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	)	

NOTICE OF FILING

TO: See Attached Service List

PLEASE TAKE NOTICE that I have today filed with the Office of the Clerk of the Pollution Control Board the following documents:

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

WRITTEN TESTIMONY OF J. MICHAEL CALLAHAN;

WRITTEN TESTIMONY OF DENNIS STREICHER; and

IAWA Exhibit List

a copy of which is served upon you.

ILLINOIS ASSOCIATION OF WASTEWATER AGENCIES,

By: ______________________
One of Its Attorneys

Dated: June 15, 2004

Sheila H. Deely
Roy M. Harsch
GARDNER CARTON & DOUGLAS LLP
191 Wacker Drive – Suite 3700
Chicago, Illinois 60606
(312) 569-1000

THIS FILING PRINTED ON RECYCLED PAPER

CERTIFICATE OF SERVICE

The undersigned certifies that a copy of the foregoing:

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

WRITTEN TESTIMONY OF J. MICHAEL CALLAHAN;

WRITTEN TESTIMONY OF DENNIS STREICHER; and

IAWA Exhibit List

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 Wacker Drive, Chicago, IL on Tuesday, June 15, 2004.

CH02/ 22319687.1

Service List

R2004-025

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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

I am Dr. James Garvey, Assistant Professor in the Fisheries and Illinois Aquaculture Center at Southern Illinois University in Carbondale. I have been engaged by the Illinois Association of Wastewater Agencies (IAWA), along with my colleague, Dr. Matt Whiles, to scientifically evaluate the current State of Illinois dissolved oxygen standard and to provide recommendations about how the Illinois standard might be revised and updated, if warranted by our scientific evaluation.

Both Dr. Whiles and I are broadly trained in aquatic ecology. My specialty is the ecology of fishes, with much of my research focusing on how environmental conditions affect fish physiology, abundance, and distribution. My Short Curriculum Vita has been submitted as IAWA's Exhibit 5. Dr. Whiles, a professor in the Department of Zoology, is an expert on the ecology of aquatic invertebrates and their role in streams and lakes. His Resume has been submitted as IAWA's Exhibit 6. Our combined experience qualified us to provide an objective assessment of the current state of knowledge about how dissolved oxygen affects aquatic organisms and to evaluate the current statewide, one-day minimum standard of 5 mg/L. We did not intensively evaluate the application of the state standards to Lake Michigan, and IAWA has not proposed to revise that standard.

Dr. Whiles and I began our assessment by reviewing published, typically peer-reviewed research on how dissolved oxygen affects aquatic organisms and how dissolved oxygen varies in lakes and streams. We also reviewed the National Ambient Water Quality Criteria Document for Dissolved Oxygen (NCD) published by the United States Environmental Protection Agency (USEPA) in 1986, and submitted as IAWA's Exhibit
In the final report, Dr. Whiles and I emphasize that using biological- and habitat-
2. We evaluated the current monitoring of water quality in Illinois and conferred with
quality criteria to evaluate suitability for aquatic life use in the surface waters of Illinois
Illinois EPA concerning the scientific basis for the current Illinois dissolved oxygen
is of paramount importance and should be continued to be emphasized in monitoring
standard. We then prepared a written report of our findings, which is submitted as IAWA
programs. It is unlikely that any one water quality parameter such as dissolved oxygen
Exhibit 1.
concentration will capture the capacity of a stream or lake to support aquatic life. Although our recommended dissolved oxygen standards are sufficiently protective of aquatic life in Illinois, we recommend that regulators strive to maintain dissolved oxygen concentrations well above these minima when possible. We agree with the concerns voiced by some colleagues that the state should move toward a region-specific set of water-quality criteria and aquatic life goals, although comprehensive regional data to guide these decisions for Illinois are not yet available.

As the NCD suggests, dissolved oxygen concentrations in lakes and streams fluctuate diurnally. During warm, summer months, dissolved oxygen concentrations decline due to water's reduced capacity to hold oxygen at elevated temperatures and the high respiratory demand of aquatic communities. A single dissolved oxygen standard such as that in Illinois does not realistically capture these diurnal and seasonal fluctuations. Although comprehensive surface water data are lacking for the state, many pristine aquatic systems largely unaffected by agricultural run-off or municipal discharges most likely experience occasional, non-lethal declines in dissolved oxygen below the state's current minimum of 5 mg/L.

Our recommendations in the report include seasonally appropriate means and minima that more realistically account for natural fluctuations in dissolved oxygen concentrations, while remaining sufficiently protective of aquatic life. These recommendations are based largely on potential responses of all life stages of native Illinois fishes that fall in the NCD's non-salmonid category. As with the NCD, we define these as typically warm-water fishes, although much variation in temperature and oxygen tolerance occurs among taxa in this group.

Research summarized in the 1986 NCD was used to set our recommended dissolved oxygen standards above those concentrations expected to slightly impair production of fishes. Research conducted since publication of the report generally confirms that the seasonal standards we recommend are sufficiently protective of fishes and other aquatic organisms in Illinois surface waters. During spring through early summer, most early life stages of fishes and other aquatic organisms are produced. These early reproducing organisms are typically the most susceptible to low dissolved oxygen concentrations and thus require the most stringent protection. Our reanalysis of data within the NCD and our review of the literature led to the development of a standard proposed to be applicable during March 1 through June 30, which specifically protects these early life stages and includes both a one-day minimum identical to the current Illinois standard of 5 mg/L and a seven-day mean of 6 mg/L. During warmer, productive months throughout the remainder of the year when species with sensitive early life stages have largely completed reproduction, we recommend a one-day minimum of 3.5 mg/L and a seven-day mean minimum of 4 mg/L, which is a more realistic general expectation for Illinois surface waters than the current minimum standard of 5 mg/L.

Our recommended standards are based on our current understanding of the short- and long-term responses of aquatic organisms to low dissolved oxygen. In most natural aquatic systems, habitat use by juvenile and adult fish is largely unaffected by dissolved oxygen until concentrations decline below 3 mg/L. Acute lethal effects on post-larval, warm-water fishes do not occur until concentrations decline below 2 mg/L. As we note in the report, chronic effects of long-term exposure to low dissolved oxygen concentrations are not well understood. See IAWA Ex. 1 at 18. Some impairment of growth likely occurs in many warm-water species when dissolved oxygen concentrations are chronically below 4 mg/L, which none of our recommended standards allow.

Initially, Dr. Whiles and I summarized our findings and outlined our recommendations in a draft report that was distributed to IAWA and the Illinois Department of Natural Resources (IDNR). Dr. Whiles also presented our findings to a special meeting of IAWA this spring, where representatives from Illinois EPA (ILEPA) and Prairie Rivers Network were present. During this time, I also distributed the draft report to the U.S. Fish and Wildlife Service, Region 3, Carterville Fisheries Resource Office; the U.S. Fish and Wildlife Service, Region 3, Ecological Services Sub-Office; the IDNR, Office of Resource Conservation; the IDNR, Office of Realty and Environmental Planning, Division of Natural Resource Review and Coordination; the Illinois Natural History Survey/U.S. Geological Service, Long-Term Resource Monitoring Program, Great Rivers Field Station; and the Illinois Chapter of the American Fisheries Society (ILAFS). On June 10, 2004, I met with the extended Executive Committee of the ILAFS to discuss the report. Questions voiced by many of the participants of the IAWA meeting held this spring were answered in the final draft of the report. After circulating the draft, I received informal comments from the IDNR Office of Resource Conservation, which also were addressed in the final draft. The IDNR Office of Realty and Planning informally found the science to support the recommended changes. During my recent meeting with the Executive Committee of the ILAFS, I answered questions about the report and the proposed changes to the current Illinois standards. I agreed with the primary conclusion of the group that a set of regional standards are needed for Illinois. The other groups have provided neither informal nor formal feedback to me to date.

A letter dated 28 May 2004 written by Ms. Beth Wentzel of Prairie Rivers Network to the Division of Water Pollution Control, ILEPA raised several specific concerns about our report. Ms. Wentzel noted that our report was not entirely consistent with the NCD. Although the NCD recommends adopting the most conservative standards for all early life stages of fish through thirty-days post hatching whenever these life stages occur, our report only recommends adopting these conservative standards through June. Of the forty-eight fish taxa in Illinois that we surveyed, forty likely complete the reproductive portion of their life cycle by the end of June or earlier throughout Illinois. Given that fluctuating oxygen concentrations occur naturally in Midwestern streams and lakes during summer, the remainder of species that continue to reproduce during these months must have adaptations that allow them to persist when ambient oxygen concentrations occasionally approach our recommended summer minimum. Hence, our report indeed departs from the NCD in that it attempts to generate more realistic expectations for dissolved oxygen concentrations and the responses of native aquatic life in Illinois.

Another criticism voiced by Ms. Wentzel was that we failed to address the responses of cool-water species such as smallmouth bass in our recommended criteria. This is untrue. These species were generally grouped under our warm-water categorization, because temperature requirements of non-salmonid fishes are not well-delineated. Rather, species-specific temperature needs vary widely along a gradient from cool to warm water among fish in the Midwest. Although cold-water salmonids can be categorized by their high oxygen and low temperature requirements, I know of no specific research that identifies Midwestern cool-water fishes as having substantially different oxygen requirements during non-reproductive periods than warm-water counterparts. The main difference between species with cool- and warm- water requirements appears to be their temperature-dependent growth optima and lethal maximum temperatures, which is a separate issue regarding the interaction between habitat quality and temperature. Interestingly, although smallmouth bass is specifically listed in the NCD as a sensitive, cool-water fish, it has similar temperature requirements as many conventional warm-water fishes. Further, smallmouth bass adults have a minimum lethal dissolved oxygen limit of 1.2 mg/L (see Table I, IAWA Ex. 1), which is well below our recommended Illinois minimum standard.

Ms. Wentzel noted that we omitted a thirty-day mean standard from our recommendations, although such a long-term moving average is recommended in the NCD. In our view, fishes and other aquatic organisms will respond at a much shorter time scale to declining oxygen than thirty days, requiring a more frequently updated moving average of seven days. A thirty-day mean may erroneously miss periods of chronically low dissolved oxygen if high concentrations occur during the remainder of the thirty-day monitoring period.

Another argument made against our report's validity is that it focuses primarily on fish. Fish were selected as the regulatory focus because they were the model in the NCD and, as it was in 1986, most research on dissolved oxygen is available for this group. Fish are also of recreational and economic importance. Although the data for other taxa are indeed quite limited, we did address the influence of dissolved oxygen on other organisms, specifically mussels and aquatic insects, and have found a pattern that appears to be consistent with that for fish. As we outline in the report, species that have high oxygen requirements tend to inhabit areas of consistently high and environmentally predictable dissolved oxygen concentrations. In a stream, this would be a riffle habitat in which high gaseous exchange occurs between the water and the atmosphere. In our report, we recommend quantifying oxygen in areas and during times when dissolved oxygen concentrations are expected to be lowest such as a stream pool before dawn. These locations should be more susceptible to declining oxygen than areas in which high exchange elevates oxygen concentrations and typically harbors the most sensitive species such as darters and mayflies.

We take issue with Ms. Wentzel's supposition that our recommendations would render Illinois's dissolved oxygen standards the weakest in the nation. I have assessed the standards for our peer State of Ohio. From what I understand, Ohio has various aquatic use designations that are similar to but more specific than those recommended for Illinois. Each of these specific designations has a different daily minimum and one-day average dissolved oxygen concentration. Probably the most common designation for surface waters in Ohio is "warm water" which includes a daily minimum of 4 mg/L and a one-day average of 5 mg/L, which appears to apply to the entire year. Clearly, Ohio's general standard is less conservative than our recommended statewide standard during spring, because its minimum of 4 mg/L is 1 mg/L less than our proposed minimum standard. And Ohio's minimum is not significantly different than our proposed minimum standard of 3.5 mg/L during the remainder of the year. Ohio's seasonal salmonid and coldwater designations are analogous to the Lake Michigan standards, which we do not recommend modifying.

In my assessment, the largest difference between current standards within Ohio and Illinois is that Ohio has developed more regional-specific criteria to protect waters that they deem important. Ohio's "exceptional warm water" criteria are very similar to those that Illinois currently has adopted for the entire state, where Ohio's daily minimum is 5 mg/L and its one-day average is 6 mg/L. Given that all the surface waters in Illinois would certainly not be categorized as "exceptional", it is clear that the current general aquatic use Illinois dissolved oxygen standard is too strict. Our recommended standards do provide similar protection as Ohio's "exceptional" waters during the critical peak reproductive times of the year.

During my conversations with other scientists, resource managers, and water regulators, I have received many comments about how the recommended standards are based on sound science and needed in the state. I recognize and somewhat understand the perception by some individuals that our recommendations would weaken the Illinois standards. However, the weight of information available for aquatic organisms suggests that the proposed standards set more realistic expectations for surface waters in Illinois and will not degrade the biological integrity of these systems. I agree that more research is needed in many areas and hope that the proposed standard changes will be viewed as one step in a dynamic, continuing process. It is my view that the state should move toward developing region-specific biotic integrity, habitat quality, and water quality criteria, as credible long-term data sets become available.

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BEFORE THE ILLINOIS POLLUTION CONTROL BOARD

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

<u>WRITTEN TESTIMONY OF J. MICHAEL CALLAHAN</u>

My name is John M. Callahan. I am the Executive Director of the Bloomington and Normal Water Reclamation District (BNWRD) of McLean County, Illinois. I have been in the employment of the BNWRD for thirty one years during which time I have held positions of increasing responsibility from that of Chemist to my current position of Executive Director. I have received a B.S. Degree from Illinois State University with majors in Biological Sciences and Environmental Health. I have also received an M.A. Degree from the University of Missouri (Columbia) in Ecology with an emphasis on nutrient cycling. I pursued Doctoral Studies in Biological Sciences at Illinois State University, again with an emphasis on nutrient cycling. I hold an Illinois Environmental Protection Agency Class I Wastewater Treatment Plant Operator License. I have been a member of the Phi Sigma National Biological Honor Society for thirty years and a member of the Sigma Xi Scientific Research Society for twenty three years. I have been actively involved in professional organizations representing various aspects of the wastewater treatment industry and have held positions of leadership in such organizations. These organizations include the Illinois Association of Wastewater Agencies, the Illinois Water Pollution Control Operators Association and the Central States Water Environment Association. I have been a member of the Water Environment Federation for more than twenty five years. During my career I have served in several stakeholder study groups organized by the Illinois

Environmental Protection Agency to assist in the formulation of standards and policies concerning both Illinois water quality and various issues regarding wastewater treatment within the State. I have published and/or presented numerous papers on various aspects of wastewater treatment throughout my career.

It has been my privilege to previously appear before the Illinois Pollution Control Board to offer input on key issues of widespread importance to our state. I thank the Illinois Pollution Control Board for the opportunity to appear again today to discuss the need for a re-evaluation of the Illinois dissolved oxygen water quality standard. I am offering testimony on behalf of the Illinois Association of Wastewater Agencies (IAWA) and in support of Mr. Dennis Streicher who is directing this IAWA initiative. The need for a revised Illinois dissolved oxygen standard has existed for some time. However, two relatively new initiatives in water quality improvement within the State have mandated that the issue of revising the dissolved oxygen standard be undertaken at this time. These mandates are in response to the need to develop scientifically derived nutrient standards and to more precisely direct the adoption of total maximum daily load allocations to Illinois waters listed as not attaining designated use support.

Since its inception, approximately four years ago, I have been a member of the IEPA Nutrient Science Advisory Workgroup. This workgroup was assembled by IEPA to develop a strategy for scientifically deriving water quality standards for nitrogen and phosphorus. Historically the Workgroup was chaired by Mr. Robert Mosher of IEPA. Recently, Mr. Paul Terrio of the U.S Geological Survey has replaced Mr. Mosher as Workgroup Chair. The water quality degradation ascribed to phosphorus and nitrogen is a phenomenon called eutrophication.

condition which develops when the naturally limiting nutrient of an ecosystem is increased to the extent that the overall balance of ecosystem dynamics is upset. The limiting nutrient of most freshwater ecosystems is phosphorus. Degrading concentrations of phosphorus effectively "over fertilize" the fresh water aquatic system and result in enhanced algal growth. Such algae are aerobic organisms. During daylight hours algae photosynthesize. A by product of photosynthesis is oxygen. As a result of this photosynthesis, during early stages in the development of eutrophication, daytime dissolved oxygen levels can be maintained such that little negative effect is realized in an aquatic system. However, during the night, when no sunlight is present to power photosynthesis, the increased algae population must continue cellular respiration as must the remaining aerobic biota of a freshwater ecosystem. Ultimately, the total oxygen demand required by these respiring organisms exceeds the ambient night time re-aeration capability of a water body. Consequently, oxygen sensitive species are put at stress and population levels of such organisms may significantly diminish. A self-perpetuating downward spiral of aquatic organism diversity can thus easily develop as eutrophic conditions continue to persist.

The IEPA Nutrient Science Advisory Workgroup immediately recognized the determination of the concentration of phosphorus at which the eutrophication cycle begins to cause problematic dissolved oxygen depletion to be one of the first essential steps in developing an effective and scientifically derived phosphorus standard. Regrettably, it was also recognized that this critical concentration of dissolved oxygen was not known. However, many professionals throughout Illinois agreed that the current Illinois dissolved oxygen water quality standard does not represent the dissolved oxygen concentration which is critical to preventing the onset of eutrophication. In fact, there exists general agreement among professionals that the ambient dissolved oxygen concentrations of the waters of Illinois frequently naturally fall beneath the existing dissolved oxygen water quality standard. Mr. Mosher, as Chair of the workgroup, was one of the individuals that initially suggested a re-evaluation of the Illinois dissolved oxygen water quality standard was a timely consideration.

Although there existed widespread agreement several years ago within the Workgroup that a reassessment of our state's dissolved oxygen water quality standard was warranted, IEPA indicated the Agency did not have the resources or manpower to undertake such an effort at that time. Realizing this need and the lack of available IEPA resources, I asked Mr. Mosher if IEPA would be receptive to and supportive of a third party investigation into the issue of the dissolved oxygen standard issue. Such action was not unprecedented. The IEPA had supported the IAWA in a previous issue brought before the Illinois Pollution Control Board involving the ammonia nitrogen water quality standard. I was advised that IEPA would support such an undertaking, but definitely wanted input into the design of the research investigation. I then approached the IAWA membership asking if sufficient interest existed for IAWA to fund a third party analysis of both the existing Illinois dissolved oxygen standard as well as an investigation that would provide a recommendation for an appropriate dissolved oxygen standard for Illinois. The IAWA membership readily agreed to fund such work and directed me to investigate both the methods by which such a research study could be undertaken as well as the willingness of qualified professionals within Illinois to undertake the study.

I initially contacted Dr. Mat Whiles of the Southern Illinois University Fisheries Research Laboratory to both inquire of his possible interest in undertaking such work as well as his recommendation of any other qualified individuals of which he was aware that might be interested in the research. Dr. Whiles indicated that he was quite interested in the project and that he thought a colleague of his, Dr. James Garvey, would be very interested in assisting him with the work. I reported back to the IAWA membership that Dr. Whiles and Dr. Garvey had expressed considerable interest in undertaking the project. The IAWA membership then unanimously voted to retain the services of the two gentlemen. This agreement was reached in the summer of 2002.

On September 30, 2002, Dr. Whiles and I met with Mr. Mosher, Mr. Greg Goode and other IEPA staff to discuss aspects of the issue that IEPA felt were critical to the investigation such that a technically justifiable dissolved oxygen standard supportable by sound science could be developed. Agreement was reached among those in attendance on the key issues which Dr. Whiles and Dr. Garvey should investigate to satisfactorily address all concerns. I had previously suggested to the IAWA membership that the conclusions of the work done by Dr. Whiles and Dr. Garvey should not be released publicly until both the IEPA and the IAWA had opportunity to review them. The IAWA readily agreed to this qualification. I advised those in attendance at the IEPA meeting that such was the qualification IAWA had placed on the work to be done by Dr. Whiles and Dr. Garvey. Again, this was the procedure previously agreed upon between IEPA and IAWA during the ammonia nitrogen water quality standard development. The IEPA representatives were appreciative of this consideration.

Dr. Whiles and Dr. Garvey presented their initial draft report on their investigation to me in early January of 2004. I immediately circulated copies of the report to the IAWA Executive Committee and the IAWA Nutrient Subcommittee as well as to IEPA. It was at this point in the proceedings that I withdrew from a lead role in the development of the standard and Mr. Streicher volunteered to coordinate the upcoming rule making proposal.

The previous discussion presents the need for a sound understanding of dissolved oxygen dynamics in the waters of our state such that meaningful and technically justifiable nutrient standards can be developed. Addressing either water quality parameter, nutrients or oxygen, without consideration and a sound understanding of the other will not result in a comprehensive and effective resolution of the eutrophication problem. I personally find it quite surprising and very sad that we know no more about the interaction of these parameters than we presently do. However, such is indeed the situation. I assure everyone present that the cost of addressing the nutrient issue in Illinois will be extreme. However, I suggest that we look beyond the actual monetary cost of such requirements. A statistic I have heard often quoted regarding the wastewater treatment industry states that for every pound of carbonaceous waste we currently remove from wastewater, four pounds of carbon in the form of carbon dioxide are released to the atmosphere through the energy generation required for removal of that pound of waste. Nutrient removal will only add to this energy requirement. A thorough understanding of the dynamics and interaction of nutrients and oxygen is absolutely essential for effective and efficient stewardship which addresses this issue. A valid and scientifically based dissolved oxygen standard is fundamental to this understanding.

The second mandate involving the need for a current reassessment of the dissolved oxygen standard, to which I earlier referred, involves the effort currently under way to develop total maximum daily load allocations (TMDLs) for waters of the State which are determined not to be achieving full use designation. The TMDL procedure evaluates a watershed in an attempt to determine what the assimilation rate of that watershed is for various parameters. Hypothetically, both point source and non-point source contributions of various parameters are considered in determining the reduction in loading necessary to realize use attainment for each parameter of concern. However, there regrettably exists little apparent regulatory control other than voluntary best management practices that can force non-point contributions of various parameters to be reduced to levels which are not detrimental to a watershed. The readily controlled and regulated contributions to a water body come from point sources.

There may or may not be effective additional controls which can be applied to point sources that will assist in achieving full use attainment. I believe that a specific solution for a specific location will not universally solve the problems experienced by all use impaired waters across the State. The dynamics and physical conditions of each water body must be assessed and considered as unique to that particular location. However, inadequate dissolved oxygen is listed on the IEPA draft 303(d) list as a fairly universal parameter contributing to non use attainment and subsequent inclusion of water bodies on that list. The draft 2004 303(d) list contains approximately 300 water body segments in Illinois listed as impaired, at least in part, by inadequate dissolved oxygen concentrations. Approximately 800 water bodies are listed on the draft 2004 303(d) list. Therefore approximately one third of the water bodies listed on the draft

303(d) list are listed, at least in part, because of a dissolved oxygen standard which many professionals have indicated is overly protective and not specific to the needs of the waters of Illinois.

This dissolved oxygen contribution to non-attainment is based on the current Illinois dissolved oxygen water quality standard which, as previously discussed, has long been considered to be of questionable validity. Some point source dischargers are now having a minimum dissolved oxygen limit included in their NPDES permits. In many situations I believe that compliance with an effluent dissolved oxygen permit limit of 6.0 mg/l will have virtually no effect on improving receiving stream dissolved oxygen concentrations when the naturally occurring ambient diurnal dissolved oxygen minima of that stream might easily be 4.5 mg/l. One might speculate that over-protection is not necessarily unwarranted in its own right. However, I again respectfully remind the Board that compliance with a standard, over protective or not, has a cost inherently associated with it. Increased dissolved oxygen concentrations in effluents require that air be supplied to these waters before discharge. This air comes from blowers which are powered by electricity.

As I previously mentioned, a rule of thumb in our industry currently estimates that one pound of carbonaceous waste removed from wastewater results in four pounds of carbon in the form of carbon dioxide released to the atmosphere. Are we as a society, through the TMDL program, going to require that we aerate treatment plant effluents or provide additional treatment within our plants to comply with a flawed dissolved oxygen standard and thereby perhaps contribute another pound or two of carbon dioxide to the atmosphere for the energy required to do so on a per unit basis? I certainly hope that our society chooses not to follow that path. Rather, I strongly encourage the Board to adopt the dissolved oxygen standard being proposed in this proceeding. It has been developed by professional aquatic biologists in consideration of the requirements of the aquatic biota of our state. The proposed standard is based upon, and more conservative than, the USEPA recommended guidance for development of dissolved oxygen standards. Thank you for this opportunity to again provide testimony and appear before the Illinois Pollution Control Board.

