Attachment A:

DRBC (Delaware River Basin Commission). 1979. Dissolved Oxygen Requirements of a "Fishable" Delaware River Estuary. Report to the Delaware River Basin Commission by the Ad Hoc Task Force to Evaluate Dissolved Oxygen Requirements of Indigenous Estuary Fish. 11 pgs.

{available online at http://www.state.nj.us/drbc/library/documents/del-estuary_DOrequirements_1979report.pdf }

DISSOLVED OXYGEN REQUIREMENTS OF A "FISHABLE" DELAWARE RIVER ESTUARY

Report to the

Delaware River Basin Commission

Ad-Hoc Task Force to Evaluate Dissolved Oxygen Requirements of Indigenous Estuary Fish

March 1979

Introduction

This report and its recommendations are the result of deliberations and study by an ad-hoc task force appointed by the Delaware River Basin Commissioners. The Task Force to Evaluate Dissolved Oxygen Requirements of Indigenous Estuary Fish consisted of ten persons (Appendix 1) representing each of the four signatory states and the federal government. The Committee met on five occasions in the September, 1978 to January, 1979 period. Support services were provided by Delaware River Basin Commission staff.

The Task Force was established to provide fisheries expertise and guidance to two Commission programs: The Delaware River Basin Level B Water Resources planning effort (nearing completion) and the Commission's program to reevaluate its current waste load allocations and water quality standards, (underway). Both programs require a determination of a level of fisheries resource in the Estuary which would satisfy the "fishable"goal of 1972 and 1977 federal water pollution control legislation and a determination of associated dissolved oxygen levels. It was the purpose of the Task Force to make these determinations for input to the two Commission programs.

Definition of Fishable

Water Use: The "fishable" goal of the 1972 Water Pollution Control Act Amendments calls for water quality which"provides for the protection and propagation of fish, shellfish and wildlife ... wherever attainable." Current DRBC adopted water uses provides for fish passage and for the maintenance and propagation of resident fish in Zones 2 and 5; and maintenance only of resident fish in Zones 3 and 4. Existing standards violations severely impair adopted water uses, particularly in Zones 3 and 4.

The absence of propagation as a water use in Zones 3 and 4 results in a water use goal that is not consistent with the National goal. The Task Force believes that adopted water uses should provide for "fishable" water quality in every zone.

The Task Force perceives a contradiction in terminology, however. From a fisheries viewpoint a resident fish is one that spends its entire life cycle in a zone, including propagation stages. The attainment of a resident fish population of desirable fish species would, under the Task Force definition result in meeting the National "fishable" goal.

Based upon the knowledge of individual Task Force members and data concerning past and present Delaware Estuary Fisheries, the Task Force developed a list of thirteen migratory fish, thirteen resident fish and one endangered fish species (Table 1). This tabulation represents a target Estuary fish population in terms of sensitive game, forage, commercial and other desired fish species rather than a total anticipated population. Total Estuary fish populations are assumed to increase proportionately to the target species.

TABLE I

Selected Fish of Interest by Zone and Activity

Aquatic Species	DELAWARE RIVER ZONE*											
	2			3			4			5		
Migratory or Marine/Estuarine:	S	N	P	S	N	P	S	N	P	S	N	P
Striped bass	o	o	x	o	o	x	o	o	x	x	x	x
Alewife	x	x	x		x	x		o	x		x	x
Blueback herring	x	x	x		x	x		o	x		x	x
American shad	o	x	x	o	o	x	o	o	x			x
Mummichog			x**			x	x	x	x	x	x	x
Bay anchovy											x	x
Menhaden								x	x		x	x
Bluefish											x	x
Weakfish											x	x
Spot											x	x
Atlantic croaker											x	x
Atlantic silversides											x	x
Blue crab			x**			x**			x**		x	x
Resident (freshwater/brackish water):												
Pumpkinseed/bluegill	x	x	x	x	x	x	o	o	x	x	x	x
Largemouth bass	x	x	x	o	o	x	o	o	o	o	o	o
Walleye	x+	x	x									
Channel catfish	x	x	x	x	x	x	o	o	x	x	x	x
Black crappie	x	x	x	o	o	o	o	o	o			x
Golden shiner	x	x	x	x	x	x	o	o	o			x
White perch	x	x	x	x	x	x	o	o	x	x	x	x
Silvery minnow	x	x	x	x	x	x	o	o	x	x	x	x
Carp	x	x	x	x	x	x	x	x	x	x	x	x
Goldfish	x	x	x	x	x	x	x	x	x	x	x	x
Brown bullhead	x	x	x	x	x	x	x	x	x	x	x	x
Yellow perch												x
Endangered Species												
Short nose sturgeon	x	x	x		o	x		o	x		x	x

*Key

S = Spawning
N = Nursery
P = Passage
o = potential
x = existing

**Limited or occasional presence (limited for reasons other than water quality)
+ Limited spawning in area (limited for reasons other than water quality)

For each target fish, Table 1 presents existing and potential activities (spawning, nursery and passage) by Estuary zone. The Task Force feels that current limitations on existing activities and population sizes, particularly in Zone 4, do not meet the intent of the National "fishable" goal. Restoration of fish populations to include the listed potential activities, however, will result in the minimal level of fisheries required to satisfy the national goal.

Recommended Dissolved Oxygen levels

Figure 1 depicts the current DRBC dissolved oxygen standards for the Estuary. These standards have not yet been attained year round for portions of the Estuary, particularly Zones 3 and 4. Key features of the Standards are the minimum 24-hour average concentration of 3.5 mg/l promulgated for Zone 3, Zone 4 and Zone 5 (portion); and an Estuary-wide seasonal average of 6.5 mg/l applicable for seasons defined as April 1 to June 15 and September 16 to December 31.

An immediate reaction by the Task Force is the unacceptability of standards expressed as a 24-hour or daily average. From a fisheries management viewpoint events occurring in time periods much less than twenty-four hours can be detrimental to fish survival. A conclusion of the Task Force, therefore, is that any Estuary dissolved oxygen standard should be promulgated as a 'minimum' (at any time) value.

Because of past estimates of a 3 mg/l difference between 24-hour average and minimum dissolved oxygen values, and the implications thereof, the Task Force requested that DRBC staff examine the dissolved oxygen variability observed at various Estuary monitoring stations over the last fifteen years. The initial results indicate a smaller variability than past estimates. The Task Force recommends that the DRBC staff prepare a report on their data analyses.

Individually and collectively the Task Force members examined the pertinent fisheries literature concerning the minimum dissolved oxygen requirements of the fishes and activities recommended in Table 1. Sublethal threshold response values measuring growth, movement, reproduction, reactions, etc., rather than lethal levels, were used to the extent possible since the latter were not considered pertinent to the goal of fish protection and propagation.

This information and the expertise of the Task Force results in Figures 2 and 3 which present the Task Force's recommended dissolved oxygen criteria; the latter for the critical summer season. The key features of the recommendation are the minimum dissolved oxygen criteria of 4.0 mg/l in Zone 4 and upper Zone 5 and the higher criteria, as shown, elsewhere.

It is envisioned that the bottom of the dissolved oxygen sag curve will be the only area with the 4.0 mg/l minimum value. Areas above and below the sag curve bottom, while having a minimum standard of 4.0 mg/l, will actually have higher dissolved oxygen concentrations since they are transition areas. These transition areas will require future refinement based upon Estuary model runs, and where possible the minimum dissolved oxygen criterion will be adjusted upward to reflect anticipated water quality.

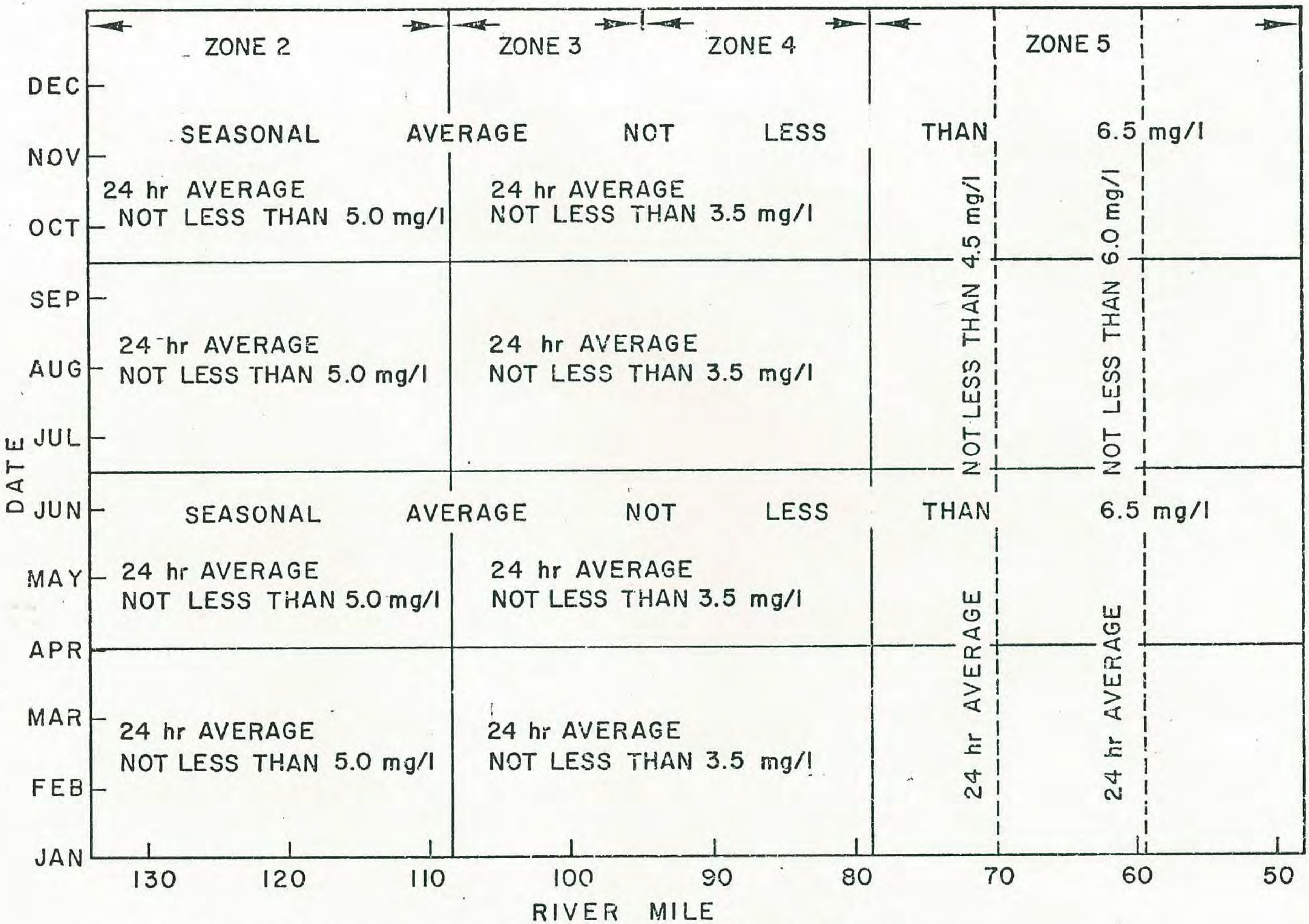

FIGURE I. EXISTING ESTUARY DISSOLVED OXYGEN STANDARDS

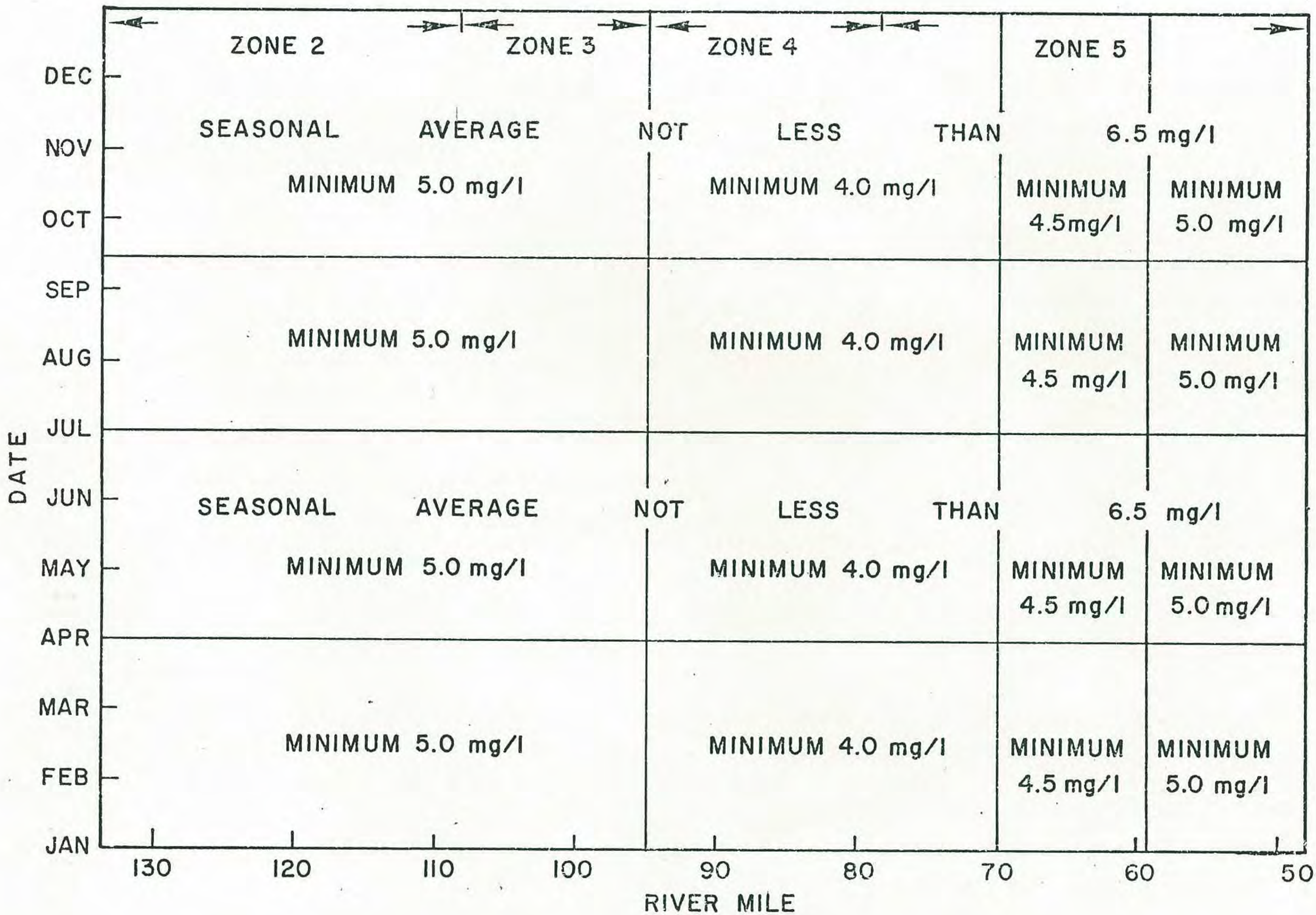

FIGURE 2. RECOMMENDED ESTUARY DISSOLVED OXYGEN STANDARDS

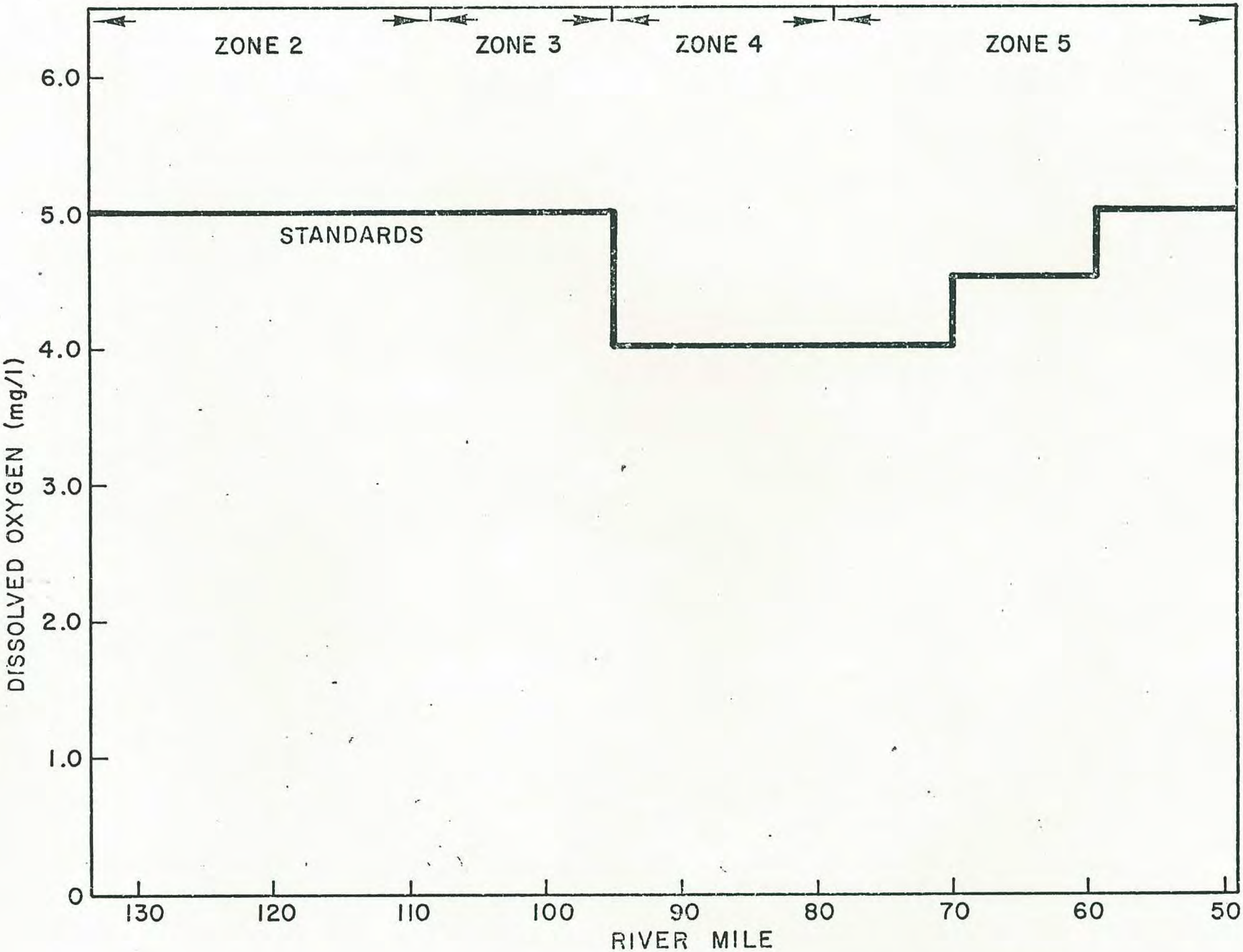

FIGURE 3. RECOMMENDED DISSOLVED OXYGEN STANDARDS - SUMMER PROFILE. ALL VALUES AS MINIMUMS. JULY 1 TO SEPTEMBER 15.

Recommended Changes to the Fish Passage Seasons

The number of American shad returning to and from non-tidal spawning areas is affected by dissolved oxygen levels, flows and other factors during the passage season. The current DRBC fish passage seasonal average dissolved oxygen standard is acceptable to the Task Force. In order to increase the probability of successful adult shad emigration from the upper river the Task Force recommends that the spring passage season be extended from June 15 to June 30.

Policy Considerations and Alternatives

The technical, political and financial feasibility of pollution abatement efforts beyond current strategies was not examined by the Task Force. The dissolved oxygen concentration necessary for fish survival and propagation are independent from these factors. A fish community cannot adjust its requirements for life.

Technical, political and financial feasibility considerations, however, are inherent in the Task Force recommendations. The recommendations represent minimally acceptable standards rather than optimal or ultimately desired standards.

The optimal or ultimately desired standards are presented in Figure 4. Implementation of an abatement program to reach these future objectives will result in fish population which is optimal in size, species diversity and distribution including migratory species in non-estuary areas. (Due to irreversible loss of habitat and other factors the optimal fish population is not necessarily equivalent to "natural").

Adoption of the optimal dissolved oxygen standards (Figure 4) as a long range goal with the recommended standards (Figure 2) as an interim goal; should be considered by the Delaware River Basin Commission.

In its deliberations the Task Force recognized that parameters other than dissolved oxygen influence fish populations either independently or in combination with dissolved oxygen. Toxic and tainting substances were of particular concern. The abatement of these problems was assumed to occur concurrently with improved dissolved oxygen in order that a "fishable" Delaware Estuary is attained.

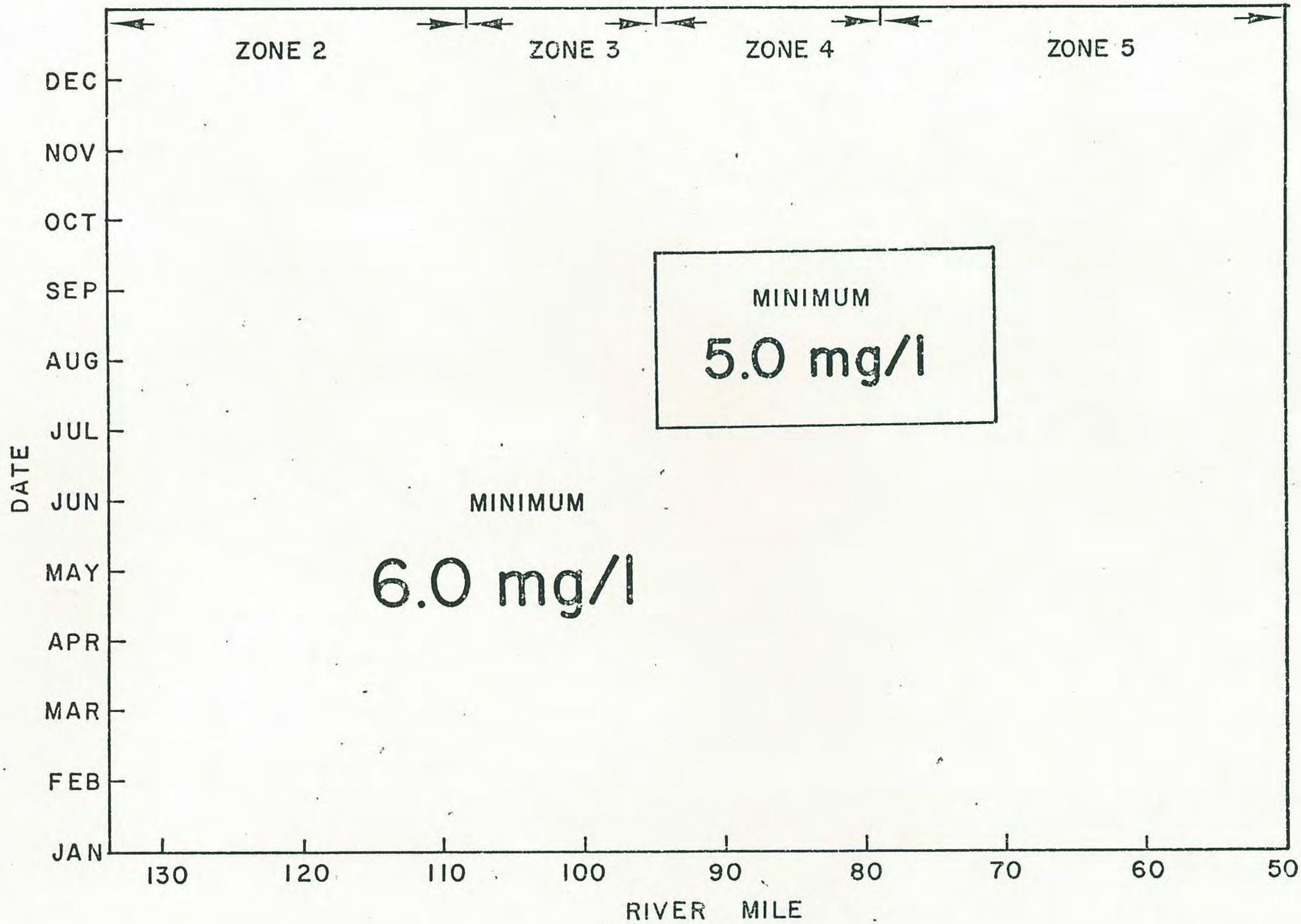

FIGURE 4. RECOMMENDED ULTIMATE DISSOLVED OXYGEN STANDARDS

Conclusions and Recommendations

(1) Federal water pollution control legislation establishes a National goal of water quality which provides for the protection and propagation of fish: the so-called "fishable" goal. The absence of propagation of resident fish as a water use in Zones 3 and 4 results in currently-adopted DRBC water uses providing for less than "fishable" water quality in those zones. The Task Force believes that fish "residency" must be defined in water use descriptions as including all life stages including propagation.

(2) The attainment of "fishable" water quality in every zone should be a goal of the Commission's water quality management program. Fishable water quality is necessary for conformance with national goals and for improvement of estuary fisheries.

(3) A definition of "fishable" specific for the Delaware River Estuary is presented. Restoration of Estuary fisheries to include sizeable populations of the listed fish and activities would result in a minimum level of fisheries that satisfies the intent of the national "fishable" water quality goal.

(4) Current DRBC Dissolved Oxygen standards are expressed as a "minimum 24-hour average concentration". Fisheries protection requires the expression of standards in terms of minimum at any time. A report analyzing daily dissolved oxygen variability, as observed in the Estuary, should be prepared by the DRBC staff.

(5) Although existing dissolved oxygen standards have not been met, higher dissolved oxygen levels are recommended in Figure 2. These levels are considered the minimally acceptable levels which will result in the minimum level of "fishable" water as defined in Table 1. Adequate margins of safety and increased dissolved oxygen levels as represented in Figure 4 will result in a greater increase and protection of "fishable" fisheries. These levels should be considered for adoption.

(6) The spring fish passage season should be extended from June 15 to June 30. This change plus the dissolved oxygen improvement recommended above (Figure 2) will have a positive affect on the Delaware River Basin shad fishery. Attainment of the dissolved oxygen levels presented in Figure 4 will result in an optimum shad fishery.

(7) Attainment of "fishable" water quality requires the concurrent abatement of toxic and tainting substances and other parameters which may act independently or in combination with oxygen to reduce fish populations.

APPENDIX I

Members and Participants

Ad-Hoc Task Force to Evaluate Dissolved Oxygen Requirements for Indigenous Estuary Fish

Federal:

Royal Nadeau EPA-Region II (member)
Roland Hemmett EPA-Region II
Joseph Miller, U.S. Fish and Wildlife Service

Delaware:

Roy W. Miller, Division of Fish and Wildlife, Department of Natural Resources and Environmental Control (member)

New Jersey:

Douglas M. Clark, Division of Water Resources, Department of Environmental Protection (member)
Don Jacangelo, Division of Fish, Game and Shellfisheries, Department of Environmental Protection

New York:

Lawrence Skinner, Division of Fish and Wildlife, Department of Environmental Conservation (member)

Pennsylvania:

Richard W. Marshall, Pennsylvania Fish Commission (member)
Thomas A. Strekal, Norristown Regional Office, Department of Environmental Resources (member)
Charles Emery, Pennsylvania Fish Commission

Delaware River Basin Commission:

Seymour D. Selzer, Planning Branch
David P. Pollison, Planning Branch
Richard C. Albert, Planning Branch
Robert C. Kausch, Environmental Unit
Alison A. Anderson, Level B Study

Attachment B:

DRBFWMC (Delaware River Basin Commission Fish & Wildlife Management Cooperative). 2014. Letter to DRBC's Acting Executive Direction, Richard Gore, on "Dissolved Oxygen concentrations in the Delaware River;" signed by Policy Board Chair, Leroy M. Young Jr.; dated April 15, 2014. 2 pgs.

Delaware River Basin Fish and Wildlife Management Cooperative

Delaware Division of Fish and Wildlife • New Jersey Division of Fish, Game, and Wildlife
Pennsylvania Fish and Boat Commission • New York State Division of Fish, Wildlife and Marine Resources
U.S. Fish and Wildlife Service • National Marine Fisheries Service

Liaisons: Delaware River Basin Commission • National Park Service

April 15, 2014

Richard Gore, Acting Executive Director
Delaware River Basin Commission
25 State Police Drive
P. O. Box 7360
West Trenton, NJ 08628-0360

Subject: Dissolved Oxygen concentrations in the Delaware River

Dear Mr. Gore,

The Delaware River Basin Fish and Wildlife Management Cooperative (Co-op) includes the fish and wildlife management agencies of New York, Pennsylvania, New Jersey and Delaware, as well as the U.S. Fish and Wildlife Service and the National Marine Fisheries Service (NMFS). We are writing to raise awareness about habitat requirements for reproduction of the Delaware River spawning stock of Atlantic sturgeon. That stock is included in the New York Bight Distinct Population Segment by the National Marine Fisheries Service. Last April, the Service ruled that the New York Bight Distinct Population Segment of Atlantic Sturgeon is endangered. Conservation of the Delaware River spawning stock is now guided by the Endangered Species Act.

At the turn of the 20^{th} century the stock was severely over-fished, and as water pollution increased, water quality declined into an anoxic condition during summer. Anoxia would certainly have reduced or eliminated successful reproduction of Atlantic sturgeon and has almost certainly been a major factor causing their critically low abundance today. In particular, we are writing about the need to maintain higher levels of dissolved oxygen in the River during the summer than the present levels, in order to ensure the ability of young sturgeon to survive and grow. Peer-reviewed laboratory research has found that sturgeon less than one year of age are more sensitive to dissolved oxygen than rainbow trout.

In the Delaware River, the lowest values of dissolved oxygen revealed by ongoing monitoring are at, or close to, values that produced death in very young sturgeon in laboratory experiments. In addition to possible direct mortality, these low levels of dissolved oxygen can reduce the growth rate of very young sturgeon. The current summertime Delaware River Basin Commission (DRBC) dissolved oxygen criterion for Zones 3, 4 and part of Zone 5 during the summer months is a 24 hour average of 3.5 mg/l.

Field research by the Delaware Division of Fish and Wildlife has confirmed the presence of young-of-year Atlantic sturgeon in 2009, 2011 and 2012 in Zone 4, meaning this section of the River is critical nursery habitat, and possibly spawning habitat, for Atlantic sturgeon. The Ad-Hoc Task Force to Evaluate Dissolved Oxygen Requirements of Indigenous Estuarine Fish reported to the Commission in 1979, in its report titled "Dissolved oxygen requirements of a"fishable" Delaware River estuary," that the criterion form of a 24-hour average allows for minimum values to be as much as 3 mg/l below the average, or as low as 0.5 mg/l. The Task Force stated that a minimum value should be employed, rather than a 24-hour average, since fish could be negatively affected by minimum values. Dissolved oxygen monitoring data in the River has revealed that, since January 1, 2000, 111 days had minimum values below 3.5 mg/l and the lowest value reported was 2.2 mg/l.

The pattern of variation among years in YOY sturgeon collection has paralleled the variation among years in oxygen levels, suggesting that oxygen levels could be controlling or influencing reproductive success even today in this stock. In 2009 and 2011, field researchers confirmed successful reproduction in the River by collecting dozens of Atlantic sturgeon only a few months old. However, no young sturgeon were collected in 2010, despite extensive attempts. In 2012, only one individual was found. These results suggest that reproductive success may be sporadic. The two years with one or no very young sturgeon collected, 2010 and 2012, had lower levels of dissolved oxygen when compared to the two years with numbers of newly born sturgeon. This result suggests that the lower levels of dissolved oxygen in the Delaware River during the summers of 2010 and 2012 could have caused mortality of very young sturgeon.

