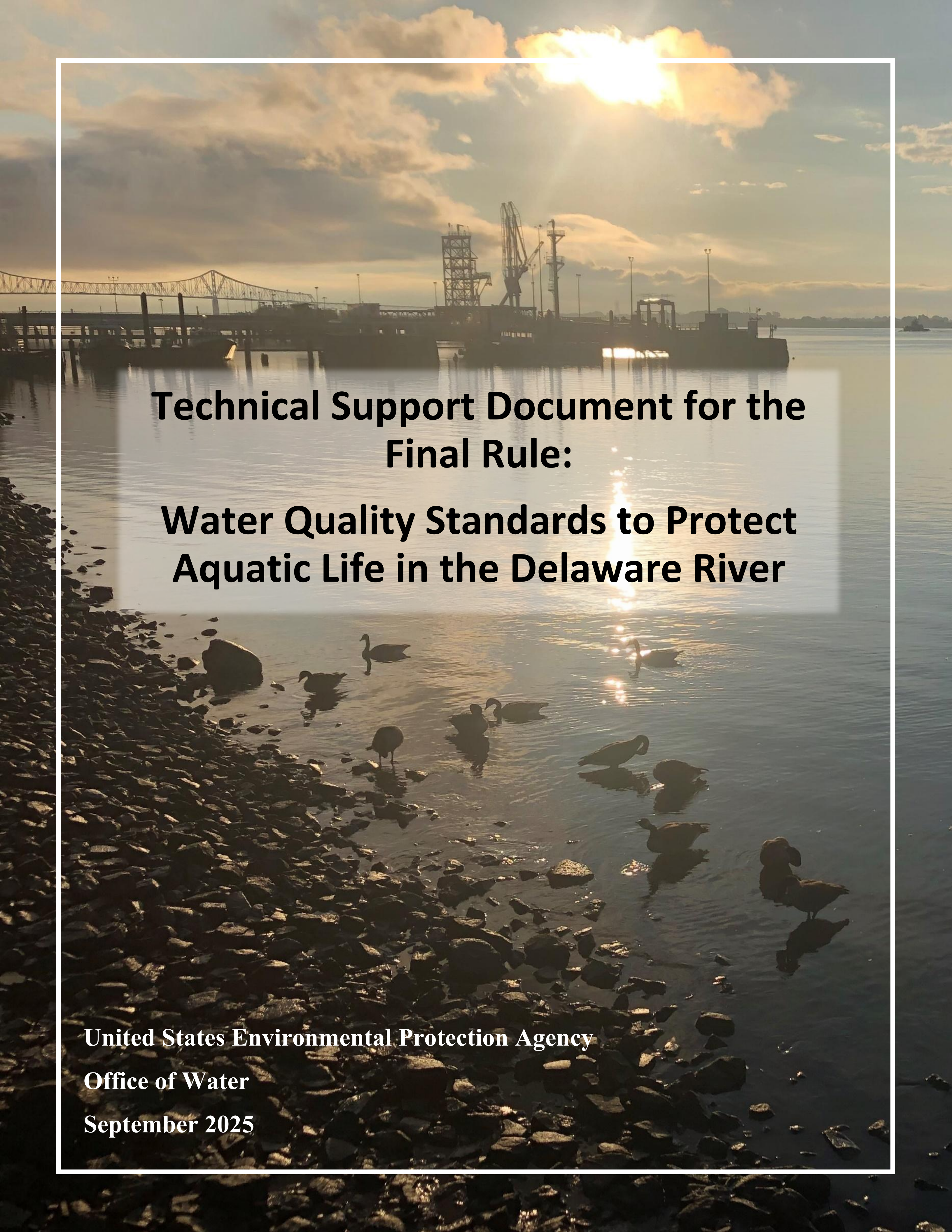

Technical Support Document for the Final Rule:

Water Quality Standards to Protect Aquatic Life in the Delaware River

United States Environmental Protection Agency

Office of Water

September 2025

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Acronyms and Abbreviations

"Ammonia Nitrogen"	Combination of ammonia (NH_3) and ammonium (NH_4^+)
CPUE	Catch Per Unit Effort
CSO	Combined Sewer Overflow
DNREC	Delaware Department of Natural Resources and Environmental Control
DPS	Distinct Population Segment
DRBC	Delaware River Basin Commission
EFDC	Environmental Fluid Dynamics Code
EPA	United States Environmental Protection Agency
ESA	Endangered Species Act
GAM	Generalized Additive Model
HSI	Habitat Suitability Index
LC50	The dissolved oxygen level causing 50% mortality in 24 hours
LC5	The dissolved oxygen level causing 5% mortality in 24 hours
mg/L	Milligrams per Liter
mg-N/L	Milligrams Nitrogen per Liter
NH_3	Ammonia
NH_4^+	Ammonium
NMFS	National Oceanic and Atmospheric Administration, National Marine Fisheries Service
POSAT	Percent Oxygen Saturation
ppt	Parts Per Thousand
QGAM	Quantile Generalized Additive Model
"Relevant Zones" or "Specified Zones"	Mainstem Delaware River in Zone 3, Zone 4, and the upper portion of Zone 5 (in total, river miles 108.4 to 70.0)
"Restored Scenario"	Dissolved oxygen levels following implementation of pollution control actions at certain wastewater treatment plants
USGS	United States Geological Survey
WASP	Water Quality Analysis Simulation Program
°C	Degrees Celsius
%	Percent
> , = , <	Greater Than, Equal To, Less Than

Executive Summary

This document explains the basis and derivation of the U.S. Environmental Protection Agency's (EPA's) dissolved oxygen criteria for the final rule, *Water Quality Standards to Protect Aquatic Life in the Delaware River,* for the mainstem Delaware River in Zone 3, Zone 4, and the upper portion of Zone 5 (in total, river miles 108.4 to 70.0). The EPA's dissolved oxygen criteria cover three distinct seasons – *Spawning and Larval Development* (March 1 – June 30), *Juvenile Development* (July 1 – October 31), and *Overwintering* (November 1 – February 28/29) – and are intended to protect all oxygen-sensitive species in the relevant zones of the Delaware River (Table ES-1). To derive criteria for each season, the EPA focused on the oxygen requirements of the Shortnose Sturgeon and Atlantic Sturgeon, which are recognized to be the most oxygen-sensitive species in the relevant zones of the Delaware River. Therefore, criteria that protect these sturgeon species will also protect other species. The EPA's final criteria are based on the best available scientific information and are protective of aquatic life designated uses that include propagation.

To derive criteria for the *Juvenile Development* season, the EPA developed an Atlantic Sturgeon cohort model that describes the effects of water temperature, salinity, and dissolved oxygen on the potential growth and mortality of a hypothetical cohort of juvenile fish spawned during a single year. The EPA's cohort model predicts the maximum fraction of the cohort that survives through October 31 and the maximum potential production of biomass from July 1 to October 31. Using outputs of the cohort model along with recent water quality monitoring data, the EPA defined a habitat suitability index based on water temperature, salinity, and dissolved oxygen, where suitable habitat is defined as habitat that supports the potential for increasing biomass of the annual cohort. The EPA selected dissolved oxygen criteria magnitudes and exceedance frequencies based on the distribution of dissolved oxygen values that, if attained, would provide suitable habitat during the *Juvenile Development* season.

To derive criteria for the *Spawning and Larval Development* and *Overwintering* seasons, the EPA determined – based on fish physiology and water temperature trends throughout the year – that the dissolved oxygen threshold that is protective of juvenile Atlantic Sturgeon experiencing stressful (high) water temperatures during the *Juvenile Development* season would also be protective of larvae and overwintering juveniles not experiencing high water temperatures.

Table ES-1. The EPA's Final Dissolved Oxygen Criteria

Season	Magnitude (Percent Oxygen Saturation)	Duration	Exceedance Frequency
Spawning and Larval Development *(March 1 – June 30)*	66%	Daily Average	12 Days Cumulative *(10% of the 123-day season)*
Juvenile Development *(July 1 – October 31)*	66%	Daily Average	12 Days Cumulative *(10% of the 123-day season)*
	74%	Daily Average	61 Days Cumulative *(50% of the 123-day season)*
Overwintering *(November 1 – February 28/29)*	66%	Daily Average	12 Days Cumulative *(10% of the 123-day season)*