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35 Ill. Adm. Code 302.206	)	

WRITTEN TESTIMONY OF DENNIS STREICHER

My name is Dennis Streicher, and I am Director of Water and Wastewater with the City of Elmhurst, Illinois. I have been employed by the City of Elmhurst at the Wastewater Treatment Plant since 1972. I began my career in Elmhurst as a chemist graduated with a biology degree. I worked in the lab for approximately 15 years and was promoted to plant superintendent, then to Assistant Director of Public Works, then to Director of a newly created Department of Water & Wastewater. My responsibilities include, in addition to operation of the wastewater treatment plant, operation of the public water supply and of all storm water pumping utilities in the City. I hold an Illinois Environmental Protection Agency Class 1 Operators License and an Illinois Environmental Protection Agency Class "A" Potable Water Operators License. A copy of my resume has been submitted as IAWA Exhibit 3. I come before you today, however, representing the Illinois Association of Wastewater Agencies (IAWA) as the committee chair for dissolved oxygen standards in Illinois. I am also the current vice president of administration with the IAWA.

The IAWA is a professional association representing the major wastewater treatment plants in the state of Illinois. We have about 100 members and affiliate members, which includes approximately 55 districts and municipalities throughout the state. These agencies operate dozens of publicly owned treatment works (POTWs). In addition to these POTWs, water reclamation districts and municipalities, the largest Illinois private wastewater treatment utility, which operates 12 plants, is also a member. The representatives of these organizations are public officials, and include both elected and appointed trustees of districts and appointed officials at municipalities throughout the state. Our constituents are the citizens and taxpayers of Illinois and are the same constituents as any other state or public agency.

My goal is not to present the technical aspects of the proposed rule change; Dr. James Garvey is the expert in that area. My hope is to present the IAWA perspective on the existing dissolved oxygen regulations in Illinois and why we feel that it is time to update those standards.

The managers of the POTWs in Illinois have two interests in mind: one is the integrity of the environment in which they work; the second is to responsibly represent their constituents and charge reasonable rates for service. Our jobs as managers of the states' POTWs are the real life application of the water quality standards as promulgated in Illinois to the operation of sometimes large but always-complex water treatment facilities. These POTWs have an excellent record of producing treated effluent in conformance with applicable NPDES permit limitations, due in large part to the investment of public dollars to construct and upgrade the facilities and the experience and dedication of those that operate and maintain the plants.

This proposed rulemaking is consistent with IAWA's purpose and past practice, to ensure that the standards by which it operates are based on sound science and to take action to update standards where scientific information supports such a change. IAWA has engaged the highest qualified experts consistent with its purpose, and has performed a variety of assessments that have been used by Illinois EPA and the Board to assess Illinois standards governing the discharges of its members. IAWA proposed the rulemaking that resulted in revision of certain water quality standards governing ammonia nitrogen in R02-19, and the Board adopted a revised rule in 2002.

IAWA had participated in a prior rulemaking brought by the Illinois EPA to revise the ammonia regulations. During the pendency of that rulemaking, U.S. EPA revised the national criteria document for ammonia. After discussing this revision with representatives of the Illinois EPA, it became apparent that the Illinois EPA did not have the interest or resources to initiate rulemaking to again revise the ammonia regulations. Because of the impact that the recently adopted ammonia regulations had on wastewater treatment plants and because the regulations were in fact based upon outdated science, IAWA initiated and saw to completion the rulemaking in R02-19 and ultimately the accompanying Illinois EPA implementation regulations to ensure that Illinois' ammonia effluent limitations were consistent with U.S. EPA's national criteria document and based upon sound current science. The managers and officials who operate wastewater treatment plants and who needed to invest in upgrades for their facilities, were able to make the case to their respective District Boards and City Councils for authorization for the necessary dollars to meet an appropriate and justifiable ammonia standard.

IAWA is committed to following the same course of action as it did in the ammonia rules whenever it is apparent that effluent limitations and water quality standards that have a significant impact on POTWs are in need of revision and the Illinois EPA does not have the resources or the inclination to initiate the appropriate evaluation and ultimate regulatory proceedings. This dissolved oxygen rulemaking is IAWA's second such effort. Various IAWA members were involved in a series of discussions with representatives of the Illinois EPA and other regulators, many of whom had publicly stated that the existing Illinois dissolved oxygen water quality standard found at 35 Ill. Admin. Code Section 203 was not based on sound science was inconsistent with USEPA's national criteria document and was too stringent. At the same time, IAWA was aware that many water bodies throughout Illinois were not in compliance with the existing dissolved oxygen water quality standard or would not be found to be in compliance if dissolved oxygen measurements were taken early in the morning due to the naturally occurring diurnal dissolved oxygen fluctuation cycle.

IAWA decided to undertake a scientific assessment of the dissolved oxygen standard almost three years ago. In 2002, IAWA engaged Dr. James Garvey and Dr. Matt Whiles, who concluded that the Illinois standard was too rigid and not consistent with the U.S. EPA's National Criteria Document (NCD) for dissolved oxygen. Dr Jim Garvey and Dr. Matt Wiles have done an excellent job in putting together a review of data that has been generated since the 1980's, have applied their knowledge and skills and training to their understanding of all of the data generated since that time, and have made recommendations that the IAWA feels are reasonable and accurate. Because revision of the dissolved oxygen standard was not a priority of

Illinois EPA, the IAWA elected to itself bring this petition to the Illinois Pollution Control Board.

The IAWA is very concerned that the existing dissolved oxygen standard is triggering other legal requirements that are not warranted by scientific information. The Illinois EPA is currently insisting on imposition of a dissolved oxygen water quality effluent limitation in NPDES Permits of 6 mg/L to be met continuously. It is IAWA's understanding that this effluent limitation is being placed in NPDES Permits to ensure that the existing water quality standard is not violated. In instances where POTWs are unable to comply with this limitation, the Illinois EPA has granted construction schedules requiring investment of public dollars to meet it.

Illinois EPA is required by Section 305(b) of the Clean Water Act to assess the water quality of Illinois waters and prepare a report, commonly known as the 305(b) report. Based on this report, Illinois EPA is additionally required by Section 303(d) of the Clean Water Act to develop a list of impaired waters in Illinois, commonly known as the 303(d) List. While IAWA has not counted the water body segments in the 305(b) report or the stream segments in the 303(d) report for purposes of reference there were 741 segments listed in the 1998 303(d) report and 798 segments in the final 2002 303(d) report.

The Illinois EPA is in the process of finalizing the 2004 Section 305(b) and Section 303(d) reports. IAWA has reviewed the draft reports. The Illinois EPA lists approximately 251 water body segments as not complying with the dissolved oxygen standard in the draft 305(b) report. There are 302 segments listed in the 303(d) report as impaired for dissolved oxygen. The 305(b) and 303(d) reports are then used to determine the waters and parameters for which Total Maximum Daily Loads (TMDLs) will be established, establishing load limits for dischargers to each listed waterway. All of these requirements adhere to the current standards, even if those standards are not scientifically based, as we believe to be the case with the Illinois dissolved oxygen standard. This can only result in unrealistic and unwarranted permit limits requiring expensive capital improvements and modifications to wastewater treatment facilities at taxpayer expense, or unjustified reasons for plant expansion.

In my position at the City of Elmhurst, I together with other IAWA member agencies have watched and participated with great interest in the Illinois EPA's efforts to establish TMDLs for the West Branch of the DuPage River, East Branch of the DuPage River and Salt Creek Basins. These three TMDLs mark the first effort by the Illinois EPA to develop TMDLs in urban areas with significant potential impact from POTWs, combined sewer overflows, storm sewer discharges, and other urban impacts. In the initial drafts the TMDLs for the East Branch of the DuPage River and Salt Creek would have required limitations on CBOD and ammonia because these streams were listed as impaired under the existing standard for dissolved oxygen. The potential for the TMDLs to be finalized with an ultimate requirement for more restrictive CBOD and ammonia limitations in existing NPDES Permits could have a significant impact on POTW discharges. Either expensive capital investment would be required with increased operational expenses or a loss in the existing treatment plant capacity that has been built to service future growth may be required. Additional efforts were discussed as well including stream re-aeration and dam removal as additional potential means of meeting the existing dissolved oxygen water quality standard. The IAWA and I believe that these consequences of failure to meet the standard should only result if there is an actual environmental problem applying a scientifically sound dissolved oxygen water quality limitation. Let me illustrate with a description of what is happening today in the Salt Creek basin. The plant I manage discharges to Salt Creek in DuPage County. As I said, the Illinois EPA has or is about to submit a completed TMDL on Salt Creek to the USEPA. That TMDL has found Salt Creek to be impaired for dissolved oxygen and had recommended that significant additional effluent limits on CBOD and ammonia be imposed on POTWs in the watershed. The TMDL estimated costs for those improvements to be about 18 million dollars. These are costs that the POTWs will bear alone. At this time stakeholders in the basin, and I am one of them, are deeply involved in an effort to form a watershed committee, one of the goals of this committee will be to attempt to develop more meaningful data, including biotic data, to further refine the TMDL study and hopefully mitigate the future costs. There is no guarantee that we will be successful. The cost of this effort in time and dollars will certainly be significant.

IAWA believes that given the large number of water body and stream segments that are listed as non-compliant with the current dissolved oxygen standard or impaired for dissolved oxygen reasons, Illinois should insure that the existing dissolved oxygen water quality standard is an appropriate standard based upon sound science and consistent with USEPA's national criteria document. The costs now being incurred on the Salt Creek and East Branch of the DuPage River basin could be multiplied by each of those additional basins identified as impaired for dissolved oxygen using the existing inappropriate standard.

IAWA believes this proposed dissolved oxygen rulemaking is consistent with Section 303(c) of the Clean Water Act, 33 U.S.C. 1313(c), which requires the states review and re-evaluate existing water quality standards within three years of adoption of revised national criteria by USEPA. To date, despite the acknowledgement by many within the Illinois EPA that the existing dissolved water quality standard is out of date and inconsistent with the NCD, Illinois has not undertaken such a review.

Dr. Garvey points out in **"An Assessment of National and Illinois Dissolved Oxygen Water Quality Criteria"** that dissolved oxygen concentrations fluctuate in natural systems. Dissolved oxygen has a diel fluctuation, it has a seasonal fluctuation, and concentrations could be different through the water column. Animals living in those conditions have evolved a tolerance for those fluctuations. The current regulation does not take into account seasonal fluctuations.

My own career began at the same time as the development of many of today's water quality regulations. I have been able to observe that development from the inception of the Clean Water Act to today. I observed the infant Illinois EPA and the Illinois Pollution Control Board struggling with the proposal and adoption of water quality standards and were faced with almost insurmountable demands to develop them quickly. At that time there was a rash of new standards being developed with the aim of quickly attaining water quality goals. Many of those standards are still in effect today. The dissolved oxygen standard used in Illinois today was promulgated during that initial period almost three decades ago and has not been revised since.

When the work of Dr. Garvey and Dr. Whiles and the proposed regulation were completed, I was excited to volunteer to represent the IAWA in the effort to see this study through rules making at the pollution control board and to be a part of the process to develop realistic dissolved oxygen standards in Illinois. As part of this effort I contacted and shared the report with a number of other groups within the state to look for their support and for their comments on the study. I sent letters to the Illinois Department of Agriculture, the Illinois Farm Bureau (ILFB), the Illinois Environmental Regulatory Group (IERG), and the Illinois State Water Survey. I personally spoke to members of all of those agencies that I mentioned and asked them for their thoughts and if they had concerns to let me know and to follow up on my letters sent to them. Those letters are submitted as IAWA's Exhibit 4. In every single instance the persons I spoke to expressed support and a hope that the board would adopt this rule.

I also copied many of the citizen advocacy groups such as the Sierra Club, Prairie Rivers Network, The Salt Creek Watershed Alliance, DuPage Conservation Foundation and the Environmental Law and Policy Center.

Our goal was to offer those folks an opportunity to comment as well. The goal of IAWA was to be as inclusive as possible.

In summary, it is commonly known throughout the state that the current dissolved oxygen regulation is not scientifically justifiable. Because of its importance in the regulatory regime in Illinois, an accurate and realistic dissolved oxygen standard is critical. IAWA has spent considerable time and incurred significant expense to ensure that it has the most recent and strongest scientific data to support its rulemaking. I urge the Board to proceed with the rulemaking as proposed by the IAWA. Thank you for this opportunity to address this issue before the Board.

CH02/ 22319408.1

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JUN 15 2004

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	)	

IAWA EXHIBIT LIST

The Illinois Association of Wastewater Agencies ("IAWA"), by its attorneys Gardner Carton & Douglas, submits these exhibits to the pre-filed written testimony of its witnesses for the hearings in this matter.

1. An Assessment of National and Illinois Dissolved Oxygen Water Quality Criteria, Dr. James E. Garvey and Dr. Matt R. Whiles of Southern Illinois University (previously filed).

2. United States Environmental Protection Agency's National Criteria Document ("NCD") for Dissolved Oxygen (1986).

3. Resume of Dennis Streicher.

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

5. Resume of Dr. James Garvey.

6. Resume of Dr. Matt Whiles.

Respectfully submitted,

One of the Attorneys for ~~Petitioner~~

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CH02/ 22319686.1

Exhibit 1

An Assessment of National and Illinois Dissolved Oxygen Water Quality Criteria, Dr. James E. Garvey and Dr. Matt R. Whiles of Southern Illinois University

(Appended to Petition).

Exhibit 2

United States
Environmental Protection
Agency

Office of Water
Regulations and Standards
Criteria and Standards Division
Washington, DC 20460

EPA 440/5-86-003
April 1986

PB86-208253

Water

EPA

Ambient Water Quality Criteria for Dissolved Oxygen

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. EPA 440/5-86-003	2.	3. Recipient's Accession No. PB86 208253/AS

4. Title and Subtitle Ambient Water Quality Criteria for Dissolved Oxygen.	5. Report Date April, 1986
	6.
7. Author(s) Chapman, Gary	8. Performing Organization Rept. No.
9. Performing Organization Name and Address U. S. Environmental Protection Agency Office of Research and Development Environmental Research Laboratories Duluth, Minnesota Narragansett, Rhode Island	10. Project/Task/Work Unit No. 11. Contract(C) or Grant(G) No. (C) (G)
12. Sponsoring Organization Name and Address U. S. Environmental Protection Agency Office of Water Regulations and Standards Criteria and Standards Division (WH-585) 401 M St., S.W. Washington, D. C. 20460	13. Type of Report & Period Covered 14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

The Document reviews data which are currently available on the effects of low levels of dissolved oxygen on the health, growth and reproduction of freshwater aquatic organisms. Criteria for the protection of freshwater aquatic organisms are developed, based principally on data derived from studies on fish. The Criteria are presented in terms of cold and warm water species, early life stages and other life stages, as well as the length of exposure to low D. O. concentrations.

17. Document Analysis a. Descriptors

Dissolved Oxygen; Oxygen; Water Quality; Freshwater; Aquatic Life; Fish.

b. Identifiers/Open-Ended Terms

Ambient Water Quality Criteria; Surface Water Quality

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Release Unlimited	20. Security Class (This Page)	22. Price

(See ANSI–Z39.18) See Instructions on Reverse

OPTIONAL FORM 272 (4–77)
(Formerly NTIS–35)
Department of Commerce

Ambient Aquatic Life Water Quality Criteria for Dissolved Oxygen

(Freshwater)

U.S. Environmental Protection Agency
Office of Research and Development
Environmental Research Laboratories
Duluth, Minnesota
Narragansett, Rhode Island

NOTICES

This document has been reviewed by the Criteria and Standards Division, Office of Water Regulations and Standards, U.S. Environmental Protection Agency, and approved for publication.

Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

This document is available to the public through the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Virginia 22161.

FOREWORD

Section 304(a)(1) of the Clean Water Act of 1977 (PL 95-217) requires the Administrator of the Environmental Protection Agency to publish water quality criteria that accurately reflect the latest scientific knowledge on the kind and extent of all identifiable effects on health and welfare that might be expected from the presence of pollutants in any body of water, including groundwater. This document is a revision of proposed criteria based upon a consideration of comments received from other Federal agencies, State agencies, special interest groups, and individual scientists. Criteria contained in this document replace any previously published EPA aquatic life criteria for the same pollutant(s).

The term "water quality criteria" is used in two sections of the Clean Water Act, Section 304(a)(1) and Section 303(c)(2). This term has a different program impact in each section. In Section 304, the term represents a non-regulatory, scientific assessment of ecological effects. Criteria presented in this document are such scientific assessments. If water quality criteria associated with specific stream uses are adopted by a State as water quality standards under Section 303, they become enforceable maximum acceptable pollutant concentrations in ambient waters within that State. Water quality criteria adopted in State water quality standards could have the same numerical values as criteria developed under Section 304. However, in many situations States might want to adjust water quality criteria developed under Section 304 to reflect local environmental conditions and human exposure patterns before incorporation into water quality standards. It is not until their adoption as part of State water quality standards that criteria become regulatory.

Guidelines to assist States in the modification of criteria presented in this document, in the development of water quality standards, and in other water-related programs of this agency, have been developed by EPA.

William A. Whittington
Director
Office of Water Regulations and Standards

ACKNOWLEDGEMENTS

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Environmental Research Laboratory
Narragansett, Rhode Island

Clerical Support: Nancy Lanpheare

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Ambient Water Quality Criteria for Dissolved Oxygen

FRESHWATER AQUATIC LIFE

I. Introduction

A sizable body of literature on the oxygen requirements of freshwater aquatic life has been thoroughly summarized (Doudoroff and Shumway, 1967, 1970; Warren et al., 1973; Davis, 1975a,b; and Alabaster and Lloyd, 1980). These reviews and other documents describing the dissolved oxygen requirements of aquatic organisms (U.S. Environmental Protection Agency, 1976; International Joint Commission, 1976; Minnesota Pollution Control Agency, 1980) and more recent data were considered in the preparation of this document. The references cited below are limited to those considered to be the most definitive and most representative of the preponderance of scientific evidence concerning the dissolved oxygen requirements of freshwater organisms. The guidelines used in deriving aquatic life criteria for toxicants (Federal Register, 45 FR 79318, November 28, 1980) are not applicable because of the different nature of the data bases. Chemical toxicity data bases rely on standard 96-h LC50 tests and standard chronic tests; there are very few data of either type on dissolved oxygen.

Over the last 10 years the dissolved oxygen criteria proposed by various agencies and researchers have generally reflected two basic schools of thought. One maintained that a dynamic approach should be used so that the criteria would vary with natural ambient dissolved oxygen minima in the waters of concern (Doudoroff and Shumway, 1970) or with dissolved oxygen requirements of fish expressed in terms of percent saturation (Davis, 1975a,b). The other maintained that, while not ideal, a single minimum allowable concentration should adequately protect the diversity of aquatic life in fresh waters (U.S. Environmental Protection Agency, 1976). Both approaches relied on a simple minimum allowable dissolved oxygen concentration as the basis for their criteria. A simple minimum dissolved oxygen concentration was also the most practicable approach in waste load allocation models of the time.

Expressing the criteria in terms of the actual amount of dissolved oxygen available to aquatic organisms in milligrams per liter (mg/l) is considered more direct and easier to administer compared to expressing the criteria in terms of percent saturation. Dissolved oxygen criteria expressed as percent saturation, such as discussed by Davis (1975a,b), are more complex and could often result in unnecessarily stringent criteria in the cold months and potentially unprotective criteria during periods of high ambient temperature or at high elevations. Oxygen partial pressure is subject to the same temperature problems as percent saturation.

The approach recommended by Doudoroff and Shumway (1970), in which the criteria vary seasonally with the natural minimum dissolved oxygen concentrations in the waters of concern, was adopted by the National Academy of Sciences and National Academy of Engineering (NAS/NAE, 1973). This approach has some merit, but the lack of data (natural minimum concentrations) makes its application difficult, and it can also produce unnecessarily stringent or unprotective criteria during periods of extreme temperature.

The more simplistic approach to dissolved oxygen criteria has been supported by the findings of a select committee of scientists specifically established by the Research Advisory Board of the International Joint Commission to review the dissolved oxygen criterion for the Great Lakes (Magnuson et al., 1979). The committee concluded that a simple criterion (an average criterion of 6.5 mg/l and a minimum criterion of 5.5 mg/l) was preferable to one based on percent saturation (or oxygen partial pressure) and was scientifically sound because the rate of oxygen transfer across fish gills is directly dependent on the mean difference in oxygen partial pressure across the gill. Also, the total amount of oxygen delivered to the gills is a more specific limiting factor than is oxygen partial pressure per se. The format of this otherwise simple criterion was more sophisticated than earlier criteria with the introduction of a two-concentration criterion comprised of both a mean and a minimum. This two-concentration criteria structure is similar to that currently used for toxicants (Federal Register, 45 FR 79318, November 28, 1980). EPA agrees with the International Joint Commission's conclusions and will recommend a two-number criterion for dissolved oxygen.

The national criteria presented herein represent the best estimates, based on the data available, of dissolved oxygen concentrations necessary to protect aquatic life and its uses. Previous water quality criteria have either emphasized (Federal Water Pollution Control Administration, 1968) or rejected (National Academy of Sciences and National Academy of Engineering, 1972) separate dissolved oxygen criteria for coldwater and warmwater biota. A warmwater-coldwater dichotomy is made in this criterion. To simplify discussion, however, the text of the document is split into salmonid and nonsalmonid sections. The salmonid-nonsalmonid dichotomy is predicated on the much greater knowledge regarding the dissolved oxygen requirements of salmonids and on the critical influence of intergravel dissolved oxygen concentration on salmonid embryonic and larval development. Nonsalmonid fish include many other coldwater and coolwater fish plus all warmwater fish. Some of these species are known to be less sensitive than salmonids to low dissolved oxygen concentrations. Some other nonsalmonids may prove to be at least as sensitive to low dissolved oxygen concentrations as the salmonids; among the nonsalmonids of likely sensitivity are the herrings (Clupeidae), the smelts (Osmeridae), the pikes (Esocidae), and the sculpins (Cottidae). Although there is little published data regarding the dissolved oxygen requirements of most nonsalmonid species, there is apparently enough anecdotal information to suggest that many coolwater species are more sensitive to dissolved oxygen depletion than are warmwater species. According to the American Fisheries Society (1978), the term "coolwater fishes" is not vigorously defined, but it refers generally to those species which are distributed by temperature preference between the "coldwater" salmonid communities to the north and the more diverse, often centrarchid-dominated "warmwater" assemblages to the south. Many states have more stringent dissolved oxygen standards for colder waters, waters that contain either salmonids, nonsalmonid coolwater fish, or the sensitive centrarchid, the smallmouth bass.

The research and sociological emphasis for dissolved oxygen has been biased towards fish, especially the more economically important species in the family Salmonidae. Several authors (Doudoroff and Shumway, 1970; Davis, 1975a,b) have discussed this bias in considerable detail and have drawn similar conclusions regarding the effects of low dissolved oxygen on freshwater invertebrates. Doudoroff and Shumway (1970) stated that although some invertebrate species are about as sensitive as the moderately susceptible fishes, all invertebrate species need not be protected in order to protect the food source for fisheries because many invertebrate species, inherently more tolerant than fish, would increase in abundance. Davis (1975a,b) also concluded that invertebrate species would probably be adequately protected if the fish populations are protected. He stated that the composition of invertebrate communities may shift to more tolerant forms selected from the resident community or recruited from outside the community. In general, stream invertebrates that are requisite riffle-dwellers probably have a higher dissolved oxygen requirement than other aquatic invertebrates. The riffle habitat maximizes the potential dissolved oxygen flux to organisms living in the high water velocity by rapidly replacing the water in the immediate vicinity of the organisms. This may be especially important for organisms that exist clinging to submerged substrate in the riffles. In the absence of data to the contrary, EPA will follow the assumption that a dissolved oxygen criterion protective of fish will be adequate.

One of the most difficult problems faced during this attempt to gather, interpret, assimilate, and generalize the scientific data base for dissolved oxygen effects on fish has been the variability in test conditions used by investigators. Some toxicological methods for measuring the effects of chemicals on aquatic life have been standardized for nearly 40 years; this has not been true of dissolved oxygen research. Acute lethality tests with dissolved oxygen vary in the extreme with respect to types of exposure (constant vs. declining), duration of exposure (a few hours vs. a week or more), type of endpoint (death vs. loss of equilibrium), type of oxygen control (nitrogen stripping vs. vacuum degassing), and type of exposure chamber (open to the atmosphere vs. sealed). In addition there are the normal sources of variability that influence standardized toxicity tests, including seasonal differences in the condition of test fish, acclimation or lack of acclimation to test conditions, type and level of feeding, test temperature, age of test fish, and stresses due to test conditions. Chronic toxicity tests are typically of two types, full life cycle tests or early life stage tests. These have come to be rather rigorously standardized and are essential to the toxic chemical criteria established by EPA. These tests routinely are assumed to include the most sensitive life stage, and the criteria then presume to protect all life stages. With dissolved oxygen research, very few tests would be considered legitimate chronic tests; either they fail to include a full life cycle, they fail to include both embryo and larval stages, or they fail to include an adequate period of post-larval feeding and growth.

