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STATE OF ILLINOIS
Pollution Control Board

ILLINOIS POLLUTION CONTROL BOARD

IN THE MATTER OF:	)	
	)	
PROPOSED AMENDMENTS TO	)	R04-25
DISSOLVED OXYGEN STANDARD 35 ILL.	)	(Rulemaking - Water)
ADM. CODE 302.206	)	

EXHIBIT LIST

First Hearing: June 29, 2004, Chicago

Exhibit 1: "An Assessment of National and Illinois Dissolved Oxygen Water Quality Criteria" James E. Garvey and Matt R. Whiles (Apr. 2004)

Exhibit 2: "Ambient Water Quality Criteria for Dissolved Oxygen" USEPA (Apr. 1986)

Exhibit 3: Resume of Dennis Streicher

Exhibit 4: Copies of letters from Dennis Streicher to various organizations concerning the proposed rulemaking

Exhibit 5: Resume of James E. Garvey

Exhibit 6: Resume of Matt R. Whiles

Exhibit 7: From R02-19, written testimony of Robert J. Sheehan & Table 1 "Spawning periods for fishes in Illinois"

Exhibit 8: "Influences of Hypoxia and Hyperthermia on Fish Species Composition in Headwater Streams" Martin A. Smale and Chalres F. Rabeni (1995)

Second Hearing: August 12, 2004, Springfield

Exhibit 9: Pre-filed Testimony of Dr. James E. Garvey, with attached July 2004 report entitled "Long Term Dynamics of Oxygen and Temperature in Illinois Streams" by Dr. Garvey.

Exhibit 10: Electronic comments by Gary Chapman in the margins of "An Assessment of National and Illinois Dissolved Oxygen Water Quality Criteria" James E. Garvey and Matt R. Whiles (Apr. 2004)

Exhibit 11: One-page hard copy of e-mail sent July 22, 2004 at 8:52 a.m. from Roy M. Harsch regarding IEPA "implementation rules"

Exhibit 12: Letter entitled ""'Fight Effort to Lower Fox Oxygen Criteria," from David J. Horn, appearing on the Opinion page of the *Daily Herald*

Exhibit 13: Letter dated July 30, 2004 from David L. Thomas, PhD, Chief of the Illinois Natural History Survey to Lieutenant Governor Pat Quinn

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DISSOLVED OXYGEN STANDARD	)	
35 Ill. Adm. Code 302.206	)	

NOTICE OF FILING

TO: See Attached Service List

PLEASE TAKE NOTICE that on **Monday, August 2, 2004,** we filed the attached **Written Testimony of Dr. James E. Garvey Fisheries and Illinois Aquaculture Center Southern Illinois University, Carbondale, Illinois** with the Illinois Pollution Control Board, a copy of which is herewith served upon you.

Respectfully submitted,

By: Sheila H. Deely
One of Its Attorneys

Roy M. Harsch
Sheila H. Deely
GARDNER CARTON & DOUGLAS LLP
191 N. Wacker Drive – Suite 3700
Chicago, IL 60606
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THIS FILING IS SUBMITTED ON RECYCLED PAPER

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STATE OF ILLINOIS
Pollution Control Board

BEFORE THE ILLINOIS POLLUTION CONTROL BOARD

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

WRITTEN TESTIMONY OF DR. JAMES E. GARVEY
FISHERIES AND ILLINOIS AQUACULTURE CENTER
SOUTHERN ILLINOIS UNIVERSITY, CARBONDALE, ILLINOIS

Thank you for the opportunity to testify before the Illinois Pollution Control Board during this second hearing in Springfield, Illinois. As I noted in the first hearing before the Board, I am an Assistant Professor in the Fisheries and Illinois Aquaculture Center and Department of Zoology at Southern Illinois University, Carbondale. My research interests revolve around fish and aquatic ecology in lakes and streams. The Illinois Association of Wastewater Agencies asked Dr. Matt Whiles and me to assess the current Illinois state dissolved oxygen standard which 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. In our report, we concluded that this standard is unrealistic for most streams in the state, because oxygen concentrations fluctuate both seasonally and daily, often declining below the state standards. These conclusions were based largely on published studies summarizing research conducted outside of Illinois in addition to my unpublished data in tributaries of the Ohio River, which were discussed during the first hearing.

Proposed Recommendations

To make the state general use standard more realistic, Dr. Whiles and I recommended that during March 1 through June 30 when early life stages of sensitive species are present, a minimum identical to the current Illinois standard of 5 mg/L and a seven-day mean of 6 mg/L should be adopted. During warmer, productive months and the remainder of the year when species with sensitive early life stages have largely completed reproduction, we recommended a minimum of 3.5 mg/L and a seven-day mean minimum of 4 mg/L. It is important to emphasize that we included running means to avoid chronically low dissolved oxygen concentrations. For the proposed standard to be supported, minima must not be violated, ensuring that concentrations never approach critically lethal limits.

Analysis of Illinois Stream Data

In response to questions about fluctuations of oxygen in Illinois surface waters, I analyzed the applicability of both the current state standard and the proposed standard to eight Illinois streams, in which dissolved oxygen and temperature were intensively monitored. My analysis is attached as Exhibit 1. I was made aware of these data during a meeting with the USEPA on June 18, 2004. It is my understanding that the United States Geological Survey (USGS) and Illinois Environmental Protection Agency (IEPA) began collecting these data to address concerns about the applicability of the current state standard to streams in the state. I requested these data from Paul Terrio, a hydrologist with USGS, shortly following the first hearing. I also reviewed oxygen and temperature data in other reports for streams in Illinois. I have summarized my analysis of these data in a recent report submitted to the Illinois Association of Wastewater Agencies and submitted as exhibit ##. Paul Terrio (USGS), Robert Mosher (IEPA), and Matt Whiles (Southern Illinois University) have provided comments on this report that I have incorporated into the final draft. These long-term data are unprecedented. I am aware of no other similarly comprehensive data set for streams of the Midwestern United States. We now have access to robust data that will allow us to ground truth the proposed dissolved oxygen standards.

The eight, intensively studied stream reaches were North Fork Vermilion River near Bismarck, Middle Fork Vermilion River near Oakwood, Vermilion River near Danville, Lusk Creek near Eddyville, Mazon River near Coal City, Rayse Creek near Waltonville, Salt Creek near Western Springs, and Illinois River near Valley City. During late summer 2001 through fall 2003, semi-continuous dissolved oxygen and temperature data were collected by IEPA and USGS. The stream segments varied widely in physical characteristics, surrounding land use, and latitude. Five of the eight stream segments are currently considered impaired and included on the most recent 303-d list compiled by IEPA. The nature of impairment varies from nutrient enrichment in Rayse Creek to mercury and PCB contamination in the Illinois River.

Dissolved Oxygen Patterns in Illinois Streams

The results from this analysis uphold the conclusions of the Garvey and Whiles report. As expected, dissolved oxygen concentrations declined in all streams during summer, with diurnal fluctuations varying among them. All eight streams violated the Illinois state standard, although violations occurred as infrequently as 1% of days and as frequently as 65% of days. Among the unlisted, unimpaired stream segments, oxygen dynamics varied widely, with Lusk Creek, a functioning stream in a forested watershed, regularly violating the Illinois standard of 5 mg/L during 22% of days. In two of the impaired, 303-d listed streams, the Illinois standard was violated frequently, with concentrations often declining below 2 mg/L, which is regarded to be lethal for many aquatic organisms. However, in other listed streams, dissolved oxygen concentrations were typically greater than the 5 mg/L minimum.

We might expect that nutrient enrichment is the primary factor affecting dissolved oxygen dynamics. Streams with greater nutrient loading should have lower oxygen. However, Salt Creek, an impaired stream with low biotic integrity and high nutrient enrichment, had higher average dissolved oxygen concentrations than the Mazon River, which was only listed for PCB and pathogen contamination. Nutrient enrichment must interact with other factors such as stream physical habitat to affect oxygen dynamics.

Application of the Proposed Standard

Adoption of the proposed standard greatly reduced the number of violations in unimpaired streams such as Lusk Creek while still capturing violations in impaired streams. In fact, the proposed standard increased the frequency of violations in two of the severely oxygen-impaired streams and identified the time period when oxygen problems occurred. It may be tempting to regard Lusk Creek as an intermediate between a functioning and an impaired system and suggest that its frequent violations of the current state standard are a warning signal. However, this is quite far from the truth. This stream segment is in the Lusk Creek Wilderness area of the Shawnee National Forest and is considered to be in a pristine state, with a highly regarded, intact, and diverse fish and macroinvertebrate assemblage. A concern of the Board during the first hearing was that minimum oxygen concentrations of 3.5 mg/L which occurred during summer in Lusk Creek would negatively affect summer-spawned, early life stages of resident species. It is quite clear, given the robust assemblage in this system that natural, summer declines in dissolved oxygen concentration below the state mandated 5 mg/L and occasionally reaching 3.5 mg/L did not negatively affect fishes reproducing during this time. Lusk Creek demonstrates that the seasonally appropriate proposed standard protects both spring and summer reproducing species.

Temperature Effects

Dissolved oxygen concentrations were quantified in a pooled area of Lusk Creek as recommended in the implementation guidelines of the Garvey and Whiles report. It is in this area that we would expect to encounter the most conservative dissolved oxygen concentrations. In contrast, the Middle Fork of the Vermilion River, in which oxygen concentrations were consistently the highest, had a logger located about 100 m below a riffle area, where we would expect oxygenated water to be abundant. Although it may be argued that Lusk Creek is a southern Illinois stream and warm temperatures may be responsible for declines in oxygen during summer, dissolved oxygen concentrations were lowest at intermediate summer temperatures, indicating that it is not the seasonal maxima of streams that reduce oxygen concentrations. Further, I found no substantive differences in temperature among streams across the north-south gradient in the state. These data effectively show that the proposed standard effectively captures oxygen dynamics that occur in natural, fully functioning Illinois streams such as Lusk Creek. A revised general use dissolved oxygen standard in Illinois such as that proposed by Garvey and Whiles is needed.

Habitat Modification

Some investigators have argued that artificially pooling streams or rivers by building dams will reduce oxygen and therefore negatively affect resident species. Recent reports in the Fox and DuPage Rivers have shown that pooled areas of streams violate the current standard more than open reaches and that fish composition differs between them. The problem with implicating violations of the current dissolved oxygen standard as responsible for altering or degrading species composition in pooled reaches is that the habitat of the river changes as well as the oxygen dynamics. In short, flow declines, sedimentation increases, and more fish that rely on accumulation of organic matter and open water will prosper. Oxygen declines because of the increased biochemical oxygen demand of the sediment and increased retention time of the water. As long as oxygen concentrations remain above the proposed standard in pools, species adapted to pool conditions will be abundant while flow-dwelling species will be rare or absent. Of course, if oxygen concentrations decline below the proposed standards, even species adapted to pooled conditions will cease to persist. Garvey and Whiles recommend monitoring pooled areas of natural streams, because of their lower expected oxygen concentration.

The eight intensively monitored streams provide more insight into the problem of teasing apart changes among habitat, oxygen, and other water quality parameters. Across the streams, no relationship existed between biotic integrity scores and oxygen minima as estimated by frequency of violations of either the current or proposed standards. Typically, integrity scores are closely related to measures of habitat quality, which include factors such as a stream's substrate, habitat diversity, and riparian vegetation. Habitat quality fosters the diversity of organisms by providing food, shelter, and reproductive areas. As such, it appears that habitat rather than oxygen primarily influences species composition. Reduced oxygen concentrations and increased diurnal fluctuations are a secondary effect of habitat degradation or modification.

Comparison between Oxygen and Ammonia Standards

The most conservative ammonia standards for the state are designed to protect early life stages of all fish species for the duration of spawning, which may extend through October. In the first hearing, I was asked why the most conservative proposed oxygen standard extended only through June, while the conservative ammonia standard is extended through the entire reproductive cycle of fishes. Dynamics of total ammonia and oxygen differ in streams. The total concentration of ammonia in streams typically depends on discharge and does not vary naturally on a seasonal basis. Further, the toxicity of total ammonia increases with increasing temperature during summer, necessitating stringent standards for all early life stages of fish, particularly those that are produced during summer. Conversely, the data summarized in my report clearly show that oxygen concentrations in the pooled area of a natural, functioning stream do decline well below the current standard during summer but not below the proposed, seasonally appropriate one. As I noted earlier, because the community in such a stream is intact, summer-spawning fish species must reproduce successfully during this time, demonstrating that the proposed standard better reflects natural fluctuations in this system while protecting resident fishes.

Review by Gary Chapman, Author of the National Criteria Document

To determine whether the seasonal standard was consistent with the United States Environmental Protection Agency's 1986 National Criteria Document, I solicited a review from its author, Gary Chapman, following the first hearing. He had provided a review to the Water Quality Section of the Illinois Chapter of the American Fisheries Society on June 28, 2004 and forwarded this review to me. To summarize, he felt that the timing of seasonal standards depended on a working knowledge of the fish community in the state and should be "left to the experts". His largest concern was the omission of a 30-day running average of 5.5 mg/L in the proposed standards. Although I still think that such a standard is generated over such a large time scale that it is generally biologically meaningless, it may be worth considering as part of the proposed standards given his expert opinion. His other comments were relatively minor, revolving around the interpretation of recent findings in dissolved oxygen research. He supported our implementation recommendations and thought that they should be adopted. Regarding protection of fish during summer, he commented: "I have seen no data over the past 20 years that would indicate that the 3 mg/L minimum would not be adequately protective against lethal effects".

Chemical Interactions with Oxygen

In the first hearing, I was asked about the potential effects of low dissolved oxygen concentrations on water chemistry in streams and lakes. To the best of my knowledge, reduction–oxidation chemical reactions are unaffected by oxygen concentrations until they decline far below the proposed 3.5 mg/L minimum.

Conclusions

In summary, much more is known about fluctuations in oxygen and temperature in streams in the state of Illinois than during the first hearing. Results of the new analysis confirm the conclusions of the Garvey and Whiles report for other aquatic systems. Semi-continuous measurements in pristine, forested Lusk Creek were quantified in the appropriate location and provide a useful baseline by which general expectations for dissolved oxygen concentrations can be generated. Although the proposed standards may be generally applied across the state, either regional standards or a stream classification system should be adopted to better reflect use expectations. Such a system will need to incorporate biotic integrity, habitat quality, and water quality goals rather than focusing solely on dissolved oxygen expectations. Given the data from the eight Illinois streams and other systems in the state, the likelihood that the current dissolved oxygen standard will not apply to many of these systems and produce false violations is confirmed. Adopting the proposed standard and standardized monitoring outlined in the Garvey and Whiles report will not only reduce the probability of detecting a false violation in functioning streams but it will provide robust, long-term water quality data sets for improving management of surface waters in the state.

CERTIFICATE OF SERVICE

The undersigned certifies that a copy of the foregoing **Notice of Filing** and **Written Testimony of Dr. James E. Garvey Fisheries and Illinois Aquaculture Center Southern Illinois University, Carbondale, Illinois** was filed by hand delivery with 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 191 N. Wacker Drive, Chicago, Illinois on Monday, August 2, 2004.

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R2004-025

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Exhibit 1

Long term dynamics of oxygen and temperature in Illinois streams

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Department of Zoology
Southern Illinois University
Carbondale, IL 62901-6511

Prepared for Illinois Association of Wastewater Agencies

July 2004

Introduction

Garvey and Whiles (2004) concluded that the current Illinois dissolved oxygen standard is unrealistic, because naturally fluctuating dissolved oxygen concentrations in surface waters of the state should occasionally or frequently decline below the critical minimum. Specifically, the Illinois general use standard requires that dissolved oxygen concentrations within surface waters of the state never decline below 5 mg/L and remain above 6 mg/L at least 16 hours each day. Although the Garvey and Whiles (2004) report cited published studies showing that dissolved oxygen is heterogeneous within aquatic systems and that concentrations in natural systems often decline below 5 mg/L during summer, little stream data within Illinois were available to support this conclusion. Since that report was completed, a continuous monitoring data set has become available (Paul Terrio, United States Geological Survey and Robert Mosher, Illinois Environmental Protection Agency, unpublished data) in which dissolved oxygen concentrations and temperatures were quantified semi-continuously in eight stream reaches during a two-year period. These streams were distributed both along a north-south gradient and a gradient of land-use (i.e., urban, agriculture, and forest). Quality of streams was also considered in the selection of monitoring sites, with the streams varying from fully functioning to impaired, with some included on the 2004, IL-EPA 303d list.

I obtained these data and analyzed them relative to the current IL dissolved oxygen standard and the standards proposed in Garvey and Whiles (2004). Following the National Criteria Document (Chapman 1986), Garvey and Whiles (2004) recommended:

- A minimum of 5.0 mg/L spring through early summer (i.e., March 1 through June 30)
- A 7-d mean of 6.0 mg/L spring through early summer (i.e., March 1 through June 30)
- A minimum of 3.5 mg/L the remainder of the year (i.e., July 1 through February 28 or 29)
- A 7-d mean minimum of 4.0 mg/L the remainder of the year (i.e., July 1 through February 28 or 29)

In this report, I evaluate how the current and proposed standards characterize streams in the state relative to season, stream quality and geographic location. Oxygen and temperature dynamics are interpreted in light of the extant biotic communities and the location of the logger within each stream.

Study Sites

North Fork Vermilion River near Bismarck, IL. This east-central Illinois stream reach (IL-EPA, BPG-09) averages 20-m wide at base flow and is 0.3- to 1-m deep at the location of the logger. Total surface water for this stream is 1.14 km^2. The drainage for this stream reach is primarily agricultural. Substrate is gravel riffle with vegetation occurring in the channel during summer. Annual mean stream flow is 8.8 m^3/s. This stream was 303-d listed as a high priority for impairment by pathogens.

Middle Fork Vermilion River near Oakwood, IL. This east-central, "wild and scenic river" stream site (IL-EPA, BPK-07) is about 30-m wide, with 5.4 km^2 surface area at normal flows. The logger was placed at an area 1-m deep near a rock riffle on the outside of a gradual bend. Some growth of aquatic vegetation occurs in the riffle during late summer. Land-use in the area is primarily agricultural. Annual mean stream flow is 11.4 m^3/s.

Vermilion River near Danville, IL. This stream site (IL-EPA, BP-08) in east-central Illinois is located in an area with about 91% agricultural and 4% urban land-use. This stream has a gravel and sand substrate and is about 50-m wide at base flow. Surface area of this stream is 24.3 km^2. Depth at logger location was 2-3 meters at base flow. Annual mean stream flow is 28.9 m^3/s.

Lusk Creek near Eddyville, IL. Located in the southeastern - Illinois Shawnee National Forest and draining the Lusk Creek Wilderness area, this 0.22-km^2, meandering stream (IL-EPA, AK-02) has a bed composed of sand, gravel, cobble, and bedrock. The site was located in a pool of about 2-m deep and 10-m across. Land use is 76% forested and about 18% agricultural. Woody debris and vegetation occur in the channel; surface flow between the pool and the channel can become disconnected. Annual mean stream flow is 1.7 m^3/s.

Mazon River near Coal City, IL. This 17-km^2 north-central Illinois river (IL-EPA, DV-04) is listed as impaired for PCBs and pathogens. Agriculture dominates the land-use (94%), with urban being the next most abundant class (4%). Stream width averages at 50 m, with vegetation growing in the channel and on the rock and gravel riffle at the site. Annual mean stream flow is 9.9 m^3/s.