1 Introduction

On December 1, 2022, the U.S. Environmental Protection Agency determined that revised water quality standards are necessary to protect aquatic life in certain water quality management zones of the Delaware River. Specifically, the EPA issued an Administrator's Determination, pursuant to Clean Water Act section 303(c)(4)(B), finding that a revised designated use to protect aquatic life propagation and corresponding dissolved oxygen criteria to protect that use are necessary in the mainstem Delaware River in Zone 3, Zone 4, and the upper portion of Zone 5 (in total, river miles 108.4 to 70.0; hereafter, referred to as "specified zones" or "relevant zones") (Figure 1). This technical support document contains the scientific information, methods, and technical analyses the EPA used to derive the dissolved oxygen criteria for the final rule, *Water Quality Standards to Protect Aquatic Life in the Delaware River*. The dissolved oxygen criteria protect the EPA's promulgated aquatic life designated use for New Jersey and Pennsylvania, as well as Delaware's current aquatic life designated use, all of which include aquatic life propagation.[1]

1.1 Background

The Delaware River has historically been home to numerous species of ecological, recreational, and economic importance; however, centuries of anthropogenic water quality impacts and habitat degradation, peaking in the mid-twentieth century, made portions of the river unsuitable for many aquatic species. In the 1700s and 1800s, many native fish species in the Delaware River faced declining populations due to overharvesting and the installation of

[1] More information regarding applicable designated uses is available in the preamble to the EPA's final rule.

physical barriers that prevented fish passage.[2] Further population declines of native oxygen-sensitive species – such as the Atlantic Sturgeon (*Acipenser oxyrinchus oxyrinchus*), Shortnose Sturgeon (*A. brevirostrum*), American Shad (*Alosa sapidissima*), and Striped Bass (*Morone saxatilis*), among others[3] – were linked to accelerating degradation of water quality through the first half of the 1900s, including seasonal anoxia (i.e., absence of oxygen) by the mid-twentieth century in the mainstem Delaware River in Zone 3, Zone 4, and the upper portion of Zone 5.[4]

Dissolved oxygen is an important water quality parameter that can significantly influence the distribution and abundance of aquatic organisms and their ecological relationships in aquatic ecosystems. Aquatic organisms need to obtain adequate levels of dissolved oxygen to maintain and support normal functions, especially during the sensitive early life history when spawning, larval development, and juvenile growth occur.[5] As dissolved oxygen levels decrease in a waterbody, the rate at which aquatic organisms can obtain oxygen from the water decreases, resulting in impaired growth and reduced survival. Maintaining a healthy ecosystem requires dissolved oxygen at levels that do not impair growth and survival of aquatic species.

1.1.1 Causes of Low Dissolved Oxygen in the Specified Zones of the Delaware River

Discharges of untreated or poorly treated municipal and industrial wastewater into the Delaware River have historically been a major cause of water quality degradation, including oxygen depletion, in the specified zones.[6] While conditions have significantly improved, inputs of oxygen-consuming wastes from wastewater dischargers, especially ammonia (NH_3) and ammonium (NH_4^+) (which in combination are hereafter referred to as "ammonia nitrogen"), as

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[2] Hardy, C. A. (1999). Fish or Foul: A History of the Delaware River Basin Through the Perspective of the American Shad, 1682 to the Present. Pennsylvania History, 66(4), 506-534. https://digitalcommons.wcupa.edu/hist_facpub/13;
Secor, D.H. and Waldman, J. (1999). Historical abundance of Delaware Bay Atlantic sturgeon and potential rate of recovery. American Fisheries Society Symposium. 23. 203-216. https://www.researchgate.net/publication/291783957_Historical_abundance_of_Delaware_Bay_Atlantic_sturgeon_and_potential_rate_of_recovery;
Smith, T.I.J., & Clugston, J.P. (1997) Status and management of Atlantic sturgeon, Acipenser oxyrinchus, in North America. Environmental Biology of Fishes 48, 335–346. https://doi.org/10.1023/A:1007307507468;
National Marine Fisheries Service. (1998). Recovery Plan for the Shortnose Sturgeon (Acipenser brevirostrum). Prepared by the Shortnose Sturgeon Recovery Team for the National Marine Fisheries Service, Silver Spring, Maryland. 104 pages. https://repository.library.noaa.gov/view/noaa/15971.