Instead of establishing year-round criteria to protect all life stages, it may be possible to establish seasonal criteria based on the life stages present. Thus, special early life stage criteria are routinely accepted for salmonid early life stages because of their usual intergravel environment. The same concept may be extended to any species that appear to have more stringent dissolved oxygen requirements during one period of their life history. The flexibility afforded by such a dichotomy in criteria carries with it the responsibility to accurately determine the presence or absence of the more sensitive stages prior to invocation of the less stringent criteria. Such presence/absence data must be more site-specific than national in scope, so that temperature, habitat, or calendar specifications are not possible in this document. In the absence of such site-specific determinations the default criteria would be those that would protect all life stages year-round; this is consistent with the present format for toxic chemical criteria.

II. Salmonids

The effects of various dissolved oxygen concentrations on the well-being of aquatic organisms have been studied more extensively for fish of the family Salmonidae (which includes the genera *Coregonus*, *Oncorhynchus*, *Prosopium*, *Salmo*, *Salvelinus*, *Stenodus*, and *Thymallus*) than for any other family of organisms. Nearly all these studies have been conducted under laboratory conditions, simplifying cause and effect analysis, but minimizing or eliminating potentially important environmental factors, such as physical and chemical stresses associated with suboptimal water quality, as well as competition, behavior, and other related activities. Most laboratory studies on the effects of dissolved oxygen concentrations on salmonids have emphasized growth, physiology, or embryonic development. Other studies have described acute lethality or the effects of dissolved oxygen concentration on swimming performance.

A. Physiology

Many studies have reported a wide variety of physiological responses to low dissolved oxygen concentrations. Usually, these investigations were of short duration, measuring cardiovascular and metabolic alterations resulting from hypoxic exposures of relatively rapid onset. While these data provide only minimal guidance for establishing environmentally acceptable dissolved oxygen concentrations, they do provide considerable insight into the mechanisms responsible for the overall effects observed in the entire organism. For example, a good correlation exists between oxygen dissociation curves for rainbow trout blood (Cameron, 1971) and curves depicting the reduction in growth of salmonids (Brett and Blackburn, 1981; Warren et al., 1973) and the reduction in swimming ability of salmonids (Davis et al., 1963). These correlations indicate that the blood's reduced oxygen loading capacity at lower dissolved oxygen concentrations limits the amount of oxygen delivered to the tissues, restricting the ability of fish to maximize metabolic performance.

In general, the significance of metabolic and physiological studies on the establishment of dissolved oxygen criteria must be indirect, because their applicability to environmentally acceptable dissolved oxygen concentrations requires greater extrapolation and more assumptions than those required for data on growth, swimming, and survival.

B. Acute Lethal Concentrations

Doudoroff and Shumway (1970) summarized studies on lethal concentrations of dissolved oxygen for salmonids; analysis of these data indicates that the test procedures were highly variable, differing in duration, exposure regime, and reported endpoints. Only in a few cases could a 96-hr LC50 be calculated. Mortality or loss of equilibrium usually occurred at concentrations between 1 and 3 mg/l.

Mortality of brook trout has occurred in less than one hour at 10°C at dissolved oxygen concentrations below 1.2 mg/l, and no fish survived exposure at or below 1.5 mg/l for 10 hours (Shepard, 1955). Lethal dissolved oxygen concentrations increase at higher water temperatures and longer exposures. A 3.5 hr exposure killed all trout at 1.1 and 1.6 mg/l at 10 and 20°C, respectively (Downing and Merkens, 1957). A 3.5-day exposure killed all trout at 1.3 and 2.4 mg/l at 10 and 20°C, respectively. The corresponding no-mortality levels were 1.9 and 2.7 mg/l. The difference between dissolved oxygen concentrations causing total mortality and those allowing complete survival was about 0.5 mg/l when exposure duration was less than one week. If the period of exposure to low dissolved oxygen concentrations is limited to less than 3.5 days, concentrations of dissolved oxygen of 3 mg/l or higher should produce no direct mortality of salmonids.

More recent studies confirm these lethal levels in chronic tests with early life stages of salmonids (Siefert et al., 1974; Siefert and Spoor, 1973; Brooke and Colby, 1980); although studies with lake trout (Carlson and Siefert, 1974) indicate that 4.5 mg/l is lethal at 10°C (perhaps a marginally acceptable temperature for embryonic lake trout).

C. Growth

Growth of salmonids is most susceptible to the effects of low dissolved oxygen concentrations when the metabolic demands or opportunities are greatest. This is demonstrated by the greater sensitivity of growth to low dissolved oxygen concentrations when temperatures are high and food most plentiful (Warren et al., 1973). A total of more than 30 growth tests have been reported by Herrmann et al. (1962), Fisher (1963), Warren et al. (1973), Brett and Blackburn (1981), and Spoor (1981). Results of these tests are not easily compared because the tests encompass a wide range of species, temperatures, food types, and fish sizes. These factors produced a variety of control growth rates which, when combined with a wide range of test durations and fish numbers, resulted in an array of statistically diverse test results.

The results from most of these 30-plus tests were converted to growth rate data for fish exposed to low dissolved oxygen concentrations and were compared to control growth rates by curve-fitting procedures (JRB Associates, 1984). Estimates of growth rate reductions were similar regardless of the type of curve employed, but the quadratic model was judged to be superior and was used in the growth rate analyses contained in this document. The apparent relative sensitivity of each species to dissolved oxygen depletion may be influenced by fish size, test duration, temperature, and diet. Growth rate data (Table 1) from these tests with salmon and trout fed unrestricted rations indicated median growth rate reductions of 7, 14, and 25 percent for fish held at 6, 5, and 4 mg/l, respectively (JRB Associates, 1984). However, median growth rate reductions for the various species ranged from 4 to 9 percent at 6 mg/l, 11 to 17 percent at 5 mg/l, and 21 to 29 percent at 4 mg/l.

Table 1. Percent reduction in growth rate of salmonids at various dissolved oxygen concentrations expressed as the median value from n tests with each species (calculated from JRB Associates, 1984).

Dissolved Oxygen (mg/l)	Species (number of tests)					
	Chinook Salmon (6)	Coho Salmon (12)	Sockeye Salmon (1)	Rainbow Trout (2)	Brown Trout (1)	Lake Trout (2)
9	0	0	0	0	0	0
8	0	0	0	1	0	0
7	1	1	2	5	1	2
6	7	4	6	9	6	7
5	16	11	12	17	13	16
4	29	21	22	25	23	29
3	47	37	33	37	36	47
Median Temp. (°C)	15	18	15	12	12	12

Considering the variability inherent in growth studies, the apparent reductions in growth rate sometimes seen above 6 mg/l are not usually statistically significant. The reductions in growth rate occurring at dissolved oxygen concentrations below about 4 mg/l should be considered severe; between 4 mg/l and the threshold of effect, which variably appears to be between 6 and 10 mg/l in individual tests, the effect on growth rate is moderate to slight if the exposures are sufficiently long.

Within the growth data presented by Warren et al. (1973), the greatest effects and highest thresholds of effect occurred at high temperatures (17.8 to 21.7°C). In two tests conducted at about 8.5°C, the growth rate reduction at 4 mg/l of dissolved oxygen averaged 12 percent. Thus, even at the maximum feeding levels in these tests, dissolved oxygen levels down to 5 mg/l probably have little effect on growth rate at temperatures below 10°C.

Growth data from Warren et al. (1973) included chinook salmon tests conducted at various temperatures. These data (Table 2) indicated that growth tests conducted at 10-15°C would underestimate the effects of low dissolved oxygen concentrations at higher temperatures by a significant margin. For example, at 5 mg/l growth was not affected at 13°C but was reduced by 34 percent if temperatures were as high as 20°C. Examination of the test temperatures associated with the growth rate reductions listed in Table 1 shows that most data represent temperatures between 12 and 15°C. At the higher temperatures often associated with low dissolved oxygen concentrations, the growth rate reductions would have been greater if the generalizations of the chinook salmon data are applicable to salmonids in general. Coho salmon growth studies (Warren et al., 1973) showed a similar result over a range of temperatures from 9 to 18°C, but the trend was reversed in two tests near 22°C (Table 3). Except for the 22°C coho tests, the coho and chinook salmon results support the idea that effects of low dissolved oxygen become more severe at higher temperatures. This conclusion is supported by data on largemouth bass (to be discussed later) and by the increase in metabolic rate produced by high temperatures.

Table 2. Influence of temperature on growth rate of chinook salmon held at various dissolved oxygen concentrations (calculated from Warren et al., 1973; JRB Associates, 1984).

Dissolved Oxygen (mg/l)	Percent Reduction in Growth Rate at					
	8.4°C	13.0°C	13.2°C	17.8°C	18.6°C	21.7°C
9	0	0	0	0	0	0
8	0	0	0	0	2	0
7	0	0	4	0	8	2
6	0	0	8	5	19	14
5	0	0	16	16	34	34
4	7	4	25	33	53	65
3	26	22	36	57	77	100

Table 3. Influence of temperature on growth rate of coho salmon held at various dissolved oxygen concentrations (calculated from Warren et al., 1973; JRB Associates, 1984).

Dissolved Oxygen (mg/l)	Percent Reduction in Growth Rate at					
	8.6°C	12.9°C	13.0°C	18.0°C	21.6°C	21.8°C
10	0	0	0	0	0	0
9	0	0	0	5	0	0
8	0	1	2	10	0	0
7	1	4	6	17	0	6
6	4	10	13	27	0	1
5	9	18	23	38	0	7
4	17	29	36	51	4	19
3	28	42	51	67	6	37

Effects of dissolved oxygen concentration on the growth rate of salmonids fed restricted rations have been less intensively investigated. Thatcher (1974) conducted a series of tests with coho salmon at 15°C over a wide range of food consumption rates at 3, 5, and 8 mg/l of dissolved oxygen. The only significant reduction in growth rate was observed at 3 mg/l and food consumption rates greater than about 70 percent of maximum. In these studies, Thatcher noted that fish at 5 mg/l appeared to expend less energy in swimming activity than those at 8 mg/l. In natural conditions, where fish may be rewarded for energy expended defending preferred territory or searching for food, a dissolved oxygen concentration of 5 mg/l may restrict these activities.

The effect of forced activity and dissolved oxygen concentration on the growth of coho salmon was studied by Hutchins (1974). The growth rates of salmon fed to repletion at a dissolved oxygen concentration of 3 mg/l and held at current velocities of 8.5 and 20 cm/sec were reduced by 20 and 65 percent, respectively. At 5 mg/l, no reduction of growth rate was seen at the slower velocity, but a 15 percent decrease occurred at the higher velocity.

The effects of various dissolved oxygen concentrations on the growth rate of coho salmon ($\sim$ 5 cm long) in laboratory streams with an average current velocity of 12 cm/sec have been reported by Warren et al. (1973). In this series of nine tests, salmon consumed aquatic invertebrates living in the streams. Results at temperatures from 9.5° to 15.5°C supported the results of earlier laboratory studies; at higher growth rates (40 to 50 mg/g/day), dissolved oxygen levels below 5 mg/l reduced growth rate, but at lower growth rates (0 to 20 mg/g/day), no effects were seen at concentrations down to 3 mg/l.

The applicability of these growth data from laboratory tests depends on the available food and required activity in natural situations. Obviously, these factors will be highly variable depending on duration of exposure, growth rate, species, habitat, season, and size of fish. However, unless effects of these variables are examined for the site in question, the laboratory results should be used. The attainment of critical size is vital to the smolting of anadromous salmonids and may be important for all salmonids if size-related transition to feeding on larger or more diverse food organisms is an advantage. In the absence of more definitive site-specific, species-specific growth data, the data summary in Tables 1, 2, and 3 represent the best estimates of the effects of dissolved oxygen concentration on the potential growth of salmonid fish.

D. Reproduction

No studies were found that described the effects of low dissolved oxygen on the reproduction, fertility, or fecundity of salmonid fish.

E. Early Life Stages

Determining the dissolved oxygen requirements for salmonids, many of which have embryonic and larval stages that develop while buried in the gravel of streams and lakes, is complicated by complex relationships between the dissolved oxygen supplies in the gravel and the overlying water. The dissolved oxygen supply of embryos and larvae can be depleted even when the dissolved oxygen concentration in the overlying body of water is otherwise acceptable. Intergravel dissolved oxygen is dependent upon the balance between the combined respiration of gravel-dwelling organisms, from bacteria to fish embryos, and the rate of dissolved oxygen supply, which is dependent upon rates of water percolation and convection, and dissolved oxygen diffusion.

Water flow past salmonid eggs influences the dissolved oxygen supply to the microenvironment surrounding each egg. Regardless of dissolved oxygen concentration in the gravel, flow rates below 100 cm/hr directly influence the oxygen supply in the microenvironment and hence the size at hatch of salmonid fish. At dissolved oxygen levels below 6 mg/l the time from fertilization to hatch is longer as water flow decreases (Silver et al., 1963; Shumway et al., 1964).

The dissolved oxygen requirements for growth of salmonid embryos and larvae have not been shown to differ appreciably from those of older salmonids. Under conditions of adequate water flow (≥100 cm/hr), the weight attained by salmon and trout larvae prior to feeding (swimup) is decreased less than 10 percent by continuous exposure to concentrations down to 3 mg/l (Brannon, 1965; Chapman and Shumway, 1978). The considerable developmental delay which occurs at low dissolved oxygen conditions could have survival and growth implications if the time of emergence from gravel, or first feeding, is critically related to the presence of specific food organisms, stream flow, or other factors (Carlson and Siefert, 1974; Siefert and Spoor, 1974). Effects of low dissolved oxygen on early life stages are probably most significant during later embryonic development when critical dissolved oxygen concentrations are highest (Alderdice et al., 1958) and during the first few months post-hatch when growth rates are usually highest. The latter authors studied the effects of 7-day exposure of embryos to low dissolved oxygen at various stages during incubation at otherwise high dissolved oxygen concentrations. They found no effect of 7-day exposure at concentrations above 2 mg/l (at a water flow of 85 cm/hr).

Embryos of mountain whitefish suffered severe mortality at a mean dissolved oxygen concentration of 3.3 mg/l (2.8 mg/l minimum) and some reduction in survival was noted at 4.6 mg/l (3.8 mg/l minimum); at 4.6 mg/l, hatching was delayed by 1 to 2 weeks (Sieffert et al., 1974). Delayed hatching resulted in poorer growth at the end of the test, even at dissolved oxygen concentrations of 6 mg/l.

Evaluating intergravel dissolved oxygen concentrations is difficult because of the great spatial and temporal variability produced by differences in stream flow, bottom topography, and gravel composition. Even within the same redd, dissolved oxygen concentrations can vary by 5 or 6 mg/l at a given time (Koski, 1965). Over several months, Koski repeatedly measured the dissolved oxygen concentrations in over 30 coho salmon redds and the overlying stream water in three small, forested (unlogged) watersheds. The results of these measurements indicated that the average intraredd dissolved oxygen concentration was about 2 mg/l below that of the overlying water. The minimum concentrations measured in the redds averaged about 3 mg/l below those of the overlying water and probably occurred during the latter period of intergravel development when water temperatures were warmer, larvae larger, and overlying dissolved oxygen concentrations lower.

Coble (1961) buried steelhead trout eggs in streambed gravel, monitored nearby intergravel dissolved oxygen and water velocity, and noted embryo survival. There was a positive correlation between dissolved oxygen concentration, water velocity, and embryo survival. Survival ranged from 16 to 26 percent whenever mean intergravel dissolved oxygen concentrations were below 6 mg/l or velocities were below 20 cm/hr; at dissolved oxygen concentrations above 6 mg/l and velocities over 20 cm/hr, survival ranged from 36 to 62 percent. Mean reductions in dissolved oxygen concentration between stream and intergravel waters averaged about 5 mg/l as compared to the 2 mg/l average reduction observed by Koski (1965) in the same stream. One explanation for the different results is that the intergravel water flow may have been higher in the natural redds studied by Koski (not determined) than in the artificial redds of Coble's investigation. Also, the density of eggs near the sampling point may have been greater in Coble's simulated redds.

A study of dissolved oxygen concentrations in brook trout redds was conducted in Pennsylvania (Hollander, 1981). Brook trout generally prefer areas of groundwater upwelling for spawning sites (Witzel and MacCrimmon, 1983). Dissolved oxygen and temperature data offer no indication of groundwater flow in Hollender's study areas, however, so that differences between water column and intergravel dissolved oxygen concentrations probably represent intergravel dissolved oxygen depletion. Mean dissolved oxygen concentrations in redds averaged 2.1, 2.8, and 3.7 mg/liter less than the surface water in the three portions of the study. Considerable variation of intergravel dissolved oxygen concentration was observed between redds and within a single redd. Variation from one year to another suggested that dissolved oxygen concentrations will show greater intergravel depletion during years of low water flow.

Until more data are available, the dissolved oxygen concentration in the intergravel environment should be considered to be at least 3 mg/l lower than the oxygen concentration in the overlying water. The 3 mg/l differential is assumed in the criteria, since it reasonably represents the only two available studies based on observations in natural redds (Koski, 1965; Hollender, 1981). When siltation loads are high, such as in logged or agricultural watersheds, lower water velocity within the gravel could additionally reduce dissolved oxygen concentrations around the eggs. If either greater or lesser differentials are known or expected, the criteria should be altered accordingly.

F. Behavior

Ability of chinook and coho salmon to detect and avoid abrupt differences in dissolved oxygen concentrations was demonstrated by Whitmore et al. (1960). In laboratory troughs, both species showed strong preference for oxygen levels of 9 mg/l or higher over those near 1.5 mg/l; moderate selection against 3.0 mg/l was common and selection against 4.5 and 6.0 mg/l was sometimes detected.

The response of young Atlantic salmon and brown trout to low dissolved oxygen depended on their age; larvae were apparently unable to detect and avoid water of low dissolved oxygen concentration, but fry 6-16 weeks of age showed a marked avoidance of concentrations up to 4 mg/l (Bishai, 1962). Older fry (26 weeks of age) showed avoidance of concentrations up to 3 mg/l.

In a recent study of the rainbow trout sport fishery of Lake Taneycomo, Missouri, Weithman and Haas (1984) have reported that reductions in minimum daily dissolved oxygen concentrations below 6 mg/l are related to a decrease in the harvest rate of rainbow trout from the lake. Their data suggest that lowering the daily minimum from 6 mg/l to 5, 4, and 3 mg/l reduces the harvest rate by 20, 40, and 60 percent, respectively. The authors hypothesized that the reduced catch was a result of reduction in feeding activity. This mechanism of action is consistent with Thatcher's (1974) observation of lower activity of coho salmon at 5 mg/l in laboratory growth studies and the finding of Warren et al. (1973) that growth impairment produced by low dissolved oxygen appears to be primarily a function of lower food intake.

A three-year study of a fishery on planted rainbow trout was published by Heimer (1984). This study found that the catch of planted trout increased during periods of low dissolved oxygen in American Falls reservoir on the Snake River in Idaho. The author concluded that the fish avoided areas of low dissolved oxygen and high temperature and the increased catch rate was a result of the fish concentrating in areas of more suitable oxygen supply and temperature.

G. Swimming

Effects of dissolved oxygen concentrations on swimming have been demonstrated by Davis et al. (1963). In their studies, the maximum sustained swimming speeds (in the range of 30 to 45 cm/sec) of juvenile coho salmon were reduced by 8.4, 12.7, and 19.9 percent at dissolved oxygen concentrations of 6, 5, and 4 mg/l, respectively. Over a temperature range from 10 to 20°C, effects were slightly more severe at cooler temperatures. Jones (1971) reported 30 and 43 percent reductions of maximal swimming speed of rainbow trout at dissolved oxygen concentrations of 5.1 (14°C) and 3.8 (22°C) mg/l, respectively. At lower swimming speeds (2 to 4 cm/sec), coho and chinook salmon at 20°C were generally able to swim for 24 hours at dissolved oxygen concentrations of 3 mg/l and above (Katz et al., 1958). Thus, the significance of lower dissolved oxygen concentrations on swimming depends on the level of swimming performance required for the survival, growth, and reproduction of salmonids. Failure to escape from predation or to negotiate a swift portion of a spawning migration route may be considered an indirect lethal effect and, in this regard, reductions of maximum swimming performance can be very important. With these exceptions, moderate levels of swimming activity required by salmonids are apparently little affected by concentrations of dissolved oxygen that are otherwise acceptable for growth and reproduction.

H. Field Studies

Field studies of salmonid populations are almost non-existent with respect to effects of dissolved oxygen concentrations. Some of the systems studied by Ellis (1937) contained trout, but of those river systems in which trout or other salmonids were most likely (Columbia River and Upper Missouri River) no stations were reported with dissolved oxygen concentrations below 5 mg/l, and 90 percent of the values exceeded 7 mg/l.

III. Non-Salmonids

The amount of data describing effects of low dissolved oxygen on non-salmonid fish is more limited than that for salmonids, yet must cover a group of fish with much greater taxonomic and physiological variability. Salmonid criteria must provide for the protection and propagation of 38 species in 7 closely related genera; the non-salmonid criteria must provide for the protection and propagation of some 600 freshwater species in over 40 diverse taxonomic families. Consequently, the need for subjective technical judgment is greater for the non-salmonids.

Many of the recent, most pertinent data have been obtained for several species of Centrarchidae (sunfish), northern pike, channel catfish, and the fathead minnow. These data demonstrate that the larval stage is generally the most sensitive life stage. Lethal effects on larvae have been observed at dissolved oxygen concentrations that may only slightly affect growth of juveniles of the same species.

A. Physiology

Several studies of the relationship between low dissolved oxygen concentrations and resting oxygen consumption rate constitute the bulk of the physiological data relating to the effect of hypoxia on nonsalmonid fish. A reduction in the resting metabolic rate of fish is generally believed to represent a marked decrease in the scope for growth and activity, a net decrease in the supply of oxygen to the tissues, and perhaps a partial shift to anaerobic energy sources. The dissolved oxygen concentration at which reduction in resting metabolic rate first appears is termed the critical oxygen concentration.

Studies with brown bullhead (Grigg, 1969), largemouth bass (Cech et al., 1979), and goldfish and carp (Beamish, 1964), produced estimates of critical dissolved oxygen concentrations for these species. For largemouth bass, the critical dissolved oxygen concentrations were 2.8 mg/l at 30°C, < 2.6 mg/l at 25°C, and < 2.3 mg/l at 20°C. For brown bullheads the critical concentration was about 4 mg/l. Carp displayed critical oxygen concentrations near 3.4 and 2.9 mg/l at 10 and 20°C, respectively, and goldfish critical concentrations of dissolved oxygen were about 1.8 and 3.5 mg/l at 10 and 20°C, respectively. A general summary of these data suggest critical dissolved oxygen concentrations between 2 and 4 mg/l, with higher temperatures usually causing higher critical concentrations.

Critical evaluation of the data of Beamish (1964) suggest that the first sign of hypoxic stress is not the decrease in oxygen consumption, but rather an increase, perhaps as a result of metabolic cost of passing an increased ventilation volume over the gills. These increases were seen in carp at 5.8 mg/l at 20°C and at 4.2 mg/l at 10°C.

B. Acute Lethal Concentrations

Based on the sparse data base describing acute effects of low dissolved oxygen concentrations on nonsalmonids, many non-salmonids appear to be considerably less sensitive than salmonids. Except for larval forms, no non-salmonids appear to be more sensitive than salmonids. Spoor (1977) observed lethality of largemouth bass larvae at a dissolved oxygen concentration of 2.5 mg/l after only a 3-hr exposure. Generally, adults and juveniles of all species studied survive for at least a few hours at concentrations of dissolved oxygen as low as 3 mg/l. In most cases, no mortality results from acute exposures to 3 mg/l for the 24- to 96-h duration of the acute tests. Some non-salmonid fish appear to be able to survive a several-day exposure to concentrations below 1 mg/l (Moss and Scott, 1961; Downing and Merkens, 1957), but so little is known about the latent effects of such exposure that short-term survival cannot now be used as an indication of acceptable dissolved oxygen concentrations. In addition to the unknown latent effects of exposure to very low dissolved oxygen concentrations, there are no data on the effects of repeated short-term exposures. Most importantly, data on the tolerance to low dissolved oxygen concentrations are available for only a few of the numerous species of non-salmonid fish.

C. Growth

Stewart et al. (1967) conducted several growth studies with juvenile largemouth bass and observed reduced growth at 5.9 mg/l and lower concentrations. Five of six experiments included dissolved oxygen concentrations between 5 and 6 mg/l; dissolved oxygen concentrations of 5.1 and 5.4 mg/l produced reductions in growth rate of 20 and 14 percent, respectively, but concentrations of 5.8 and 5.9 mg/l had essentially no effect on growth. The efficiency of food conversion was not reduced until dissolved oxygen concentrations were much lower, indicating that decreased food consumption was the primary cause of reduced growth.