The Co-op requests that the DRBC increase the dissolved oxygen criteria for the Delaware River to ensure that low dissolved oxygen levels do not threaten survival, growth and reproductive success of Atlantic sturgeon. During the 1890s, the Delaware River spawning stock of Atlantic sturgeon was by far the largest on the Atlantic coast, and produced very large fishery landings and economic value. With adequate water quality, consistent reproduction of this stock of anadromous fish can be restored, and the spawning stock could be rebuilt, just as the Delaware River spawning stocks of striped bass and American shad have been rebuilt once water quality was improved to meet their needs. In the case of Atlantic sturgeon, the evidence suggests that water quality in the Delaware does not yet consistently meet the needs of this species.

Sincerely,

Leroy M. Young, Jr., Director
Bureau of Fisheries
Pennsylvania Fish and Boat Commission and
Chair, Policy Board
Delaware River Basin Fish and Wildlife Management Cooperative

Attachment C:

USEPA. 1986. Ambient Water Quality Criteria for Dissolved Oxygen. U.S. Environmental Protection Agency, Office of Research and Development, Environmental Research Laboratories. EPA 440/5-86-003. 54 pgs.

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

Water

EPA

Ambient Water Quality Criteria for

Dissolved Oxygen

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
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Clerical Support: Nancy Lanpheare

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FIGURES

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 (~ 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.

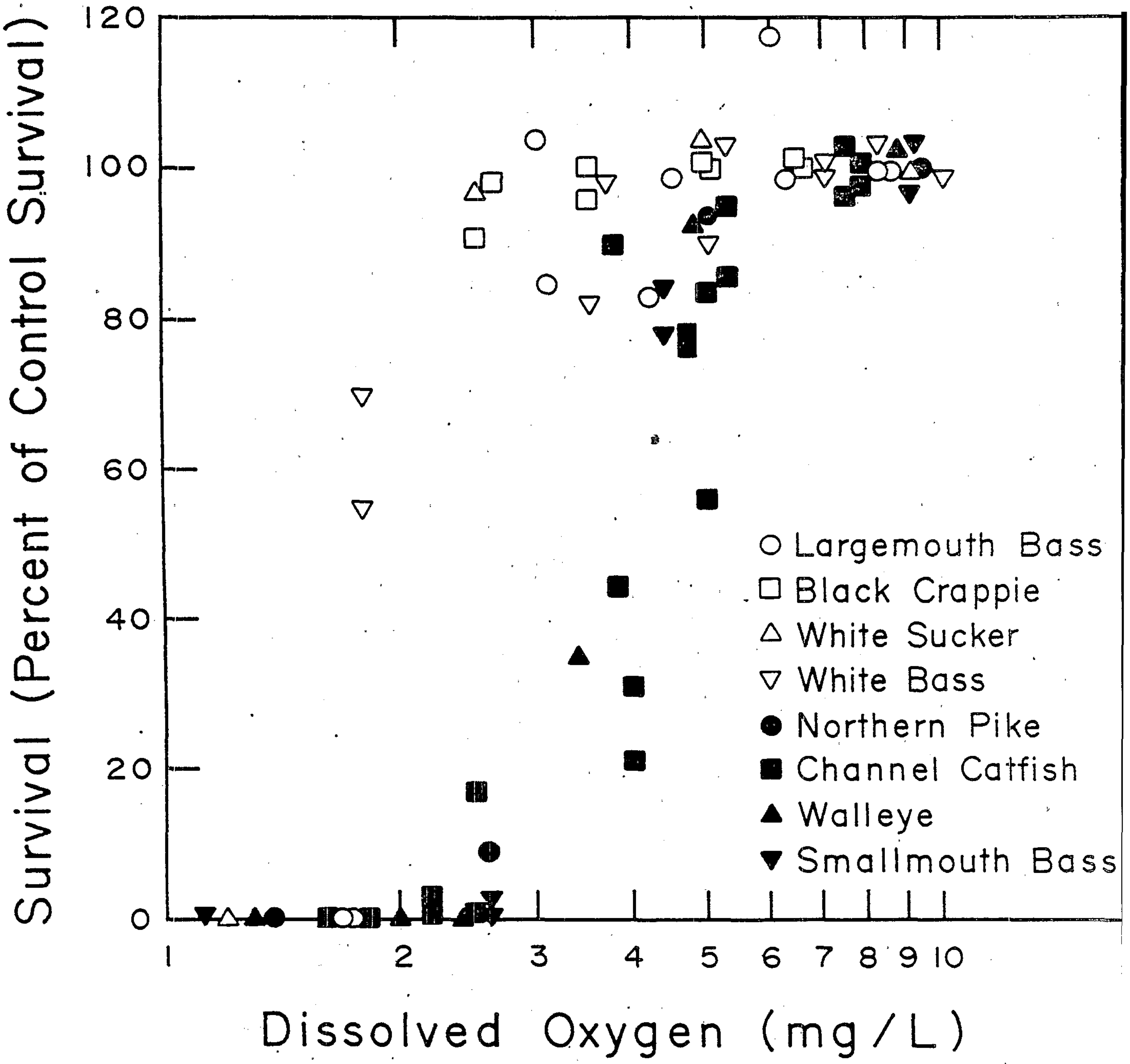

Figure 1. Effect of continuous exposure to various mean dissolved oxygen concentrations on survival of embryonic and larval stages of eight species of nonsalmonid fish. Minima recorded in these tests averaged about 0.3 mg/l below the mean concentrations.

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. <u>Salmonid Waters</u>

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 <u>intergravel</u> 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. <u>Nonsalmonid Waters</u>

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. <u>Invertebrates</u>

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

<u>Added Note</u>

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: Mean	Minimum	Percent Survival	Water Velocity, cm/hr	Mean Survival (Flow > 15 cm/hr)
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 Quality Criteria for Water (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. The Criteria and Monitoring and Design Conditions

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.

VIII. REFERENCES

Adelman, I. R., and L. L. Smith. 1970. Effect of oxygen on growth and food conversion efficiency of northern pike. Prog. Fish-Cult. 32:93-96.

Adelman, I. R., and L. L. Smith. 1972. Toxicity of hydrogen sulfide to goldfish (Carassius auratus) as influenced by temperature, oxygen, and bioassay techiques. J. Fish. Res. Bd. Canada 29:1309-1317.

Alabaster, J. S., and R. L. Welcomme. 1962. Effect of concentration of dissolved oxygen on survival of trout and roach in lethal temperatures. Nature 194:107.

Alabaster, J. S., and R. Lloyd. 1980. Water Quality Criteria for Freshwater Fish. Butterworths, London. 297 p.

Alderdice, D. F., W. P. Wickett, and J. R. Brett. 1958. Some effects of temporary exposure to low dissolved oxygen levels on Pacific salmon eggs. J. Fish. Res. Bd. Canada 15:229-250.

American Fisheries Society. 1978. Selected Coolwater Fishes of North America. R. L. Kendall, Ed. Special Publication No. 11, American Fisheries Society, Washington, D.C. 437 p.

Andrews, J. W., T. Murai, and G. Gibbons. 1973. The influence of dissolved oxygen on the growth of channel catfish. Trans. Amer. Fish. Soc. 102:835.

Bailey, R. M., J. E. Fitch, E. S. Herald, E. A. Lachner, C. C. Lindsey, C. R. Robins, and W. B. Scott. 1970. A list of common and scientific names of fishes from the United States and Canada (third edition). American Fisheries Society Special Publication No. 6. Washington, D.C. 150 p.

Beamish, F. W. H. 1964. Respiration of fishes with special emphasis on standard oxygen consumption. III. Influence of oxygen. Can. J. Zool. 42:355-366.

Benedetto, L. 1970. Observations on the oxygen needs of some species of European plecoptera. Int. Rev. Ges. Hydrobiol., 55:505-510.

Bishai, H. M. 1962. Reactions of larval and young salmonids to water of low oxygen concentration. J. Cons. Perm. Int. Explor. Mer., 27:167-180.

Bouck, G. R. 1972. Effects of diurnal hypoxia on electrophoretic protein fractions and other health parameters of rock bass (Ambloplites rupestris). Trans. Amer. Fish. Soc. 101:448-493.

Bouck, G. R., and R. C. Ball. 1965. Influence of a diurnal oxygen pulse on fish serum proteins. Trans. Amer. Fish. Soc. 94:363-370.

Brake, L. A. 1972. Influence of dissolved oxygen and temperature on the growth of a juvenile largemouth bass held in artificial ponds. Masters Thesis. Oregon State University, Corvallis. 45 p.

Brannon, E. L. 1965. The influence of physical factors on the development and weight of sockeye salmon embryos and alevins. International Pacific Salmon Fisheries Commission, Progress Report No. 12. New Westminster, B.C., Canada. 26 p.

Brett, J. R., and J. M. Blackburn. 1981. Oxygen requirements for growth of young coho salmon (Orconhynchus kisutch) and sockeye (O. nerka) salmon at 15°C. Can. J. Fish. Aquat. Sci. 38:399-404.

Brinley, F. J. 1944. Biological studies. House Document 266, 78th Congress, 1st Session; Part II, Supplement F. p. 1275-1353.

Brooke, L. T., and P. J. Colby. 1980. Development and survival of embryos of lake herring at different constant oxygen concentrations and temperatures. Prog. Fish-Cult. 42:3-9.

Brungs, W. A. 1971. Chronic effects of low dissolved oxygen concentrations on fathead minnow (Pimephales promelas). J. Fish. Res. Bd. Canada, 28:1119-1123.

Cairns, J., and A. Scheier. 1957. The effects of periodic low oxygen upon the toxicity of various chemicals to aquatic organisms. Proc. 12th Industrial Waste Conf., Purdue Univ. Eng. Bull. No. 94. p. 165-176.

Cameron, J. N. 1971. Oxygen dissociation characteristics of the blood of rainbow trout, Salmo gairdneri. Comp. Biochem. Physiol. 38:699-704.

Carlson, A. R., J. Blocker, and L. J. Herman. 1980. Growth and survival of channel catfish and yellow perch exposed to lowered constant and diurnally fluctuating dissolved oxygen concentrations. Prog. Fish-Cult. 42:73-78.

Carlson, A. R., and L. J. Herman. 1978. Effect of long-term reduction and diel fluctuation in dissolved oxygen on spawning of black crappie, Pomoxis nigromaculatus. Trans. Amer. Fish. Soc. 107:742-746.

Carlson, A. R., and R. E. Siefert. 1974. Effects of reduced oxygen on the embryos and larvae of lake trout (Salvelinus namaycush) and largemouth bass (Micropterus salmoides). J. Fish. Res. Bd. Canada, 31:1393-1396.

Carlson, A. R., R. E. Siefert, and L. J. Herman. 1974. Effects of lowered dissolved oxygen concentrations on channel catfish (Ictalurus punctatus) embryos and larvae. Trans. Amer. Fish. Soc. 103:623-626.

Cech, J. J., Jr., C. G. Campagna, and S. J. Mitchell. 1979. Respiratory responses of largemouth bass (Micropterus salmoides) to environmental changes in temperature and dissolved oxygen. Trans. Amer. Fish. Soc. 108:166-171.

Chapman, G. A., and D. L. Shumway. 1978. Effects of sodium pentachlorophenate on the survival and energy metabolism of larval steelhead trout. pp. 285-299. In: K. Ranga Rao, ed. Pentachlorophenol: chemistry, pharmacology, and environmental toxicology. Proceedings of a symposium held in Pensacola, Florida, June 27-29, 1977. Plenum Press, New York.

Coble, D. W. 1961. Influence of water exchange and dissolved oxygen in the redds on survival of steelhead trout embryos. Trans. Amer. Fish. Soc. 90:469-474.

Coble, D. W. 1982. Fish populations in relation to dissolved oxygen in the Wisconsin River. Trans. Amer. Fish. Soc. 111:612-623.

Cuenco, M. L., R. L. Stickney, and W. E. Grant. 1985a. Fish bioenergetics and growth in aquaculture ponds: I. Individual fish model development. Ecol. Modelling, 27:169-190.

Cuenco, M. L., R. L. Stickney, and W. E. Grant. 1985b. Fish bioenergetics and growth in aquaculture ponds: II. Effects of interactions among size, temperature, dissolved oxygen, unionized ammonia, and food on growth of individual fish. Ecol. Modelling, 27:191-206.

Cuenco, M. L., R. L. Stickney, and W. E. Grant. 1985c. Fish bioenergetics and growth in aquaculture ponds: III. Effects of intraspecific competition, stocking rate, stocking size and feeding rate on fish productivity. Ecol. Modelling, 28:73-95.

Dahlberg, M. L., D. L. Shumway, and P. Doudoroff. 1968. Influence of dissolved oxygen and carbon dioxide on swimming performance of largemouth bass and coho salmon. J. Fish. Res. Bd. Canada, 25:49-70.

Davis, G. E., J. Foster, C. E. Warren, and P. Doudoroff. 1963. The influence of oxygen concentration on the swimming performance of juvenile Pacific salmon at various temperatures. Trans. Amer. Fish. Soc. 92:111-124.

Davis, J. C. 1975a. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review. J. Fish. Res. Bd. Canada, 32:2295-2232.

Davis, J. C. 1975. Waterborne dissolved oxygen requirements and criteria with particular emphasis on the Canadian environment. National Research Council of Canada, Associate Committee on Scientific Criteria for Environmental Criteria, Report No. 13, NRCC 14100:111 p.

Doudoroff, P., and D. L. Shumway. 1967. Dissolved oxygen criteria for the protection of fish. pp. 13-19. In: American Fisheries Society Special Publication No. 4.

Doudoroff, P., and D. L. Shumway. 1970. Dissolved oxygen requirements of freshwater fishes. Food Agriculture Organization of the United Nations. FAO Technical Paper No. 86. Rome, Italy. 291 p.

Downing, K. M., and J. C. Merkens. 1955. The influence of dissolved oxygen concentration on the toxicity of unionized ammonia to rainbow trout (*Salmo gairdnerii* Richardson). Ann. Appl. Biol. 43:243-246.

Downing, K. M., and J. C. Merkens. 1957. The influence of temperature on the survival of several species of fish in low tensions of dissolved oxygen. Ann. Appl. Biol. 45:261-267.

Eddy, R. M. 1972. The influence of dissolved oxygen concentration and temperature on the survival and growth of chinook salmon embryos and fry. M.S. Thesis, Oregon State University, Corvallis. 45 p.

Ellis, M. M. 1937. Detection and measurement of stream pollution. Bull. U.S. Bureau of Sport Fisheries and Wildlife 48(22):365-437.

Ellis, M. M. 1944. Water purity standards for freshwater fishes. Special Scientific Report No. 2, U.S. Department of Interior, Fish and Wildlife Service.

Federal Water Pollution Control Administration. 1968. Water Quality Criteria. Report of the National Technical Advisory Committee of the Secretary of Interior. U.S. Dept. of Interior, Washington, D.C. 234 p.

Fisher, R. J. 1963. Influence of oxygen concentration and its diurnal fluctuation on the growth of juvenile coho salmon. M.S. Thesis, Oregon State University, Corvallis. 48 p.

Fox, H. M., and J. Sidney. 1953. The influence of dissolved oxygen on the respiratory movements of caddis larvae. J. Exptl. Biol., 30:235-237.

Fox, H. M., C. A. Wingfield, and B. G. Simmonds. 1937. The oxygen consumption of ephemerid nymphs from flowing and from still waters in relation to the concentration of oxygen in the water. J. Exptl. Biol., 14:210-218.

Gaufin, A. R. 1973. Water quality requirements of aquatic insects. EPA-660/3-73-004, September 1973. Ecological Research Series. U.S. Environmental Protection Agency, Washington, D.C. 79 p.

Grigg, G. C. 1969. The failure of oxygen transport in a fish at low levels of ambient oxygen. Comp. Biochem. Physiol. 29:1253-1257.

Haley, R., S. P. Davis, and J. M. Hyde. 1967. Environmental stress and Aeromonas liquefascians in American and threadfin shad mortalities. Prog. Fish-Cult. 29:193.

Heimer, J. T. 1984. American Falls-Snake River fisheries investigations. Final Report to Idaho Power Company from Idaho Dept. of Fish and Game. 35 p.

Herrmann, R. B., C. E. Warren, and P. Doudoroff. 1962. Influence of oxygen concentration on the growth of juvenile coho salmon. Trans. Amer. Fish. Soc. 91:155-167.

Hollender, B. A. 1981. Embryo survival, substrate composition, and dissolved oxygen in redds of wild brook trout. M.S. Thesis, University of Wisconsin, Stevens Point. 87 p.

Homer, D. H., and W. E. Waller. 1983. Chronic effects of reduced dissolved oxygen on Daphnia magna. Water, Air, and Soil Pollut., 20:23-28.

Hutchins, F. E. 1974. Influence of dissolved oxygen concentration and swimming velocity on food consumption and growth of juvenile coho salmon. M.S. Thesis, Oregon State University, Corvallis. 66 p.

International Joint Commission. 1976. Dissolved oxygen. In: Great Lakes Water Quality, Annual Report of the Water Quality Objectives Subcommittee and the Task Force on the Scientific Basis for Water Quality Criteria. 83 p.

Jacob, U., H. Walther, and R. Klenke. 1984. Aquatic insect larvae as indicators of limiting minimal contents of dissolved oxygen. Aquatic Insects, 6:185-190.

Jones, D. R. 1971. The effect of hypoxia and anemia on the swimming performance of rainbow trout (Salmo gairdneri). J. Exptl. Biol. 44:541-551.

JRB Associates. 1984. Analysis of data relating dissolved oxygen and fish growth. Report submitted to EPA under contract 68-01-6388 by JRB Associates, McLean, Virginia.

Kapoor, N. N., and W. Griffiths. 1975. Oxygen consumption of nymphs of Phasganophora capitata (Pictet) (Plecoptera) with respect to body weight and oxygen concentrations. Can. J. Zool., 53:1089-1092.

Katz, M., A. Pritchard, and C. E. Warren. 1959. Ability of some salmonids and a centrarchid to swim in water of reduced oxygen content. Trans. Amer. Fish. Soc. 88:88-95.

Knight, A. W., and A. R. Gaufin. 1963. The effect of water flow, temperature, and oxygen concentration on the Plecoptera nymph, Acroneuria pacifica Banks. Proc. Utah Acad. Sci., Arts, and Letters, 40(II):175-184.

Knight, A. W., and A. R. Gaufin. 1965. Function of stonefly gills under reduced dissolved oxygen concentration. Proc. Utah Acad. Sci., Arts, and Letters, 42(II):186-190.

Koski, K. V. 1965. The survival of coho salmon (Oncorhynchus kisutch) from egg deposition to emergency in three Oregon coastal streams. M.S. Thesis, Oregon State University, Corvallis. 81 p.

Lloyd, R. 1961. Effect of dissolved oxygen concentration on the toxicity of several poisons to rainbow trout (Salmo gairdnerii Richardson). J. Exptl. Biol. 38:447-455.

Magnuson, J. J., P. O. Fromm, J. R. Brett, and F. E. J. Fry. 1979. Report of the review committee for the dissolved oxygen objective for the Great Lakes. A report submitted to the Great Lakes Science Advisory Board, International Joint Commission, Windsor, Ontario, Canada.

Meyer, F. P. 1970. Seasonal fluctuations in the incidence of disease on fish farms. In: A Symposium on Diseases of Fish and Shellfishes. Spec. Publ. No. 5. Amer. Fish. Soc. Washington, D.C. p. 21-29.

Minnesota Pollution Control Agency. 1980. Dissolved oxygen standard justification. MPCA, Water Quality Division. Unpublished manuscript. 35 p.

Moss, D. D., and D. C. Scott. 1961. Dissolved oxygen requirements of three species of fish. Trans. Amer. Fish. Soc. 90:377-393.

National Academy of Sciences/National Academy of Engineering. 1973. Water Quality Criteria. 1972. p. 131-135. EPA-R/73-033. 594 p.

Nebeker, A. V. 1972. Effect of low oxygen concentration on survival and emergence of aquatic insects. Trans. Amer. Fish. Soc., 101:675-679.

Peterka, J. J., and J. S. Kent. 1976. Dissolved oxygen, temperature, survival of young at fish spawning sites. Environmental Protection Agency Report No. EPA-600/3-76-113, Ecological Research Series. 36 p.

Pickering, Q. H. 1968. Some effects of dissolved oxygen concentrations upon the toxicity of zinc to the bluegill, Lepomis macrochirus Raf. Water Res. 2:187-194.

Raible, R. W. 1975. Survival and growth rate of channel catfish as a function of dissolved oxygen concentration. Water Resources Research Center, Arkansas University, PB 244 708, NTIS, Springfield, Virginia.

Shepard, M. P. 1955. Resistance and tolerance of young speckled trout (Salvelinus fontinalis) to oxygen lack, with special reference to low oxygen acclimation. J. Fish. Res. Bd. Canada, 12:387-446.

Shumway, D. L., C. E. Warren, and P. Doudoroff. 1964. Influence of oxygen concentration and water movement on the growth of steelhead trout and coho salmon embryos. Trans. Amer. Fish. Soc. 93:342-356.

Siefert, R. E., A. R. Carlson, and L. J. Herman. 1974. Effects of reduced oxygen concentrations on the early life stages of mountain whitefish, smallmouth bass, and white bass. Prog. Fish-Cult. 36:186-190.

Siefert, R. E., and L. J. Herman. 1977. Spawning success of the black crappie, Pomoxis nitromaculatus, at reduced dissolved oxygen concentrations. Trans. Amer. Fish. Soc. 106:376-379.

Siefert, R. E., and W. A. Spoor. 1974. Effects of reduced oxygen on embryos and larvae of the white sucker, coho salmon, brook trout, and walleye. pp. 487-495. In: J. H. S. Blaxter, ed. The early life history of fish. The proceedings of an international symposium, Oban, Scotland, May 17-23, 1973. Springer-Verlag, Berlin.

Siefert, R. E., W. A. Spoor, and R. F. Syrett. 1973. Effects of reduced oxygen concentrations on northern pike (Esox lucius) embryos and larvae. J. Fish. Res. Bd. Canada, 30:849-852.

Silver, S. J., C. E. Warren, and P. Doudoroff. 1963. Dissolved oxygen requirements of developing steelhead trout and chinook salmon embryos at different water velocities. Trans. Amer. Fish. Soc. 92:327-343.

Snieszko, S. F. 1974. The effects of environmental stress on outbreaks of infectious diseases of fish. Fish. Biol. 6:197-208.

Sowden, T. K., and G. Power. 1985. Prediction of rainbow trout embryo survival in relation to groundwater seepage and particle size of spawning substrates. Trans. Amer. Fish. Soc., 114:804-812.

Spoor, W. A. 1977. Oxygen requirements of embryo and larvae of the large-mouth bass, Micropterus salmoides (Lacepede). J. Fish. Biol. 11:77-86.

Spoor, W. A. 1981. Growth of trout at different oxygen concentrations. Preliminary report from USEPA, Environmental Research Laboratory -- Duluth, Minnesota. 9 p.

Sprague, J. B. 1963. Resistance of four freshwater crustaceans to lethal high temperatures and low oxygen. J. Fish. Res. Bd. Canada, 20:387-415.

Stewart, N. E., D. L. Shumway, and P. Doudoroff. 1967. Influence of oxygen concentration on the growth of juvenile largemouth bass. J. Fish. Res. Bd. Canada, 24:475-494.

Thatcher, T. O. 1974. Some effects of dissolved oxygen concentration on feeding, growth, and bioenergetics of juvenile coho salmon. Ph.D. Thesis. Oregon State University, Corvallis. 70 p.

Thurston, R. V., G. R. Phillips, R. C. Russo, and S. M. Hinkins. 1981. Increased toxicity of ammonia to rainbow trout (Salmo gairdneri) resulting from reduced concentrations of dissolved oxygen. Can. J. Fish. Aquat. Sci. 38:983-988.

U.S. Environmental Protection Agency. 1976. Quality Criteria for Water. Washington, D.C. 256 p.

U.S. Environmental Protection Agency. 1982. Water Quality Standards Regulation. Federal Register 47:49239. October 29.

Warren, C. E., P. Doudoroff, and D. L. Shumway. 1973. Development of dissolved oxygen criteria for freshwater fish. U.S. Environmental Protection Agency, Ecological Research Series Report EPA-R3-73-019. Washington, D.C. 121 p.

Wedemeyer, F. A. 1974. Stress as a predisposing factor in fish diseases. U.S. Department of the Interior, Fish and Wildlife Service Leaflet FDL-38. 8 p.

Weithman, A. S., and M. A. Haas. 1984. Effects of dissolved oxygen depletion on the rainbow trout fishery in Lake Taneycomo, Missouri. Trans. Amer. Fish. Soc. 113:109-124.

Whitmore, C. M., C. E. Warren, and P. Doudoroff. 1960. Avoidance reactions of salmonid and centrarchid fishes to low oxygen concentrations. Trans. Amer. Fish. Soc. 89:17-26.

Whitworth, W. R. 1968. Effects of diurnal fluctuations of dissolved oxygen on the growth of brook trout. J. Fish. Res. Bd. Canada, 25:579-584.

Witzel, L. D., and H. R. McCrimmon. 1983. Redd-site selection by brook trout and brown trout in southwestern Ontario streams. Trans. Amer. Fish. Soc., 112:760-771.

Attachment D:

PADEP. 2013. Rationale for the Development of Ambient Water Quality Criteria for Dissolved Oxygen (Protection of Aquatic Life Use). 2013 Triennial Review document presented to the Pennsylvania Environmental Quality Board; revised 2/01/2023 and dated 7/09/2013; 13 pages

(available at
https://www.dep.pa.gov/PublicParticipation/EnvironmentalQuality/2013/Pages/default.aspx
and

https://files.dep.state.pa.us/PublicParticipation/Public%20Participation%20Center/PubPartCenterPortalFiles/Environmental%20Quality%20Board/2013/April%2016%20EQB/TRIENNIAL/finalTR13_Rationale-Dissolved_Oxygen_Criteria-020113-072013.pdf)

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF ENVIRONMENTAL PROTECTION
BUREAU OF POINT AND NON-POINT SOURCE MANAGEMENT

RATIONALE FOR THE DEVELOPMENT OF AMBIENT WATER QUALITY CRITERIA FOR

DISSOLVED OXYGEN

PROTECTION OF AQUATIC LIFE USE

Revised 02/01/13

Statement of Issue

Aquatic life in Pennsylvania freshwater waterbodies are currently being protected from adverse impacts associated with low dissolved oxygen by four categories of dissolved oxygen criteria (DO), which is found in PA Code Chapter 93.7 Table 3. Only slight revisions have been made to the numerical component of the dissolved oxygen aquatic life criteria since the Department of Health Sanitary Water Board adopted their Rules and Regulations in 1967. Since then, many new resources of new scientific literature and information have been made available, including EPA's review of literature that resulted in a dissolved oxygen criteria recommendation in the "Quality Criteria for Water 1986" (also known as the "Gold Book"). Based on the availability of updated scientific studies and recent concerns about the appropriateness of the current dissolved criteria, a review of the current information regarding dissolved oxygen requirements of aquatic life was undertaken.

Background

Dissolved oxygen refers to the oxygen gas that is dissolved in the water and made available to aquatic life. Oxygen gets into the water by diffusion from the surrounding air, by aeration from moving water or as a product of photosynthesis. The solubility of oxygen in water is highly dependent on the temperature of the water, but is also affected by atmospheric pressure and salinity. Dissolved oxygen fluctuates diurnally in a freshwater ecosystem due to photosynthesis and respiration. Additionally, DO fluctuates seasonally mostly due to change in water temperatures.

DO requirements for aquatic organisms were highly studied until the 1980's. As such, there are many peer-reviewed studies on the topic. The abundance of literature relating to lethal and sub-lethal effects is helpful to understanding the deleterious effects of low dissolved oxygen concentrations. Many lab experiments studying DO requirements of fish focused on determining minimum DO concentrations necessary to avoid mortality in both adult and larval stages of fishes. Other field and lab studies that examined sub-lethal effects of varying DO conditions have shown stress responses in the form of avoidance, decreased swimming performance, reduction in metabolic rate, reduced growth, and changes in behavior that may increase risk of predation. Additionally, low DO concentrations have been shown to prevent spawning, and reduce fecundity of female fish in lab experiments. Stress due to low DO has also been shown to increase fish susceptibility to disease and increase the toxicity of certain chemicals and pollutants. The consensus of many DO studies is that early life stages of fish, such as embryonic and larval stages, are generally more sensitive to low DO concentrations than adult life stages. Salmonids generally require higher concentrations of DO than fish that inhabit warmwater ecosystems, however, some warm and cool species of fish such as shad, herring, pike, sculpins and smallmouth bass, are known to be more sensitive than other warm water species.

The determination of appropriate minima, means, frequency and duration for DO criteria is difficult since the lab experiments typically exposed organisms to a constant DO concentration. The DO concentration used in the experiments represents both the minima and the average. EPA states in the 1986 Recommended Criteria document, "biological effects of low dissolved oxygen concentrations depend upon means, minima, the duration and frequency of the minima and the period of averaging." There is a lack of information on the duration and frequency components of DO criteria; therefore most criteria consist of minima and means.

The Department recognizes and respects both the value and the limitations that this data provides. Developing criteria from existing scientific literature is challenging for numerous reasons. The application of study data for criteria development (a controlled environment vs. a multi-variable environment) must be carefully examined. In reality, an inter-relationship exists among parameters within an aquatic ecosystem; a relationship that cannot be adequately captured within the scope of a scientific study. Thus, the application of study data must take into consideration the natural dynamic of the ecosystem to which it is being applied. For example, some of the literature that exists on DO requirements involves studies based on laboratory experiments where the conditions are artificial in several important aspects. With this understanding, the Department has examined the available data and carefully applied it to the selection of the proposed DO criteria.

Pennsylvania Dissolved Oxygen Criteria

Pennsylvania's first dissolved oxygen criteria were found in the Sanitary Water Board Rules and Regulations and were adopted as follows:

b- *Dissolved Oxygen*

b_1 - *Minimum daily average 6.0 mg/l; No value less than 5.0 mg/l*

b_2 - *Minimum daily average 5.0 mg/l; No value less than 4.0 mg/l*

b_3 - *Minimum daily average not less than 5.0 mg/l, except during the period of 4/1 - 6/15 and 9/16 – 12/31, not less than 6.5 mg/l*

b_4 - *Minimum daily average not less than 3.5 mg/l, except during the period of 4/1 - 6/15 and 9/16 – 12/31, not less than 6.5 mg/l*

The following dissolved oxygen criteria were added December 20, 1967:

b_5 – *For the period 3/15 to 6/30 of any year; no value less than 5.0 mg/l. for the remainder of the year,; no value less than 4.0 mg/l*

b_6 – *No value less than 7.0 mg/l*

b_7 – *For lakes, ponds and impoundments only; no value less than 4.0 mg/l in the epilimnion*

b_8 – *For lakes, ponds and impoundments only; no value less than 5.0 mg/l*

Dissolved oxygen criteria b_1 and b_2 corresponded to cold water fishes (CWF) use and warm water (WWF) fishes use, respectively. DRBC dissolved oxygen criteria for the Delaware River and Estuary were incorporated as b_3 and b_4. The b_5 criterion corresponded to the trout stocking use and b_6 corresponded to conservation areas (conservation areas became high quality waters in the 1978-79 rulemakings; both the trout stocking use and conservation area use were added in 1967). The b_7 criterion corresponded to warm water lakes, ponds and impoundments, while the b_8 criterion corresponded to and cold water lakes, ponds and impoundments.

