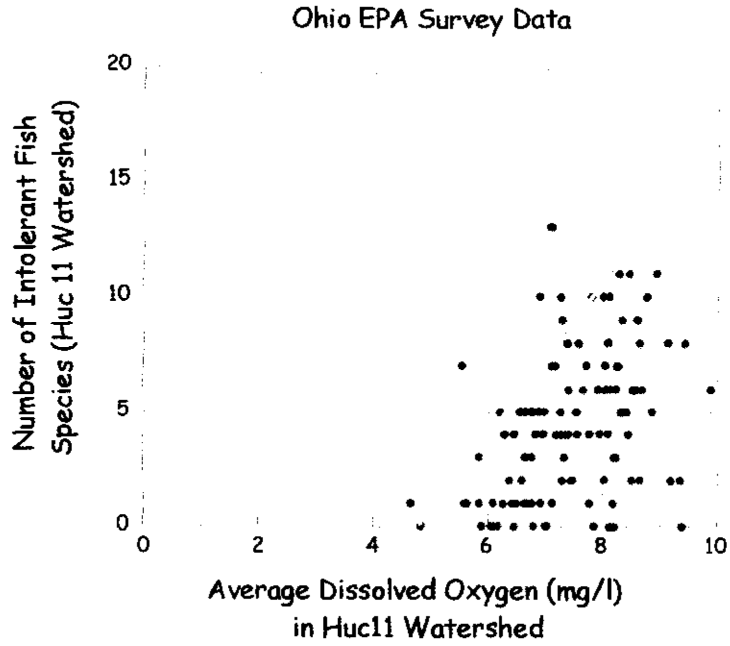


Figure 4. Plots of selected species relative abundances vs. dissolved oxygen values at wadeable stream sites in Ohio. Dashed line represents Ohio's warmwater criteria for average concentration of dissolved oxygen.



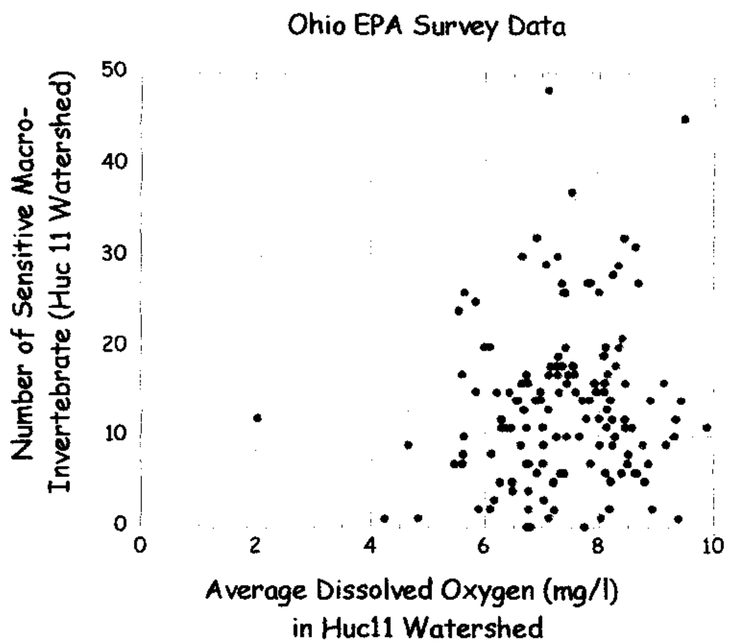


Figure 5 . Cumulative total intolerant fish species (top) and sensitive macroinvertebrate taxa bottom) in Ohio Huc11 scale watersheds). Dashed line represents Ohio's warmwater criteria for average concentration of dissolved oxygen. Solid lines are 95th percentile threshold lines drawn by eye.

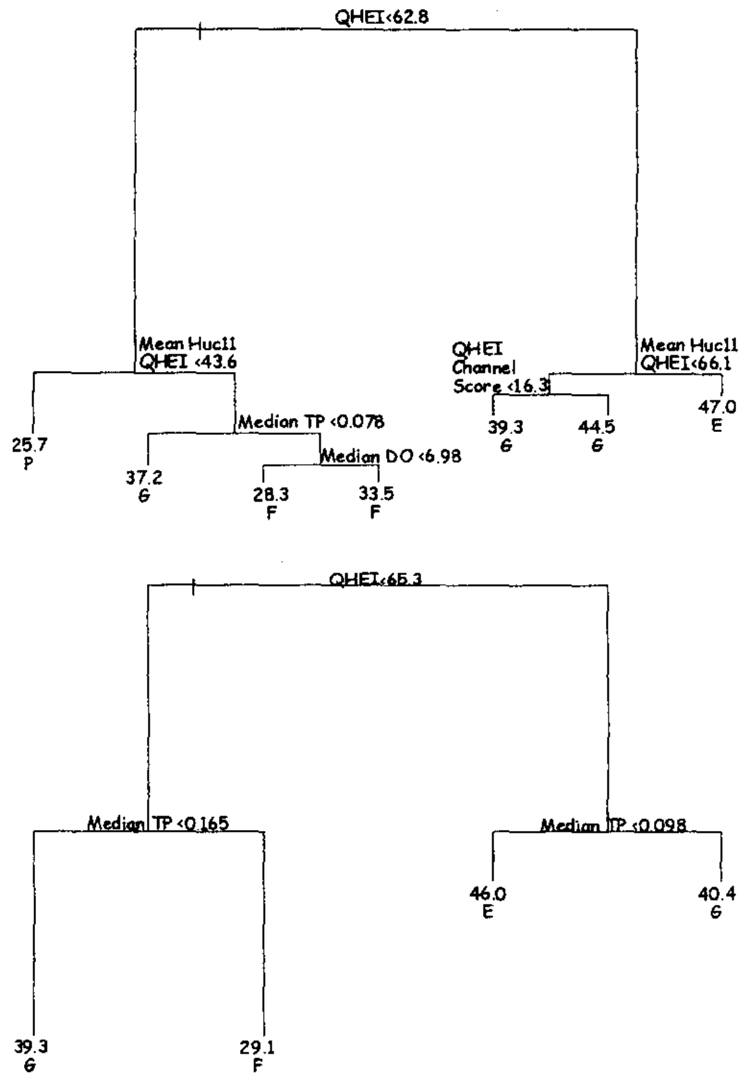


Figure 8. Example regression trees for major NPS stressors to aquatic life in the ECBP and HELP ecoregions of Ohio. Data is from 1994-2001 and represents stations unimpaired or influence by nonpoint sources of pollution. Response variable on top is IBI and on bottom is ICI. IBI and ICI scores with narrative codes are at the end of each node (E – Excellent, G – Good, F – Fair, P – Poor, VP – Very Poor.

Multiple Stressors and Cumulative Impacts to Watersheds
The accrual of multiple stressors at a watershed scale can hinder restoration of aquatic life in stream reaches within such watersheds. In Midwest streams, low DO, especially from NPS is typically associated with increased organic enrichment, increase nutrients, and degraded habitats. Figures 7 (top, bottom) identify a limiting threshold of dissolved oxygen associated with the maximum, cumulative number of intolerant fish species (top) and sensitive macroinvertebrate taxa (bottom) expected in a watershed. Watersheds with mean dissolved oxygen values greater than 7 mg/l (indicates a high proportion of sites with DO values > 5 mg/l) can have 10 or more sensitive species, a number typically associated with Ohio's EWH aquatic life use. Watersheds with mean DO values between 6-7 mg l^{-1} rarely have more than 5 intolerant species in these watersheds indicating an increasing number of sites likely exceeding warmwater DO criteria in Ohio ($\overline{X}$ = 5 mg l^{-1}, min. = 4 mg l^{-1}). Average watershed DO values < 6 mg/l rarely have more than 1 intolerant species and these watersheds are likely those with high nutrients, high siltation and degraded habitats. The biological response variables in areas affected by NPS stressors are more strongly associated with habitat conditions and nutrients such as total phosphorus (TP) than with DO concentrations, at least as they are reflected in the sampled DO regime. Regression tree analyses and other multivariate exploration techniques have identified some of these associations for the ECBP and HELP ecoregions (Rankin and Armitage 2004). Typical regression trees are illustrated in Figure 8 for IBI (top) and ICI (bottom). These analyses do not eliminate the important of DO as ecological mechanism of impairment, but identify the strong controlling influence of habitat and nutrients in explaining observed fish and macroinvertebrate impairment and reinforce the need to incorporate habitat in NPS restoration scenarios.