When channel catfish fingerlings held at 8, 5, and 3 mg/l were fed as much as they could eat in three daily feedings, there were significant reductions in feeding and weight gain (22 percent) after a 6 week exposure to 5 mg/l (Andrews et al., 1973). At a lower feeding rate, growth after 14 weeks was reduced only at 3 mg/l. Fish exposed to 3 mg/l swam lethargically, fed poorly and had reduced response to loud noises. Raible (1975) exposed channel catfish to several dissolved oxygen concentrations for up to 177 days and observed a graded reduction in growth at each concentration below 6 mg/l. However, the growth pattern for 6.8 mg/l was comparable to that at 5.4 mg/l. He concluded that each mg/l increase in dissolved oxygen concentrations between 3 and 6 mg/l increased growth by 10 to 13 percent.

Carlson et al. (1980) studied the effect of dissolved oxygen concentration on the growth of juvenile channel catfish and yellow perch. Over periods of about 10 weeks, weight gain of channel catfish was lower than that of control fish by 14, 39, and 54 percent at dissolved oxygen concentrations of 5.0, 3.4, and 2.1 mg/l, respectively. These differences were produced by decreases in growth rate of 5, 18, and 23 percent (JRB Associates, 1984), pointing out the importance of differentiating between effects on weight gain and effects on growth rate. When of sufficient duration, small reductions in growth rate can have large effects on relative weight gain. Conversely, large effects on growth rate may have little effect on annual weight gain if they occur only over a small proportion of the annual growth period. Yellow perch appeared to be more tolerant to low dissolved oxygen concentrations, with reductions in weight gain of 2, 4, and 30 percent at dissolved oxygen concentrations of 4.9, 3.5, and 2.1 mg/l, respectively.

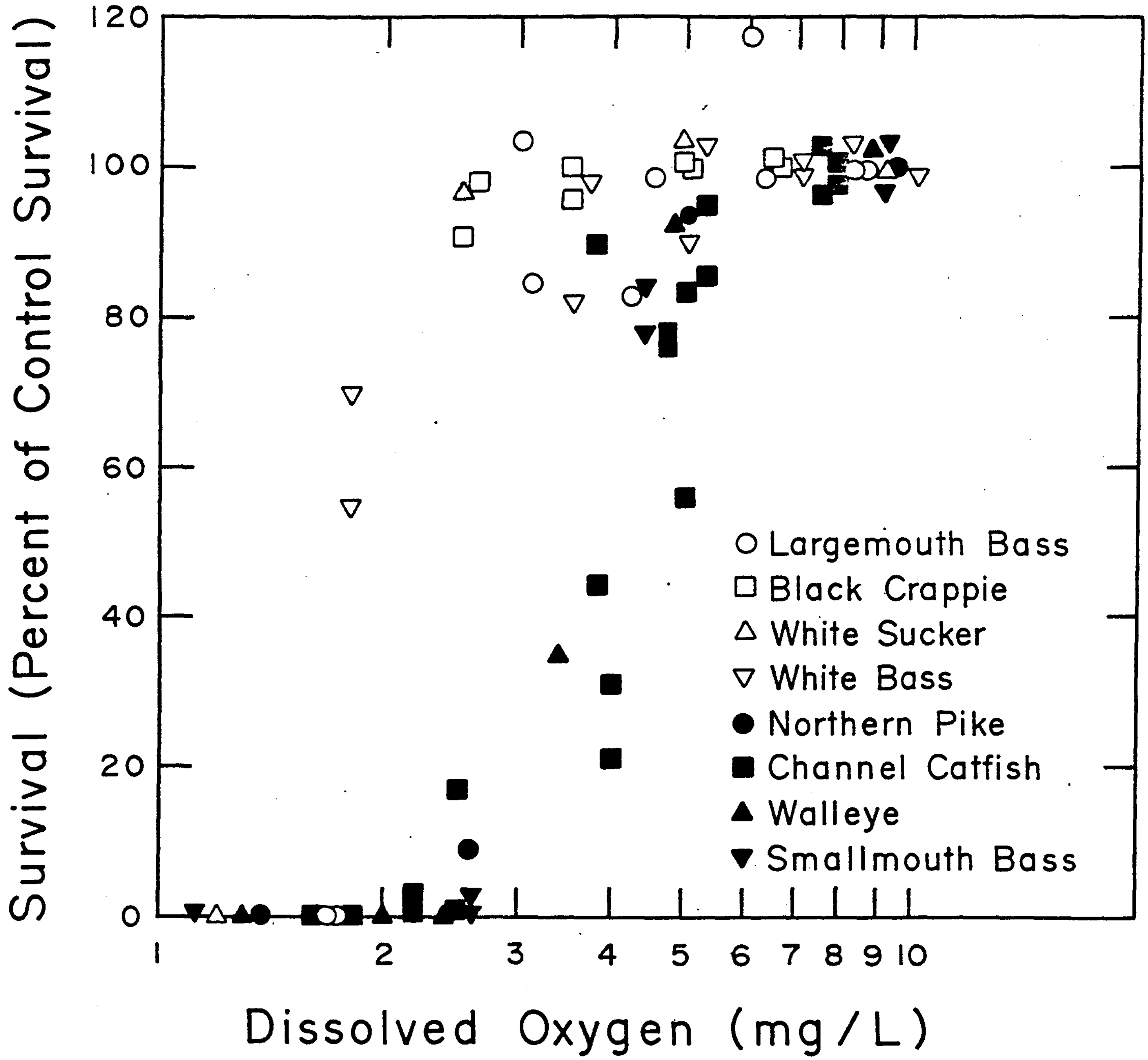

Figure 1. Effect of continuous exposure to various mean dissolved oxygen concentrations on survival of embryonic and larval stages of eight species of nonsalmonid fish. Minima recorded in these tests averaged about 0.3 mg/l below the mean concentrations.

The data of Stewart et al. (1967), Carlson et al. (1980), and Adelman and Smith (1972) were analyzed to determine the relationship between growth rate and dissolved oxygen concentration (JRB Associates, 1984). Yellow perch appeared to be very resistant to influences of low dissolved oxygen concentrations, northern pike may be about as sensitive as salmonids, while largemouth bass and channel catfish are intermediate in their response (Table 4). The growth rate relations modeled from Adelman and Smith are based on only four data points, with none in the critical dissolved oxygen region from 3 to 5 mg/l. Nevertheless, these growth data for northern pike are the best available for nonsalmonid coldwater fish. Adelman and Smith observed about a 65 percent reduction in growth of juvenile northern pike after 6-7 weeks at dissolved oxygen concentrations of 1.7 and 2.6 mg/l. At the next higher concentration (5.4 mg/l), growth was reduced 5 percent.

Table 4. Percent reduction in growth rate of some nonsalmonid fish held at various dissolved oxygen concentrations expressed as the median value from n tests with each species (calculated from JRB Associates, 1984).

Dissolved Oxygen (mg/l)	Species (number of tests)			
	Northern Pike (1)	Largemouth Bass (6)	Channel Catfish (1)	Yellow Perch (1)
9	0	0	0	0
8	1	0	0	0
7	4	0	1	0
6	9	0	3	0
5	16	1	7	0
4	25	9	13	0
3	35	17	20	7
2	--	51	29	22
Median Temp (°C)	19	26	25	20

Brake (1972) conducted a series of studies on juvenile largemouth bass in two artificial ponds to determine the effect of reduced dissolved oxygen concentration on consumption of mosquitofish and growth during 10 2-week exposures. The dissolved oxygen in the control pond was maintained near air-saturation (8.3 to 10.4 mg/l) and the other pond contained mean dissolved oxygen concentrations from 4.0 to 6.0 mg/l depending upon the individual test. The temperature, held near the same level in both ponds for each test, ranged from 13 to 27°C. Food consumption and growth rates of the juvenile bass, maintained on moderate densities of forage fish, increased with temperature and decreased at the reduced dissolved oxygen concentrations except at 13°C. Exposure to that temperature probably slowed metabolic processes of the bass so much that their total metabolic rates were not limited by dissolved oxygen except at very low concentrations. These largemouth bass studies clearly support the idea that higher temperatures exacerbate the adverse effects of low dissolved oxygen on the growth rate of fish (Table 5). Comparisons of Brake's pond studies with the laboratory growth studies of Stewart et al. (1967) suggest that laboratory growth studies may significantly underestimate the adverse effect of low dissolved oxygen on fish growth. Stewart's six studies with largemouth bass are summarized in Table 4 and Brake's data are presented in Table 5. All of Stewart's tests were conducted at 26°C, about the highest temperature in Brake's studies, but comparison of the data show convincingly that at dissolved oxygen concentrations between 4 and 6 mg/l the growth rate of bass in ponds was reduced 17 to 34 percent rather than the 1 to 9 percent seen in the laboratory studies. These results suggest that the ease of food capture in laboratory studies may result in underestimating effects of low dissolved oxygen on growth rates in nature.

Table 5. Effect of temperature on the percent reduction in growth rate of largemouth bass exposed to various dissolved oxygen concentrations in ponds (after Brake, 1972; JRB Associates, 1984).

Temperature (°C)	Percent Reduction in Growth Rate at		
	4.2 ± 0.2 mg/l	4.9 ± 0.2 mg/l	5.8 ± 0.2 mg/l
13.3	0	--	--
13.6	--	--	7
16.3	--	18	--
16.7	--	--	15
18.1	--	19	--
18.6	--	34	--
18.7	18	--	--
23.3	26	--	--
26.7	--	--	17
27.4	31	--	--

Brett and Blackburn (1981) reanalyzed the growth data previously published by other authors for largemouth bass, carp, and coho salmon in addition to their own results for young coho and sockeye salmon. They concluded for all species that above a critical level ranging from 4.0 to 4.5 mg/l, decreases in growth rate and food conversion efficiency were not statistically significant in these tests of relatively short duration (6 to 8 weeks) under the pristine conditions of laboratory testing. EPA believes that a more accurate estimate of the dissolved oxygen concentrations that have no effect on growth and a better estimate of concentration:effect relationships can be obtained by curve-fitting procedures (JCB Associates, 1984) and by examining these results from a large number of studies. Brett and Blackburn added an additional qualifying statement that it was not the purpose of their study to seek evidence on the acceptable level of dissolved oxygen in nature because of the problems of environmental complexity involving all life stages and functions, the necessary levels of activity to survive in a competitive world, and the interaction of water quality (or lack of it) with varying dissolved oxygen concentrations. Their cautious concern regarding the extrapolation to the real world of results obtained under laboratory conditions is consistent with that of numerous investigators.

D. Reproduction

A life-cycle exposure of the fathead minnow beginning with 1- to 2-month old juveniles was conducted and effects of continuous low dissolved oxygen concentrations on various life stages indicated that the most sensitive stage was the larval stage (Brungs, 1971). No spawning occurred at 1 mg/l, and the number of eggs produced per female was reduced at 2 mg/l but not at higher concentrations. Where spawning occurred, the percentage hatch of embryos (81-89 percent) was not affected when the embryos were exposed to the same concentrations as their parents. Hatching time varied with temperature, which was not controlled, but with decreasing dissolved oxygen concentration the average incubation time increased gradually from the normal 5 to nearly 8 days. Mean larval survival was 6 percent at 3 mg/l and 25 percent at 4 mg/l. Mean survival of larvae at 5 mg/l was 66 percent as compared to 50 percent at control dissolved oxygen concentrations. However, mean growth of surviving larvae at 5 mg/l was about 20 percent lower than control larval growth. Siefert and Herman (1977) exposed mature black crappies to constant dissolved oxygen concentrations from 2.5 mg/l to saturation and temperatures of 13-20°C. Number of spawnings, embryo viability, hatching success, and survival through swim-up were similar at all exposures.

E. Early Life Stages

Larval and juvenile non-salmonids are frequently more sensitive to exposures to low dissolved oxygen than are other life stages. Peterka and Kent (1976) conducted semi-controlled experiments at natural spawning sites of northern pike, bluegill, pumpkinseed, and smallmouth bass in Minnesota. Dissolved oxygen concentrations were measured 1 and 10 cm from the bottom, with observations being made on hatching success and survival of embryos, sac larvae, and, in some instances, larvae. Controlled exposure for up to 8 hours was performed *in situ* in small chambers with the dissolved oxygen controlled by nitrogen stripping. For all species tested, tolerance to short-term exposure to low concentrations decreased from embryonic to larval stages. Eight-hour exposure of embryos and larvae of northern pike to dissolved oxygen concentrations caused no mortality of embryos at 0.6 mg/l but was 100 percent lethal to sac-larvae and larvae. The most sensitive stage, the larval stage, suffered complete mortality following 8 hours at 1.6 mg/l; the next higher concentration, 4 mg/l, produced no mortality. Smallmouth bass were at least as sensitive, with nearly complete mortality of sac-larvae resulting from 6-hour exposure to 2.2 mg/l, but no mortality occurred after exposure to 4.2 mg/l. Early life stages of bluegill were more hardy, with embryos tolerating 4-hour exposure to 0.5 mg/l, a concentration lethal to sac-larvae; sac-larvae survived similar exposure to 1.8 mg/l, however. Because the most sensitive stage of northern pike was the later larval stage, and because the younger sac-larval stages of smallmouth bass and bluegill were the oldest stages tested, the tests with these latter species may not have included the most sensitive stage. Based on these tests, 4 mg/l is tolerated, at least briefly, by northern pike and may be tolerated by smallmouth bass, but concentrations as high as 2.2 mg/l are lethal.

Several studies have provided evidence of mortality or other significant damage to young non-salmonids as a result of a few weeks exposure to dissolved oxygen concentrations in the 3 to 6 mg/l range. Siefert et al. (1973) exposed larval northern pike to various dissolved oxygen concentrations at 15 and 19°C and observed reduced survival at concentrations as high as 2.9 and 3.4 mg/l. Most of the mortality at these concentrations occurred at the time the larvae initiated feeding. Apparently the added stress of activity at that time or a greater oxygen requirement for that life stage was the determining factor. There was a marked decrease in growth at concentrations below 3 mg/l. In a similar study lasting 20 days, survival of walleye embryos and larvae was reduced at 3.4 mg/l (Siefert and Spoor, 1974), and none survived at lower concentrations. A 20 percent reduction in the survival of smallmouth bass embryos and larvae occurred at a concentration of 4.4 mg/l (Siefert et al., 1974) and at 2.5 mg/l all larvae died in the first 5 days after hatching. At 4.4 mg/l hatching occurred earlier than in the controls and growth among survivors was reduced. Carlson and Siefert (1974) concluded that concentrations from 1.7 to 6.3 mg/l reduced the growth of early stages of the largemouth bass by 10 to 20 percent. At concentrations as high as 4.5 mg/l, hatching was premature and feeding was delayed; both factors could indirectly influence survival, especially if other stresses were to occur simultaneously. Carlson et al. (1974) also observed that embryos and larvae of channel catfish are sensitive to low dissolved oxygen during 2- or 3-week exposures. Survival at 25°C was slightly reduced at 5 mg/l and significantly reduced at 4.2 mg/l. At 28°C survival was slightly reduced at 3.8, 4.6, and 5.4 mg/l; total mortality occurred at 2.3 mg/l. At all reduced dissolved oxygen concentrations at both temperatures, embryo pigmentation was lighter, incubation period was extended, feeding was delayed, and growth was reduced. No effect of dissolved oxygen concentrations as low as 2.5 mg/l was seen on survival of embryonic and larval black crappie (Sieffert and Herman, 1977). Other tolerant species are the white bass and the white sucker, both of which evidenced adverse effect to embryo larval exposure only at dissolved oxygen concentrations of 1.8 and 1.2 mg/l, respectively (Sieffert et al., 1974; Sieffert and Spoor, 1974).

Data (Figure 1) on the effects of dissolved oxygen on the survival of embryonic and larval nonsalmonid fish show some species to be tolerant (largemouth bass, white sucker, black crappie, and white bass) and others nontolerant (channel catfish, walleye, northern pike, smallmouth bass). The latter three species are often included with salmonids in a grouping of sensitive coldwater fish; these data tend to support that placement.

F. Behavior

Largemouth bass in laboratory studies (Whitmore et al., 1960) showed a slight tendency to avoid concentrations of dissolved oxygen of 3.0 and 4.6 mg/l and a definite avoidance of 1.5 mg/l. Bluegills avoided a concentration of 1.5 mg/l but not higher concentrations. The environmental significance of such a response is unknown, but if large areas are deficient in dissolved oxygen this avoidance would probably not greatly enhance survival. Spoor (1977) exposed largemouth bass embryos and larvae to low dissolved oxygen for brief exposures of a few hours. At 23 to 24°C and 4 to 5 mg/l, the normally quiescent, bottom-dwelling yolk-sac larvae became very active and swam vertically to a few inches above the substrate. Such behavior in natural systems would probably cause significant losses due to predation and simple displacement from the nesting area.

G. Swimming

Effects of low dissolved oxygen on the swimming performance of largemouth bass were studied by Katz et al. (1959) and Dahlberg et al. (1968). The results in the former study were highly dependent upon season and temperature, with summer tests at 25°C finding no effect on continuous swimming for 24 hrs at 0.8 ft/sec unless dissolved oxygen concentrations fell below 2 mg/l. In the fall, at 20°C, no fish were able to swim for a day at 2.8 mg/l, and in the winter and 16° no fish swam for 24 hours at 5 mg/l. These results are consistent with those seen in salmonids in that swimming performance appears to be more sensitive to low dissolved oxygen at lower temperatures.

Dahlberg et al. (1968) looked at the effect of dissolved oxygen on maximum swimming speed at temperatures near 25°C. They reported slight effects (less than 10% reduction in maximum swimming speed) at concentrations between 3 and 4.5 mg/l, moderate reduction (16-20%) between 2 and 3 mg/l and severe reduction (30-50%) at 1 to 1.5 mg/l.

H. Field Studies

Ellis (1937) reported results of field studies conducted at 982 stations on freshwater streams and rivers during the months of June through September, 1930-1935. During this time, numerous determinations of dissolved oxygen concentrations were made. He concluded that 5 mg/l appeared to be the lowest concentration which may reasonably be expected to maintain varied warmwater fish species in good condition in inland streams. Ellis (1944) restated his earlier conclusion and also added that his study had included the measurement of dissolved oxygen concentrations at night and various seasons. He did not specify the frequency or proportion of diurnal or seasonal sampling, but the mean number of samples over the 5-year study was about seven samples per station.

Brinley (1944) discussed a 2-year biological survey of the Ohio River Basin. He concluded that in the zone where dissolved oxygen is between 3 and 5 mg/l the fish are more abundant than at lower concentrations, but show a tendency to sickness, deformity, and parasitization. The field results show that the concentration of 5 mg/l seems to represent a general dividing line between good and bad conditions for fish.

A three-year study of fish populations in the Wisconsin River indicated that sport fish (percids and centrarchids) constituted a significantly greater proportion of the fish population at sites having mean summer dissolved oxygen concentrations greater than 5 mg/l than at sites averaging below 5 mg/l (Coble, 1982). The differences could not be related to any observed habitat variables other than dissolved oxygen concentration.

These three field studies all indicate that increases in dissolved oxygen concentrations above 5 mg/l do not produce noteworthy improvements in the composition, abundance, or condition of non-salmonid fish populations, but that sites with dissolved oxygen concentrations below 5 mg/l have fish assemblages with increasingly poorer population characteristics as the dissolved oxygen concentrations become lower. It cannot be stressed too strongly that these field studies lack definition with respect to the actual exposure conditions experienced by the resident populations and the lack of good estimates for mean and minimum exposure concentrations over various periods precludes the establishment of numerical criteria based on these studies. The results of these semi-quantitative field studies are consistent with the criteria derived later in this document.

IV. Invertebrates

As stated earlier, there is a general paucity of information on the tolerance of the many forms of freshwater invertebrates to low dissolved oxygen. Most available data describe the relationship between oxygen concentration and oxygen consumption or short-term survival of aquatic larvae of insects. These data are further restricted by their emphasis on species representative of relatively fast-flowing mountain streams.

One rather startling feature of these data is the apparently high dissolved oxygen requirement for the survival of some species. Before extrapolating from these data one should be cautious in evaluating the respiratory mode(s) of the species, its natural environment, and the test environment. Thus, many nongilled species respire over their entire body surface while many other species are gilled. Either form is dependent upon the gradient of oxygen across the respiratory surface, a gradient at least partially dependent upon the rate of replacement of the water immediately surrounding the organism. Some insects, such as some members of the mayfly genus, Baetis, are found on rocks in extremely swift currents; testing their tolerance to low dissolved oxygen in laboratory apparatus at slower flow rats may contribute to their inability to survive at high dissolved oxygen concentrations. In addition, species of insects that utilize gaseous oxygen, either from bubbles or surface atmosphere, may not be reasonably tested for tolerance of hypoxia if their source of gaseous oxygen is deprived in the laboratory tests.

In spite of these potential problems, the dissolved oxygen requirements for the survival of many species of aquatic insects are almost certainly greater than those of most fish species. Early indication of the high dissolved oxygen requirements of some aquatic insects appeared in the research of Fox et al. (1937) who reported critical dissolved oxygen concentrations for mayfly nymphs in a static test system. Critical concentrations for six species ranged from 2.2 mg/l to 17 mg/l; three of the species had critical concentrations in excess of air saturation. These data suggest possible extreme sensitivity of some species and also the probability of unrealistic conditions of water flow. More recent studies in water flowing at 10 cm/sec indicate critical dissolved oxygen concentrations for four species of stonefly are between 7.3 and 4.8 mg/l (Benedetto, 1970).

In a recent study of 22 species of aquatic insects, Jacob et al. (1984) reported 2-5 hour LC50 values at unspecified "low to moderate" flows in a stirred exposure chamber, but apparently with no flow of replacement water. Tests were run at one or more of five temperatures from 12 to 30°C; some species were tested at only one temperature, others at as many as four. The median of the 22 species mean LC50s was about 3 mg/l, with eight species having an average LC50 below 1 mg/l and four in excess of 7 mg/l. The four most sensitive species were two mayfly species and two caddisfly species. The studies of Fox et al. (1937), Benedetto (1970), and Jacob et al. (1984) were all conducted with European species, but probably have general relevance to North American habitats. A similar oxygen consumption study of a North American stonefly (Kapoor and Griffiths, 1975) indicated a possible critical dissolved oxygen concentration of about 7 mg/l at a flow rate of 0.32 cm/sec and a temperature of 20°C.

One type of behavioral observation provides evidence of hypoxic stress in aquatic insects. As dissolved oxygen concentrations decrease, many species of aquatic insects can be seen to increase their respiratory movements, movements that provide for increased water flow over the respiratory surfaces. Fox and Sidney (1953) reported caddisfly respiratory movements over a range of dissolved oxygen from 9 to 1 mg/l. A dissolved oxygen decrease to 5 mg/l doubled the number of movements and at 1 to 2 mg/l the increase was 3- to 4-fold.

Similar data were published by Knight and Gaufin (1963) who studied a stonefly common in the western United States. Significant increases occurred below 5 mg/l at 16°C and below 2 mg/l at 10°C. Increases in movements occurred at higher dissolved oxygen concentrations when water flow was 1.5 cm/sec than 7.6 cm/sec, again indicating the importance of water flow rate on the respiration of aquatic insects. A subsequent paper by Knight and Gaufin (1965) indicated that species of stonefly lacking gills are more sensitive to low dissolved oxygen than are gilled forms.

Two studies that provide the preponderance of the current data on the acute effects of low dissolved oxygen concentrations on aquatic insects are those of Gaufin (1973) and Nebeker (1972) which together provide reasonable 96-hr LC50 dissolved oxygen concentrations for 26 species of aquatic insects (Table 6). The two studies contain variables that make them difficult to compare or evaluate fully. Test temperatures were 6.4°C in Gaufin's study and 18.5°C in Nebeker's. Gaufin used a vacuum degasser while Nebeker used a 30-foot stripping column that probably produced an unknown degree of supersaturation with nitrogen. The water velocity is not given in either paper, although flow rates are given but test chamber dimensions are not clearly specified. The overall similarity of the test results suggests that potential supersaturation and lower flow volume in Nebeker's tests did not have a significant effect on the results.

Because half of the insect species tested had 96-h LC50 dissolved oxygen concentrations between 3 and 4 mg/l it appears that these species (collected in Montana and Minnesota) would require at least 4 mg/l dissolved oxygen to ensure their survival. The two most sensitive species represent surprisingly diverse habitats, *Ephemerella doddsi* is found in swift rocky streams and has an LC50 of 5.2 mg/l while the pond mayfly, *Callibaetis montanus*, has an LC50 of 4.4 mg/l. It is possible that the test conditions represented too slow a flow for *E. doddsi* and too stressful flow conditions for *C. montanus*.