The Sanitary Water Board's dissolved oxygen criteria were similar to, but in some cases, less stringent than, the Federal Water Pollution Control Administration's recommendations in the 1968 "Report of the Committee on Water Quality Criteria" (The "Green Book"). The Green Book recommended that dissolved oxygen criteria in a warm water fishery should be "above 5.0 mg/l assuming normal seasonal and daily variations are above this concentration. Under extreme conditions, however, they may range between 5 and 4 mg/l for short periods during any 24-hour period, provided that the water quality is favorable in all other aspects." For cold water species, the Green book stated that "it is desirable that DO concentrations be at or near saturation. This is especially important in spawning areas where DO levels must not be below 7 mg/l at any time. For good growth and general well being of trout, salmon and their associated biota, DO concentrations should not be below 6 mg/l. Under extreme conditions, they may range between 6 and 5 mg/l provided the water quality is favorable in all other respects and daily and seasonal fluctuations occur."

DER adopted a few changes to the DO criteria in 1973 and 1974. The changes were as follows (underlined):

b_3 - *Minimum daily average not less than 5.0 mg/l, except during the period of 4/1 - 6/15 and 9/16 – 12/31, not less than 6.5 mg/l* <u>as a seasonal average</u>

b_4 - *Minimum daily average not less than 3.5 mg/l, except during the period of 4/1 - 6/15 and 9/16 – 12/31, not less than 6.5 mg/l* <u>as a seasonal average</u>

b_5 – *For the period* <u>2/15 – 7/31</u> *of any year* <u>minimum daily average of 6.0 mg/l</u>., *no value less than 5.0 mg/l. For the remainder of the year* <u>minimum daily average 5.0 mg/l</u>., *no value less than 4.0 mg/l.*

*Added:

<u>b_9 - Minimum daily average 7.0 mg/l, No value less than 6.0 mg/l</u>

In the 1976 Quality Criteria for Water, also known as the "Red Book," EPA recommended "a minimum concentration of dissolved oxygen to maintain good fish populations is 5.0 mg/liter. The criterion for Salmonid spawning is a minimum of 5.0 mg/liter in the interstitial water of the gravel." DER Chapter 93 criteria remained as a minimum daily average of 5.0 mg/l and minimum of 4.0 mg/l for warm water fishes, and 6.0 mg/l minimum daily average and 5.0 minimum for cold water fishes.

In 1979 DER adopted additional changes in Table 3; these changes include: the deletions of b_7, b_8 and b_9. Language from the lakes, ponds and impoundment criteria (b_7, b_8) was combined with b_1 and b_2. Additionally, the symbol "b" was replaced with "DO".

In 1986, EPA revised the national water quality criteria recommendations in "Quality for Water 1986," also known as the "Gold Book." EPA reviewed a large body of literature in order to make these recommendations relating to warm water fishes and cold water fishes (including salmonids).

DER made minor reformatting revisions to the DO criteria in Chapter 93.7 Table 3 in 1988, but did not incorporate the 1986 Recommendations for unknown reasons.

DRBC criteria were deleted from Chapter 93.7 Table 3 during the 2000 Triennial Review and referenced in the appropriate segments in 93.9. Consequently, criteria b_3 and b_4 were deleted and the remaining D.O. criteria were renumbered in Table 3.

In 2005, the DO_1 criterion was revised to clarify the criterion that applies to lakes, ponds and impoundments to incorporate reference to the natural stratification that may occur in those waterbodies.

The current dissolved oxygen criteria, as outlined in Chapter 93.7 Table 3 are as follows:

DO_1	For flowing waters, minimum daily average 6.0 mg/l; minimum 5.0 mg/l. For lakes, ponds and impoundments, minimum 5.0 mg/l.	CWF HQ-WWF HQ- TSF
DO_2	Minimum daily average 5.0 mg/l; minimum 4.0 mg/l.	WWF
DO_3	For the period February 15 to July 31 of any year, minimum daily average 6.0 mg/l; minimum 5.0 mg/l. For the remainder of the year, minimum daily average 5.0 mg/l; minimum 4.0 mg/l.	TSF
DO_4	Minimum 7.0 mg/l.	HQ-CWF

Review of "Ambient Water Quality Criteria for Dissolved Oxygen" (1986)

EPA reviewed and considered a large number of studies on dissolved oxygen for the development of the recommended criteria for freshwater aquatic life. Although there are typically two main ways to express a dissolved oxygen criterion: concentration (mg/L) or percent saturation, EPA determined that it is more direct and easier to express the dissolved oxygen criteria as a minimum concentration.

Much of the DO research has focused on acute responses such as mortality or loss of equilibrium. However, there is extreme variability in test conditions even among those studies that focus on a common endpoint (i.e. mortality), such as: constant or declining exposure to low DO conditions, duration of exposure

EPA recommended two separate sets of aquatic life criteria for dissolved oxygen: coldwater criteria for the protection of salmonids and other coldwater species and warmwater criteria for the protection of species indigenous to warm water habitats. The national criteria also differentiate the protection needed for adult fishes and that needed for the early life stages of those same fishes. Early life stages include spawning, incubation of embryos and larvae up to 30 days after hatch.

EPA's rationale for the 1986 criteria included a discussion of the different life stages and thresholds of salmonids and non-salmonids affected by dissolved oxygen, including metabolic and physiological effects, growth, reproduction, behavioral responses, swimming and acute lethal responses. DO requirements for aquatic macroinvertebrates were evaluated as well as other additive responses such as stress from chemicals, temperature and disease.

Salmonids

Of particular interest are the DO concentrations necessary for early life stages of salmonids. Since most species of salmonids have embryonic and larval stages that develop while buried in the gravel of streams or lakes, protection of DO concentrations in the gravel is required. The area where a female salmonid lays her eggs in the gravel is called a "redd." It's complicated to determine what concentration of DO in the surface water in required in order to protect the redds since there are so many variables that affect the DO in the redds. EPA determined that intergravel DO was generally 3 mg/L lower than that of the overlaying surface water by reviewing several studies on DO and redds.

Nonsalmonids (warmwater fish)

The EPA rationale explained that developing criteria for warmwater fish was more difficult than deriving criteria for salmonids because there is less literature available and much more diversity of fishes in a warmwater ecosystem.

Based on literature review, EPA determined that, except for larval stages, non-salmonid species were less sensitive to low dissolved oxygen concentrations than salmonids. However, literature shows that many species of non-salmonids have early life stages that are much more sensitive to low dissolved oxygen concentrations than adult life stages.

The EPA literature review yielded a few generalizations, such as: adults and juveniles of all species studied survive for at least a few hours at DO concentrations as low 3 mg/L, but there is little knowledge about chronic exposure to low DO concentrations. Reduced concentrations of DO also caused reduced growth in studies. For example, Stewart et al. (1967) observed reduced growth in largemouth bass juveniles below 5.8 mg/L.

Macroinvertebrates
EPA stated that there is much less information available on the DO requirements of macroinvertebrates compared to information available on fish. However, even with limited amount of macroinvertebrate studies, EPA stated that the DO requirements for the survival of aquatic macroinvertebrates are "almost certainly greater than those of most fish species." Chronic effects of low DO on macroinvertebrates are not well known, but EPA suggested that "concentrations adequate to avoid impairment of fish production probably will provide reasonable protection for invertebrates as long as lethal concentrations are avoided."

Temperature Stress
EPA examined studies to evaluate the synergistic effect of temperature and DO on fishes. EPA concluded that "high temperatures almost certainly increase the adverse effects of low dissolved oxygen concentrations." Since most of the laboratory experiments on fish DO requirements are performed using temperatures near the mid-range of the fishes' temperature tolerances, criteria based on these lab studies alone may be under protective at high temperatures that are stressful to fish.

Chemical Stress
EPA discussed several laboratory studies that evaluated the effect of low DO concentrations on the toxicity of various chemicals, such as lead, zinc, copper, monohydric phenols, ammonia, hydrogen sulfide, napthenic acid and potassium cyanide. Some of these chemicals are commonly found in oxygen-demanding wastes. Overall, the studies showed that low DO concentrations increased the toxicity of these chemicals in the fish species studies.

Disease Stress
EPA reviewed the results of several studies that suggest that fish become more susceptible to disease when stressed by low DO concentrations. These studies suggest that many fish pathogens are continuously present in many waterbodies, but fish are only susceptible to infection when their defenses are compromised by stress.

<u>Discussion of DO Literature</u>
EPA summarized a large body of literature in its revisions of recommended DO criteria. This review resulted in a risk level assessment to protect aquatic life from impacts due to low DO concentrations. The qualitative levels of risk include: no production impairment, slight production impairment, moderate production impairment, severe production impairment and limit to avoid acute mortality. Production impairment refers to production impairments in a fishery. EPA summarized the DO concentrations judged to achieve protection at the qualitative levels of risk in a table in the recommended criteria. The recommended criteria were then derived from the DO concentrations in this table.

The DO concentrations that correspond to each risk level were derived from growth data for "other life stages" and are approximately equivalent to 10%, 20% and 40% growth impairment for slight production impairment, moderate production impairment and severe production impairment, respectively. EPA states that, "growth impairment of 50% or greater is often accompanied by mortality, and conditions allowing a combination of severe growth impairment and mortality are considered as no protection."

DO concentrations corresponding to risk levels for early life stages are based on subjective judgments and generalizations of the response curve shape between what would result in no production and impairment and the acute mortality limit. EPA's recommended criteria is based on the DO concentrations judged to be equivalent to the level of risk that was determined to be appropriate for a national criterion.

Proposed Dissolved Oxygen Criteria

The Department proposes to incorporate the DO concentrations from EPA's risk level assessment in its DO criteria. Instead of incorporating values associated with severe production impairment and protection of only acute mortality, the Department proposes to incorporate the slight production impairment as 7-day averages and the moderate production values as minima for early life stages and other life stages to protect aquatic life. It is important to note that the proposed criteria apply to flowing freshwater streams, the epilimnion of a naturally stratified lake and throughout the waterbody of non-stratified lakes.

CWF Criteria

In Pennsylvania, three species of salmonids are commonly found, due to natural reproduction or stocking: brook trout, brown trout and rainbow trout. Steelhead trout are found in the tributaries of Lake Erie and in Lake Erie; Steelhead are a subspecies of rainbow trout.

The Department proposes adopting criteria for coldwater embryonic and larval stages for the appropriate season, depending on whether the species historically spawns in the fall or in the spring. These time periods are based on discussions with Pennsylvania Fish and Boat Commission and can be found in §93.7 (b). The criteria will apply to water column concentrations and therefore will need to achieve intergravel concentrations that will be protective of embryonic and larval stages up to 30 days after hatch. The Department proposes 9.0 mg/l on a 7-day average and 8.0 mg/l as a minimum as the criteria protective of early life stages developing in redds. For the remainder of the year, or year-round in surface waters where natural Salmonid reproduction does not occur: a 7-day average of 6.0 mg/l and minimum of 5.0 mg/l were calculated from the slight production impairment and the moderate impairment value, respectively.

§93.7(b) is added to describe the times of the year the criteria for early life stages apply. Protected early life stages include those embryonic and larval life stages resulting from natural reproduction and is not intended to protect stocked trout fingerlings. The spring spawning Salmonids include Steelhead trout in the Lake Erie basin and the few populations of naturally reproducing rainbow trout [other than Steelhead] around the state. The fall spawning salmonids include brown trout and brook trout.

§93.7(b) also includes language that allows discretion to be applied where it can be demonstrated that natural reproduction of salmonids does not occur and is documented that reproduction has not occurred historically. The criteria for determining whether or not natural salmonid reproduction occurs are based on criteria used by Pennsylvania Fish and Boat Commission to document trout reproduction.

WWF Criteria
The Department proposes to adopt the criteria for warmwater early life stages as the criteria for warm water fishes (WWF). Proposed criteria for WWF are 5.5 mg/l as a 7-day average and 5.0 mg/l as a minimum. Based on discussions with Pennsylvania Fish and Boat Commission, these values are appropriate since PA warm water fisheries are so diverse and include fish species that spawn from early spring to late summer. For example, smallmouth bass typically spawn in the months of May and June in Pennsylvania and therefore early life stages are present during the summer. Late summer spawners (ex: green sunfish and bluegill) lead to the presence of early life stages during the fall and winter. Furthermore, the seasonal change in water temperature is what prompts many warm water species to spawn, and the exact calendar date which these water temperature changes will occur cannot be predicted from year to year. As a result of such variation, it is difficult to discern the specific times of year that require protection of early life stages; therefore, it is appropriate to offer protection of early life stages year-round. An extensive literature search also indicates that the proposed criteria are protective for growth of warm water species in the warm summer months, migration of diadromous fish species and survival of macroinvertebrates.

Laboratory studies on early life stages of warm water fishes show that larval life stages are more sensitive to DO than are embryonic and adult life stages. Many studies show that Centrarchid (bass family) juveniles may be the most sensitive of all warm water fishes to low DO concentrations. In Whitmore's (1960) laboratory experiment, largemouth bass juveniles avoided DO levels equal to or less than 4.5mg/L, and no avoidance occurred at 6 mg/L DO. In experiments by Spoor, larval smallmouth bass were shown to be highly sensitive to low DO from day two through day ten after hatching and hatched at a larger size, but grew slower than largemouth bass (Spoor 1977;1984). At or below dissolved oxygen concentrations of 4.5 mg/L, smallmouth bass hatching and larvae survival was observed to be significantly reduced (Siefert et al., 1974; Spoor, 1984). Lethal and sublethal effects of reduced D.O. (less than 5 mg/L) witnessed in laboratory experiments were, in general, directly related to exposure times which ranged from hours to days (Mount, 1964; Doudoroff & Shumway, 1970; Siefert et al., 1974; Spoor, 1984).

In addition, Spoor (1984) notes that that raising the temperature from 20°C (68°F) to 25°C (77°F) increased the smallmouth bass larvae's sensitivity to oxygen deficiency. It is also important to note that smallmouth bass typically spawn in May and June in Pennsylvania and therefore early life stages are present in the summer. Ambient stream temperatures may reach in excess of 30°C (86°F) in the summer. Chapter 93 Temperature Criteria for June is 84°F and 87°F in July and August.

"Doudoroff and Shumway (1970) were tasked with developing recommendations for DO criteria for freshwater fishes and suggested using various curves to calculate seasonal DO criteria corresponding to the natural DO of a water body and various protection levels. Other indices have been developed that relate fishery performance/suitability to DO concentrations given a particular species. The Habitat Suitability index developed by the USFWS for Smallmouth bass provides a wealth of species information including a model for DO (Edwards et al., 1983). In this model, 5 mg/L DO is associated with a Suitability Index value of approximately 70%. Similarly in Doudoroff and Shumway (1970), the multi-species, multi-life stage averaged trend line in Figure 2 (Relative Performance Index vs. DO, p. 270) generally agrees with Edwards et al. (1983), scoring slightly higher at approximately 83% Relative Performance Index (at 5 mg/L DO). At 5 mg/L, both indices indicate a reduction in environmental conditions potentially resulting in suboptimal population condition (growth rates, swimming speeds, weight at hatching, survival, etc.)" (Fischer 2009).

Several field studies concerning dissolved oxygen have been conducted; these studies support a minimum of 5 mg/l for protection of warm water fish species. After performing an extensive field study of dissolved oxygen conditions, Ellis (1937) stated that 5 mg/l dissolved oxygen is the "lowest value which may be reasonably be expected to maintain in good condition varied fish faunae of warm-water fishes" when the temperature is above 20°C (68°F) and that 5 mg/l is "approximately the lower limit of favorable conditions". Coble (1982) related fish populations from the Wisconsin River to dissolved oxygen concentration and concluded that percent sport fish, percent walleyes and yellow perch, percent Centrarchidae (bass family), number of fish species, and number of species of sport fish were all greater at sites where the average summer DO concentration exceeded 5 mg/L. Coble (1982) stated that the level of 5 mg/L could be identified as a threshold from poor to good fish populations and strongly supported a DO criterion of no less than 5 mg/L.

Since the anadromous American shad use the Susquehanna and Delaware River basins to complete their life stages, and blueback herring and alewife (collectively river herring) utilize the Delaware River basin, criteria in these WWF river basins must also protect for these migratory Clupeid species. Stier and Crance (1985) determined that dissolved oxygen concentrations less than 5 mg/l would create a migratory block for American shad adults and juveniles. DO concentrations of 5 mg/l are required throughout the American Shad's spawning area. A study referenced by Stier and Crance found no shad eggs in water where DO concentrations were less than 5 mg/l. Maes et al (2007) modeled migration of migratory fish species in Europe (including a species of shad) and concluded that a "baseline concentration of 5 mg/l considerably increases the opportunity for diadromous fish species to pass."

Pennsylvania Fish and Boat Commission summarized that "Given the data and observations in the available literature, largemouth and smallmouth bass are sensitive enough to depressed D.O. concentrations that avoidance may initiate at 4.5 mg/L. Sublethal and lethal effects, in general, are inversely correlated with D.O. concentration. Environmental degradation may significantly complicate threshold values of D.O. for fishes. "Activity and the presence of toxic materials probably would raise the critical concentration substantially." (Mount, 1964). Data presented by researchers and conclusions published by literature reviewers all bottle neck toward a common threshold value of approximately 5 mg/L for freshwater fishes. A prudent and responsible approach to choosing a criterion would not be to accept the highest D.O. concentration where harmful effects are witnessed, but to choose a criterion that prevents D.O. levels from reaching those harmful effects (Fischer 2009)." "Additional stressors such as various pollutions and increased water temperatures during low flow periods would increase this D.O. threshold; therefore, 5 mg/L should be viewed as a value providing a minimal margin of protection to a multi-species warm water fishery throughout all life stages. Such an assertion is supported by the relation of a single criterion of 5 mg/L to the models provided by Doudoroff and Shumway

(1970) [and Edwards et al. (1983) specifically for Smallmouth bass] and the conclusions drawn by Coble (1982)". (Fischer 2009).

TSF Criteria

The Department proposes to adopt the Salmonid other life stages slight production impairment value (6.0 mg/l) as a 7-day average and the Salmonid other life stages moderate production impairment value (5.0 mg/l) as a minimum for during the period of February 15 through July 31 to protect for stocked trout; and nonsalmonid early life stages slight production impairment value (5.5 mg/l) as a 7-day average and the nonsalmonid early life stages moderate production impairment value (5.0 mg/l) as a minimum as the criteria for the remainder of the year for Trout Stocking use (TSF). Proposed criteria for TSF are "For the period February 15 to July 31 of any year, 7-day average 6.0 mg/l; minimum 5.0 mg/l. For the remainder of the year, 7-day average 5.5 mg/l; minimum 5.0 mg/l."

HQ designated streams

Revisions to D.O. criteria do not include specific minima for high quality streams. As stated in chapter 93, "the water quality of High Quality Waters shall be maintained and protected, except as provided in §93.4c.(b)(1)(iii)." Since existing quality must be maintained, a D.O. criterion for these streams is unnecessary.

Use of averages and minima

The Department is proposing to adopt all averages as 7-day averages and instantaneous minima to simplify the criteria. EPA's national criteria include 30-day averages and 7-day mean minima. EPA stated that the averaging period for criteria for protection of early life stages should not exceed 7 days to ensure it is adequately protective.

Although it would be ideal to have minima, means, duration and frequency components in the proposed DO criteria, the information is not available to determine the protective duration and frequency. Also, it cannot be assumed a minimum criterion will only occur occasionally and for short periods of time just because it is paired with a protective mean value criterion. Since DO conditions may fluctuate widely diurnally, especially when there is a large amount of algal activity, a mean value could be misleadingly high and obtained even when a minimum is reached every day/night for many hours and oxygen is supersaturated during the other part of the day. Therefore, it is important to have both average and minimum but it is necessary for the minimum to be protective even if it occurs every day, and not use an extreme low value that only protects for acute survival.

Proposed Dissolved Oxygen Criteria

Dissolved Oxygen	The following specific dissolved oxygen criteria recognize the natural process of stratification in lakes, ponds and impoundments. These criteria apply to flowing freshwater and to the epilimnion of a naturally stratified lake, pond or impoundment. The hypolimnion in a naturally stratified lake, pond or impoundment is protected by the narrative water quality criteria in § 93.6 (relating to general water quality criteria). For nonstratified lakes, ponds or impoundments, the dissolved oxygen criteria apply throughout the lake, pond or impoundment to protect the critical uses.

Symbol	*Criteria*	*Critical Use**
DO_1	For flowing waters, 7-day average 6.0 mg/l; mg/l; minimum 5.0 mg/l. For salmonid early life stages, applied in accordance with (b), 7-day average 9.0 mg/l; minimum 8.0 mg/l. For lakes, ponds and impoundments, minimum 5.0 mg/l.	CWF
DO_2	7-day average 5.5 mg/l; minimum 5.0 mg/l.	WWF
DO_3	For the period February 15 to July 31 of any year, 7-day average 6.0 mg/l; minimum 5.0 mg/l. For the remainder of the year, 7-day average 5.5 mg/l; minimum 5.0 mg/l.	TSF

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(b) For naturally reproducing salmonids, protected early life stages include: all embryonic and larval stages and all juvenile forms to 30 days after hatching. The DO_1 standard for naturally reproducing Salmonid early life stages shall apply during October 1 through May 31.

The DO_1 standard for naturally reproducing Salmonid early life stages applies unless it can be demonstrated to the Department's satisfaction, that the following conditions are documented: 1) the absence of young of the year salmonids measuring less than 150 mm in the surface water; and 2) the absence of multiple age classes of salmonids in the surface water. These conditions shall only apply to salmonids resulting from natural reproduction occurring in the surface waters. Additional biological information may be considered by the Department which evaluates the presence or absence of early life stages.

REFERENCES USED IN THIS EVALUATION

Coble, D.W. 1982. Fish Populations in Relation to Dissolved Oxygen in the Wisconsin River. Transactions of the American Fisheries Society. 111:612-623

Davis, J.C. 1975. Minimal Dissolved Oxygen Requirements of Aquatic Life with Emphasis on Canadian Species: a Review. Journal of Fisheries Research Board of Canada. 32(12).

Doudoroff, P. and D.L. Shumway. Dissolved Oxygen Requirements of Freshwater Fishes. Food and Agriculture Organization of the United Nations Fisheries Technical Paper 86.

Edwards, E.A., G. Gebhart and O.E. Maughan. 1983. Habitat suitability information: Smallmouth bass. U.S. Department of the Interior, Fish and Wildlife Service. FWS/OBS-82/10.36. 47pp.

Ellis, M.M. 1937. Detection and measurement of stream pollution. United States Bureau of Fisheries Bulletin 48: 365-437.

Federal Water Pollution Control Administration. 1968. Report of the National Technical Advisory Committee to the Secretary of the Interior: Water Quality Criteria. Page 33.

Fischer, D.P. 2009. Literature Review of Dissolved Oxygen. Fish and Criteria: Implications for the Susquehanna River. Pennsylvania Fish and Boat Commission, Division of Environmental Services.

Kramer, D.L. 1987. Dissolved oxygen and fish behavior. Environmental Biology of Fishes. 18(2):81-92.

Maes, J., M. Stevens and J. Breine. 2007. Modelling the migration opportunities of diadromous fish species along a gradient of dissolved oxygen concentration in a European tidal watershed. Estuarine, Coastal and Shelf Science. 75(1-2): 151-162.

McMahon, T. E., and J. W. Terrell. 1982. Habitat suitability index models: Channel catfish. U.S. Fish and Wildlife Service. FWS/OBS-82/l0.2. 29 pp.

Moss, D.D. and D.C. Scott. 1961. Dissolved-Oxygen Requirements of Three Species of Fish. Transactions of the American Fisheries Society. 90(4):377-392.

Mount, D.I. 1964. Development of a System for Controlling Dissolved-Oxygen Content of Water.

Pennsylvania Bulletin. Volume 30, No. 47: 6090-6091. November 28, 2000.

Pennsylvania Code. Title 25. Chapter 93. Water Quality Standards.

Peterka, J.J. and J.S. Kent. 1976. Dissolved Oxygen, Temperature, Survival of Young at Fish Spawning Sites. EPA-600/3-76-113.

Siefert, R.E., A.R. Carlson and L.J. Herman. 1974. Effects of Reduced Oxygen Concentrations on the Early Life Stages of Mountain Whitefish, Smallmouth Bass, and White Bass. 1974. The Progressive Fish Culturist. 36(4):186-190.

Spoor, W.A. 1977. Oxygen requirements of larvae of embryo and larvae of the largemouth bass, *Micropterus salmoides* (Lacépède). Journal of Fish Biology. 11:77-86.

Spoor, W.A. 1984. Oxygen requirements of larvae of smallmouth bass, *Micropterus dolomieui* Lacépède. Journal of Fish Biology. 25:587-592.

Stewart, N.E., D.L. Shumway and P. Doudoroff. 1967. Influence of Oxygen Concentration on the Growth of Juvenile Largemouth Bass. Journal of Fisheries Research Board of Canada. 24:475-494.

Stier, D.J. and J.H. Crance. 1985. Habitat Suitability Models and Instream Flow Suitability Curves: American Shad. U.S. Fish and Wildlife Service. Biological Report 82 (10.88). 34 pp.

Stuber, R. J., G. Gebhart, and O. E. Maughan. 1982. Habitat suitability index models: Bluegill. U.S. Fish and Wildlife Service. FWS/OBS-82/10.8. 26 pp.

Stuber, R. J., G. Gebhart, and O. E. Maughan. 1982. Habitat suitability index models: Largemouth bass. U.S. Fish and Wildlife Service. FWS/OBS-82/10.16. 32 pp.

U.S. Environmental Protection Agency 1976. Quality Criteria for Water.[The Red Book]. EPA 440/9-76-023.

U.S. Environmental Protection Agency.1986. Ambient Water Quality Criteria for Dissolved Oxygen. EPA 440/5-86-003.

U.S. Environmental Protection Agency. 1986. Quality Criteria for Water 1986. [The Gold Book]. EPA 440/5-86-001.

Whitmore, C.M., C.E. Warren and P. Doudoroff. 1960. Avoidance Reactions of Salmonid and Centrarchid Fishes to Low Dissolved Oxygen Concentrations. Transactions of the American Fisheries Society. 89(1).

Attachment E:

DRBC. 1993. Commission Resolution 93-14, “A Resolution authorizing the Executive Director to seek funding from the U.S. Environmental Protection Agency (EPA) to evaluate and recalibrate or replace the dissolved oxygen model for the Delaware Estuary. Adopted August 4, 1993.

NO. 93-14

A RESOLUTION authorizing the Executive Director to seek funding from the U.S. Environmental Protection Agency (EPA) to evaluate and recalibrate or replace the dissolved oxygen model for the Delaware Estuary.

WHEREAS, the Commission has completed a Use Attainability Analysis for the Delaware Estuary; and

WHEREAS, the Commission has held hearings to upgrade dissolved oxygen criteria to be consistent with the goals of the Federal Clean Water Act; and

WHEREAS, the Commission initiated the development of regulations for revised wasteload allocations; and

WHEREAS, questions have been raised concerning the predictive capability of the Estuary oxygen model (DYN-DEL) currently being used to develop revised wasteload allocations; and

WHEREAS, the Commission is developing a comprehensive combined sewer overflow (CSO) strategy for the Delaware Estuary (Resolution 91-14 dated August 18, 1991); and

WHEREAS, DYN-DEL model was to be used in developing control strategies for CSOs; and

WHEREAS, a reliable model is necessary for revised wasteload allocations and/or CSO controls; and

WHEREAS, grant funds are available from EPA under Section 104(b)3 of the Federal Clean Water Act; now therefore

BE IT RESOLVED by the Delaware River Basin Commission:

The Executive Director is authorized to seek a grant from EPA and accept and expend funds to evaluate, and based upon the evaluation, if necessary upgrade or replace the dissolved oxygen model for the Delaware Estuary.

Caren E. Glotfelty, Chairman pro tem

Susan M. Weisman, Secretary

ADOPTED: August 4, 1993

Attachment F:

DRBC. 2009. Water Quality Advisory Committee (WQAC) meeting minutes for July 21, 2009 meeting. 3 pgs.

(available at: https://www.nj.gov/drbc/library/documents/WQAC/wqac_july09.pdf)

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Carol R. Collier
Executive Director

Robert Tudor
Deputy Executive Director

MINUTES (FINAL)
WATER QUALITY ADVISORY COMMITTEE
JULY 21, 2009

ATTENDEES:

NY Not in attendance	**DE DNREC** Not in attendance
EPA Denise Hakowski, EPA Region III Izabela Wojtenko, EPA Region II	**PA DEP (via telephone)** Thomas Barron
NJ DEP Debra Hammond, Water Quality Standards & Assmt.	**Academia Representative** John Jackson, Stroud Water Res. Cntr.
Environmental Organization Representatives Tracy Carluccio, Del Riverkeeper (Alternate)	**Regulated Community Representatives** Alfred Pagano, E.I. DuPont Mary Neutz, City of Wilmington (Alternate)
National Park Service Allan Ambler, Biologist	**Local Watershed Organization** Not in attendance
DRBC Jessica Sanchez, Basin Planner John Yagecic, Supervisor, Stds. & Assmt. Kenneth Najjar, Manager, Plan & Information Tech. Thomas Fikslin, Manager, Modeling, Monitoring & Assmt. Erik Silldorff, Aquatic Biologist, Stds. & Assmt. Ed Santoro, Monitoring Coordinator Nicole Blake, DRBC Intern	**Other Attendees:** Jason Cruz, Philadelphia Water Dept. Josef Kardos, Philadelphia Water Dept. Bart Ruiter, E.I. DuPont Jack Gibs, US Geological Survey

The meeting was called to order at 9:40 am by Committee Chair, Alfred Pagano.

<u>Approval of Agenda & Minutes</u>

The 2010 Integrated Assessment portion of the agenda was removed and a separate public meeting will be conducted; the WQAC, TAC, and MAC members will be invited. The agenda was approved by the committee with this change.

Minutes from the June 23, 2009 meeting were approved by the WQAC with the following changes:

- **Attendees**: If member is present, member's name should be listed under corresponding category. If alternate is present, alternate's name should be listed under corresponding category. If both are present, member is to be listed under corresponding category and alternate is to be listed under "Other Attendees". If neither is present, "Not in attendance" is to be listed under corresponding category.

- **Page 1 –** remove reference to travel restrictions.

WQAC Practice and Procedures

The Practice and Procedures document was presented to the WQAC. The following changes were suggested:

- **Membership –** Community of environmental professionals should be changed to environmental community at large.

- **Committee Officers –** A - specify term of one fiscal year as July 1-June 30.
  B - Remove "at the June meeting" and specify as "fiscal" year.
  D – Delete.

- **Voting –** Add statement that quorum is needed for a vote or the official action and a quorum consists of 6 or more members.
  B – Remove references to "alternates". Shall read "motions are passed if a majority of the members present affirm the motion."
  D – shall be "In the event of a tie vote, the matter will be tabled."