Species and Taxa Specific DO Tolerance Values
One of the more challenging parts of an assessment is identifying the stressor responsible for aquatic life impairment. While laboratory tests can provide useful data, often such data is only available for a handful of macroinvertebrate taxa or fish species. Data sets like the one we used here are useful for "mining" stressor-response relationships between stressor variables and abundances of a species or taxa. A ranking of species responses allow consideration of biological signatures for these stressors. Taxa that are abundant in the ambient environment at depressed concentrations of dissolved oxygen and remain after other taxa disappear can help distinguish situations where DO is a primary stressor. Conversely, high populations of taxa that only occur at high, background DO levels can provide evidence that DO is not an important stressor. Parameter specific tolerance rankings can provide an improvement over "general" tolerance rankings where identification of multiple stressors is difficult.

One method to calculate parameter-specific tolerance ratings is to calculate weighted mean stressor values for parameters where the weighting is done based on the relative abundance of a specific organism at a site. This requires data with consistent quantitative methods to control for error due to sampling variability. Organism that are common at high stressor levels will have higher weighted average parameter values than an organism that has its populations depressed or eliminated at a similar parameter concentrations. Where data is sufficient the organisms can be ranked and divided into quartiles or some other distribution as way to assign narrative tolerance rankings (e.g., tolerant, moderately tolerant, moderate intolerant, intolerant). When this is done for multiple taxa the "biological signatures" become more compelling (Rankin and Yoder 1995). Dissolved oxygen is somewhat problematic because although low oxygen is clearly a stressor to respiration, very high DO concentrations may be an indicator that nighttime DO is depressed related to high algal respiration. Tables 1 and 2 provide data on weighted dissolved oxygen values for macroinvertebrate taxa and fish species in Ohio. Ohio's general tolerance rankings[1] are provided for comparison. We excluded taxa where there were less than 100 DO data points or about 20 stations that had biological and DO data. We used the minimum dissolved oxygen value from each station to generate the weighed parameter value as the best indicator of stress conditions and this was paired with taxa or species abundances collected at these same sites during the same summer period. We also generated unweighted statistics from all of the DO data associated with each species from all samples at all sites (means, 25^{th} and 10^{th} percentiles).

We compared the general tolerance ratings for fish and macroinvertebrate taxa with the weighted DO values we generated to examine concordance between these ranking methods (Tables 3 and 4). We divided the weighted DO rankings into quintiles and assigned them the same narrative ratings used in the general tolerance rankings: intolerant, sensitive or moderately intolerant, intermediate, moderately tolerant, and tolerant Agreement among rankings indicates a general correspondence between general tolerance and DO-specific tolerance (Tables 3 and 4) with some variability.

Table 3. Comparison of general tolerance vs. DO tolerance for 93 Ohio fish species where there were at least 20 sites with DO data and a species occurrence. General tolerance based on Ohio EPA's tolerance rankings for the IBI.

DO Tolerance	General Tolerance				
	Tolerant	Mod. Tolerant	Intermediate	Sensitive	**Intolerant**
Intolerant	1		6	3	**8**
Sensitive		1	7	**5**	6
Intermediate	2		**9**	6	1
Mod. Tolerant	3	**3**	13		
Tolerant	**7**	3	9		

[1] "General" tolerance rankings are assessment of a taxa or species tolerance to a wide range of stressors and are typically used in IBI and other multimetric indices. These are often species that have declined in abundance compared to their historic geographic ranges and often in response to multiple stressors including habitat degradation, siltation, organic enrichment, and toxic chemicals. These assignments are typically made from a combination of fish distribution texts and data, literature, examination of ambient datasets, and best professional judgment.

Outliers can be useful to explain variation between general and specific tolerances. In the fish comparison, one species, blacknose dace, is an outlier with a general tolerance rating of tolerant, but a DO rating of intolerant. This species is generally associated with cool headwater streams, but can be extremely tolerant of industrial discharges and is not a generally a habitat specialist.

Table 4. Comparison of general tolerance vs. DO tolerance for 171 Ohio macroinvertebrate taxa where there were at least 20 sites with DO data and a taxa occurrence. General tolerance based on recent Ohio EPA's rankings of general tolerance.

DO Tolerance	General Tolerance				
	Tolerant	Mod. Tolerant	Intermediate	Sensitive	Intolerant
Intolerant	1		6	3	8
Sensitive		1	7	5	6
Intermediate	2		9	6	1
Mod. Tolerant	3	3	13		
Tolerant	7	3	9		

The greatest variability was in comparisons between intermediate rankings of general tolerance and dissolved oxygen tolerance rankings where intermediate general sensitivity was broadly distributed with both DO intolerant as well as DO tolerant species and taxa (Tables 3 and 4). Some of this was variation was related to coldwater species considered generally intermediate to certain general impacts (e.g., mottled sculpin, trout sp. [stocked]), but sensitive to temperature and DO and another group of species associated with wetland and prairie habitats that are habitat specialists, but are associated with naturally lower DO regimes (tadpole madtom, warmouth, least darter) than found in more common high gradient Midwest streams.

Derivation of Dissolved Oxygen Criteria

Criteria for dissolved oxygen for streams are typically structured as a two number criteria with a minimum (never to be exceeded) value and as daily average values. Even though most state dissolved oxygen criteria are based on methodologies generated from controlled studies as outline in the 1986 EPA guidelines (U.S. EPA 1986) some states have modified criteria on the basis of ambient field data (Ohio EPA 1996) or have methodologies for site specific derivation of criteria due to natural conditions (SCDHEC 1999; MO DNR 2004) that are were considered either over or under-protected by existing statewide criteria. These modifications of criteria typically rely on reference sites without substantial anthropogenic impacts.

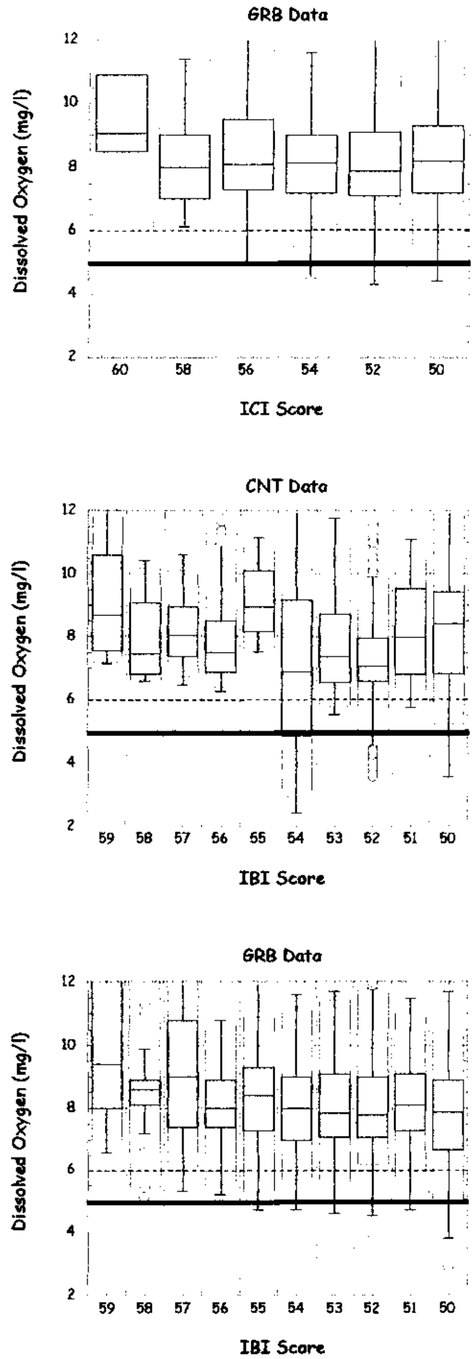


Figure 8. Box and whisker plots of dissolved oxygen (GRB, top and bottom, CNT, middle) vs. ICI (top) and IBI (middle and bottom) scores above 50. Dotted line represents the WWH average criteria and the solid line the minimum criteria for DO.

Ohio EPA's original EWH dissolved oxygen criteria was originally based on best professional judgment related to the perceived need that the biota of EWH streams were more sensitive to low DO than the biota typical of WWH streams (Ohio EPA 1996). The minimum DO criteria for EWH streams was then set to be equivalent to Ohio's coldwater aquatic life use (6 mg/l minimum). Ambient data similar to that presented here was used to provide evidence that EWH index scores (IBI, ICI) occurred commonly at DO values between 5-6 mg/l, but not less than 5 mg/l (Ohio EPA 1996) to justify a 5 mg/l minimum value for these waters. This is also supported with additional data examined here. For example, the intolerant black redhorse and variegate darters that are associated with EWH streams and rivers show abundant populations down to 5 mg/l, but quickly disappear below that level (see Figure 6). These species-based graphs were done with GRB data and are conservative because they miss some of the lower nighttime values measured in the CNT data.

