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Linking Aquatic Life Uses with Dissolved Oxygen Conditions in the Delaware River Estuary

Technical Report No. 2022-X

Managing, Protecting and Improving the Water Resources of the Delaware River Basin since 1961

Delaware River Basin Commission
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<u>Editors' Note</u>

This report is one of the four listed below, issued in support of DRBC's *Analysis of Attainability: Improving Dissolved Oxygen and Aquatic Life Uses in the Delaware River Estuary,* a draft of which was released in September 2022 for review by members of the Commission's Water Quality Advisory Committee, co-regulator agencies, Tier 1 dischargers, and DRBC Commissioners.

1. Modeling Eutrophication Processes in the Delaware River Estuary: Three-Dimensional Hydrodynamic Model (DRBC, 2021 Draft)

2. Modeling Eutrophication Processes in the Delaware River Estuary: Three-Dimensional Water Quality Model (DRBC, 2022a Draft)

3. Social and Economic Factors Affecting the Attainment of Aquatic Life Uses in the Delaware River Estuary (DRBC, 2022b Draft)

4. Linking Aquatic Life Uses with Dissolved Oxygen Conditions in the Delaware River Estuary (DRBC, 2022c Draft)

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- The Delaware River Estuary co-regulator agencies, including staff and experts from the Delaware Department of Natural Resources and Environmental Control (DNREC), New Jersey Department of Environmental Protection (NJDEP), Pennsylvania Department of Environmental Protection, (PADEP) and United States Environmental Protection Agency (EPA).
- Members of DRBC's Water Quality Advisory Committee.
- Delaware River Basin Fish and Wildlife Management Cooperative, comprised of fisheries representatives from the Delaware Division of Fish and Wildlife, New Jersey Division of Fish and Wildlife, New York State Division of Marine Resources, Pennsylvania Fish and Boat Commission, U.S. Fish and Wildlife Service, and NOAA Fisheries. DRBC also acknowledges with appreciation the entities that, together with DRBC, serve as liaison members of the Co-op, including the National Park Service, Philadelphia Water Department, and The Nature Conservancy.
- The Academy of Natural Sciences of Drexel University, and in particular, Richard J. Horwitz, Allison Stoklosa, David Keller, and Raffaela Marano, who performed a literature review to identify fish species of the Delaware Estuary that are sensitive to dissolved oxygen and determine the dissolved oxygen requirements of each. The investigators assembled their research into the report, *A Review of Dissolved Oxygen Requirements for Key Sensitive Species in the Delaware Estuary* (Stoklosa et al., 2018) for DRBC.

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LIST OF ACRONYMS/ABBREVIATIONS

CMC	Criteria Minimum Concentration
DO	dissolved oxygen
DRBC	Delaware River Basin Commission (or Commission)
EPA	U.S. Environmental Protection Agency (or USEPA)
ESA	Endangered Species Act Endangered Species Act
LC5	Lethal concentration at which 5% mortality occurs (basis for CMC)
LC50	Lethal concentration at which 50% mortality occurs over a specified period
NOAA	National Oceanic and Atmospheric Administration
PBF	physical and biological features (NOAA Fisheries parlance)
RM	river mile
USGS	U.S. Geological Survey
Zone	DRBC water quality management Zone

1. Background and Purpose

The Delaware River Estuary[1] is divided into five water quality assessment and management zones, numbered 2 through 6. The most urbanized segment of the Delaware River is the 38-mile reach of the Estuary that extends from Philadelphia to Wilmington, encompassing Zones 3 and 4 and the upper portion of Zone 5. The designated aquatic life uses of this reach, which were established in 1967, include "maintenance of resident fish and other aquatic life" and "passage of anadromous fish" (DRB Water Code, §§ 3.30.3 – 3.30.5; DRBC, 2013). Unlike the adjoining reaches of the tidal Delaware River upstream in Zone 2 and downstream within Zones 5 and 6, these uses do not include propagation.[2] In 1967, fish maintenance and fish passage were aspirational goals through much of the Estuary, and levels of dissolved oxygen (DO) sufficient to support propagation were believed to be unattainable in the Estuary's most densely developed sections. Thanks to the collective efforts of the DRBC, Congress, the EPA, Estuary states, and wastewater treatment plant owners and operators, DO levels in the Estuary over the past 50 years have recovered such that the daily average dissolved oxygen in Zones 3, 4 and upper Zone 5 today remains above the 3.5 mg/L required by the current water quality standards. In 2015, DRBC conducted an analysis of fish propagation in the Estuary (DRBC, 2015). The study revealed that some degree of propagation has been observed for a number of fish species, including several DO-sensitive species like Atlantic Sturgeon (*Acipenser oxyrhinchus*) and Striped Bass (*Morone saxatilis*), in the compromised zones.

Recognizing the significant water quality improvements achieved in the Estuary, the DRBC Commissioners unanimously approved Resolution No. 2017-4 (the Resolution), directing staff to determine, in close consultation with the Commission's Water Quality Advisory Committee, co-regulators and stakeholders, the appropriate water quality standards, including aquatic life uses and water quality criteria necessary to support those uses, for the 38-mile reach referred to at times as the "fish maintenance area," or "FMA."

The purpose of this report is to synthesize the aquatic life use studies conducted pursuant to Resolution No. 2017-4 to determine the ranges of DO values that support propagation of DO-sensitive species. The aquatic life use studies required by the Resolution and the activities undertaken to satisfy these studies are described below.

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[1] The coastal water body where freshwater from rivers and streams mixes with salt water from the ocean is called an estuary. The estuary formed by the Delaware River, referred to interchangeably in this document as the "Delaware River Estuary," the "Delaware Estuary," and the "Estuary," consists of both a tidal river and a bay. The Delaware River Estuary therefore includes both the tidal Delaware River (Zones 2–5) and the Delaware Bay (Zone 6).

[2] "Propagation" includes reproduction (spawning), larval and juvenile development, and ultimately, recruitment to adults for resident species and recruitment through outmigration for anadromous species.

1) "input on the DO requirements of aquatic species"

   DRBC engaged the Academy of Natural Sciences of Drexel University (ANSDU) to perform a literature review of the DO requirements of sensitive aquatic species in the Delaware Estuary (Stoklosa et al., 2018). The objectives of this study were to create a candidate list of DO-sensitive species and to identify relevant literature on the oxygen requirements of each at different life stages.

2) "field studies of the occurrence, spatial and temporal distribution of the life stages of Estuary fish species"

   Although the ANSDU study identified the seasonal and spatial occurrences of key species at different life stages, actual data on occurrence, spatial and temporal distribution of life stages were obtained primarily from ichthyoplankton sampling (PSEG, 2018) performed by Environmental Consulting Services, Inc. to fulfill permit requirements for Salem Generating Station. DRBC supplemented these data in several ways, as described in Section 2.3 below.

3) "input from consultations related to the Endangered Species Act"

   Formal consultation between the U.S. Environmental Protection Agency (EPA) and NOAA Fisheries (formerly, National Marine Fisheries Service or "NMFS") pursuant to Section 7 of the Endangered Species Act (ESA) is expected to occur with regard to the Atlantic Sturgeon and Shortnose Sturgeon in connection with EPA's review and approval of water quality standards established by the Estuary states through the DRBC. Outside of that process, DRBC has consulted with both EPA and NOAA Fisheries. DRBC will provide technical support to the EPA as needed during the ESA consultation process.

This report does not propose revised water quality criteria. The development of criteria will occur in collaboration with an interagency team of co-regulators and the Commission's Water Quality Advisory Committee, based on the science the report presents. The adoption of revised water quality standards, comprised of updated aquatic life uses and the criteria to support these uses, will occur through a rulemaking process in which all stakeholders and members of the public have an opportunity to provide their input and perspectives.

2. Evaluation of Suitability for Aquatic Life Use

2.1 Use of Dissolved Oxygen to Define Degree of Support for Propagation

Fish in the Delaware River Estuary face many stressors, including variable salinity and temperature conditions, mortality from ship strikes, losses through impingement and entrainment in water intakes, inadequate prey availability, and loss of spawning habitat; however, it is widely understood that for many fish species, propagation is strongly related to and dependent upon DO levels in the water column. The amount of DO in the water available to fish for uptake is determined by the percent (%) of DO saturation (i.e., concentration of DO in equilibrium with atmosphere). DO saturation is dependent primarily on temperature and atmospheric pressure, and is also affected by salinity and other dissolved constituents. Fish "breathe" by transferring DO to their blood as water moves past their gills. The transfer efficiency is reduced under lower degree of saturation. As a result, when DO saturation drops, fish may experience hypoxic conditions that impair living resources. The effects of hypoxia on fishes include reduced growth, reduced metabolic efficiency, and mortality.

For this reason, DRBC is using DO concentration as the basis for assessing whether and the extent to which water quality conditions support aquatic life uses, and fish propagation in particular. In effect, aquatic life use is understood to be the degree of propagation associated with a given DO condition. The word “condition” is important, because the level of DO is dynamic in both space throughout the Estuary and time throughout the year. The balance of this chapter describes the occurrence and distribution of DO-sensitive species and identifies the range of DO levels they require.

2.2 Identification of DO-Sensitive Fish Species

In November 2018, ANSDU completed a literature review, the purposes of which were to create a list of DO-sensitive species within the Delaware Estuary and identify relevant literature on their oxygen requirements at different life stages (Stoklosa et al., 2018). The review was conducted in two phases.

The first phase produced a comprehensive list of species in the Estuary that were deemed to be sensitive to low DO because they had high observed mortality or behavioral changes in conditions of lowered DO or were identified as having relatively high lethal or sub-lethal DO requirements (typically DO >3.5 mg/l). Published scientific sources were generally used, with special effort made to identify and obtain the most recent and reliable studies and reports. Unpublished data were used where available, relevant, and of high technical quality. The resulting sensitive species list included 36 fish species and 15 invertebrate species (ANSDU, 2018).

The second phase of the review involved paring down the list of candidate DO-sensitive species to key species, determining their seasonal and spatial occurrences within the Delaware Estuary at different life stages,[3] and compiling DO thresholds and associated effects for each species. The species list was consolidated by comparing seasonal and spatial occurrences. Where several sensitive species overlapped in time and space, the least tolerant species was selected as the primary sensitive species. Fourteen species of fish and invertebrates were determined to be the key oxygen-sensitive species for the Delaware Estuary: Shortnose Sturgeon (*Acipenser brevirostrum*), Atlantic Sturgeon, American Shad (*Alosa sapidissima*), blue crab (*Callinectes sapidus*), Atlantic rock crab (*Cancer irroratus*), eastern elliptio (*Elliptio 4omplanate*), scud (*Gammarus* spp.), Channel Catfish (*Ictalurus punctatus*), Largemouth Bass (*Micropterus salmoides*), White Perch (*Morone americana*), Striped Bass, Summer Flounder (*Paralichthys dentatus*), Yellow Perch (*Perca flavescens*), and Bluefish (*Pomatomus saltatrix*). A more detailed explanation of the literature review methodology can be found in Stoklosa et al. (2018).

DRBC further narrowed the list to eight fish species found in the portion of the Estuary comprising the FMA: Shortnose Sturgeon, Atlantic Sturgeon, American Shad, Channel Catfish, Largemouth Bass, White Perch, Striped Bass, and Yellow Perch. Special attention was given to Atlantic Sturgeon and Shortnose Sturgeon because these species have been designated as endangered under the ESA (see Appendix A).

2.3 Spatial and Temporal Distribution

Figure 2-1 shows the patterns of spatial (by water quality management zone) and temporal (by season) occurrence for all life stages[4] for each of the eight DO-sensitive fish species, based on a combination of observational data, literature, and professional experience. Observational data were primarily from ichthyoplankton sampling (PSEG, 2018) performed by Environmental Consulting Services, Inc. ("ECSI") to fulfill permit requirements for Salem Generating Station. The study was expanded geographically by DRBC to cover the entire Delaware Estuary. Notably, the ECSI ichthyoplankton survey targeted fish with free-drifting pelagic eggs and larvae, like alosines (river herrings and shad) and moronids (striped bass and white perch). Species with demersal eggs, such as sturgeons, or shallow-water nest/cavity spawners, such as largemouth bass and channel catfish, are under-sampled by this study methodology. In order to determine the spatial and temporal distributions for species under-sampled by the ECSI ichthyoplankton survey, DRBC also considered: 1) data from the NOAA Fisheries Endangered Species Act Section 7 mapper for the endangered sturgeon species (see Appendix A); 2) literature reviews performed by ANSDU (Stoklosa et al., 2018) and DRBC; and 3) professional experience. The representations in Figure 2-1 constitute conservative estimates of the presence (both timing and distribution) of sensitive species in the Delaware Estuary. By "conservative" in this context, we mean that the presence of a species is more likely to be over- than under-represented.

[3] Life stages with regard to fish species include eggs, larvae, juveniles, and adults.

[4] For the purpose of documenting occurrence, life stages are subdivided into adult, juveniles and "all," the latter of which also includes egg and larval stages.

Spring (April 1 - June 30)

Zone	Shortnose Sturgeon	Atlantic Sturgeon	American Shad	White Perch	Striped Bass	Channel Catfish	Largemouth Bass	Yellow Perch
2								
3				*All life stages present*				
4								
5								
6		*Juveniles and adults present*					*Absent*	

Summer (July 1 - September 30)

Zone	Shortnose Sturgeon	Atlantic Sturgeon	American Shad	White Perch	Striped Bass	Channel Catfish	Largemouth Bass	Yellow Perch
2								
3				*All life stages present*				
4								
5								
6		*Juveniles and adults present*					*Absent*	

Fall (October 1 - November 30)

Zone	Shortnose Sturgeon	Atlantic Sturgeon	White Perch	Striped Bass	Channel Catfish	Largemouth Bass	Yellow Perch	American Shad
2								
3					*Juveniles and adults present*			*Juveniles present*
4								
5								
6						*Absent*		

Winter (December 1 - March 31)

Zone	Shortnose Sturgeon	Atlantic Sturgeon	White Perch	Striped Bass	Channel Catfish	Largemouth Bass	Yellow Perch	American Shad
2								
3					*Juveniles and adults present*			*Juveniles present*
4								
5								
6						*Absent*		

Figure 2-1: Summary of occurrence by zone and by season of sensitive species in the Delaware Estuary

2.4 Seasonal Considerations

DRBC evaluated the spatial (by zone) and temporal patterns of spawning and nursery (i.e., egg and larval development) activity as well as juvenile development for the eight DO-sensitive fish species present in the FMA. Data from ECSI's ichthyoplankton sampling provide important information on the timing of spawning in the Delaware Estuary. On behalf of PSEG and DRBC, ECSI sampled early life stages of fish throughout the Estuary, mainly targeting species such as alosines (river herrings and shad) and moronids (striped bass and white perch), which produce free-drifting eggs and larvae, and generally excluding species with demersal eggs (i.e., eggs deposited on the bottom), like sturgeons. A summary of relevant sensitive species captured by ECSI's ichthyoplankton sampling (Figure 2-2) shows a steep drop-off in the presence of egg and larval life stages after the end of June. With regard to Atlantic Sturgeon, the critical habitat designation by NOAA Fisheries states that "temperatures of 13 to 26 °C likely support spawning habitat" (NOAA, 2017, p. 39217). In the Delaware Estuary, water temperatures generally exceed 26°C beginning in July (e.g., USGS 0147750 Delaware River at Chester).