Rayse Creek near Waltonville, IL. Although this southern-Illinois stream (IL-EPA, NK-01) resides in a predominantly agricultural watershed, about 17% of the surrounding land is forested. The stream site is a slow moving and turbid pool, with a flashy hydrograph and much debris. The stream will dry during periods of low precipitation. The reach is about 6-m wide and < 1 m deep, although these measurements vary widely with stream flow. This 0.62-km^2 stream is a tributary of the Big Muddy which is impounded downstream to form Rend Lake. Annual mean stream flow is 2.5 m^3/s. It is 303-d listed with nutrients, low pH, enrichment, pathogens, and suspended solids as causes of impairment.

Salt Creek near Western Springs, IL. This is the northernmost stream (IL-EPA, GL-09) located primarily in the urban (80% of land use) Chicago area. Surface area is about 7 km^2 and width averages 23 meters. The site has a partial riffle with heavy aquatic growth occurring during summer. Annual mean stream flow is 3.8 m^3/s. This stream segment also is 303-d impaired, with nutrients, salinity, and pathogens as causes.

Illinois River near Valley City, IL. This large segment (1,003 km^2 surface area; IL-EPA, D-32) in east-central Illinois averages at 200-m wide. Location of logger was about 8-m deep. Annual mean stream flow is 643.5 m^3/s. Surrounding land use is about 77% agriculture with the remainder being approximately half forested and half urban. This segment is also 303-d listed for metal and PCB contamination.

Data Collection and Analysis

Data collection was a joint effort between the USGS and IEPA. At each stream site, temperature and dissolved oxygen concentration (mg/L) were quantified every 30-minutes during late summer 2001 through fall 2003. Monitors were typically mounted in areas where they remained continually submerged, including bridge piers. Depth of loggers ensured that they were 3-5 centimeters below the point of zero flow in the streams. At routine or high flow, probes were likely at > 50% depth.

For each stream, I calculated daily averages and daily minima. For the Illinois standard, I determined the hours within each day that dissolved oxygen concentration was less than 5 mg/L and 6 mg/L.

For the proposed standard (Garvey and Whiles 2004), a minimum dissolved oxygen concentration was defined as the lowest allowable concentration during any given day. A 7-day mean was derived by generating daily averages and then determining a running average across 7 days. Maximum water concentrations that exceeded air saturation were corrected (i.e., decreased) to air saturation values. Seven-day mean minima were calculated by generating a running mean of daily minima across 7 days.

Within the proposed standard, seasons reflect times when most early life stages of warmwater fishes (i.e., eggs, embryos, and larvae, typically 30-d post spawning) are either present (March through June) or absent (July through February) in Illinois waters. We hypothesized that warmwater species that spawn later during summer should have adaptations for naturally occurring reductions in dissolved oxygen concentrations expected to occur during warm months. Hence, in systems in which dissolved oxygen concentrations declined during summer near the proposed minimum, we should still expect the stream to be unimpaired (i.e., unlisted) with a robust biota. Those that frequently declined below the minima would likely show impairment and be 303-d listed by IL-EPA.

Results

As expected, dissolved oxygen concentrations declined in all streams during summer, with each segment violating the current Illinois standard as infrequently as 2% and as frequently as 65% of the days across the two-year period. These patterns were not clearly delineated by latitude, stream quality, or stream size.

North Fork Vermilion River near Bismarck, IL. Although 303-d listed, this stream segment declined below 5 mg/L only 1% of days (Figure 1; Table 1). This stream only violated the rule of declining below 6 mg/L no more than 8-h each day only 2% of days as well (Figure 1; Table 1, 2). With the proposed standard, the violations of the spring and summer critical minima and 7-d means declined to near zero (Table 1).

Middle Fork Vermilion River near Oakwood, IL. This full attainment stream site below a riffle area had the consistently highest dissolved oxygen concentrations of the eight segments (Figure 2). It still violated the Illinois standards on greater than 1% of days (Table 1, 2). With the proposed standard, no violations occurred during either season (Table 1).

Vermilion River near Danville, IL. Although unlisted, this stream site violated the Illinois standard on 6% and 7% of days for the 5 and 6 mg/L rules, respectively (Figure 3; Table 1, 2). Adoption of the proposed standard reduced the frequency of violations (Table 1). However, violations still occurred during the summer months – particularly the 7-d mean minimum of 4 mg/L when this rule was violated 9% of the time (Table 1). This suggests that dissolved oxygen concentrations in this reach may be chronically low during summer, requiring some restoration efforts.

Lusk Creek near Eddyville, IL. This heterogeneous stream residing in a predominantly forested watershed very frequently (22% and 32% of days) violated the current state standard (Figure 4; Table 1, 2). Adoption of the proposed standard greatly reduced the frequency of violations during spring months; however, the 7-d mean minimum of 4 mg/L was violated 3% of days (Table 1). The critical minimum during summer of 3.5 mg/L was violated 1% of dates (Table 1). However, the minimum dissolved oxygen concentration typically declined by < 0.5 mg/L below this threshold (Figure 4).

Mazon River near Coal City, IL. This 303-d listed stream frequently experienced very low dissolved oxygen concentrations during summer (Figure 5), violating both the Illinois standard and the proposed standard (Table 1, 2). The higher frequency of violations of the proposed summer standards suggests that summer eutrophication is a problem in this stream (Table 1).

Rayse Creek near Waltonville, IL. This impaired stream violated the Illinois standard and the proposed standard most frequently (Figure 6; Table 1, 2). The proposed 7-d mean minimum of 4 mg/L was in fact more sensitive than the Illinois standard to violations in this system (Table 1). Spring dissolved oxygen concentrations were chronically below 6 mg/L and often declined below the proposed spring minimum of 5 mg/L (Table 1; Figure 6). Dissolved oxygen concentrations often declined to chronically low levels (< 2 mg/l) during summer through fall (Figure 6).

Salt Creek near Western Springs, IL. This 303-d listed stream violated the Illinois standards of 5 mg/L and 6 mg/L on 9% and 16% of days, respectively (Table 1, 2; Figure 7). When the proposed standard was applied, violations declined somewhat. The majority occurred during the spring months when the 5 mg/L critical minimum was violated 6% of days (Table 1).

Illinois River near Valley City, IL. This largest of the stream segments violated the current Illinois standard of 5 mg/L on 11% of days and 6 mg/L on 21% of days (Table 1, 2; Figure 8). Violations declined with the proposed standard, although violations continued to occur most frequently during the spring. The 7-d mean minimum of 6 mg/L was violated 16% of days (Table 1).

Temperature-Dissolved Oxygen Relationships among Streams. Lusk Creek, the southernmost stream, was warmest during winter months, typically remaining above freezing (Figure 9). During summer months, considerable overlap in monthly average temperatures occurred, although Salt Creek and North Fork Vermilion River had lower average temperatures. Mazon River, another northern system, had consistently warmer averages than its counterparts. Differences in monthly averages among all streams were $< 4^{\circ}C$ during summer (Figure 9), with the greatest differences occurring between Rayse (the warmest) and Salt (the coolest).

Temperature and dissolved oxygen concentration were negatively related in all streams (Table 3). However, the strength of the relationship varied among streams, with temperature only explaining 33% of the variation in oxygen in the Mazon River and 84% in the Illinois River (Table 3). In Lusk Creek, an apparently sound system with dissolved oxygen concentrations that approached the proposed critical minimum of 3.5 mg/L during summer, low oxygen occurred most frequently during intermediate (25°C), rather than high, summer temperatures (Table 4). This refutes the assumption that the greatest oxygen declines occur during the warmest temperatures in streams. Rather periods of reduced flow coupled with intermittently high production in the pool of Lusk Creek was responsible for the observed patterns.

Discussion

My goal was to identify expected seasonal and diel oxygen curves for streams in Illinois by which we can set realistic standards. With the current Illinois standard, all streams within the state will likely produce violations. The frequency of violations of the current Illinois standard does not appear to be associated with stream impairment. To illustrate, a forested, functioning stream (i.e., Lusk Creek) violated the current standard far more frequently than two of the listed streams (i.e., North Fork Vermilion and Salt Creek). The proposed standards greatly reduced (although did not eliminate) the probability of a violation in Lusk Creek, while not greatly reducing the violations in the clearly oxygen-impaired Rayse Creek and Mazon River. In fact, the proposed standard increased the frequency of violations for Rayse Creek, and provided a seasonal context for interpreting the violation. Land use and alteration of the watershed in addition to flow likely are major factors influencing the oxygen dynamics in these streams, and the proposed standard would lend insight into the degradation of the biota within them.

Implementation of the proposed oxygen standards and interpretation of the oxygen dynamics resulting from monitoring depend greatly on the location of the probes. Garvey and Whiles (2004) recommend placing loggers in pools at two-thirds depth to ensure that areas with the greatest oxygen reductions are sampled. The loggers used in this study were typically at depths > 50% of the water column in areas where they could be conveniently deployed (Paul Terrio, personal communication). Thus, the largely microbial oxygen demand of stream bottoms was likely integrated into oxygen dynamics in many of the deeper stream sites.

Although the recommendation of logger depth was generally upheld, longitudinal location of loggers varied among streams. For example, the least violations of either the current or proposed oxygen standard occurred in the Middle Fork Vermilion River, which is a highly valued stream resource. However, the logger at this site was placed below a riffle. High gaseous oxygen exchange with the atmosphere may have elevated dissolved oxygen concentrations relative to an area with slower, less turbulent upstream flow. Conversely, in small, intermittently flowing Lusk Creek, the logger was placed in a pool with surface flow that becomes disconnected from the stream. In Garvey and Whiles (2004), this is considered the best location for quantifying oxygen dynamics because it provides a clear picture of the "worst case" of oxygen declines in a stream. Clearly, the heterogeneous vertical and horizontal distribution of oxygen within stream sites will render standardization challenging. Further, the dynamic effects of factors such as flow, geomorphology, geology, groundwater, shading, sediment, land use, and temperature will make interpretation of resulting oxygen curves a daunting task.

The Garvey and Whiles (2004) report did not develop standards unique to cool and warm water assemblages in the state. Although some temperature differences did appear to occur across the latitudinal gradient in the state, they appeared to be most pronounced during winter when oxygen stress is unimportant rather than during summer. During summer, slightly warmer conditions occurred in southern streams, particularly in small Lusk Creek, which has the lowest average flow. However, given that the lowest oxygen concentrations occurred at intermediate summer temperatures, the linkage between oxygen stress and high temperature stress for resident organisms appears to be relatively unimportant.

Rather than linking temperature and oxygen, understanding the relationship between flow and oxygen will likely be more informative for predicting effects on resident organisms. As noted earlier and in Garvey and Whiles (2004), pooled areas of streams and rivers, albeit natural or artificial, should have lower oxygen concentrations and should be targeted for monitoring. These sites will elicit the most conservative estimate of oxygen dynamics in a stream reach. Recent studies in the Fox River and DuPage River systems support this, in which oxygen concentrations were typically lower in the pooled portions (Santucci and Gephard 2003; Hammer and Linke 2003). In pooled areas, species with adaptations to increased siltation, reduced flow, and increased open water are abundant while flow-dwelling species are rare or absent. In artificially pooled reaches, altered habitat rather than reduced oxygen likely is ultimately responsible for shifts in the community. Aquatic life adapted to these modified, lentic environments will persist whereas species adapted to flowing water will not be present because the appropriate flow and substrate will be unavailable. Of course, if oxygen concentrations in pools do not meet the proposed standards for aquatic life outlined in Garvey and Whiles (2004), few organisms will be able to persist, regardless of habitat adaptations.

Conclusions

I have summarized the most comprehensive, long-term dissolved oxygen and temperature data set available in the state of Illinois and perhaps for streams in general. It is clear that the proposed standards better capture oxygen violations in truly impaired streams (i.e., those with modified biota such as Rayse Creek) relative to fully functioning streams such as Lusk Creek with high quality habitat and a diverse aquatic biotic assemblage. If the frequent violations of the Illinois standard were biologically meaningful, then Lusk Creek would have a greatly reduced or modified assemblage and would be listed as impaired. This is not the case and the frequent declines in dissolved oxygen concentration approaching the proposed summer minimum within the pools of this system during summer do not compromise spawning fishes or other organisms. As noted in Garvey and Whiles (2004), those species reproducing during summer clearly have adaptations for natural fluctuations in oxygen that occur during this time of year. Although it may be argued that the southern Lusk Creek is much warmer and thus may have a warm-water assemblage adapted to naturally low oxygen, the apparently minor (< 4°C average) differences in stream temperatures across the state coupled with weak oxygen-temperature relationships makes this argument tenuous. More likely, modifications to streams that alter both surface and below-ground flow and habitat quality will greatly affect the composition of stream communities. Of course, strongly impaired, enriched streams which frequently violate the proposed standard will have high incidences of oxygen stress and loss of aquatic life.

References

Chapman, G. 1986. Ambient water quality criteria for dissolved oxygen. EPA 440/5-86-003, United States Environmental Protection Agency, Office of Water Regulations and Standards, Washington, DC.

Garvey, J.E., and M.R. Whiles. 2004. An assessment of national and Illinois dissolved oxygen water quality criteria. Final Report. Prepared for the Illinois Association of Wastewater Agencies. Southern Illinois University, Carbondale.

Hammer, J., and R. Linke. 2003. Assessments of the impacts of dams on the DuPage River. Final Report. The Conservation Foundation.

Santucci, V.J., Jr., and S.R. Gephard. 2003. Fox River fish passage feasibility study. Final Report. Max McGraw Wildlife FOudnation. Submitted to Illinois Department of Natural Resources.

Table 1. Proportion frequency of days in which the current Illinois standard and the proposed standards were violated in each stream reach during late summer 2001 through fall 2003. Running means were only generated if seven contiguous days of data were present in the data set. For the proposed standard, spring is defined as March through June and other as July through February. Number of days is the number of days by which either a critical minimum was determined or a mean with seven preceding dates was available.

	Illinois Standard Minima			Proposed Minima				Proposed 7-d running averages			
Stream	IL <5	IL <6	N days	<5 spring	< 3.5 other	Spring days	Other days	Spring mean < 6	Other < 4 mean	Spring days	Other days
*NF Vermilion near Bismark	0.01	0.02	751	0	0	231	520	0	0.01	190	369
MF Vermilion near Oakwood	0.01	0.02	574	0	0	140	434	0	0	132	390
Vermilion near Danville	0.06	0.07	458	0	0.04	84	374	0	0.09	66	250
Lusk near Eddyville	0.22	0.32	653	0.01	0	204	449	0	0.03	182	429
*Mazon near Coal City	0.17	0.15	606	0.05	0.11	181	425	0.05	0.18	152	335
*Rayse near Waltonville	0.62	0.65	523	0.13	0.7	139	384	0.23	0.78	96	380
*Salt at Western Springs	0.09	0.16	590	0.06	0.02	208	382	0	0	167	365
*Illinois River at Valley City	0.11	0.21	638	0.03	0.02	240	398	0.16	0.03	159	334

*Denotes 303-d listed stream segment (2002 cycle).

Table 2. Frequency of days that dissolved oxygen concentrations was lower than 5 and 6 mg/L at 4-h increments in eight Illinois streams during summer 2001 through spring 2003.

		Number of Days per Stream Reach							
Violation	Total Number of Hours per Day	NF Vermilion	MF Vermilion	Vermilion	Lusk Creek	Mazon River	Rayse Creek	Salt Creek	Illinois River
< 5 mg/L	0	740	567	431	508	504	200	536	569
	4	5	2	7	51	18	8	3	14
	8	3	5	4	24	37	8	7	10
	12	1	0	12	28	38	12	21	12
	16	1	0	4	15	8	31	19	8
	20	1	0	0	10	1	43	4	2
	24	0	0	0	17	0	221	0	23
< 6 mg/L	0	721	553	402	415	454	175	471	465
	4	8	4	14	12	27	7	15	17
	8	7	7	12	17	32	2	10	24
	12	4	8	12	34	58	5	24	18
	16	4	2	11	49	32	9	41	17
	20	5	0	5	29	1	16	20	7
	24	2	0	2	97	2	309	9	90

Table 3. Linear regression results of temperature (°C) versus dissolved oxygen concentration (mg/L) quantified each half hour in eight Illinois streams during late summer 2001 through fall 2003.

Stream	N	F	A	b	r^2
NF Vermilion near Bismark	37022	75493	-0.28	14.5	0.67
MF Vermilion near Oakwood	27982	32959	-0.20	13.5	0.54
Vermilion near Danville	22907	23361	-0.31	15.6	0.50
Lusk near Eddyville	32034	125863	-0.31	13.7	0.79
Mazon near Coal City	29906	14910	-0.23	13.3	0.33
Rayse near Waltonville	25812	26061	-0.36	12.1	0.50
Salt at Western Springs	26975	85886	-0.29	13.4	0.76
Illinois River at Valley City	29155	163067	-0.30	13.7	0.84

Table 4. Frequency of half-hour intervals in Lusk Creek, Illinois in which dissolved oxygen concentrations declined below 5 or 4 mg/L as a function of temperature (°C) during late summer 2001 through fall 2003. This stream was chosen due to the wide variation in temperatures and dissolved oxygen concentrations that occurred.