WWH Dissolved Oxygen Criteria

The same approach used to examine and provide justification for the EWH criteria can be applied to the WWH criteria as well. Ambient biological data indicates that attainment of WWH biological index scores occurs at stations with DO values of 4 mg/l or above, but much less frequently when DO is less than 4 mg/l. Interestingly, there was a slight difference in the range of minimum dissolved oxygen values at stations with WWH IBI scores (40-49) between stations with grab data at sites with datasonde data (see Figure 4a) and grab samples at a broad range of sites represented by the statewide data set. The distribution of minimum DO values at stations with IBI scores of 40-49 are summarized in the histograms for stations in the statewide data set (Figure 9, top) and a subset of this data that also had datasonde data. The presence of lower DO values at statewide sites is partly a result of larger sample sizes, but may also be related to datasonde samplers being more commonly set at complex sites where multiple stressors are common and point sources occur. At such sites, lower DO values are more likely to co-occur with toxicants and other acute stressors, and thus they less frequently co-occured with IBI scores of 40-49. The statewide data includes more sites where DO is the predominant stress and low DO values co-occur more frequently with IBI scores of 40-49.

Stations with DO values less than 4 mg/l primarily comprise the "tail" of the distribution (Figure 9, top). An examination of sensitive species that are charactistic of WWH streams such as the golden redhorse and rainbow darter show fewer organisms below a DO of 4 mg/l although populations do occur at lower DO values. Some data points below the criteria should be expected because the chemical grab samples are an imperfect estimate of the magnitude and duration of a chemical stress. The abundance of a fish species characteristic of EWH streams (variegate darter, Figure 10, bottom) illustrates the greater restriction in abundance along the DO gradient observed in EWH streams justifying the higher minimum DO (5 mg/l vs. 4 mg/l) for these waters.

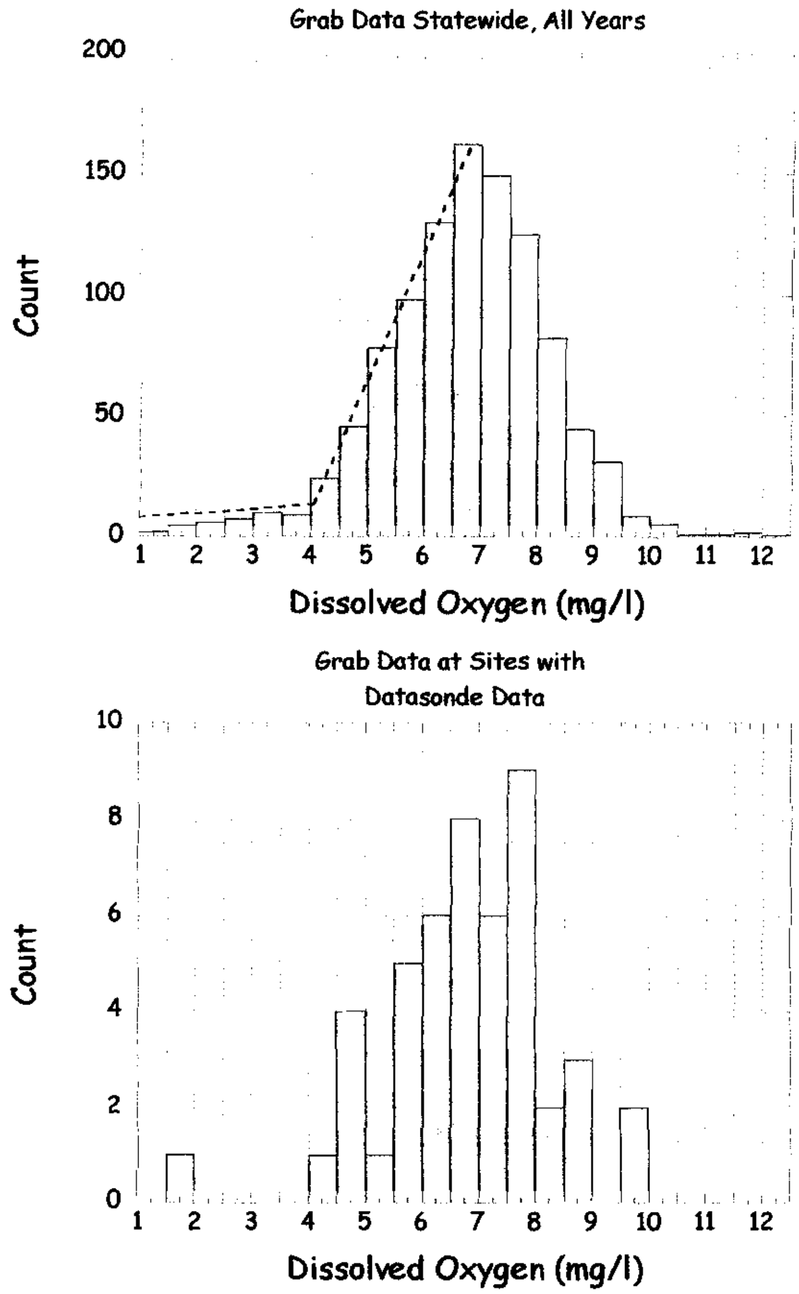


Figure 9. Histograms of minimum dissolved oxygen data (mg/l) at stations with IBI values of 40-49 (WWH range) from a statewide Ohio data set (top) and a subset of sites that also had datasonde data (bottom).

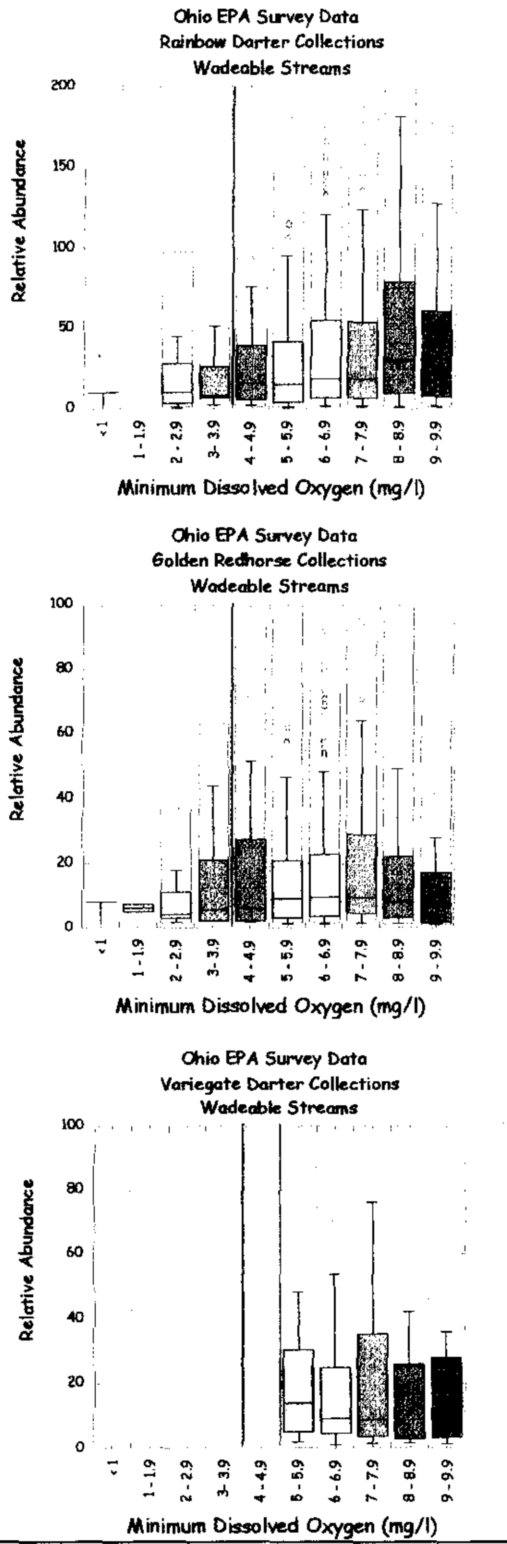


Figure 8. Box and whisker plots of rainbow darter, golden redhorse, and variegate darter vs. minimum dissolved oxygen concentrations in Ohio streams.Red lines denote the minimum DO criteria for WWH streams; blue lines for EWH streams.