It is reasonable, therefore, to define a critical spawning/nursery period beginning on May 1, when dissolved oxygen levels begin to decrease such that they become relevant to fish propagation, through June 30. The remainder of the time during which low DO events can be expected to occur, from July 1 through October 15, can be viewed as a critical growth/development period. Of course, spawning begins much earlier than May 1, and juvenile development continues past October 15; however, the period from May 1 to June 30 is when DO conditions are especially important for spawning and nursery success, and the period from July 1 to October 15 is when DO conditions are especially important for juvenile development. For example, although American Shad spawn as early March 1, and juvenile development occurs year-round throughout the Estuary, DO levels during the critical spawning/nursery and growth/development periods from May 1 to October 15 may substantially affect American shad recruitment.

DRBC evaluated the water temperature patterns in the Delaware Estuary and defined seasons such that recurring peak temperatures are captured in the summer, and the demarcation between spring and summer aligns with the designation of critical spawning/nursery and growth/development periods: spring is April 1 through June 30; summer is July 1 through September 30; fall is October 1 through November 30; and winter is December 1 through March 31.

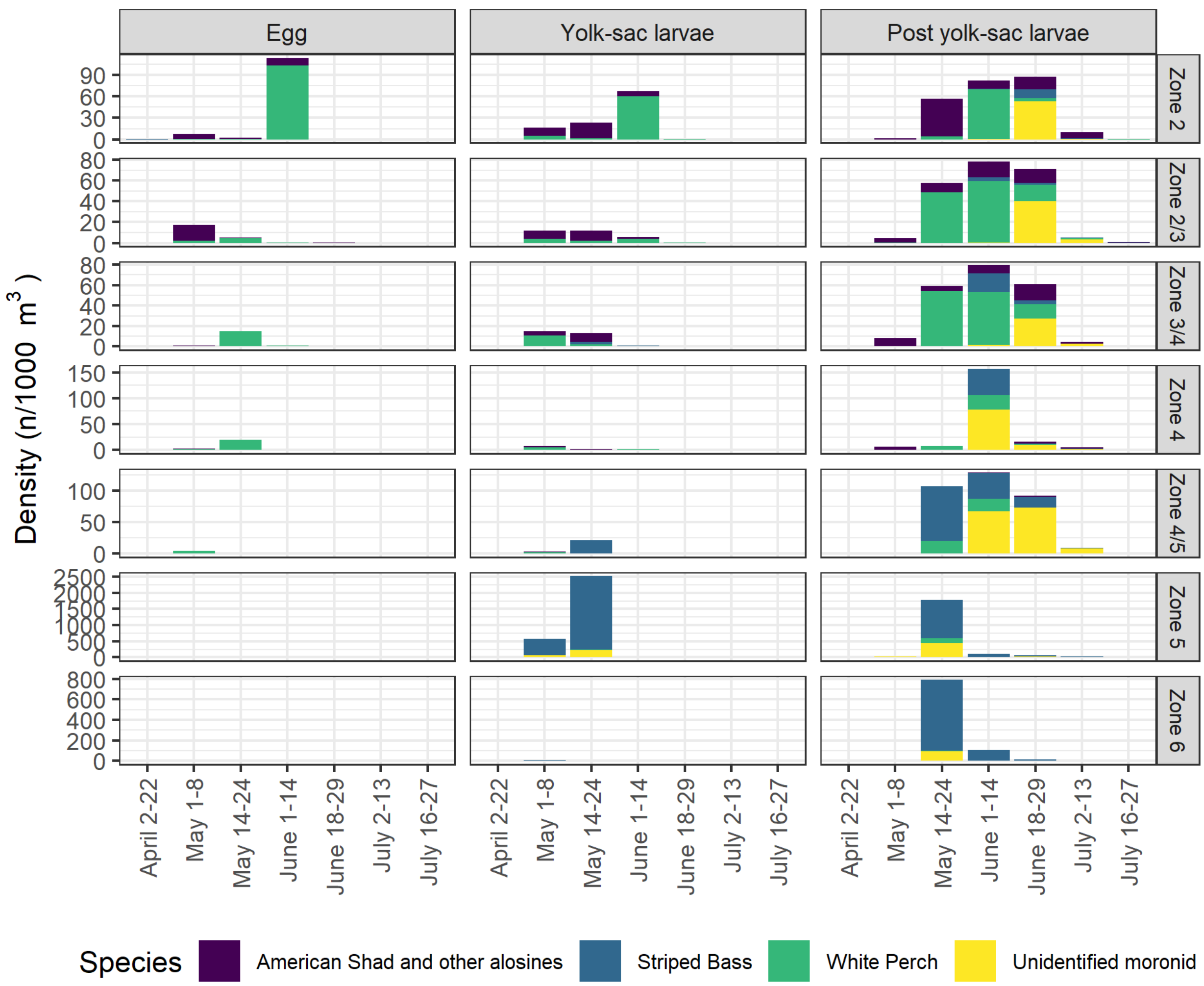

Figure 2-2: Spatial and temporal occurrence of egg and larvae stages of sensitive species captured during ECSI ichthyoplankton sampling

2.5 Identification of Key DO Thresholds

Based on the literature review and other available information, DRBC identified three types of DO thresholds for propagation of each of the eight DO-sensitive fish species (Table 2-1). For some species, gaps in the literature prevented the assignment of one or more of these thresholds.

- *Minimum Suitability Threshold*: The minimum suitability threshold represents a DO concentration below which acute mortality will occur for at least one sensitive species in the Delaware Estuary under certain conditions, such that water quality can be characterized as unsuitable for propagation.

- *Upper DO Threshold*: The upper DO threshold is the DO value above which no additional benefit from increased DO is expected. Functionally, this represents the highest value identified in the literature at which a Delaware Estuary DO-sensitive species showed a DO response. Above this value, no additional benefit in terms of propagation success has been observed.

- *Protective values*: These are the DO values between the minimum suitability and upper threshold that have been determined to be protective of propagation in various contexts and circumstances. The exact level of propagation corresponding to each will depend on the timing, frequency, and duration of exposure. Infrequent exposures of short duration to dissolved oxygen values near the minimum suitability threshold may still be supportive of fish propagation, especially if these conditions do not occur at times when fish are at their most vulnerable stages.

Table 2-1: Key Suitability Thresholds for DO-Sensitive Fish in Delaware Estuary

Species	Stage	DO	Type	Source	Notes
Shortnose Sturgeon	Juvenile	4.3	Minimum	EPA 2003	EPA developed Criteria Minimum Concentrations of 4.3 mg/L at stressful temperatures (>29°C) and 3.2 mg/L at normal temperatures.
Atlantic Sturgeon	Juvenile	4.3	Minimum	EPA 2003 / NOAA 2017	EPA developed Criteria Minimum Concentration of 4.3 mg/L at stressful temperatures (>29°C) and 3.2 mg/L at normal temperatures. Value of 4.3 mg/L cited by NOAA in critical habitat designation.
Atlantic Sturgeon	Juvenile	5.0	Protective	EPA 2003 / Moberg and DeLucia 2016	Interpretation of experimental studies concluded 60% saturation level (5 mg/L @25°C) would protect sturgeon from nonlethal effects.
Atlantic Sturgeon	Juvenile	>5.0 for >30d	Protective	NOAA Fisheries 2017	Interpretation of experimental studies concluded DO less than 5.0 mg/L for longer than 30 days is less likely to support rearing when water temperature is greater than 25°C.
Atlantic Sturgeon	Juvenile	5.9	Upper Threshold	Niklitschek and Secor 2009b	Bioenergetics modeling of experimental results showed max growth rate achieved at 5.5; max metabolic rates at 5.9 mg/L.
Atlantic Sturgeon	Juvenile	6.0	Upper Threshold	NOAA Fisheries 2017	Interpretation of experimental studies concluded 6.0 mg/L likely supports juvenile rearing habitat.
American Shad	Adult	5.0	Protective	Walburg and Nichols 1967 as in Stier and Crance 1985	Habitat suitability index cited observational study that found DO was 5 mg/L or more throughout spawning areas.
American Shad	Egg & Larval	5.0	Minimum*	Marcy 1976 as in Stier and Crance 1985	Habitat suitability index cited observational study that found no shad eggs at DO less than 5 mg/L.*

Species	Stage	DO	Type	Source	Notes
American Shad	Juvenile	4.0	Minimum	Tagatz 1961	Experimental study found no mortalities occurred when dissolved oxygen was maintained between 2 and 4 mg/L.
Channel Catfish	Adult	5.0	Protective	Andrews et al. 1973; Carlson et al. 1974 as in McMahon and Terrell 1982	Habitat suitability index cited experimental studies that found DO levels of 5.0 mg/L were adequate for growth and survival.
Channel Catfish	Adult	7.0	Upper Threshold	Andrews et al. 1973; Carlson et al. 1974 as in McMahon and Terrell 1982	Habitat suitability index cited experimental studies that found DO levels ≥ 7.0 mg/L were optimal.
Channel Catfish	Egg & Larval	4.2	Minimum*	Carlson et al. 1974	Experimental study found decreased hatching success and survival.*
Channel Catfish	Juvenile	5.0	Protective	Andrews et al. 1973; Carlson et al. 1974 as in McMahon and Terrell 1982	Habitat suitability index cited experimental studies that found DO levels of 5.0 mg/L were adequate for growth and survival.
Largemouth Bass	Juvenile	4.0	Minimum	Stewart et al. 1967	Experimental study found growth substantially reduced at 26°C; the value of 4.0 mg/L is commonly applied as a minimum DO to support warmwater fisheries.
White Perch	Adult	4.0	Minimum	Meldrim, Gift, and Petrosky 1974	Experimental study found avoidance of areas with this DO.
Striped Bass	Egg & Larval	5.0	Minimum*	Turner and Farley 1971	Experimental study found decreased hatching success and survival.*
Striped Bass	Juvenile	4.0	Protective	Brandt et al. 2009	Experimental study found lowered consumption and growth.
Striped Bass	Juvenile	5.0	Protective	Krouse 1968 as in Bain and Bain 1982	Habitat suitability index cited an experimental study that found high survival.

Species	Stage	DO	Type	Source	Notes
Yellow Perch	Adult	5.0	Protective	Krieger et al. 1983	Habitat suitability index concluded 5 mg/L would be lower optimum limit.
Yellow Perch	Juvenile	5.0	Protective	Krieger et al. 1983	Habitat suitability index concluded 5 mg/L would be lower optimum limit.
Yellow Perch	Juvenile	7.0	Upper Threshold	Thorpe 1977	Literature review revealed restricted activity.

* applicable during critical spawning and nursery period (May01 through June30)

[shaded] Bounding thresholds that define suitability range over all species.

DO thresholds were identified from the technical literature that define a suitability range for propagation applicable to all eight DO-sensitive fish species. Two types of minimum suitability thresholds were identified, one applicable generally and the other specific to the spawning period. Bounding thresholds are shaded in Table 2-1 and summarized below.

- Minimum Suitability DO Threshold: 4.3 mg/L

  The value of 4.3 mg/L is driven by the minimum values for juveniles of both sturgeon species. It is consistent with criteria established by EPA for the Chesapeake Bay (EPA, 2003 and EPA, 2017) and with NOAA Fisheries' critical habitat designation for Atlantic and Shortnose Sturgeon (NOAA, 2017). Similarly, the value of 4.0 mg/L, identified as a minimum suitability threshold for juvenile American Shad, Largemouth Bass and White Perch, is commonly applied as a minimum DO to support warmwater fisheries.

  The EPA established DO criteria for the Chesapeake Bay (EPA, 2003 and EPA, 2017) based on criteria minimum concentrations (CMCs)[5] of 3.2 and 4.3 mg/L calculated for non-stressful and stressful temperatures, respectively, specifically designed to support "survival of threatened/ endangered sturgeon species" (e.g., EPA, 2017, p. 6). EPA's 2003 report identifies Shortnose Sturgeon and Atlantic Sturgeon as the ESA-listed sturgeon species that would be protected by the 3.2 mg/L criterion, and EPA (2003 and 2017) states that Shortnose Sturgeon require a minimum of 4.3 mg/L under stressful temperatures defined as those above 29°C. In establishing these criteria, EPA relied on Jenkins et al. (1993), Secor and Gunderson (1998), Secor and Niklitschek (2003), and Campbell and Goodman (2003), as described in Appendix A. The same research indicates that Atlantic Sturgeon are more sensitive to high temperatures; the stressful temperature for Atlantic Sturgeon may be 26°C, which is encountered throughout much of the summer in the Delaware Estuary. Since summer water temperatures in the Delaware Estuary typically reach 29°C, DRBC selected 4.3 mg/L as a minimum suitability level in order to establish the range of DO concentrations that are protective under all temperature conditions.

  In its designation of critical habitat for Atlantic Sturgeon (NOAA, 2017), NOAA Fisheries described "PBFs," or "physical or biological features essential for conservation that may require special management considerations or protection" (pp. 39217-39219). With regard to the New York Bight and Chesapeake Bay Atlantic Sturgeon populations, NOAA identified a number of PBFs, including water quality factors, essential to conservation of the species. Importantly, NOAA states that "these PBFs may be ephemeral or vary spatially across time. Thus, areas designated as critical habitat are not required to have the indicated values at all times and within all parts of the area"

[5] The CMC is an estimate of the lowest concentration of a material in ambient water to which an aquatic community can be exposed briefly without resulting in an unacceptable adverse effect. This is the acute criterion. For reference, EPA guidance for establishing a CMC seeks to protect 95% of individuals from mortality within 24 hours, an approximation of an LC5 (the lethal concentration at which 5% mortality occurs).