Table 6. Acutely lethal concentrations of dissolved oxygen to aquatic insects.

Species	96-h LC50 (mg/l)	Source*
Stonefly		
Acroneuria pacifica	1.6 (H)**	G
Acroneuria lycorias	3.6	N
Acrynopteryx aurea	3.3 (H)	G
Arcynopteryx parallela	< 2 (H)	G
Diura knowltoni	3.6 (L)	G
Nemoura cinctipes	3.3 (H)	G
Pteronarcys californica	3.9 (L)	G
Pteronarcys californica	3.2 (H)	G
Pteronarcys dorsata	2.2	N
Pteronarcella badia	2.4 (H)	G
Mayfly		
Baetisca laurentina	3.5	N
Callibaetis montanus	4.4 (L)	G
Ephemerella doddsi	5.2 (L)	G
Ephemerella grandis	3.0 (H)	G
Ephemerella subvaria	3.9	N
Hexagenia limbata	1.8 (H)	G
Hexagenia limbata	1.4	N
Leptophlebia nebulosa	2.2	N
Caddisfly		
Brachycentrus occidentalis	< 2 (L)	G
Drusinus sp.	1.8 (H)	G
Hydropsyche sp.	3.6 (L)	G
Hydropsyche betteri	2.9 (21°C)	N
Hydropsyche betteri	2.6 (18.5°C)	N
Hydropsyche betteri	2.3 (17°C)	N
Hydropsyche betteri	1.0 (10°C)	N
Lepidostoma sp.	< 3 (H)	G
Limnophilus ornatus	3.4 (L)	G
Neophylax sp.	3.8 (L)	G
Neothremma alicia	1.7 (L)	G
Diptera		
Simulium vittatum	3.2 (L)	G
Tanytarsus dissimilis	< 0.6	N

* G = Gaufin (1973) -- all tests at 6.4°C.
N = Nebeker (1972) -- all tests at 18.5°C except as noted/flow 125 ml/min.

** H = high flow (1000 ml/min); L = low flow (500 ml/min).

Other freshwater invertebrates have been subjected to acute hypoxic stress and their LC50 values determined. Gaufin (1973) reported a 96-h LC50 for the amphipod Gammarus limnaeus of < 3 mg/l. Four other crustaceans were studied by Sprague (1963) who reported the following 24-h LC50s: 0.03 mg/l, Asellus intermedius; 0.7 mg/l, Hyalella azteca; 2.2 mg/l, Gammarus pseudolimnaeus; and 4.3 mg/l, Gammarus fasciatus. The range of acute sensitivities of these species appears similar to that reported for aquatic insects.

There are few long-term studies of freshwater invertebrate tolerance to low dissolved oxygen concentrations. Both Gaufin (1973) and Nebeker (1972) conducted long-term survival studies with insects, but both are questioned because of starvation and potential nitrogen supersaturation, respectively. Gaufin's data for eight Montana species and 17 Utah species suggest that 4.9 mg/l and 3.3 mg/l, respectively, would provide for 50 percent survival for from 10 to 92 days. Nebeker lists 30-d LC50 values for five species, four between 4.4 and 5.0 mg/l and one < 0.5 mg/l. Overall, these data indicate that prolonged exposure to dissolved oxygen concentrations below 5 mg/l would have deterimental effects on a large proportion of the aquatic insects common in areas like Minnesota, Montana, and Utah. Information from other habitat types and geographic locations would provide a broader picture of invertebrate dissolved oxygen requirements.

A more classic toxicological protocol was used by Homer and Waller (1983) in a study of the effects of low dissolved oxygen on Daphna magna. In a 26-d chronic exposure test, they reported that 1.8 mg/l significantly reduced fecundity and 2.7 mg/l caused a 17 percent reduction in final weight of adults. No effect was seen at 3.7 mg/l.

In summarizing the state of knowledge regarding the relative sensitivity of fish and invertebrates to low dissolved oxygen, it seems that some species of insects and other crustaceans are killed at concentrations survived by all species of fish tested. Thus, while most fish will survive exposure to 3 mg/l, many species of invertebrates are killed by concentrations as high as 4 mg/l. The extreme sensitivity of a few species of aquatic inects may be an artifact of the testing environment. Those sensitive species common to swift flowing, coldwater streams may require very high concentrations of dissolved oxygen. On the other hand, those stream habitats are probably among the least likely to suffer significant dissolved oxygen depletion.

Long-term impacts of hypoxia are less well known for invertebrates than for fish. Concentrations adequate to avoid impairment of fish production probably will provide reasonable protection for invertebrates as long as lethal concentrations are avoided.

V. Other Considerations

A. Effects of Fluctuations

Natural dissolved oxygen concentrations fluctuate on a seasonal and daily basis, while in most laboratory studies the oxygen levels are held essentially constant. In two studies on the effects of daily oxygen cycles the authors concluded that growth of fish fed unrestricted rations was markedly less than would be estimated from the daily mean dissolved oxygen concentrations

(Fisher, 1963; Whitworth, 1968). The growth of these fish was only slightly above that attainable during constant exposure to the minimum concentrations of the daily cycles. A diurnal dissolved oxygen pulse to 3 mg/l for 8 hours per day for 9 days, with a concentration of 8.3 mg/l for the remainder of the time, produced a significant stress pattern in the serum protein fractions of bluegill and largemouth bass but not yellow bullhead (Bouck and Ball, 1965). During periods of low dissolved oxygen the fish lost their natural color, increased their ventilation rate, and remained very quiet. At these times food was ignored. Several times, during the low dissolved oxygen concentration part of the cycle, the fish vomited food which they had eaten as much as 12 hours earlier. After comparable exposure of the rock bass, Bouck (1972) observed similar results on electrophoretic patterns and feeding behavior.

Stewart et al. (1967) exposed juvenile largemouth bass to patterns of diurnally-variable dissolved oxygen concentrations with daily minima near 2 mg/l and daily maxima from 4 to 17 mg/l. Growth under any fluctuation pattern was almost always less than the growth that presumably would have occurred had the fish been held at a constant concentration equal to the mean concentration.

Carlson et al. (1980) conducted constant and diurnally fluctuating exposures with juvenile channel catfish and yellow perch. At mean constant concentrations of 3.5 mg/l or less, channel catfish consumed less food and growth was significantly reduced. Growth of this species was not reduced at fluctuations from about 6.2 to 3.6 and 4.9 to 2 mg/l, but was significantly impaired at a fluctuation from about 3.1 to 1 mg/l. Similarly, at mean constant concentrations near 3.5 mg/l, yellow perch consumed less food but growth was not impaired until concentrations were near 2 mg/l. Growth was not affected by fluctuations from about 3.8 to 1.4 mg/l. No dissolved oxygen-related mortalities were observed. In both the channel catfish and the yellow perch experiments, growth rates during the tests with fluctuating dissolved oxygen were considerably below the rate attained in the constant exposure tests. As a result, the fluctuating and constant exposures could not be compared. Growth would presumably have been more sensitive in the fluctuating tests if there had been higher rates of control growth.

Mature black crappies were exposed to constant and fluctuating dissolved oxygen concentrations (Carlson and Herman, 1978). Constant concentrations were near 2.5, 4, 5.5, and 7 mg/l and fluctuating concentrations ranged from 0.8 to 1.9 mg/l above and below these original concentrations. Successful spawning occurred at all exposures except the fluctuation between 1.8 and 4.1 mg/l.

In considering daily or longer-term cyclic exposures to low dissolved oxygen concentrations, the minimum values may be more important than the mean levels. The importance of the daily minimum as a determinant of growth rate is common to the results of Fisher (1963), Stewart (1967), and Whitworth (1968). Since annual low dissolved oxygen concentrations normally occur during warmer months, the significance of reduced growth rates during the period in question must be considered. If growth rates are normally low, then the effects of low dissolved oxygen concentration on growth could be minimal; if normal growth rates are high, the effects could be significant, especially if the majority of the annual growth occurs during the period in question.

B. Temperature and Chemical Stress

When fish were exposed to lethal temperatures, their survival times were reduced when the dissolved oxygen concentration was lowered from 7.4 to 3.8 mg/l (Alabaster and Welcomme, 1962). Since high temperature and low dissolved oxygen commonly occur together in natural environments, this likelihood of additive or synergistic effects of these two potential stresses is a most important consideration.

High temperatures almost certainly increase the adverse effects of low dissolved oxygen concentrations. However, the spotty, irregular acute lethality data base provides little basis for quantitative, predictive analysis. Probably the most complete study is that on rainbow trout, perch, and roach conducted by Downing and Merkens (1957). Because their study was spread over an 18-month period, seasonal effects could have influenced the effects at the various test temperatures. Over a range from approximately 10 to 20°C, the lethal dissolved oxygen concentrations increased by an average factor of about 2.6, ranging from 1.4 to 4.1 depending on fish species tested and test duration. The influence of temperature on chronic effects of low dissolved oxygen concentrations are not well known, but requirements for dissolved oxygen probably increase to some degree with increasing temperature. This generalization is supported by analysis of salmon studies reported by Warren et al. (1973) and the largemouth bass studies of Brake (1972).

Because most laboratory tests are conducted at temperatures near the mid-range of a species temperature tolerance, criteria based on these test data will tend to be under-protective at higher temperatures and over-protective at lower temperatures. Concern for this temperature effect was a consideration in establishing these criteria, especially in the establishing of those criteria intended to prevent short-term lethal effects.

A detailed discussion and model for evaluating interactions among temperature, dissolved oxygen, ammonia, fish size, and ration on the resulting growth of individual fish (Cuenco et al., 1985a,b,c) provides an excellent, in-depth evaluation of potential effects of dissolved oxygen on fish growth.

Several laboratory studies evaluated the effect of reduced dissolved oxygen concentrations on the toxicity of various chemicals, some of which occur commonly in oxygen-demanding wastes. Lloyd (1961) observed that the toxicity of zinc, lead, copper, and monohydric phenols was increased at dissolved oxygen concentrations as high as approximately 6.2 mg/l as compared to 9.1 mg/l. At 3.8 mg/l, the toxic effect of these chemicals was even greater. The toxicity of ammonia was enhanced by low dissolved oxygen more than that of other toxicants. Lloyd theorized that the increases in toxicity of the chemicals were due to increased ventilation at low dissolved oxygen concentrations; as a consequence of increased ventilation, more water, and therefore more toxicant, passes the fish's gills. Downing and Merkens (1955) reported that survival times of rainbow trout at lethal ammonia concentrations increased markedly over a range of dissolved oxygen concentrations from 1.5 to 8.5 mg/l. Ninety-six-hr LC50 values for rainbow trout indicate that ammonia became more toxic with decreasing dissolved oxygen concentrations from 8.6 to 2.6 mg/l (Thurston et al., 1981). The maximum increase in toxicity was by about a factor of 2. They also compared ammonia LC50 values at reduced dissolved oxygen concentrations after 12, 24, 48, and 72 hrs. The shorter the time period, the more pronounced the positive relationship between the LC50 and dissolved oxygen concentration. The authors recommended that dissolved oxygen standards for the protection of salmonids should reflect background concentrations of ammonia which may be present and the likelihood of temporary increases in those concentrations. Adelman and Smith (1972) observed that decreasing dissolved oxygen concentrations increased the toxicity of hydrogen sulfide to goldfish. When the goldfish were acclimated to the reduced dissolved oxygen concentration before the exposure to hydrogen sulfide began, mean 96-hr LC50 values were 0.062 and 0.048 mg/l at dissolved oxygen concentrations of 6 and 1.5 mg/l, respectively. When there was no prior acclimation, the LC50 values were 0.071 and 0.053 mg/l at the same dissolved oxygen concentrations. These results demonstrated a less than doubling in toxicity of hydrogen sulfide and little difference with regard to prior acclimation to reduced dissolved oxygen concentrations. Cairns and Scheier (1957) observed that bluegills were less tolerant to zinc, naphthenic acid, and potassium cyanide at periodic low dissolved oxygen concentrations. Pickering (1968) reported that an increased mortality of bluegills exposed to zinc resulted from the added stress of low dissolved oxygen concentrations. The difference in mean LC50 values between low (1.8 mg/l) and high (5.6 mg/l) dissolved oxygen concentrations was a factor of 1.5.

Interactions between other stresses and low dissolved oxygen concentrations can greatly increase mortality of trout larvae. For example, sublethal concentrations of pentachlorophenol and oxygen combined to produce 100 percent mortality of trout larvae held at an oxygen concentration of 3 mg/l (Chapman and Shumway, 1978). The survival of chinook salmon embryos and larvae reared at marginally high temperatures was reduced by any reduction in dissolved oxygen, especially at concentrations below 7 mg/l (Eddy, 1972).

In general, the occurrence of toxicants in the water mass, in combination with low dissolved oxygen concentration, may lead to a potentiation of stress responses on the part of aquatic organisms (Davis, 1975a,b). Doudoroff and Shumway (1970) recommended that the disposal of toxic pollutants must be controlled so that their concentrations would not be unduly harmful at prescribed, acceptable concentrations of dissolved oxygen, and these acceptable dissolved oxygen concentrations should be independent of existing or highest permitted concentrations of toxic wastes.

C. Disease Stress

In a study of 5 years of case records at fish farms, Meyer (1970) observed that incidence of infection with *Aeromonas liquefasciens* (a common bacterial pathogen of fish) was most prevalent during June, July, and August. He considered low oxygen stress to be a major factor in outbreaks of *Aeromonas* disease during summer months. Haley et al. (1967) concluded that a kill of American and threadfin shad in the San Joaquin River occurred as a result of *Aeromonas* infection the day after the dissolved oxygen was between 1.2 and 2.6 mg/l. In this kill the lethal agent was *Aeromonas* but the additional stress of the low dissolved oxygen may have been a significant factor.

Wedemeyer (1974) reviewed the role of stress as a predisposing factor in fish diseases and concluded that facultative fish pathogens are continuously present in most waters. Disease problems seldom occur, however, unless environmental quality and the host defense systems of the fish also deteriorate. He listed furunculosis, Aeromonad and Pseudomonad hemorrhagic septicemia, and vibriosis as diseases for which low dissolved oxygen is one environmental factor predisposing fish to epizootics. He stated that to optimize fish health, dissolved oxygen concentrations should be 6.9 mg/l or higher. Snieszko (1974) also stated that outbreaks of diseases are probably more likely if the occurrence of stress coincides with the presence of pathogenic microorganisms.

VI. Conclusions

The primary determinant for the criteria is laboratory data describing effect on growth, with developmental rate and survival included in embryo and larval production levels. For the purpose of deriving criteria, growth in the laboratory and production in nature are considered equally sensitive to low dissolved oxygen. Fish production in natural communities actually may be significantly more, or less, sensitive than growth in the laboratory, which represents only one simplified facet of production.

The dissolved oxygen criteria are based primarily on data developed in the laboratory under conditions which are usually artificial in several important respects. First, they routinely preclude or minimize most environmental stresses and biological interactions that under natural conditions are likely to increase, to a variable and unknown extent, the effect of low dissolved oxygen concentrations. Second, organisms are usually given no opportunity to acclimate to low dissolved oxygen concentrations prior to tests nor can they avoid the test exposure. Third, food availability is unnatural because the fish have easy, often unlimited, access to food without significant energy expenditure for search and capture. Fourth, dissolved oxygen concentrations are kept nearly constant so that each exposure represents both a minimum and an average concentration. This circumstance complicates application of the data to natural systems with fluctuating dissolved oxygen concentrations.

Considering the latter problem only, if the laboratory data are applied directly as minimum allowable criteria, the criteria will presumably be higher than necessary because the mean dissolved oxygen concentration will often be significantly higher than the criteria. If applied as a mean, the criteria could allow complete anoxia and total mortality during brief periods of very low dissolved oxygen or could allow too many consecutive daily minima near the lethal threshold. If only a minimum or a mean can be given as a general criterion, the minimum must be chosen because averages are too independent of the extremes.

Obviously, biological effects of low dissolved oxygen concentrations depend upon means, minima, the duration and frequency of the minima, and the period of averaging. In many respects, the effects appear to be independent of the maxima; for example, including supersaturated dissolved oxygen values in the average may produce mean dissolved oxygen concentrations that are misleadingly high and unrepresentative of the true biological stress of the dissolved oxygen minima.

Because most experimental exposures have been constant, data on the effect of exposure to fluctuating dissolved oxygen concentrations is sketchy. The few fluctuating exposure studies have used regular, repeating daily cycles of an on-off nature with 8 to 16 hours at low dissolved oxygen and the remainder of the 24 hr period at intermediate or high dissolved oxygen. This is an uncharacteristic exposure pattern, since most daily dissolved oxygen cycles are of a sinusoidal curve shape and not a square-wave variety.

The existing data allow a tentative theoretical dosing model for fluctuating dissolved oxygen only as applied to fish growth. The EPA believes that the data of Stewart et al. (1967) suggest that effects on growth are reasonably represented by calculating the mean of the daily cycle using as a maximum value the dissolved oxygen concentration which represents the threshold effect concentration during continuous exposure tests. For example, with an effect threshold of 6 mg/l, all values in excess of 6 mg/l should be averaged as though they were 6 mg/l. Using this procedure, the growth effects appear to be a reasonable function of the mean, as long as the minimum is not lethal. Lethal thresholds are highly dependent upon exposure duration, species, age, life stage, temperature, and a wide variety of other factors. Generally the threshold is between 1 and 3 mg/l.

A most critical and poorly documented aspect of a dissolved oxygen criterion is the question of acceptable and unacceptable minima during dissolved oxygen cycles of varying periodicity. Current ability to predict effects of exposure to a constant dissolved oxygen level is only fair; the effects of regular, daily dissolved oxygen cycles can only be poorly estimated; and predicting the effects of more stochastic patterns of dissolved oxygen fluctuations requires an ability to integrate constant and cycling effects.

Several general conclusions result from the synthesis of available field and laboratory data. Some of these conclusions differ from earlier ones in the literature, but the recent data discussed in this document have provided additional detail and perspective.

- Naturally-occurring dissolved oxygen concentrations may occasionally fall below target criteria levels due to a combination of low flow, high temperature, and natural oxygen demand. These naturally-occurring conditions represent a normal situation in which the productivity of fish or other aquatic organisms may not be the maximum possible under ideal circumstances, but which represent the maximum productivity under the particular set of natural conditions. Under these circumstances the numerical criteria should be considered unattainable, but naturally-occurring conditions which fail to meet criteria should not be interpreted as violations of criteria. Although further reductions in dissolved oxygen may be inadvisable, effects of any reductions should be compared to natural ambient conditions and not to ideal conditions.

- Situations during which attainment of appropriate criteria is most critical include periods when attainment of high fish growth rates is a priority, when temperatures approach upper-lethal levels, when pollutants are present in near-toxic quantities, or when other significant stresses are suspected.

- Reductions in growth rate produced by a given low dissolved oxygen concentration are probably more severe as temperature increases. Even during periods when growth rates are normally low, high temperature stress increases the sensitivity of aquatic organisms to disease and toxic pollutants, making the attainment of proper dissolved oxygen criteria particularly important. For these reasons, periods of highest temperature represent a critical portion of the year with respect to dissolved oxygen requirements.

- In salmonid spawning habitats, intergravel dissolved oxygen concentrations are significantly reduced by respiration of fish embryos and other organisms. Higher water column concentrations of dissolved oxygen are required to provide protection of fish embryos and larvae which develop in the intergravel environment. A 3 mg/l difference is used in the criteria to account for this factor.

- The early life stages, especially the larval stage, of non-salmonid fish are usually most sensitive to reduced dissolved oxygen stress. Delayed development, reduced larval survival, and reduced larval and post-larval growth are the observed effects. A separate early life stage criterion for non-salmonids is established to protect these more sensitive stages and is to apply from spawning through 30 days after hatching.

- Other life stages of salmonids appear to be somewhat more sensitive than other life stages of the non-salmonids, but this difference, resulting in a 1.0 mg/l difference in the criteria for other life stages, may be due to a more complete and precise data base for salmonids. Also, this difference is at least partially due to the colder water temperatures at which salmonid tests are conducted and the resultant higher dissolved oxygen concentration in oxygen-saturated control water.

- Few appropriate data are available on the effects of reduced dissolved oxygen on freshwater invertebrates. However, historical concensus states that, if all life stages of fish are protected, the invertebrate communities, although not necessarily unchanged, should be adequately protected. This is a generalization to which there may be exceptions of environmental significance. Acutely lethal concentrations of dissolved oxygen appear to be higher for many aquatic insects than for fish.

- Any dissolved oxygen criteria should include absolute minima to prevent mortality due to the direct effects of hypoxia, but such minima alone may not be sufficient protection for the long-term persistence of sensitive populations under natural conditions. Therefore, the criteria minimum must also provide reasonable assurance that regularly repeated or prolonged exposure for days or weeks at the allowable minimum will avoid significant physiological stress of sensitive organisms.

Several earlier dissolved oxygen criteria were presented in the form of a family of curves (Doudoroff and Shumway, 1970) or equations (NAS/NAE, 1973) which yielded various dissolved oxygen requirements depending on the qualitative degree of fishery protection or risk deemed suitable at a given site. Although dissolved oxygen concentrations that risk significant loss of fishery production are not consistent with the intent of water quality criteria, a qualitative protection/risk assessment for a range of dissolved oxygen concentrations has considerable value to resource managers. Using qualitative descriptions similar to those presented in earlier criteria of Doudoroff and Shumway (1970) and Water Quality Criteria 1972 (NAS/NAE, 1973), four levels of risk are listed below:

No Production Impairment. Representing nearly maximal protection of fishery resources.

Slight Production Impairment. Representing a high level of protection of important fishery resources, risking only slight impairment of production in most cases.

Moderate Production Impairment. Protecting the persistence of existing fish populations but causing considerable loss of production.

Severe Production Impairment. For low level protection of fisheries of some value but whose protection in comparison with other water uses cannot be a major objective of pollution control.

Selection of dissolved oxygen concentrations equivalent to each of these levels of effect requires some degree of judgment based largely upon examination of growth and survival data, generalization of response curve shape, and assumed applicability of laboratory responses to natural populations. Because nearly all data on the effects of low dissolved oxygen on aquatic organisms relate to continuous exposure for relatively short duration (hours to weeks), the resultant dissolved oxygen concentration-biological effect estimates are most applicable to essentially constant exposure levels, although they may adequately represent mean concentrations as well.

The production impairment values are necessarily subjective, and the definitions taken from Doudoroff and Shumway (1970) are more descriptive than the accompanying terms "slight," "moderate," and "severe." The impairment values for other life stages are derived predominantly from the growth data summarized in the text and tables in Sections II and III. In general, slight, moderate, and severe impairment are equivalent to 10, 20, and 40 percent growth impairment, respectively. Growth impairment of 50 percent or greater is often accompanied by mortality, and conditions allowing a combination of severe growth impairment and mortality are considered as no protection.

Production impairment levels for early life stages are quite subjective and should be viewed as convenient divisions of the range of dissolved oxygen concentrations between the acute mortality limit and the no production impairment concentrations.

Production impairment values for invertebrates are based on survival in both long-term and short-term studies. There are no studies of warmwater species and few of lacustrine species.

The following is a summary of the dissolved oxygen concentrations (mg/l) judged to be equivalent to the various qualitative levels of effect described earlier; the value cited as the acute mortality limit is the minimum dissolved oxygen concentration deemed not to risk direct mortality of sensitive organisms:

1. Salmonid Waters

a. Embryo and Larval Stages

- No Production Impairment = 11* (8)
- Slight Production Impairment = 9* (6)
- Moderate Production Impairment = 8* (5)
- Severe Production Impairment = 7* (4)
- Limit to Avoid Acute Mortality = 6* (3)

(* Note: These are water column concentrations recommended to achieve the required intergravel dissolved oxygen concentrations shown in parentheses. The 3 mg/l difference is discussed in the criteria document.)

b. Other Life Stages

- No Production Impairment = 8
- Slight Production Impairment = 6
- Moderate Production Impairment = 5
- Severe Production Impairment = 4
- Limit to Avoid Acute Mortality = 3

2. Nonsalmonid Waters

a. Early Life Stages

- No Production Impairment = 6.5
- Slight Production Impairment = 5.5
- Moderate Production Impairment = 5
- Severe Production Impairment = 4.5
- Limit to Avoid Acute Mortality = 4

b. Other Life Stages

- No Production Impairment = 6
- Slight Production Impairment = 5
- Moderate Production Impairment = 4
- Severe Production Impairment = 3.5
- Limit to Avoid Acute Mortality = 3

3. Invertebrates

- No Production Impairment = 8
- Some Production Impairment = 5
- Acute Mortality Limit = 4

Added Note

Just prior to final publication of this criteria document, a paper appeared (Sowden and Power, 1985) that provided an interesting field validation of the salmonid early life stage criterion and production impairment estimates. A total of 19 rainbow trout redds were observed for a number of parameters including percent survival of embryos, dissolved oxygen concentration, and calculated intergravel water velocity. The results cannot be considered a rigorous evaluation of the criteria because of the paucity of dissolved oxygen determinations per redd (2-5) and possible inaccuracies in determining percent survival and velocity. Nevertheless, the qualitative validation is striking.