Temperature	< 5 mg/L	< 4 mg/L
15	0	0
17	1	0
19	13	0
21	21	0
23	196	4
25	826	41
27	1105	35
29	434	12
31	49	0
33	0	0
35	0	0

List of Figures

North Fork Vermilion near Bismarck

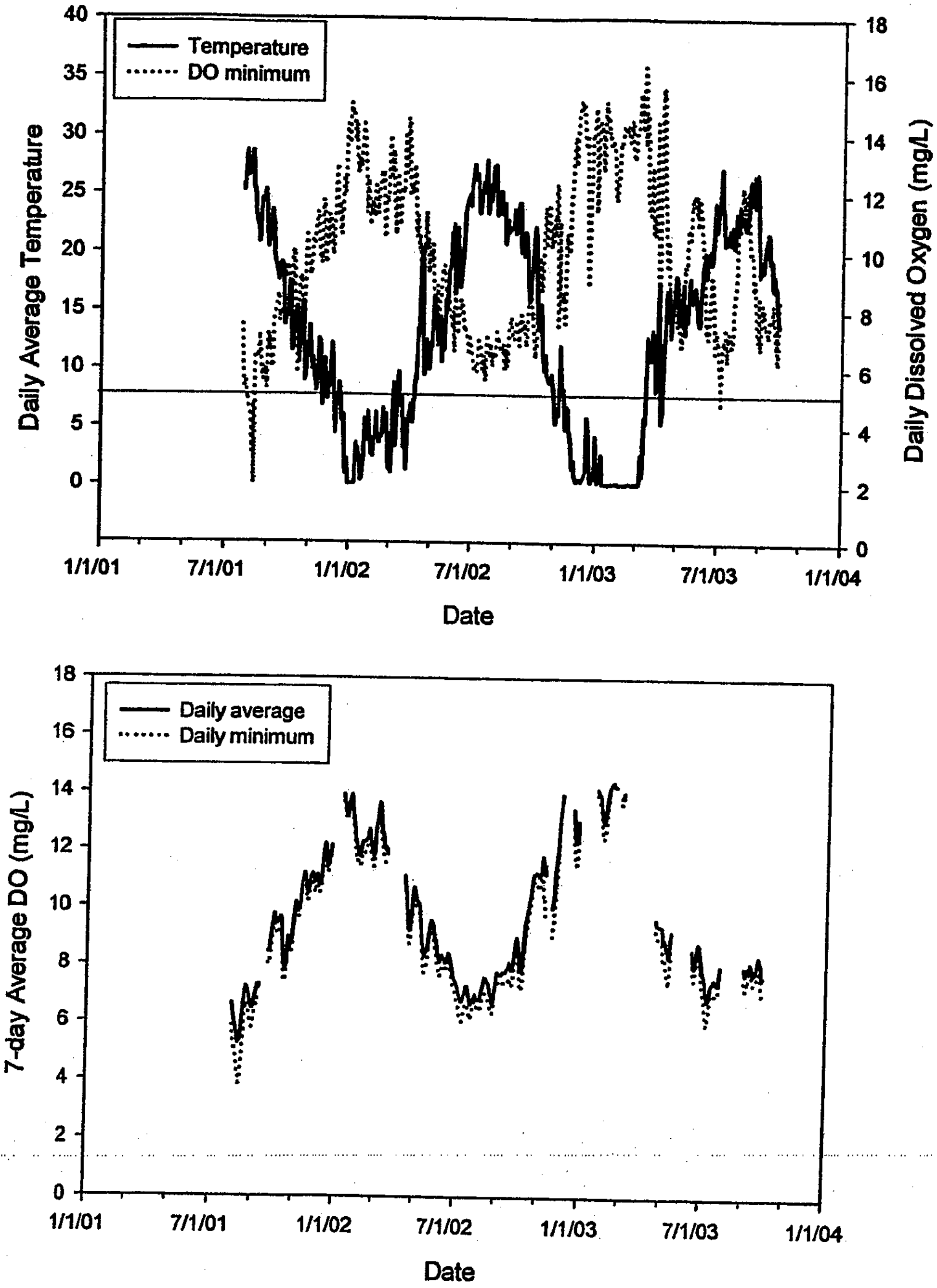


Figure 1

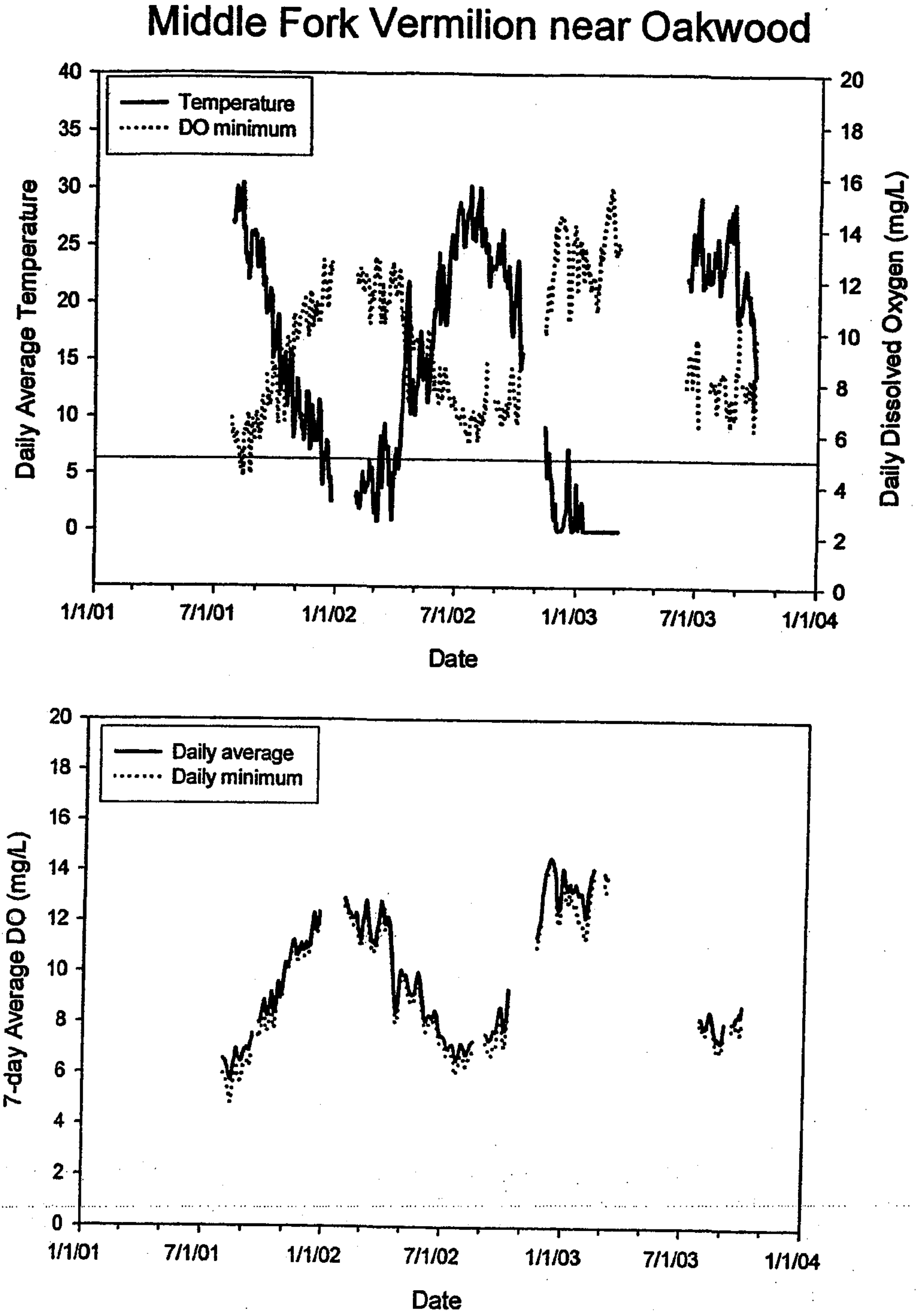
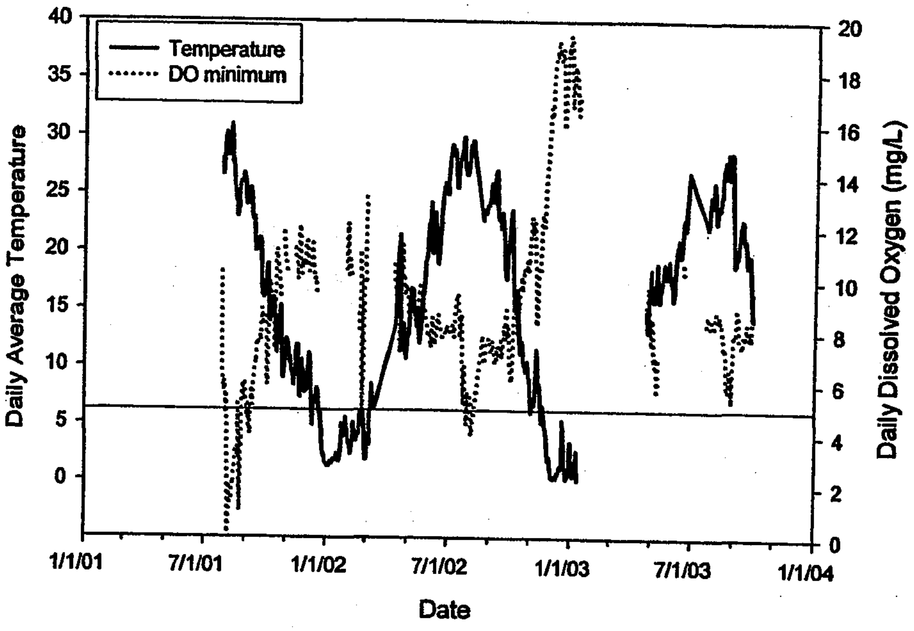

Middle Fork Vermilion near Oakwood

Figure 2

Vermilion River near Danville



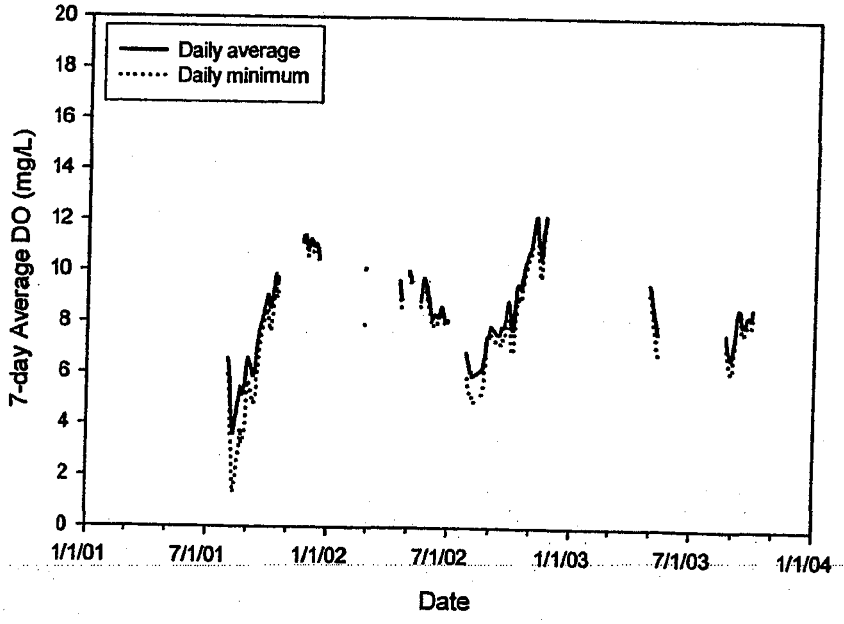


Figure 3

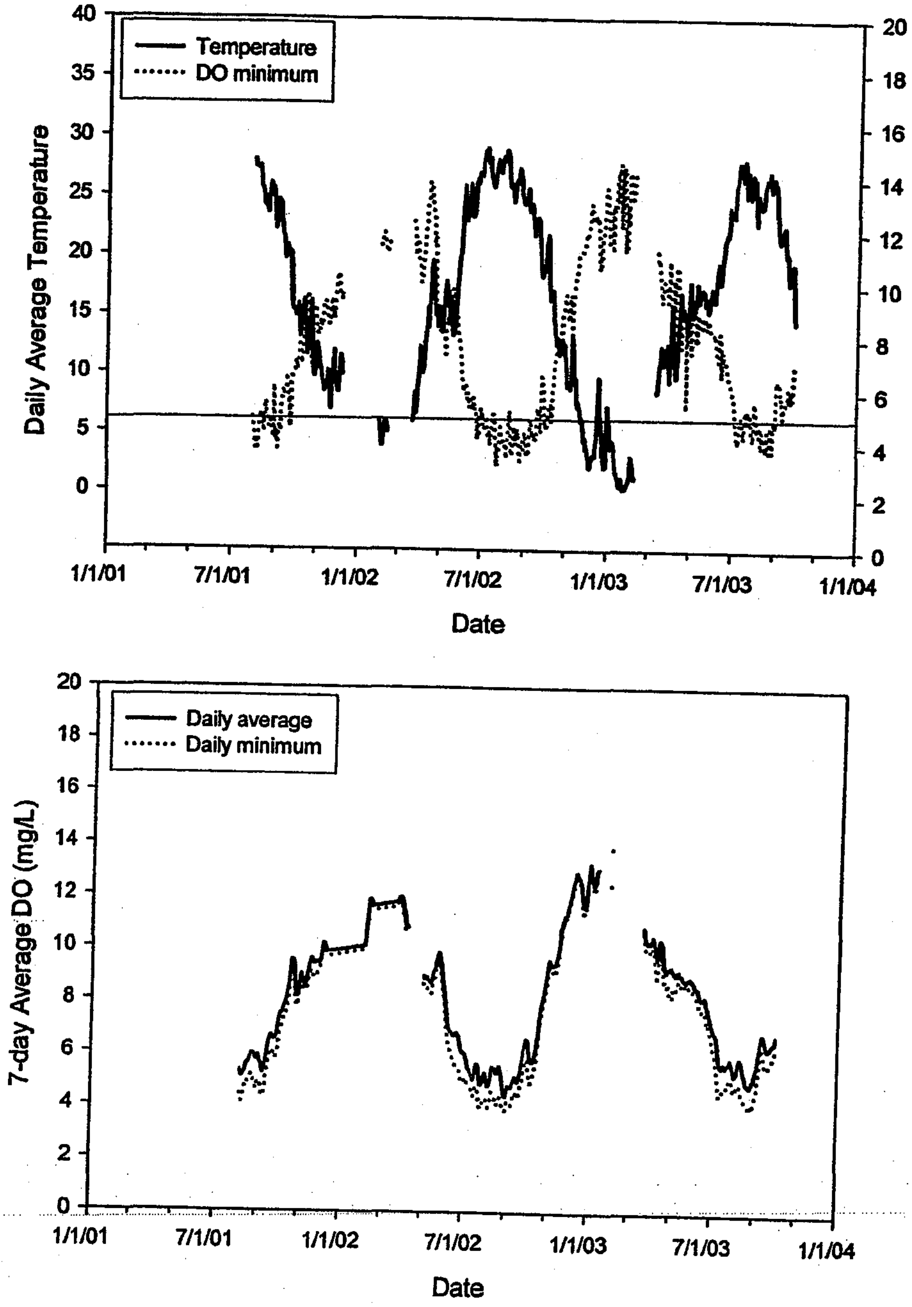

Lusk Creek near Eddyville

Figure 4

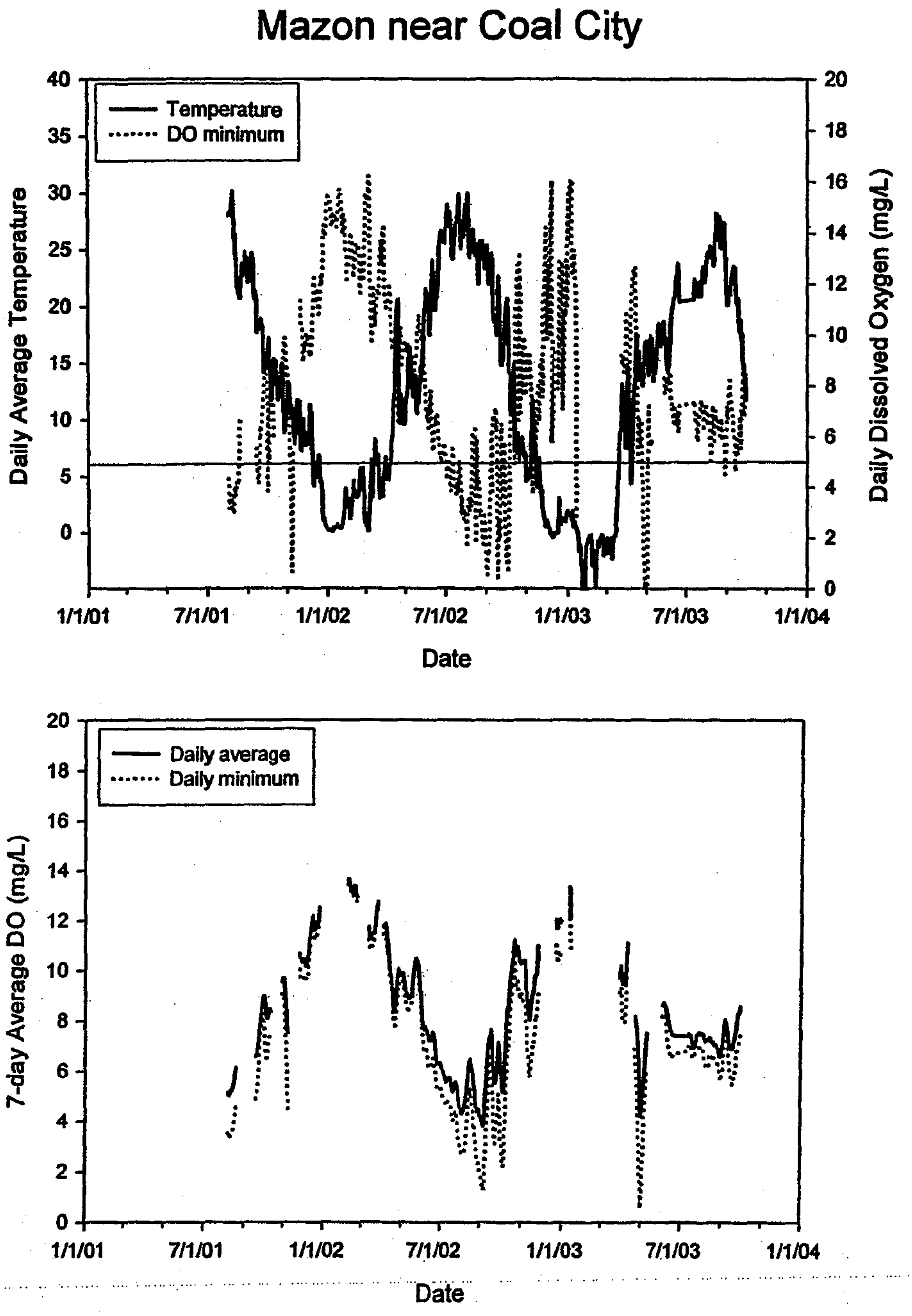
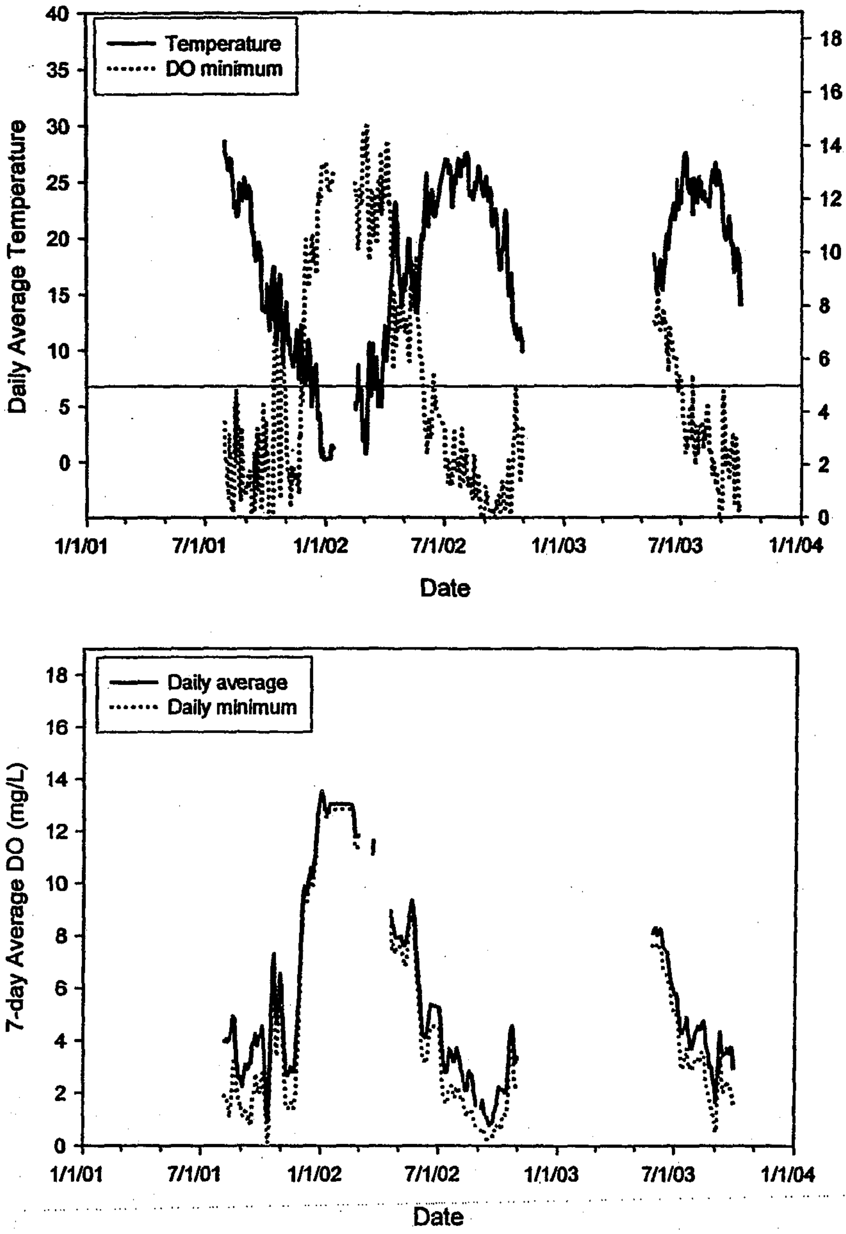