(p. 39219). As shown in Table 2-1, DRBC identified the minimum suitability value of 4.3 mg/L DO as necessary to support propagation by Atlantic sturgeon in the Estuary based on the PBF NOAA specified to support Atlantic Sturgeon conservation:

> Water quality conditions, especially in the bottom meter of the water column, between the river mouths and spawning sites with temperature and oxygen values that support: (1) Spawning; (2) annual and inter-annual adult, subadult, larval, and juvenile survival; and (3) larval, juvenile, and subadult growth, development, and recruitment. Appropriate temperature and oxygen values will vary interdependently, and depending on salinity in a particular habitat. For example, 6.0 mg/L DO or greater likely supports juvenile rearing habitat, whereas DO less than 5.0 mg/L for longer than 30 days is less likely to support rearing when water temperature is greater than 25 °C. In temperatures greater than 26 °C, DO greater than 4.3 mg/L is needed to protect survival and growth. (NOAA, 2017, p. 39219)

- Minimum Suitability DO Threshold for spawning season: 5.0 mg/L

  The value of 5.0 mg/L as a minimum DO concentration to support spawning is supported by data for both American Shad (Stier and Crance, 1985) and Striped Bass (Turner and Farley, 1971). The USFWS habitat suitability index for American shad cites observational studies that found no shad eggs at DO levels less than 5.0 mg/L and concludes that DO concentrations of 5 mg/L or more are required throughout the spawning area (Stier and Crance, 1985). An experimental study found decreased survival of striped bass eggs and larvae at DO concentrations less than 5 mg/L (Turner and Farley, 1971). While this bounding threshold is specific to spawning periods, it could conservatively be considered applicable to the entire critical spawning/nursery period ending June 30.

- Upper DO Threshold: 7.0 mg/L

  A literature review of several juvenile Yellow Perch studies revealed restricted activity at DO below 7.0 mg/L (Thorpe 1977), and the United States Fish and Wildlife Service (USFWS) habitat suitability index for Channel Catfish concludes a DO concentration of 7.0 mg/L is optimal (McMahon and Terrell 1982). Juvenile Atlantic Sturgeon exhibited reduced metabolism at DO below 5.9 mg/L (Niklitschek and Secor, 2009). DRBC therefore selected the higher value of 7.0 mg/L as the level of DO above which additional DO is not likely to benefit any of the DO-sensitive fish species in the Delaware Estuary.

3. Application to Delaware Estuary

3.1 DO Suitability Gradient

3.1.1 Bounding DO Thresholds

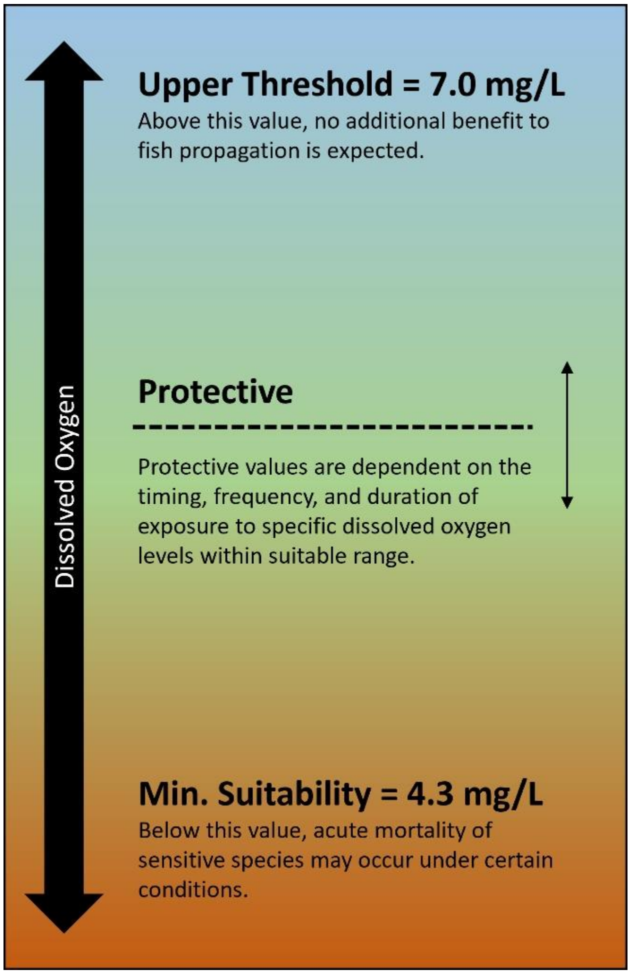

Figure 3-1: Summer gradient relating aquatic life suitability to dissolved oxygen levels

The bounding thresholds described in Section 2.5 above were used to develop a DO gradient for the support of fish propagation in the Delaware Estuary (Figure 3-1). Future water quality management scenarios that result in more areas of the Estuary exhibiting higher DO levels for longer periods of time, up to a level of 7.0 mg/L, can be expected to enhance support for aquatic life uses, and in particular for propagation of DO-sensitive fish species. On the other hand, management scenarios that result in DO levels that dip below 4.3 mg/L or approach 4.3 mg/l for longer periods of time in the summer, when water temperatures regularly exceed 26 °C, will not fully support fish propagation in the Estuary.

Importantly, in defining this conceptual model DRBC is not suggesting that either 4.3 mg/L or 7.0 mg/L should be established as a DO criterion to support aquatic life uses. Rather, protective DO values can be identified within the range of 4.3 mg/L to 7.0 mg/L that, depending on the timing, frequency and duration of water quality condition, will form the basis for criteria to support aquatic life uses in the Delaware Estuary.

3.1.2 Protective DO Values

Within the range of DO bounded by the minimum suitability concentration of 4.3 mg/L and the upper DO threshold of 7.0 mg/L, Table 2-1 shows relevant protective DO values for multiple species, including Atlantic Sturgeon. A key DO-sensitive species, Atlantic Sturgeon were once abundant. Their populations crashed in the 1900s because of overharvesting, habitat destruction, poor water quality, and commercial shipping. In 2012, NOAA Fisheries (then the National Marine Fisheries Service) designated the Atlantic Sturgeon an endangered species, and in August 2017, the Delaware Estuary was designated as critical habitat for the New York Bight Distinct Population Segment of Atlantic Sturgeon (NOAA 2017). The minimum suitability value of 4.3 mg/L in Table 2-1 is driven by the water quality needs of juvenile Atlantic Sturgeon. Similarly, multiple other agencies and researchers have attempted to identify protective DO levels for Atlantic Sturgeon, as summarized below. Additional discussion of Atlantic and Shortnose Sturgeon research is provided in Appendix A.

- In establishing criteria for the Chesapeake Bay (EPA 2003), EPA deemed that 60% DO saturation (or 5 mg/L at 25°C) would afford protection from non-lethal effects on juvenile Atlantic Sturgeon (citing data from Secor and Niklitschek, 2001). EPA adopted 5.0 mg/L as a criterion for spawning and nursery use for migratory fish in the Chesapeake applicable for the period from February 1 through May 31.

- The Atlantic State Marine Fisheries Commission reviewed the habitat requirements of diadromous fish species in its 2009 report, *Atlantic Coast Diadromous Fish Habitat: A Review of Utilization, Threats, Recommendations for Conservation, and Research Needs* (Green et al., 2009). Citing data from Niklitschek and Secor (2001), Green et al. concluded that a DO concentration of 5.0 mg/L would be optimal for juvenile Atlantic Sturgeon.

- In 2016, The Nature Conservancy (TNC) reviewed the impacts of DO on Atlantic Sturgeon in its report, *Potential Impacts of Dissolved Oxygen, Salinity and Flow on the Successful Recruitment of Atlantic Sturgeon in the Delaware River* (Moberg and DeLucia, 2016). In reliance on several of the above studies and those in Appendix A, these TNC investigators determined that a DO concentration of 5.0 mg/L is suitable for Atlantic Sturgeon.

  Notably, Moberg and DeLucia also concluded that DO below 4.0 mg/L is impaired (i.e., unsuitable), and that 6.0 mg/L DO is optimal for Atlantic Sturgeon. These values are very similar to the minimum suitability and upper DO thresholds of 4.3 mg/L and 5.9 mg/L, respectively, identified for Atlantic Sturgeon in Table 2-1.

- A research paper (Schlenger et al., 2013) proposed using “habitat volumes calculated based on threshold physiological tolerances (fixed criteria) and potential growth (bioenergetics) for Atlantic sturgeon *Acipenser oxyrinchus.*” The paper is instructive because its authors included both David Secor and Edwin Niklitschek, two of the most prominent Atlantic Sturgeon researchers, and because it proposed using physiological tolerance thresholds of 3.3 mg/L (“required”) and 5.0 mg/L (“optimal”). These thresholds were labeled as “required and optimal physiological tolerances used for fixed-criteria thresholds of young-of-the-year and yearling Atlantic sturgeon” (Schlenger at al., 2013, Table 1).

- As stated above, DRBC identified three key thresholds based on NOAA Fisheries’ critical habitat designation for Atlantic Sturgeon, issued in 2017. In response to a comment received on the proposed designation, NOAA Fisheries clarified in the preamble to its final rule that in developing the water quality examples in its proposed rule, “Our intent was to provide an example . . . of a set of conditions that we expect to correlate to Atlantic sturgeon use of an area; it was not our intent to provide an example of the DO levels that are necessary for the survival of any particular age class of Atlantic sturgeon." (NOAA Fisheries 2017, p. 39177). In addition to the minimum suitability value of 4.3 mg/L, DRBC identified the protective value of 5.0 mg/L and the upper threshold value of 6.0 mg/L from the following examples (NOAA, 2017, p. 39219), consistent with NOAA Fisheries' articulated intent.

- "In temperatures greater than 26 °C, DO greater than 4.3 mg/L is needed to protect survival and growth."
- "DO less than 5.0 mg/L for longer than 30 days is less likely to support rearing when water temperature is greater than 25 °C."
- "6.0 mg/L DO or greater likely supports juvenile rearing habitat."

3.2 Graphical Tool to Assess Degree of Suitability

A graphical tool was developed combining species distribution data with DO thresholds to visualize the degree of suitability for fish propagation in the reach of the Estuary currently designated for fish maintenance and fish passage (but not propagation) during each season. Appendix B consists of charts illustrating the methodology for Zone 3 (at Penn's Landing), Zone 4 (at Chester), and the upper portion of Zone 5 (at Delaware Memorial Bridge) during the spring (April – June), summer (July – September) and fall (October – November) seasons. Each of the nine charts (three zones in three seasons) displays the species present in the particular zone/season and the relevant DO thresholds (Table 2-1). The values for a given species represent the most stringent value of all the life stages present for that species in each zone and season. Minimum suitability thresholds for spawning were applied to spring, which ends June 30, coincident with the critical spawning and nursery period.

The symbols on the charts represent the DO thresholds identified in Table 2-1 for each relevant species: "+" is an upper DO threshold, "o" is a protective value, and "x" is a minimum suitability value. Due to gaps in the available literature, values for each of the three thresholds are not assigned for every species. The shaded regions of the plots represent levels of suitability for all species in each zone and season. The blue shading represents DO values above all upper DO thresholds, above which no additional benefit from increased DO is expected. The red shading represents DO levels below at least one minimum suitability threshold, indicating a condition unsuitable for at least one species in each zone and season. The gradient between the minimum suitability and upper DO thresholds represents conditions that are protective against acute mortality and that would support fish propagation at a level commensurate with the timing and duration of exposure to particular DO concentrations in this range. Within this gradient, higher DO concentrations would provide more support for fish propagation than lower DO concentrations.

Each plot also contains a dashed line that captures the estimated minimum DO under current conditions in each zone and season. To capture the minimum DO without capturing unrepresentative anomalies, DRBC calculated seasonal 1st percentile DO values. The current condition was characterized at the USGS water quality gages in each zone within the FMA portion of the Estuary using all available data from 2012 through the end of 2021. Zone 3 was represented by Penn's Landing #01467200; Zone 4 was represented by Chester #01477050; and the upper portion of Zone 5 was represented by the Delaware Memorial Bridge #01482100. Note that no dashed line is shown for the spring season in Zone 5 because the water quality monitor at the Delaware Memorial Bridge is relatively new, and no spring data are available through 2021.

As an example, the suitability illustration for Delaware River at Chester (Zone 4) during the summer is provided as Figure 3-2 below. The minimum suitability line is shown at 4.3 mg/L (that line is set to 5.0 mg/L in the spring illustrations to reflect the critical spawning/nursery period). At Chester, the 1st percentile of DO data, a representation of the current condition, is 4.0 mg/L, below the minimum suitability value of 4.3 mg/L. Notably, although this demonstrates attainment of the current water quality standards, it suggests that propagation is not currently supported at this location. Similarly, the illustration for Delaware River at Penn's Landing (Zone 3) during the summer demonstrates that the 1st percentile of DO data (a representation of current condition) of 3.8 mg/L falls below the DO minimum suitability threshold of 4.3 mg/L during the summer.

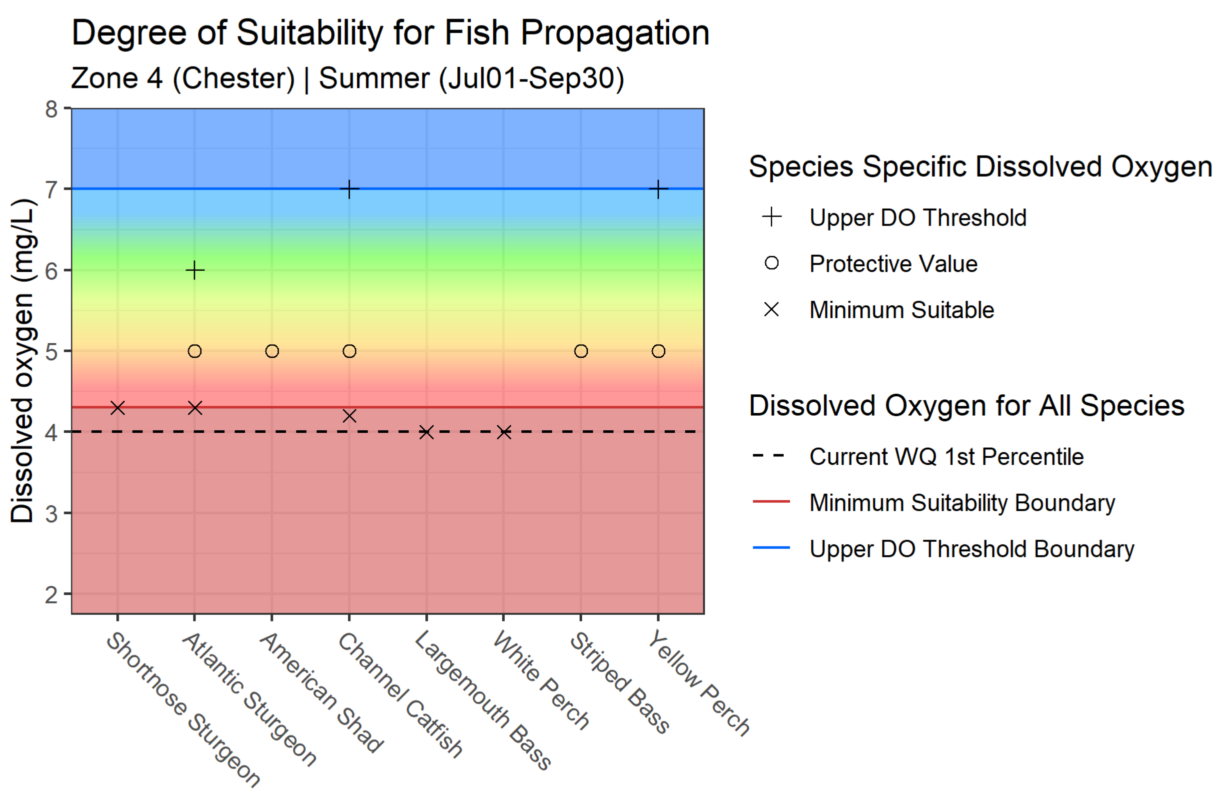

Figure 3-2: Visual evaluation of suitability at Chester during Summer (Example)

4. TECHNICAL SUMMARY AND NEXT STEP

This synthesis report of available research, including interpretations of that research by expert federal agencies, provides a scientific basis to inform and establish criteria supportive of propagation in the Delaware Estuary. The report can be summarized as follows.