The generalization drawn from Coble's (1961) study that good survival occurred when mean intergravel dissolved oxygen concentrations exceeded 6.0 mg/l and velocity exceeded 20 cm/hr was confirmed; 3 of the 19 redds met this criterion and averaged 29 percent embryo survival. The survival in the other 16 redds averaged only 3.6 percent. The data from the study are summarized in Table 7. The critical intergravel water velocity from this study appears to be about 15 cm/hr. Below this velocity even apparently good dissolved oxygen

Table 7. Survival of rainbow trout embryos as a function of intergravel dissolved oxygen concentration and water velocity (Sowden and Power, 1985) as compared to dissolved oxygen concentrations established as criteria or estimated as producing various levels of production impairment.

Criteria Estimates	Dissolved Oxygen Concentration mg/l		Percent Survival	Water Velocity, cm/hr	Mean Survival (Flow > 15 cm/hr)
	Mean	Minimum			
Exceeded Criteria	8.9	8.0	22.1	53.7	
	7.7	7.0	43.5	83.2	29.0
	7.0	6.4	1.1	9.8	
	6.9	5.4	21.3	20.6	
Slight Production Impairment	7.4	4.1	0.5	7.2	
	7.1	4.3	21.5	16.3	
	6.7	4.5	4.3	5.4	15.6
	6.4	4.2	0.3	7.9	
	6.0	4.2	9.6	17.4	
Moderate Production Impairment	5.8	3.1	13.4	21.6	
	5.3	3.6	5.6	16.8	6.5
	5.2	3.9	0.4	71.0	
Severe Production Impairment	4.6	4.1	0.9	18.3	0.9
	4.2	3.3	0.0	0.4	
Acute Mortality	3.9	2.9	0.0	111.4	
	3.6	2.1	0.0	2.6	
	2.7	1.2	0.0	4.2	0.0
	2.4	0.8	0.0	1.1	
	2.0	0.8	0.0	192.0	

characteristics do not produce reasonable survival. At water velocities in excess of 15 cm/hr the average percent survival in the redds that had dissolved oxygen concentrations that met the criteria was 29.0 percent. There was no survival in redds that had dissolved oxygen minima below the acute mortality limit. Percent survival in redds with greater than 15 cm/hr flow averaged 15.6, 6.5, and 0.9 percent for redds meeting slight, moderate, and severe production impairment levels, respectively.

Based on an average redd of 1000 eggs, these mean percent survivals would be equivalent to 290, 156, 65, 9, and 0 viable larvae entering the environment to produce food for other fish, catch for fishermen, and eventually a new generation of spawners to replace the parents of the embryos in the redd. Whether or not these survival numbers ultimately represent the impairment definitions is moot in the light of further survival and growth uncertainties, but the quantitative field results and the qualitative and quantitative impairment and criteria values are surprisingly similar.

VII. National Criterion

The national criteria for ambient dissolved oxygen concentrations for the protection of freshwater aquatic life are presented in Table 8. The criteria are derived from the production impairment estimates on the preceding page which are in turn based primarily upon growth data and information on temperature, disease, and pollutant stresses. The average dissolved oxygen concentrations selected are values 0.5 mg/l above the slight production impairment values and represent values between no production impairment and slight production impairment. Each criterion may thus be viewed as an estimate of the threshold concentration below which detrimental effects are expected.

Criteria for coldwater fish are intended to apply to waters containing a population of one or more species in the family Salmonidae (Bailey et al., 1970) or to waters containing other coldwater or coolwater fish deemed by the user to be closer to salmonids in sensitivity than to most warmwater species. Although the acute lethal limit for salmonids is at or below 3 mg/l, the coldwater minimum has been established at 4 mg/l because a significant proportion of the insect species common to salmonid habitats are less tolerant of acute exposures to low dissolved oxygen than are salmonids. Some coolwater species may require more protection than that afforded by the other life stage criteria for warmwater fish and it may be desirable to protect sensitive coolwater species with the coldwater criteria. Many states have more stringent dissolved oxygen standards for cooler waters, waters that contain either salmonids, nonsalmonid coolwater fish, or the sensitive centrarchid, the smallmouth bass. The warmwater criteria are necessary to protect early life stages of warmwater fish as sensitive as channel catfish and to protect other life stages of fish as sensitive as largemouth bass. Criteria for early life stages are intended to apply only where and when these stages occur. These criteria represent dissolved oxygen concentrations which EPA believes provide a reasonable and adequate degree of protection for freshwater aquatic life.

The criteria do not represent assured no-effect levels. However, because the criteria represent worst case conditions (i.e., for wasteload allocation and waste treatment plan design), conditions will be better than the criteria

Table 8. Water quality criteria for ambient dissolved oxygen concentration.

	Coldwater Criteria		Warmwater Criteria	
	Early Life Stages[1,2]	Other Life Stages	Early Life Stages[2]	Other Life Stages
30 Day Mean	NA[3]	6.5	NA	5.5
7 Day Mean	9.5 (6.5)	NA	6.0	NA
7 Day Mean Minimum	NA	5.0	NA	4.0
1 Day Minimum[4,5]	8.0 (5.0)	4.0	5.0	3.0

[1] These are water column concentrations recommended to achieve the required intergravel dissolved oxygen concentrations shown in parentheses. The 3 mg/l differential is discussed in the criteria document. For species that have early life stages exposed directly to the water column, the figures in parentheses apply.

[2] Includes all embryonic and larval stages and all juvenile forms to 30-days following hatching.

[3] NA (not applicable).

[4] For highly manipulatable discharges, further restrictions apply (see page 37)

[5] All minima should be considered as instantaneous concentrations to be achieved at all times.

nearly all the time at most sites. In situations where criteria conditions are just maintained for considerable periods, the criteria represent some risk of production impairment. This impairment would probably be slight, but would depend on innumerable other factors. If slight production impairment or a small but undefinable risk of moderate production impairment is unacceptable, then continuous exposure conditions should use the no production impairment values as means and the slight production impairment values as minima.

The criteria represent annual worst case dissolved oxygen concentrations believed to protect the more sensitive populations of organisms against potentially damaging production impairment. The dissolved oxygen concentrations in the criteria are intended to be protective at typically high seasonal environmental temperatures for the appropriate taxonomic and life stage classifications, temperatures which are often higher than those used in the research from which the criteria were generated, especially for other than early life stages.

Where natural conditions alone create dissolved oxygen concentrations less than 110 percent of the applicable criteria means or minima or both, the minimum acceptable concentration is 90 percent of the natural concentration. These values are similar to those presented graphically by Doudoroff and Shumway (1970) and those calculated from Water Quality Criteria 1972 (NAS/NAE, 1973). Absolutely no anthropogenic dissolved oxygen depression in the potentially lethal area below the 1-day minima should be allowed unless special care is taken to ascertain the tolerance of resident species to low dissolved oxygen.

If daily cycles of dissolved oxygen are essentially sinusoidal, a reasonable daily average is calculated from the day's high and low dissolved oxygen values. A time-weighted average may be required if the dissolved oxygen cycles are decidedly non-sinusoidal. Determining the magnitude of daily dissolved oxygen cycles requires at least two appropriately timed measurements daily, and characterizing the shape of the cycle requires several more appropriately spaced measurements.

Once a series of daily mean dissolved oxygen concentrations are calculated, an average of these daily means can be calculated (Table 9). For embryonic, larval, and early life stages, the averaging period should not exceed 7 days. This short time is needed to adequately protect these often

Table 9. Sample calculations for determining daily means and 7-day mean dissolved oxygen concentrations (30-day averages are calculated in a similar fashion using 30 days data).

	Dissolved Oxygen (mg/l)		
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[a]	8.0	9.5[b]
5	10.0	8.0	9.0
6	11.0	9.0	10.0
7	12.0[a]	10.0	10.5[c]
Σ		57.0	65.0
1-day Minimum		7.0	
7-day Mean Minimum		8.1	
7-day Mean			9.3

[a] Above air saturation concentration (assumed to be 11.0 mg/l—for this example).
[b] (11.0 + 8.0) ÷ 2.
[c] (11.0 +10.0) ÷ 2.

short duration, most sensitive life stages. Other life stages can probably be adequately protected by 30-day averages. Regardless of the averaging period, the average should be considered a moving average rather than a calendar-week or calendar-month average.

The criteria have been established on the basis that the maximum dissolved oxygen value actually used in calculating any daily mean should not exceed the air saturation value. This consideration is based primarily on analysis of studies of cycling dissolved oxygen and the growth of largemouth bass (Stewart et al., 1967), which indicated that high dissolved oxygen levels (> 6 mg/l) had no beneficial effect on growth.

During periodic cycles of dissolved oxygen concentrations, minima lower than acceptable constant exposure levels are tolerable so long as:

1. the average concentration attained meets or exceeds the criterion;

2. the average dissolved oxygen concentration is calculated as recommended in Table 9; and

3. the minima are not unduly stressful and clearly are not lethal.

A daily minimum has been included to make certain that no acute mortality of sensitive species occurs as a result of lack of oxygen. Because repeated exposure to dissolved oxygen concentrations at or near the acute lethal threshold will be stressful and because stress can indirectly produce mortality or other adverse effects (e.g., through disease), the criteria are designed to prevent significant episodes of continuous or regularly recurring exposures to dissolved oxygen concentrations at or near the lethal threshold. This protection has been achieved by setting the daily minimum for early life stages at the subacute lethality threshold, by the use of a 7-day averaging period for early life stages, by stipulating a 7-day mean minimum value for other life stages, and by recommending additional limits for manipulatable discharges.

The previous EPA criterion for dissolved oxygen published in <u>Quality Criteria for Water</u> (USEPA, 1976) was a minimum of 5 mg/l (usually applied as a 7Q10) which is similar to the current criterion minimum except for other life stages of warmwater fish which now allows a 7-day mean minimum of 4 mg/l. The new criteria are similar to those contained in the 1968 "Green Book" of the Federal Water Pollution Control Federation (FWPCA, 1968).

A. <u>The Criteria and Monitoring and Design Conditions</u>

The acceptable mean concentrations should be attained most of the time, but some deviation below these values would probably not cause significant harm. Deviations below the mean will probably be serially correlated and hence apt to occur on consecutive days. The significance of deviations below the mean will depend on whether they occur continuously or in daily cycles, the former being more adverse than the latter. Current knowledge regarding such deviations is limited primarily to laboratory growth experiments and by extrapolation to other activity-related phenomena.

Under conditions where large daily cycles of dissolved oxygen occur, it is possible to meet the criteria mean values and consistently violate the mean minimum criteria. Under these conditions the mean minimum criteria will clearly be the limiting regulation unless alternatives such as nutrient control can dampen the daily cycles.

The significance of conditions which fail to meet the recommended dissolved oxygen criteria depend largely upon five factors: (1) the duration of the event; (2) the magnitude of the dissolved oxygen depression; (3) the frequency of recurrence; (4) the proportional area of the site failing to meet the criteria; and (5) the biological significance of the site where the event occurs. Evaluation of an event's significance must be largely case- and site-specific. Common sense would dictate that the magnitude of the depression would be the single most important factor in general, especially if the acute value is violated. A logical extension of these considerations is that the event must be considered in the context of the level of resolution of the monitoring or modeling effort. Evaluating the extent, duration, and magnitude of an event must be a function of the spatial and temporal frequency of the data. Thus, a single deviation below the criterion takes on considerably less significance where continuous monitoring occurs than where sampling is comprised of once-a-week grab samples. This is so because based on continuous monitoring the event is provably small, but with the much less frequent sampling the event is not provably small and can be considerably worse than indicated by the sample.

The frequency of recurrence is of considerable interest to those modeling dissolved oxygen concentrations because the return period, or period between recurrences, is a primary modeling consideration contingent upon probabilities of receiving water volumes, waste loads, temperatures, etc. It should be apparent that return period cannot be isolated from the other four factors discussed above. Ultimately, the question of return period may be decided on a site-specific basis taking into account the other factors (duration, magnitude, areal extent, and biological significance) mentioned above. Future studies of temporal patterns of dissolved oxygen concentrations, both within and between years, must be conducted to provide a better basis for selection of the appropriate return period.

In conducting waste load allocation and treatment plant design computations, the choice of temperature in the models will be important. Probably the best option would be to use temperatures consistent with those expected in the receiving water over the critical dissolved oxygen period for the biota.

B. The Criteria and Manipulatable Discharges

If daily minimum dissolved oxygen concentrations are perfectly serially correlated, i.e., if the annual lowest daily minimum dissolved oxygen concentration is adjacent in time to the next lower daily minimum dissolved oxygen concentration and one of these two minima is adjacent to the third lowest daily minimum dissolved oxygen concentration, etc., then in order to meet the 7-day mean minimum criterion it is unlikely that there will be more than three or four consecutive daily minimum values below the acceptable 7-day mean minimum. Unless the dissolved oxygen pattern is extremely erratic, it is also unlikely that the lowest dissolved oxygen concentration will be appreciably below the acceptable 7-day mean minimum or that daily minimum values below the 7-day mean minimum will occur in more than one or two weeks each year. For some discharges, the distribution of dissolved oxygen concentrations can be manipulated to varying degrees. Applying the daily minimum to manipulatable discharges would allow repeated weekly cycles of minimum acutely acceptable dissolved oxygen values, a condition of probable stress and possible adverse biological effect. If risk of protection impairment is to be minimized, the application of the one day minimum criterion to manipulatable discharges should either limit the frequency of occurrence of values below the acceptable 7-day mean minimum or impose further limits on the extent of excursions below the 7-day mean minimum. For such controlled discharges, it is recommended that the occurrence of daily minima 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 fish and 3.5 mg/l for warmwater fish. Such decisions could be site-specific based upon the extent of control, serial correlation, and the resource at risk.

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Exhibit 3

DENNIS STREICHER
City of Elmhurst, Illinois
209 North York Street
Elmhurst, Illinois 60126
630.530.3046

EDUCATION and CERTIFICATION	B.S. in Biology from Northern Illinois University. Illinois Class 1 Sewage Treatment Works Operator Illinois Class "A" Public Water Supply Operator
WORK EXPERIENCE	City of Elmhurst, May 1972 to present
	1972-1981 — WWTP Chemist
	1981-1982 — Assistant Superintendent
	1982-1990 — Superintendent
	1991-2000 — Assistant Director of Public Works/ Water and Wastewater.
	2000-Present — Director of Water & Wastewater
PROFESSIONAL ACTIVITIES	Member of the A.W.W.A. Member Water Environment Federation Member of Central States Water Environment Assoc. Chairman of the Central States Education Committee Past president of the Central States Illinois Section Vice-president of the Illinois Association of Wastewater Agencies Served as the northeast representative on the Operators Certification Committee for six years.
AWARDS	2000 Illinois EPA Operator of the Year 1996 CSWEA Operations Award
INTERESTS	Active in local environmental groups especially bird watching (birding) organizations. Wildlife photography especially birds in wild habitats. Natural history studies.

Exhibit 4

April 2, 2004

Mr. Dennis P. McKenna
Deputy Administrator
Illinois Department of Agriculture
P.O. Box 19281
Springfield, IL 62794-9281

Re: Illinois Association of Wastewater Agencies Dissolved Oxygen Study

Dear Dennis,

As a follow up on our conversation of April 1, 2004, I'd like to thank you for your interest in the Illinois Association Wastewater Agencies (IAWA) dissolved oxygen study. As you are aware IAWA is very interested in implementing this study and modifying the Illinois water quality standards as regards to dissolved oxygen. It is our opinion that many other water quality standards will be enhanced by a scientifically well founded dissolved oxygen standard in Illinois. We feel the study has followed closely the USEPA protocols and builds upon the previous water quality standard. In addition it incorporates the special features of the Illinois warm water chemistry. Note that the study specifically excludes Lake Michigan and wetlands from consideration for DO limits changes.

The IAWA commissioned this study with the goal of incorporating a previous study by Chapman in 1986; then adding new data that has been developed since that time. The final draft will then make recommendations to modify Illinois water quality standards for DO based on natural fluctuations in aquatic systems and physiological tolerances of native aquatic life. The most significant recommendations are the incorporation of seven day running averages for the mean and minimum DO concentrations. The mean would be 7-d mean of 6.0 mg/L when most early life stages of fish are present and a 7-d mean minimum of 4.0 mg/L when most early life stages of fish are absent. This feature alone adds significantly to the standards as it recognizes the seasonality of the natural aquatic systems in Illinois. The recommended standards are either equivalent to or more conservative than the previously established national dissolved oxygen standards.

I have transmitted a copy of the report to you; we would appreciate your thoughts on the study. Also, please don't hesitate to share the study with others in the agricultural communities to elicit their responses as well. The goal of IAWA is to include comments of all interested stakeholders. Further we wish to sure that the concerns of the agricultural community are answered before the IAWA makes the move to ask the pollution control board to modify the standards in Illinois.

Once again it was enjoyable speaking with you and if you have any questions don't hesitate to give me a call at (630) 530-3046.

Sincerely,

Dennis Streicher
Director of Water & Wastewater
630.530.3046 office
630.834.0298 fax

Cc: IAWA DO file

June 14, 2004

Ms. Nancy Erickson
Director of Natural and Environmental Research
Illinois Farm Bureau
1701 Towanda Avenue
Bloomington, IL 61701

Re: Illinois Association of Wastewater Agencies Dissolved Oxygen Study
IPCB Docket Number R04-25

Dear Ms. Erickson,

As a follow up to our conversation of May 25, 2004, I'd like to thank you for your interest in the Illinois Association Wastewater Agencies (IAWA) dissolved oxygen study. Earlier in April of 2004 I had transmitted a copy of the study to you for comments.

As you are aware IAWA is very interested in implementing this study and modifying the Illinois water quality standards as regards to dissolved oxygen. It is our opinion that many other water quality standards will be enhanced by a scientifically well founded dissolved oxygen standard in Illinois. We feel the study has followed closely the USEPA protocols and builds upon the previous water quality standard. In addition it incorporates the special features of the Illinois warm water chemistry. Note that the study specifically excludes Lake Michigan and wetlands from consideration for DO limits changes.

The IAWA commissioned this study with the goal of incorporating a previous study by Chapman in 1986; then adding new data that has been developed since that time. The final draft will then make recommendations to modify Illinois water quality standards for DO based on natural fluctuations in aquatic systems and physiological tolerances of native aquatic life. The most significant recommendations are the incorporation of seven day running averages for the mean and minimum DO concentrations. The mean would be 7-d mean of 6.0 mg/L when most early life stages of fish are present and a 7-d mean minimum of 4.0 mg/L when most early life stages of fish are absent. This feature alone adds significantly to the standards as it recognizes the seasonality of the natural aquatic systems in Illinois. The recommended standards are either equivalent to or more conservative than the previously established national dissolved oxygen standards.

At this time the IAWA has filed a petition with the Illinois Pollution Control Board (IPCB) to incorporate the studies results into Illinois general use water standards. The IPCB has agreed to hear the petition and has set dates in June and August to receive testimony from interested stakeholders. We would appreciate your thoughts on the study. Also, please don't hesitate to share the study with others in the agricultural communities to elicit their responses as well. The goal of IAWA is to include comments of all interested stakeholders.

Once again it was enjoyable speaking with you and if you have any questions don't hesitate to give me a call at (630) 530-3046.

Sincerely,

Dennis Streicher
Director of Water & Wastewater
630.530.3046 office
630.834.0298 fax

Cc: IAWA DO file

April 2, 2004

Alec Messina
IL Environmental Regulatory Group
3150 Roland Avenue
Springfield, IL 62703

Re: Illinois Association of Wastewater Agencies Dissolved Oxygen Study

Dear Alec,

As a follow up on our conversation of April 2, 2004, I'd like to thank you for your interest in the Illinois Association Wastewater Agencies (IAWA) dissolved oxygen study. As you are aware IAWA is very interested in implementing this study and modifying the Illinois water quality standards as regards to dissolved oxygen. It is our opinion that many other water quality standards will be enhanced by a scientifically well founded dissolved oxygen standard in Illinois. We feel the study has followed closely the USEPA protocols and builds upon the previous water quality standard. In addition it incorporates the special features of the Illinois warm water chemistry. Note that the study specifically excludes Lake Michigan and wetlands from consideration for DO limits changes.

The IAWA commissioned this study with the goal of incorporating a previous study by Chapman in 1986; then adding new data that has been developed since that time. The final draft will then make recommendations to modify Illinois ~~water quality standards~~ for DO based on natural fluctuations in aquatic systems and physiological tolerances of native aquatic life. The most significant recommendations are the incorporation of seven day running averages for the mean and minimum DO concentrations. The mean would be 7-d mean of 6.0 mg/L when most early life stages of fish are present and a 7-d mean minimum of 4.0 mg/L when most early life stages of fish are absent. This feature alone adds significantly to the standards as it recognizes the seasonality of the natural aquatic systems in Illinois. The recommended standards are either equivalent to or more conservative than the previously established national dissolved oxygen standards.

I have transmitted a copy of the report to you; we would appreciate your thoughts on the study. Also, please don't hesitate to share the study with others that you represent to elicit their responses as well. The goal of IAWA is to include comments of all interested stakeholders. Further we wish to sure that the concerns of the industrial discharger community are answered before the IAWA makes the move to ask the pollution control board to modify the standards in Illinois.

Once again it was enjoyable speaking with you and if you have any questions don't hesitate to give me a call at (630) 530-3046.

Sincerely,

Dennis Streicher
Director of Water & Wastewater
630.530.3046 Office
630.834.0298 fax

Cc: IAWA DO file

April 12, 2004

Dr. Edward Krug
Illinois State Water Survey
2204 Griffith Dr
Champaign, IL 61820

Re: Illinois Association of Wastewater Agencies Dissolved Oxygen Study

Dear Dr. Krug,

As a follow up on our conversation of April 12, 2004, I'd like to thank you for your interest in the Illinois Association Wastewater Agencies (IAWA) dissolved oxygen study. As you are aware IAWA is very interested in implementing this study and modifying the Illinois water quality standards as regards to dissolved oxygen. It is our opinion that many other water quality standards will be enhanced by a scientifically well founded dissolved oxygen standard in Illinois. We feel the study has followed closely the USEPA protocols and builds upon the previous water quality standard. In addition it incorporates the special features of the Illinois warm water chemistry. Note that the study specifically excludes Lake Michigan and wetlands from consideration for DO limits changes.

The IAWA commissioned this study with the goal of incorporating a previous study by Chapman in 1986; then adding new data that has been developed since that time. The final draft will then make recommendations to modify Illinois water quality standards for DO based on natural fluctuations in aquatic systems and physiological tolerances of native aquatic life. The most significant recommendations are the incorporation of seven day running averages for the mean and minimum DO concentrations. The mean would be 7-d mean of 6.0 mg/L when most early life stages of fish are present and a 7-d mean minimum of 4.0 mg/L when most early life stages of fish are absent. This feature alone adds significantly to the standards as it recognizes the seasonality of the natural aquatic systems in Illinois. The recommended standards are either equivalent to or more conservative than the previously established national dissolved oxygen standards.

I have transmitted a copy of the report to you; we would appreciate your thoughts on the study. Also, please don't hesitate to share the study with others that you represent to elicit their responses as well. The goal of IAWA is to include comments of all interested stakeholders. Further we wish to sure that the concerns of the industrial discharger community are answered before the IAWA makes the move to ask the pollution control board to modify the standards in Illinois.

Once again it was enjoyable speaking with you and if you have any questions don't hesitate to give me a call at (630) 530-3046.