Mazon near Coal City
Temperature
DO minimum
Daily Average Temperature
Daily Dissolved Oxygen (mg/L)
40
35
30
25
20
15
10
5
0
20
18
16
14
12
10
8
6
4
2
0
1/1/01
7/1/01
1/1/02
7/1/02
1/1/03
7/1/03
1/1/04
Date
Daily average
Daily minimum
7-day Average DO (mg/L)
20
18
16
14
12
10
8
6
4
2
0
1/1/01
7/1/01
1/1/02
7/1/02
1/1/03
7/1/03
1/1/04
Date

Figure 5



Rayse Creek near Waltonville

Figure 6

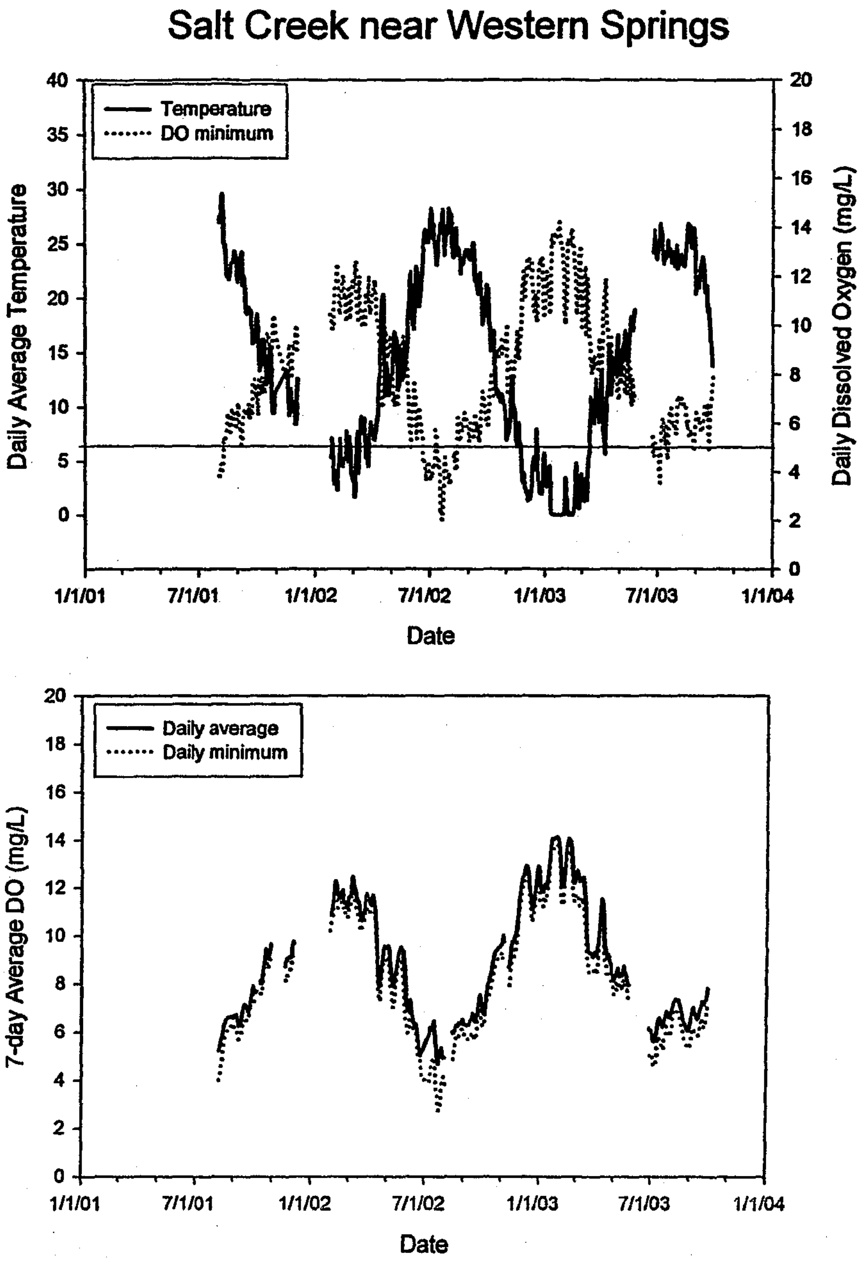

Salt Creek near Western Springs
Temperature
DO minimum
Daily Average Temperature
Daily Dissolved Oxygen (mg/L)
40
35
30
25
20
15
10
5
0
20
18
16
14
12
10
8
6
4
2
0
1/1/01
7/1/01
1/1/02
7/1/02
1/1/03
7/1/03
1/1/04
Date
Daily average
Daily minimum
7-day Average DO (mg/L)
20
18
16
14
12
10
8
6
4
2
0
1/1/01
7/1/01
1/1/02
7/1/02
1/1/03
7/1/03
1/1/04
Date

Figure 7

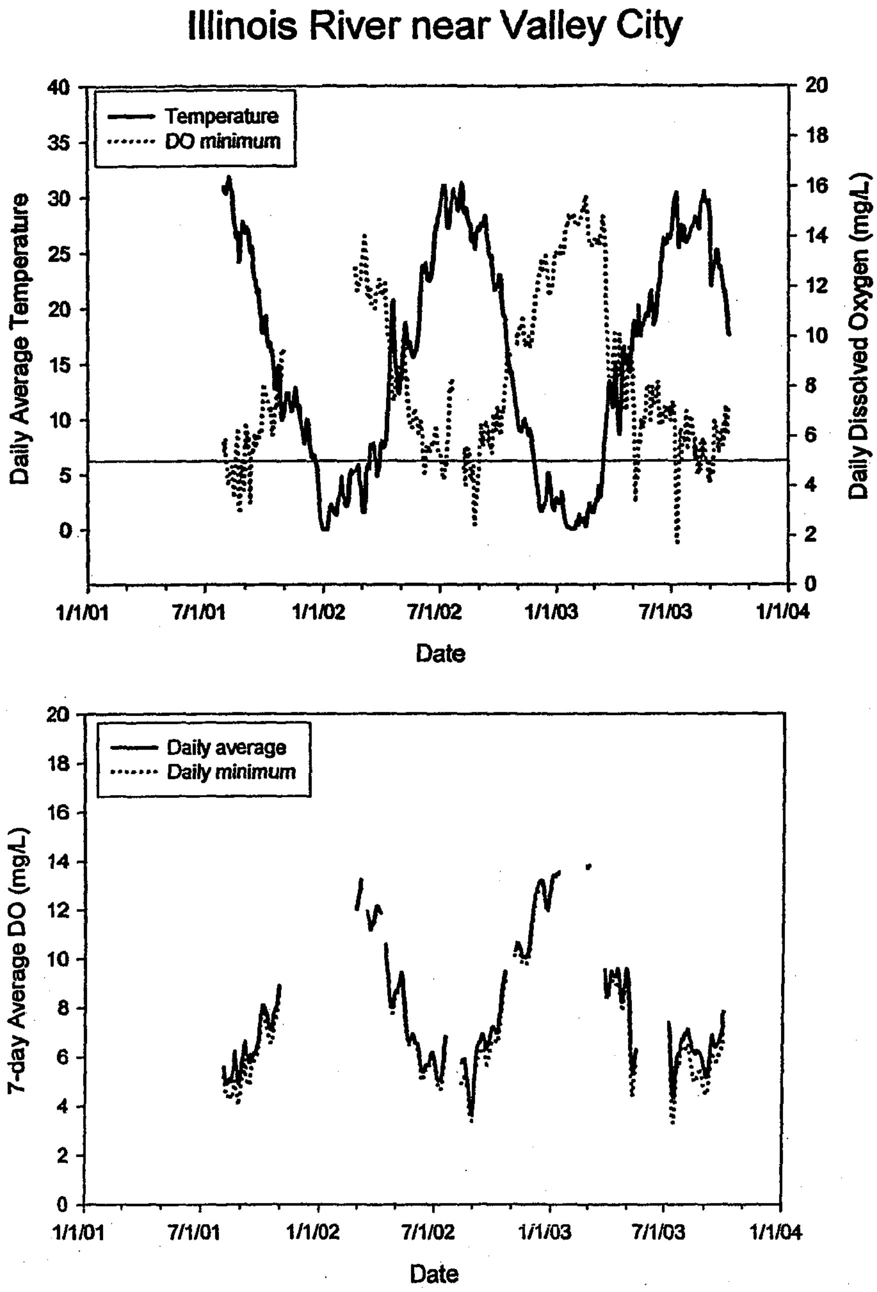

Illinois River near Valley City

Figure 8

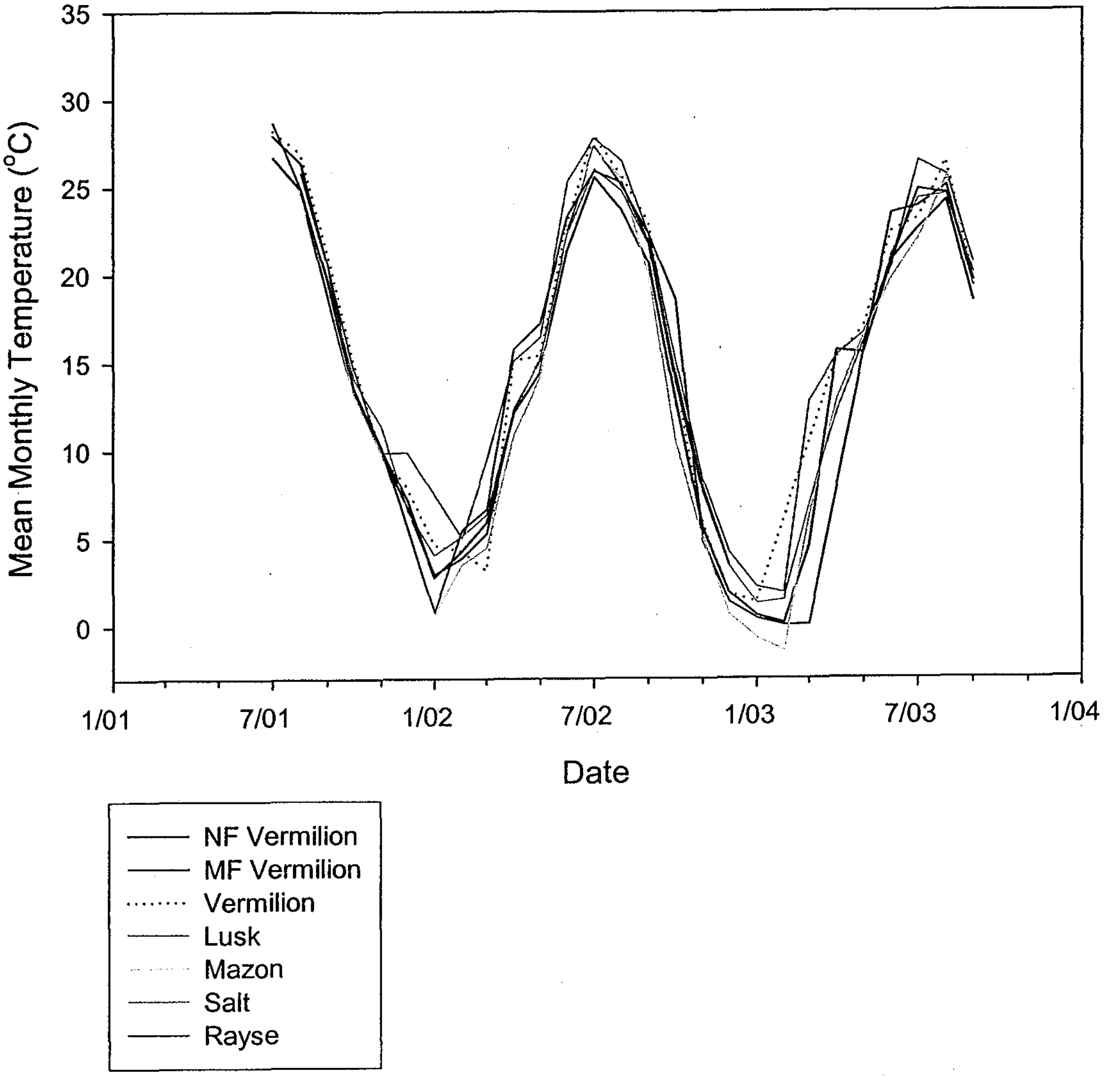

35
30
25
20
15
10
5
0
Mean Monthly Temperature (°C)
1/01
7/01
1/02
7/02
1/03
7/03
1/04
Date
NF Vermilion
MF Vermilion
Vermilion
Lusk
Mazon
Salt
Rayse

Figure 9

An Assessment of National and Illinois Dissolved Oxygen Water Quality Criteria

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For:

Illinois Association of Wastewater Agencies

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Executive Summary

Dissolved oxygen is an important limiting resource in aquatic systems and is directly affected by human activities such as organic enrichment, increased nutrient loading, and habitat alteration. We reviewed the published literature on responses of warmwater freshwater systems to dynamics of dissolved oxygen and then assessed current Illinois and national water quality standards in light of these findings. For fish, aquatic insects, freshwater mussels, and other organisms typically found in warmwater surface waters of Illinois, reduced dissolved oxygen has long been understood to inhibit growth, survival, and reproduction, primarily by interfering with aerobic metabolism. More recently, low dissolved oxygen has been suggested to act as an endocrine disruptor in fish, reducing reproductive viability. Dissolved oxygen concentrations vary widely both among and within natural streams and lakes, although mean and minimum concentrations should decline with organic enrichment. In systems with low oxygen minima, only organisms specifically adapted to hypoxic conditions should persist.

Comment: I dispute this interpretation.

Comment: This should be relevant only to natural low minima

Our assessment of the published data generally affirms the guidelines set forth for warmwater assemblages by the 1986 U.S. Environmental Protection Agency's national dissolved oxygen water quality standards document. The current emphasis in Illinois on biotic indicators for assessing the integrity of streams and lakes should be continued and continually refined in our view. Conversely, the current dissolved oxygen water quality standard set by the Illinois Pollution Control Board (minimum of 5.0 mg/L) is too conservative and may place many aquatic systems with naturally occurring dissolved oxygen concentrations that occasionally decline below the state minimum standard in violation. This document recommends a standard that includes seasonally appropriate means and minima that more realistically account for natural fluctuations in dissolved oxygen concentrations, while remaining sufficiently protective of aquatic life and life stages. In general, our recommended standards are either equivalent to or more conservative than the established national dissolved oxygen standards.

Comment: This statement is consistent with the national criteria.

Comment: I believe this is generally true.

We recommend for surface waters in Illinois (not including Lake Michigan or wetlands; also see Table 5):

- A 1-day minimum of 5.0 mg/L spring through early summer (i.e., March 1 through June 30)
- A 7-d mean of 6.0 mg/L spring through early summer (i.e., March 1 through June 30)
- A 1-d minimum of 3.5 mg/L the remainder of the year (i.e., July 1 through February 28 or 29)
- A 7-d mean minimum of 4.0 mg/L the remainder of the year (i.e., July 1 through February 28 or 29)
- Areas in proximity to discharges in which dissolved oxygen concentrations can be manipulated should be monitored closely, with daily minima occurring no more than 3 weeks per year, not including spring through early summer (i.e., March 1 through June 30), or the 1-d minimum be increased to 4.0 mg/L

Comment: There is no higher mean required and this, I believe, is underprotective. National criteria require a 30-day mean of 5.5 mg/L.

A 1-day minimum dissolved oxygen concentration is the lowest allowable concentration during any given day. A 7-day mean is derived by generating time-weighted daily averages (including the daily minimum and maximum) and then determining a running average across 7 days. Maximum water concentrations that exceed air saturation should be corrected (i.e., decreased) to air saturation values. Seven-day mean minima are calculated by generating a running mean of daily minima across 7 days.

Seasons reflect times when most early life stages of warmwater fishes (i.e., eggs, embryos, and larvae, typically 30-d post spawning) are either present (March through June) or absent (July through February) in Illinois waters (see Table 3). Warmwater species that spawn later during summer should have adaptations for naturally occurring reductions in dissolved oxygen concentrations expected to occur during warm months.

Comment: I don't know the species involved or if this statement is true or not.

Our review of the literature revealed that many gaps in our knowledge persist about relations among diel oxygen curves, nutrient status, and primary production. Mechanistic research rather than correlational field studies must be conducted to develop more precise and meaningful criteria for dissolved oxygen and other water quality measures. Similarly, our understanding of biological responses to oxygen dynamics is typically correlational. Laboratory-derived, physiological tolerance estimates rarely correspond well to field patterns. Improved criteria that are relevant on a regional and habitat-specific basis will require a better understanding of how organisms respond to experimentally manipulated variables in natural systems.

Comment: This is probably less true for DO than for chemical pollutants.

Table of Contents

Section **Page**

Overview

This document reviews the current literature on dissolved oxygen in natural systems and the potential effects of hypoxia (i.e., low dissolved oxygen concentrations) on aquatic life. It then evaluates the current Illinois dissolved oxygen water quality standard (Illinois Pollution Control Board 302.206, 302.502) and the national criteria (Chapman 1986) in light of this information. The final sections make recommendations for re-evaluating and modifying current Illinois state water quality criteria that are based on published research on natural fluctuations in aquatic systems and physiological tolerances of native aquatic life. We conclude with recommendations for research that, in our view, will improve the scientific foundation underlying dissolved oxygen criteria for freshwater systems in Illinois.

Oxygen in freshwater habitats

Dissolved oxygen is a critical resource in freshwater systems because it is essential to aquatic organisms for aerobic respiration, and thus most biological activity and associated processes. Further, because of oxygen's low solubility in water, it is less abundant, and thus more limiting, in aquatic habitats compared to terrestrial habitats. The amount of dissolved oxygen in freshwater habitats that is available to organisms is a function of many biotic and abiotic factors including metabolic processes (photosynthesis and respiration), temperature, salinity, atmospheric and water pressure, and diffusion. Dissolved oxygen that is available to aquatic biota is generally measured and expressed as mg/L or percentage saturation. Depending on the array of aforementioned physical and biological factors, dissolved oxygen levels in natural freshwater habitats can range from near zero (anoxic or anaerobic conditions) to supersaturated.

Anthropogenic influences on oxygen in freshwater habitats

Along with the myriad natural process that influence dissolved oxygen levels in freshwater habitats, many human activities can have profound effects. In particular, the addition of nutrients (nutrient enrichment and eutrophication) leads to reduced oxygen concentrations because of increased productivity and biochemical oxygen demand (BOD). Numerous other types of pollution (e.g., sediments, thermal discharges, pesticides) and other types of anthropogenic disturbances (e.g., stream channelization, catchment logging) can influence oxygen levels because they influence the combination of biotic and abiotic factors that control it. Oxygen depletion as a result of eutrophication receives most attention because this is a prevalent problem associated with human activities (e.g., sewage effluent, agricultural activities, urbanization) that is often linked to reduced water quality and the loss and degradation of natural resources such as fisheries (Cooper 1993). Eutrophication has also received much recent attention because of related large-scale issues such as the hypoxic zone in the Gulf of Mexico, which has been linked to elevated nutrient loads in the Mississippi River and its tributaries (Rabalais et al. 2002).