- Eight DO-sensitive fish species have been identified, and their spatial and temporal distributions at various life stages have been characterized based upon available data and research.
- Two of the eight DO-sensitive species, the Atlantic Sturgeon and the Shortnose Sturgeon, have been classified as federally endangered species. Their status along with research regarding their DO needs for propagation have been considered.
- Critical periods of the year when DO levels are especially relevant for spawning/nursery use (May 1 to June 30) and growth/development (July 1 to October 15), respectively, have been identified.
- A range of DO concentrations has been defined that, depending on various exposure factors, can be supportive of fish propagation throughout the Delaware Estuary.
    - This range is bounded on the low side by a minimum suitability threshold that represents a DO concentration below which acute mortality will occur for at least one sensitive species in the Estuary.
        - A DO concentration of 4.3 mg/L is considered a minimum DO concentration required to support endangered sturgeon and other sensitive species in the Estuary under stressful temperatures that occur during the summer.
        - A minimum suitability threshold of 5.0 mg/L during the critical spawning/nursery use period of May 1 to June 30 has been identified.
    - An upper threshold of 7.0 mg/L represents the DO level above which there appears to be no further benefit to sensitive species in the Estuary.
- A visual tool was developed to evaluate the degree of suitability, which can be adapted for various criteria and locations.

DRBC regulations will be updated to incorporate revised water quality standards (designated uses and criteria) developed based upon guidance provided by the EPA for implementation of the Clean Water Act. More than one criterion will likely be adopted to account for seasonal and temporal variations in DO. The water quality criteria will consist of numeric values for DO together with the appropriate averaging period(s) (e.g., minimum, daily mean, 7-day mean), spatial extents, and periods of applicability. The development of water quality criteria based upon sound scientific rationale will be performed in collaboration with co-regulators and with input from the Commission's Water Quality Advisory Committee. A final proposal will be the subject of rulemaking to include propagation as a designated use throughout the Estuary, including in Zones 3, 4 and the upper portion of Zone 5, and to adopt water quality criteria to protect that use.

The development of criteria will consider candidate protective thresholds for the most sensitive fish species, based on the scientific literature referenced in this report. EPA guidance, EPA national criteria, and criteria developed or approved by EPA to protect similar uses (see e.g., Table 4-1) will also be considered as pertinent examples of how other states or tribes and the EPA have implemented protective values as criteria. This project also benefits from having a temporally dynamic and spatially explicit model of DO levels under critical design conditions. The model allows for volumetric comparisons (e.g., percent of volume that meets various thresholds over a particular time and spatial extent) and frequency and duration evaluations that can be used to help determine the most appropriate means of expressing criteria over time and space in the Estuary.

EPA approval of water quality standards established by states (including by joint action of states through the DRBC) may constitute a federal action that requires formal consultation with NOAA Fisheries pursuant to Section 7 of the Endangered Species Act (ESA) when, as here, the standards could impact listed species. DRBC will collaborate with and support the interagency co-regulator team, including EPA, as needed during a formal ESA consultation process.

Table 4-1: DO criteria applicable to Atlantic Sturgeon Distinct Population Segment waters

Atlantic Sturgeon Distinct Population Segment (DPS)	State	Classification / Use	Criteria	Duration	Conditions
Chesapeake Bay	MD VA	migratory fish spawning and nursury use	6 mg/L	7-d avg (Feb 1 to May 31)	salinity <0.5 ppt
		surivival/growth of larval/juvenile fish incl T&E	5.0 mg/L	minimum (Feb 1 to May 31)	
		open water fish and shellfish growth of larval, juvenile and adult fish incl T&E	5.5 mg/L	30-d avg	salinity <0.5 ppt
			5.0 mg/L	30-d avg	salinity >0.5 ppt
			4 mg/L	7-d avg	
			3.2 mg/L*	minimum	temperature < 29°C
			4.3 mg/L*	minimum	temperature > 29°C
NY Bight	PA	Passage, maintenance and propagation of warmwater, anadromous and catadromous fishes	5.5 mg/L	7-d avg	tidal
			5 mg/L	minimum at any time	
	NJ	Maintenance, migration and propagation of the natural and established biota	5 mg/L	24-hr avg	freshwater nontrout
			4 mg/L	minimum at any time	freshwater and estuarine
	NY	fish propagation and survival	5 mg/L	daily avg	freshwater nontrout
			4 mg/L	at any time	
		fish propagation and survival	4.8 mg/L	daily avg with allowabe excursions	estuarine
			3.0 to 4.8 mg/L	allowable excursions**	
		fish propagation and survival	4 mg/L	at any time	estuarine fishing
	CT	marine fish including larval recruitment	3.0 mg/L	at any time	estuarine: good to excellent
			3.0 to 3.5 mg/L	up to 2 days	
			3.5 to 4.0 mg/L	up to 7 days	
			4.0 to 4.5 mg/L	up to 14 days	
			4.5 to 4.8 mg/L	up to 30 days	
Carolinas	NC	aquatic life	5.0 mg/L	daily avg	freshwater/estuarine
			4.0 mg/L	instantaneous minimum	freshwater
	SC	survival and propagation of balanced indigenous aquatic community of fauna and flora	5.0 mg/L	daily avg	freshwater and estuarine
			4.0 mg/L	instantaneous minimum	

* Established by USEPA specifically to protect sturgeon species (including Atlantic sturgeon) and other T&E

** The DO concentration may fall below 4.8 mg/L for a limited number of days, as defined by the formula:
DOi = 13.0/2.80 + 1.84*e-0.1*ti
where: DOi = DO concentration in mg/L between 3.0-4.8 mg/L; and ti = time in days.
This equation is applied by dividing the DO range of 3.0-4.8 mg/L into a number of equal intervals. DOi is the lower bound of each interval (i) and ti is the allowable number of days that the DO concentration can be within that interval. The actual number of days that the measured DO concentration falls within each interval (i) is divided by the allowable number of days that the DO can fall within interval (ti). The sum of the quotients of all intervals (i...n) cannot exceed 1.0: i.e.,
nti (actual)
Σ< 1.0
i=1ti (allowed)
The DO concentration may not fall below the acute standard of 3.0 mg/L at any time.

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Appendix A: Atlantic and Shortnose Sturgeon Research

This appendix documents relevant research specifically related to Atlantic Sturgeon and Shortnose Sturgeon, both of which are listed as endangered under the ESA.

ESA Mapper

DRBC supplemented the observations from the ECSI ichthyoplankton survey with data from NOAA Fisheries' Endangered Species Act Section 7 mapper for the early life stages of endangered sturgeon species in the Delaware Estuary. These data are summarized below and reflected in the species distribution tables within the body of this report.

Atlantic Sturgeon Eggs and Yolk-sac Larvae (04/-1 – 08/31)

Atlantic Sturgeon eggs and yolk-sac larvae may be present in spawning locations between Claymont, DE/Marcus Hook, PA and the fall line at Trenton, NJ from April 1-August 31. Timing and range are based on the spawning time/range in the Delaware River (Breece et al., 2013, p. 5-6; Simpson, 2008, p. 66) plus an extra 30 days to account for the yolk-sac larvae stage.

Atlantic Sturgeon Post Yolk-sac Larvae (04/01 – 09/30)

Atlantic Sturgeon post yolk-sac larvae may be present in the Delaware River from the upstream limit of the spawning area at Trenton, NJ (Simpson, 2008, p. 62) to the downstream limit of the saltwater line. We expect post yolk-sac larvae to be present from April 1-September 30. Timing is based on the spawning time in the Delaware River (Breece et al., 2013, p. 5; Simpson 2008, p. 66) plus an extra 60 days to account for the post yolk-sac larvae stage. DRBC has monthly spreadsheets showing where the salt line (250 mg/L) occurs. River mile (RM) 51 by DRBC RM measurement (approximately at the Hope Creek Generating Station), recorded in March 2016, is the furthest downstream location of the salt line in the past 6 years (since the beginning of 2011). However, DRBC (2013) says the average salt front range is RM 67-76 (approximately New Castle, DE to Claymont, DE).

Shortnose Sturgeon Post Yolk-sac Larvae (03/15 – 07/31)

Shortnose Sturgeon post yolk-sac larvae may be present in the Delaware River from the upstream limit of the spawning area in Lambertville to the downstream limit of the saltwater line (DBRC, 2016). We expect post yolk-sac larvae to be present from March 15-July 31. Timing is based on the spawning time in the Delaware River (SSSRT, 2010, p. 193) plus an extra 60 days to account for the post yolk-sac larvae stage.

Primary literature regarding DO responses

The field of literature on Atlantic Sturgeon is somewhat limited. Approximately 15 studies have been cited on the dissolved oxygen requirements of Atlantic Sturgeon in the Delaware Estuary; however only five of these studies represent novel, peer-reviewed literature articles. The remaining studies are often interpretations (or interpretations of interpretations) of these initial studies. These few novel, experimental studies on Atlantic Sturgeon are valuable contributions to understanding this species' dissolved oxygen requirements; however, they do not prescribe criteria protective of Sturgeon. Due to laboratory testing limitations in the levels of dissolved oxygen treatments, age of fish, length of exposure, and coeffects of multiple parameters, it is necessary to apply professional judgment when interpreting these values. Below are the primary literature articles relating to the dissolved oxygen requirements of Atlantic Sturgeon and the closely related Shortnose Sturgeon along with a DRBC interpretive conclusion for each.

Study	**Author(s)**	**Year**
Tolerance of Shortnose Sturgeon, *Acipenser brevirostrum*, juveniles to different salinity and dissolved oxygen concentrations.	Jenkins et al.	1993
Effects of hypoxia and temperature on survival, growth and respiration of juvenile Atlantic Sturgeon, *Acipencer oxyrinchus*.	Secor and Gunderson	1998
Bioenergetics modeling and assessment of suitable habitat for juvenile Atlantic and Shortnose Sturgeons in Chesapeake Bay.	Niklitschek	2001
Acute sensitivity of juvenile Shortnose Sturgeon to low dissolved oxygen concentrations.	Campbell and Goodman	2003
Dissolved oxygen, temperature and salinity effects on the ecophysiology and survival of juvenile Atlantic Sturgeon in estuarine waters: I. Laboratory results.	Niklitschek and Secor	2009a
Dissolved oxygen, temperature and salinity effects on the ecophysiology and survival of juvenile Atlantic Sturgeon in estuarine waters: II. Model development and testing.	Niklitschek and Secor	2009b
Experimental and field evidence of behavioral habitat selection by juvenile Atlantic *Acipenser oxyrinchus oxyrinchus* and Shortnose *Acipenser brevirostrum* Sturgeons.	Niklitschek and Secor	2010
An experimental approach to evaluate the effects of low dissolved oxygen acting singly and in binary combination with toxicants on larval Atlantic Sturgeon, *Acipenser oxyrinchus oxyrinchus*.	Wirgin and Chambers	2018

Jenkins et al. (1993)

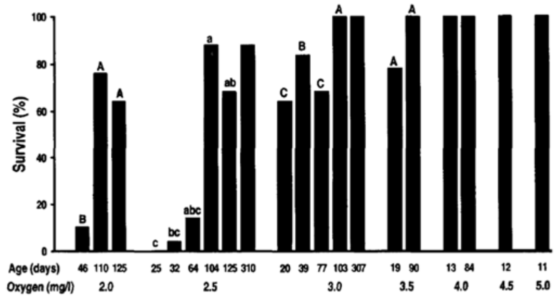


Figure 2. Survival of various aged shortnose sturgeon exposed to different oxygen concentrations. Data with same letter (anova=uppercase; Kruskal-Wallis=lowercase) within a particular test concentration are not significantly different.

The effects of short-term (6 hr) dissolved oxygen exposures on juvenile Shortnose Sturgeon (age 11-310 days) at non-stressful temperatures were examined. Cultured Shortnose Sturgeon juveniles, from Savannah River wild stock exposed to different salinity (0-35 ppt) and dissolved oxygen concentrations (2.0-5.0 mg/L, by 0.5 mg/L) at a temperature of 22.5°C. The study determined values that could be considered absolute minimum tolerance levels. No mortality was seen at values greater than or equal to 4.0 mg/L. Survival decreased as DO dropped below 4.0 mg/L, and the lethal effects at these levels were stronger in young fish than old fish.

Conclusion: Dissolved oxygen values ≥4.0 mg/L for 6 hrs or less are protective of YOY Shortnose Sturgeon mortality. Hypoxia driven mortality at levels below 4.0 mg/L is dependent on sturgeon age.

Secor and Gunderson (1998)

Table 2

Replicate tank deaths during the nested survival and growth experiment. Experiments are labeled according to the temperature treatment and whether tanks were sealed or unsealed (unsealed tanks permitted access by sturgeon to surface water). Dissolved oxygen (DO) levels, low and high, refer to prescribed levels of 3 mg/L and 7 mg/L, respectively. Rep. = replicate(s).

Experiment	DO level	Rep.	Experimental day 1	2	3	4	5	6	7	8	9	10	Survival (%)
26°C unsealed 1	Low	1			6	1	1						0
		2			2		4					2	0
		3		4			1	2	1				0
		4				1		1		1	1		50
26°C unsealed 2	High	1											100
		2											100
		3											100
		4											100
26°C sealed	Low	1	8										0
		2	7	1									0
	High	1											100
		2											100
19°C unsealed	Low	1			1		1						75
		2			1			1					75
	High	1											100
		2											100
19°C sealed	Low	1							1				88
		2						1	1				75
	High	1											100
		2											100

This study performed the first DO tests on Atlantic Sturgeon. The investigators tested the effects of hypoxia (~3 vs 7 mg/L) on survival, growth, and respiration of juvenile Atlantic Sturgeon (> 10 cm total length) at stressful (26°C) and non-stressful (19°C) temperatures over 10 days. Fish were spawned from Hudson River wild stock and salinity values were held between 1.5 and 3 ppt. Survival, growth, and respiration were all affected by hypoxia, with mortality occurring in only the ~3 mg/L treatments. Survival was significantly higher at low temps (78%) than high temps (8%) during ~3 mg/L treatments. Timing of mortality was variable, with most mortality occurring after day one.