The committee suggested that voting issues or possible voting issues be listed on the agenda as "voting matter."

> **Action:** Revise and redistribute Practice and Procedures document to be voted on at September 15, 2009 meeting.

Selection of Chair and Vice-Chair

Motions for John Jackson of the Stroud Water Research Center as Committee Chair and Thomas Barron of Pennsylvania Department of Environmental Protection as committee Vice-Chair were voted on and passed unanimously.

Nutrient Management Measures (Erik Silldorff)

Erik Silldorff reported that the NSC shall finalize the recommendations during their next meeting and present to the WQAC at the September meeting.

At the June 2009 WQAC meeting, however, the need and process for revising Dissolved Oxygen criteria was raised and discussed. This discussion was continued based on a series of slides presenting the DRBC understanding and the options moving forward. DRBC staff suggested there are two sets of actions to be taken, one short-term and the other long-term. The short-term is the issue of existing use. There can be progress within the next year and a half in which Zones 3, 4, & 5 can be upgraded, but not to the highest attainable use, by simply changing the designated use, which is believed to be lower than the existing use and re-classifying the designated use to match the existing use. The long-term issue is the actual discussion of highest attainable use, which will involve the eutrophication model for the system, as well as questions of what can be attained by the various point source and non-point source loadings to the system in terms of all the water quality criteria affecting the designated and existing uses.

The DRBC therefore proposed a four step process to address both short-term and long-term revisions of the uses and Dissolved Oxygen criteria in the estuary:

- Step 1 – Change designated use to match existing uses in zones 3, 4, & 5.
- Step 2 – Develop DO criteria to support new designated use.
- Step 3 – Identify highest attainable use.
- Step 4 - Develop new DO criteria to support highest attainable use.

The role of an expert panel was again highlighted for many steps in the process. DRBC staff emphasized how the Fisheries Coop would be an important source for feedback along with a formal expert panel. A suggestion was made to develop a white paper for step 1 to be reviewed by the expert panel as part of the process.

> **Action:** Based on the discussion by the WQAC, the Nutrient Subcommittee will present for a possible vote, revised recommendations at the September WQAC meeting.

> **Action:** The expert panel process will be discussed at the WQAC September meeting.

Meeting Adjournment

Meeting adjourned at 12:00 pm. The next WQAC meeting will be September 15, 2009 at the DRBC offices in Trenton, NJ.

Attachment G:

Hartman, K.J. 2023. Review of Relevant Literature Pertaining to Atlantic Sturgeon Dissolved Oxygen Criteria for Delaware River. White paper report to Delaware Riverkeeper Network; May 2023; 18 pgs.

Review of Relevant Literature Pertaining to Atlantic Sturgeon Dissolved Oxygen Criteria for Delaware River

May 2023

Kyle J. Hartman, Ph.D.

Professor, West Virginia University

Prepared for:

Delaware Riverkeeper Network

Review of Relevant Literature Pertaining to Atlantic Sturgeon Dissolved Oxygen Criteria for Delaware River

Foreword

Relative to other fish and invertebrate species found in the Delaware River, Atlantic Sturgeon (AS) are more sensitive to low dissolved oxygen (DO), particularly at summer temperatures. As a result, dissolved oxygen (DO) levels that are protective of endangered Atlantic sturgeon will also likely protect other key species such as Shortnose sturgeon (also endangered), striped bass, etc.

Understanding how DO affects critical habitat of Atlantic sturgeon is benefitted by several sentinel studies of the interplay between temperature, DO, and salinity. These studies have examined acute and chronic effects of hypoxia (low or depleted oxygen levels in water) as well as impacts of DO levels upon how organisms acquire and transform energy in order to perform biological work (bioenergetics). Difficulties in completing experimental designs (mortality of young sturgeon at high temperatures and low DO) and modeling artifacts (discussed below) mean these studies must be considered carefully, and with an understanding of the physical (abiotic) conditions in the Delaware River in the area where Atlantic sturgeon are found. Given these caveats, these studies provide good evidence of the levels of DO required to protect Atlantic sturgeon in the Delaware River.

Environmental conditions in the Delaware River

The combinations of high temperatures and low dissolved oxygen most likely to negatively affect aquatic organisms in the Delaware River occur during the June through September period. These conditions, along with salinity and location of the salt line, vary spatially along the river and from year to year due to freshwater discharge. Thus, identifying when and where Atlantic sturgeon are found within the Delaware River is critical to understanding the current and potential future water quality conditions fish may experience and how that compares with science related to critical temperature and DO levels to support them.

Several publications provide insights into where Atlantic sturgeon reside in the Delaware River during late spring and summer when high temperatures and low DO occur. Although adult Atlantic sturgeon are less sensitive to high temperatures and hypoxia than earlier life stages (see below), their distribution during spawning is critical in identifying locations where the most sensitive life stages (eggs, larval, young-of-year) will be found. Atlantic sturgeon spawn in freshwater over hard substrate meaning that variations in the location of the salt front due to annual differences in river discharge will cause the location of spawning and subsequent sturgeon eggs, larvae and young-of-year to vary.

The available information on adult spawning locations in Delaware River is in general agreement (Breece et al. 2013; DRBC 2022; Moberg and DeLucia 2016; NOAA, NMFS 2017; Simpson 2008). Historically the salt front has ranged from zone 5 (~RM 48) to zone 3 ~(RM 102 historical drought location of the salt front), (Moberg and DeLucia 2016). Spawning by Adult Atlantic sturgeon takes place above the salt front in the Delaware and Hudson Rivers (Breece et al. 2013; Van Eenennaam et al. 1996). Thus, zones 2 through 5 span the freshwater tidal areas of the river, where the correct spawning substrate (Breece et al. 2013) overlaps with potential location of the salt front (DRBC 2022; Moberg and DeLucia 2016).

The DRBC report (November 2022 draft) identifies zones 2 through 6 as being occupied by juvenile and adult AS during warm water periods (1 June to 30 September) when hypoxia is known to be present. Collectively, the zones where all life stages of AS are found encompass the salt line and low salinity (< 8 ppt) areas of the river. Water temperatures in these zones in summer commonly reach 26-31 C while DO is frequently less than 5 mg/l. Several important studies were published (detailed below) that examined salinity, as well as temperature and DO effects on survival and growth of sturgeon that can be used as the best available science in understanding DO levels that support propagation of all life stages.

Life Stage Sensitivity

Studies with several sturgeon species have documented that as a group, sturgeon are sensitive to hypoxia (Secor and Gunderson 1998; Burggren and Randall 1978; Ruer et al. 1987; Delage et al. 2020). As all life stages of AS are potentially found throughout zones 2-6 in Delaware River in summer, identification of the most sensitive life stages is warranted in guiding any proposed DO requirements or guidelines. Studies have found that sturgeon early life stages tend to be more sensitive to hypoxia than older juveniles and adults (Campbell and Goodman 2004; Jenkins et al. 1993). Guy et al (2015) related this sensitivity of early life stages as the mechanism for failed reproduction (ie., recruitment failure) by pallid sturgeon in the upper Missouri River. Given the prevalence of hypoxic conditions in tidal fresh waters of the eastern United States, similar mechanisms may be contributing to poor recruitment of Atlantic sturgeon as well. In fact, empirical evidence from the Delaware River also supports a hypoxia-failed reproduction hypothesis (Moberg and DeLucia 2016; Park 2020).

Limited information exists on the early life stage sensitivity of Atlantic sturgeon to temperature and hypoxia. A recent study of early life stages of a closely related sturgeon species, European sturgeon, is likely applicable to early life stages of Atlantic and shortnose sturgeon. Delage et al. (2020) found significant effects of temperature and DO_{SAT} (DO percent saturation) on the survival and viability of eggs and larval sturgeon. Irrespective of DO, embryonic survival was highest at 20C declining at 23C, and 26C with complete mortality at 30C even when DO_{SAT} was as high as 90%. Larval survival in the first 48h post-hatch was >80% at temperatures $\leq$ 23C but dropped to 40% survival at 26C. ***At 26C and 70% DO_{SAT} no larva survived***. They further found that oxygen depletion induced sub-lethal effects (larval deformities and respiration rates) at 70% DO_{SAT} and lethal effects (death of individual fish) at 50% DO_{SAT} and no larva were able to hatch at less than 50% DO_{SAT} regardless of temperature. Delage et al. (2020) conclude that the effects of oxygen depletion on sturgeon embryo development and survival are stronger than those induced by high temperatures (Figure A).

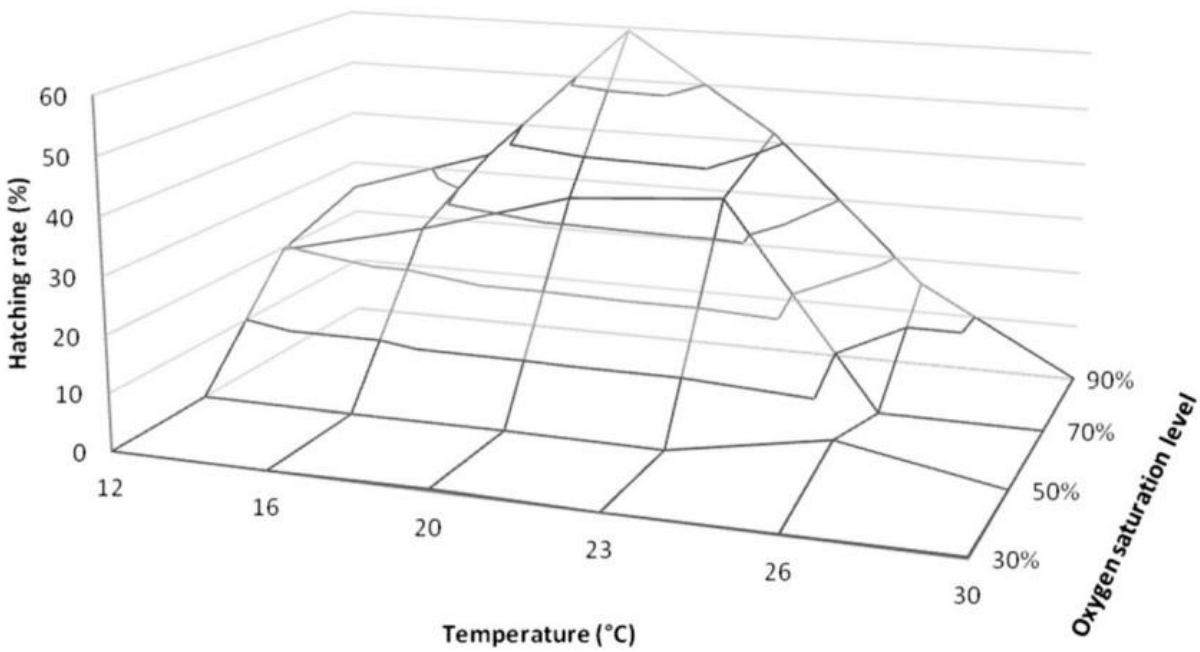

Figure A. Hatching rate (%) of European sturgeon embryos (N = 102). ***No data were collected for 50 and 30% O2 sat at 12, 16 and 23 °C and for 70% O2 sat at 26 and 30 °C due to complete mortality***. {Reproduced from Figure 2 in Delage et al. 2020}.

Review of Primary Literature

Critical review of the primary Atlantic sturgeon and shortnose sturgeon literature was undertaken with the goal of identifying three DO thresholds: (1) Minimum sustainability (acute mortality threshold, i.e. the DO level below which death occurs); (2) Upper DO Threshold (the area where no additional benefit is obtained by increased DO levels); and (3) Protective values (the range of values between the minimum sustainability and upper threshold of DO).

As an endangered species, care must be taken in identifying a minimum DO threshold that does not result in mortality of any life stage. Several studies looked (either directly or indirectly) at acute levels of DO and temperature that resulted in mortality of Atlantic or shortnose sturgeon. For shortnose sturgeon, Campbell and Goodman (2004) reported 24-hour LC50[‡] levels of 2.3 to 3.1 mg/l DO depending on temperatures and fish ages, but importantly, 53-90% of juvenile fish

[‡] The LC50 is the DO level at which half the sturgeon tested will die from experiencing the low DO.

died within 2 hours. Younger ages (77 or 100 day-old) reached LC50 at higher DO concentrations (2.7-3.1 mg/L) than 104 or 134 day-old fish (2.2 mg/L) suggesting greater sensitivity to hypoxia among younger individuals. The highest temperature tested (28.4-29.2 C) also had the highest 24-hour LC50 value of 3.1 mg/L. Jenkins et al. (1993) tested survival of 11-330 day-old shortnose sturgeon at 22.5 C at a range of DO levels. At that temperature they reported no mortality within 6h at 4.0-5.0 mg/L DO. However, significant mortality did occur at D.O. $\leq$ 3.5 mg/L. Suggesting a higher DO - mortality threshold even at 22.5 C than observed in Campbell and Goodman (2004) at > 28.4 C.

A study by Secor and Gunderson (1998) examined respiration and growth of juvenile Atlantic sturgeon at 1.5-3.0 ppt salinity, two temperature and two DO treatment levels. The growth study was complicated by repeating experiments with and without surface access to reduce possible confounding effects (DO stratification near the surface or gulping air to offset low DO). In respiration experiments for juvenile Atlantic sturgeon Secor and Gunderson (1998) found all fish died at low DO and high temperature in less than 24 hrs. Thus, in the 26C treatment (which was actually 25.2-25.3 C) and 3.6-4.5 mg/L DO, no fish survived the 42 h respiration experiments. Given the water quality error estimates reported in Table 1 in Secor and Gunderson (1998) fish in the sealed tanks at high temperatures (25.2-25.3 C) may have experienced DO between 3.4 and 4.9 mg/L. This suggests the acute mortality threshold should be greater than 4.9 mg/L DO at 25C.

Perhaps the most important laboratory study concerning mortality of young Atlantic sturgeon was conducted by Niklitscek and Secor (2009a). As expected, the researchers found no appreciable mortality of YOY Atlantic sturgeon at 12-28 C and 100% DO_{SAT} conditions (Figure B). However, at 70% DO_{SAT} instantaneous daily mortality rate increased over four-fold from 20C to 28 C and was comparable to mortality observed at 20 C and 30% DO_{SAT}. These results clearly show that at summer temperatures commonly found or exceeded in the Delaware River that DO_{SAT} levels of 70% are not safe, as significant mortality of YOY Atlantic sturgeon is likely occurring. This strongly argues for minimum DO level requirements to be higher than 70% DO_{SAT} for Delaware River. Due to the diminished capacity of water to hold oxygen at warmer temperature a DO concentration limit rather than a DO_{SAT} level provides a margin of safety. For example, at 30 C and only 80% DO_{SAT} the resulting DO level would be about 6.0 mg/l.

A report by Moberg and DeLucia (2016) examined dissolved oxygen conditions during spawning through age-1 for Delaware River Atlantic sturgeon comparing several years with recruitment (2009, 2011 and 2014) versus years when no recruitment was observed (2005-2008, 2010, 2012 and 2013). The authors report that in years with observed recruitment, the minimum daily DO was > 5.0 mg/l in 90% of the observations and that in years without documented reproduction that median minimum daily DO was between 4.0 and 5.0 mg/L. The authors recommend that an ***instantaneous DO*** $\geq$ 5.0 mg/l (i.e. DO always at or above 5.0 mg/L) supports successful recruitment. **This is a critical distinction between an instantaneous criteria vs median minimum or other summary values**.

Although Moberg and DeLucia (2016) focused on 5.0 mg/L as correlated with detection of AS recruitment, the empirical data showed that in years when recruitment of Atlantic sturgeon was *observed*, June, July, and September ***minimum median daily DO*** levels at RM 100 were > 6.0 mg/L. Criteria should be based on successful reproduction and not merely reproduction.

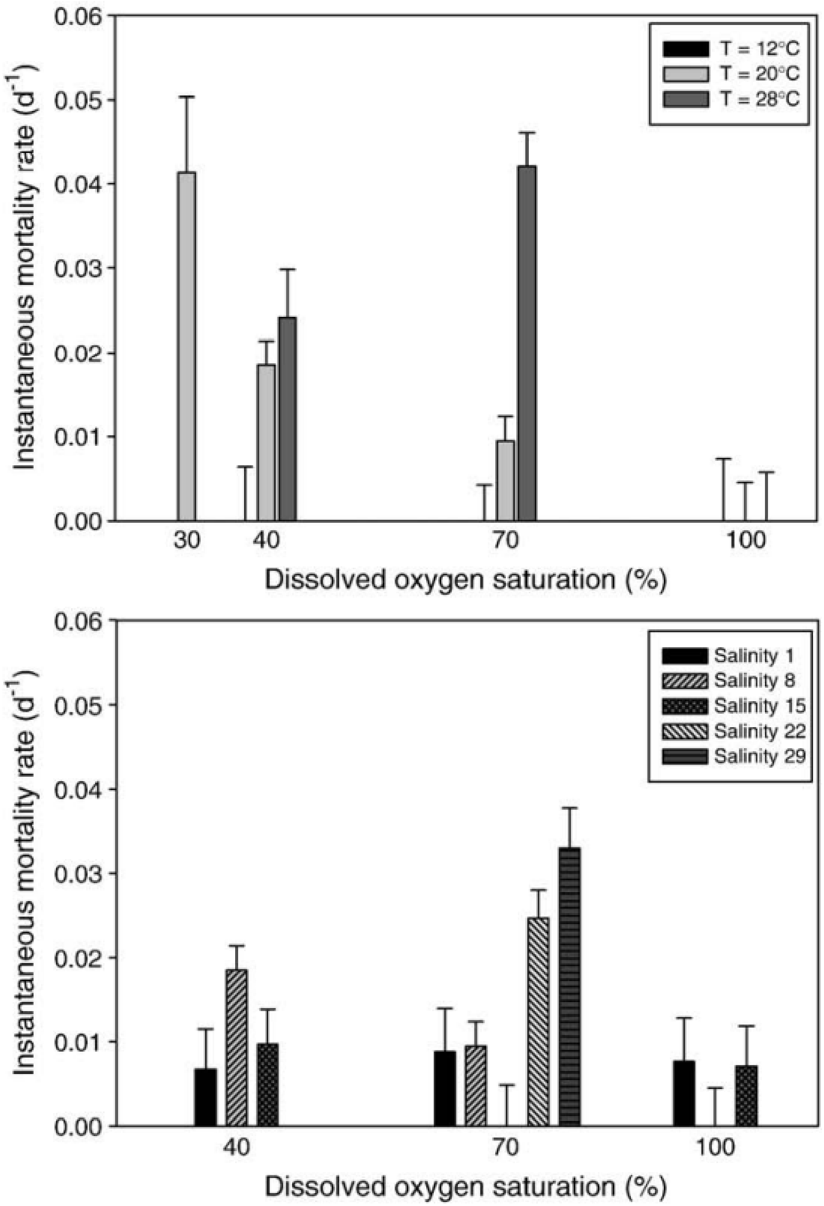

Figure B. Reproduced from Figure 7 in Niklitschek & Secor (2009a). Instantaneous mortality rate (d^{-1}) for YOY Atlantic sturgeon, previously acclimated to an incomplete factorial combination of dissolved oxygen saturation, temperature and salinity conditions. Upper panel shows dissolved oxygen and temperature effects at a fixed salinity of 8. Lower panel shows dissolved oxygen saturation and salinity effects at 20^{o}C.

The presence of age-0 sturgeon in a year is not necessarily evidence of *good* recruitment and conditions providing the capacity for good recruitment should be our metric of success and threshold. Median minimum daily DO levels when recruitment was not detected were < 5.0 mg/L therefore a higher threshold than that is required.

As the early life stages appear to be most sensitive to hypoxia, threshold criteria based on those ages would be protective of other life stages***. Based on the experimental studies and empirical data observed in Delaware River, a safe minimum DO level during summer to support Atlantic Sturgeon would be 6.0 mg/L.***

DO threshold of "no additional benefit"

The upper DO threshold at which no additional benefit to AS is accrued can be approximated by considering the primary literature and examining under what conditions bioenergetic measures suggest some level of impairment. The most compelling information for sub-lethal effects of water conditions and Atlantic sturgeon comes from the Niklitschek and Secor (2009a) study. The researchers measured growth, food consumption, routine and postprandial metabolism, egestion and survival of age-0 and age-1 Atlantic sturgeon as functions of DO, temperature and salinity. The study design called for 4 temperature treatments (6, 12, 20, 28 C), 4 DO_{SAT} treatments (30, 40, 70, and 100%) and 5 salinity treatments (1, 8, 15, 22, and 28 ppt). However, the authors noted they were killing too many fish attempting to run the experiments at 28C and 70% DO_{SAT} so they lowered the replication. As a result, the only nearly complete design was attained at 8 ppt. Replicates at 28C were restricted to 70% DO_{SAT} and the 1, 8 and 15 ppt salinity (See their Table 1 reproduced below).

Table 1
Summary of the incomplete experimental designs used to evaluate bioenergetics and survival effects of dissolved oxygen saturation, temperature and salinity upon juvenile Atlantic sturgeon.

Temperature	Dissolved oxygen saturation	Salinity				
		1	8	15	22	29
6	70		3			
12	40		3			
	70	3	6	3(3)		
	100		3			
20	30		3			
	40	3	5	4(3)		
	70	3(3)	6	3(3)	4(3)	2(3)
	100	2	5	2(3)		
28	40		2			
	70	4	5	4(3)		
	100		3			

Number of replicates corresponding to each growth-consumption experiments indicated for YOY and yearlings (in parenthesis).

Based upon where young Atlantic sturgeon are expected to reside, the experimental results at 1-8 ppt are most relevant to the Delaware River. The incomplete design resulted in the full suite of DO_{SAT} treatments only occurring at 8 ppt. This necessitates a comparison of energetic performance at 1 vs 8 ppt to assess hypoxia at 28C. Figure 2 of Niklitschek and Secor (2009a) is reproduced as Figure C below. The authors depict the instantaneous growth rate (IGR) for age-0 and age-1 sturgeon across salinity treatments. The IGR of age-0 fish was higher at 8 and 15 ppt than at 1 ppt suggesting increasing performance with salinity to 15 ppt and declining at higher salinities. For age-0 fish, food consumption rate (FCR) also increased with salinity then declined above 15 ppt. The IGR and consumption patterns for age-1 sturgeon showed little variation with salinity.

Due to the incomplete experimental design, the Niklitschek and Secor (2009a) figure is misleading when looking at DO_{SAT} effects. It appears to show IGR and FCR to level or decline between 70% and 100% DO_{SAT}. However, this is an artifact of incomplete replication at 1 ppt and the lack of measures at 40% and 100% DO_{SAT} (see Table 1). Examination of Figure 3 in Niklitschek and Secor (2009a) (reproduced as Figure D below) shows IGR and FCR increase with salinity for age-0 fish from 1 to 8 ppt (and to 15 ppt for FCR). As a result, the top panels in Figure C appear to show no additional benefit to age-0 or age-1 sturgeon as DO_{SAT} increases from 70% to 100%, when additional benefits are obtained at DO_{SAT} > 70% (Figure D).

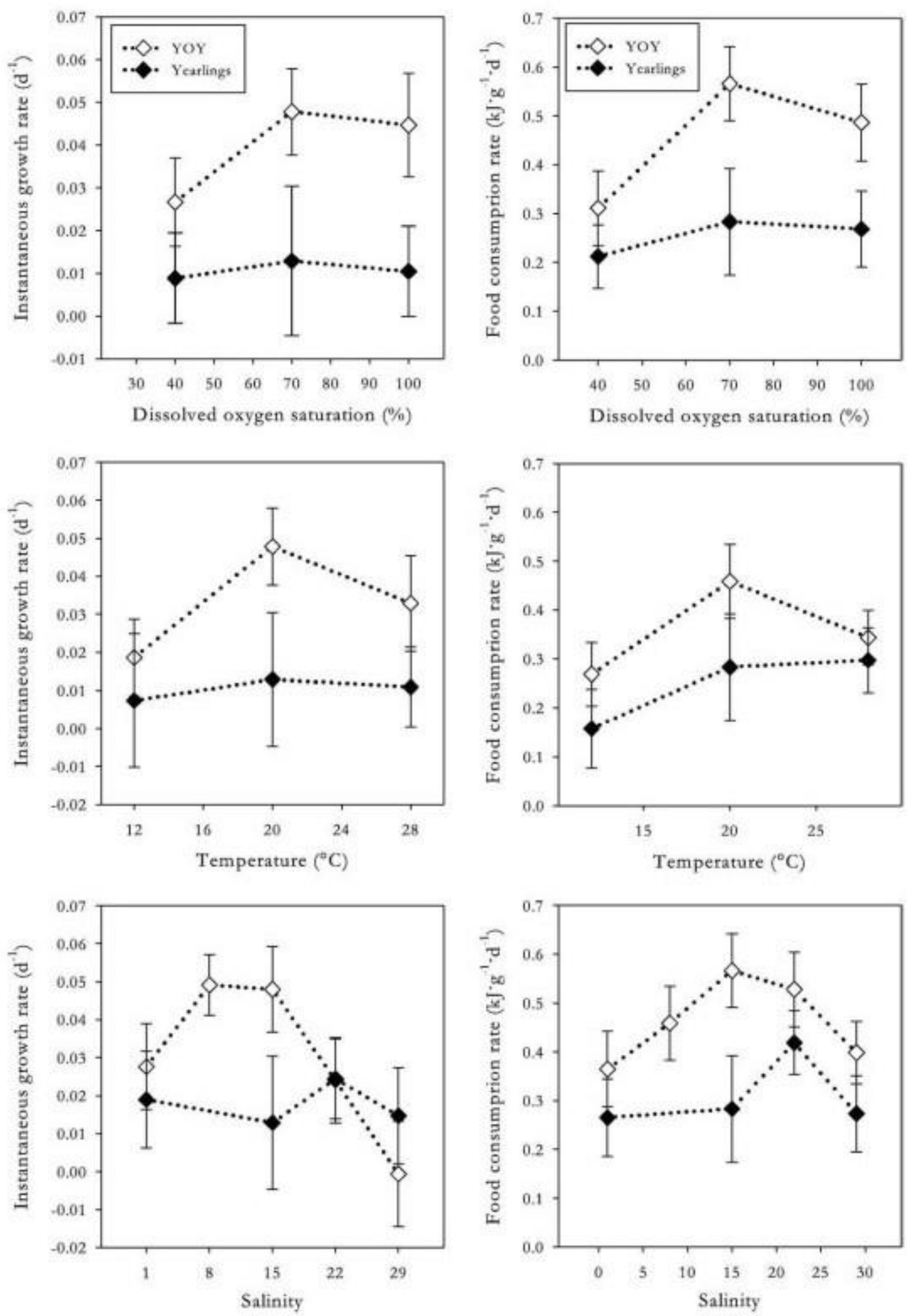

Figure C. *Copied from Figure 2 in Niklitschek and Secor (2009a).* Comparative effects of temperature and salinity upon instantaneous growth rate (left panel) and food consumption (right panel) rates in YOY (6-64 g, open diamonds) and yearlings (100-300 g, filled diamonds) Atlantic sturgeon. Figures show variability caused by dissolved oxygen, temperature, and salinity (top, middle and lower panel, respectively), while keeping the remaining two factors at fixed conditions (≥70% DO_{SAT}, 20 C, and/or salinity =8). Means are connected by lines to facilitate interpretation.

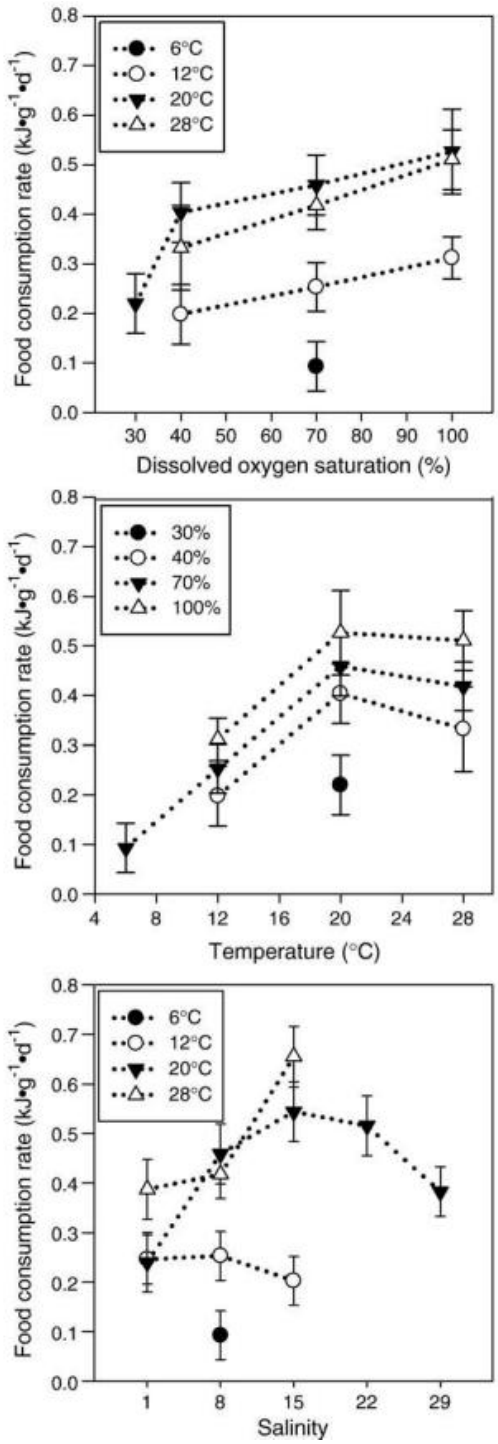

Figure D. Effects of dissolved oxygen saturation, temperature, and salinity on food consumption rates of YOY Atlantics sturgeon (means ± SE). Figures show variability caused by two factors at a time, while keeping the third at fixed conditions (salinity = 8 for the top and middle panels, $DO_{SAT} \geq 70\%$ for the bottom panel). Means are connected by lines to facilitate interpretation. *Reproduced from Fig.3 in Niklitschek and Secor (2009a).*

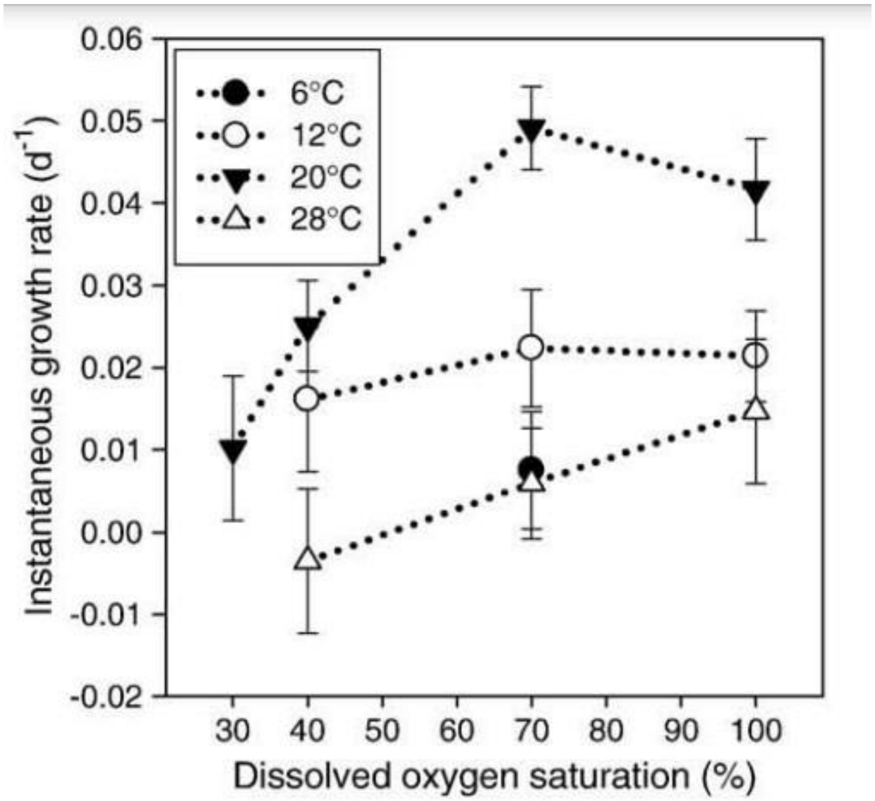

Figure E. Taken from Fig. 1 in Niklotschek and Secor (2009a). Effects of DO_{SAT} and temperature (salinity held constant) on instantaneous growth rates (IGR) of juvenile Atlantic sturgeon.