Figure 10 probably underestimates the effects of the lowest DO because it does not include sites where a species should occur, but has been eliminated because of low DO or other stressors. The development of species distribution and abundance models along natural gradients of habitat, elevation, stream gradient, and flow could provide estimates of expected abundance of an organism. Relationships between stressors like DO and expected abundance could result in more precise estimates of the influence of a stressor such as DO on individual species or taxa.

Using ambient biological data to help or adjust criteria such as dissolved oxygen takes advantage of the strength of well-founded biological monitoring to integrate the often complex pathways of influence of DO. The selection of the biological target is a critical choice in this effort. Ohio has developed biological targets through their development of biological criteria. The difficulty is in determining which chemical number is a protective and reasonable target for protection of aquatic life. The appropriate role of the biological data is as a response indicators to the suite of stressor that occur in the environment and the chemical stressors are best used as design endpoints and to help identify cause of biological impairments. The focus on this paper was to identify DO values that can be protective and reasonable design criteria and provide information for various management efforts on cause of impairment. We know that a reliance on chemical assessment of aquatic life use attainment and impairment, in the absence of biological data, outside of where values will obviously result in acute impacts, can result in large errors in identifying impairment with the error tendencies strongly skewed to missing impairments (Rankin 2003). A reliance on biological data for assessment impairment is consistent with the NRC TMDL Committee that argued that indicators should be as direct measures of the designated use as possible (NRC 2001). There is more concern with the precision of the criteria number when using DO data alone to estimate impairment, than when using DO data as a support to biological assessments to identify impairment.

There are a number of methods being explored as tools for deriving accurate criteria from ambient data. Paul (2004) has proposed a conditional probability approach using probabilistic survey data. As with other methods it relies on the ability to derive sound biological targets or endpoints. Such advances are compatible with U.S. EPA's strategy for its WQS and Criteria programs because and touches a number of the 28 "Strategic Actions" in the Draft Strategy for Water Quality Standards and Criteria (U.S. EPA 2002). Here we outlined what is a multiple line of evidence approach to determine DO concentrations that appear to protective on the basis of large scale analyses of databases, site specific examples of attainment of a tiered use at various DO levels, and the identification of DO sensitive or tolerant taxa that can be used to support attainment decisions where data is ambiguous. Because many of the stressors are moderately to highly correlated the choice of the numeric chemical target can be difficult and often depends on multiple lines of evidence. Some of the newer approaches may provide more standardized methods to achieve ambient based criteria.

Perhaps as important a process as the derivation of criteria is consideration of how attainment and impairment decisions are made. Some of the weakness with attainment decisions, as for example the 305(b) and 303(d) process, lies with the inappropriate reliance on stressor indicators to identify impairment rather than on response indicators. The strength of stressor criteria is with the derivation of appropriate treatment and management strategies and causes of impairment. Because of weaknesses with using stressor data to identify impairment, outside of where values will obviously result in acute impacts, biological data should be the indicator of choice to determine aquatic life use impairment. As mentioned above, the DO sampling regime does not always clearly identify impairments and there is a risk of identifying a water as attaining an aquatic life use with this data when it is actually impaired (Rankin 2003). Many of these concerns fade when an adequate monitoring approach is used that provides confidence in identifying impairment and is able to employ multiple approaches to identifying the cause of impairment.

Summary

In this paper we explored the relationships between CNT and GRB DO data and the response of biological data to gradients of DO data across Ohio. Ohio EPA (1996) used a similar approach to justify a two-number criteria for its EWH aquatic life use including a addition of a minimum criteria of 5 mg/l for EWH streams. Both community-level and taxa and species specific data were used to identify that attainment of an EWH aquatic life use was rare below a DO of 5 mg/l, but became more common between DO values of 5-6 mg/l. Similarly, for WWH streams, attainment of the use was uncommon below a DO of 4 mg/l, but became more common between DO values of 4-5 mg/l. Ohio EPA (1996) provided more case examples supporting the 5 mg/l minimum value for DO for EWH streams and the standard laboratory-based approach supports the WWH criteria. We also derived a fish species and a macroinvertebrate taxa sensitivity list for DO that shows differences from the general tolerance sensitivities. We envision this as a tool for use in the stressor identification process. It is clear from the watershed scale patterns we have presented that restoration of streams can be limited by watershed scale influences and that multiple stressors are the rule rather than exception. It is also clear that aquatic life have a continuum of response to DO and that tiered aquatic life uses provide great advantages for water resource management and the derivation of reasonable and protective DO criteria.

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Table 1. Weighted mean and other statistics for dissolved concentrations by macoinvertebrate taxa ranked by the weighted mean DO value.

Species	No. Stations	Weighted Mean	Mean	Median	25th %tile	10th %tile
[04935] - Erpobdella punctata punctata [T]	74	3.4882	5.4007	7.50000	5.00000	3.04000
[05800] - *Caecidotea* sp [MT]	301	3.6346	5.7784	7.70000	6.10000	4.20000
[83600] - Kiefferulus (K.) dux [MT]	26	3.6364	4.2731	6.20000	4.22500	3.10000
[82770] - *Chironomus (C.) riparius group* [VT]	117	3.6609	5.2152	7.70000	6.12000	4.20000
[82730] - *Chironomus (C.) decorus group* [T]	353	3.6880	5.2858	7.60000	6.00000	4.10000
[06201] - Hyalella azteca [F]	211	4.2822	5.3877	7.00000	5.40000	4.20000
[78401] - Natarsia species A (sensu Roback, 1978) [MT]	70	4.3925	5.7471	6.40000	4.17500	2.70000
[04664] - Helobdella stagnalis [T]	71	4.4502	4.8470	6.30000	3.70000	2.50000
[83051] - Dicrotendipes simpsoni [T]	375	4.5597	4.9994	6.85000	5.20000	3.80000
[08200] - Orconectes sp [F]	53	4.6024	5.1070	7.10000	5.80000	4.10000
[77355] - Clinotanypus pinguis [MT]	24	4.6058	5.2500	6.80000	4.70000	3.38000
[04666] - Helobdella triserialis [T]	86	4.6132	5.0440	7.40000	5.30000	3.80000
[84010] - Parachironomus "abortivus" (sensu Simpson &	50	4.6981	5.1760	7.00000	5.30000	4.20000
[77130] - Ablabesmyia rhamphe group [MT]	167	4.7572	5.5494	7.20000	5.90000	4.70000
[83002] - Dicrotendipes modestus [F]	29	4.8260	5.3497	7.80000	6.20000	4.30000
[77115] - Ablabesmyia janta [F]	37	5.0363	5.7524	7.10000	5.90000	4.79000
[84790] - Tribelos fuscicorne [F]	158	5.0533	5.6172	6.70000	5.70000	4.90000
[84800] - Tribelos jucundum [F]	149	5.1060	5.5517	6.80000	5.60000	4.60000
[03600] - Oligochaeta [T]	1927	5.1247	6.0965	7.70000	6.30000	4.60000
[78101] - Labrundinia becki [ ]	25	5.2174	5.7800	7.20000	6.10000	5.00000
[83158] - Endochironomus nigricans [F]	64	5.2762	5.5247	6.90000	5.30000	4.00000
[84520] - Polypedilum (Tripodura) halterale group [F]	77	5.3000	5.9468	7.50000	6.20000	5.40000
[80510] - *Cricotopus (Isocladius) sylvestris group* [VT]	58	5.3106	5.4724	7.10000	5.40000	4.20000
[85200] - Cladotanytarsus sp [F]	70	5.3675	5.7129	7.30000	6.10000	4.70000
[81630] - Parakiefferiella sp [ ]	25	5.3765	5.8920	7.10000	5.90000	4.96000
[83050] - Dicrotendipes lucifer [MT]	271	5.4008	5.3974	7.20000	5.60000	4.20000
[01200] - *Cordylophora lacustris* [F]	59	5.4125	5.6695	7.50000	6.30000	5.30000
[81240] - Nanocladius (N.) distinctus [MT]	503	5.4790	5.7290	7.40000	5.90000	4.40000
[81201] - Nanocladius (N.) sp [ ]	88	5.4973	5.7489	7.60000	6.30000	4.80000
[78650] - Procladius sp [MT]	229	5.5312	5.7576	7.20000	5.80000	4.20000
[84020] - Parachironomus carinatus [F]	63	5.5542	5.6365	6.90000	5.70000	4.40000
[84540] - Polypedilum (Tripodura) scalaenum group [F]	1161	5.5646	6.1448	7.70000	6.30000	4.80000
[78600] - Pentaneura inconspicua [F]	64	5.5950	5.8755	8.20000	6.40000	5.00000

Table 1. Weighted mean and other statistics for dissolved concentrations by macoinvertebrate taxa ranked by the weighted mean DO value.