Conclusion: A dissolved oxygen concentration of 3.3 mg/L at high temps is lethal to Atlantic Sturgeon (presumed on the timescale of multiple hours to days as most of the sturgeon tested survived at least one day under these conditions). Non-lethal effects will occur at 3.3 mg/L.

Campbell and Goodman (2003)

TABLE 2.—Estimated median lethal concentrations (LC50s) and 95% confidence intervals (CIs) for young-of-year shortnose sturgeon of different ages exposed to low dissolved oxygen at selected temperatures.

Fish age (d)	Temperature (°C)	Duration (h)	LC50 (mg/L)	95% CI (mg/L)
~77	24.6–25.0	24	2.7	2.3–3.1
~100	~28.4–29.2	24	3.1	[a]
~104	21.8–22.4	24	2.2	2.2–2.3
~134	26.0–26.4	24	2.2	2.0–2.4
		48	2.2	1.9–2.4
		72	2.2	1.9–2.4

[a] Not determined.

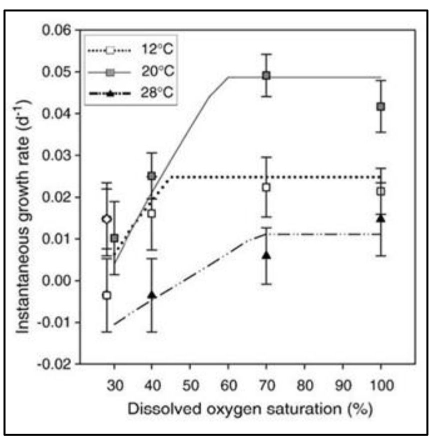
The authors developed 24-hour LC50s for Shortnose Sturgeon. A 24-hour LC50 of 3.1 mg/L was developed for juvenile Shortnose Sturgeon at stressful temperatures. LC50s ranged from 2.2 – 2.7 at lower temperatures. Data from this study were used by EPA (2003) along with guidance from EPA (2000) to develop Criteria Minimum Concentrations for dissolved oxygen which represent LC5 values for Shortnose Sturgeon (3.2 mg/L at temperatures below 29°C and 4.3 mg/L above 29°C).

Conclusion: LC50 for Shortnose Sturgeon at stressful temps for 24 hrs is 3.1 mg/L. Minimum protective concentrations (LC5) for Shortnose Sturgeon are 3.2 mg/L at temperatures below 29°C and 4.3 mg/L above 29°C.

Niklitschek (2001)

A doctoral dissertation by Edwin Niklitschek produced three important studies on the effects of hypoxia on Atlantic Sturgeon.

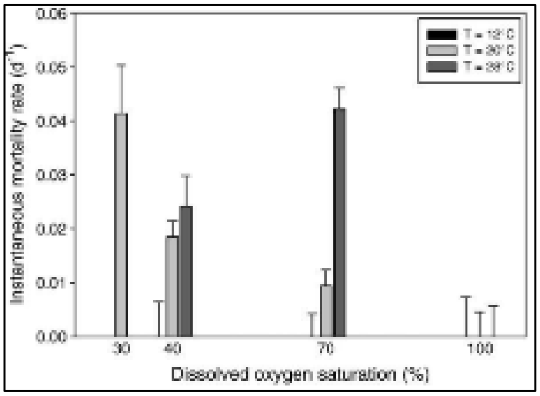
Niklitschek and Secor (2009a)

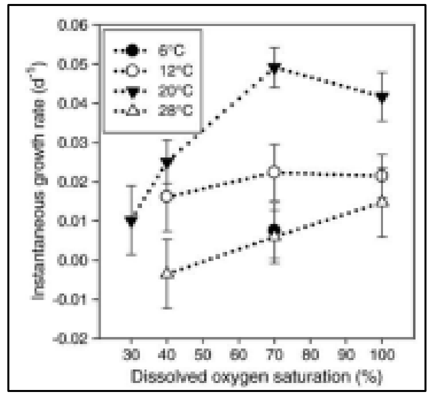


This experimental mesocosm study tested the effects of four dissolved oxygen levels (30, 40, 70, and 100% saturation) in combination with temperature (12, 20 and 28°C) and salinity (1, 8 , 15, 22, 29 ppt) over 21-day trials. Hatchery-produced Atlantic Sturgeon juveniles, offspring from Hudson River parents were used in the study. At 20°C, growth rates were higher at 70% dissolved oxygen saturation vs 30% or 40% saturation. Across all temperatures, mortality was seen at all treatment levels except 100% DO saturation. Trends in mortality were dependent on temperature.

Conclusion: At 20°C, growth and survival rates are higher at 70% DO saturation (~6.3 mg/L) than 30% or 40% saturation (~2.7 mg/L or ~3.6 mg/L).

Niklitschek and Secor (2009b)

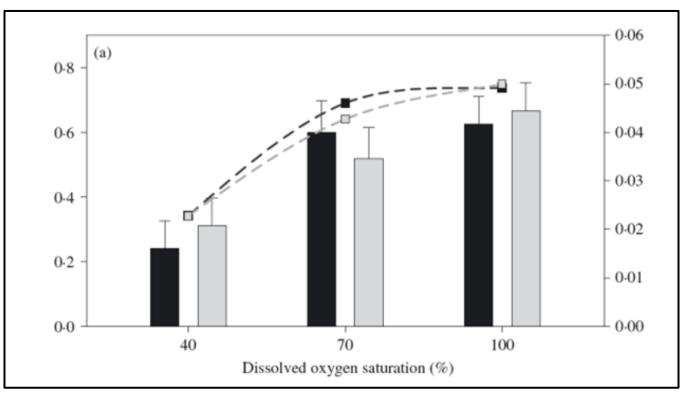




This follow-up paper developed a bioenergetics model incorporating the results of the previous study. According to the bioenergetics models, the effects of dissolved oxygen on growth and metabolism often plateaued at levels less than 70% saturation. When converted to concentrations these asymptotic values relate to 4.9 - 5.9 mg/L.

Conclusion: Upper DO saturation threshold at 20°C for juvenile Atlantic Sturgeon appears to be in the 60-65% range (~5.5 mg/L to ~5.9 mg/L) based on the bioenergetics model (see discussion below regarding upper threshold for Atlantic Sturgeon).

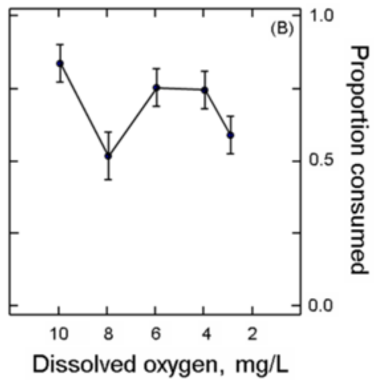
Niklitschek and Secor (2010)



The third paper from the dissertation work examined behavioral effects using the same experimental setup on hatchery-raised Atlantic (Hudson River stock) and Shortnose Sturgeon (Savannah River stock). DO tests were conducted at 20°C and a salinity of 8 ppt. Both species avoided habitats with 40% DO saturation in favor of habitats with 70 or 100% DO saturation.

Conclusion: Juvenile Shortnose Sturgeon and Atlantic Sturgeon showed preference for habitat with 70 or 100% DO saturation over 40% at 20°C and a salinity of 8 ppt.

Wirgin and Chambers (2018)



This experimental study tested the effects of DO and toxicants on larval Atlantic Sturgeon. DO concentrations of 3, 4, 6, 7, 8, and 10 mg/L were tested in combinations with toxicants over 21-day trials at non-stressful temperatures. Test organisms were hatchery-spawned Atlantic Sturgeon from Canada and South Carolina. Results varied between the sources of sturgeon (South Carolina sturgeon were younger, which could have made them more susceptible to the effects). DO affected prey consumption; however effects on mortality were inconclusive, making conclusions about meaningful DO thresholds difficult to draw.

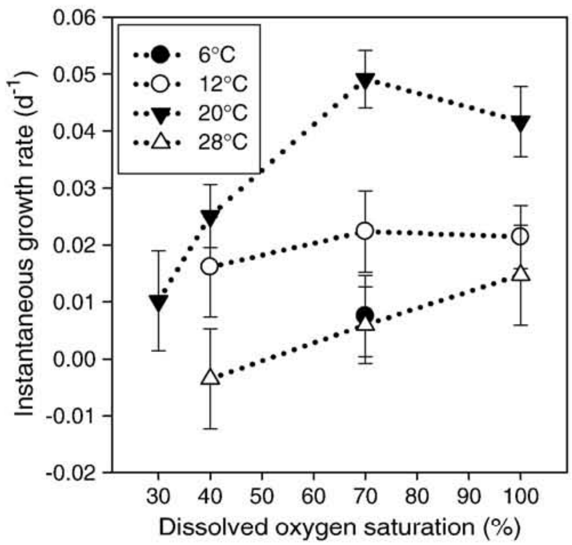
Conclusion: Mortality results were inconclusive, but non-lethal effects were seen at lower DO concentrations.

Upper Threshold for juvenile Atlantic Sturgeon

A closer look at the threshold above which DO no longer impacts juvenile Atlantic Sturgeon is warranted, because a statement made in a research paper has been misinterpreted to suggest that a minimum DO concentration of 6.3 mg/L is required to support propagation of Atlantic Sturgeon. As set forth above, two studies were published by Niklitscheck and Secor in 2009—a laboratory study and a fish bioenergetics model that interprets and explains the laboratory results. The following statement in the first paper (Niklitschek and Secor, 2009b) was repeated in the literature survey performed by the ANSDU (Stoklosa et al., 2018):

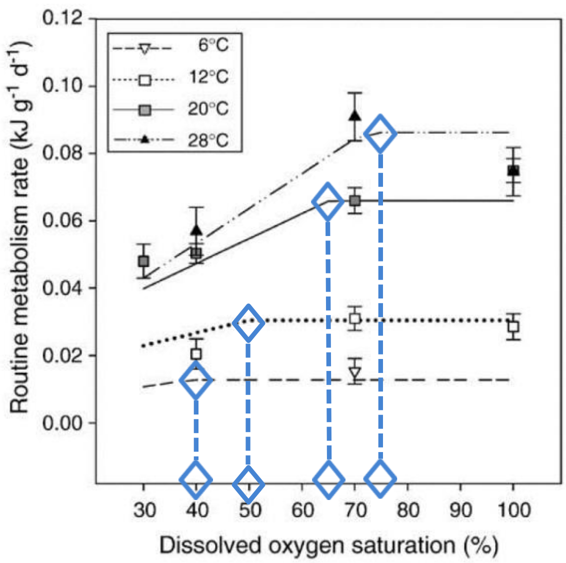
> For illustration purposes, if optimal growth or survival rates were used as criteria to set a hypoxia threshold for juvenile Atlantic sturgeon, that value would rise from 40 to 70% DO_{SAT} if temperature increased from 12 to 20 °C. At salinity 1 these values would correspond to concentrations of 4.3 and 6.3 mg l^{-1}, respectively.

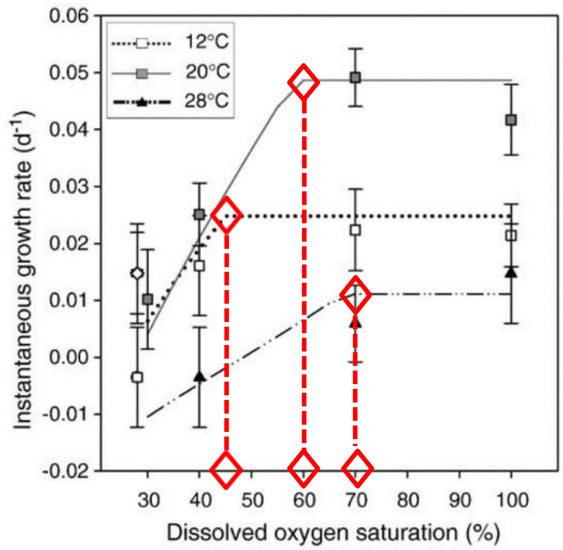
This statement appears in the conclusions section of the paper to illustrate by way of example the author's main point that at different temperatures, juvenile Atlantic Sturgeon respond differently to the same DO saturation level. This finding is counterintuitive, since fish generally respond directly to the level of DO saturation, due to the mechanism by which they extract DO from the water in their gills. The statement is illustrative and hypothetical: if 40% is your critical level of DO saturation at 12 degrees, that would be expected to change to 70% at 20 °C. The basis for the example is this figure (Niklitschek and Secor, 2009a, pS153):



In reality of course, these are simply experimental results. They do not show the level of DO saturation that would have produced the highest growth under these particular laboratory conditions, only that higher growth was seen at 70% than at 30% and 40%. Also, while the author references "growth and survival rates," the value of 6.3 mg/L (70% saturation at 20°C) was derived solely from the growth rate curve above, in which no further improvement in growth rate was observed from 70% to 100% saturation level. (The results actually show a decrease in growth rate, but this is assumed to be insignificant.) The mortality data show conflicting results at different temperatures, but do not indicate that mortality ceases to be important once 70% saturation level is reached. The authors' intent in mentioning mortality in the same sentence as growth rate appears to be to suggest that, like growth rate, the response of mortality rate to different DO saturation levels will vary depending on temperature (and salinity, for that matter).