Fish ecologists often consider growth as the ultimate expression of well-being (Brandt et al. 1992). One of the most critical findings of relevance to identifying upper levels of benefit for increasing DO_{SAT} comes from Figure 1 in Niklitschek and Secor (2009a), labeled Figure E for this write up. Here, the measured IGR at each temperature relative to DO_{SAT} (with salinity held constant) shows that at 28C (a temperature commonly met or exceeded in summer in the Delaware River) that IGR increases with DO_{SAT}. IGR shows incremental increases even between 70% and 100% DO_{SAT} at 28C. The IGR overlaps zero at 28C and 70% DO_{SAT}. This suggests the upper threshold of "no additional benefit" for DO occurs above 70% DO_{SAT} at 28C. ***Assuming a conservative threshold of 85% DO_{SAT} (midpoint between 70% and 100% DO_{SAT}) at 28 C would yield 6.65 mg/L as the level of no significant additional benefit.***

It should be noted that even these IGR measures likely overestimate how wild sturgeon would perform at summer temperatures. Fish in this study were fed to satiation (*maximum consumption*) on an artificial diet (Biokyowa ® pellets*).* Wild fish typically feed at only 40-60% of *maximum consumption* measures in the laboratory (Hartman and Kitchell 2008). Further, the energy content of commercial diets is much more energy rich (@ 5x higher) than natural diets of consumed by fish. The Biokyowa ® pellets have a reported energy density of 21.9 kJ/g compared with potential natural prey such as benthic crustaceans (3.1-3.7 kJ/g; Ciancia et al. 2013) or small fish (3.3-4.3 kJ/g; Hartman and Brandt 1995). In Figure E the IGR at 28C and 70% DO_{SAT} overlaps zero even using the Biokyowa ® pellets. Thus, if fish were fed natural prey the growth performance observed in Niklitschek and Secor (2009a) would be much worse and fish would likely experience negative growth at 28C and 70% DO_{SAT}.

A second paper by Niklitschek and Secor (2009b) utilized laboratory measures of energetics to develop bioenergetics models and response surfaces to explore interactive effects of temperature, DO_{SAT} and salinity upon routine metabolism, food consumption, egestion (energy lost in feces), and growth rates. This paper appears to depict no additional benefits to IGR at DO_{SAT} levels above 70% (see their Fig 8. Reproduced as Figure F here). This is in fact an artifact of the model. It should not be used to argue that no additional benefit is accrued at increases in DO_{SAT} above 70% at 28C. In the original paper (Niklitschek and Secor 2009a) shown in their Figure 1 (Figure E above) that IGR increases linearly from 40 to 70 to 100% DO_{SAT} at 28C. In fact, the authors state in the paper, "….***at 28 °C growth rates increased continuously along the DO$_{SAT}$ gradient****, at 12 and 20 °C growth remained relatively constant above 70% DO$_{SAT}$ …..*" Thus, the suggestion of 70% DO_{SAT} at 28 C as the level of no significant additional benefit is not supported by the data and the true level of no significant benefit is between 70% and 100% DO_{SAT}.

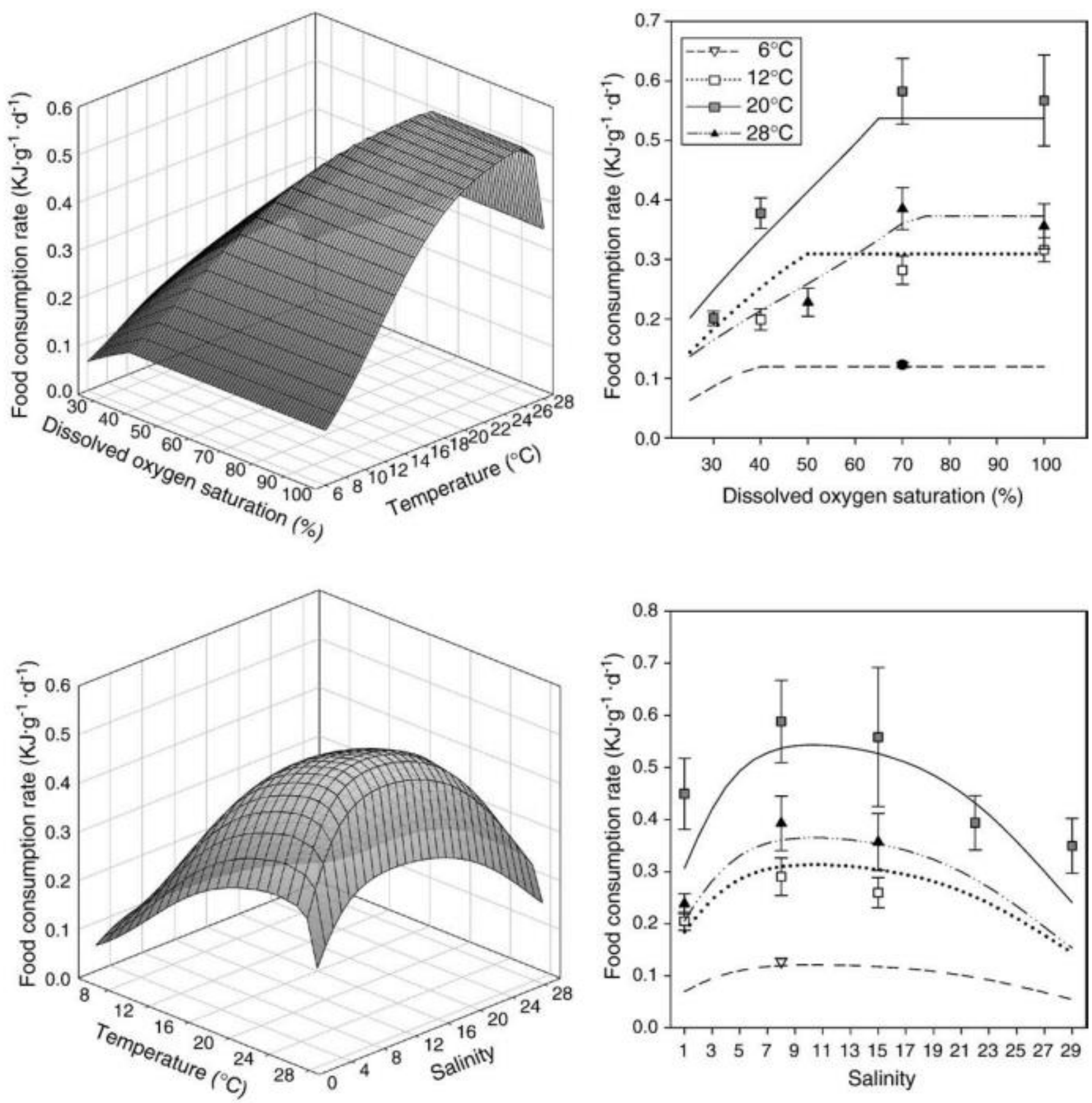

Figure F. *Reproduction of figure 8 from Niklitschek and Secor (2009b).* Predicted (left panels) and means observed + (right panels) effects of temperature, dissolved oxygen saturation and salinity on instantaneous growth rate in juvenile Atlantic sturgeon. Figures show variability caused by two factors at a time, holding the third fixed at conditions (salinity 9 for top panels, 100% DO_{SAT} for bottom panels). Predicted values are weight normalized to represent a 20g fish. ***Smoothing by their model creates the illusion that IGR levels off above 70% DO_{SAT} at 28C.***

Other Considerations

Indirect effects of hypoxia on AS should be considered. Atlantic sturgeon are benthic feeders. Therefore, reductions in DO that may not be lethal to sturgeon may greatly reduce feeding conditions by impairing production of benthic invertebrates and fish that they feed upon. For example, juvenile blue crabs are very intolerant of hypoxia with a 96h LC_{50} of 5.6 mg/L DO reported at 30C and 10 ppt. (Stickle et al. 1989). Community-based studies of benthic communities in the Chesapeake Bay reported lower species diversity, lower biomass, and lower proportions of deep-dwelling (> 5 cm) biomass at sampling stations with low DO (Dauer et al. 1992).

Sub-acute impacts of hypoxia should be considered with respect to recruitment failure in Atlantic sturgeon. Several researchers have suggested hypoxia may be responsible for poor recruitment in sturgeon species (Cech et al. 1984; Secor and Niklitcshek et al. 2002; Guy et al. 2015) and even found correlation between failed and observed recruitment related to hypoxia levels (Moberg and DeLucia 2016; Park 2020). Lower benthic species diversity or biomass related to low DO levels may hinder successful first feeding in Atlantic sturgeon larvae at settlement or thereafter, and result in lowered survival or even recruitment failure even when DO remains sufficient to support life.

It is also important to note that young sturgeon may be exposed to multiple interacting stressors in these waters including impairment due to PCBs under section 303(d) of the Clean Water Act (DRBC 2003). Wirgin and Chambers (2018) examined interactive effects of short-term hypoxia and toxicants on Atlantic sturgeon larvae finding significant effects of hypoxia, several contaminants and their interaction upon consumption by AS. They also reported larvae from two sources differed dramatically in their survival related to contaminants calling to question the role genetics may play in response to stressors.

Conclusions

Collectively the available empirical and experimental evidence suggests summer dissolved oxygen levels of 6.0 mg/L are needed to protect reproduction and survival of young Atlantic sturgeon in the Delaware River. At 26 C and 70% DO_{SAT} (~ 5.8 mg/L) complete mortality was observed in the closely related European sturgeon. At ***minimum median daily DO*** levels below 6.0 mg/L, Delaware River Atlantic sturgeon had unsuccessful reproduction. Young Atlantic sturgeon feeding and growth rates increased as DO_{SAT} increased from 40 to 70 to 100% documenting continued benefit to the species at DO_{SAT} levels above ~ 5.8 mg/L.

Finally, the NOAA/NMFS (2017) documentation for Atlantic sturgeon DPS cites 6.0 mg/L DO as protective which is consistent with my review of the literature and empirical data. I suggested 6.0 mg/L as the minimum sustainability threshold. I also proposed a conservative threshold of 85% DO_{SAT} at 28 C. This would yield 6.65 mg/L as the level of no significant additional benefit.

Taken together this yields a narrow range of 6.0 -6.65 mg/L DO as the level protective of Atlantic sturgeon in Delaware River.

At summer temperatures ($\geq$ 25 C) the available literature all points to a DO threshold higher than 5.0 mg/L for protection of all Atlantic sturgeon life stages. Studies with European sturgeon embryos and larva suggest even short durations (< 48 hrs) at 70% DO_{SAT} and 26C (approximately 5.8 mg/L) results in total mortality (Delage et al. 2020). Empirical evidence from the Delaware River suggests that when summer minimum median DO fall below 6.0 mg/L Atlantic sturgeon do not successfully reproduce. In respiration experiments, Secor and Gunderson (1998) found all young Atlantic sturgeon died at 25.3 C and 3.6-4.9 mg/L within 42 h suggesting the acute mortality threshold for young fish should be greater than 4.9 mg/L at 25C and be even higher at warmer temperatures. Niklitschek and Secor (2009a) attempted to complete experiments on age-0 and age-1 AS at for 4 temperature treatments (6, 12, 20, and 28 C), 4 DO_{SAT} treatments (30, 40, 70, and 100%) and 5 salinity treatments (1, 8, 15, 22, and 28ppt). However, the authors noted they were killing too many fish attempting to run the experiments at 28C and 70% DO_{SAT} so they lowered the replication. For age-0 sturgeon FCR increases from 40 to 70 to 100% DO_{SAT} at 12, 20, and 28 C providing evidence of continued benefits to sturgeon as DO_{SAT} increases under summer water temperatures.

Summer DO levels in the Delaware River are influenced by water temperature, biological oxygen demand (BOD), and discharge. Conditions worsen under low discharge as temperatures rise and a greater volume of the river is comprised of sanitation waters-- increasing BOD. Little can be done to control precipitation and discharge leaving only nutrient/nitrification as a means of managing DO levels to support aquatic life in the river. A DO criteria of 5.0 mg/L would be below that required to support all life stages of Atlantic sturgeon. Further it would carry with it no margin of safety for years when higher than usual temperatures and low discharge cause DO levels to drop below criteria standards as is predicted under climate change.

Literature Cited

Brandt, S.B., D.M. Mason, and E.V. Patrick. 1992. Spatially-explicit models of fish growth rate. Fisheries 17(2):23-35.

Breece M.W., M.J. Oliver, M.A. Cimino, and D.A. Fox. 2013. Shifting Distributions of Adult Atlantic Sturgeon Amidst Post-Industrialization and Future Impacts in the Delaware River: a Maximum Entropy Approach. PLoS ONE 8(11): e81321. doi:10.1371/journal.pone.0081321

Burggren, W.W. and D.J. Randall. 1978. Oxygen uptake and transport during hypoxic exposure in the sturgeon Acipenser transmontanus. Respiration Physiology 34(2):171-183.

Campbell, J.G, and L.R. Goodman. 2004. Acute sensitivity of juvenile shortnose sturgeon to low dissolved oxygen concentrations. Transactions of the American Fisheries Society 133:772-776.

Cech, J.J., S.J. Mitchell, and T.E. Wragg. 1984. Comparative growth of juvenile white sturgeon and striped bass: Effects of temperature and hypoxia. Estuaries 7(10):12-18.

Ciancio, J., N. Suarez, and P. Yorio. 2013. Energy density empirical predictor models for three coastal crab species in the southwestern Atlantic Ocean. Crustacean Biology 33(5):667-671.

Dauer, D.M. and J. A, Ranasinghe. 1992. Effects of low dissolved oxygen events on the macrobenthos of the lower Chesapeake Bay. Estuaries 15(3);384-391.

Delage, N., J. Cachot, E. Rochard, R. Fraty, and P. Jatteau. 2014. Hypoxia tolerance of European sturgeon (Acipenser sturia L., 1758) young stages at two temperatures. Journal of Applied Ichthyology 30:1195-1202.

Delage, N., B. Couturier, P. Jatteau, T. Larcher, M. Ledevin, H. Goubin, J. Cachot, and E. Rochard. 2020. Oxythermal window drastically constrains the survival and development of European sturgeon early life phases. Environmental Science and Pollution Research 27:3651-3660.

DRBC (Delaware River Basin Commission). 2022. Linking Aquatic Life Uses with Dissolved Oxygen Conditions in the Delaware River Estuary. November 2022 Draft.

DRBC (Delaware River Basin Commission). 2003. TOTAL MAXIMUM DAILY LOADS FOR POLYCHLORINATED BIPHENYLS (PCBs) FOR ZONES 2 - 5 OF THE TIDAL DELAWARE RIVER. https://www.nj.gov/drbc/library/documents/PCB_Zone2-5final-rpt_Dec2003.pdf

Guy, C.S., H.B. Treaner, K.M. Kappenman, E.A. Scholl, J.E. Ilgen, and M.A.H. Webb. 2015. Broadening the regulated-river management paradigm: a case study of the forgotten dead zone hindering pallid sturgeon recovery. Fisheries 40(1):6-14.

Hartman, K. J. and S. B. Brandt. 1995. Estimating energy density of fish. Transactions of the American Fisheries Society 124:347-355.

Hartman, K. J. and J. F. Kitchell. 2008. Bioenergetics modeling progress since the last synthesis. Transactions of the American Fisheries Society 137:216-223.

Jenkins, W.E., T.I.J. Smith, L.D. Heyward, and D.M. Knott. 1993. Tolerance of shortnose sturgeon, *Acipenser brevirostrum*, juveniles to different salinity and dissolved oxygen concentrations. Proc. Annu. Conf. SEAFWA 47:476-484.

Moberg, T. and M. DeLucia. 2016. Potential Impacts of Dissolved Oxygen, Salinity and Flow on the Successful Recruitment of Atlantic Sturgeon in the Delaware River. The Nature Conservancy. Harrisburg,PA.

Niklitschek, E.J. and D. H. Secor. 2009a. Dissolved oxygen, temperature and salinity effects on the ecophysiology and survival of juvenile Atlantic sturgeon in estuarine waters: I. Laboratory results. Journal of Experimental Marine Biology and Ecology 381:S150-S160.

Niklitschek, E.J. and D. H. Secor. 2009b. Dissolved oxygen, temperature and salinity effects on the ecophysiology and survival of juvenile Atlantic sturgeon in estuarine waters: II. Model development and testing. Journal of Experimental Marine Biology and Ecology 381:S161-S172.

NOAA, NMFS. 2017. Designation of critical habitat for the Gulf of Maine, New York Bight, and Chesapeake Bay distinct population segments of Atlantic sturgeon. ESA Section 4(b)2 Impact analysis and biological source document with the economic analysis and final regulatory flexibility analysis finalized June 3, 2017. Greater Altantic Regional Fisheries Office. 244 pp.

Park, I. 2020. Conservation and recovery of juvenile sturgeons in the Delaware River. Final Report to Section 6 Species Recovery Grants Program Award Number: NA16NMF4720072.

Ruer, P.M., J.J. Cech Jr., and S.I. Doroshov. 1987. Routine metabolism of the white sturgeon, *Acipenser transmontanus*: Effect of population density and hypoxia. Aquaculture 62(1):45-52.

Secor, D.H. and T.E. Gunderson. 1998. Effects of hypoxia and temperature, survival, growth, and respiration of juvenile Atlantic sturgeon, *Acipenser oxyrinchus*. Fishery Bulletin 96:601-613.

Secor, D.H. and E.J. Niklitschek. 2002. Sensitivity of sturgeons to environmental hypoxia: A review of physiological and ecological evidence. Fish Physiology, Toxicology and Water Quality Proceedings of the 6th International Symposium, La Paz B.C.S. Mexico.

Simpson, P.C. 2008. Movements and habitat use of Delaware River Atlantic sturgeon. MS Thesis. Delaware State University, Dover. 128 pp.

Stickle, W.B., M.A. Kapper, L.L. Liu, E. Gnaiger, and S.Y. Wang. 1989. Metabolic Adaptations of Several Species of Crustaceans and Molluscs to Hypoxia: Tolerance and Microcalorimetric Studies. The Biological Bulletin, 177, 303-312.

Van Eenennaam, J.P., S.I. Doroshov, G.P. Moberg, J.G. Watson, D.S. Moore and J. Linares. 1996. Reproductive conditions of the Atlantic sturgeon (*Acipenser oxyrinchus*) in the Hudson River. Estuaries 19: 769-777.

Wirgin, I., and R.C. Chambers. 2018. Effects of Toxicants and Dissolved Oxygen on Atlantic Sturgeon Larvae. Final Report.

Attachment H:

Hartman, K.J. 2024. Letter report to Maya K van Rossum, Delaware Riverkeeper, reviewing USEPA proposed Water Quality Standards to Protect Aquatic Life in the Delaware River. February 14, 2024; 5 pgs.

Maya K. van Rossum
CEO, Delaware River Keeper
925 Canal Street 7th Floor Suite 3701
Bristol, PA 19007

14 February 2024

I am writing this letter to comment on the USEPA's proposed rule: Water Quality Standards to Protect Aquatic Life in the Delaware River. In an earlier white paper, I provided my review of relevant literature on sturgeon relative to dissolved oxygen, temperature, and their interaction to arrive at dissolved oxygen levels that protect reproduction and survival of young Atlantic Sturgeon.

Atlantic Sturgeon are an endangered species and in Delaware River they are arguably the most sensitive of aquatic biota to low dissolved oxygen, particularly in early life stages. Therefore, it is appropriate to use Atlantic Sturgeon as the bellwether; as water quality improvements that benefit Atlantic Sturgeon will benefit other aquatic life. Pursuant to that, the USEPA has constructed models to estimate the benefits of improved dissolved oxygen (D.O.) levels in the Delaware River upon Atlantic Sturgeon using available data, bioenergetic models, and habitat suitability models (HSI). The modeling exercise is complex. However, it is important to note that models represent an abstraction of our view of reality and error propagation when combining models is a concern.

The EPA's proposed dissolved oxygen criteria sets values based on daily averages within life-stage-specific periods. The proposed criteria also set allowances for cumulative exceedance of the criteria reproduced below in EPA Table 6.

TABLE 6—THE EPA'S PROPOSED DISSOLVED OXYGEN CRITERIA

Season	Magnitude (percent oxygen saturation)	Duration	Exceedance frequency
Spawning and Larval Development *(March 1–June 30)*.	66	Daily Average	10% *(12 Days Cumulative).*
Juvenile Development *(July 1–October 31)*	66	Daily Average	10% *(12 Days Cumulative).*
	74	Daily Average	50% *(61 Days Cumulative).*
Overwintering *(November 1–February 28/29)*	66	Daily Average	10% *(12 Days Cumulative).*

Should EPA Table 6 be implemented, there are several issues with the proposed criteria that result in underestimation of the impact to Atlantic Sturgeon and thus impacts to the designated use.

Concerns and Suggestions for the USEPA Atlantic Sturgeon Cohort Model and Water Quality Standards for Delaware River.

1. The seasonal D.O. criteria proposed by EPA are problematic. The USEPA has proposed seasonal D.O. criteria based on life stages of Atlantic Sturgeon that include two levels of daily average D.O. saturation and cumulative exceedance frequency of 10% and 50%. From purely a biological

perspective this makes sense to look at criteria that protect each life stages. However, the intricate reliance of D.O. saturation levels upon temperature means that further refinement is needed. As an example, the Juvenile Development Season runs from July 1 through October 31. Including the September and October periods in the juvenile growth stage makes biological sense. However, from an environmental influence perspective, including months with cooler temperatures with warmer months for cumulative exceedance dilutes the criteria and its effectiveness at protecting the endangered species when temperatures exceed 26C. The current overwintering season runs from November 1 – February 28/29. Water temperatures at this time are cooler and the higher D.O. capacity of water at lower temperatures means criteria protective of sturgeon based on warm temperatures will also be protective at cooler periods.

My recommendation would be to set one overarching D.O. level that will protect all life stages when water temperatures are at or near 28C (the August 1st median water temperature, the highest daily median for the Delaware River). Although percent D.O. saturation is more biologically relevant, setting the standard in mg/L at the peak temperature would make meeting the criteria easier at lower temperatures due to the increased solubility of oxygen as temperature drops. Setting a single D.O. criteria in mg/L would simplify monitoring and enforcement and if the ***correct value*** was selected would be protective of all life stages of Atlantic Sturgeon.

2. The EPA relies on the HSI value to set the D.O. criteria. This, then fails to account for the effect of laboratory feeding on fish growth. The HSI is based on the habitat suitability model proposed by Niklitschek and Secor (2005) for Chesapeake Bay. EPA then selected an HSI value of 0 for identifying the D.O. percent level that would protect Atlantic Sturgeon propagation use under restored conditions (*see pp 35* in USEPA 2023). The HSI model necessarily overestimates growth of Atlantic Sturgeon because the laboratory data it is based on greatly exaggerates fish growth. Fish were fed to satiation with commercial pellet feed (see Hartman 2023). Wild fish tend to feed at 40-60% of lab satiation values (Hartman and Margraf 1992; Hartman and Brandt 1995b; Petersen and Paukert 2005; Hartman and Cox 2008) and commercial fish feed is 5 times higher energy content per gram than wild food items (see Hartman 2023). Both experimental parameters will interact to predict much higher growth (or HSI) than will be possible for wild Atlantic Sturgeon. Recognizing or correcting for the overestimates of growth in the HSI model would likely lead to adjustment in the scale (but perhaps not the shape) of these HSI curves, and making these corrections is expected to lead to selection of higher and more protective dissolved oxygen criteria based on these selected thresholds.

3. The Hartman (2023) white paper makes a clear case that for propagation use, Atlantic Sturgeon require 6.0-6.65 mg/L of D.O. at the high water temperatures routinely observed in Delaware River each year. Empirical data show Atlantic Sturgeon in the Delaware River had unsuccessful reproduction at minimum median daily D.O. levels below 6.0 mg/L. At 28C, very little additional benefit was accrued to young Atlantic Sturgeon above 6.65 mg/L D.O. Thus, a range of 6.0 to 6.65 mg/L (76.7% to 85% DOSAT at 28C) are required for propagation of Atlantic Sturgeon in Delaware River.

4. If EPA chose to stick with the currently proposed D.O. criteria for different seasons (instead of using a single value of at least 6.0 mg/L) further refinements are needed to be fully protective. The seasons defined for proposed D.O. criteria do not closely match water temperatures which define D.O. solubility in water, and D.O. requirements of Atlantic Sturgeon, particularly during warm water periods. Atlantic Sturgeon would be better supported by a monthly criteria and exceedance frequency to match temperature cycles. Larval development is the most sensitive life stage and by mid-June, median water temperatures are 24 C and upper percentiles are 26 C. Similarly, water temperatures in October are much cooler than the rest of the *juvenile development* season (median water temperatures drop from 23 C on Oct 1st to 20 C on Oct 16th to 16 C on Oct 31st). Therefore, establishing monthly criteria for June through September and moving October to the *Overwintering season* (or some other term) makes bioenergetic sense.

5. The proposed EPA criteria defines no hard floor for a minimum D.O. level despite the EPA Gold Book's freshwater criteria of 6.0 mg/L as a 7-day mean and 5.0 mg/L as a 1-day minimum. Best available science shows that at less than 6.0 mg/L survival of sturgeon at warm temperatures is on a knife's edge. In European Sturgeon 100% of embryos and larva died in <48 h at 26C and 5.8 mg/L (71.5% D.O. saturation; Delage et al. 2020). Niklitschek and Secor (2009a) could not complete growth experiments with age-0 and age-1 Atlantic Sturgeon exposed to 70% D.O. saturation at 28C (5.48 mg/L) because they were "killing too many fish." Biologically, why would the criteria for an oxygen sensitive endangered species be lower than the general EPAs current standard for freshwater? {SEE PP 18 of Tech. Supp. Doc.}. The site-specific empirical data on reproduction substantiate the need for at least 6.0 mg/L as an instantaneous minimum in the Delaware River.

6. Models represent an abstraction of our view of reality and error propagation when combining models is a concern. It is for that reason that I place more confidence in using the data, relationships, and interpretations to define D.O. needs for Atlantic Sturgeon in the Delaware River over the EPA's HSI model.

Closing comments:

- While the seasons proposed by EPA make biological sense, the water temperatures within these seasons vary too greatly to provide meaningful protection. Because the solubility of oxygen in water decreases with increasing temperatures D.O. saturation values that are protective of sturgeon at 28C will also be protective at cooler temperatures. For that reason, I advocate for setting a single D.O. criteria in mg/L at the high but typical maximum water temperature experienced by sturgeon to simplify enforcement and protect use.

- Collectively the available empirical and experimental evidence suggests instantaneous minimum summer dissolved oxygen levels of 6.0 mg/L are needed to protect reproduction and survival of young Atlantic sturgeon in the Delaware River.

- Other scientific groups have already identified 6.0 mg/L D.O. as protective of Atlantic Sturgeon in the Chesapeake Bay DPS (NOAA/NMFS 2017).

- The Hartman (2023) white paper suggested 6.0 mg/L as the minimum sustainability threshold. I also proposed a conservative threshold of 85% D.O. saturation at 28 C. This would yield 6.65 mg/L as the level of no significant additional benefit. Taken together this yields a narrow range of 6.0 to 6.65 mg/L D.O. (76.7 to 85% D.O. Saturation at 28C) as the level protective of Atlantic sturgeon in Delaware River, and as the level providing limited additional benefit, respectively.

- Due to the simplicity of measurement and interpretation of standards I recommend the dissolved oxygen criteria be based on oxygen concentration (mg/L) rather than percent saturation. Using these D.O. units and establishing the criteria at the warmest temperature sturgeon will experience in the river will necessarily be protective at lower temperatures.

Given all this, any improvements in dissolved oxygen concentrations in the Delaware River during the warm season D.O. sag will provide some benefit to Atlantic Sturgeon and other species. However, to fully support the propagation use, the instantaneous minimum D.O. levels should be 6.0 mg/L and the median D.O. levels should be 6.65 mg/L.

I am happy to discuss this further or contribute in any way to assist in selection of appropriate D.O. criteria for Atlantic Sturgeon in Delaware River.

Sincerely,

Kyle J. Hartman, Ph.D.

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West Virginia University
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Morgantown, WV 26506-6125
(304) 293-4797
Kyle.hartman@mail.wvu.edu

References (Not Already Cited in the Hartman (2023) white paper):

Hartman, K. J. and S. B. Brandt. 1995. Trophic resource partitioning, diets, and growth of sympatric estuarine predators. Transactions of the American Fisheries Society 124:520-537.

Hartman, K. J., and M. K. Cox. 2008. Refinement and testing of a brook trout bioenergetics model. Transactions of the American Fisheries Society 137:357–363.

Hartman, K. J. and F. J. Margraf. 1992. Effects of prey and predator abundances on prey consumption and growth of walleyes in western Lake Erie. Transactions of the American Fisheries Society 121:245-260.

Niklischek, E.J. and D.H. Secor. 2005. Modeling spatial and temporal variation of suitable nursery habitats for Atlantic sturgeon in the Chesapeake Bay. Estuarine and Coastal Shelf Science 64:135-148.

Petersen, J. H., and C. P. Paukert. 2005. Development of a bioenergetics model for humpback chub and evaluation of water temperature changes in the Grand Canyon, Colorado River. Transactions of the American Fisheries Society 134:950–974.