Sincerely,

Dennis Streicher
Director of Water & Wastewater
630.530.3046 Office
630.834.0298 fax

Cc: IAWA DO file

Exhibit 5

Short Curriculum Vita

Name James E. Garvey

Title Assistant Professor

Address Fisheries and Illinois Aquaculture Center
Department of Zoology
Southern Illinois University – Carbondale
jgarvey@siu.edu
http://www.science.siu.edu/zoology/garvey/index.html

Degrees 1997 Ph.D., Zoology, The Ohio State University, Ohio
1992 M.S., Zoology, The Ohio State University, Ohio
1990 B.A., *cum laude*, Zoology, Miami University, Ohio

Experience

2000-	Assistant Professor, Department of Zoology, Southern Illinois University
1998-2000	Assistant Professor, Division of Biology, Kansas State University
1997-1998	Postdoctoral Fellow, Department of Biology, Queen=s University, Ontario
1997	Research Associate, Department of Zoology, The Ohio State University
1996-1997	Presidential Fellow, Graduate School, The Ohio State University
1990-1996	Graduate Research Associate, Department of Zoology, The Ohio State University
1990-1996	Graduate Teaching Associate, Department of Zoology, The Ohio State University
1988-1990	Research Technician, Department of Zoology, Miami University
1988	Student Researcher, School for Field Studies, St. John, U.S. Virgin Islands

Fields of Research Competence

Aquatic ecology, fish ecology, basic and applied fish biology, limnology, food web dynamics, bioenergetics, life history modeling

Honors and Awards

2001	Best Oral Presentation, Annual Meeting of the Illinois Chapter of the American Fisheries Society, February 2001
2000	Best Oral Presentation, 2000 Annual Meeting of the Kansas Chapter of the American Fisheries Society, Manhattan, Kansas
1999	Article titled ACompetition between larval fishes in reservoirs: the role of

relative timing of appearance@ (co-author, R.A. Stein) was among 5 nominated by a selection committee for Best Paper in Transactions of the American Fisheries Society (out of –100 articles)

1999 American Society of Limnology and Oceanography=s DIALOG III Symposium, Bermuda, October 1999

1998 Graduate Faculty Status, Kansas State University, November 1998

1996 Best Poster, Annual Meeting of the American Fisheries Society, Dearborn, Michigan, August 1996

1996 University Presidential Fellowship, July 1996

1995 Honorable Mention, Best Oral Presentation, Annual Meeting of the American Fisheries Society, Tampa, Florida, August 1995

Student Awards

2004 Dean Sherman, Honorable Mention, Best Poster Award, Undergraduate Research Forum, Southern Illinois University, Carbondale, March 2004

2004 Laura Csoboth, Student Travel Award, Illinois American Fisheries Society Meeting, Champaign, Illinois, March 2004

Selected Professional Service (last five years)

2004	Reviewer, National Science Foundation proposal, Ecology Panel (RUI proposal)
2004	Member, Skinner Award Committee, American Fisheries Society (second term)
2004	North Central Representative, Early Life History Section, American Fisheries Society.
2003	Workshop Presenter, Analysis of Fisheries Data, Illinois Chapter of the American Fisheries Society Continuing Education Workshop, Springfield, Illinois, April 2003
2003	Moderator, River Session, Illinois Chapter of the American Fisheries Society, Rend Lake, IL, February 2003
2002	Reviewer, National Science Foundation proposal, Ecology Panel, August 2002
2002	Chair, Student Judging of Oral Presentations, National American Fisheries Society Meeting, Baltimore, Maryland, August 2002
2002-present	Associate Editor, *Transactions of the American Fisheries Society* (handle ~ 10 manuscripts per year)
2001-2003	Judge, Regional Science Fair, SIUC campus, February 2001-2003
1999-2001	Member, Skinner Award Committee, American Fisheries Society (first term)
2001	Reviewer, National Science Foundation proposal, Ecology Panel, February 2001
2001	Moderator, Fisheries Session, Illinois Renewable Natural Resources Meeting, February 2001
2000	Judge, Student Paper Presentations, American Fisheries Society

	National Meeting, August 2000
1994-present	Peer Reviewer, *Behaviour, Biological Invasions, Canadian Journal of Zoology Transactions of the American Fisheries Society, North American Journal of Fisheries Management, Ecology, Ecological Applications, Great Basin Naturalist, American Midland Naturalist, Prairie Naturalist, Journal of Plankton Research, Animal Behaviour, Journal of the North American Benthological Society, Northwest Science, North American Journal of Aquaculture, Proceedings of the Royal Academy of Science –Great Britain*

Current Society Memberships

2003-present	Honorary Member, American Institute of Biological Sciences
1990-present	Ecological Society of America
1990-present	American Fisheries Society
1990-1996, 1999-present	North American Benthological Society
2001-present	Illinois Chapter of the American Fisheries Society
1999-present	Full Member, Sigma Xi

Invited Presentations

2003	Upper Mississippi Conservation Committee, Prairie du Chien, Wisconsin, August 2003
2002	Ecology Consortium, Southern Illinois University, Carbondale, November 2002
2000	Sam Parr Biological Station, Illinois Natural History Survey, June 2000
2000	Northeast Division Meeting of the American Fisheries Society, April 2000
2000	Department of Zoology, University of Wisconsin - Madison, February 2000
1999	Department of Biology, William Jewell College, Missouri, September 1999
1998	Department of Biology, Queen=s University, Kingston, Ontario, January 1998
1997	Apple Valley Fishing Club, Apple Valley, Ohio, October 1997
1996	Department of Biological Sciences, University of Pittsburgh, December 1996.

Technical Reports

Garvey, J.E., and M.R Whiles. 2003. An assessment of national and Illinois dissolved oxygen water quality criteria. Illinois Association of Wastewater Agencies. 52 pages

Garvey, J.E., B.D. Dugger, M.R. Whiles, S.R. Adams, M.B. Flinn, B.M. Burr, and R.J.

Sheehan. 2003. Responses of fish, waterbirds, invertebrates, vegetation, and water quality to environmental pool management: Mississippi River Pool 25. U.S. Army Corps of Engineers. 181 pages.

Garvey, J.E. 2002. Winter habitat used by fishes in Smithland Pool, Ohio River. U.S. Fish and Wildlife Service and U.S. Army Corps of Engineers, 90 pages.

Garvey, J.E., and R.J. Sheehan. 2001. Winter habitat associations of riverine fishes: predictions for the Ohio River, U.S. Fish and Wildlife Service and U.S. Army Corps of Engineers, 39 pages.

Garvey, J.E., R.A. Wright, R.A. Stein, E.M. Lewis, K.H. Ferry, and S.M. Micucci. 1998. Assessing the influence of size on overwinter survival of largemouth bass in Ohio on-stream impoundments. Ohio Division of Wildlife Final Report. Federal Aid in Sport Fish Restoration Program 29, 288 pages.

Stein, R.A., and **J.E. Garvey**. 1996. A review of a technical report prepared for the Cuyahoga River (Ohio) Community Planning Organization by EnvironScience Inc.

Theses and Dissertations

Garvey, J.E. 1997. Strong interactors and community structure: testing predictions for reservoir food webs, Ph.D. dissertation, 235 pages.

Garvey, J.E. 1992. Selective predation as a mechanism of crayfish species replacement in northern Wisconsin lakes. M.S. thesis, The Ohio State University, 88 pages.

Book Chapters

S.R. Chipps, and **J.E. Garvey.** In press. Assessment of food habits and feeding patterns. *In* M.L. Brown and C.S. Guy, editors. Analysis and Interpretation of Freshwater Fisheries Data. 41 MS pages, 2 tables, 4 figures, 13 boxes. 1 April 2001.

Book Reviews

Garvey, J.E. 2003. Searching for scales in fisheries. Review of "Hierarchical Perspectives on Marine Complexities: Searching for Systems in the Gulf of Maine" by Spencer Apollonio. Columbia University Press, New York. 2002. 229 pp. Appeared in BioScience 53(10):1004-1006. (Invited)

Peer-Reviewed Publications (Selected Abstracts at http://www.science.siu.edu/zoology/garvey/pubs.html)

Garvey, J.E., K.G. Ostrand, and D.H. Wahl. In press. Interactions among allometric scaling, predation and ration affect size-dependent growth and mortality of fish during winter. Ecology. Aug. 2003.

Ostrand, K.G., S.J. Cooke, **J.E. Garvey**, and D.H. Wahl. In press. The energetic impact of overwinter prey assemblages on age-0 largemouth bass. Environmental Biology of Fishes.

Colombo, R.E., P.S. Wills, and **J.E. Garvey**. 2004. Use of ultrasound imaging to

determine sex of shovelnose sturgeon *Scaphirhynchus platorynchus* from the Middle Mississippi River. North American Journal of Fisheries Management 24:322-326.

Roberts, M.R., JE. Wetzel, III, R.C. Brooks, and **J.E. Garvey**. 2004. Daily incrementation in the otoliths of the red spotted sunfish, *Lepomis miniatus*. North American Journal of Fisheries Management 24:270-274.

Garvey, J.E., and E.A. Marschall. 2003. Understanding latitudinal trends in fish body size through models of optimal seasonal energy allocation. Canadian Journal of Fisheries and Aquatic Sciences 60(8):938-948.

Micucci, S.M., **J.E. Garvey**, R.A. Wright, and R.A. Stein. 2003. Individual growth and foraging responses of age-0 largemouth bass to mixed prey assemblages during winter. Environmental Biology of Fishes 67(2):157-168.

Garvey, J.E., J.E. Rettig, R.A. Stein, D.M. Lodge, and S.P. Klosiewski. 2003. Scale-dependent associations among fish predation, littoral habitat, and distributions of native and exotic crayfishes. Ecology 84(12): 3339-3348.

Whiles, M.J., and **J.E. Garvey**. In press. Aquatic resources of the Shawnee and Hoosier National Forests, USDA Forest Service.

Garvey, J.E., R.A. Stein, R.A. Wright, and M.T Bremigan. 2003. Largemouth bass recruitment in North America: quantifying underlying ecological mechanisms along environmental gradients Black bass: ecology, conservation and management. Edited by D. Philipp and M. Ridgway. American Fisheries Society Symposium 31:7-23.

Garvey, J.E., D.R. DeVries, R.A. Wright, and J.G. Miner. 2003. Energetic adaptations along a broad latitudinal gradient: implications for widely distributed communities. BioScience 53(2):141-150.

Garvey, J.E., T.P. Herra, and W.C. Leggett. 2002. Protracted reproduction in sunfish: the temporal dimension in fish recruitment revisited. Ecological Applications 12:194-205.

Garvey, J.E., R.A. Wright, K.H. Ferry, and R.A. Stein. 2000. Evaluating how local- and regional- scale processes interact to regulate growth of age-0 largemouth bass. Transactions of the American Fisheries Society 129:1044-1059.

Fullerton, A.H., **J.E. Garvey**, R.A. Wright, and R.A. Stein. 2000. Overwinter growth and survival of largemouth bass: interactions among size, food, origin, and winter duration. Transactions of the American Fisheries Society 129:1-12.

Wright, R.A., **J.E. Garvey**, A.H. Fullerton, and R.A. Stein. 1999. Using bioenergetics to explore how winter conditions affect growth and consumption of age-0 largemouth bass. Transactions of the American Fisheries Society 128:603-612.

Garvey, J.E., and R.A. Stein. 1998. Competition between larval fishes in reservoirs: the role of relative timing of appearance. Transactions of the American Fisheries Society 127:1023-1041.

Garvey, J.E., R.A. Wright, and R.A. Stein. 1998. Overwinter growth and survival of age-0 largemouth bass: revisiting the role of body size. Canadian Journal of Fisheries and Aquatic Sciences 55:2414-2424.

Garvey, J.E., N.A. Dingledine, N.S. Donovan, and R.A. Stein. 1998. Exploring spatial and temporal variation within reservoir food webs: predictions for fish assemblages. Ecological Applications 8:104-120.

Garvey, J.E., and R.A. Stein. 1998. Linking bluegill and gizzard shad assemblages to growth of age-0 largemouth bass in reservoirs. Transactions of the American Fisheries Society 127:70-83.

Lodge, D.M., R.A. Stein, K.M. Brown, A.P. Covich, C. Brönmark, **J.E. Garvey**, and S.P. Klosiewski. 1998. Predicting impact of freshwater exotic species on native biodiversity: challenges in spatial and temporal scaling. Australian Journal of Ecology 23:53-67.

Garvey, J.E., E.A. Marschall, and R.A. Wright. 1998. From star charts to stoneflies: detecting relationships in continuous bivariate data. Ecology 79(2):442 447.

Schaus, M.H., M.J. Vanni, T.E. Wissing, M. Bremigan, **J.E. Garvey**, and R.A. Stein. 1997. Nitrogen and phosphorus excretion by the detritivorous gizzard shad (*Dorosoma cepedianum*) in a reservoir ecosystem. Limnology and Oceanography 42(6):1386-1397.

Garvey, J.E., R.A. Stein, and H.M. Thomas. 1994. Assessing how fish predation and interspecific prey competition influence a crayfish assemblage. Ecology 75:532-547.

Garvey, J.E., and R.A. Stein. 1993. Evaluating how chela size influences the invasion potential of an introduced crayfish, *Orconectes rusticus*. American Midland Naturalist 129:172-181.

Garvey, J.E., H.A. Owen, and R.W. Winner. 1991. Toxicity of copper to the green alga, *Chlamydomonas reinhardtii* (Chlorophycea), as affected by humic substances of terrestrial and freshwater origin. Aquatic Toxicology 19:89-96.

<u>Oral Presentations and Posters (Last Five Years)</u>

Williamson, C.J., and **J.E.** Garvey. Growth and mortality of silver carp: implications for its rise to dominance in the Middle Mississippi River. Illinois Chapter of the American Fisheries Society, Champaign, IL, March 2004. (Oral presentation by Williamson)

Koch, B.T., **J.E. Garvey**, and M. Lydy. The effects of land use on organochlorine accumulation in middle Mississippi River shovelnose sturgeon: intersexuality and reproductive consequences. Illinois Chapter of the American Fisheries Society, Champaign, IL, March 2004. (Oral presentation by Koch)

Csoboth, L.A., D.W. Schultz, K. DeGrandChamp, **J.E. Garvey**, and R.M. Neumann. Fish response at a backwater-river interchange: the Swan Lake rehabilitation and enhancement project. Illinois Chapter of the American Fisheries Society, Champaign, IL, March 2004. (Poster presentation)

Colombo, R.E., **J.E. Garvey**, and R.C. Heidinger. Comparing demographics of channel catfish in fished and un-fished reaches of the Wabash River. 64th Meeting of the Midwest Fish and Wildlife Conference. Kansas City, December 2003. (Oral presentation by Colombo)

Spier, T., **J.E. Garvey**, R.C. Heidinger, R.J. Sheehan, P. Wills, K. Hurley, R.E. Colombo, R.C. Brooks. Pallid and shovelnose sturgeon movement and habitat usage in the middle Mississippi River. 64th Meeting of the Midwest Fish and Wildlife Conference. Kansas City, December 2003 (Oral presentation by Spier)

Marschall, E.A., and **J.E. Garvey**. Understanding latitudinal trends in fish body size through models of optimal seasonal energy allocation. 88th Meeting of the Ecological Society of America, Savannah, Georgia, July 2003 (Oral presentation by Marschall)

Braeutigam, B.J., and **J.E. Garvey**. Winter habitat used by fish in Smithland Pool, Ohio River. Ohio River Research Review, Indiana, August 2003. (Oral presentation by Braeutigam)

Garvey, J.E. Importance of flood-plain connectivity to fish assemblages in the Mississippi River. Middle Mississippi River Workgroup Meeting, Carbondale, IL, June 2003. (Oral presentation by Garvey)

O'Neill, B.J., **J.E. Garvey**, M.R. Whiles, and K.R. Lips. Scale-dependent interrelationships among, fish, landscape characteristics, and ambystomatid salamanders in forest ponds. Annual Meeting of the American Society of Ichthyologists and Herpetologists, Manaus, Brazil, June 2003 (Oral presentation by O'Neill)

Spier, T., **J. Garvey**, R. Heidinger, R. Sheehan, P. Wills, and K. Hurley. Demographics and habitat usage of pallid sturgeon in the Middle Mississippi River. Meeting of the Illinois Chapter of American Fisheries Society, Rend Lake, IL, February 2003 (Oral presentation by Spier)

Jackson, N.D., **J.E. Garvey**, R.C. Heidinger, and R.J. Sheehan. Age and mortality of shovelnose sturgeon, *Scaphirhynchus platorynchus*, in the Middle Mississippi River and Lower Wabash Rivers, Illinois. Meeting of the Illinois Chapter of American Fisheries Society, Rend Lake, IL, February 2003 (Oral presentation by Jackson)

Flinn, M.B., S. R. Adams, M.R. Whiles, **J.E. Garvey**, B.M. Burr, and R.J. Sheehan. Fish and macroinvertebrate responses to environmental pool management in Mississippi River Pool 25. Meeting of the Illinois Chapter of American Fisheries Society, Rend Lake, IL, February 2003 (Oral presentation by Flinn)

Colombo, R.E., **J.E. Garvey**, R.C. Heidinger and R.J. Sheehan. Population demographics of channel catfish *Ictalurus punctatus* in the Wabash River. Meeting of the Illinois Chapter of American Fisheries Society, Rend Lake, IL, February 2003 (Oral presentation by Colombo)

Garvey, J.E. Early growth of centrarchids along a productivity gradient: setting the stage for future interactions. American Fisheries Society Meeting, Baltimore, MD, August 2002 (Oral presentation)

Ostrand, K.G., S.J. Cooke, **J.E. Garvey**, D.H. Wahl. Age-0 largemouth bass: the overwinter effects of prey type on growth and spring swimming performance. American Fisheries Society Meeting, Baltimore, MD, August 2002 (Oral presentation by Ostrand)

Garvey, J.E., S.M. Micucci, R.A. Wright, and R.A. Stein. Prey assemblage structure during winter influences the condition of age-0 largemouth bass. Midwest Fish and Wildlife Meeting, Des Moines, IA, December 2001 (Oral presentation)

Garvey, J.E. Using optimal allocation models to explain latitudinal trends in recruitment of largemouth bass. Illinois Renewable Natural Resources Conference, Peoria, IL, February 2001 (Oral presentation; received Best Oral Presentation)

Bremigan, M.T., R.A. Stein, and **J.E. Garvey**. Variable gizzard shad recruitment and its effects along a reservoir productivity gradient. American Society of Limnology and Oceanography Meeting - Copenhagen, Denmark, June 2000 (Poster presentation).

Evans-White, M., W.K. Dodds, and **J.E. Garvey**. Crayfish biomass, growth, and production in a tallgrass prairie stream. North American Benthological Society Meeting, Colorado, May 2000 (Oral presentation by Dodds).

Garvey, J.E. Patterns of sportfish recruitment in natural lakes and reservoirs: do generalities exist? Kansas Chapter of the American Fisheries Society Meeting, February 2000 (Oral presentation; received Best Oral Presentation).

Garvey, J.E. From fish in lakes to crayfish in prairie streams: searching for general recruitment mechanisms and ecosystem consequences. KSU Ecology Research Seminar Series, November 1999 (Oral presentation).

Garvey, J.E., T.P. Herra, and W.C. Leggett. Mechanisms underlying the spatial distribution of larval sunfish (*Lepomis* spp.) in Lake Opinicon, Ontario. American Fisheries Society Meeting - Charlotte, North Carolina, August 1999 (Oral presentation).

Garvey, J.E. Interactions between ecosystems and life histories: predicting fish community structure in lakes. Kansas EPSCoR Conference, Topeka, KS, April 1999 (Poster presentation).

Exhibit 6

MATT ROWLAND WHILES

Department of Zoology
Southern Illinois University
Carbondale, Illinois 62901-6501
Phone: (618) 453-7639

PERSONAL INFORMATION

Born December 4, 1964; Kansas City, Missouri.

Married 1998, 1 daughter and 1 son

EDUCATION

9/91-6/95 University of Georgia, Athens, Georgia; **Ph.D. Ecology.**
Dissertation: Disturbance, recovery, and invertebrate communities in southern Appalachian headwater streams.

9/88-9/91 University of Georgia, Athens, Georgia; **M.S. Entomology.**
Thesis: First-year recovery of a southern Appalachian headwater stream following an insecticide induced disturbance.

8/84-8/88 Kansas State University, Manhattan, Kansas; **B.S. Biology.**

AREAS OF SPECIALIZATION

Ecosystem ecology with emphasis on freshwater ecosystem structure and function (mainly streams and wetlands), the role of invertebrates in ecosystems, ecosystem-level consequences of extinctions, energetic linkages between aquatic and terrestrial systems, the role of disturbance, and biological assessment of freshwater habitats.

PROFESSIONAL EXPERIENCE

2003- **Associate Professor of Zoology**, Southern Illinois University
Teaching Freshwater Invertebrates, Stream Ecology, and General Ecology.
Advising graduate research in freshwater ecosystem ecology.

2000- **Assistant Professor of Zoology**, Southern Illinois University
Teaching Freshwater Invertebrates, Stream Ecology, and General Ecology.
Advising graduate research in freshwater ecosystem ecology.

2000- **Adjunct Assistant Professor of Entomology**, Kansas State University
Serving as a graduate committee member for students pursuing studies in the area of aquatic invertebrate ecology

PROFESSIONAL EXPERIENCE (continued)

1997-00	**Assistant Professor of Entomology** (non-tenure track), Kansas State University Taught Insect Ecology, Insects and People, Economic Entomology, and an interdisciplinary Environmental Concerns course. Advised graduate research in invertebrate ecology.
1995-97	**Assistant Professor of Biology**, Wayne State College Taught Introductory Zoology, Invertebrate Zoology, Entomology, Vertebrate Zoology, Ecology, and General Biology (majors and non-majors). Advised undergraduate research in freshwater invertebrate ecology.
1996-	**Adjunct Graduate Faculty**, University of Memphis Graduate committee member for students working in aquatic ecology.
1989-95	**Graduate Teaching Assistant**, University of Georgia Instructed numerous laboratory courses including General Biology, Entomology, Animal Behavior, Aquatic Entomology, General Ecology, and Insect Ecology.
1994	**Laboratory Coordinator**, University of Georgia Instructed, scheduled, and supervised graduate teaching assistants for the General Biology program.
1988-94	**Research Assistant**, University of Georgia Investigated the role of aquatic invertebrates in stream ecosystem function. Participated in all aspects of a long-term study including sampling and processing of invertebrate communities, organic matter, and water chemistry.
1987-88	**Research Assistant**, Kansas State University Investigated effects of nutrient enrichment on algal growth and invertebrate grazer densities in streams on LTER sites across the country.
1987-87	**Undergraduate Research Assistant**, Kansas State University Investigated small mammal behavior on islands in the Sea of Cortez with and without reptilian predators.
1985-87	**Undergraduate Research Assistant**, Kansas State University Examined macroinvertebrate community dynamics in streams with contrasting hydrologic regimes on the Konza Prairie Research Natural Area.

HONORS AND AWARDS

1997	Professor of the Year, Math and Sciences Division, Wayne State College.
1996	Professor of the Year, Math and Sciences Division, Wayne State College.
1995	Outstanding Teaching Assistant, University of Georgia.
1994-1995	University-Wide Assistantship Award, University of Georgia.
1994-1995	Merit Assistantship Award; Outstanding Teaching and Research, Univ. of GA.
1993-1994	Merit Assistantship Award; Outstanding Teaching and Research, Univ. of GA
1988	Nominee for Outstanding Senior Biology Student, Kansas State University.
1987	Hydrolab Award; best poster, North American Benthological Society meetings
1984	Designated Kansas State Scholar.

PROFESSIONAL PUBLICATIONS

Dodds, W. K., and **M. R. Whiles**. *In press*. Factors related to quality and quantity of suspended particles in rivers: general continent-scale patterns in the United States. *Environmental Management:*

Whiles, M. R., J. B. Jensen, J. G. Palis, and W. G. Dyer. *In press*. Diets of larval flatwoods salamanders, *Ambystoma cingulatum*, from Florida and South Carolina. *Journal of Herpetology*.

Whiles, M. R., and J. E. Garvey. *In press*. Freshwater resources within the Shawnee-Hoosier Ecological Assessment Region. Special Publication of the USDA Forest Service:

Dodds, W. K., K. Gido, **M. R. Whiles**, K. M. Fritz, and W. J. Matthews. 2004. Life on the Edge: Ecology of Prairie Streams. *Bioscience* 54: 205-216

Ranvestel, A. W., K. R. Lips, C. M. Pringle, **M. R. Whiles**, and R. J. Bixby. 2004. Neotropical tadpoles influence stream benthos: evidence for ecological consequences of amphibian declines. *Freshwater Biology* 49: 274-285.

Webber, J. A., K. W. J. Williard, **M. R. Whiles**, M. L. Stone, J. J. Zaczek, and K. D. Davie. 2004. Watershed scale assessment of the impact of forested riparian zones on stream water quality. Pages 114-120 In: Van Sambeek, J.W.; J.O. Dawson; F. Ponder, Jr.; E.F. Loewenstein; and J.S. Fralish, eds. Proceedings, 13th Central Hardwood Forest Conference; Urbana, IL. Gen. Tech. Rep. NC-234. St. Paul, MN: USDA Forest Service, North Central Research Station.

Evans-White, M. A., W. K. Dodds, and **M. R. Whiles**. 2003. Ecosystem significance of crayfishes and central stonerollers in a tallgrass prairie stream: functional differences between co-occurring omnivores. *Journal of the North American Benthological Society*: 22: 423-441.

Callaham, M. A., Jr., J. M. Blair, T. C. Todd, D. J. Kitchen, and **M. R. Whiles**. 2003. Macroinvertebrates in North American tallgrass prairie soils: Effects of fire, mowing, and fertilization on density and biomass. *Soil Biology and Biochemistry* 35:1079-1093.