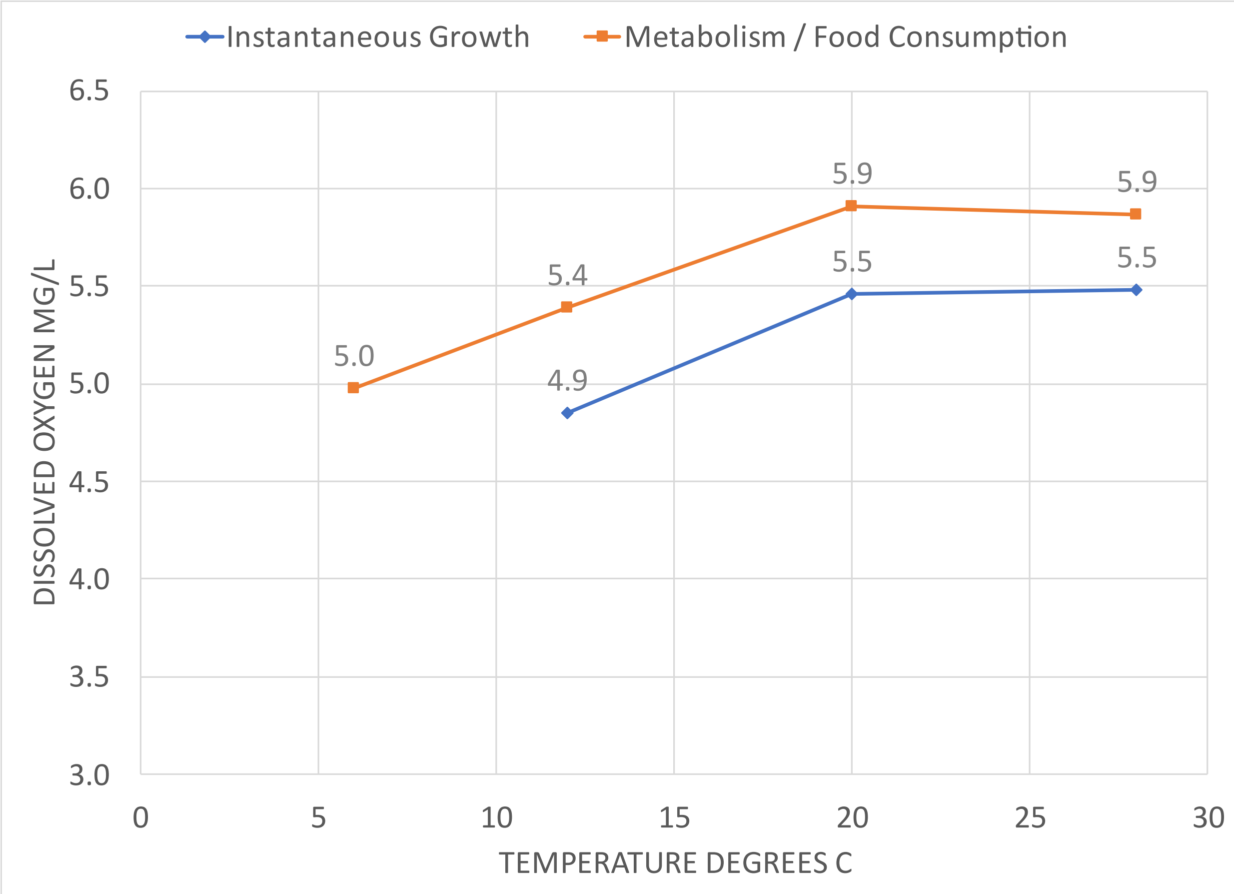
While the experimental data in the first 2009 paper are not fine enough to discern a threshold for metabolic impacts, the authors themselves developed a fish bioenergetics model that elucidates what might be expected between observed values. The temperature curves for routine metabolism (Niklitschek and Secor, 2009b, fig4) and growth rate (Niklitschek and Secor, 2009b, fig8), respectively, relative to DO saturation level, are shown below. Also shown are the thresholds above which DO no longer impacts metabolism and growth of juvenile Atlantic Sturgeon, which DRBC identified based on the underlying graphs.





The two graphs reflect the researchers' estimates, based on bioenergetics modeling and experimental findings, of the DO saturation level, at each temperature, above which metabolism and growth rate, respectively, are no longer impacted. Regarding growth rate (the basis for the 6.3 mg/L), the upper threshold level at 20°C is achieved at 60% saturation (~5.5 mg/L), not 70% (~6.3 mg/L). Interestingly, the growth rate upper threshold level at 28°C is 70% saturation, which also corresponds to a DO level of 5.5 mg/L.

For a frame of reference, DRBC identified the upper threshold values for growth, metabolism, and food consumption from Niklitschek and Secor's bioenergetics study (2009b) and plotted the DO levels (assuming atmospheric pressure of 1atm and 1% salinity) against temperature in the figure below. The values in blue, for growth rate, show that the upper threshold based on growth rate would be 5.5 mg/L, and that threshold concentration remains the same at 20°C and 28°C. The values for metabolism and food consumption were nearly identical and are plotted together in orange. They also show that the threshold concentration remains the same at 20°C and 28°C.



Niklitschek and Secor's bioenergetics study (2009b) thus identifies 5.5 mg/L, 5.9 mg/L, or perhaps somewhere in between, as the dissolved oxygen level above which no further benefit can be demonstrated; the study does not support a threshold DO value of 6.3 mg/L. In addition, the 5.5 - 5.9 mg/L values represent upper thresholds, meaning that further DO increases produce no demonstrated benefit. Establishing an upper response threshold as a minimum required value to support growth and development would be neither appropriate nor precedented. As the discussion in Sections 2 and 3 of this report explain at length, those are two different things entirely.

Appendix A References

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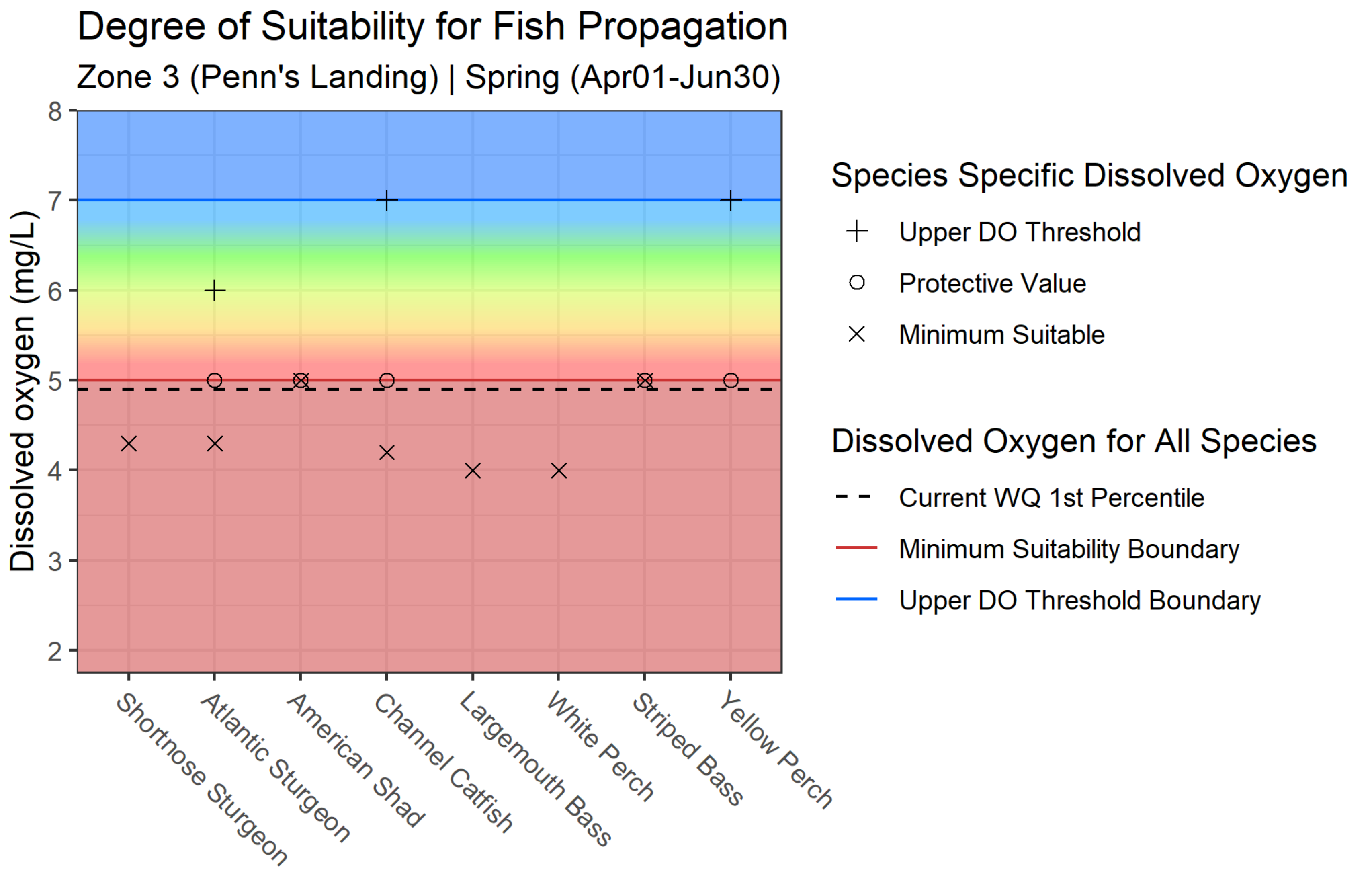
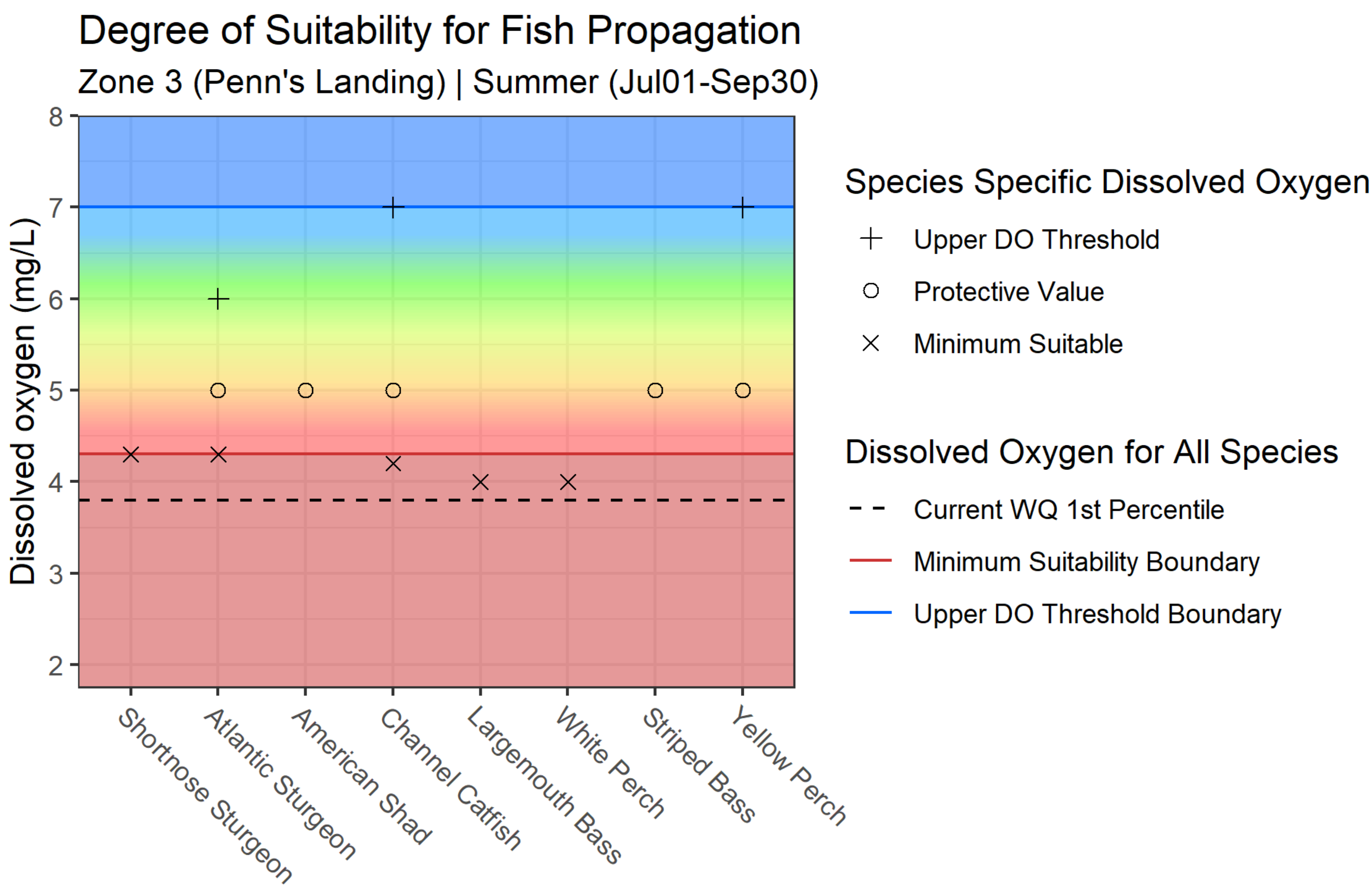
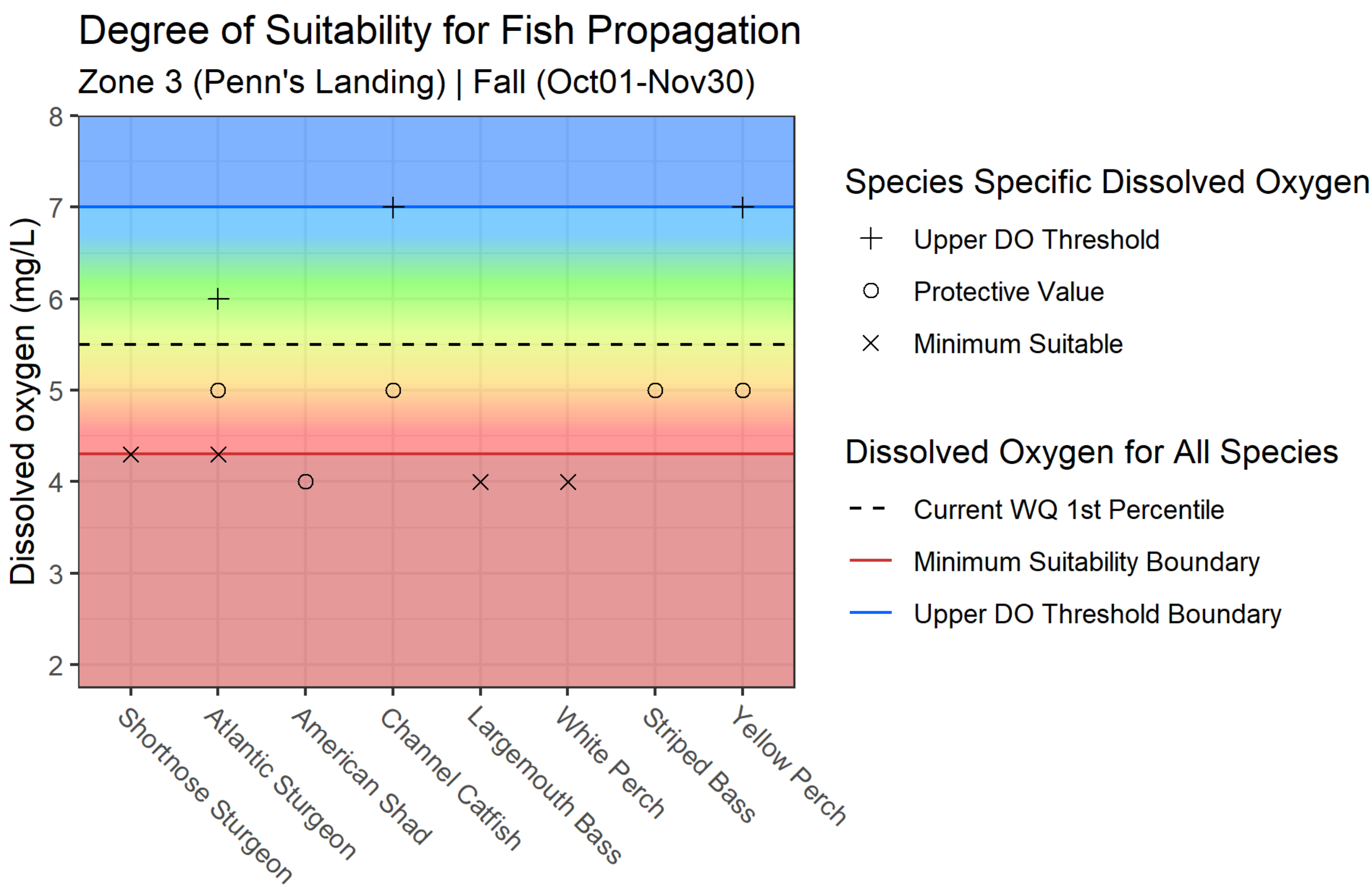
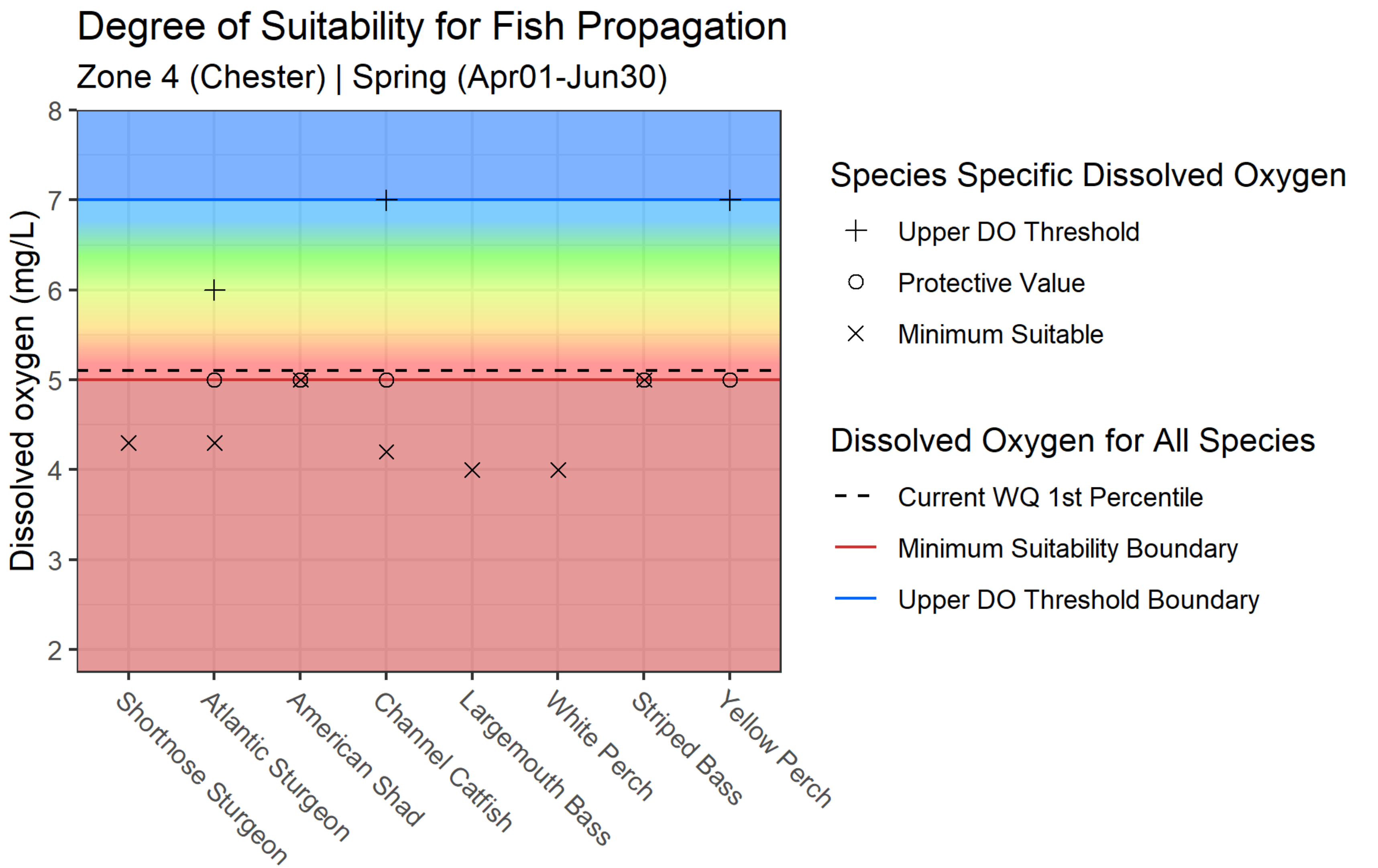
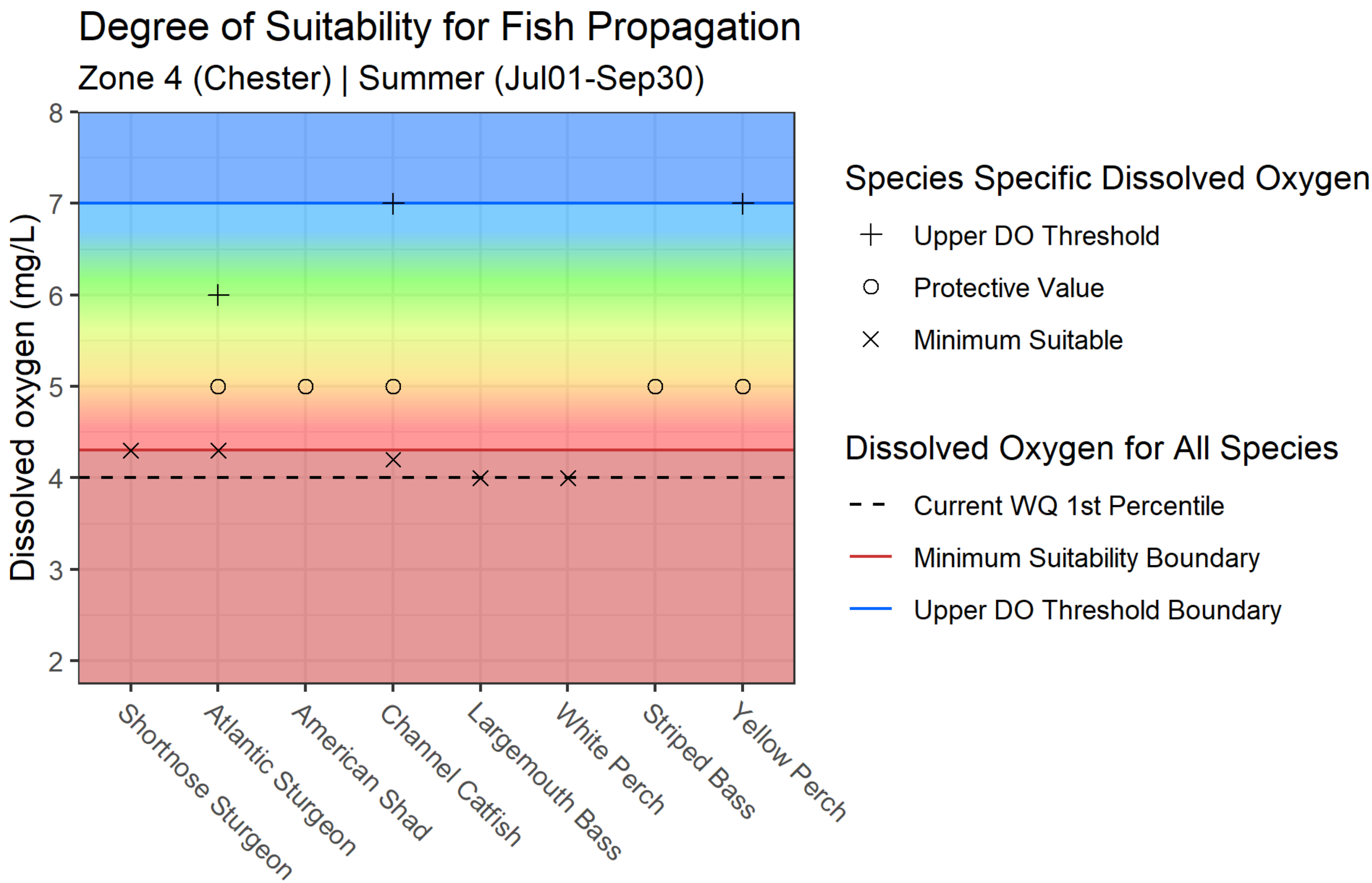
Appendix B: Suitability Illustrations for Delaware Estuary