Attachment I:

DRBC and USEPA. 2023. Draft presentation slides for March 7, 2023, DRBC Commissioner's Caucus meeting, titled "Aquatic Life Designated Use: Water Quality Standards for Delaware River Estuary." 26 slides

Aquatic Life Designated Use

Water Quality Standards for Delaware River Estuary

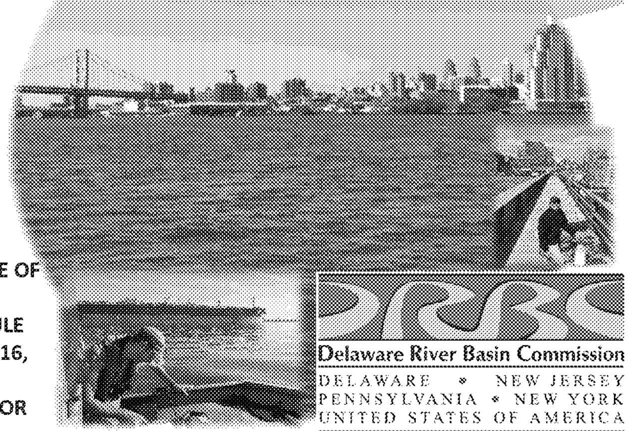
DRBC:
Thomas Amidon, Jake Bransky, Namsoo Suk

EPA:
Greg Voight, Wayne Jackson, Erica Fleisig

DRBC Commissioners' Caucus Meeting

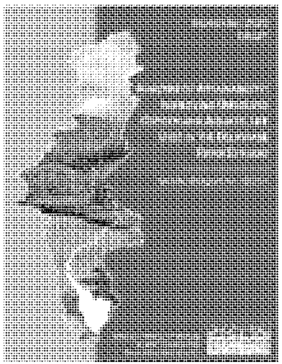
March 7, 2023

THIS DRAFT IS CONFIDENTIAL AND FOR THE SOLE PURPOSE OF REVIEW BY THE DRBC COMMISSIONERS AND THEIR REPRESENTATIVES AS THEY DELIBERATE ON A PENDING RULE UNDER THE DRB COMPACT. PURSUANT TO 18 C.F.R. 401.116, THIS DRAFT REMAINS DELIBERATIVE AND CONFIDENTIAL WHEN DISCLOSED TO OTHER GOVERNMENT EMPLOYEES FOR USE IN THEIR WORK IN COOPERATION WITH THE DRBC.



Delaware River Basin Commission
DELAWARE • NEW JERSEY
PENNSYLVANIA • NEW YORK
UNITED STATES OF AMERICA

DRBC Findings



- Resolution No. 2017-4:
  - Directed the Executive Director to initiate DRBC rulemaking to revise the designated aquatic life uses consistent with the results of the identified studies and the objectives and goals of the federal Clean Water Act.
  - Published draft analysis of attainability (AA) and other identified studies in 2022.
- Findings in draft AA Report:
  - "[...] water quality supporting the aquatic life use of *fish propagation* is attainable throughout the Estuary, including in the FMA."
  - "The Commission should proceed with rulemaking to add fish propagation as a designated use within the reach of the Estuary currently designated for fish maintenance, and that it should adopt revised DO water quality criteria that support the new use."

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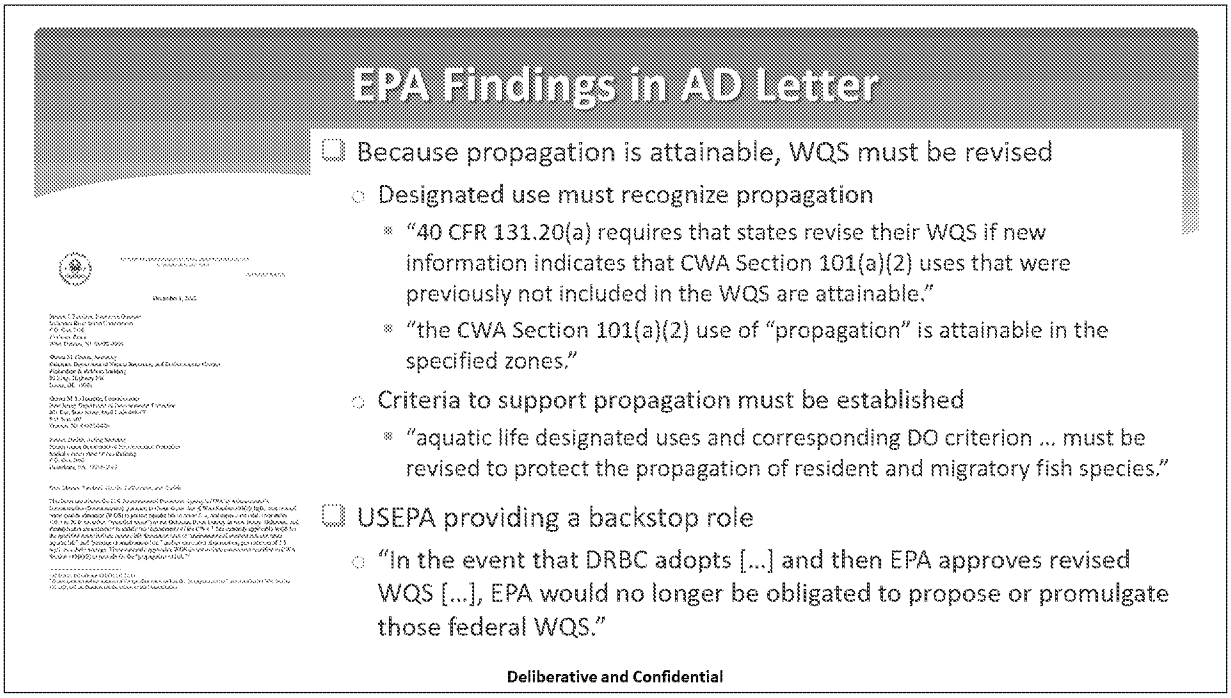
Namsoo and Greg

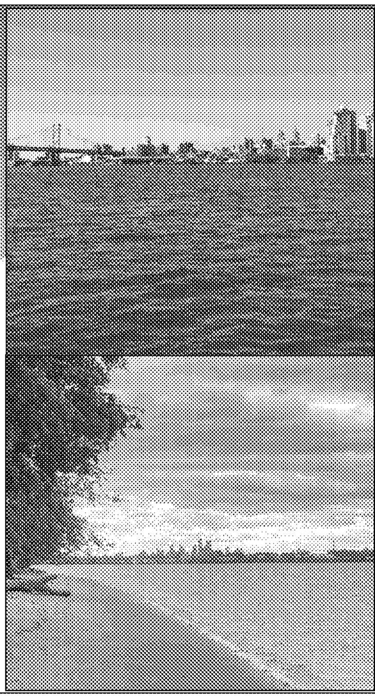


Greg (or Erica)

Mutual Findings by DRBC and EPA

- Propagation is attainable, WQS must be revised
  - Designated use must recognize propagation
  - Criteria to support propagation must be established
- Technical staff work together
  - Co-regulators work group to develop revised aquatic life use and dissolved oxygen criteria to protect the use

Namsoo and Greg



Rulemaking co-regulator coordination

Thomas Amidon, DRBC
Greg Voight, EPA Region 3

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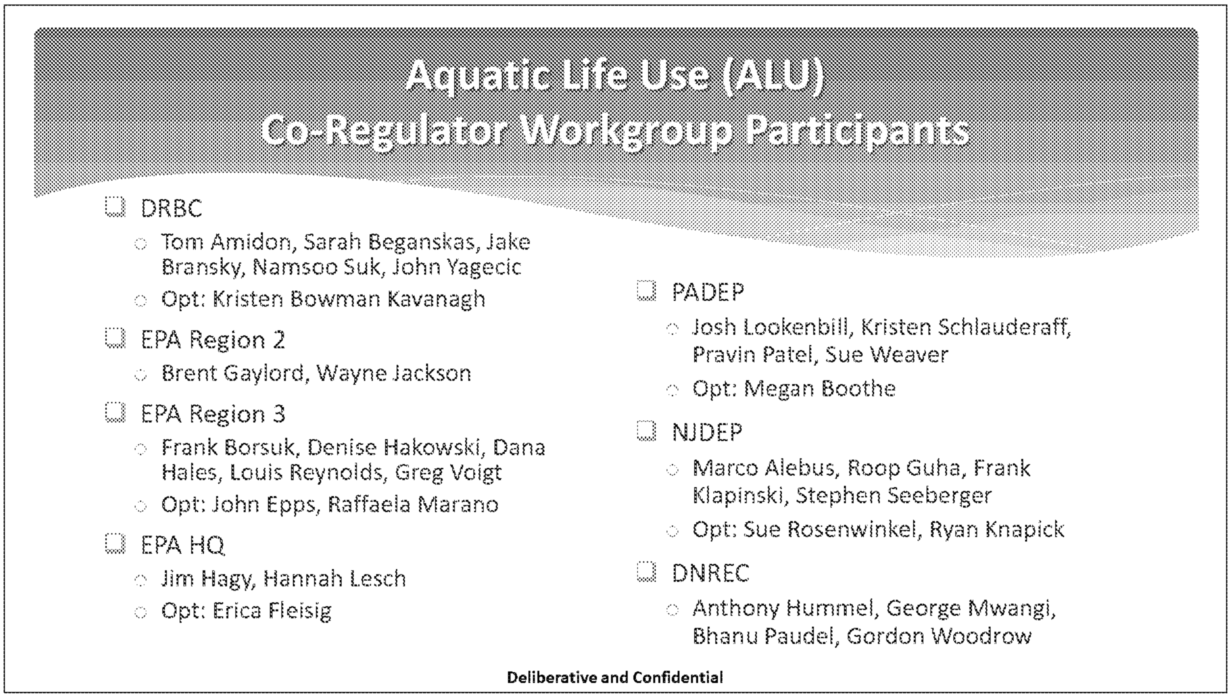
Tom


Aquatic Life Use (ALU)
Co-Regulator Workgroup Participants
DRBC
Tom Amidon, Sarah Beganskas, Jake Bransky, Namsoo Suk, John Yagecic
Opt: Kristen Bowman Kavanagh
EPA Region 2
Brent Gaylord, Wayne Jackson
EPA Region 3
Frank Borsuk, Denise Hakowski, Dana Hales, Louis Reynolds, Greg Voigt
Opt: John Epps, Raffaela Marano
EPA HQ
Jim Hagy, Hannah Lesch
Opt: Erica Fleisig
PADEP
Josh Lookenbill, Kristen Schlauderaff, Pravin Patel, Sue Weaver
Opt: Megan Boothe
NJDEP
Marco Alebus, Roop Guha, Frank Klapinski, Stephen Seeberger
Opt: Sue Rosenwinkel, Ryan Knapick
DNREC
Anthony Hummel, George Mwangi, Bhanu Paudel, Gordon Woodrow
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Tom

Workgroup Charge

- DRBC to work together with USEPA in collaboration with Estuary States
- Develop Estuary-specific WQS
  - Upgrade Aquatic Life Use to include propagation
  - Develop DO criteria to support propagation of DO-sensitive fish
  - "promulgatable" and approvable
- Content for rule proposals by 11/30/2023
  - Including any basis and background documents
- Rule proposals to be developed concurrently by DRBC and EPA

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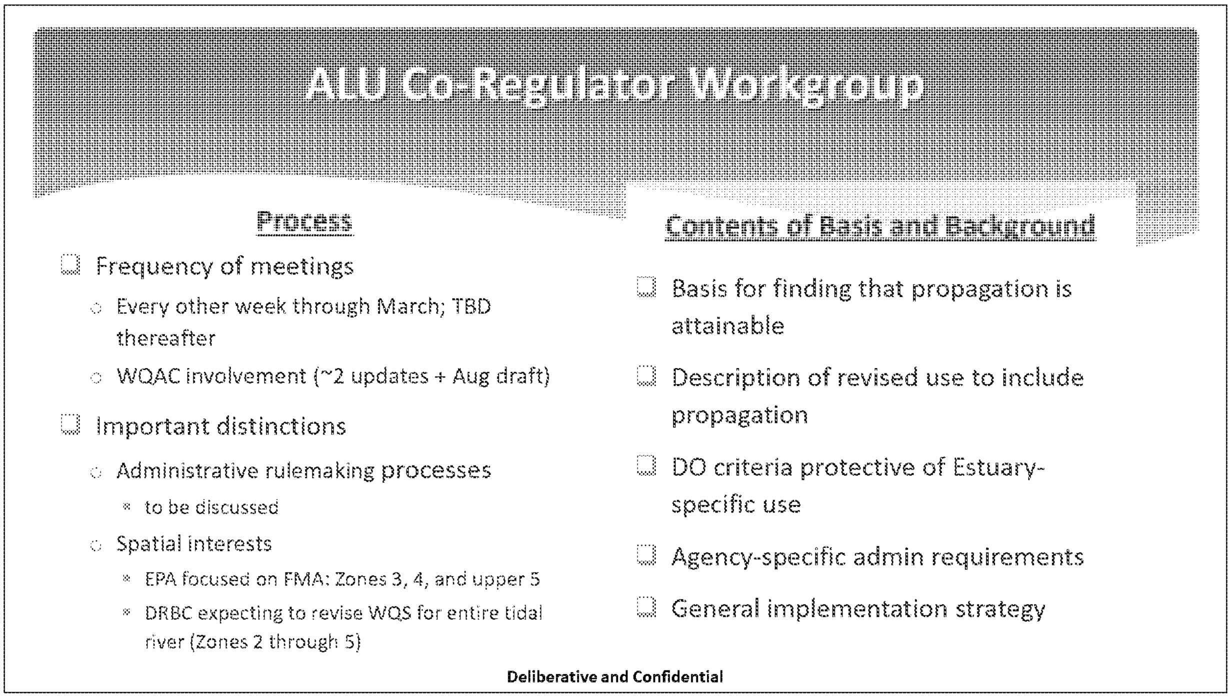
Greg



Tom and maybe Greg

Regulatory Distinctions among the Estuary States

- **States of DE and NJ**
  - Designated uses and criteria established by DRBC for the Delaware River apply
  - State uses and criteria are applicable for parameters not regulated by DRBC
- **Commonwealth of Pennsylvania**
  - DRBC criteria apply for water quality standards that are more stringent than PA's

- State of Delaware WQS (7401.4.4)
  For waters of the Delaware River and Delaware Bay, duly adopted Delaware River Basin Commission (DRBC) Water Quality Regulations shall be the applicable criteria. If the DRBC has not developed an applicable regulatory standard or criteria for these waters, and Delaware has, Delaware's criteria shall be applicable.
- State of New Jersey SWQS (7:9B-1.13)
  - The designated uses for the mainstem Delaware River and Delaware Bay are those contained in the DRBC Water Quality Regulations.
  - For parameters with criteria in the DRBC Water Quality Regulations, the criteria contained therein are the applicable criteria.
- Commonwealth of PA WQS (Chapter 93)
  When appropriate, "Exceptions to Specific Criteria" provide reference to the Delaware River Basin Commission (DRBC) water quality regulations [...] which specify the criteria that apply **if a water quality standard is more stringent** than those in this title.

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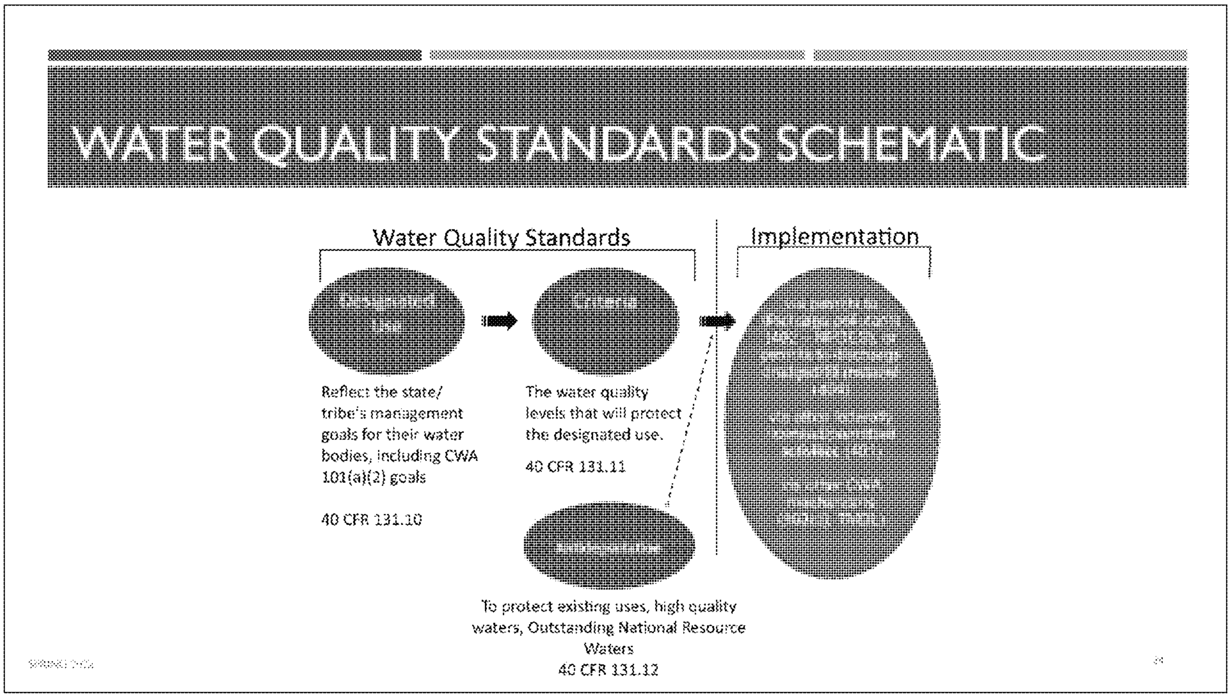
Tom

CWA 303: BASIS FOR WATER QUALITY STANDARDS

- WQS define the water quality goals for a waterbody.
- WQS provide a regulatory basis for many actions, e.g.,
  - Reporting on water quality conditions and status.
  - Developing water quality-based effluent limits in National Pollutant Discharge Elimination System (NPDES) permits for point sources.
  - Setting targets for Total Maximum Daily Loads (TMDLs).
- An important function of WQS is to provide a regulatory basis for the water quality management activities authorized under the CWA.

Wayne


WATER QUALITY STANDARDS SCHEMATIC
Water Quality Standards
Implementation
Reflect the state/ tribe's management goals for their water bodies, including CWA 101(a)(2) goals
40 CFR 131.10
The water quality levels that will protect the designated use.
40 CFR 131.11
To protect existing uses, high quality waters, Outstanding National Resource Waters
40 CFR 131.12

Wayne

WATER QUALITY CRITERIA (40 CFR 131.3(b))

- The water quality levels that will protect the designated use.
- "Elements of State water quality standards, expressed as constituent concentrations, levels or narrative statements, representing water quality that supports a particular designated use. When criteria are met, water quality will generally protect the designated use."
- Requirements for state/tribe's criteria adoption: 40 CFR 131.11
  - Must support the most sensitive use
  - Based on a sound, scientific rationale
  - Sufficient parameters to protect designated use

Wayne

AQUATIC LIFE CRITERIA

- Aquatic life criteria protect aquatic life from specific pollutants in the water column.
- An aquatic life criterion typically contains three components:
  - **Magnitude** (or concentration) – how much of a parameter
  - **Duration** – period of time over which the instream concentration is averaged
  - **Frequency** – how often the magnitude can be exceeded
    - ❑ The term "exceedance" means the concentration contravenes a threshold
    - ❑ For criteria like dissolved oxygen where the thresholds are expressed as minimum rather than maximum values, "exceedance" means "less than"

Aquatic Life Designated Uses in Current DRBC Regulations since 1967

	Zone	River Mile	Aquatic Life Use	Migratory Fishes	24-hour average D.O. Criteria
	2	108.4 – 133.4	maintenance and **propagation** of resident fish and other aquatic life	**passage** of anadromous fish	5.0 mg/l
Urbanized portion of Delaware Estuary or Fish maintenance area (FMA)	3	95 – 108.4	maintenance of resident fish and other aquatic life	**passage** of anadromous fish	3.5 mg/l
	4	78.8 – 95	maintenance of resident fish and other aquatic life	**passage** of anadromous fish	3.5 mg/l
	5	70 – 78.8	maintenance of resident fish and other aquatic life	**passage** of anadromous fish	3.5 mg/l
		48.2 – 70	maintenance and **propagation** of resident fish and other aquatic life	**passage** of anadromous fish	4.5 – 6.0 mg/l
The Delaware Bay	6	0 – 48.2	maintenance and **propagation** of resident fish and other aquatic life maintenance and **propagation** of shellfish	**passage** of anadromous fish	6.0 mg/l

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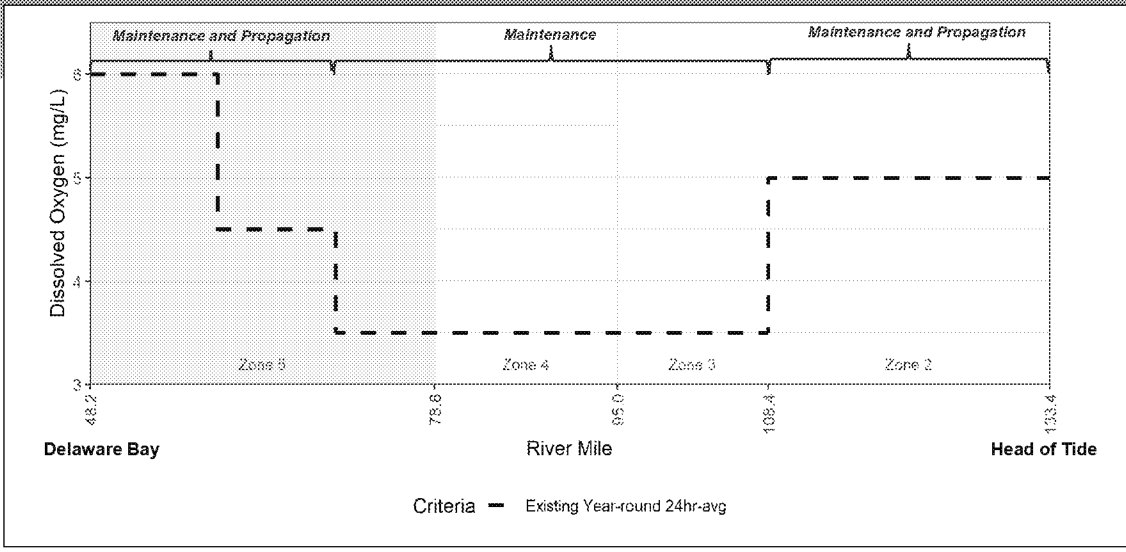
RM 70 to 108.4 designated for fish maintenance only rather than maintenance and propagation with daily average criteria of 3.5 mg/L .
At the time, this designation was aspirational, since actual DO was zero for long periods of each summer, precluding even fish passage.

Currently Applicable DO Criteria



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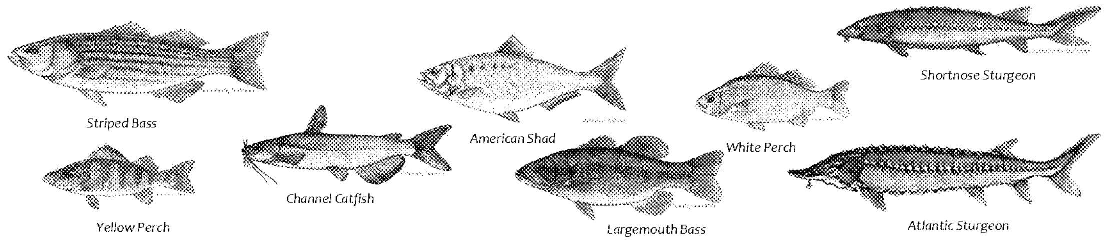
Recommended Estuary-Specific Aquatic Life Use

"Maintenance, migration, and propagation of resident fish, diadromous fish, shellfish, and other aquatic life inhabiting the Delaware River Estuary."

- Applies to DRBC Water Quality Management Zones 2 through 5



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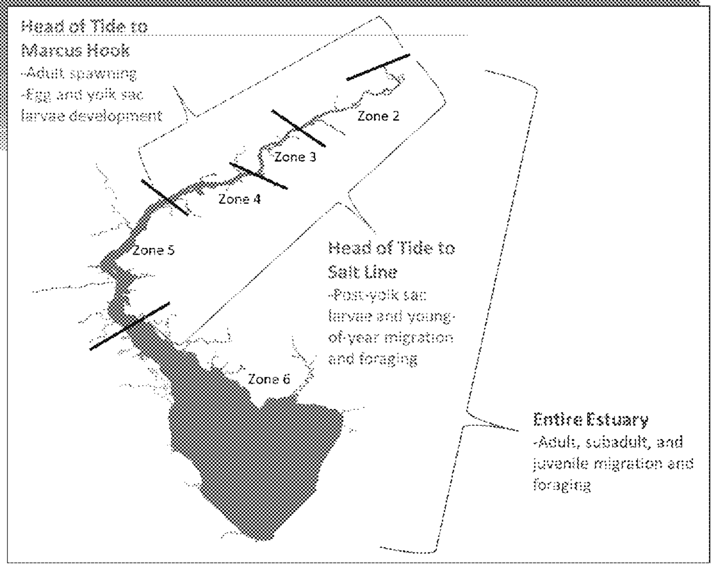
Propagation includes spawning, nursery, growth and development, and recruitment

Application of Use to Entire Tidal River

- DO-sensitive species are widely distributed throughout the tidal river
- Entire tidal river has been designated as critical habitat for endangered Atlantic Sturgeon
- Existing designated uses do not protect all aquatic life, even in zones where designated uses include propagation
- Bay (Zone 6) is excluded from current revision because it is more saline and contains different species



Atlantic Sturgeon Designated Critical Habitat in the Delaware Estuary (NOAA Fisheries)

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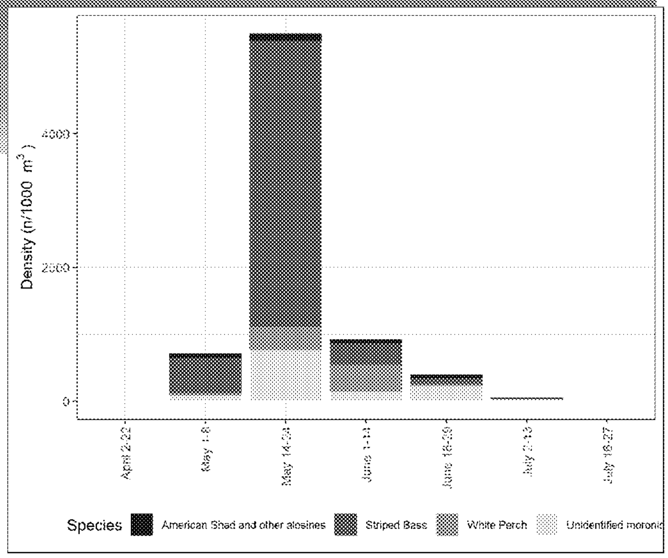
Seasonal Considerations

- At early life stages, fish are more vulnerable to low DO events
  - Physiological effects
  - Mobility
- Seasonally, more stringent DO criteria are needed
- DRBC is proposing 3 seasons for criteria
  - **Spawning:** March 01 – June 30
  - **Growth:** July 01 – October 31
  - **Overwinter:** November 01 – February 28



Density of early life stages of sensitive species captured in the Delaware Estuary.

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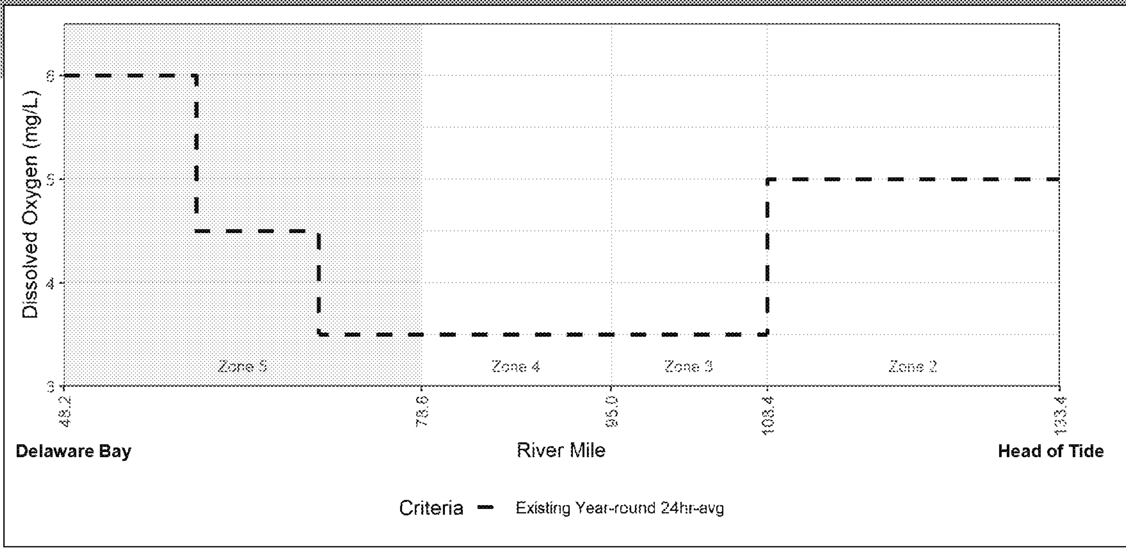
Currently Applicable DO Criteria



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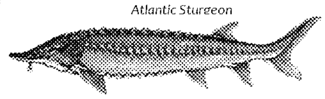
PA DO Criteria vs DRBC Draft DO Criteria

- DRBC has reviewed the PA DO rationale document as it relates to DRBC draft criteria
- Key Distinctions…
  - Different Fish Communities
    - PA criteria protect a much larger group of species (all fish in PA)
    - DRBC draft criteria have been developed using best current science, and tailored to the specific needs of the unique Estuary fish community
  - Different Temporal Applications
    - PA applies a single DO criteria year-round to protect aquatic life in all seasons
    - Seasonal considerations in DRBC criteria provide equal or better protections during the critical spawning season and less stringent criteria during the summer growth season

Smallmouth Bass

Atlantic Sturgeon



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DRBC DELIVERABLES
(Supplemental Documents)

- ☐ Hydrodynamics model calibration report
- ☐ Water quality model calibration report
- ☐ Socioeconomic evaluation study report

} Independent Document Form by 6/30/2023

- ☐ Linking aquatic life uses & DO conditions report
- ☐ Analysis of attainability report

} Independent Document Form or Merged into the Basis and Background Document by 7/31/2023

Note: Implementation Strategy will be addressed in the B&B document with a generalized guideline. Detailed individual wasteload allocations will be developed after the adoption of the Rule.