Whiles, M. R., and W. K. Dodds. 2002. Relationships between stream size, suspended particles, and filter-feeding macroinvertebrates in a Great Plains drainage network. *Journal of Environmental Quality* 31: 1589-1600.

Jonas, J., **M. R. Whiles**, and R. E. Charlton. 2002. Aboveground invertebrate responses to land management differences in a central Kansas grassland. *Environmental Entomology* 31: 1142-1152.

Stagliano, D. M., and **M. R. Whiles**. 2002. Macroinvertebrate production and trophic structure in a tallgrass prairie headwater stream. *Journal of the North American Benthological Society* 21: 97-113.

Callaham, M. A., **M. R. Whiles**, and J. M. Blair. 2002. Annual fire, mowing, and fertilization effects on two annual cicadas (Homoptera: Cicadidae) in tallgrass prairie. *American Midland Naturalist* 148: 90-101.

Meyer, C. K., **M. R. Whiles**, and R. E. Charlton. 2002. Life history, secondary production, and ecosystem significance of acridid grasshoppers in annually burned and unburned tallgrass prairie. *American Entomologist* 48: 52-61.

PROFESSIONAL PUBLICATIONS (continued)

Whiles, M. R., and B. S. Goldowitz. 2001. Hydrologic influences on insect emergence production from central Platte River wetlands. *Ecological Applications* 11: 1829-1842.

Whiles, M. R. M. A. Callaham, C. K. Meyer, B. L. Brock, and R. E. Charlton. 2001. Emergence of periodical cicadas from a Kansas riparian forest: densities, biomass, and nitrogen flux. *American Midland Naturalist* 145: 176-187.

Schrank, S. J., C. S. Guy, **M. R. Whiles**, and B. L. Brock. 2001. Assessment of Physicochemical and watershed features influencing Topeka shiner *Notropis topeka* distribution in Kansas streams. *Copeia* 2001: 413-421.

Dodds, W. K., M. A. Evans-White, N. M. Gerlanc, L. J. Gray, D. A.Gudder, M. J. Kemp, A. L. López, D. Stagliano, E. A. Strauss, J. L. Tank, **M. R. Whiles,** W. M. Wollheim. 2001. Quantification of the nitrogen cycle in a prairie stream. *Ecosystems*: 3: 574-589.

Whiles, M. R., B. L. Brock, A. C. Franzen, and S. Dinsmore II. 2000. Stream invertebrate communities, water quality, and land use patterns in an agricultural drainage basin of northen Nebraska. *Environmental Management*: 26: 563-576.

Jensen, J. B., and **M. R. Whiles.** 2000. Diets of sympatric *Plethodon petraeus* and *Plethodon glutinosus*. *Journal of the Elisha Mitchell Scientific Society* 116: 245-250.

Callaham, M. A., Jr., **M. R. Whiles**, C. K. Meyer, B. L. Brock, and R. E. Charlton. 2000. Feeding ecology and emergence production of annual cicadas (Homoptera: Cicadidae) in tallgrass prairie. *Oecologia* 123: 535-542.

Alexander, K. A., and **M. R. Whiles**. 2000. A new species of *Ironoquia* Banks (Trichoptera: Limnephilidae) from the central Platte River, Nebraska. *Entomological News*: 111: 1-7.

Whiles, M. R., B. S. Goldowitz, and R. Charlton. 1999. Life history and production of a semi-terrestrial limnephilid caddisfly in a Platte River wetland. *Journal of the North American Benthological Society* 18: 533-544.

Goldowitz, B. S., and **M. R. Whiles**. 1999. Investigations of fish, amphibians, and aquatic invertebrates within the middle Platte River system. Published final Report, Platte Watershed Program, Cooperative Agreement X99708101, USEPA.

Whiles, M. R., and B. S. Goldowitz. 1998. Biological responses to hydrologic fluctuation in wetland sloughs of the central Platte River. *In* Lingle, G. (ed.) *Proceedings of the Ninth Platte River Basin Ecosystem Symposium*. USFWS and USEPA Region VII.

Whiles, M. R., and J. B. Wallace. 1997. Litter decomposition and macroinvertebrate communities in headwater streams draining pine and hardwood catchments. *Hydrobiologia* 353: 107-119.

Wallace, J. B., T. F. Cuffney, S. L. Eggert, and **M. R. Whiles**. 1997. Stream organic matter inputs, storage, and export for Satellite Branch at Coweeta Hydrologic Laboratory, North Carolina, USA. *Journal of the North American Benthological Society* 16: 67-74.

Whiles, M. R. and J. B. Wallace. 1996. Macroinvertebrate production in a headwater stream during recovery from anthropogenic disturbance and hydrologic extremes. *Canadian Journal of Fisheries and Aquatic Sciences* 52: 2402-2422.

Wallace, J. B., J. W. Grubaugh, and **M. R. Whiles**. 1996. The influence of coarse woody debris on stream habitats and invertebrate biodiversity. *In* McMinn, J. W. and D. A. Crossley, Jr.

(eds.). Biodiversity and coarse woody debris in southern forests. Gen. Tech. Rept. SE-94. USDA Forest Service, Southeastern Forest Experiment Station.

PROFESSIONAL PUBLICATIONS (continued)

Wallace, J. B., J. W. Grubaugh, and **M. R. Whiles**. 1996. Biotic indices and stream ecosystem processes: results from an experimental study. *Ecological Applications* 6: 140-151

Whiles, M. R. and J. W. Grubaugh. 1996. Coarse woody debris and amphibian and reptile biodiversity in southern forests. *In* McMinn, J. W. and D. A. Crossley, Jr. (eds.). Biodiversity and coarse woody debris in southern forests. Gen. Tech. Rept. SE-94. USDA Forest Service, Southeastern Forest Experiment Station.

Wallace, J. B., **M. R. Whiles**, S. Eggert, T. F. Cuffney, G. J.Lugthart, and K. Chung. 1995. Long-term dynamics of coarse particulate organic matter in three Appalachian Mountain streams. *Journal of the North American Benthological Society* 14: 217-232.

Whiles, M. R., K. Chung, and J. B. Wallace. 1993. Influence of *Lepidostoma* (Trichoptera: Lepidostomatidae) on leaf litter processing in disturbed streams. *American Midland Naturalist* 130: 356-363.

Wallace, J. B., **M. R. Whiles**, J. R. Webster, T. F. Cuffney, G. J. Lugthart, and K. Chung. 1993. Dynamics of particulate inorganic matter in headwater streams: linkages with invertebrates. *Journal of the North American Benthological Society* 12: 112-125.

Whiles, M. R. and J. B. Wallace. 1992. First-year benthic recovery of a southern Appalachian stream following three years of insecticide treatment. *Freshwater Biology* 28: 81-91.

Hooker, K. L. and **M. R. Whiles**. 1988. A technique for collection and study of subterranean invertebrates. *Southwestern Naturalist* 33: 375-376.

ORAL PRESENTATIONS

Meyer, C. K., **M. R. Whiles**, S. G. Baer, and B. S. Goldowitz. 2004. Macroinvertebrate communities and ecosytem function in backwater sloughs of the central Platte River: influence of hydrologic gradients and restoration activities. Invited symposia: Entomology in Prairie Ecosystems. Annual meetings of the North Central Branch of the Entomological Society of America, Kansas City, MO.

Regester, K.J., K. R. Lips, and **M. R. Whiles**. 2004. The significance of pond-breeding salamanders to energy flow and subsidies in an Illinois forest ecosystem. Midwest Ecology and Evolution Conference, University of Notre Dame, March 5-7.

Walther, D. A., **M. R. Whiles**, D. W. Butler, and M. B. Flinn. 2004. Community level estimation of non-predatory chironomid production in a southern Illinois stream. Annual meetings of the North Central Branch of the Entomological Society of America, Kansas City, MO.

Meyer, C. K., **M. R. Whiles**, and S. G. Baer. 2003. Aboveground production and belowground biomass in natural and restored Platte River slough wetlands. Annual meetings of the Society for Ecological Restoration, Austin, TX.

Whiles, M. R. 2003. Freshwater macroinvertebrate communities and disturbance: tools for basic and applied investigations in freshwater ecosystems. Invited seminar speaker, Purdue University Department of Forestry, Fisheries, and Wildlife.

Callaham, M.A., Jr., **M.R. Whiles**, P.F. Hendrix, and J.M. Blair. 2003. Using natural abundance stable isotopes to examine the feeding ecology of cicadas in tallgrass prairie. Invited symposium presentation, Entomological Society of America Annual Meetings, Cincinnati OH.

Whiles, M. R. 2003. Biological responses to hydrologic variability and restoration activities in central Platte River backwater wetlands. Invited seminar speaker, Eastern Illinois University Dept. of Biology.

Callaham, M.A., Jr., P.F. Hendrix, J.M. Blair, and **M.R. Whiles**. 2003. Natural abundance and tracer applications of stable isotopes for examination of soil invertebrate feeding ecology. Invited symposium presentation at Soil Science Society of America Annual Meetings, Denver, CO.

Whiles, M. R. 2003. Biological responses to hydrologic variability in Platte River backwater wetlands. Invited seminar speaker, University of Illinois Dept. of Natural Resources and Environmental Sciences.

Flinn, M. B., **M. R. Whiles**, and S. R. Adams. 2003. Response of aquatic macroinvertebrates to environmental pool management and vegetation in Mississippi River backwater wetlands. Annual Meetings of the North American Benthological Society, Athens, GA.

Stone, M. L., **M. R. Whiles**, J. A. Webber, and K. J. Williard. 2003. Influence of riparian vegetation on water quality, in-stream habitat, and macroinvertebrates in southern Illinois agricultural streams. Annual Meetings of the North American Benthological Society, Athens, GA.

Oneill, B. J., J. E. Garvey, **M. R. Whiles**, and K. A. Lips. 2003. Scale-dependent interrelationships among fish, landscape characteristics, and ambystomatid salamanders in forest ponds. Joint meeting of ichthyologists and herpetologists, Manaus, Brazil.

Flinn, M. B., S. R. Adams, **M. R. Whiles**, J. E. Garvey, B. M. Burr, and R. J. Sheehan. 2003. Fish and macroinvertebrate responses to environmental pool management in Mississippi River pool 25. Illinois Chapter of the American Fisheries Society, Rend Lake, IL.

Adams, S. R. M. B. Flinn, B. M. Burr, R. J. Sheehan, and **M. R. Whiles**. 2002. Larval ecology of blue sucker (*Cycleptus elongatus*) in the Mississippi River. American Society of Ichthyologists and Herpetologists meetings, Kansas City, MO.

Whiles, M. R. 2002. Ecology and ecosystem significance of cicadas in a tallgrass prairie landscape. Invited seminar speaker, Dept. of Biology, University of Memphis.

Whiles, M. R., and B. S. Goldowitz. 2002. Influence of hydrology and fish on macroinvertebrate communities in backwater sloughs of the central Platte River, Nebraska. Annual Meetings of the North American Benthological Society, Pittsburgh.

Whiles, M. R., M. L. Stone, J. Webber, and K. Williard. 2001. The influence of forested riparian buffers on water quality and stream invertebrates in Sugar Creek drainage, Illinois. Governor's Conference on Management of the Illinois river system, Peoria, Il.

Webber, J. A., K. W. Williard, **M. R. Whiles**, and M. L. Stone. 2001. Watershed-scale assessment of the impact of forested riparian buffer strips on stream water quality and biotic integrity. Ecological Society of America 2nd International Nitrogen Conference, Potomac, MD.

Evans-White, M. A., W. K. Dodds, and **M. R. Whiles**. 2001. Trophic basis of production of crayfish and central stonerollers in a prairie stream. Annual Meetings of the North American Benthological Society, Lacrosse, WI.

Whiles, M. R., and W. K. Dodds. 2001. Relationships between stream size, suspended particles, and filter-feeding macroinvertebrates in a Great Plains river system. Annual Meetings of the North American Benthological Society, Lacrosse, WI.

Whiles, M. R. and M. L. Stone. 2001. Relationships between riparian zone vegetation, water quality, and stream invertebrate communities. Midwestern Renewable Natural Resources Conference, Peoria, Illinois.

Jensen, J. B., C. Camp, J. L. Marshall, and **M. R. Whiles**. 2001. Recent advances in the knowledge of distribution and natural history of the Pigeon Mountain salamander (*Plethodon petraeus*). Joint annual meeting of the Herpetologists League and the Society for the Study of Amphibians and Reptiles, Indianapolis, Indiana.

Stagliano, D. M. and **M. R. Whiles**. 2000. Aquatic invertebrate trophic structure and secondary production in a tallgrass prairie stream. Annual Meetings of the North American Benthological Society, Keystone, Colorado.

Meyer, C. K., **Whiles, M. R.**, and R. E. Charlton. 2000. Secondary production and energetics of grass-feeding acridids in tallgrass prairie. Annual meetings of the Southwestern Branch of the Entomological Society of America, Dallas, TX.

Jonas, J. L., **M. R. Whiles**, and R. E. Charlton. 2000. Land use patterns and insect diversity in a central Kansas grassland. Annual meetings of the Southwestern Branch of the Entomological Society of America, Dallas, TX.

Dodds, W. K., M. Evans-White, N. M. Gerlanc, L. Gray, D. Gudder, M. J. Kemp, A. Lopez, D. M. Stagliano, E. A. Strauss, J. L. Tank, **M. R. Whiles**, and W. M. Wollheim. 2000. Quantification of the nitrogen cycle in a prairie stream: Konza LINX. Annual Meetings of the North American Benthological Society, Keystone, Colorado.

Whiles, M. R., and B. S. Goldowitz. 1999. Influence of hydrology on aquatic insect emergence production from backwater sloughs of the central Platte River, Nebraska. Annual meetings of the North American Benthological Society, Duluth, MN.

Meyer, C. K., **M. R. Whiles**, and R. E. Charlton. 1999. Secondary production and energetics of a dominant grass-feeding grasshopper in tallgrass prairie. Annual meetings of the Entomological Society of America, Atlanta.

Stagliano, D., **M. R. Whiles**, and R. E. Charlton. 1999. Aquatic insect production and functional structure in a tallgrass prairie headwater stream. Annual meetings of the Entomological Society of America, Atlanta.

Whiles, M. R. 1999. Natural History and emergence production patterns of cicadas (Homoptera: Cicadidae) on the Konza Prairie Research Natural Area, Kansas. Invited seminar speaker, University of Kansas, November 4, 1999.

Jeffrey, J. D., and **M. R. Whiles**. 1999. Effects of the PGA-class Colbert Hills golf course construction on prairie amphibians. 26th meetings of the KS Herp. Society, Pratt.

Whiles, M. R. 1999. Ecology and significance of cicadas in a tallgrass prairie ecosystem. Invited seminar speaker, University of Maine, October 21, 1999.

Evans-White, M. A., W. K. Dodds, M. J. Kemp, L. A. Gray, A. Lopez, J. L. Tank, and **M. R. Whiles**. 1999. Patterns of nitrogen cycling in a prairie stream food web. Annual meetings of the North American Benthological Society, Duluth, MN.

Goldowitz, B. S., and **M. R. Whiles**. 1999. Influence of hydrologic fluctuations on aquatic vertebrate communities in central Platte River Wetlands. Annual meetings of the Ecological Society of America, Spokane, WA.

Whiles, M. R. 1999. Significance of arthropods to prairie ecosystem function. Invited symposium speaker, annual meetings of the Central States Entomological Society, Manhattan, KS.

Whiles, M. R. 1999. Aquatic invertebrate communities and disturbance: tools for basic and applied investigations. Invited seminar speaker, Southern Illinois University.

Whiles, M. R., A. Franzen, S. Dinsmore, and B. L. Brock. 1998. Use of invertebrate rapid bioassessment for identification of stream reaches contributing to water quality degradation in a northeast Nebraska reservoir. Joint meetings of the Association of Limnologists and Oceanographers and the Ecological Society of America, St. Louis, MO.

Evans-White, M. A., W. K. Dodds, M. J. Kemp, L. A. Gray, J. L. Tank, **M. R. Whiles**, and A. Lopez. 1998. Nitrogen transfer through a prairie stream food web. Annual meetings of the Great Plains Limnological Society, Pittsburg, KS.

Whiles, M. R. and B. S. Goldowitz. 1998. Biological responses to hydrologic fluctuation in wetland sloughs of the central Platte River. The 9th Platte River Basin Ecosystem Symposium, Kearney, NE.

Whiles, M. R. 1997. Invertebrate bioassessment: advantages, techniques, and applications. Invited speaker, ann. meetings of the Nebraska Natural Resource Districts, Kearney, NE.

Whiles, M. R. 1997. Invertebrate communities and ecosystem processes in disturbed lotic systems. Invited seminar speaker, Kansas State University, Manhattan, KS.

Whiles, M. R. 1996. Disturbance, invertebrate communities, and stream ecosystem processes in southern Appalachian streams. Invited seminar speaker, Texas Tech University, Lubbock.

Whiles, M. R. 1995. Stream ecosystem research at Coweeta Hydrologic Laboratory. Invited seminar speaker, Southeastern Oklahoma State University, Durant, Oklahoma.

Whiles, M. R., and J. Bruce Wallace. 1995. Leaf litter decomposition and shredder communities in streams draining mixed hardwood and white pine watersheds. Annual meetings of the North American Benthological Society, Keystone, Colorado.

Wallace, J. B., J. W. Grubaugh, and **M. R. Whiles**. 1995. Biotic indices and stream ecosystem processes: results from an experimental study. Annual meetings of the North American Benthological Society, Keystone, Colorado.

Whiles, M. R. 1995. Disturbance and aquatic invertebrate communities in southern Appalachian Mountain streams. Invited seminar speaker, University of Tennessee at Chattanooga.

Whiles, M. R. 1994. Recovery dynamics of invertebrate communities and litter processing in southern Appalachian streams following disturbance. Invited seminar, Berry College, Mount Berry, Georgia.

Whiles, M. R. and J. B. Wallace. 1994. Long-term measurements of coarse particulate organic matter export from headwater streams. Annual meeting of the North American Benthological Society, Orlando, Florida.

Grubaugh, J. W., Wallace, J. B., and **M. R. Whiles**. 1994. 1956-57 versus 1991-92: A comparison of macroinvertebrate communities and potential effects of changing land usage in a Georgia piedmont river. Annual meeting of the North American Benthological Society, Orlando, Florida.

Whiles, M. R. 1993. Coarse woody debris and amphibian and reptile diversity in southern forests. Conference on coarse woody debris in southern forests: effects on biodiversity, University of Georgia, Institute of Ecology.

Whiles, M. R., and G. J. Lugthart. 1993. Secondary production in a headwater stream during record dry and wet years. Annual meeting of the North American Benthological Society, Calgary, Alberta, Canada.

Whiles, M. R., Wallace, J. B., and K. Chung 1992. Use of a refractory litter species by a caddisfly: the role of *Lepidostoma* in stream recovery from disturbance. Annual meeting of the North American Benthological Society, Louisville, Kentucky.

Whiles, M. R., and J. B. Wallace 1991. First-year macroinvertebrate community recovery in a southern Appalachian stream following an insecticide induced disturbance. Annual meeting of the North American Benthological Society, Santa Fe, New Mexico.

Whiles, M. R., Tate, C. M., and K. L. Hooker 1988. The influence of nutrient enrichments and grazers on periphyton growth in Konza Prairie streams. Annual Division of Biology Graduate Student Forum, Kansas State University.

Tate, C.M., **Whiles, M.R.**, and K. L. Hooker 1988. Influence of nutrients and grazers on periphyton biomass in prairie streams. Annual meeting of the North American Benthological Society, Tuscaloosa, Alabama.

Tate, C.M., Hooker, K.L., and **M. R. Whiles** 1987. Seasonal response of periphyton to nutrient enrichment in prairie streams. Annual meeting of the North American Benthological Society, Orono, Maine.

POSTER PRESENTATIONS

Rowlett, J. H., D. A. Walther, and **M. R. Whiles**. 2004. A comparison of macroinvertebrate community structure on artificial rock riffles to snag and exposed streambed habitats in Cache River, Illinios. Annual meetings of the North Central Branch of the Entomological Society of America, Kansas City, MO.

Whiles, M. R., D. W. Butler, D. A. Walther, and M. B. Flinn. 2003. Temperature-dependent growth rates of non-predatory chironomids from a southern Illinois stream. Annual meeting of the North American Benthological Society, Athens, GA.

Stone, M. L., **M. R. Whiles**, J. A. Webber, and K. Williard. 2002. Relationships between riparian vegetation, water chemistry, and stream invertebrates in a southern Illinois agricultural landscape. Annual meeting of the North American Benthological Society, Pittsburgh.

Flinn, M. B., R. Adams, **M. R. Whiles**, B. Burr, and R. Sheehan. 2002. Feeding ecology of larval blue suckers (*Cycleptus elongatus*): a direct benefit of riverine backwater invertebrates to a main channel fish. Annual meeting of the North American Benthological Society, Pittsburgh.

Flinn, M. B., R. Adams, **M. R. Whiles**, B. Burr, and R. Sheehan. 2002. Feeding ecology of larval blue suckers in Mississippi River backwaters. Mississippi River Research Consortium meetings, LaCrosse, WI.

Meyer, C. K., **M. R. Whiles**, and R. E. Charlton. 2001. Secondary production and energetics of grasshoppers as affected by annual burning in tallgrass prairie. Annual meetings of the North Central Branch of the Entomological Society of America, Fort Collins, CO.

Callaham, M. A., J. M. Blair, T. C. Todd, D. J. Kitchen, and **M. R. Whiles**. 2001. Fire, mowing, and fertilization effects on macroinvertbrate assemblages in tallgrass prairie soils. Soil Ecology Society Conference, Atlanta, Georgia.

Whiles, M. R., M. A. Callaham, Jr., C. K. Meyer, and J. M. Blair. 2000. Land Management Influences on Grassland Cicada Emergence Dynamics. Ecological Society of America All Scientists meetings, Snowbird, Utah.

Corum, R. A., W. K. Dodds, and **M. R. Whiles**. 2000. Distribution of filter-feeding invertebrates in central Kansas rivers and streams. Midwest Limnological Society Meetings, Lawrence, KS.

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Jonas, J. L., **M. R. Whiles**, and R. E. Charlton. 1999. Influence of land use patterns on insect diversity in a central Kansas grassland. Annual meetings of the Entomological Society of America, Atlanta, GA.

Whiles, M. R., M. A. Callaham, C. K. Meyer, B. L. Brock, and R. E. Charlton. 1998. Periodical cicada emergence production in a northeast Kansas riparian forest. Annual meetings of the Entomological Society of America, Las Vegas, NV.

Stagliano, D., R. E. Charlton, and **M. R. Whiles**. 1998. Assessing environmental impacts on Colbert Hills using fish and aquatic insect communities. Kansas State Research and Extension Annual Conference, Manhattan, KS.

Alexander, K. A. and **M. R. Whiles**. 1998. A new species of *Ironoquia* Banks (Trichoptera: Limnephilidae) from backwaters of the central Platte River, Nebraska. North American Prairie Conference, Kearney, NE.

Dinsmore, S., **M. R. Whiles**, and R. Roberts. 1997. Use of bioassessment for identification of stream reaches contributing to eutrophication of a northeast Nebraska reservoir. Annual meetings of the Southwestern Association of Naturalists, Fayetteville, Arkansas.

Dinsmore, S., **M. R. Whiles**, and R. Roberts. 1996. Biological and chemical analysis of agriculturally impacted streams in northeast Nebraska. 31st regional meetings of the American Chemical Society, Sioux Falls, SD.

Whiles, M. R. 1993. Secondary production in a headwater stream during wet and dry years. Annual meetings of the Coweeta LTER site, Athens, Georgia.

Whiles, M. R. and K. L. Hooker 1987. Subterranean invertebrates from an artesian spring on Konza Prairie. Annual meeting of the NA Benthological Soc., Orono, Maine.

GRANT REVIEWER

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BOOK REVIEWER

Fundamentals of Ecology, 5th ed., E. P. Odum and G. Barrett
Ecology, Concepts and Applications, 2nd ed., M. C. Molles
Freshwater Ecology, W. K. Dodds

MANUSCRIPT REVIEWER

BioScience, Ecology, Ecological Applications, Limnology and Oceanography
Archiv fur Hydrobiologie, Journal of the North American Benthological Society
Environmental Management, Prairie Naturalist, American Entomologist
Environmental Entomology, Journal of Insect Science, Journal of Ecology
Journal of the Kansas Entomological Society, Bulletin of Marine Science
Journal of Cave and Karst Studies, Wetlands, Environmental Toxicology and Chemistry,
New Zealand Journal of Marine and Freshwater Research, Restoration Ecology

PROFESSIONAL SERVICE and MEMBERSHIPS

2002-03	Program Committee, North American Benthological Society
2002-03	Membership Director, American Water Resources Assoc., Illinois chapter
2000-	Entomological Society of America
1997-	Sigma Xi
1986-	North American Benthological Society