Dissolved oxygen and water quality monitoring

Given that (i) oxygen is a crucial, limiting resource to life in freshwater habitats, (ii) human activities have great potential to influence it, and (iii) it is relatively easy to monitor, regulatory agencies logically focus on dissolved oxygen levels for setting water quality standards and monitoring conditions. Most frequently, associated monitoring activities focus on daily minimum levels (often quantified pre-dawn) or averages over a period of time. Although there is general agreement that dissolved oxygen levels are an important component of water quality standards and monitoring activities, it is less clear how standards for given regions and habitats should be set and how violations of these standards are assessed (e.g., daily minimums vs. weekly averages vs. dynamics of diel oscillations). More recently, biological communities, usually fish and/or macroinvertebrate assemblages (e.g., biomonitoring), have become increasingly important components of surface water monitoring programs because they integrate and reflect the conditions within the habitat, including, among other things, oxygen levels and the factors that influence them (Plafkin et al. 1989, Loeb and Spacie 1993, Barbour et al. 1999).

National and State Criteria

Because oxygen is typically the primary factor limiting aquatic life, several attempts have been made to develop specific criteria in aquatic systems (Federal Water Pollution Control Administration 1968, National Academy of Sciences and National Academy of Engineering 1972, Magnuson et al. 1979a). The current USEPA national standard for dissolved oxygen (Chapman 1986) was built on this past work. The national criteria document adopts a two-concentration structure with both a mean and a minimum and includes specific criteria for both cool-water and warm-water systems.

Comment: Perhaps. I suspect this is a moot point.

The Illinois dissolved oxygen criterion used at present was established by the Illinois Pollution Control Board three decades ago in the early 1970s (R. Mosher, Illinois EPA, Division of Water Pollution Control, Standards Section, personal communication). It is based on a simple minimum allowable dissolved oxygen concentration. Setting such minima was common practice for establishing contaminant loads in the early regulatory setting following passage of the Clean Water Act (Chapman 1986). The current Illinois criterion, based on these early decisions, does not incorporate natural cycling in dissolved oxygen nor is it supported by the most recent scientific information on responses of aquatic life to hypoxic conditions.

Comment: I heartily agree that a single number standard is unrealistic. A single number is either greatly overprotective, or greatly underprotective.

Systems in Illinois

With the exception of the Lake Michigan system, most inland waters in Illinois are dominated by warmwater, non-salmonid faunal assemblages. Although the term warmwater has been used for decades, a formal definition is still lacking (but see Magnuson et al. 1979b). In this document, warmwater systems are defined as those that are typically diverse, centrarchid-dominated, and common in the Midwestern and southern United States (Magnuson et al. 1979b). Fishes in these systems can be quite tolerant of at least temporary periods of low dissolved oxygen (Chapman 1986, Smale and Rabeni 1995a), although certain species such as smallmouth bass (*Micropterus dolomieu*) are more sensitive.

Since the national criterion for dissolved oxygen was developed, fish continue to be emphasized because of their commercial and recreational importance. Some macroinvertebrates, such as burrowing mayflies (*Hexagenia* spp.) and freshwater mussels (Li-Yen 1998), are far less tolerant of prolonged exposure to hypoxic conditions than most fish (Chapman 1986, Winter et al. 1996, Corkum et al. 1997). However, this may be expected because many sensitive macroinvertebrate species occupy pristine, well-oxygenated benthic habitats or are riffle-dwelling. Riffles have a high dissolved oxygen flux and organisms persisting in these environments might be expected to have high oxygen requirements. Assessments of aquatic life responses to hypoxic conditions need to account for the physiological, behavioral, and life history adaptations of the resident organisms in the context of their natural environment. When developing oxygen criteria, how natural cycles in dissolved oxygen structure warmwater assemblages ~~must be~~ considered.

Comment: There is almost no data on the low oxygen tolerance of most invertebrates and especially of warm-water invertebrates.

Warmwater Organisms and Dissolved Oxygen

Setting a dissolved oxygen criterion for aquatic systems that is adequately protective to aquatic life is challenging because of the wide adaptations that exist among organisms. In warmwater systems, the richness and abundance of species within aquatic systems can often be explained by variation in dissolved oxygen, because only the most tolerant species can persist in systems with frequent or chronic hypoxia. An extensive survey of Missouri streams revealed that low oxygen, rather than high temperature, is the primary factor limiting fish distributions (Smale and Rabeni 1995a,b). Increases in the dissolved oxygen concentration and general improvement in water quality of the western basin of Lake Erie are largely responsible for improved fish and benthic macroinvertebrate communities (Ludsin et al. 2001). Similar improvements in fish communities occurred in

Swedish streams when dissolved oxygen increased and water quality improved across a thirty-year period (Eklov et al. 1998, 1999).

Many physiological responses within aquatic organisms occur to ensure survival under hypoxic conditions. Many species will initially increase ventilation to increase the exchange of oxygen across the respiratory surface (e.g., gills; Beamish 1964, Fernandes et al. 1995, MacCormick et al. 2003). Tolerance to hypoxia is ultimately affected by the capacity of blood to uptake and transport oxygen. Furmisky et al. (2003) found a marked difference in blood oxygen content of largemouth bass and smallmouth bass (*M. salmoides*) under hypoxia. Largemouth bass blood had a higher affinity for oxygen than that of smallmouth bass. Further, smallmouth bass blood contained elevated concentrations of catecholamines, stress hormones that initiate a number of physiological mechanisms that increase blood oxygen transport. In contrast to species that actively regulate oxygen concentration, other species exposed to hypoxia, typically those that are relatively inactive in benthic habitats, will reduce activity and metabolism, thereby decreasing oxygen demand of tissues (Crocker and Cech 1997, Hagerman 1998). Some organisms rely on anaerobic glycolysis and other anaerobic biochemical pathways to fuel their metabolism during temporary hypoxia (e.g., common carp, freshwater mussels), although the typical adaptation in habitats with chronically low dissolved oxygen concentrations appears to be aerobic metabolism plus efficient oxygen uptake rather than anaerobic metabolism (Childress and Siebel 1998, Wu 2002). When determining the dissolved oxygen criteria for a suite of systems, the interaction between physiological adaptations and natural environmental dissolved oxygen cycles must be considered.

Aquatic organisms will also respond behaviorally to low dissolved oxygen in the environment. Organisms usually move away from areas of low oxygen to those of higher concentrations when oxygen concentrations are locally heterogeneous. This may most commonly occur in vegetated areas of lake littoral zones in which oxygen concentrations vary both horizontally and vertically, with areas of low and high oxygen adjacent to each other (Miranda et al. 2000). Other organisms such as some stream fishes and amphipods use the air-water interface when dissolved oxygen levels are low (Henry and Danielopol 1998). Some invertebrate and vertebrate species must trade-off the use of hypoxic areas with the risk of occupying other normoxic areas that may have a greater risk of predation or lower food availability (Burleson et al. 2001). This has been well documented for zooplankton and *Chaoborus* using the hypoxic hypolimnion of lakes as a refuge from predators (Tessier and Welser 1991, Popp and Hoagland 1994, Rahel and Nutzman 1995, Dawidowicz et al. 2001). More recently hypoxic areas have been shown to be important for small fish evading predators (Chapman et al. 1996, Miranda and Hodges 2000, Burleson et al. 2001) or using these areas to forage (Rahel and Nutzman 1995).

Chapman (1986) found that the early life stages (e.g., eggs and larvae) of aquatic organisms are the most sensitive to hypoxia. For many of these organisms, much exchange of oxygen occurs cutaneously (Jobling 1995) and thus is not expected to be well-regulated. After the oxygen regulating structures such as gills are formed, the ability to regulate oxygen and thus tolerate hypoxia should improve, with the structure of gills and associated respiratory behavior reflecting species-specific oxygen demands and naturally occurring oxygen concentrations (Jobling 1995). In fresh, warm-water systems such as those in Illinois, many benthic areas where fish may deposit eggs in nests can become hypoxic or anoxic. The behavior of nest tending and fanning in adults increases the oxygen available to eggs and embryos, offsetting the effect of low oxygen (Hale et al. 2003). Other species in these systems have adaptations that allow their eggs and larvae to avoid anoxic sediments including semibuoyant eggs (e.g., asian carps) or adhesive eggs that attach to vegetation (e.g., northern pike, yellow perch). Riffle-dwelling or gravel-spawning species rely on rapid exchange of water to keep eggs oxygenated (Corbett and Powles 1986). How these adaptations allow aquatic species to cope with natural cycles and spatial heterogeneity of dissolved oxygen must be considered when developing specific criteria. Because most species in Illinois spawn in spring when flow rates are high and temperature-induced hypoxia is low, seasonal fluctuations in dissolved oxygen must also be factored into the evaluation of dissolved oxygen criteria for Illinois.

Chapman (1986) pointed out that very few investigators have used conventional toxicity tests to generate LC50s or EC50s and thus find critical dissolved oxygen concentrations of aquatic organisms. With a few rare exceptions (i.e., Nebeker et al. 1992), this has not changed since 1986. Additionally, no standardized method for conducting acute tests with dissolved oxygen yet exists. As a consequence, duration and intensity of acclimation and exposure to hypoxic conditions differ among studies. Oxygen control in studies is typically achieved either by vacuum degassing or nitrogen stripping, which may elicit different physiological responses. Acute effects of hypoxia have often been quantified as an interaction with other factors such as contaminants, temperature, and food availability. For sublethal tests, effects have been quantified as impairment of behavior, reproduction, or growth. Chronic tests in the published literature are rarer than acute ones, and are assumed to include the most sensitive life stages. Because most dissolved oxygen tests fail to include a full life cycle or, at the least, embryonic through larval stages, these tests fall short in assessing chronic effects (but see Nebeker et al. 1992). In the field, hypoxia often only occurs temporarily because dissolved oxygen concentrations fluctuate daily. Hence, quantifying recovery upon return to normoxia may also be an important requisite for standardized testing (Person-Le Ruyet 2003).

Fish Responses to Oxygen Stress

Most of the studies quantifying critical dissolved oxygen minima for warmwater fish species (i.e., nonsalmonids) in Illinois predate the 1990s. A review of these studies revealed that adults and juveniles of most species survive dissolved oxygen concentrations that occasionally decline below 3 mg/l (Chapman 1986). Higher temperatures generally increase the critical dissolved oxygen concentration necessary for survival. Many warmwater species can survive prolonged periods of low dissolved oxygen concentrations (Downing and Merkens 1957, Moss and Scott 1961, Smale and Rabeni 1995a,b). Smale and Rabeni (1995a) determined critical oxygen minima for 35 fish species that inhabit small warmwater streams (Table 1). These critical concentrations, defined as the oxygen concentration at which ventilation ceased, ranged from 0.49 mg/l to 1.5 mg/L (Table 1; Smale and Rabeni 1995a). The current national 1-day minimum dissolved oxygen criterion for adult life stages is 3 mg/L (Chapman 1986; Table 2). With the exception of the oxygen minima set by Smale and Rabeni (1985a) and tested in Smale and Rabeni (1995b), no studies to our knowledge have explicitly determined how the criteria set forth by the Illinois Pollution Control Board or the US EPA national water quality document translate to field distributions of fish. Smale and Rabeni's work suggest that the current 1-day minimum set by the national criterion for warmwater fish is sufficiently protective of stream fish assemblages.

Comment: I have seen no data over the past 20 years that would indicate that the 3 mg/L minimum would not be adequately protective against lethal effects.

Because early life stages are typically more sensitive, separate national dissolved oxygen criteria have been set for them (Table 2; Chapman 1986). An in situ test of the effect of dissolved oxygen concentration on survival of embryonic and larval bluegill, northern pike, pumpkinseed, and smallmouth bass was conducted at spawning sites in Minnesota (Peterka and Kent 1976). The investigators found that tolerance of short-term exposure to hypoxia declined from embryonic to larval stages. Upon transforming to larvae, many fishes become free-swimming and join the open-water ichthyoplankton. Hence, some larvae departing potentially hypoxic benthic spawning areas may no longer require high tolerance of low dissolved oxygen concentrations under natural conditions. Conversely, other species with benthic larvae (e.g., lampreys) should be quite sensitive to chronic low oxygen at the substrate-water interface.

To find tolerance for dissolved oxygen, we digitized embryonic and larval survival data from Figure 1 in Chapman (1986). We then subjected the data for Chapman's "tolerant" warmwater species (largemouth bass, black crappie, white sucker, and white bass) and "intolerant" species (northern pike, channel catfish, walleye, and smallmouth bass) to two sets of analyses, both of which are designed to isolate an "inflection" point in the curves of dissolved oxygen concentration versus percent survival (relative to controls). The nature of the data did not allow us to conduct a probit analysis widely used in toxicology. Rather, in the first analysis, we used non-linear regression to fit the best models to the tolerant (Michealis-Mentin) and intolerant (logistic) species data. A second analysis was used to identify the point of major change in the distributions for both tolerant and intolerant fishes. This two-dimensional Kolmogorov-Smirnov test (2DKS) has been used successfully for finding major breakpoints in bivariate data, for example when survival changes from consistently high to variable beyond or below some threshold contaminant concentration (Garvey et al. 1998a).

For the non-linear regression analysis, the curves fit the data moderately well (Figure 1). The half-saturation dissolved oxygen concentration (similar to an LC50 value) for the tolerant species was 2.8 mg/l. For the intolerant species, the dissolved oxygen concentration at which 50% survival occurred was much higher at 4.3 mg/L. In the 2DKS analysis, the threshold dissolved oxygen concentrations were 3.72 and 3.75 mg/L for the tolerant and intolerant distributions, respectively, suggesting that survival of fish varied below these values and was consistently high above them. A conservative interpretation is that intolerant embryos and larvae are indeed more sensitive to low oxygen concentrations and that survival should begin to decline below 4.3 mg/L. Early life stages of tolerant species should only begin to show survival effects below 3.7 mg/L.

Comment: The 3.75 value is lower than at least four data points with about 50 to 80 percent mortality.

Comment: I generally agree there is a threshold between 4 and 5 mg/L.

Comment: I agree.

Sublethal effects of low dissolved oxygen on growth are likely more common than direct lethal ones. Thus, carefully quantifying sublethal effects is an important requisite for

Comment: True.

setting criteria for fish and other organisms. Low dissolved oxygen concentrations can reduce growth by reducing foraging behavior and increasing metabolic costs. A review conducted by JRB Associates (1984) summarized growth responses of northern pike, largemouth bass, channel catfish, and yellow perch to reduced dissolved oxygen concentrations (data sources: Stewart et al. 1967, Adelman and Smith 1972, Carlson et al. 1980). For northern pike, growth declined from 16% to 25% between 5 and 4 mg/L, with growth reduced by 35% at the lowest concentration of 3 mg/l. Growth of channel catfish declined from 7% to 13% between 5 and 4 mg/L, with a 29% reduction at 2 mg/L. For largemouth bass and yellow perch, strong reductions in growth did not occur until concentrations were 2 mg/L, with growth reduced by 51% for largemouth bass and 22% for yellow perch.

Comment: Primary effects (in the laboratory) appear to be a result of voluntary limitation of food intake, even in the presence of abundant food.

Extrapolating growth results from laboratory experiments to the field may be problematic, primarily because of differences in food availability. Although reduced oxygen may reduce consumption, fish in laboratory studies may have easy access to food and thus not suffer the same impairment as counterparts in the field (Chapman 1986). Chapman (1986) compared the data compiled by JRB Associates (1984) to those of Brake (1972) who conducted a pond experiment exploring the effect of reduced oxygen on largemouth bass growth. Brake found that growth of largemouth bass was reduced by as much as 34% at dissolved oxygen concentrations (4-5 mg/L) that had little effect in the laboratory. Similarly, RNA-DNA ratios (an index of growth where high RNA concentrations relative to DNA suggests rapid protein synthesis and growth) were higher for bluegill under normoxic conditions than counterparts exposed to hypoxic conditions in the natural environment (Aday et al. 2000). However, this effect of hypoxia could not be replicated under laboratory conditions (Aday et al. 2000). Clearly, field conditions, including reduced food, changing temperatures, increased activity rates, and fluctuating oxygen levels, need to be incorporated into studies quantifying the intermediate- and long-term effects of hypoxia on growth.

Comment: True, but how is this to be accomplished?

Few studies have quantified the effect of reduced dissolved oxygen concentration on the reproductive viability of adult fish. Recently, hypoxia has been shown to be an endocrine disruptor, affecting fish reproductive success (Wu et al. 2003). Common carp exposed to chronic hypoxia had reduced levels of serum testosterone and estradiol. These reduced levels led to decreased gonadal development in both males and females. Spawning success, sperm motility, fertilization success, hatching rate, and larval survival were all compromised through this mechanism. Loss of reproductive capacity through reduced energy intake or increased metabolic costs has been the more typical mechanism implicated. For species in which adult behavior is important (e.g., nest guarding), adults may abandon nests or cease parental care below some threshold dissolved oxygen concentration where physiological costs outweigh the benefit of successfully producing offspring (Hale et al. 2003).

Comment: I believe this to be a natural biological response to conditions in which young would have little chance of survival. The endocrine system is simply responding appropriately to the stressful environment in a way that makes bioenergetic sense: "don't waste your energy making eggs that won't survive... wait until things get better."

The timing and periodicity of spawning should correspond with a host of ecological factors including the availability of food, avoidance of predators, and overlap with optimum abiotic conditions (e.g., temperature and oxygen concentration; Winemiller and Rose 1992). Obviously, all of these conditions typically do not co-occur in time, necessitating trade-offs for reproducing fish and other aquatic organisms. The majority of warmwater fishes in Illinois spawn during spring through early summer (i.e., as early as March and as late as June; Table 3), largely because this (i) allows young fish to overlap with a spring pulse in primary production and (ii) provides enough time during the growing season for offspring to become large and survive winter (Garvey et al. 1998b). During spring, oxygen concentrations in most stream and lake systems should not be expected to be low, because the temperature-dependent oxygen capacity of water is not limited, lakes are typically unstratified and mixed, and seasonal production and thus whole-system respiration has not yet peaked. However, a few species do spawn continuously through summer when natural oxygen concentrations may be expected to fluctuate and may reach limiting levels. Under these circumstances, fishes must have adaptations to reproduce successfully including parental care (e.g., nest fanning), riffle-dwelling offspring, or oxygen-tolerant eggs, embryos, and larvae.

Comment: This requires knowledge of spawning species, their habits, and the timing. Also, there could be effects on the energy budget of the "fanners." I cannot comment specifically on these issues, especially for Illinois.