Species	No. Stations	Weighted Mean	Mean	Median	25th %tile	10th %tile
[01801] - Turbellaria [MT]	1285	5.6051	6.1104	7.80000	6.40000	4.80000
[78100] - Labrundinia sp [F]	107	5.6500	5.9850	7.80000	6.30000	5.10000
[79100] - Thienemannimyia group [F]	449	5.6665	5.8318	7.70000	6.30000	4.60000
[06810] - Gammarus fasciatus [F]	64	5.6962	6.0175	7.80000	6.40000	5.10000
[85500] - Paratanytarsus sp [F]	696	5.7031	6.1429	7.40000	6.20000	4.90000
[07701] - Cambaridae [ ]	31	5.7087	5.5871	7.40000	6.22500	4.60000
[81631] - Parakiefferiella n.sp 1 [MI]	67	5.7121	6.6104	7.55000	6.40000	5.70000
[81260] - Nanocladius (N.) "rectinervis" (old) [ ]	55	5.7245	5.6727	7.90000	6.10000	4.44000
[18100] - Anthopotamus sp [MI]	74	5.7313	6.1216	7.80000	6.60000	5.73000
[22001] - Coenagrionidae [MT]	448	5.7388	5.7412	7.40000	5.80000	4.30000
[84470] - Polypedilum (P.) illinoense [T]	643	5.7576	5.9490	7.40000	5.90000	4.40000
[84300] - Phaenopsectra obediens group [F]	498	5.8176	6.3501	7.80000	6.30000	4.60000
[22300] - Argia sp [F]	1116	5.8194	6.0036	7.70000	6.30000	4.80000
[08260] - Orconectes (Crokerinus) sanbornii sanbornii [F]	88	5.8246	6.0420	7.50000	5.90000	4.50000
[84210] - Paratendipes albimanus or P. duplicatus [MI]	479	5.8994	6.2339	7.80000	6.50000	5.30000
[04964] - Mooreobdella microstoma [T]	87	5.9005	5.8548	7.50000	6.22500	4.60000
[83300] - Glyptotendipes (G.) sp [MT]	854	5.9360	5.7444	7.60000	6.20000	4.80000
[06700] - Crangonyx sp [MT]	252	5.9383	5.9930	7.30000	6.00000	4.60000
[85803] - Tanytarsus Type 3 [F]	46	5.9423	6.3065	7.10000	6.02500	5.10000
[85201] - Cladotanytarsus species group A [MI]	24	5.9628	5.6025	6.80000	5.72500	4.90000
[80350] - Corynoneura sp [ ]	107	5.9857	6.3252	8.00000	6.90000	5.96000
[83003] - Dicrotendipes fumidus [F]	40	5.9897	6.6150	7.50000	6.30000	5.00000
[83040] - Dicrotendipes neomodestus [F]	999	5.9948	6.1303	7.80000	6.30000	4.80000
[80420] - Cricotopus (C.) bicinctus [MT]	768	6.0105	6.1920	7.70000	6.40000	4.90000
[84302] - Phaenopsectra punctipes [F]	29	6.0357	6.0241	7.40000	6.50000	5.43000
[11200] - Callibaetis sp [F]	53	6.0461	5.7175	7.05000	4.80000	3.10000
[83900] - Nilothauma sp [F]	55	6.0556	6.1509	7.30000	6.30000	5.40000
[85400] - Micropsectra sp [F]	72	6.0563	6.1046	8.30000	6.77500	5.30000
[84460] - Polypedilum (P.) fallax group [F]	1287	6.0621	6.2470	7.60000	6.40000	5.10000
[14950] - Leptophlebia sp or Paraleptophlebia sp [MI]	84	6.0624	6.1979	7.20000	6.10000	4.90000
[11651] - Procloeon sp (w/o hindwing pads) [MI]	75	6.0681	6.0360	7.30000	6.50000	5.40000
[84960] - Pseudochironomus sp [F]	56	6.0726	5.9982	8.00000	6.45000	5.69000
[78200] - Larsia sp [F]	91	6.0753	6.0253	7.50000	5.70000	3.68000

Table 1. Weighted mean and other statistics for dissolved concentrations by macoinvertebrate taxa ranked by the weighted mean DO value.

Species	No. Stations	Weighted Mean	Mean	Median	25th %tile	10th %tile
[78140] - Labrundinia pilosella [MI]	330	6.0859	6.0976	7.30000	6.20000	5.10000
[13521] - Stenonema femoratum [F]	444	6.0933	6.2165	7.70000	6.60000	5.50000
[85230] - Cladotanytarsus mancus group [F]	43	6.0971	6.3395	7.50000	6.40000	5.70000
[77120] - Ablabesmyia mallochi [F]	728	6.1064	6.0008	7.50000	6.20000	4.80000
[18750] - Hexagenia limbata [MI]	21	6.1121	5.9571	7.25000	6.50000	5.80000
[81825] - Rheocricotopus (Psilocricotopus) robacki [MI]	476	6.1286	6.5722	7.80000	6.60000	5.50000
[21200] - Calopteryx sp [F]	438	6.1412	6.1279	7.60000	6.40000	5.20000
[83840] - Microtendipes pedellus group [MI]	472	6.1446	6.2353	7.60000	6.40000	5.20000
[81230] - Nanocladius (N.) crassicornus (old) [ ]	296	6.1533	6.0186	7.80000	6.40000	5.08000
[01320] - Hydra sp [F]	1099	6.1653	6.1094	7.80000	6.40000	5.20000
[81632] - Parakiefferiella n.sp 2 [MI]	70	6.1836	6.2983	7.60000	6.50000	5.62000
[84155] - Paralauterborniella nigrohalteralis [MI]	51	6.2051	6.2451	7.40000	6.20000	5.10000
[84315] - Phaenopsectra flavipes [MT]	213	6.2059	6.1683	7.30000	5.90000	4.20000
[77750] - Hayesomyia senata or Thienemannimyia norena	1005	6.2095	6.3178	7.80000	6.40000	4.90000
[82820] - Cryptochironomus sp [F]	258	6.2207	6.3291	7.80000	6.60000	5.50000
[81690] - Paratrichocladius sp [MI]	45	6.2544	7.1538	8.30000	7.40000	6.80000
[81231] - Nanocladius (N.) crassicornus or N. (N.)	320	6.2664	6.3248	7.70000	6.62500	5.60000
[11650] - Procloeon sp (w/ hindwing pads) [MI]	51	6.2684	6.1020	7.65000	6.50000	5.41000
[79400] - Zavrelimyia sp [F]	72	6.2737	6.2894	7.95000	6.50000	5.10000
[03360] - Plumatella sp [F]	826	6.2818	6.2965	7.90000	6.70000	5.50000
[03040] - Fredericella sp [MI]	29	6.2915	6.3728	7.75500	6.80000	6.00000
[13400] - Stenacron sp [F]	1507	6.3213	6.3213	7.80000	6.50000	5.00000
[77740] - Hayesomyia senata [F]	94	6.3252	6.2809	7.60000	6.60000	5.30000
[11020] - Acerpenna pygmaeus [I]	173	6.3335	6.3401	7.70000	6.60000	5.70000
[17200] - Caenis sp [F]	1408	6.3501	6.2785	7.90000	6.50000	5.00000
[81229] - Nanocladius (N.) crassicornus [F]	52	6.3511	6.2558	7.60000	6.50000	5.26000
[84750] - Stictochironomus sp [F]	48	6.3665	6.3717	7.70000	6.60000	5.30000
[03337] - Hyalinella punctata [F]	26	6.3699	5.9538	9.40000	7.80000	6.37000
[08250] - Orconectes (Procericambarus) rusticus [F]	154	6.3823	6.1558	7.80000	6.40000	5.10000
[16700] - Tricorythodes sp [MI]	909	6.3895	6.6733	8.20000	7.10000	6.10000
[08601] - Hydracarina [MI]	627	6.4030	6.5133	7.90000	6.80000	5.70000
[82121] - Thienemanniella lobapodema [MI]	235	6.4160	6.2729	7.50000	6.40000	5.70000
[82710] - Chironomus (C.) sp [T]	116	6.4230	5.8314	7.50000	6.20000	4.50000

Table 1. Weighted mean and other statistics for dissolved concentrations by macoinvertebrate taxa ranked by the weighted mean DO value.