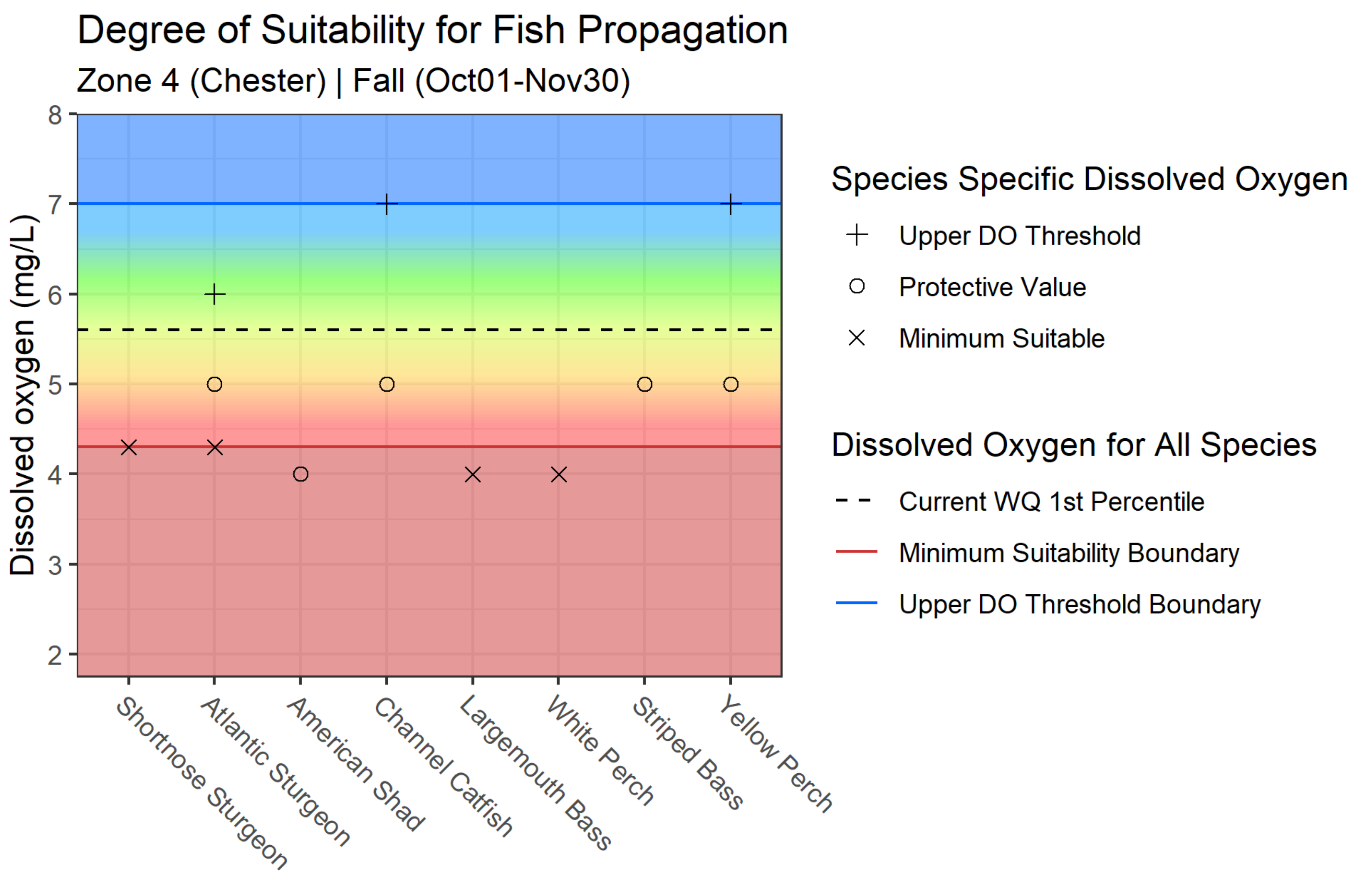

Degree of Suitability for Fish Propagation
Zone 3 (Penn's Landing) | Spring (Apr01-Jun30)
Dissolved oxygen (mg/L)
8
7
6
5
4
3
2
Shortnose Sturgeon
Atlantic Sturgeon
American Shad
Channel Catfish
Largemouth Bass
White Perch
Striped Bass
Yellow Perch
Species Specific Dissolved Oxygen
Upper DO Threshold
Protective Value
Minimum Suitable
Dissolved Oxygen for All Species
Current WQ 1st Percentile
Minimum Suitability Boundary
Upper DO Threshold Boundary