Macroinvertebrate responses to oxygen stress

Macroinvertebrate (typically larval stages of aquatic insects and freshwater mussels) responses to low oxygen situations have been characterized at the community, population, and individual levels. Macroinvertebrate communities and assemblages in habitats with low dissolved oxygen levels are generally dominated by taxa that breathe atmospheric oxygen through respiratory tubes or the use of transportable air stores (e.g., pulmonate gastropods, hemipterans, and many dipteran and coleopteran taxa) and/or those with other adaptations such as some oligochaetes and *Chironomus* midges with hemoglobin in their blood (Hynes 1960, Wiederholm 1984). Other tolerant taxa, such as the fingernail clam *Pisidium*, can perform anaerobis and go through periods of dormancy (Hamburger et al. 2000), and thus may also be abundant in low oxygen environments. In contrast, taxa associated with highly oxygenated environments, such as many Plecoptera, Ephemeroptera, and Trichoptera taxa, which primarily use tracheal gills for respiration, are usually underrepresented or absent in oxygen-limited freshwater habitats. These patterns are the basis for numerous macroinvertebrate-based biomonitoring programs because they are fairly consistent and reliable indicators of increasing organic pollution and associated decreases in oxygen availability, and can thus reflect overall system health by integrating spatial and temporal conditions associated with pollution and associated oxygen stress (e.g., Hilsenhoff 1987, Hilsenhoff 1988, Lenat 1993, Barbour et al. 1999).

Considering the incredible diversity of freshwater invertebrates, there is relatively little information regarding their oxygen requirements and tolerances. As would be expected for such a diverse group of organisms, studies to date indicate that macroinvertebrate responses to oxygen stress at both the population and individual levels vary greatly. Lethal effects are obvious and well documented for many taxa, particularly more sensitive taxa such as members of the Ephemeroptera, Plecoptera, and Trichoptera (Fox et al. 1937, Benedetto 1970, Nebeker 1972, Gaufin 1973). These studies and others (reviewed by Chapman 1986) indicate a range of lethal minima from <0.6 mg/L for the midge *Tanytarsus* to 5.2 mg/L for an ephemerellid mayfly, and a dissolved oxygen 96-hour LC-50 concentration of between 3-4 mg/L for about half of all insects examined. Similarly, tolerance to hypoxia ranges dramatically among freshwater mussels, a group that is of special concern because population declines are widespread and many species

Comment: I remain cautiously skeptical of the physical (water flow) conditions of these tests. This is a complex issue requiring a full monograph describing issues of habitat niches, feeding opportunities, and predation, as influenced by water flow and DO.

are now threatened or endangered. In laboratory experiments, survival of *Villosa* spp., a riffle-dwelling genus, was compromised under hypoxic conditions (< 2 mg/l), whereas no negative survival effects occurred for other species such as *Elliptio* spp. and *Pyganodon grandis* (Li-Yen 1998). Many of these values must be considered within the context in which they were obtained, as the most sensitive taxa often live in flowing water habitats and diffusion of oxygen into gills and other permeable surfaces is partly a function of water velocity because it determines the replacement rate of water around the diffusion surface. Using closed recirculating systems, Sparks and Strayer (1998) examined responses of juvenile *Elliptio complanata* to varying dissolved oxygen levels and found a sharp differences in behavior (e.g., gaping, siphon extending) between 2 and 4 mg/L, and individuals exposed to concentrations of 1.3 mg/L for a week died.

Along with lethal effects, there are also important sublethal responses. The most commonly reported sublethal effect of low oxygen levels on macroinvertebrates is reduced growth. Reduced growth rates occur because of decreased aerobic respiration rates and the use of energy reserves, which would normally be used for growth and reproduction, for body movements such as ventilating and/or other mechanisms for increasing oxygen uptake (Fox and Sidney 1953, Erikson et al. 1996). Pesticides and other toxicants, which are often present in polluted habitats where oxygen stress occurs, can further reduce invertebrate tolerances to low oxygen conditions because they often alter respiration rates themselves (e.g., Maki et al. 1973, Kapoor 1976). For freshwater mussels, the influence of other factors including siltation, altered habitat, and loss of fish hosts for reproduction may interact with low dissolved oxygen concentrations to reduce growth and reproductive success (Watters 1999). The consequences of sublethal effects such as reduced growth are important at the population level because adult female size is positively correlated with fecundity in a variety of invertebrates (Vannote and Sweeney 1980, Sweeney and Vannote 1981).

Environmental variation in dissolved oxygen

Dissolved oxygen concentrations fluctuate in natural systems. Even relatively pristine systems may have spatial heterogeneity in oxygen concentrations that requires organisms to move or tolerate occasional spates of hypoxia. Because hypoxia is often a natural phenomenon, most species have some adaptations that allow them to tolerate occasionally low oxygen, while other species are specifically adapted to occupy areas of chronically low oxygen (e.g., profundal amphipods; Hamburger et al. 2000, MacNeil et al. 2001). This section explores factors influencing variation in aquatic systems of Illinois, with implications for the growth, survival, and reproductive success of resident organisms.

Most field studies exploring ecological effects of dissolved oxygen correlate variation in dissolved oxygen concentrations with the distributions of fish and other organisms. If a correlation occurs, then investigators infer that dissolved oxygen is the major factor underlying observed distributions. The most typical occurrence of hypoxia in natural freshwater systems arises in stratified lakes during summer. Hypolimnetic (lower strata) waters of lakes often become depleted of oxygen during this season, causing fish and other organisms to avoid these areas. A project quantifying the vertical and horizontal spatial distribution of fishes in Lake of Egypt, Illinois during summer through fall 2003 strongly demonstrated this pattern (Sherman and Garvey, unpublished data). Threadfin shad, a species with a low tolerance to hypoxia, and hybrid striped bass, a more tolerant fish, were sampled with gill nets at three depths in three locations of the lake. Spatial distribution of these species was affected by the presence of hypoxic hypolimnetic water, with consistently scarce abundance below 4 mg/L dissolved oxygen (Figure 2). This research confirms the long-held assumption that an increase in hypoxic hypolimnetic water, expected to occur in relatively shallow, eutrophic systems, should severely restrict habitat for fish and other organisms (Nurnberg 1995a,b, 2002). Combinations of suboptimal warm temperatures and low oxygen during summer months can lead to "summerkills" of fish, particularly those species that have poor tolerance to hypoxia (e.g., shad). Although oxygen stratification is not prevalent during winter months, "winterkills" of fish may occur by the natural, biologically driven depletion of oxygen under snow-covered ice in lakes (Klinger et al. 1982, Fang and Stefan 2000, Danylchuk and Tonn 2003). This should be more typical in the northern portion of Illinois where winters are more severe.

Dissolved oxygen concentrations in streams can be influenced by many natural environmental factors. Groundwater inundation of streams may provide cool temperatures that are preferred by aquatic organisms such as fish during summer months (Matthews and Berg 1997). However, the tradeoff of seeking these waters may be that they are severely depleted in oxygen (Matthews and Berg 1997). Many streams undergo a natural, often cyclic pattern of flooding and drying. During stream drying, isolated pools provide refuge for stream organisms. However, extremes in temperature, increases in nitrogenous wastes (e.g., ammonia) and salts, and reductions in oxygen can tax the performance of resident organisms (Ostrand and Marks 2000, Ostrand and Wilde 2001). Not surprisingly, fishes native to these systems tolerate extreme conditions such as very low dissolved oxygen (Cech et al. 1990). Typically, oxygen reductions in streams and other aquatic systems are caused by an increase in oxygen demand of the microbes and perhaps autotrophs (particularly during night) through organic enrichment. However, respiration of abundant organisms such as the exotic zebra mussel can be sufficiently high to decrease dissolved oxygen concentrations within lotic systems (Caraco et al. 2000).

Many examples of alterations of aquatic communities with either spatial or temporal changes in dissolved oxygen concentrations exist. Natural variation in dissolved oxygen concentration occurs in the floodplains of streams and rivers, affecting the distribution of fish. For example, larval sunfish and shad abundance were associated with spatial variation in dissolved oxygen concentration in wetlands of the Atchafalaya River in Louisiana (Fontenot et al. 2001). When increased connectivity through flooding increased dissolved oxygen concentration (above 2 mg/L) in this system, larval fish became abundant, likely improving recruitment. Hence, natural wetlands with high connectivity to their respective river or lake should have high survival of fish and other organisms. Indeed, reductions in connectivity due to levee construction and sedimentation have been implicated in reductions in local species richness of wetlands and adjacent ecosystems. With improvements in water quality during the past few decades, increases in dissolved oxygen due to reductions in organic enrichment have enhanced fish species richness in many systems ranging from small streams (Eklov et al. 1999) to the Great Lakes (Ludsin et al. 2001).

Although field associations between oxygen and species assemblages are somewhat common, few field studies have attempted to link the oxygen-driven distribution of organisms in the field with laboratory-derived critical oxygen minima. We know of no current published literature that explicitly links the distribution of organisms to the warmwater dissolved oxygen criteria set by either the national (Chapman 1986) or Illinois water quality standards. Probably the most extensive combined field and laboratory project that tested a specific *a priori* oxygen criterion was initiated by Smale and Rabeni (1995a, b; Table 1). Oxygen minima in the eighteen headwater streams in which they worked ranged from 0.8 to 6.0 mg/L during spring through summer 1987 and 1988. Dissolved oxygen concentrations and temperatures were quantified at least monthly, and low dissolved oxygen concentrations were most frequent during warm days with low to no flow. A multivariate analysis revealed that oxygen minima affected fish assemblages more than temperature. Temperature maxima were only correlated with fish assemblage composition in well oxygenated sites. Thus, oxygen concentration was the "template" affecting fish success, with temperature only being important when oxygen concentrations were high.

Smale and Rabeni (1995b) used the laboratory-derived oxygen minima summarized in Table 1 to generate a hypoxia tolerance index. This index was calculated by multiplying the critical oxygen minimum for each species by its frequency of occurrence at each site. The values for each species were then summed to derive a site-specific index value. Mean dissolved oxygen and the hypoxia tolerance index were strongly positively correlated (r=0.85) among sites. Further, both oxygen minima and hypoxia index values differed among stream reach categories. Sites within the relatively stable, steep Ozark region streams had higher values than intermittent, lower gradient, more agricultural Prairie region streams. This research provides a framework by which streams might be characterized by fish responses to expected oxygen minima. Much like other indices, the fish assemblage integrates the long-term oxygen regime within streams, without frequent and costly water quality monitoring. However, the relative contribution of human-induced enrichment and natural factors to oxygen concentrations and hypoxia index values in the streams were not explored in this study.

Identifying critical oxygen minima appears to be a potentially useful way for characterizing systems and setting standards for regulation of dissolved oxygen. However, fluctuations in dissolved oxygen may also be important, influencing the ability for organisms to persist. Although we have a strong understanding of the mechanisms underlying fluctuations of dissolved oxygen in aquatic systems, the extent of cycling has not been well documented. Rather, most field studies quantifying oxygen concentrations in aquatic systems rely on temporally and spatially static point estimates. We do not have a clear set of expectations for the spatial extent, duration, frequency, or magnitude of dissolved oxygen fluctuations in lotic and lentic aquatic ecosystems. Nor do we clearly understand how organic enrichment and other physical changes affect many aspects of oxygen dynamics. Organic enrichment should increase the spatial extent of hypoxia within aquatic systems. Further, enrichment should lower mean dissolved oxygen concentrations, decrease minimum oxygen levels, and potentially dampen daily cycles in oxygen, with important implications for the structure of aquatic communities. Understanding the dynamics of oxygen should be particularly important for systems in which organisms have no refuge from hypoxic areas.

National water quality criteria for dissolved oxygen

National water quality criteria for dissolved oxygen are based primarily on research on the effects of low dissolved oxygen on the growth, survival, and reproduction of fishes. Chapman (1986) reviewed information on these relationships and developed standards now used by the USEPA. Chapman's recommendations are separated into criteria for coldwater (containing 1 or more species of salmonid [Bailey et al. 1970] or other coldwater or coolwater species that are similar in requirements) and warmwater fishes, and further divided into early life stages and other life stages (Table 2). Chapman's (1986) criteria reflect dissolved oxygen levels that are 0.5 mg/L above those that would be expected to result in slight impairment of production, thus representing values that lie between no impairment and slight impairment. Hence each value is a threshold below which some impairment is expected. However, there is possibility of slight impairment if criteria concentrations are barely maintained for considerable lengths of time (Chapman 1986).

For averages, the period of averaging is important and should be a moving average for the period of interest. Seven-day averages are used because the early life stages of fish exist for short periods and are very sensitive to oxygen stress during this period. If more than seven days are included in the averaging, oxygen stress to early life stages during the critical period may be underestimated. Longer averaging periods (e.g., 30 days) can be used for other life stages. Daily averages can be reasonably approximated from daily maximum and minimum readings if diel cycles are sinusoidal. If diel cycles are not close to sinusoidal, time weighted averaging can be used. However, with the increasing availability and affordability of data logging oxygen meters, estimating daily averages with these methods is becoming obsolete and monitoring dissolved oxygen concentrations over time is becoming easier and more accurate. For averaging, daily maximum values that are above air saturation cannot be used (e.g., they should be adjusted to 100% air saturation) because they will artificially inflate daily averages and do not represent any benefits to fishes (Stewart et al. 1967).

Comment: I agree.

Comment: This is still my recommendation.

Daily minimum values are near the lethal thresholds for sensitive species and are included to prevent acute stress and/or mortality of these sensitive species. During diel cycling of dissolved oxygen, minimum values below the acceptable constant exposure levels are tolerated as long as the properly calculated averages (see above) meet or exceed criteria and the minimum values are not obviously causing stress or mortality. In some cases (i.e. where large oscillations in diel cycles of dissolved oxygen concentrations occur), mean criteria are met but mean minimum criteria are violated repeatedly. In these cases, the mean minimum criteria are the regulatory focus.

In summary, daily minima are the lowest dissolved oxygen concentrations that occur each day (Table 4). Seven-day mean minima are calculated by averaging the daily minima across seven days (Table 4). If only a maximum and minimum daily temperature is available, a 7-day mean is calculated by averaging the daily means of the maximum and minimum and then averaging across seven days (Table 4). It would be more desirable to generate a time-weighted daily average of multiple (or continuous) temperatures, including the maximum and minimum. If daily maxima exceed the air-saturation concentration (in Table 4, 11 mg/L), then the maximum is adjusted to that concentration before inclusion in the means.

To account for the unique problems associated with point discharges in which dissolved oxygen concentrations can be manipulated (henceforth manipulatable discharges), Chapman (1986) recommended that daily minimum values below the acceptable 7-day mean minimum be limited to 3 weeks per year or that the acceptable one-day minimum be increased to 4.5 mg/L for coldwater fishes and 3.5 mg/L for warmwater fishes.

Comment: These were quantitative estimates assumed (by me and not objected to in reviews) to be adequate to address a real qualitative issue.

Under some natural conditions (e.g., wetlands), expected dissolved oxygen concentrations may be lower than means or minima set by the national criterion. Under these circumstances, the minimum acceptable concentration would be 90 percent of the natural concentration. A low "natural concentration" is defined by Chapman (1986) as naturally occurring mean or minimum dissolved oxygen concentrations that are less than 110 percent of the applicable criteria means, minima, or both.

Comment: This is how I attempted to address this real world issue. There were no objections during peer or public review.

Illinois water quality criteria for dissolved oxygen

The current Illinois general use water quality standard (Illinois Pollution Control Board, 302.206) permits dissolved oxygen concentrations to be less than 6.0 mg/L no more than 16 hours a day. At no time can dissolved oxygen concentrations decline below 5.0 mg/L. This criterion is similar to that set by the USEPA in 1976, which stated that dissolved oxygen concentrations should not decline below 5.0 mg/L in aquatic systems (USEPA 1976). This early national standard was influenced heavily by a joint National Academy of Sciences and National Academy of Engineering Report on water quality in 1972 that encompassed a single dissolved oxygen criterion for coldwater and warmwater species. Unlike the current national criterion (Chapman 1986, previous section), this earlier national standard and the current Illinois standard are based on a single minimum, rather than acknowledging that fluctuations may occur, necessitating the inclusion of an average. It also does not develop separate criteria for different taxonomic groups (e.g., coldwater versus warmwater fishes), systems (e.g., semi-permanent streams versus permanent lakes), or ecoregions (e.g., central corn belt versus interior river lowland).

Comment: This was not a well-documented criterion and was in error regarding Lake Titicaca D.OI

Comment: This was a much more sophisticated criterion than the 1976 criterion and in some respects (levels of protection) was a seed for the current criteria.

Comment: I will not comment in Illinois-specific issues as others are much, much more knowledgeable than I am.

Illinois EPA summarizes the state's water quality in accordance with Section 305(b) of the Clean Water Act (IL EPA 2002). Annual reports are generated that assess the quality of surface and groundwaters of the state. In general, surface waters are divided into streams, lakes, and Lake Michigan, of which we will focus primarily on assessments for streams and lakes. Several monitoring programs provide data for surface water quality assessment including the Ambient Water Quality Monitoring Network (AWQMN), Intensive Basin Surveys (IBS), Facility-Related Stream Surveys (FRSS), the Ambient Lake Monitoring Program (ALMP), the Illinois Clean Lakes Monitoring Program (ICLP), the Volunteer Lake Monitoring Program (VLMP), and the Source Water Assessment Program (SWAP).

Illinois EPA has adopted several designated use categories for water including aquatic life, primary contact (swimming), secondary contact (recreation), public water supply, fish consumption, and indigenous aquatic life (ILEPA 2002). In this report, we summarize the applicability of dissolved oxygen standards primarily for the aquatic life use designation, which is intended to provide full support for aquatic organisms. The indigenous aquatic life designation is reserved for systems in Illinois which do not fall under Illinois EPA's general use designation (e.g., Lake Calumet and shipping canals). We do not explore the applicability of standards for these nonindigenous use waters, although the criterion for dissolved oxygen is a minimum of 4.0 mg/L, 1 mg/L lower than the statewide overall use standard.

Illinois EPA's approach toward determining whether a water body meets the aquatic life designation is to first use a relevant biotic indicator such as the Index of Biotic Integrity for fish (IBI; Karr 1981, Karr et al. 1986, Bertrand et al. 1996) or Macroinvertebrate Biotic Index (MBI) (IL EPA 1994). Secondarily, the Illinois EPA turns to legally established narrative and numeric water quality standards, such as the one set for dissolved oxygen. This approach is valid because it uses accepted biological indicators to integrate the overall effects of water and habitat quality within a stream or lake.

Adherence to water standards such as the one set for dissolved oxygen can then be used to identify the causes of impairment.

Aquatic life use in Illinois streams is evaluated based on a "weight of evidence" approach endorsed by USEPA (IL EPA 2002). If possible, IBI and MBI data are evaluated. These biotic integrity values are compared to established criteria and then stream reaches are categorized as being in full, partial, or nonsupport of the aquatic life designated use. If index values are incomplete or available, then water chemistry data are used to assess quality. It is under this scenario that the Illinois standard for dissolved oxygen might be used to determine whether a stream reach is in compliance with this use designation. Water quality data for streams derive from several sources including the IBS, which generates IBI and MBI data and two or three water chemistry samples at intensive survey basin sites. AWQMN stations also generate water chemistry data to be used in assessments (about nine samples per year). FRSS stations are located at point sources and provide an additional two or three water chemistry samples per station. Although this combination of biological and water quality data provide a useful general assessment of stream reach integrity, dissolved oxygen concentrations deriving from these sampling regimes are limited at best and probably do not capture the natural daily and seasonal fluctuations that occur. Limited point estimates of dissolved oxygen concentration may not fully reflect the oxygen dynamics occurring in stream reaches.

