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

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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)

An Assessment of National and Illinois Dissolved Oxygen Water Quality Criteria

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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.

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.

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

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.

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.

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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.

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.

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.

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.

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.

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 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.

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.

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).

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.

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 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).

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.

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.

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).

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.

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).

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.

Spring through Early Summer

- 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

- 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.

- 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

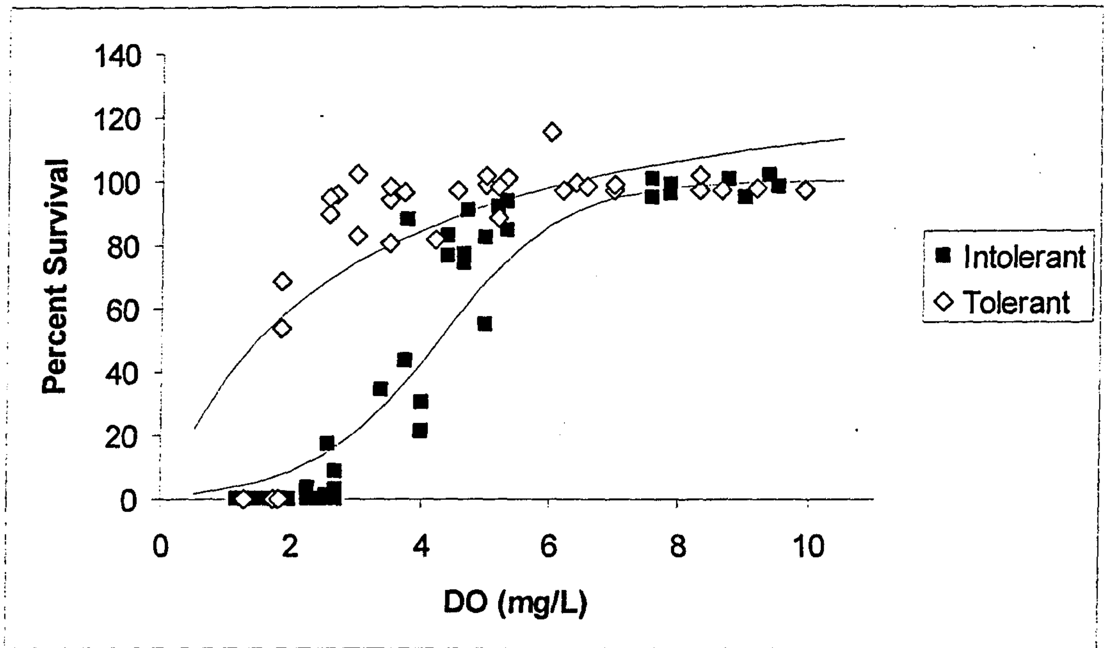

Figure 1. Percent survival (relative to controls) of "tolerant" (i.e., largemouth bass, black crappie, white sucker, white bass) and "intolerant" (i.e., northern pike, channel catfish, walleye, and smallmouth bass) fish larvae and embryos (adapted from Chapman 1986).

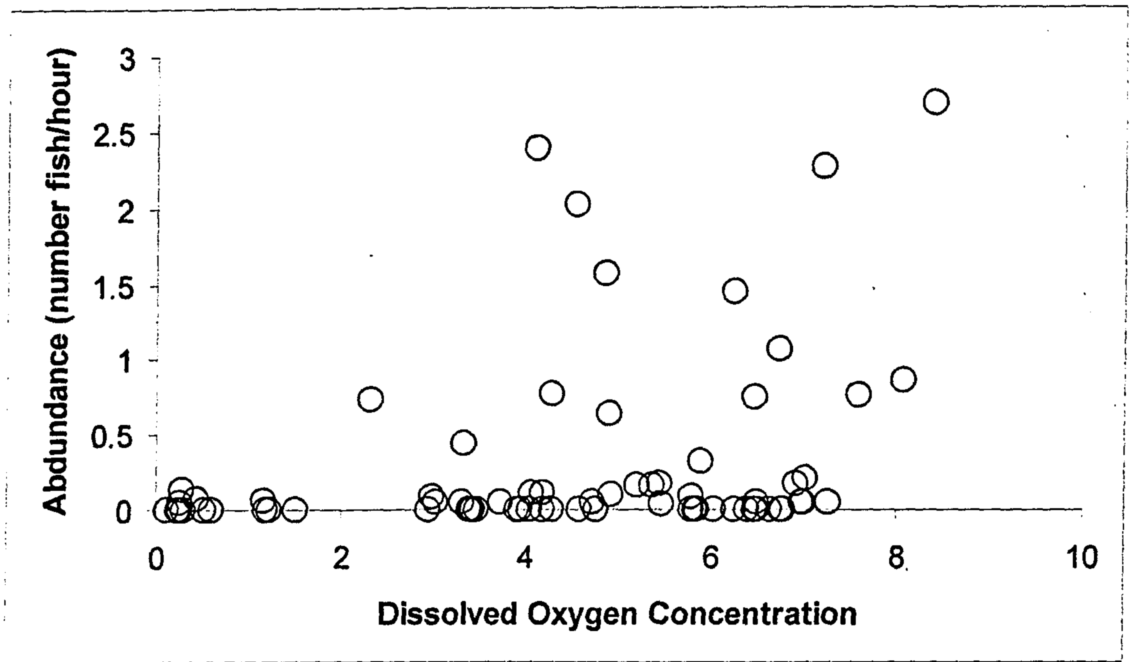

Figure 2. Effect of vertical distribution in dissolved oxygen on the occurrence of threadfin shad and hybrid striped bass in Lake of Egypt, Illinois during summer through fall 2003. Fish avoided the deep, hypolimnetic water of the lake when dissolved oxygen concentrations declined below 4 mg/L.