Species	No. Stations	Weighted Mean	Mean	Median	25th %tile	10th %tile
[11400] - *Centroptilum* sp or *Procloeon* sp (formerly in	167	6.4293	6.2287	7.80000	6.40000	5.20000
[13560] - *Stenonema pulchellum* group [ ]	138	6.4524	6.1529	7.80000	6.70000	5.70000
[85800] - *Tanytarsus* sp [MI]	623	6.4548	6.4312	7.80000	6.40000	4.61600
[77500] - *Conchapelopia* sp [F]	908	6.4562	6.4307	7.80000	6.40000	4.70000
[84700] - *Stenochironomus* sp [F]	178	6.4851	6.4394	7.80000	6.90000	6.08000
[11100] - *Baetis* sp [ ]	656	6.5108	6.3796	7.90000	6.50000	4.90000
[85814] - *Tanytarsus glabrescens* group [F]	1184	6.5127	6.3247	7.80000	6.40000	4.90000
[03451] - *Urnatella gracilis* [F]	226	6.5263	6.4492	8.40000	7.30000	6.20000
[77800] - *Helopelopia* sp [F]	633	6.5361	6.4823	7.80000	6.70000	5.70000
[18700] - *Hexagenia* sp [MI]	21	6.5506	6.6571	7.80000	6.80000	6.13000
[80370] - *Corynoneura lobata* [MI]	973	6.5700	6.4344	7.70000	6.55000	5.50000
[85710] - *Stempellinella* sp [MI]	52	6.5908	6.6962	7.90000	7.00000	6.20000
[11300] - *Procloeon* sp (formerly in *Centroptilum*) [ ]	88	6.6027	6.4625	7.90000	6.80000	5.80000
[84040] - *Parachironomus frequens* [F]	124	6.6091	6.2485	8.10000	6.80000	5.60000
[21300] - *Hetaerina* sp [F]	171	6.6120	6.7719	8.00000	7.00000	6.00000
[13000] - *Leucrocuta* sp [I]	422	6.6139	6.6788	8.10000	7.10000	6.20000
[82141] - *Thienemanniella xena* [F]	630	6.6141	6.5022	7.80000	6.70000	5.50000
[05900] - *Lirceus* sp [F]	235	6.6320	6.0894	7.80000	6.40000	5.20000
[13550] - *Stenonema mexicanum integrum* [MI]	353	6.6333	6.6083	8.20000	7.10000	6.10000
[82130] - *Thienemanniella similis* [I]	86	6.6498	6.7687	8.00000	7.00000	6.20000
[85802] - *Tanytarsus curticornis* group [MI]	242	6.6513	6.6555	7.80000	6.60000	5.50000
[84450] - *Polypedilum (P.) flavum* [F]	1350	6.6602	6.5412	8.10000	6.90000	5.80000
[13570] - *Stenonema terminatum* [MI]	629	6.6692	6.6610	8.00000	6.60000	5.00000
[78750] - *Rheopelopia paramaculipennis* [MI]	132	6.6737	6.8205	8.70000	7.50000	6.50000
[78450] - *Nilotanypus fimbriatus* [MI]	691	6.6800	6.5535	8.00000	6.90000	5.90000
[85625] - *Rheotanytarsus exiguus* group [MI]	1491	6.6807	6.5038	8.00000	6.80000	5.80000
[80410] - *Cricotopus (C.)* sp [F]	668	6.6833	6.6127	8.00000	6.90000	5.90000
[83310] - *Glyptotendipes (Trichotendipes) amplus* [F]	36	6.6853	6.2861	8.40000	7.00000	6.00000
[13510] - *Stenonema exiguum* [I]	376	6.6868	6.5894	8.10000	7.00000	6.10000
[80430] - *Cricotopus (C.) tremulus* group [F]	685	6.6916	6.6153	7.90000	6.90000	5.80000
[03121] - *Paludicella articulata* [MI]	93	6.6997	6.5678	8.20000	7.10000	6.10500
[11130] - *Baetis intercalaris* [MI]	721	6.7058	6.6364	7.90000	6.90000	6.00000
[79085] - *Telopelopia okoboji* [F]	86	6.7558	6.6110	8.40000	7.20000	5.84000

Table 1. Weighted mean and other statistics for dissolved concentrations by macoinvertebrate taxa ranked by the weighted mean DO value.

Species	No. Stations	Weighted Mean	Mean	Median	25th %tile	10th %tile
[11700] - *Acentrella sp or Plauditus sp (formerly in*	41	6.7575	6.8610	8.80000	7.60000	6.24000
[84060] - *Parachironomus pectinatellae* [MI]	41	6.7718	6.6415	8.30000	7.30000	6.07000
[23909] - *Boyeria vinosa* [F]	120	6.7826	6.5200	7.80000	6.80000	5.80000
[12200] - *Isonychia sp* [I]	838	6.7866	6.7911	8.20000	7.20000	6.30000
[13580] - *Stenonema tripunctatum* [ ]	305	6.8237	6.2413	7.80000	6.38750	4.60000
[81270] - *Nanocladius (N.) spiniplenus* [MI]	130	6.8252	6.5410	7.90000	6.90000	6.00000
[83820] - *Microtendipes "caelum" (sensu Simpson & Bode,*	154	6.8302	6.7748	8.00000	7.00000	6.10000
[15000] - *Paraleptophlebia sp* [MI]	260	6.8341	6.3125	7.80000	6.50000	5.20000
[83000] - *Dicrotendipes sp* [ ]	52	6.8674	5.9423	7.70000	6.10000	4.66000
[85615] - *Rheotanytarsus distinctissimus group* [MI]	311	6.8688	6.7564	7.90000	7.00000	6.10000
[80204] - *Brillia flavifrons group* [F]	118	6.8824	6.8076	8.20000	7.20000	6.10000
[80351] - *Corynoneura n.sp 1* [MI]	36	6.9143	6.9000	8.20000	7.02500	6.10000
[18600] - *Ephemera sp* [MI]	107	6.9317	6.6271	8.00000	6.90000	6.00000
[13540] - *Stenonema mediopunctatum* [I]	111	6.9488	6.6946	8.20000	7.17500	6.20000
[78350] - *Meropelopia sp* [F]	72	6.9517	6.9503	8.00000	6.80000	5.40000
[80360] - *Corynoneura "celeripes" (sensu Simpson & Bode,*	238	6.9746	6.8375	8.10000	7.20000	6.30000
[13590] - *Stenonema vicarium* [MI]	305	6.9956	6.8807	8.10000	7.00000	6.00000
[85720] - *Stempellinella n.sp nr. flavidula* [MI]	113	6.9999	6.6885	7.90000	6.70000	5.90000
[13561] - *Stenonema pulchellum* [I]	777	7.0343	6.8568	8.30000	7.30000	6.40000
[16324] - *Serratella deficiens* [I]	51	7.0570	7.1980	8.50000	7.50000	6.72000
[84430] - *Polypedilum (P.) albicorne* [F]	21	7.0740	7.0476	8.10000	7.30000	6.48000
[80440] - *Cricotopus (C.) trifascia group* [F]	54	7.1006	7.0407	8.40000	7.30000	5.80000
[81650] - *Parametriocnemus sp* [MI]	201	7.1515	7.0805	8.40000	7.30000	6.20000
[11120] - *Baetis flavistriga* [MI]	378	7.1774	6.9175	8.20000	7.20000	6.30000
[82101] - *Thienemanniella taurocapita* [I]	179	7.2049	7.1067	8.20000	7.40000	6.50000
[81250] - *Nanocladius (N.) minimus* [F]	145	7.2780	6.4120	7.90000	6.70000	5.40000
[82200] - *Tvetenia bavarica group* [MI]	70	7.3119	7.2629	8.50000	7.55000	6.71000
[85752] - *Sublettea coffmani* [MI]	66	7.3567	7.2491	8.50000	7.67500	6.90000
[85600] - *Rheotanytarsus sp* [ ]	35	7.3791	7.3457	8.50000	7.60000	6.80000
[80310] - *Cardiocladius obscurus* [MI]	78	7.3822	7.3992	8.70000	7.80000	7.13000
[84440] - *Polypedilum (P.) aviceps* [MI]	37	7.4003	7.5054	8.90000	7.80000	7.00000
[85261] - *Cladotanytarsus vanderwulpi group Type 1* [I]	71	7.4872	7.1408	8.50000	7.50000	6.50000
[15501] - *Ephemerellidae* [MI]	28	7.4951	7.2786	8.50000	7.62500	7.00000

Table 1. Weighted mean and other statistics for dissolved concentrations by macoinvertebrate taxa ranked by the weighted mean DO value.