In recognition of the limitations of single water chemistry estimates, Illinois EPA uses criteria based on the age and abundance of water quality samples (IL EPA 2002). For example, a specific water quality criterion can be used to assess aquatic life use if ten or more samples less than 5 years old are available. Under these conditions, a system would be impaired for aquatic life use if dissolved oxygen concentrations declined below the state standard in greater than 10% of samples. If greater than 25% of samples are below the standard, then the reach is considered severely impaired. This approach better integrates potential fluctuations in dissolved oxygen concentration. However, if minimum dissolved oxygen criteria used by the state are too conservative, minima within natural fluctuations in oxygen concentration may be interpreted as impairment. Because the Illinois EPA designation process requires that biologists account for other site-specific factors such as habitat quality and biotic integrity indicators, the likelihood that a system would be considered impaired solely as a function of low dissolved oxygen concentration is low.

A similar approach is used for the assessment of aquatic life use in inland lakes in Illinois (IL EPA 2002). Chemical, physical, and biological data derive from many sources, and include as many as 2,000 lakes. Probably the most intensive survey program is the ALMP, which includes about 50 lakes per year. Lakes are monitored five times per year, and dissolved oxygen profiles are included in the sampling protocol. Other data derive from the ILCP and VLMP. The Illinois EPA's Aquatic Life Use Impairment Index (ALI) is the primary indicator used for assessing the level of support of aquatic life use. The ALI integrates the mean trophic state index (TSI; Carlson 1977), macrophyte coverage, and concentration of nonvolatile suspended solids. ALI values increase with increasing impairment (e.g., high productivity, high vegetation coverage, high suspended solids).

These ALI values are used to score each lake for overall use support. The overall use scores are then averaged for a lake when more than one measurement is available. Low dissolved oxygen concentration is considered as a potential cause of impairment (i.e., when the mean overall use score is high) if (1) concentrations below the minimum standard (5 mg/L at one foot below the surface) occur at least once during a sampling year or (2) the lake mean is consistently below this minimum. A fish kill corresponding with low oxygen would also qualify for designation of low oxygen as a potential cause of use impairment.

The 2002 IEPA Water Quality (305b) report summarized aquatic life use support for Illinois streams and lakes through September 2000. Of the 15,491 miles of streams that were assessed, 5,450 miles were categorized as being in partial or no support of the use designation. For 2,962 miles of the impaired stream reaches, low dissolved oxygen due to organic enrichment was implicated as a potential cause of impairment. Of 148,134 acres of lakes (N=352 lakes), 3,948 acres (N=2 lakes) were categorized as failing to support overall use. In addition, 121,648 acres (N=203 lakes) were in partial support. Organic enrichment leading to low dissolved oxygen was implicated as a cause of impairment for 80,135 acres (N=59 lakes). Clearly, low dissolved oxygen concentrations, as they are now defined by the state standard, are an important contributor to impairment of designated use in Illinois surface waters.

Assessment of IL water quality standard and recommendations

Based on our review of the literature and current standards, the current IL EPA methods for assessing health and impairment are adequate, but the Illinois dissolved oxygen standards are in need of further refinement. In particular, the focus on biological integrity for initial assessment of freshwater habitat health is the appropriate, progressive approach and the state should continue its focus on biotic integrity. However, the dissolved oxygen standards, based on daily minima, are likely too conservative for freshwater systems in this region and should be modified to more realistically reflect local conditions. In this document, we provide state-wide recommendations. However, with increased scientific information, region- or basin-specific standards likely will more realistically set criteria based upon expected conditions in oxygen, other water quality parameters, and habitat characteristics.

Comment: I agree that a one number standard will be either higher than needed for realistic acute protection, or lower than needed for realistic chronic protection.

Our recommendations are to generally adopt standards of Chapman (1986) for warmwater systems, with some modifications based on research that has been completed since this document was produced (see Table 4 for example of calculations). Thirty-day moving averages identified in Chapman (1986) are not included in our recommendations because (1) they are not appropriate for early life history stages in which development occurs at a much shorter time scale and (2) responses of all life stages to changes in oxygen concentrations are likely better captured and more biologically relevant during shorter windows of time (i.e., 1-7 days).

Comment: This is true IF the mean values are not lower than those recommended in the national criteria document (i.e. 5.5 mg/L).

Our recommendations for the State of Illinois are seasonal to (1) protect early life stages (i.e., eggs, embryos, and larvae; typically 30-d post spawning) of spring-spawning fish species (Table 3) and (2) incorporate the expected fluctuations and reduced maximum capacity of dissolved oxygen during summer months when juvenile or adult stages are largely present. Although few supporting data are available, species with offspring produced during non-spring months (Table 3) likely have adaptations that allow them to persist under natural oxygen concentrations expected during summer. Thus, our recommended criteria for non-spring months should be sufficiently protective unless further research necessitates refinement. Our recommendations are summarized in Table 5.

Comment: As noted earlier, this may or may not be the case. I leave it to Illinois biologists to evaluate this conclusion.

Spring through Early Summer

Comment: These criteria seem adequate to me.

- A 1-day minimum of 5.0 mg/L during spring through early summer (i.e., March 1 through June 30). This recommendation is based on our re-analysis of Chapman (1986)'s daily minima (5 mg/L) for early life stages of fish (Figure 1) and spawning times summarized in Table 3.

- A 7-day mean of 6.0 mg/L during spring through early summer (i.e., March 1 through June 30). This mean is defined as the average of the daily average values and should be based, whenever possible, on data collected by semi-continuous data loggers. If this is not possible, daily averages can be estimated from the daily maximum and minimum values if daily fluctuations in dissolved oxygen are approximately sinusoidal. If daily fluctuations are not sinusoidal, then appropriate time-weighted averages must be used. Regardless of method (data loggers or daily maximum and minimum), maximum values used to calculate means should not exceed the air saturation concentrations for prevailing temperature and atmospheric pressure (see Table 4 for example).

Other Months

Comment: These criteria do not protect against effects of low mean DO values on fish growth. They would be adequate if they added a 7-day mean value of 5.5 mg/L. Of course, they also require an analysis of species spawning during this period.

- A 1-day minimum of 3.5 mg/L during the remainder of the year (i.e., July 1 through February 28 or 29). This recommendation is based on our re-evaluation of Chapman (1986)'s daily minima (3 mg/L) for adult life stages and fish spawning times summarized in Table 3. It also is sufficiently higher than the critical minima for survival found for many common species of fish (e.g., see Table 1).

- A 7-day mean minimum of 4.0 mg/L during periods during the remainder of the year (i.e., July 1 through February 28 or 29). Mean minimum is defined as the average of the minimum daily recorded dissolved oxygen concentrations. Seven-day periods can represent any seven consecutive days and should be based on moving averages when possible (see Table 4).

Other Considerations

- Manipulatable discharges, defined earlier as those in which dissolved oxygen concentrations may be manipulated and are generally serially ~~correlated~~, present a special case where a seven-day mean minimum can be achieved while frequently lowering conditions to the daily minimum and likely exposing aquatic life to oxygen stress (Chapman 1986). As a result, two areas in proximity to manipulatable discharges should be monitored closely (e.g., continuously). One measurement should be taken at the zone of mixing; the other monitoring station should be downstream, at an area beyond the direct influence of the mixing zone. During the non-spring months when seven –day mean minima are allowable (July through February; Table 5), we recommend that the occurrence of daily minima values at the recommended one-day minimum (3.5 mg/L) should be limited to no more than 3 weeks total per year or that the one-day minimum be increased to 4.0 mg/L for areas in which manipulatable discharges occur. These guidelines will reduce the likelihood of exposing aquatic life influenced by manipulatable discharges to oxygen stress.

- In cases where diel fluctuations of dissolved oxygen are extreme, systems might meet mean criteria but still violate minima. Unusually large diel fluctuations are symptomatic of eutrophication and in these cases the minima should be the focus of monitoring and assessment activities.

- Although we recommend the use of continuous monitoring with data loggers, the detection of the violation of daily minima values will be more likely using this method. Thus, the detection of violations of daily minima using relatively infrequent spot checks may be indicative of larger problems than those measured with continuous monitoring. This potential issue should be acknowledged during monitoring and assessment.

- In streams, we recommend that dissolved oxygen measurements be measured in pool or run habitats (not riffles) in the water column in or near the thalweg at 67% of stream depth. Readings in streams should not be taken at the sediment/water interface, as this is a region where natural oxygen sags are expected. We recognize that many sensitive taxa reside in the benthos and may be negatively affected by hypoxia in this zone. Thus, future criteria including expected oxygen concentrations at the sediment/water interface may be useful. Research that quantifies relationships between water-column dissolved oxygen concentrations and those at the sediment boundary would be helpful for determining such standards. Natural inundation of potentially hypoxic groundwater also must be taken into account when assessing stream oxygen. In lakes, readings should be taken 1 m below the surface in the limnetic zone above the deepest point of the lake.

Comment: This whole paragraph is a good example of the type of implementation documentation that is needed for adequate application of DO standards.

- Lake Michigan represents the only large-scale, native coldwater fisheries system in Illinois and thus should be considered separately from our recommendations in this document that are focused on warmwater systems. We recommend that coldwater and coolwater fisheries associated with Lake Michigan be held to standards more appropriate for resident fish communities, which have distinctly higher oxygen requirements (Chapman 1986). The current IL EPA recommended daily minimum of 5 mg/L is adequate for the coldwater and coolwater fishes in Lake Michigan (see Chapman 1986 review of tolerance of coldwater species) unless further research indicates otherwise.

- Wetlands differ from lakes and streams in that they are often naturally productive systems with low oxygen. Wetland habitats are protected by numerous laws and other protective measures, but there is little information regarding water quality standards for wetlands. Further, wetlands are highly variable and a single, comprehensive standard may be difficult to achieve. As such, we cannot make recommendations regarding wetlands except that they should not be held to the standards we recommend for streams and lakes. Future research on water quality and associated methods and standards in Illinois should include wetlands.

- It should be noted that the criteria we recommend for streams and lakes in Illinois represent worst case conditions and thus the mimimum values that we recommend, or values near the mimimum, should not be commonplace in space or time throughout the state. Systems in which dissolved oxygen concentrations decline frequently to the recommended minima should not be designated as being in full support of aquatic life use. The frequency by which minima should be allowed to occur should depend on season. During spring when early life stages are present, weekly or more frequent declines to daily 1-d minima may be sufficient to cause stress to developing eggs, embryos, and larvae, compromising success of populations that reproduce over relatively short time periods. Conversely, twice weekly or more frequent declines to 1-d minima may be tolerated by adults during other months. Given the dearth of scientific information available, these estimates can only be made based on our knowledge of the timing of reproductive events and short-term responses of adults to hypoxia. Managers of aquatic systems in Illinois should strive to continuously improve conditions rather than avoid violations of state minimum standards. As mentioned earlier, this may be best achieved by primarily monitoring the biological components of aquatic systems (e.g., biotic integrity). We stress that focusing on biotic integrity in monitoring and assessment activities should continue as a major focus for the state of Illinois. Aquatic communities reflect the overall health of aquatic ecosystems, and can thus integrate all stressors. Water quality monitoring (e.g., continuous dissolved oxygen concentrations) and habitat assessment is critical for identifying the cause of changes in biotic integrity. Further research on specific relationships between biotic integrity, dissolved oxygen, and other water quality and habitat factors is needed.

- Research that quantifies relationships between biotic integrity and dissolved oxygen concentrations in Illinois streams will allow for development of physiologically based, hypoxic indices (e.g., Smale and Rabeni 1995b), which may prove very useful for the assessment and monitoring of surface water habitats in Illinois. Laboratory-based estimates of physiological tolerance of low dissolved oxygen concentrations often fail to integrate the host of environmental factors affecting growth, survival, and reproductive viability. Thus, future research should quantify responses under more realistic conditions.

Gaps in our knowledge

Dissolved oxygen criteria and other standards for assessing ~~freshwater ecosystem~~ health and function should continue to evolve as more information on relationships between ecosystem health and the variety of measured variables is gathered. Hence, all recommendations made within this document must be considered within the context of our current knowledge of these relationships and may need further modification as more information becomes available. There are many different knowledge gaps and research needs in Illinois, as well as at the national level. In particular, we feel that further research on quantitative relationships between diel oxygen curves, nutrient status, and primary production will provide very important information for further understanding freshwater ecosystem health and function and further modifying water quality standards. In particular, research that directly quantifies these relationships, rather than correlational analyses will be of great value for establishing realistic water quality standards. Research in this area should also focus on how diel oxygen curves are related to daily and longer-term minima and average values, and how biological (primary producer communities) and physical (nutrients, light, flow, substrates) factors interact to influence them. A more precise understanding of these relationships in different types of surface water habitats will greatly enhance our ability to develop more precise and meaningful criteria.

There is also a great need for further research on the use of biological data for assessing freshwater ecosystem health and integrity and establishing water quality standards. While dissolved oxygen criteria may accurately reflect oxygen stress related to nutrient and/or organic enrichment, biological monitoring can reflect oxygen status as well as a wide array of other potential stressors such as other forms of pollution (e.g., pesticides, metals) and physical habitat degradation, and integrate conditions over space and time (e.g., Steingraeber and Wiener 1995, Rabeni 2000, Griffith et al. 2001). Because of this and the many other benefits of biological monitoring (e.g., see Loeb and Spacie 1993, Barbour et al. 1999, and Barbour et al. 2000 for review of the many benefits of biological monitoring), and the national focus on biomonitoring, we ultimately recommend that Illinois move further towards the use of biological data for assessing freshwater habitat health and function and setting water quality criteria in Illinois. In order for this to happen, region and habitat specific tolerance values, metrics, and multimetric indices that best reflect health and function will need to be developed, tested, and calibrated throughout the state. Along with this, research on region and habitat specific reference conditions will be needed. As with research on dissolved oxygen dynamics, research that moves away from only correlational analyses and focuses more on isolating and directly testing variables will be of most value.

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Table 1. Critical minimum dissolved oxygen concentrations for 35 species of common headwater stream fishes determined from laboratory experiments (Smale and Rabeni 1995b).

		Critical minimum dissolved oxygen concentration (mg/L)	
Species	Rank	Mean	95% CI
Brook silversides	1	1.59	1.70-1.48
Rosyface shiner	2	1.49	1.67-1.30
Ozark minnow	3	1.45	1.57-1.33
Bleeding shiner	4	1.35	1.47-1.23
Smallmouth bass	5	1.19	1.29-1.08
Redfin shiner	6	1.17	1.25-1.08
Black bullhead	7	1.13	1.27-1.00
Rainbow darter	8	1.10	1.21-0.99
Hornyhead chub	9	1.06	1.20-0.92
Bluntnose minnow	10	1.04	1.11-0.97
Suckermouth minnow	11	1.04	1.09-0.98
Striped shiner	12	1.03	1.10-0.95
Bigmouth shiner	13	1.02	1.07-0.97
Fantail darter	14	0.98	1.06-0.91
White sucker	15	0.98	1.16-0.79
Common shiner	16	0.97	1.06-0.89
Central stoneroller	17	0.95	1.04-0.86
Sand shiner	18	0.93	1.11-0.75
Plains topminnow	19	0.92	1.02-0.82
Red shiner	20	0.91	0.99-0.82
Blackspotted topminnow	21	0.88	1.25-0.51
Blackstripe topminnow	22	0.88	0.90-0.85
Orangethroat darter	23	0.86	0.98-0.73
Creek chub	24	0.84	0.90-0.79
Southern redbelly dace	25	0.74	0.80-0.69
Fathead minnow	26	0.73	0.79-0.67
Johnny darter	27	0.70	0.76-0.64
Golden shiner	28	0.70	0.75-0.65
Largemouth bass	29	0.70	0.77-0.63
Longear sunfish	30	0.68	0.74-0.63
Bluegill	31	0.66	0.74-0.57
Green sunfish	32	0.63	0.68-0.57
Orangespotted sunfish	33	0.62	0.68-0.56
Slender madtom	34	0.60	0.67-0.54
Yellow bullhead	35	0.49	0.52-0.46

Table 2. USEPA water quality criteria for ambient water column dissolved oxygen concentration from Chapman (1986). Early life stages include all embryonic and larval stages and juveniles to 30 days post-hatching.

Period/Value	**Early life stages**	**Other stages**
30 day mean	NA	5.5
7 day mean	6.0	NA
7 day mean minimum	NA	4.0
1 day minimum	5.0	3.0

Table 3. Summary of spawning temperatures or times for common warmwater fish taxa (by genus or species) in Illinois. Summaries derive from Pflieger (1997) and B.M. Burr, personal communication, Department of Zoology, Southern Illinois University, Carbondale.

Common name	Genus/Species	Months or Temperatures of Spawning	Season of Spawning
Lampreys	*Ichthyomyzon* and *Lampetra*	March through May	Spring
Paddlefish	*Polyodon spathula*	April through May	Spring
Goldeye and Mooneye	*Hiodon*	March through April	Spring
Mudminnow	*Umbra limi*	April	Spring
Pikes	*Esox*	March through April	Spring
Creek chub	*Semotilus atromaculatus*	April through May	Spring
Hornyhead chub	*Nocomis biguttatus*	April through May	Spring
Stonerollers	*Campostoma*	15°C	Spring
Redhorse	*Moxostoma*	April through May	Spring
Hogsucker	*Hypentelium nigricans*	April through May	Spring
Sucker	*Catostomous*	March through May	Spring
Spotted sucker	*Minytrema melanops*	April through May	Spring
Chubsucker	*Erimyzon*	April through May	Spring
Pirate perch	*Aphredoderus sayanus*	May	Spring
Sculpin	*Cottus*	March through April	Spring
Temperate bass	*Morone*	April through May	Spring
Rock bass	*Ambloplites rupestris*	April through May	Spring
Crappie	*Pomoxis*	April through May	Spring
Walleye/Sauger	*Sander*	April	Spring
Yellow perch	*Perca flavescens*	April through May	Spring
Logperch	*Percina caprodes*	April	Spring
Darters	*Etheostoma*	March through May	Spring
Freshwater drum	*Aplodinotus grunniens*	April through May	Spring
Sturgeons	*Acipenser* and *Scaphyrhynchus*	April through June	Spring-Early Summer
Gar	*Lepisosteus*	April through June	Spring-Early Summer
Skipjack herring	*Alosa chrysochloris*	April through June	Spring-Early Summer
Gizzard/threadfin shad	*Dorosoma*	April through June	Spring-Early Summer
Common carp	*Cyprinus carpio*	March through June	Spring-Early Summer
Golden shiner	*Notemigonus crysoleucas*	April through June	Spring-Early Summer
Dace	*Rhinichthys*	April through June	Spring-Early Summer
Silverjaw minnow	*Ericymba buccata*	May through June	Spring-Early Summer
Southern redbelly dace	*Phoxinus erythrogaster*	May through June	Spring-Early Summer
Minnows	*Hybognathus*	May through June	Spring-Early Summer
Minnows	*Pimephales*	May through June	Spring-Early Summer
Buffalo	*Ictiobus*	April through June	Spring-Early Summer
Carpsuckers	*Carpiodes*	April through June	Spring-Early Summer
Catfish	*Ictalurus*	May through June	Spring-Early Summer
Madtoms	*Noturus*	May through June	Spring-Early Summer
Black bass	*Micropterus*	May through June	Spring-Early Summer
Other *Percina*	*Percina*	Varies - April through June	Spring-Early Summer

Table 3 continued.