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Namsoo

TENTATIVE SCHEDULE for DRBC's Rulemaking

Task	Responsibility	Start Date	Target End Date
Development of Aquatic Life Use and DO Criteria	Co-regulators Tech-Group	On-going	4/30/2023
Draft Basis and Background (B&B) Document	DRBC lead; co-regulators	5/1/2023	6/30/2023
Finalize Supplemental Reports	DRBC	On-going	6/30/2023
DRBC Internal Review and Revision on B&B Document	DRBC	7/1/2023	7/28/2023
Commissioner Review and Comment on Draft B&B Document	Commissioners	8/1/2023	9/15/2023
Finalize Basis and Background Document and Preamble for Notice in Registers	DRBC	9/16/2023	11/30/2023
Initiate Rulemaking Process (Notice)	DRBC	12/1/2023	12/1/2023
Public Comments, Public Hearings, and Draft Comment and Response Document (detailed schedule to be developed)	DRBC	12/1/2023	1/31/2025
Rule adoption no later than March 2025 Business Meeting	Commissioners		3/6/2025

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Namsoo

Rulemaking Schedules

DRBC

- Technical process in 2023
  - Develop aquatic life use and DO criteria by 4/30
  - Draft Basis & Background by 7/28
    - Commissioner review by 9/15
  - Finalize B&B and Preamble by 11/30
- Administrative process
  - Notice (publication) on DRBC website on 12/01/2023
  - Filing (Notice) in Federal and states Registers around 12/2023
  - Public process for Dec. 2023 – March 2024
  - CRD and promulgation by 3/6/2025

EPA

Stage	Target for Completion
Draft Rule and Economic Analysis	July 28
OMB Review	October 29
Internal EPA Finalization	November 30
Administrator Signs Rule	December 1, 2023
Public Comment Period (60 Days)	December 1, 2023 - January 30, 2024

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Erica

Rulemaking Schedules

DRBC

- Technical process in 2023
  - Develop aquatic life use and DO criteria by 4/30
  - Draft Basis & Background by 7/28
    - Commissioner review by 9/15
  - Finalize B&B and Preamble by 11/30
- Administrative process
  - Initiate rulemaking by 12/01/2023
    - Notice (publication) on DRBC website on 12/01/2023
    - Filing (Notice) in Federal and states Registers ~12/2023
  - Public process Dec. 2023 – March 2024
  - CRD and promulgation by 3/6/2025

EPA

- Technical process in 2023
  - Draft Rule and Economic Analysis by 7/28
  - OMB review by 10/29
  - Internal EPA finalization by 11/30
- Administrative process
  - Administrator signs rule by 12/01/2023
  - Public input process by 1/30/2024

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Erica

Discussion

pennsylvania
DEPARTMENT OF ENVIRONMENTAL PROTECTION

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Administrative Issue to Resolve with PA

- PA WQS for tidal Delaware River
  - Designated Uses
    - Warmwater Fishes and Migratory Fishes
  - Dissolved oxygen criteria year-round
    - > 5.5 mg/L DO as 7-d avg
    - > 5.0 mg/L DO minimum
- Delaware Estuary has a unique fish community with unique dissolved oxygen requirements
- DRBC working directly with PA to work through this issue

pennsylvania
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Tom and Josh

Attachment J:

Hagy, J.D, III. 2023. Development of an Atlantic sturgeon cohort model for the tidal fresh Delaware River. Presentation to the DRBC Water Quality Advisory Committee, March 23, 2023; 21 slides.

(available at:

https://www.nj.gov/drbc/library/documents/WQAC/032323/FishModelingTool_USEPA.pdf)

Development of an Atlantic sturgeon cohort model for the tidal-fresh Delaware River

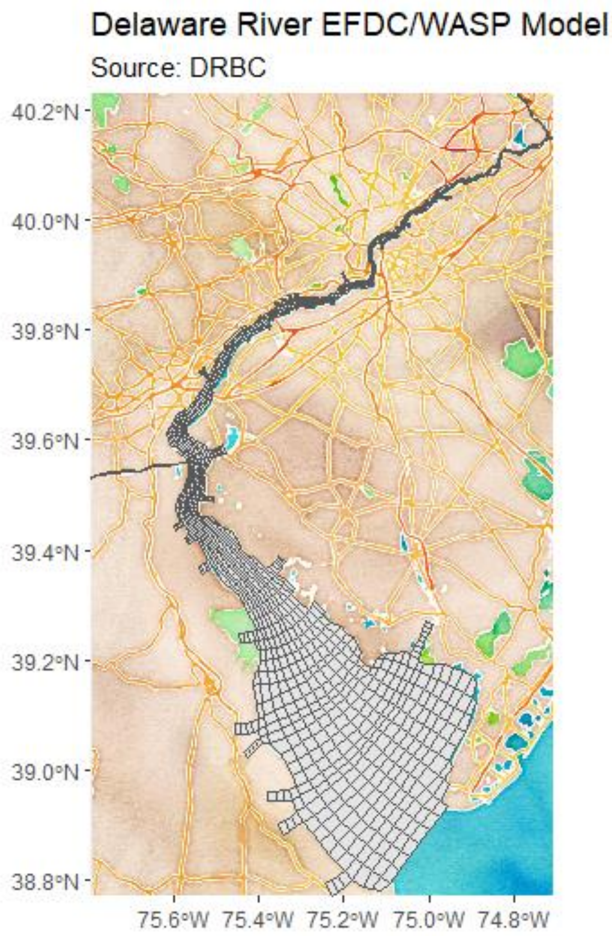
James D Hagy III

US EPA Office of Research and Development
Center for Environmental Measurement and Modeling, Narragansett, RI

At the Quarantine Station, Marcus Hook, PA

This content is draft, preliminary and for discussion at the March 23, 2023 WQAC Meeting. Content may not be published or re-posted in whole or in-part without the DRBC's permission.

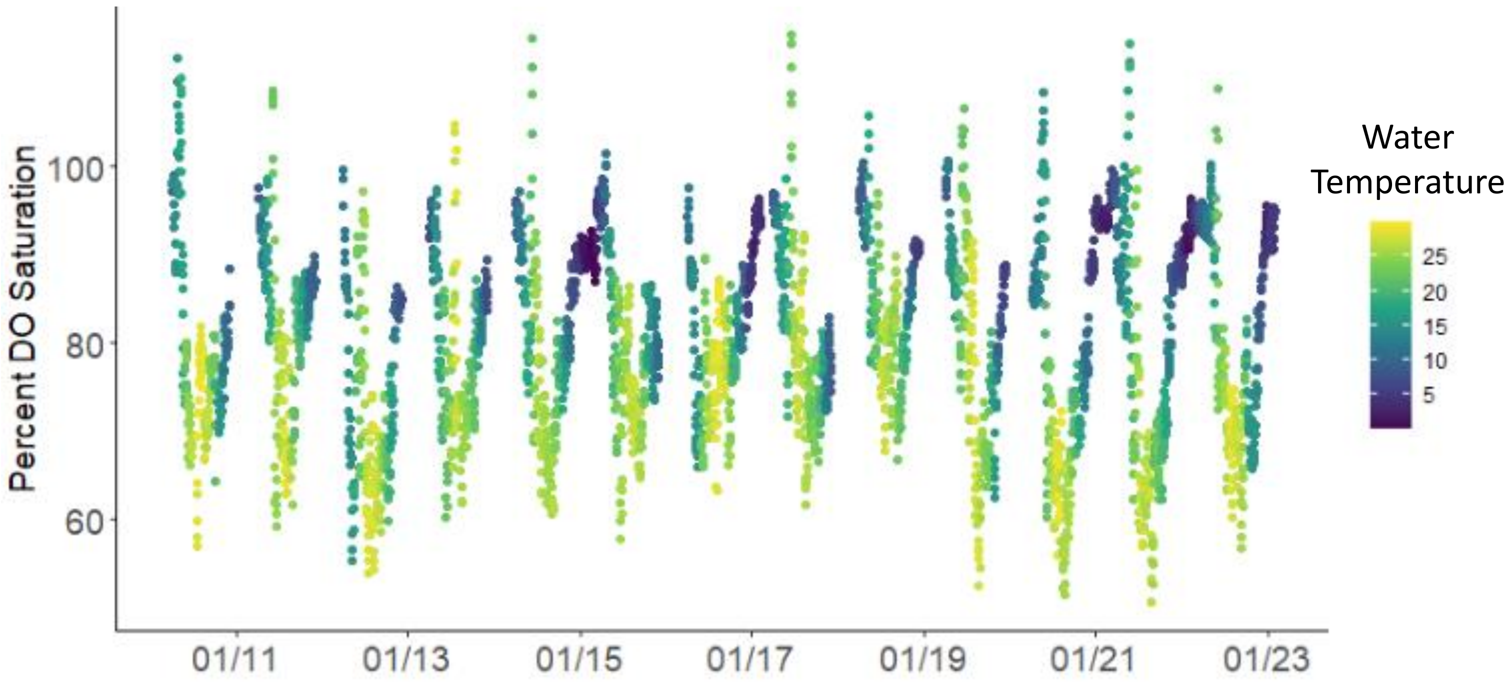
DRBC's EFDC/WASP model simulates realistic space/time data for water temperature, salinity, and dissolved oxygen throughout the river.



- 2019 Calibration Scenario
- HADO – "Highest Attainable Dissolved Oxygen" Scenarios
  - 2012
  - 2019

USGS/DRBC's continuous monitoring at several sites in the Delaware River quantify the range of water quality that occurs among years at those sites

Delaware River at Chester



Date (month/year)

Objective

Build a "tool" to translate observed and predicted water quality conditions in the Delaware River to expected growth and survival of juvenile (Age-0) Atlantic sturgeon

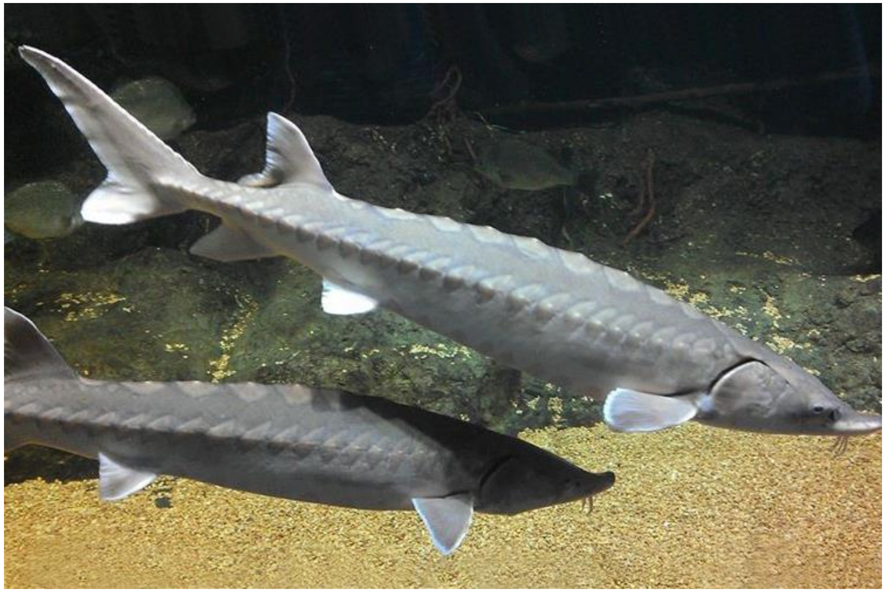
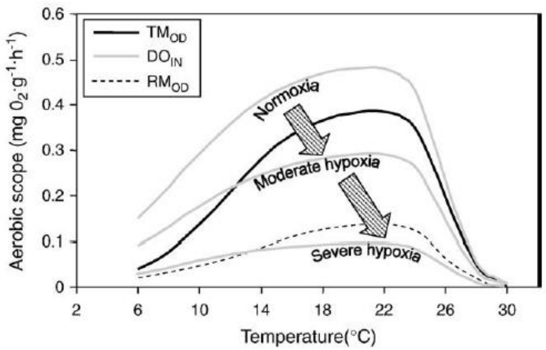
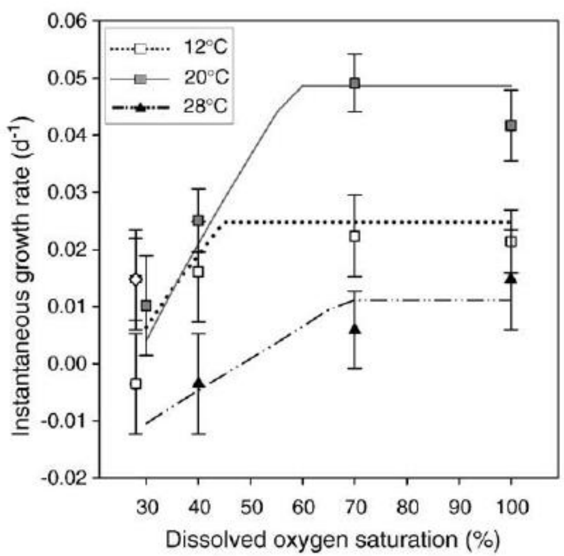


Photo: NOAA fisheries

Laboratory data and analysis using models describes the effect of water quality conditions on expected seasonal growth and survival of juvenile Atlantic sturgeon





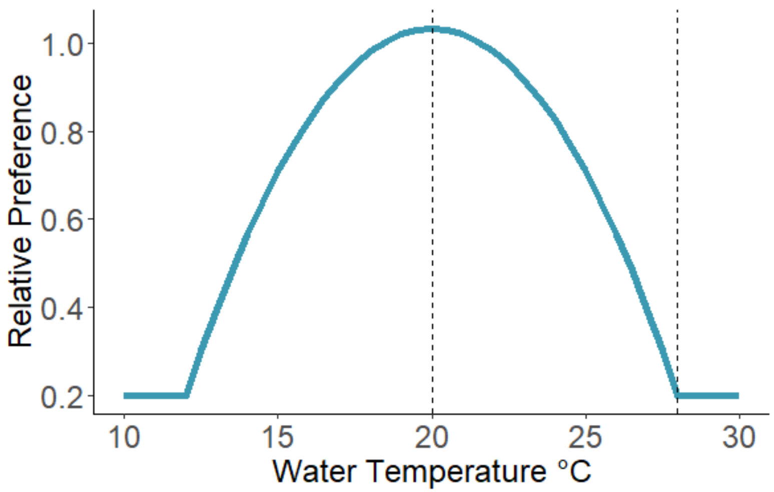
- Laboratory studies quantify effects of temperature and low oxygen on:
  - Growth (Niklitschek and Secor (2009a,b)
  - Survival (Secor and Gunderson 1998; Campbell and Goodman 2004; Niklitschek and Secor 2009a)
  - Habitat selection (Niklitschek and Secor 2010)
- A bioenergetics model combines data on T, S and DO effects on several bioenergetic rates to predict growth rate.

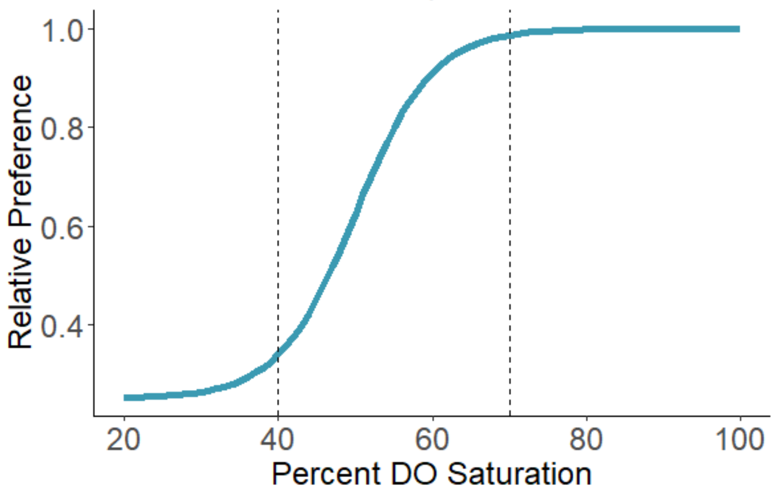
A population model was developed to predict growth and survival of juvenile Atlantic sturgeon using available exposure and response data

1. Predict **growth** rate using bioenergetic model developed by Niklitschek and Secor (2009).
2. Predict **mortality** due to low oxygen based on data from Secor and Gunderson (1998), Campbell and Goodman (2003), and Niklitschek and Secor (2009).
3. Simulate cohort growth and survival for 3 types of situations:
   a. Conditions over time at USGS/DRBC sondes
   b. Each “cell” of the DRBC model outputs
   c. Overall water quality in zones 3 and 4.
4. For simulations by zone, consider how fish behavior may affect water quality exposure.
5. Simulate a growth and survival of a cohort of juvenile sturgeon from July 1 to November 1

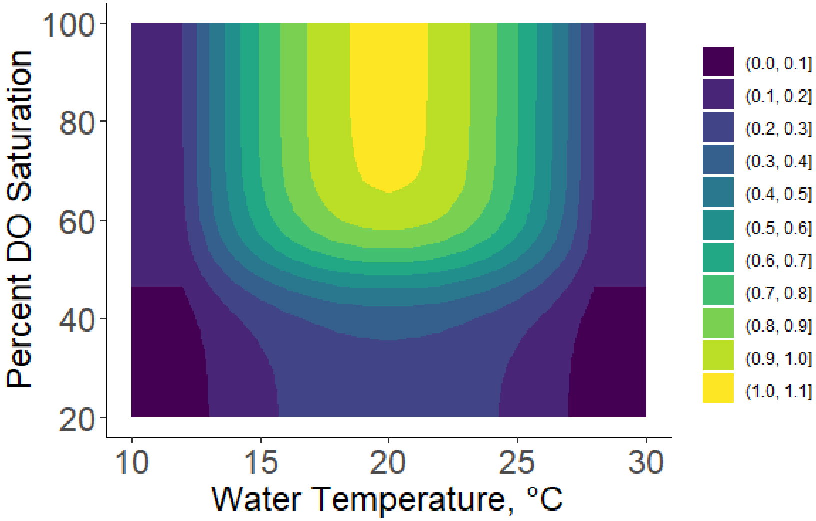
Choice tank study: Juvenile Atlantic sturgeon prefer water near 20°C vs. 28°C and DO at 70% vs. 40%

Water Temperature Preference - f(wt)





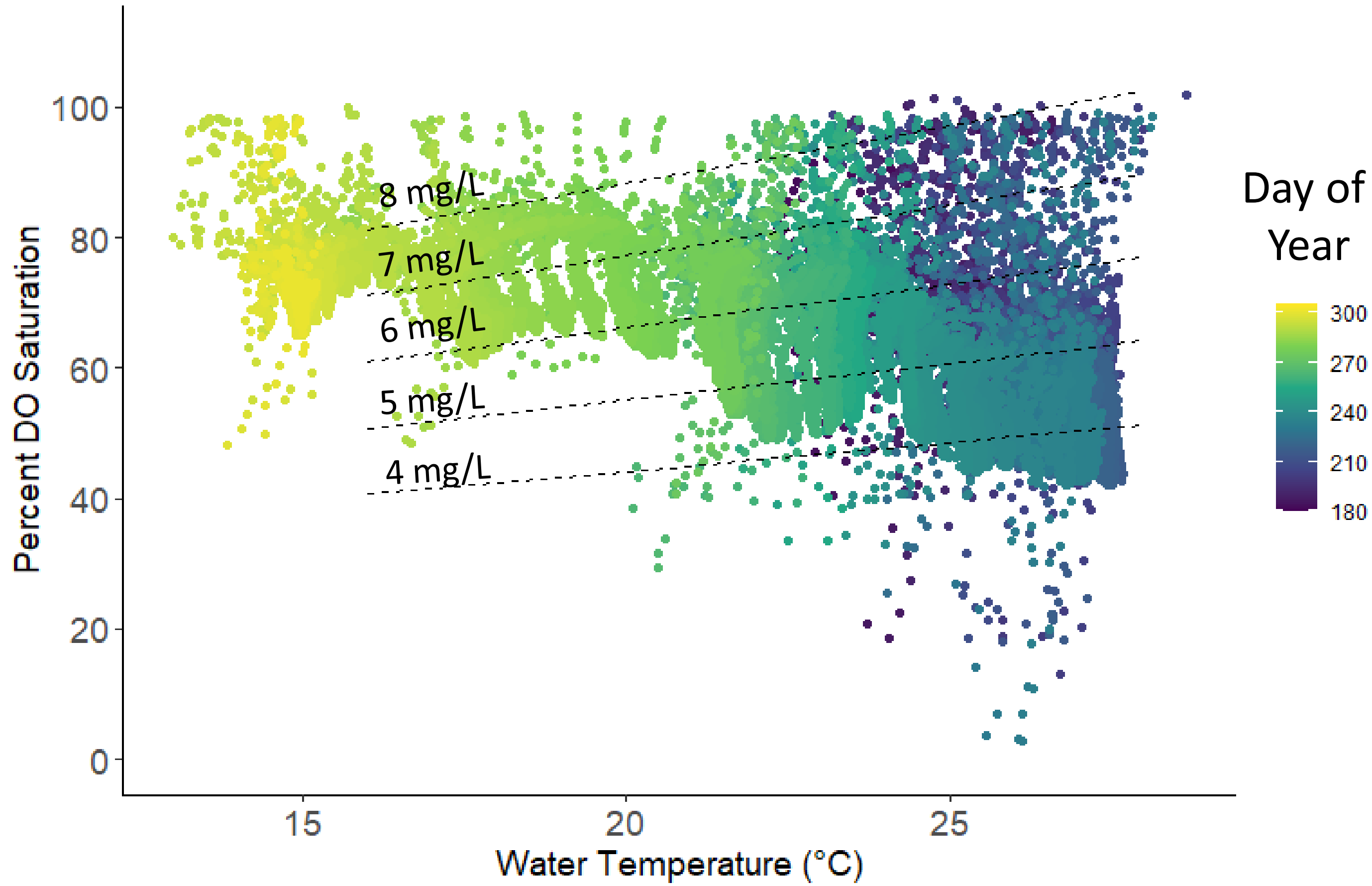
Overall Preference - f(wt) · f(posat)



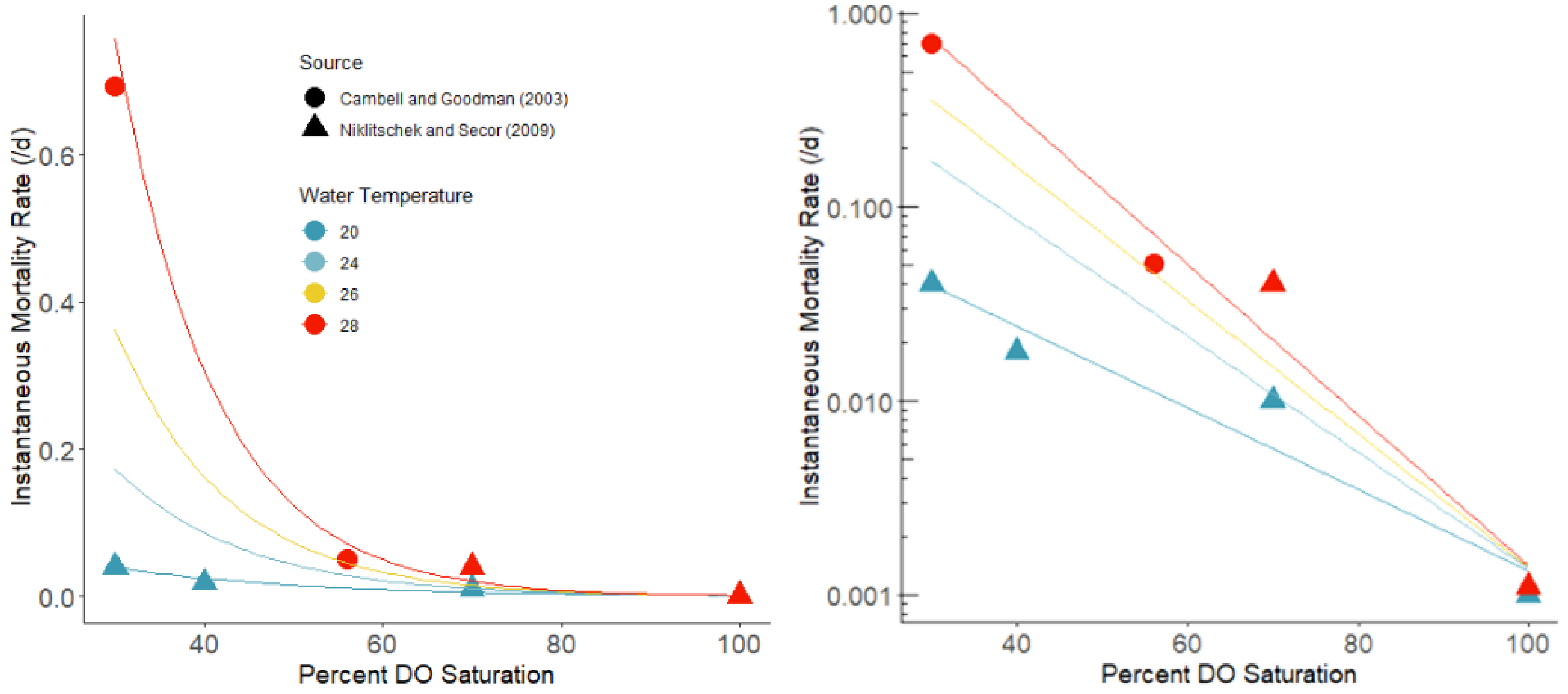
Fish rarely encounter a large spatial gradient in DO in a single day in zone 4. The effect of habitat preference on DO exposure is that zone small. For temperature, the effect is even less.

Based on Niklitschek and Secor (2010)

Percent DO saturation and water temperature combinations experienced by fish in 2019 Calibration scenario in Zone 4 from July 1 to November 1.

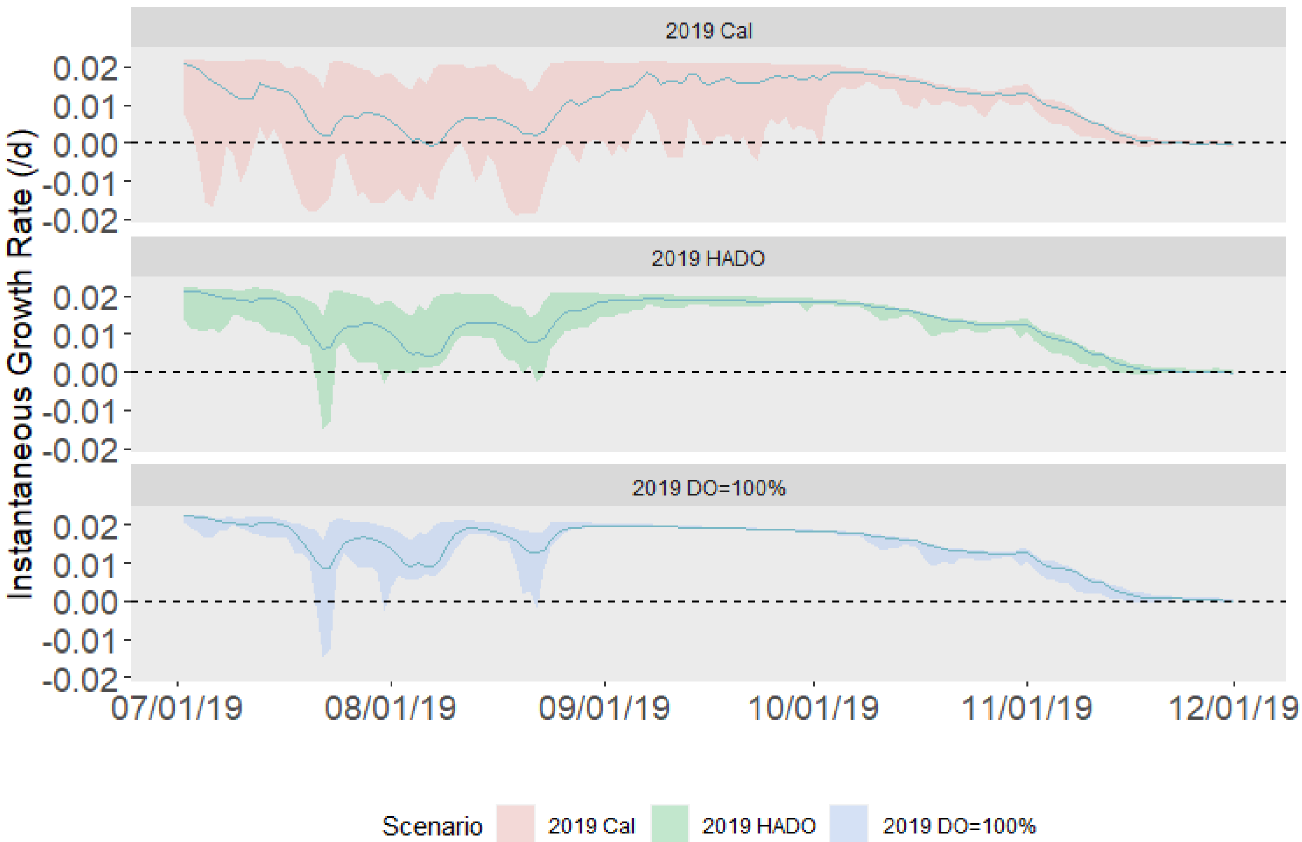


Estimated mortality rates due to low DO can be related to percent DO saturation and water temperature via a log-linear regression



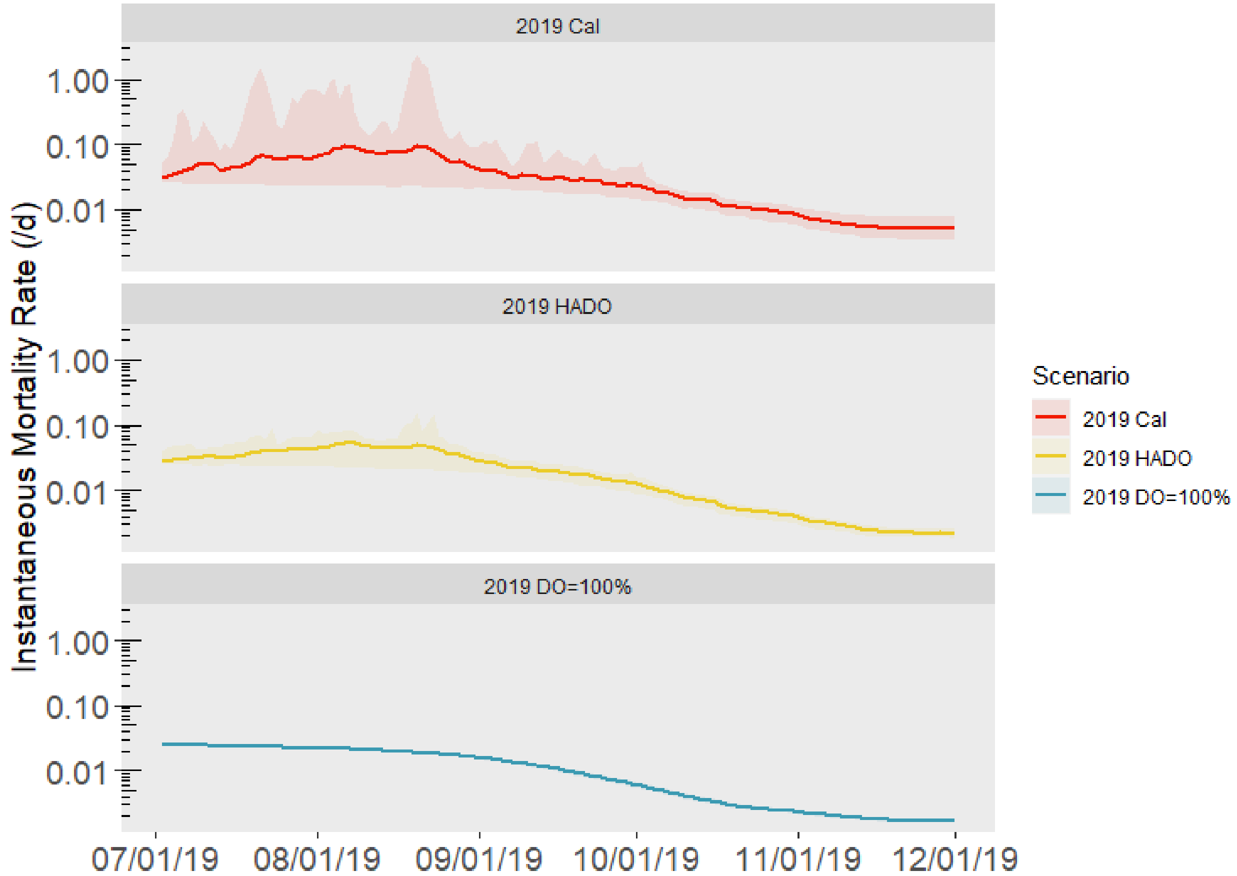
M=0.001 d^{-1} and 0.0011 d^{-1} were substituted for 0 to allow for log-transformation and graphical presentation

DO improvements in Zone 4 under the HADO scenario mostly eliminated periods with negative growth, but low DO still limited growth rate.