Species	No. Stations	Weighted Mean	Mean	Median	25th %tile	10th %tile
[82220] - Tvetenia discoloripes group [I]	164	7.5254	7.3468	8.70000	7.70000	7.00000
[16200] - Eurylophella sp [MI]	79	7.5532	7.0266	8.40000	7.40000	6.50000
[80400] - Cricotopus sp [ ]	30	7.8019	7.6200	8.70000	7.67500	6.86000
[11430] - Diphetor hageni [I]	55	8.0279	7.4964	8.80000	7.70000	6.55000
[85501] - Paratanytarsus n.sp 1 [MI]	71	8.3383	7.2296	8.70000	7.50000	6.14000
[11018] - Acerpenna macdunnoughi [I]	31	8.5008	7.3268	8.60000	7.30000	6.00000

Table 2. Weighted mean DO and other statistics for DO concentrations by fish species ranked by the weighted mean DO value.

Species	No. Stations	Weighted Mean	Mean	Median	25th %tile	10th %tile
[43-002] - GOLDFISH [T]	262	4.1318	5.2274	6.50000	4.50000	2.80000
[34-001] - CENTRAL MUDMINNOW [T]	352	4.1623	5.4271	6.50000	4.80000	3.15000
[43-042] - FATHEAD MINNOW [T]	1174	4.4812	5.5290	7.10000	5.30000	3.60000
[47-006] - BLACK BULLHEAD [P]	498	4.6736	5.2842	6.90000	5.40000	4.00000
[43-003] - GOLDEN SHINER [T]	517	4.7203	4.9787	6.50000	5.00000	3.30000
[47-005] - BROWN BULLHEAD [T]	325	4.7991	5.3660	6.80000	5.40000	3.80000
[43-028] - SPOTTAIL SHINER [P]	30	4.8268	4.6567	6.00000	4.90000	3.60000
[74-003] - WHITE PERCH [ ]	43	4.9496	4.9614	6.30000	5.00000	3.20000
[43-045] - COMMON CARP X GOLDFISH [T]	105	4.9791	4.8686	6.50000	4.90000	3.50000
[47-013] - TADPOLE MADTOM [ ]	189	5.0569	4.9556	6.50000	5.20000	3.80000
[80-001] - SAUGER [ ]	39	5.0615	5.8667	7.60000	6.40000	5.40000
[77-012] - REDEAR SUNFISH [ ]	27	5.2204	6.0222	7.30000	6.10000	5.03000
[74-001] - WHITE BASS [ ]	64	5.2217	5.7188	6.80000	5.65000	4.50000
[43-001] - COMMON CARP [T]	2075	5.2995	5.8171	7.30000	6.00000	4.50000
[43-023] - REDFIN SHINER [ ]	622	5.3079	5.3991	6.90000	5.60000	4.20000
[77-010] - ORANGESPOTTED SUNFISH [ ]	386	5.3873	5.5105	7.40000	6.00000	4.50000
[37-003] - NORTHERN PIKE [ ]	65	5.3984	5.3754	6.90000	5.35000	3.83000
[37-001] - GRASS PICKEREL [P]	771	5.4259	5.6674	7.00000	5.60000	4.10000
[40-020] - CREEK CHUBSUCKER [ ]	65	5.4449	5.0969	6.80000	4.80000	3.70000
[47-004] - YELLOW BULLHEAD [T]	2591	5.5331	5.8874	7.40000	6.00000	4.50000
[40-018] - SPOTTED SUCKER [ ]	342	5.5496	5.5791	6.95000	5.70000	4.70000
[77-008] - GREEN SUNFISH [T]	4044	5.5742	5.9769	7.40000	5.90000	4.20000
[54-002] - BLACKSTRIPE TOPMINNOW [ ]	641	5.6034	5.1951	7.10000	5.60000	4.10000
[80-005] - BLACKSIDE DARTER [ ]	1003	5.6262	5.8214	7.30000	6.20000	5.00000
[85-001] - FRESHWATER DRUM [P]	176	5.6642	5.9935	7.60000	6.27500	4.94000
[77-013] - PUMPKINSEED SUNFISH [P]	798	5.6938	6.0121	7.30000	6.10000	4.60000
[77-007] - WARMOUTH SUNFISH [ ]	284	5.7176	5.7888	7.00000	5.80000	4.50000
[80-025] - LEAST DARTER [ ]	32	5.7540	5.3344	7.30000	6.20000	4.50000
[63-001] - TROUT-PERCH [ ]	158	5.7917	6.0652	7.60000	6.37500	5.30000
[77-001] - WHITE CRAPPIE [ ]	565	5.8141	5.7192	7.30000	6.00000	4.60000
[20-003] - GIZZARD SHAD [ ]	825	5.8202	6.0197	7.50000	6.10000	4.80000
[47-007] - FLATHEAD CATFISH [ ]	48	5.8245	6.1938	8.00000	6.80000	6.00000
[77-009] - BLUEGILL SUNFISH [P]	2889	5.8582	6.1255	7.50000	6.20000	4.90000

Table 2. Weighted mean DO and other statistics for DO concentrations by fish species ranked by the weighted mean DO value.

Species	No. Stations	Weighted Mean	Mean	Median	25th %tile	10th %tile
[77-006] - LARGEMOUTH BASS [ ]	2228	5.9103	6.1253	7.50000	6.30000	5.00000
[10-004] - LONGNOSE GAR [ ]	52	5.9175	6.5442	8.20000	7.10000	6.00000
[80-014] - JOHNNY DARTER [ ]	2913	6.0059	6.2295	7.60000	6.31000	5.00000
[40-016] - WHITE SUCKER [T]	4256	6.0484	6.1273	7.50000	6.20000	4.60000
[95-001] - BROOK STICKLEBACK [ ]	192	6.0538	6.0108	7.20000	5.60000	3.80000
[77-011] - LONGEAR SUNFISH [M]	1303	6.0558	6.1109	7.40000	6.20000	4.80000
[40-005] - QUILLBACK CARPSUCKER [ ]	375	6.0604	6.2428	8.00000	6.30000	4.80000
[43-043] - BLUNTNOSE MINNOW [T]	4304	6.0833	6.1582	7.60000	6.20000	4.80000
[70-001] - BROOK SILVERSIDE [M]	164	6.0842	6.0868	7.60000	6.40000	5.20000
[43-013] - CREEK CHUB [T]	4293	6.1248	6.1424	7.50000	6.10000	4.40000
[80-023] - ORANGETHROAT DARTER [ ]	450	6.1386	6.0576	7.40000	6.00000	4.40000
[43-035] - MIMIC SHINER [I]	180	6.2736	6.6972	8.10000	7.00000	6.10000
[80-011] - LOGPERCH [M]	961	6.2921	6.3048	7.50000	6.40000	5.40000
[47-002] - CHANNEL CATFISH [ ]	374	6.3442	6.2429	7.80000	6.50000	5.50000
[43-032] - SPOTFIN SHINER [ ]	1628	6.3794	6.2976	7.80000	6.50000	5.30000
[80-003] - YELLOW PERCH [ ]	148	6.3928	6.1054	7.60000	6.30000	5.25200
[43-024] - ROSEFIN SHINER [M]	606	6.4063	6.2957	7.70000	6.50000	5.30000
[77-003] - ROCK BASS [ ]	2251	6.4072	6.3763	7.80000	6.60000	5.50000
[43-025] - STRIPED SHINER [ ]	2742	6.4319	6.3580	7.70000	6.40000	5.10000
[80-004] - DUSKY DARTER [M]	46	6.4418	6.7022	7.60000	6.70000	5.80000
[01-006] - LEAST BROOK LAMPREY [ ]	162	6.4472	6.3673	7.90000	6.62500	5.10000
[43-009] - GRAVEL CHUB [M]	22	6.4669	6.6000	9.10000	7.60000	6.70000
[43-015] - SUCKERMOUTH MINNOW [ ]	625	6.5159	6.1645	7.90000	6.50000	5.40000
[43-034] - SAND SHINER [M]	1520	6.5214	6.5285	8.10000	6.90000	6.00000
[43-026] - COMMON SHINER [ ]	766	6.5332	6.2388	7.60000	6.40000	5.00000
[43-007] - BIGEYE CHUB [I]	91	6.5414	6.8659	8.50000	7.50000	6.20000
[77-005] - SPOTTED BASS [ ]	338	6.6085	6.7308	7.60000	6.42500	5.40000
[77-004] - SMALLMOUTH BASS [M]	1586	6.6104	6.5713	8.00000	6.80000	5.70000
[80-015] - GREENSIDE DARTER [M]	2405	6.6157	6.4821	7.80000	6.70000	5.50000
[43-044] - CENTRAL STONEROLLER [ ]	3853	6.6294	6.3416	8.00000	6.40000	5.00000
[43-044] - CENTRAL STONEROLLER [ ]	3853	6.6294	6.3416	8.00000	6.40000	5.00000
[77-002] - BLACK CRAPPIE [ ]	284	6.6345	5.7687	7.20000	6.00000	4.70000
[40-010] - GOLDEN REDHORSE [M]	1392	6.6966	6.5323	7.90000	6.70000	5.70000

Table 2. Weighted mean DO and other statistics for DO concentrations by fish species ranked by the weighted mean DO value.