[3] Stoklosa, A.M., Keller, D.H., Marano, R., and Horwitz, R.J. (2018). "A Review of Dissolved Oxygen Requirements for Key Sensitive Species in the Delaware Estuary." Academy of Natural Sciences of Drexel University. November 2018. https://www.nj.gov/drbc/library/documents/Review_DOreq_KeySensSpecies_DelEstuary_ANStoDRBCnov2018.pdf.

[4] See citations in footnote 2 above; Atlantic States Marine Fisheries Commission. (1981). Interstate Fisheries Management Plan for the Striped Bass. https://asmfc.org/wp-content/uploads/2025/01/1981FMP.pdf.

[5] United States Environmental Protection Agency. (2021). Factsheet on Water Quality Parameters: Dissolved Oxygen. July 2021. Document ID: EPA 841F21007B. https://www.epa.gov/system/files/documents/2021-07/parameter-factsheet_do.pdf;
United States Environmental Protection Agency. (2023a). Indicators: Dissolved Oxygen. June 9, 2023. https://www.epa.gov/national-aquatic-resource-surveys/indicators-dissolved-oxygen.

[6] Hardy (1999); Delaware River Basin Commission. (2024a). A Pathway for Continued Restoration: Improving Dissolved Oxygen in the Delaware River Estuary. Technical Report No. 2024-6. September 2024. https://www.nj.gov/drbc/library/documents/ALDU_RestorationPathway/Report_RestorationPathway_sept2024.pdf.

well as sediment-water ammonium flux and sediment oxygen demand continue to be significant sources of oxygen demand in the specified zones of the Delaware River.[7]

Along the Delaware River, untreated wastewater discharges typically occur during and after rainfall events due to combined sewer overflows (CSOs), which are a source of nutrients (i.e., nitrogen and phosphorus), sediments, and toxic contaminants, and can lead to increased chemical and biological oxygen demand in the river.[8] Although the cumulative impact of historical CSOs on sediment oxygen demand in the Delaware River has not been estimated, over time, CSOs can increase or maintain sediment oxygen demand as untreated organic material settles on the riverbed and is broken down by oxygen consuming bacteria (thus, removing oxygen from the water column), a process that continues long after the end of an overflow event.[9] CSOs have been a persistent source of pollutants in the specified zones of the Delaware River for over a century. For example, sewer overflows from Philadelphia in the early 1900s deposited over 200,000 tons of solids per year, which, in combination with other solid wastes, created deposits 12 feet deep in the river.[10] From July 1, 2022, to June 30, 2023, Philadelphia's wastewater system alone discharged over 1.35 billion cubic feet of CSOs into the Delaware River and its tributaries.[11]

Although most point source discharges today are treated, treated effluent can still contain high levels of ammonia nitrogen, which depletes oxygen in the water as microbes oxidize ammonia into nitrite and nitrate.[12] During the reporting periods from July through October 2023, major wastewater treatment facilities along the Delaware River discharged ammonia nitrogen at monthly average concentrations ranging from a low of 0.1 milligrams nitrogen per liter (mg-N/L) at the Easton Area Joint Sewer Authority in Pennsylvania (discharging into Zone 1 of the Delaware River) to a high of 34.5 mg-N/L at the Gloucester County Utilities Authority in New Jersey (discharging into Zone 4 of the Delaware River).[13] The effect of any one discharge on dissolved oxygen in the river depends on a variety of factors, including the discharge concentration, the magnitude of the discharge, the location of the discharge, and conditions in the river, which may also be affected by other dischargers.

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[7] Delaware River Basin Commission (2024a); Delaware River Basin Commission. (2024b). Modeling Eutrophication Processes in the Delaware River Estuary: Three-Dimensional Water Quality Model. Technical Report No. 2024-5. August 2024. https://www.nj.gov/drbc/library/documents/ALDU_RestorationPathway/WQCalibration_FinalRpt_aug2024.pdf.

[8] Miskewitz, R. and Uchrin, C. (2013). In-Stream Dissolved Oxygen Impacts and Sediment Oxygen Demand Resulting from Combined Sewer Overflow Discharges. Journal of Environmental Engineering, 139(10). https://doi.org/10.1061/(ASCE)EE.1943-7870.0000739.