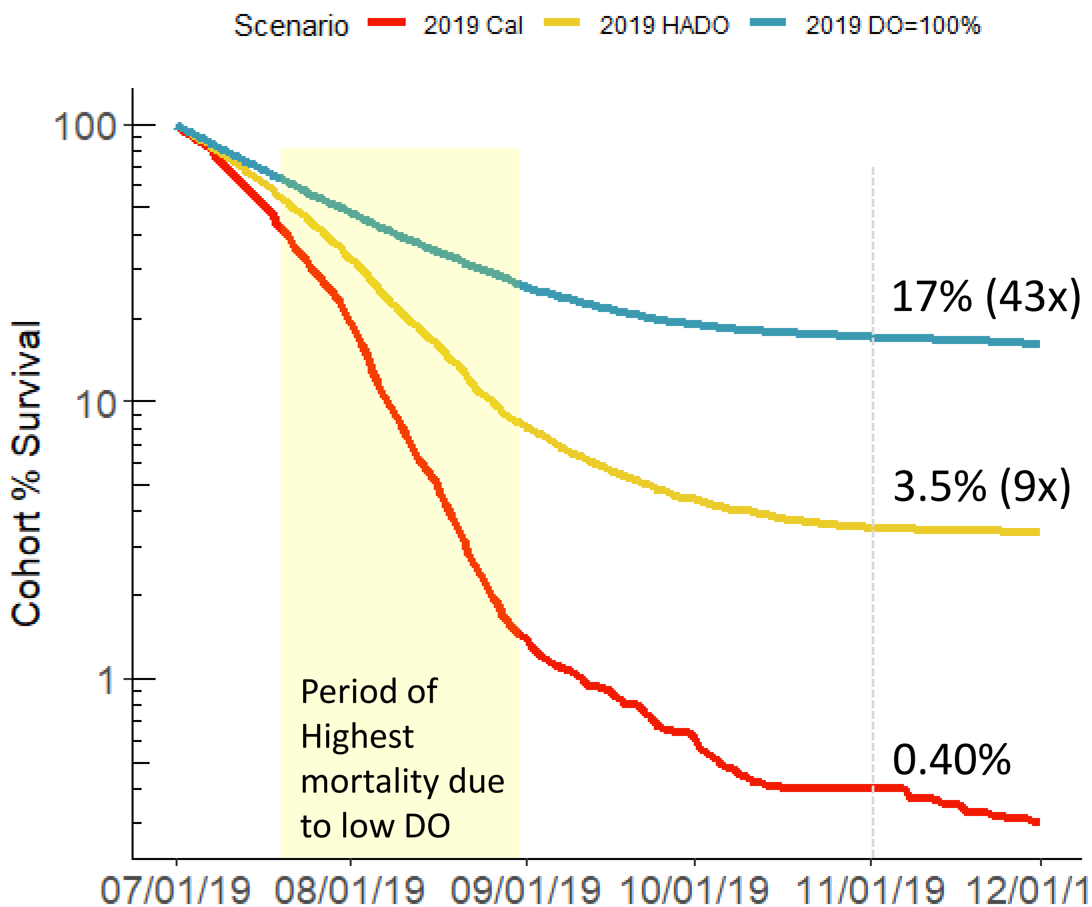
- POSAT = 100% is a diagnostic scenario … i.e., not based on any data or model simulation … shows rates with no DO impact.
- Therefore, focus on difference between scenarios.

Under the 2019 HADO scenario, mortality due to low DO was much less than in the 2019 Calibration, but low DO still caused some mortality.

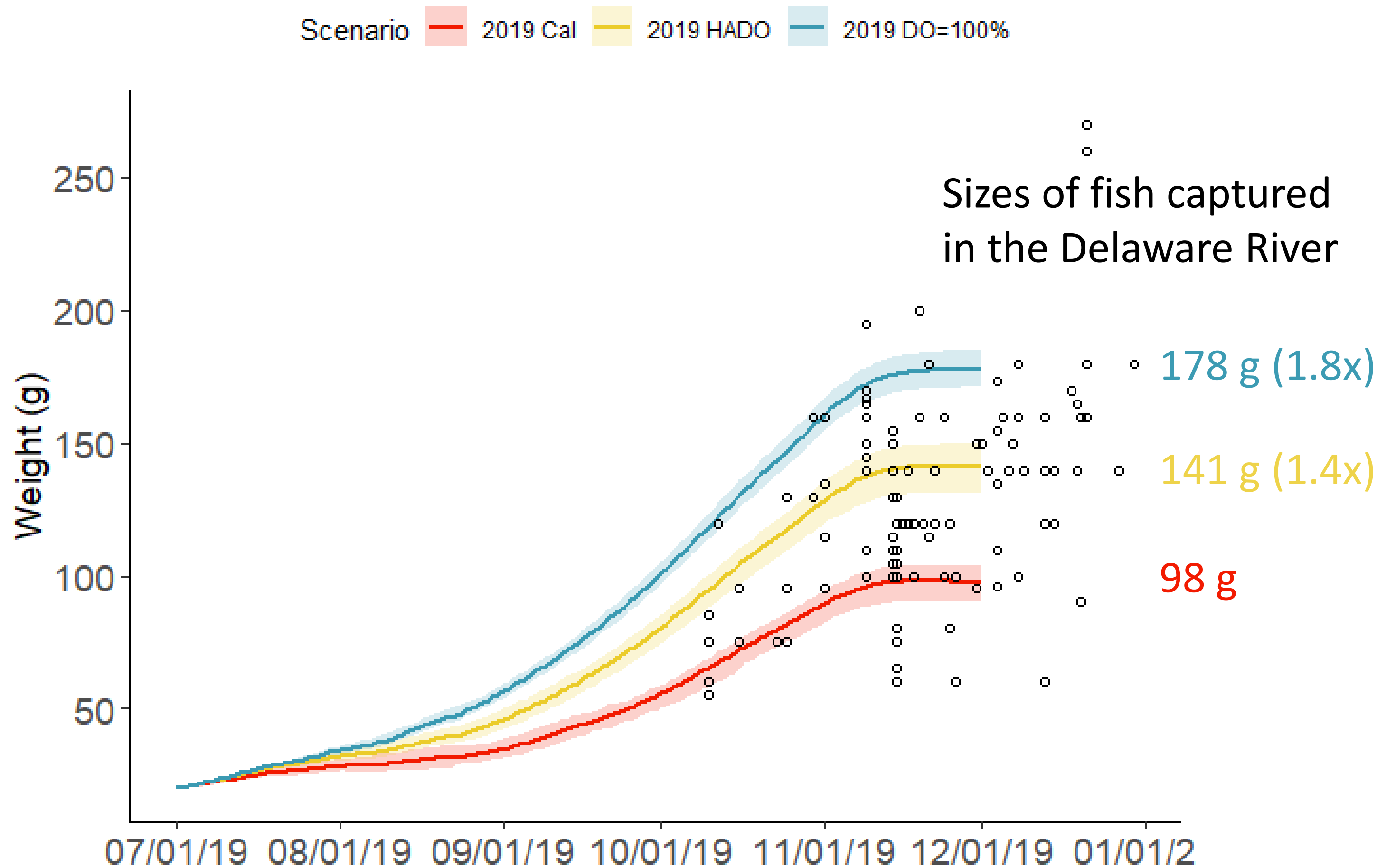


Mortality in POSAT = 100% diagnostic scenario is background rate, which decreases with increasing fish size.

The HADO scenario resulted in 9-fold greater abundance of the cohort on Nov 1, but mortality due to low DO still occurs.

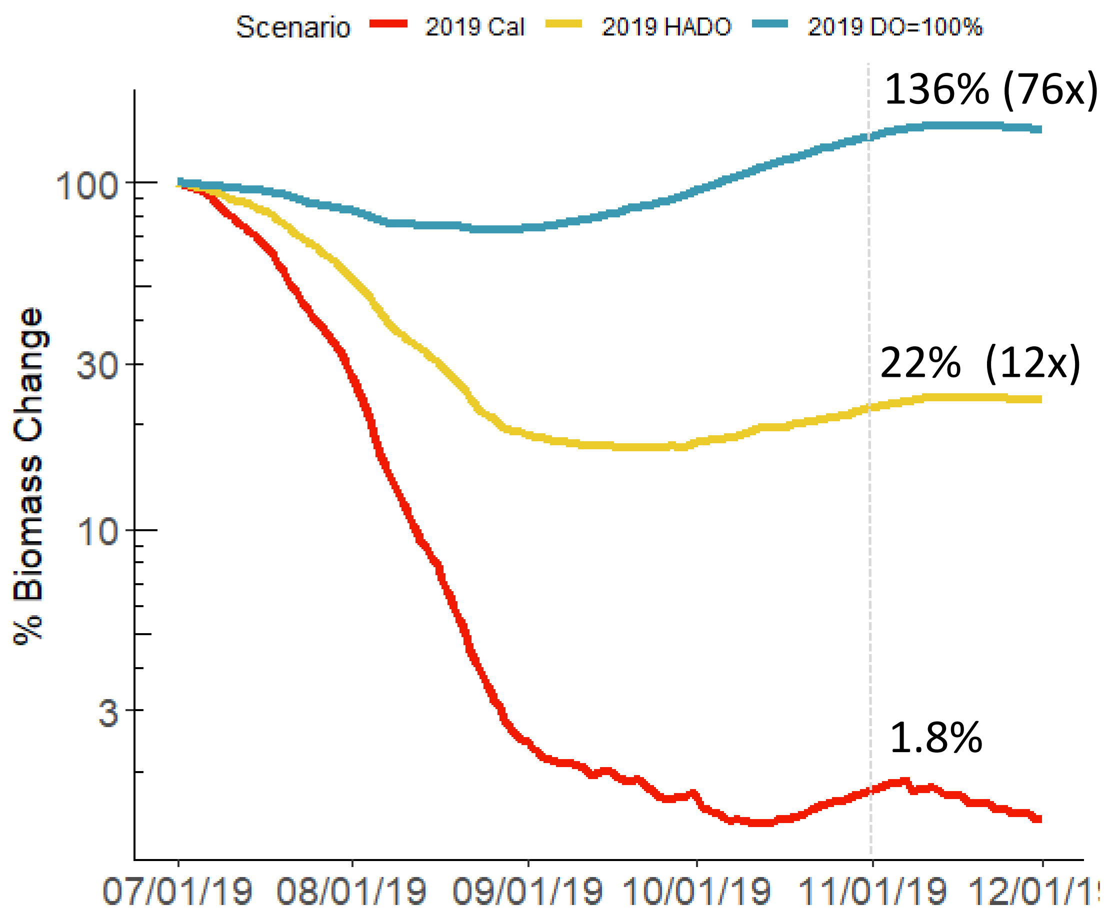


The effects of higher DO on juvenile growth are 10-20x less than the effects of DO on survival

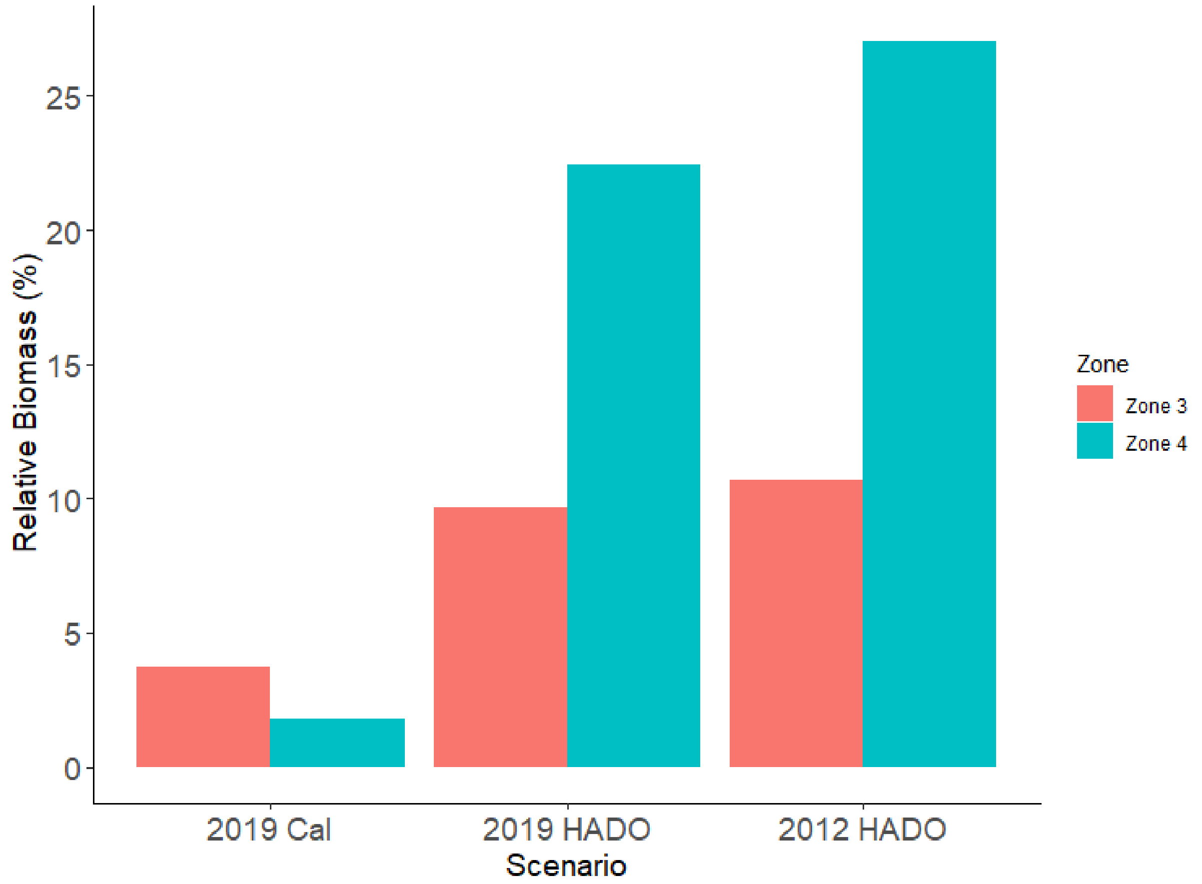


Fish data from Ian Park (DNREC)

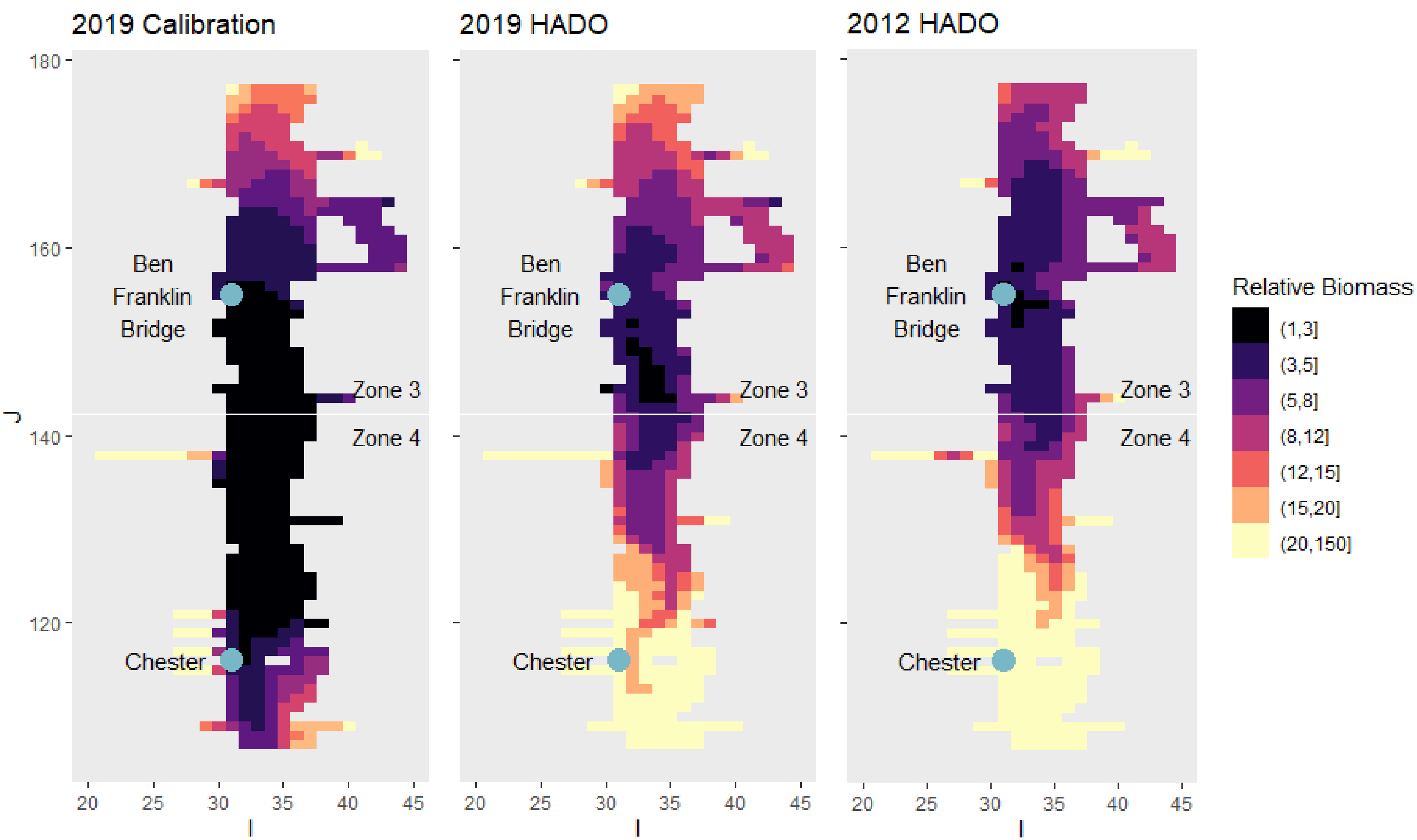
The effects of higher DO on cohort biomass reflect both growth and survival



Growth and survival was higher in Zone 3 in the 2019 Calibration, but improvement with HADO was greater in Zone 4.

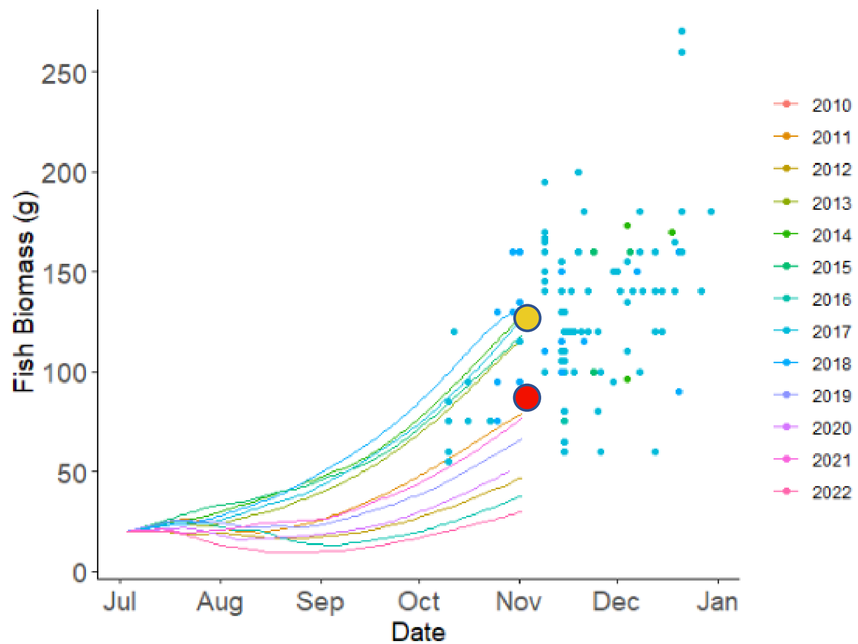


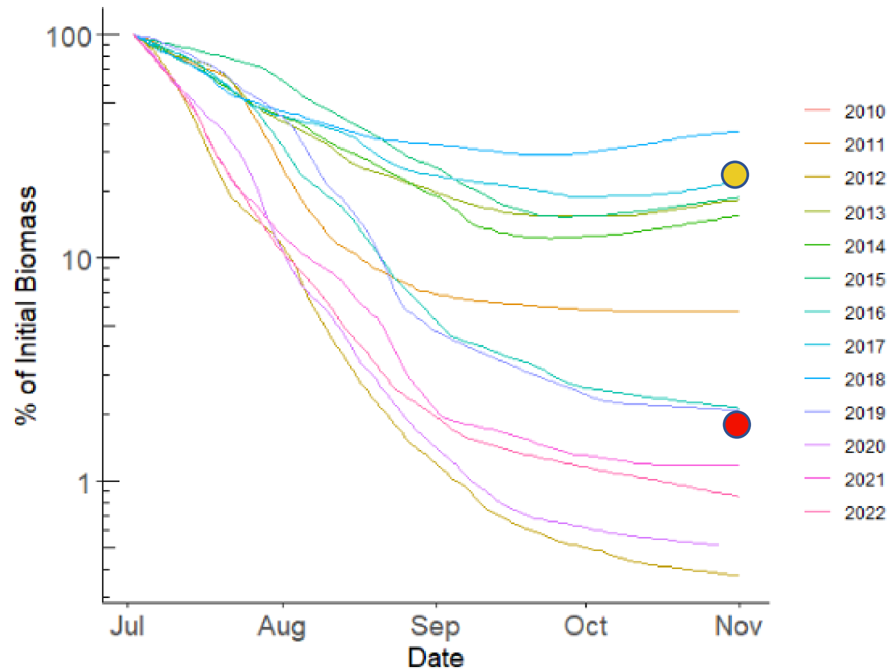
Growth and survival of juvenile Atlantic sturgeon is spatially structured. Increases in zone 4 with HADO scenario reflect increased DO overall and up-river shift



The cohort model predicts a large range of outcomes in association with water quality observed at Chester, PA

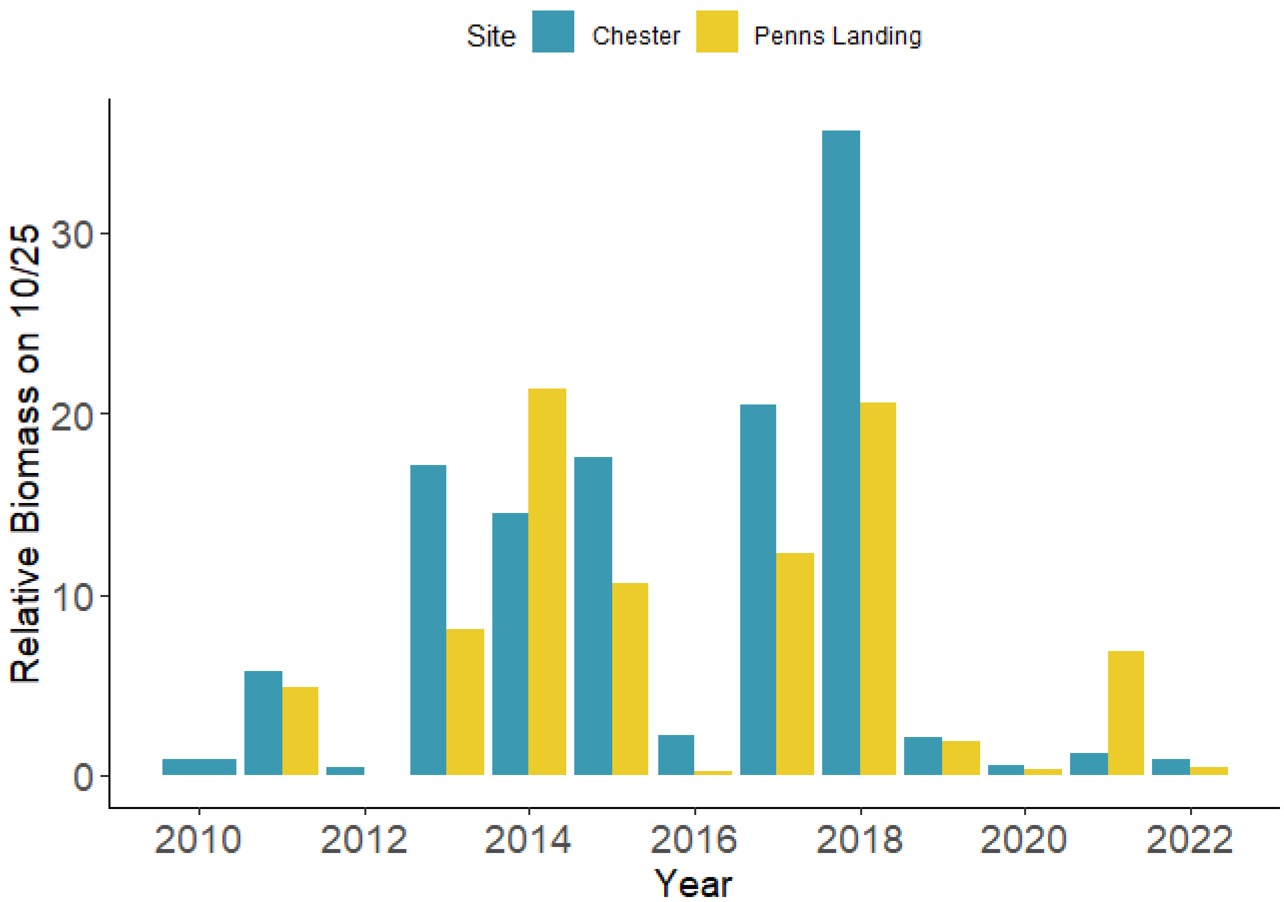
- 2019 HADO scenario for zone 4 produced cohort outcomes like the better years in the Chester time series





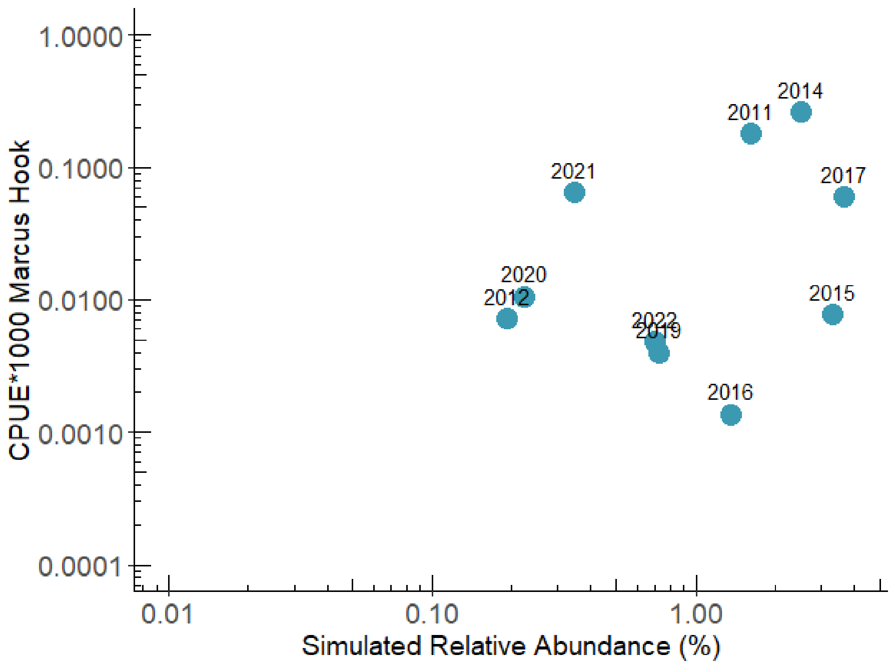
● 2019 Calibration ● 2019 HADO Scenario

Growth and survival predicted by the cohort model was usually higher for Chester than Penn's Landing, and years with favorable conditions saw better outcomes at both sites

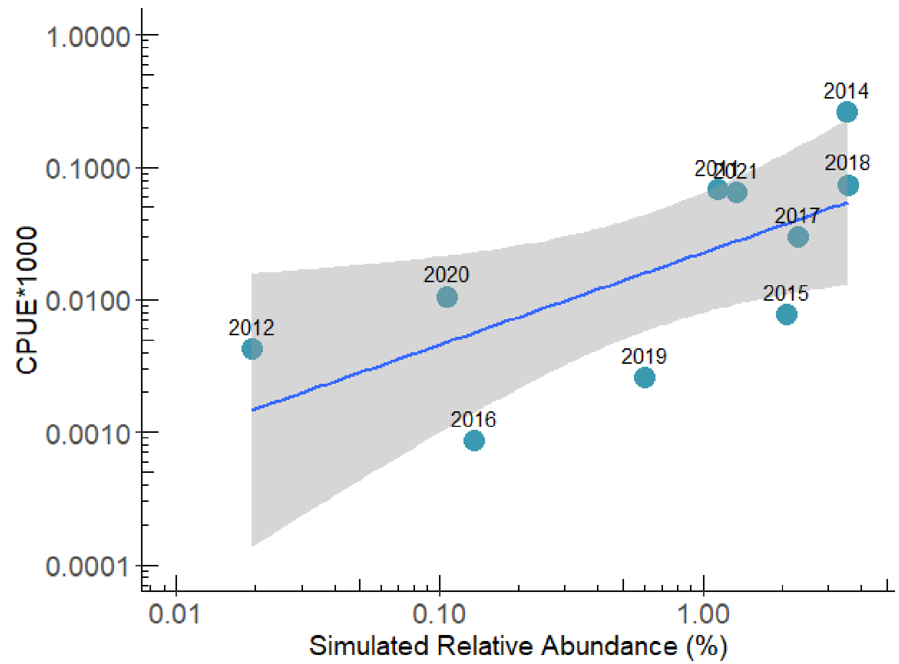


Comparison of simulated growth and survival with CPUE is variable… better correlated for Penns Landing

Simulation for Chester vs. Marcus Hook YOY CPUE



Simulation for Penns Landing vs. YOY CPUE



Conclusions

- The cohort model, although grounded in **laboratory data**, produces results **consistent with field observations** and is a useful **tool for interpreting** these data in the context of spatial and temporal water quality variability.
- The **effect of low DO on survival was quantitatively larger** than its effect on growth. However, both growth and abundance effects have been observed in data from the fish population (reported by Ian Park)
- Simulations highlight differences between the calibration and HADO management scenarios at the scale of Zones, showing **increased Atlantic sturgeon growth and survival under HADO**.
- Diagnostic simulations suggest that DO still limits Atlantic sturgeon in some of the more favorable of recent years (e.g., 2018), and that it would likely continue to limit Atlantic sturgeon in Zone 3 and 4 under the HADO scenario.
- Simulations highlight **spatial structure** of low DO in all model scenarios and their implications for growth and survival of juvenile Atlantic sturgeon.
- Model predictions highlight that **interannual variability** in water quality observed at Chester and Penn's Landing would be expected to cause large differences in Atlantic sturgeon growth and survival, **consistent with juvenile abundance data**.

This juvenile Atlantic sturgeon was caught on 10/14/2016 at Marcus Hook. It has a total length of 195 mm and weighed 30 grams. Photo by Ian Park. Collection of protected species for scientific purposes conducted under permit number 19255.