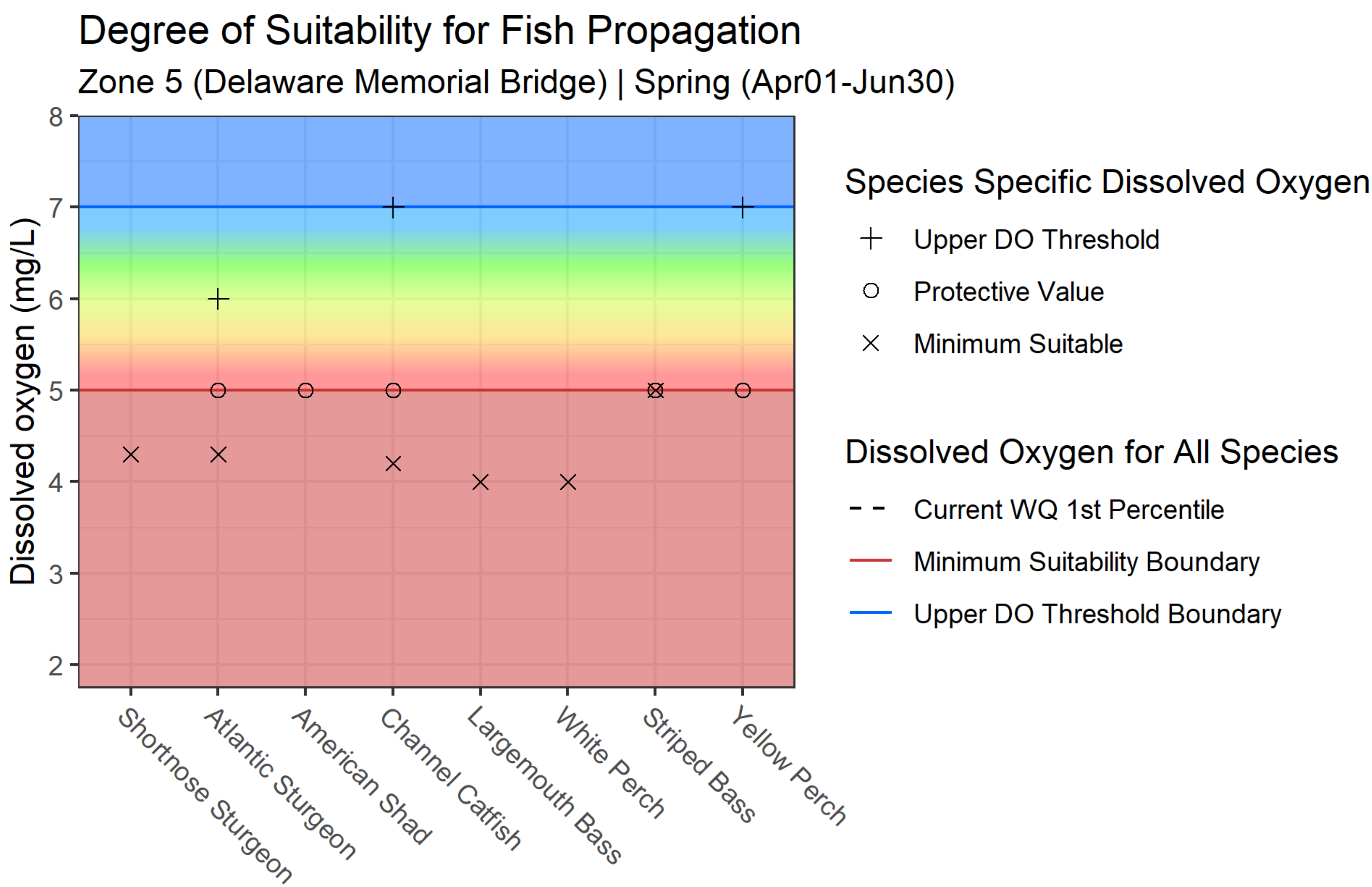

Degree of Suitability for Fish Propagation
Zone 3 (Penn's Landing) | Summer (Jul01-Sep30)
Dissolved oxygen (mg/L)
8
7
6
5
4
3
2
Shortnose Sturgeon
Atlantic Sturgeon
American Shad
Channel Catfish
Largemouth Bass
White Perch
Striped Bass
Yellow Perch
Species Specific Dissolved Oxygen
Upper DO Threshold
Protective Value
Minimum Suitable
Dissolved Oxygen for All Species
Current WQ 1st Percentile
Minimum Suitability Boundary
Upper DO Threshold Boundary

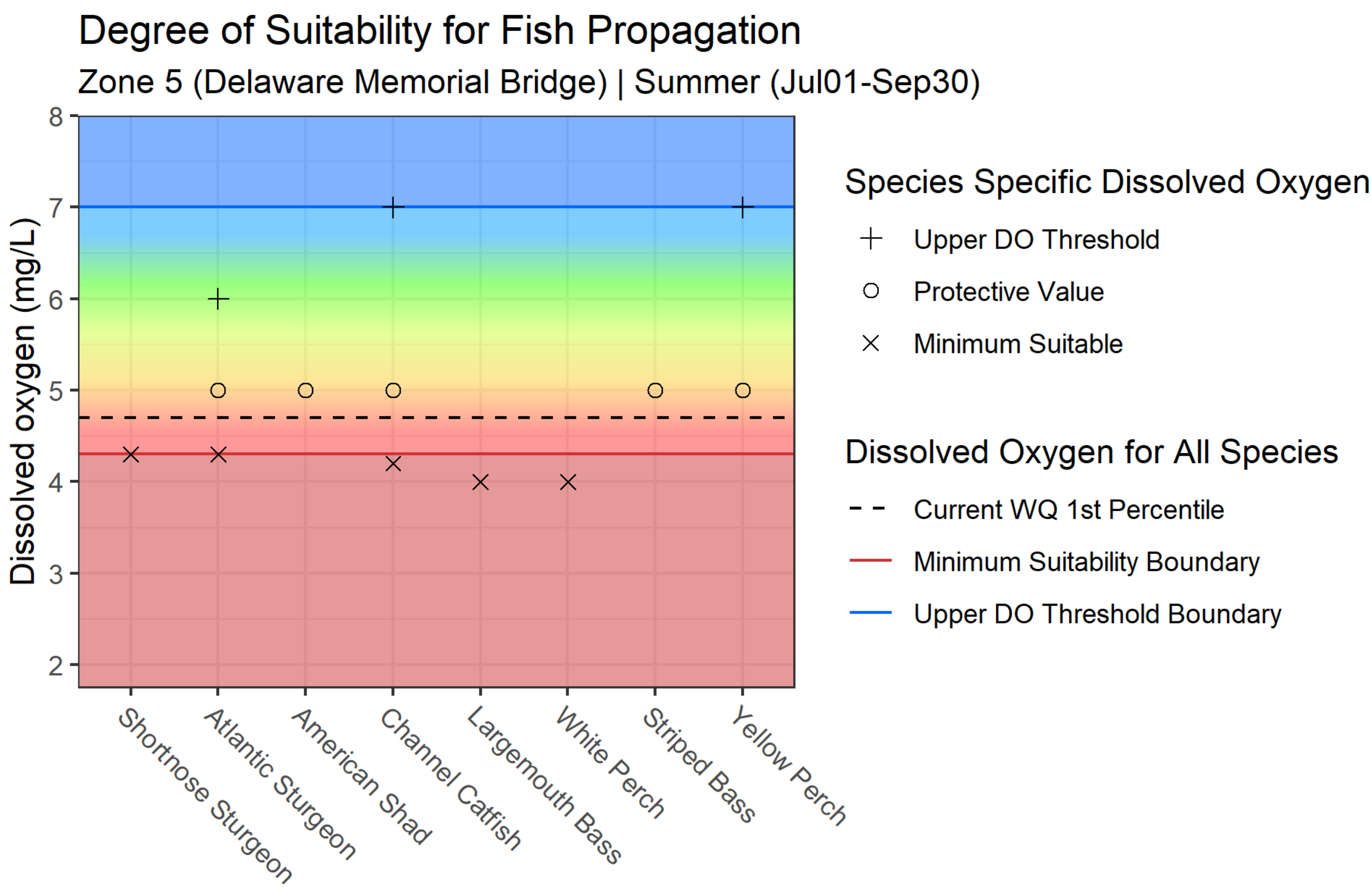

Degree of Suitability for Fish Propagation
Zone 3 (Penn's Landing) | Fall (Oct01-Nov30)
Dissolved oxygen (mg/L)
8
7
6
5
4
3
2
Shortnose Sturgeon
Atlantic Sturgeon
American Shad
Channel Catfish
Largemouth Bass
White Perch
Striped Bass
Yellow Perch
Species Specific Dissolved Oxygen
Upper DO Threshold
Protective Value
Minimum Suitable
Dissolved Oxygen for All Species
Current WQ 1st Percentile
Minimum Suitability Boundary
Upper DO Threshold Boundary

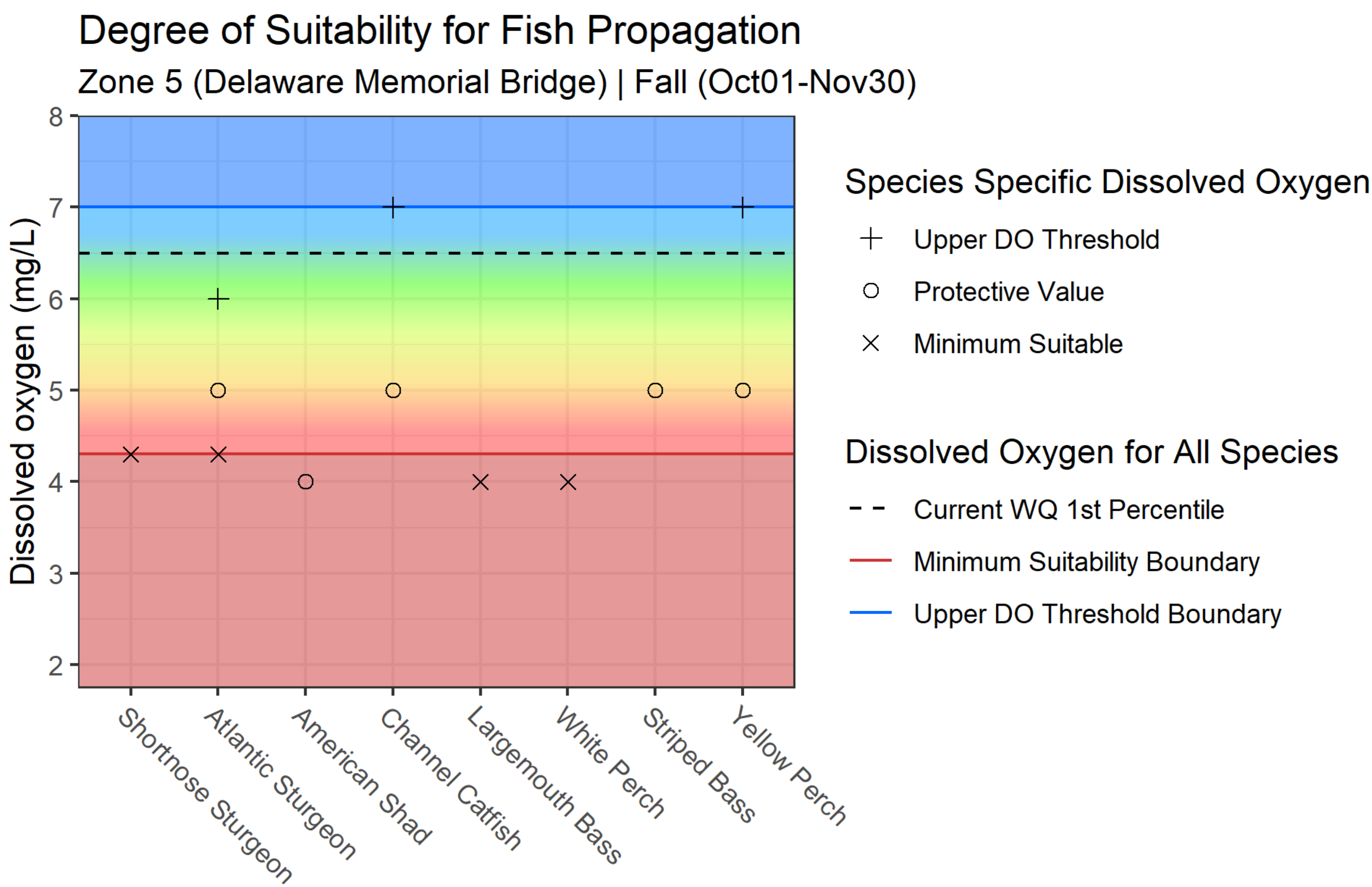

Degree of Suitability for Fish Propagation
Zone 4 (Chester) | Spring (Apr01-Jun30)
Dissolved oxygen (mg/L)
8
7
6
5
4
3
2
Shortnose Sturgeon
Atlantic Sturgeon
American Shad
Channel Catfish
Largemouth Bass
White Perch
Striped Bass
Yellow Perch
Species Specific Dissolved Oxygen
Upper DO Threshold
Protective Value
Minimum Suitable
Dissolved Oxygen for All Species
Current WQ 1st Percentile
Minimum Suitability Boundary
Upper DO Threshold Boundary


Degree of Suitability for Fish Propagation
Zone 4 (Chester) | Summer (Jul01-Sep30)
Dissolved oxygen (mg/L)
8
7
6
5
4
3
2
Shortnose Sturgeon
Atlantic Sturgeon
American Shad
Channel Catfish
Largemouth Bass
White Perch
Striped Bass
Yellow Perch
Species Specific Dissolved Oxygen
Upper DO Threshold
Protective Value
Minimum Suitable
Dissolved Oxygen for All Species
Current WQ 1st Percentile
Minimum Suitability Boundary
Upper DO Threshold Boundary


Degree of Suitability for Fish Propagation
Zone 4 (Chester) | Fall (Oct01-Nov30)
Dissolved oxygen (mg/L)
8
7
6
5
4
3
2
Shortnose Sturgeon
Atlantic Sturgeon
American Shad
Channel Catfish
Largemouth Bass
White Perch
Striped Bass
Yellow Perch
Species Specific Dissolved Oxygen
Upper DO Threshold
Protective Value
Minimum Suitable
Dissolved Oxygen for All Species
Current WQ 1st Percentile
Minimum Suitability Boundary
Upper DO Threshold Boundary


Degree of Suitability for Fish Propagation
Zone 5 (Delaware Memorial Bridge) | Spring (Apr01-Jun30)
Dissolved oxygen (mg/L)
8
7
6
5
4
3
2
Shortnose Sturgeon
Atlantic Sturgeon
American Shad
Channel Catfish
Largemouth Bass
White Perch
Striped Bass
Yellow Perch
Species Specific Dissolved Oxygen
Upper DO Threshold
Protective Value
Minimum Suitable
Dissolved Oxygen for All Species
Current WQ 1st Percentile
Minimum Suitability Boundary
Upper DO Threshold Boundary


Degree of Suitability for Fish Propagation
Zone 5 (Delaware Memorial Bridge) | Summer (Jul01-Sep30)
Dissolved oxygen (mg/L)
8
7
6
5
4
3
2
Shortnose Sturgeon
Atlantic Sturgeon
American Shad
Channel Catfish
Largemouth Bass
White Perch
Striped Bass
Yellow Perch
Species Specific Dissolved Oxygen
Upper DO Threshold
Protective Value
Minimum Suitable
Dissolved Oxygen for All Species
Current WQ 1st Percentile
Minimum Suitability Boundary
Upper DO Threshold Boundary


Degree of Suitability for Fish Propagation
Zone 5 (Delaware Memorial Bridge) | Fall (Oct01-Nov30)
Dissolved oxygen (mg/L)
8
7
6
5
4
3
2
Shortnose Sturgeon
Atlantic Sturgeon
American Shad
Channel Catfish
Largemouth Bass
White Perch
Striped Bass
Yellow Perch
Species Specific Dissolved Oxygen
Upper DO Threshold
Protective Value
Minimum Suitable
Dissolved Oxygen for All Species
Current WQ 1st Percentile
Minimum Suitability Boundary
Upper DO Threshold Boundary

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