Species	No. Stations	Weighted Mean	Mean	Median	25th %tile	10th %tile
[80-024] - FANTAIL DARTER [ ]	1920	6.6977	6.5064	7.90000	6.70000	5.50000
[43-021] - SILVER SHINER [I]	719	6.7098	6.6523	8.10000	6.90000	6.00000
[80-007] - SLENDERHEAD DARTER [R]	27	6.7104	6.6296	8.40000	7.02500	6.40000
[47-012] - BRINDLED MADTOM [I]	201	6.7257	6.5478	8.40000	7.30000	6.36000
[40-008] - SILVER REDHORSE [M]	258	6.7290	6.4643	7.90000	6.70000	5.76000
[80-016] - BANDED DARTER [I]	828	6.7564	6.7268	8.00000	6.90000	5.90000
[43-039] - SILVERJAW MINNOW [ ]	1550	6.8125	6.5634	7.90000	6.70000	5.30000
[43-031] - STEELCOLOR SHINER [P]	83	6.8197	6.4699	8.70000	7.40000	6.50000
[43-004] - HORNYHEAD CHUB [I]	255	6.8261	6.6009	8.00000	6.90000	5.99000
[43-020] - EMERALD SHINER [ ]	297	6.8326	6.5404	7.90000	6.40000	5.20000
[80-022] - RAINBOW DARTER [M]	2016	6.8488	6.6788	8.10000	6.90000	5.90000
[40-009] - BLACK REDHORSE [I]	482	6.9339	6.8943	8.20000	7.20000	6.40000
[40-011] - SHORTHEAD REDHORSE [M]	163	6.9547	6.6055	7.90000	6.80000	5.70000
[43-011] - BLACKNOSE DACE [T]	1965	6.9595	6.5343	7.80000	6.50000	4.70000
[40-015] - NORTHERN HOG SUCKER [M]	2502	7.0205	6.6912	8.00000	6.80000	5.80000
[43-016] - SOUTH. REDBELLY DACE [ ]	332	7.0376	6.5361	8.00000	6.50000	4.91000
[80-017] - VARIEGATE DARTER [I]	139	7.0680	7.0712	8.60000	7.60000	6.80000
[43-022] - ROSYFACE SHINER [I]	573	7.1774	7.1568	8.50000	7.50000	6.70000
[43-033] - BIGMOUTH SHINER [ ]	40	7.2239	6.1725	7.90000	7.00000	5.60000
[43-017] - REDSIDE DACE [I]	151	7.2335	7.0391	8.40000	6.75000	4.70000
[47-008] - STONECAT MADTOM [I]	623	7.4144	6.9350	8.30000	7.20000	6.30000
[43-005] - RIVER CHUB [I]	423	7.4902	7.2622	8.50000	7.50000	6.60000
[90-002] - MOTTLED SCULPIN [ ]	855	7.6656	7.0913	8.30000	7.30000	6.20000
[25-001] - BROWN TROUT [ ]	53	7.9166	7.9906	9.40000	8.40000	7.40000
[01-007] - AMER BROOK LAMPREY [R]	85	8.4789	8.0682	9.30000	8.40000	7.30000
[43-014] - TONGUETIED MINNOW [S]	35	8.6464	8.5314	9.75000	9.10000	8.38000
[25-002] - RAINBOW TROUT [ ]	59	8.6895	7.7805	9.00000	7.47500	5.40000

REPRODUCTIVE BIOLOGY
AND
EARLY LIFE HISTORY
OF
FISHES
IN THE
OHIO RIVER DRAINAGE

Ictaluridae—Catfish and Madtoms

VOLUME 3

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CHANNEL CATFISH

Ictalurus punctatus (Rafinesque)

Ictalurus, Greek: "fish cat"; *punctatus*, Latin: "spotted."

RANGE

Native range is central drainages of the U.S. into southern Canada, and possibly parts of the Atlantic coast; from west TX, northern Mexico along Gulf slope into peninsular FL.[1] Newly recorded from Lake Michigan drainage of IL.[105]

HABITAT AND MOVEMENT

Occupies a variety of substrates.[78,109] Occurs predominantly in streams, rivers, and big rivers in deep pools near cover or in areas with current over a firm sand or gravel, rocky bottom; also occupies the open waters of impoundments; avoids clear, cool upland streams and rivers.[1-4] Seeks deep pools, submerged logs, and overhanging banks by day, and at night moves to shallow areas to feed.[24,106] Spawners may not migrate into nearby rivers.[2,82] Prefers bendway and tailwater habitats of large rivers over main channel habitats.[87] Runoff (fraction of stream area consisting of runs) and water temperature account for nearly half the variability in biomass.[101] In IL, correlations for channel catfish 100 mm TL were not found; however, the presence of 300 mm fish was highly correlated with water velocity, percent instream cover, and percent pool.[103]

Tagging studies have shown varied and often discrepant movement patterns.[53] Approximately 50% of recaptured (tagged) fish moved less than 2.5 miles during a 2-year period; the remainder were evenly dispersed upstream and downstream with mean distances of movement of 5.1 and 5.6 miles, respectively. The greatest distances recorded were 70 miles downstream and 155 miles upstream.[67] Moves greater distances in the spring than in the fall, usually moving upstream in the spring and downstream in the fall.[56] Winter survival is high and may cause little loss in total body weight.[83]

DISTRIBUTION AND OCCURRENCE IN THE OHIO RIVER SYSTEM

Common to abundant[5,6,11] and distributed almost uniformly throughout the Ohio River.[45] In KY, generally distributed and common throughout the state.[3] Occurs throughout IL, abundant in larger streams and major rivers.[4] In PA, occurs in the Allegheny and Monongahela Rivers.[7] In WV, occurs in the Little Kanawha and Kanawha Rivers below the Falls, possibly native but may be introduced above the Falls.[8,80] Widespread and abundant in TN.[47] Present in most Tennessee River system tributaries of AL,[109] western NC,[51] and VA.[78]

SPAWNING

Location

In cavities under logs, rocks, undercut banks, or drift;[9,10,25,27,108] in burrows of muskrats and beavers;[25] in artifical nests, such as nail kegs, in ponds;[32] at depths ranging from a few inches to several feet;[9,10] also in small streams;[5] sometimes in very swift water.[31] Successful spawning in cans has been reported at depths of 5 m.[81]

Season

Late spring in NY;[9] June–August in upper Mississippi River;[65] March and April, but mostly June and July in SC;[14] June and July in OK;[15] early to late June in WI;[108] prior to mid-June in SD;[10] May to July in MO[25] and AR;[24] sometimes with two spawning peaks per season.[31] Yolk-sac larvae and early juveniles were collected mid-May through August with peaks in June and July in the Tennessee and lower Ohio Rivers;* gravid females collected as late as August in AL.[109] Begins in late May and peaks in late June–early July in VA.[78]

Temperature

Between 21 and 29.4°C;[2,9,18,24,53,65] in TX, usually between 21 and 27°C, with most spawning at 21.7°C, but spawning occurred at 15.9°C, after the water temperature had exceeded 21°C;[19] optimum about 27°C;[10] in the low to mid-70s (F) in WI.[88] Based on yolk-sac larval and early juvenile collections, estimated range of spawning temperatures is 19–31°C (optimum 22–28°C).*

Fecundity

Females 1–4 lbs produced approximately 4000 eggs; estimated fecundity for a female 660 mm was 34,500 eggs;[2] other reports of 1052[34] to 70,000[18] and 1500 to 52,000.[28,41,42,53] In IA, number of eggs per mature

Philip W. Smith

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