Trout perch	*Percopsis omiscomaycus*	March through August	Spring-Summer
Killifish	*Fundulus*	May through August	Spring-Summer
Mosquitofish	*Gambusia affinis*	May through August	Spring-Summer
Brook silverside	*Labidesthes sicculus*	May through August	Spring-Summer
Sunfish	*Lepomis*	May through August	Spring-Summer
Chubs	*Hybopsis*	Summer	Summer
Shiners	*Notropis*	May through July	Summer
Flathead catfish	*Pylodictus olivaris*	June through July	Summer
Darters	*Ammocrypta*	Unknown	Unknown

Table 4. Example calculations for 1-d minimum, 7-d mean, and 7-d mean minimum dissolved oxygen concentrations (mg/L; adapted from Chapman 1986). If only a maximum and minimum daily temperature is available, a 7-day mean is calculated by averaging the daily means (maximum plus minimum divided by two) and then averaging across seven days (see below). It would be more desirable to generate a time-weighted daily average of multiple (or continuous) daily temperatures, including the maximum and minimum.

Day	Daily Max	Daily Min	Daily Mean
1	9.0	7.0	8.0
2	10.0	7.0	8.5
3	11.0	8.0	9.5
4	12.0*	8.0	9.5*
5	10.0	8.0	9.0
6	11.0	9.0	10.0
7	12.0*	10.0	10.5*
1 day minimum		7.0	
7 day mean min.		8.1	
7 day mean			9.3

*Maximum value exceeds air saturation concentration of 11 mg/L.

Table 5. Recommended water quality criteria for ambient water column dissolved oxygen concentration in Illinois surface waters (excluding the Great Lakes, Great Lake coolwater tributaries, and wetlands).

Period/Value	Spring (March 1-June 30)	Non Spring (July 1-February 28 or 29)
1-d minimum	5.0	3.5
7-d mean	6.0	-
7-d mean minimum	-	4.0

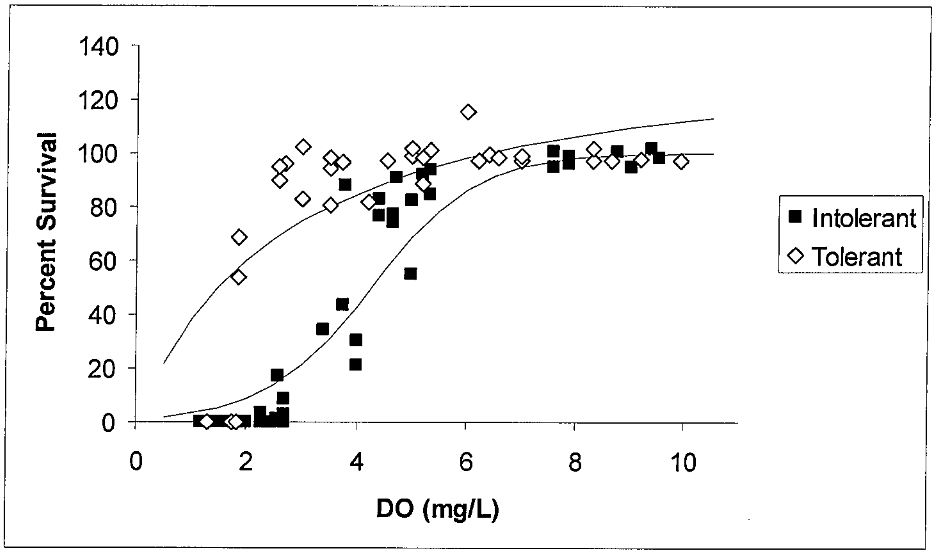

Figure 1. Percent survival (relative to controls) of "tolerant" (i.e., largemouth bass, black crappie, white sucker, white bass) and "intolerant" (i.e., northern pike, channel catfish, walleye, and smallmouth bass) fish larvae and embryos (adapted from Chapman 1986).

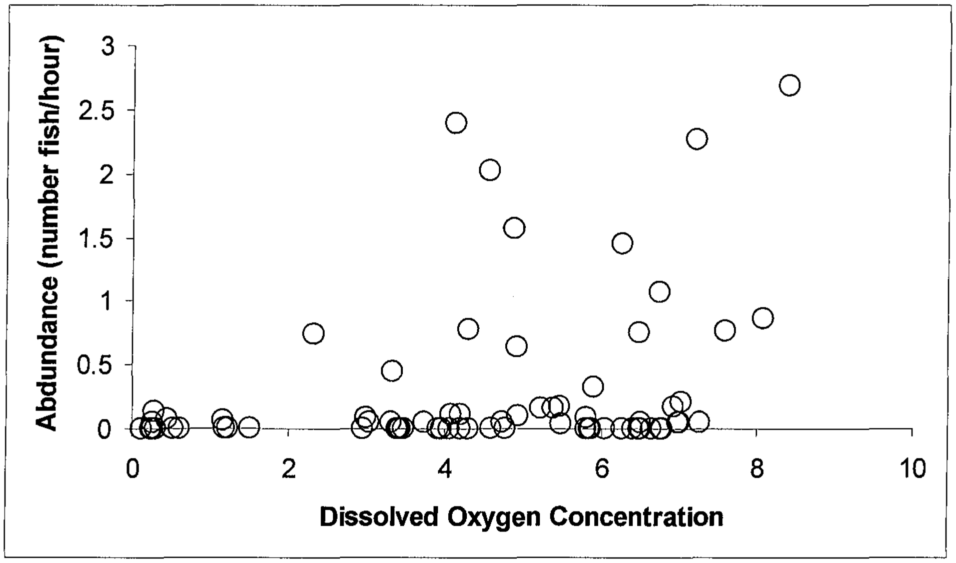

Figure 2. Effect of vertical distribution in dissolved oxygen on the occurrence of threadfin shad and hybrid striped bass in Lake of Egypt, Illinois during summer through fall 2003. Fish avoided the deep, hypolimnetic water of the lake when dissolved oxygen concentrations declined below 4 mg/L.

Cowger, Donna

From: Cowger, Donna on behalf of Harsch, Roy M.

Sent: Thursday, July 22, 2004 8:52 AM

To: 'Amessina@IERG.org'; 'Deborah.Williams@epa.state.il.us'; 'Jdonahue@geneva.il.us'; 'lfrede@cicil.net'; 'Stefanie.Diers@epa.state.il.us'; 'Toby.Frevert@epa.state.il.us'; 'Cskrukrud@earthlink.net'; 'AEttinger@elpc.org'; 'bwentzel@prairierivers.org'; 'Syonkauski@dnrmail.state.il.us'; 'KHodge@IERG.org'; 'Richard.Lanyon@mwrdgc.dst.il.us'; 'claire@posegate-denes.com'

Subject: DO Proposal

At the first hearing in this matter Toby discussed the IEPAs willingness to discuss this proposal and potential implementation rules. He has set aside the morning of August 12th for a Stakeholder meeting prior to the afternoon hearing in Springfield. Below is a list of my thoughts on the items that should be included in the IEPA Implementation Rules for the DO proposal. These are consistent with comments that Jim Garvey got from Chapman that the first full paragraph on page 39 of Jim's report "is a good example of the type of implementation documentation that is needed for adequate application of DO standards".

1. DO should be measured with continuous monitoring devices or approved methods for instantaneous results. These would include DO meters and appropriate wet chemistry methods. The rule should cite the applicable USEPA test method, etc.

2. A single reading below the proposed daily minimum would constitute a violation.

3. Values above saturation should be reduced to the DO level at saturation in calculating daily or long term averages.

4. In streams, DO should be:

   a. measured in pool or run habitats not riffles,

   b. taken at 2/3 or 67% of stream depth,

   c. and not taken at the sediment/water interface.

5. In lakes, DO should be taken one meter below the surface in the limnetic zone above the deepest point of the lake.

Please let me know if you would like to participate in this meeting. My phone number is 312 5691441 and my E Mail address is rharsch@gcd.com.

Roy Harsch

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Assistant to Roy M. Harsch
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R04-25
Exh. 11
8/12/04

"Our aim:
To fear God,
tell the truth
and make money."

H.C. Paddock
1852-1935

Opinion

Fence Post

Fight effort to lower Fox oxygen criteria

The Illinois Association of Wastewater Agencies is an organization whose members are concerned with clean streams and are responsible for wastewater collection and treatment in the state of Illinois. Members of IAWA include several water reclamation districts along the Fox River.

While IAWA claims it is concerned with clean rivers, in April 2004, IAWA proposed a rule to the Illinois Pollution Control Board that would lower the Illinois dissolved oxygen criteria from 5.0 mg/L to 3.5 mg/L.

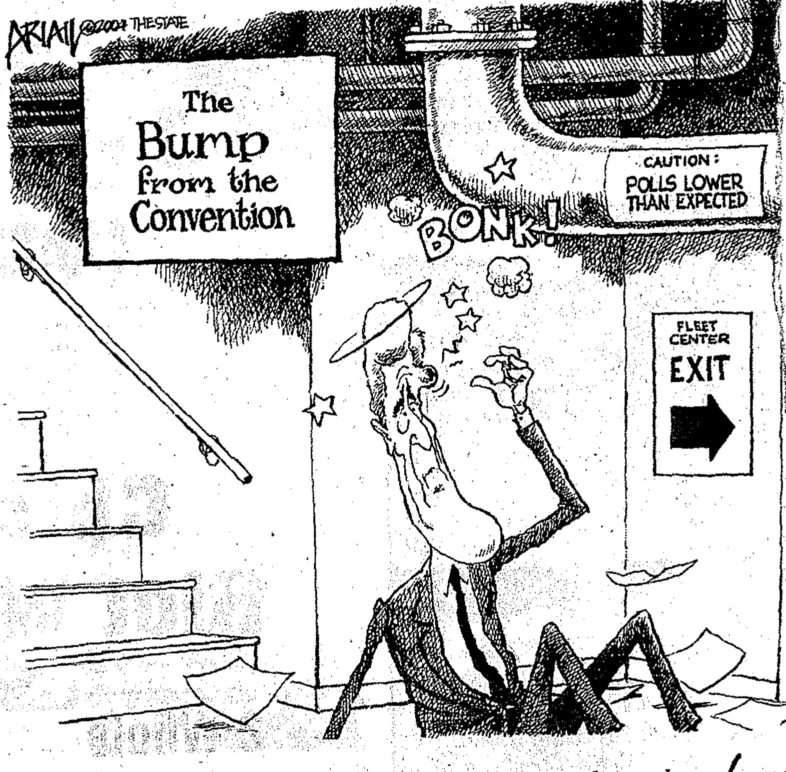
The proposed reduction in dissolved oxygen criteria will not improve the condition of Illinois streams such as the Fox River. In fact, it will have the opposite effect. In 2002, the Fox River was categorized as impaired by the Illinois Environmental Protection Agency.

One of the reasons for the river's impairment is low dissolved oxygen. Low dissolved oxygen levels in the Fox River will negatively impact fish species that spawn in late summer, and sport fish such as small mouth bass are sensitive to low dissolved oxygen levels. Freshwater mussels and other aquatic macroinvertebrates are also negatively affected by low dissolved oxygen.

Instead of requesting to lower the state's dissolved oxygen standard, IAWA, and its affiliated reclamation districts, should be leaders in ensuring that dissolved oxygen levels in Illinois Rivers including the Fox remain high.

Everyone can make a difference in protecting the Fox River ecosystem, and I ask you to take action today by calling the Illinois Pollution Control Board and asking them to deny IAWA's request to lower the dissolved oxygen criteria in Illinois.

David J. Horn
Aurora



~~Elburn, Sugar Grove could have market~~

~~The Sugar Grove Farmers Market volunteers would like an opportunity to answer a newspaper's question of two weeks ago, which asked Elburn residents "Should Elburn have a Farmers Market?" We say, Absolutely, but we also offer an invitation to Elburn farmers, small businesses and residents. Join the Sugar Grove Market and instead of two young starting markets, we can form one very strong market.~~

~~The volunteers have worked hard on planning the Sugar Grove market. We have also learned something new every week that the market has operated since our starting date of June 19. We have the groundwork laid and we would love to share what we have learned so far with our Elburn neighbors.~~

~~Elburn and Sugar Grove both seem to be facing the inevitable growth that we keep hearing is coming to our towns. By joining us in the market for now, we can both become stronger. Eventually, when both areas have enough residents supporting the market, perhaps then we could split into two markets. But hopefully, as friendships grow, an even nicer idea would be that we would never want that day to come and we could remain one strong market serving not only our communities but towns like Big Rock, Kaneville, Plano and anyone else who would like to partici-~~

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Exh. 12
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ILLINOIS
DEPARTMENT OF
NATURAL
RESOURCES

ILLINOIS
NATURAL
HISTORY
SURVEY

July 30, 2004

Pat Quinn
Lieutenant Governor
State of Illinois
Office of the Lieutenant Governor
James R. Thompson Center, Suite 15-200
Chicago, IL 60601

Dear Lt. Governor Quinn:

I am pleased to offer the following comments regarding your letter of June 24, 2004 on the dissolved oxygen proceedings now occurring before the Pollution Control Board. These comments are based upon my review of the materials submitted to the PCB, including the report by Garvey and Whiles titled "An Assessment of National and Illinois Dissolved Oxygen Water Quality Criteria". They are also derived from an independent review of the literature, which included some studies not referenced in the above document, and on my professional judgement. I have been involved in analyzing the impacts of various water quality parameters on aquatic life since the late 1960s.

The present criteria of "not less than 6.0 mg/L during at least 16 hours of any 24 hour period, nor less than 5.0 mg/L at any time" has a degree of conservatism build in that should be protective of all aquatic life in Illinois. I find the proposed change "during the months of July through February, dissolved oxygen shall not be less than a one day minimum concentration of 3.5 mg/L, and a seven day mean minimum of 4.0 mg/L" as not being conservative enough, and of potentially endangering some aquatic life in the state. Some of the reasons I reach this conclusion are addressed below.

The Garvey and Whiles report lumps Illinois fish into warm water and cold water. Many biologist recognize that there are many fishes that would fall into a more intermediate category of cool water fish. While there is no clear definition of what species could be classified as cool water fish, there would be general agreement that some fish communities thrive under conditions of more moderate summer temperatures and in well oxygenated water. Some of our finer Smallmouth bass streams would fall into this category, as would some of our spring feed streams and some of our wooded streams and lakes particularly in northeastern Illinois. The State of Oregon differentiates between salmon spawning streams, and water bodies that support cool water and warm water aquatic species. Their water quality standards for the Umatilla subbasin are a DO level for cool-water aquatic life of not less than 6.5 mg/L and the minimum for warm-water aquatic life of not less than 5.5 mg/L. The Illinois DNR has developed a preliminary list of

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R04-25
Exh. 13
8/12/04

some 55 streams and rivers in the state that they would classify as cool water. Again, while there is no strict definition of cool water streams, there is a recognition that fish communities in these streams differ (need generally better water quality) from other warm-water streams and rivers in the state.

There is a rationale in the literature for the 5 mg/L minimum, and while further studies have modified this level lower for a number of species, there are other species that probably would not be protected at lower levels. Dowling and Wiley (1986) did a review related to this issue on "The effects of dissolved oxygen, temperature, and low stream flow on fishes: a literature review". In discussing minimum oxygen standards they cite the work of Ellis (1937) who concluded that a minimum summer dissolved oxygen concentration of 5 mg/L was necessary to support good, mixed fish faunas. They also cited the work of Coble (1982), who's work in Wisconsin indicated that with a measure of dissolved oxygen concentration of daytime or averaged values, the level of 5 mg/L could be identified as a point of departure between good and poor fish populations. Chapman (1986), in a discussion of field studies, cited the above two references plus a study by Brinley (1944) who conducted a two year biological survey of the Ohio River Basin. Brinley concluded that his field results showed that a concentration of dissolved oxygen of 5 mg/l seemed to represent a general dividing line between good and bad conditions for fish.

Smale and Rabeni (1995b), in their studies of Missouri headwater streams, found that DO minimum values influenced species composition up to approximately 4-5 mg/L, which is similar to recommended standards for oxygen minima in warm-water streams (Welch and Lindell 1992). They also stated in this paper that dissolved oxygen requirements for long-term persistence of stream fishes are typically much higher than those determined in laboratory survival tests. Garvey and Whiles (2004) discuss this effect in their paper, and state that growth of a number of fish is reduced at 4 to 5 mg/L. They cite the work of Brake (1972) who found that growth of Largemouth bass was reduced by as much as 34% at DO concentrations of 4 to 5 mg/L, a level that had little effect on growth in the laboratory. And it is well documented in the literature that Largemouth bass are more tolerant of low dissolve oxygen levels than Smallmouth bass. Furimsky et al (2003) found that progressive reductions in water oxygen levels had a much greater impact on blood oxygen transport properties, acid-base status, ventilation rates, and cardiac variables in Smallmouth bass than in Largemouth bass.

The document by Garvey and Whiles recognizes that the egg and larval stages of fish are more sensitive to low DO levels than juveniles and adults. They suggested more stringent criteria for March through June (the spawning period for most fish), with lower DO minimum levels the rest of the year. However, many fish continue to spawn until later in the summer, and sunfishes and bass in particular will re-nest a number of times if early attempts to spawn fail or are delayed. In the testimony by Sheehan (Exhibit 7) he stated that "most Illinois fish species spawn in the spring and summer seasons, so the months of April through August are without doubt within the 'early life history stages present' period."

Garvey and Whiles recognize that "some macroinvertebrates, such as burrowing mayflies and freshwater mussels are less tolerant of prolonged exposure to hypoxic conditions than most fish".

Chen, Heath and Neves (2001) did a comparison of oxygen consumption in freshwater mussels during declining dissolved oxygen concentrations. They found for P. cordatum (Ohio pigtoe) found in southeastern Illinois, and Villosa iris (Rainbow) found in central and northeastern Illinois, that the former should have DO levels above 3.5 to 4.0 mg/L and the latter above 6 mg/L to ensure that aerobic metabolism remains relatively unchanged.

Garvey and Whiles state near the end of their document that DO standards in Illinois, based on daily minima, are **likely** (my emphasis) too conservative. However, there seems to be enough evidence in the literature to indicate that the new DO standards that they recommend may not be conservative enough to protect some T&E species (most of which we have little data for) or coolwater fish assemblages. The authors go on to state that "with increased scientific information, region- or basin-specific standards likely will more realistically set criteria based upon expected conditions in oxygen, other water quality parameters, and habitat characteristics." It seems that given the above it would be more prudent to keep the present standards and allow for exemptions on particular water bodies where it can be demonstrated that lower DO minimums could be protective of the aquatic species within that water body. Criteria would have to be established for making the case for an exemption.

Another approach could be to convene a panel of experts on the topic, including biologists familiar with Illinois streams, that could review the literature and available information and come up with recommendations, possibly by grouping water bodies with somewhat similar species compositions. Certainly we would want to see more stringent criteria for those streams that DNR feels would fall in the cool water stream category, or which have sensitive T&E species for which we would like to see additional protection provided.

Finally, in terms of possible impacts on sport fishes there will be significant concern in the state from sportsmen groups that Smallmouth bass streams are not adversely affected by lowered DO levels. And based on the literature, there appears to be some chance of an adverse affect on this species and fishery with the proposed lower standard.

While I appreciate the fact that the present DO standard is probably overly conservative for some of our water bodies, it probably isn't for other water bodies. If we are going to adopt one standard for the whole state then it needs to be a more conservative standard to protect some of our more sensitive species. If we decide to adopt DO standards by water body, then we can have different standards for different water bodies.

I hope the above answers some of your questions. I would be glad to provide additional information should you need it.

Sincerely,

David L. Thomas, PhD
Chief INHS
Attachment (Literature Cited)

Literature Cited

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