[9] Miskewitz and Uchrin (2013).

[10] Hardy (1999).

[11] Philadelphia Water Department. (2023). Combined Sewer Management Program Annual Report. Stormwater Management Program Annual Report. See Appendix D – "NPDES Annual CSO Status Report FY 2023," Table 2 – "Overflow Summary for 7/1/2022 – 6/30/2023." https://water.phila.gov/pool/files/fy23-npdes-annual-report.pdf.

[12] United States Environmental Protection Agency. (2023b). Ammonia. https://www.epa.gov/caddis-vol2/ammonia.

[13] Each individual reporting period is one month long. For the reporting periods ending on August 31, 2023, and October 31, 2023, the Easton Area Joint Sewer Authority discharged an average of 0.1 mg/L of ammonia. For the reporting period ending on August 31, 2023, the Gloucester County Utilities Authority discharged an average of 34.5 mg/L of ammonia. Source: U.S. Environmental Protection Agency. Integrated Compliance Information System (ICIS). Database. Retrieved May 22, 2024.

1.1.2 Endangered Species in the Specified Zones of the Delaware River

The Delaware River is home to multiple oxygen-sensitive fish species, two of which – Shortnose Sturgeon and Atlantic Sturgeon – are protected under the federal Endangered Species Act (ESA). All populations of Shortnose Sturgeon were listed as endangered in 1967.[14] Across the U.S., Shortnose Sturgeon face ongoing threats due to water pollution, habitat degradation, and fisheries bycatch, among other factors.[15] While the historic population size of Shortnose Sturgeon in the Delaware River remains unknown, in 2006 the Delaware River population was estimated to be approximately 12,000 adults.[16] The New York Bight distinct population segment (DPS) of Atlantic Sturgeon – which includes the population found in the Delaware River – was listed as endangered under the ESA in 2012.[17] In 2017, the National Oceanic and Atmospheric Administration's National Marine Fisheries Service (NMFS) designated the Delaware River, among others, as critical habitat for the New York Bight DPS of Atlantic Sturgeon,[18] and reaffirmed its endangered listing status in 2022 following a five-year review.[19] The remnant population of the New York Bight DPS of Atlantic Sturgeon faces ongoing threats due to water quality in natal rivers, such as the Delaware River, as well as ship strikes, fisheries bycatch, and entanglement in fishing gear.[20,21] Like the Shortnose Sturgeon, the historic population size of Atlantic Sturgeon is not well documented. However, in 1890, when the population was already declining, there were approximately 180,000 female Atlantic Sturgeon in the Delaware River.[22] Despite improvements in dissolved oxygen levels since the 1970s, it is estimated that only 125 – 250 adult (male and female) Atlantic Sturgeon currently return to spawn in the Delaware River.[23]

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[14] Federal Register, Vol. 32, No. 48. March 11, 1967. https://www.fisheries.noaa.gov/s3//2022-12/4000-4002.pdf.
[15] NMFS. (2023a). Shortnose Sturgeon – Overview. https://www.fisheries.noaa.gov/species/shortnose-sturgeon.
[16] *Id.*; NMFS. (2023b). Shortnose Sturgeon – Populations. https://www.fisheries.noaa.gov/species/shortnose-sturgeon#populations.
[17] Federal Register, Vol. 77, No. 24. February 6, 2012. 77 FR 5879. https://www.federalregister.gov/documents/2012/02/06/2012-1946/endangered-and-threatened-wildlife-and-plants-threatened-and-endangered-status-for-distinct.
[18] Federal Register, Vol. 82, No. 158. August 17, 2017. 50 CFR Part 226. https://www.federalregister.gov/documents/2017/08/17/2017-17207/endangered-and-threatened-species-designation-of-critical-habitat-for-the-endangered-new-york-bight.
[19] National Marine Fisheries Service. (2022). New York Bight Distinct Population Segment of Atlantic Sturgeon (*Acipenser oxyrinchus oxyrinchus*), 5-Year Review: Summary and Evaluation. February 17, 2022. https://www.fisheries.noaa.gov/resource/document/new-york-bight-distinct-population-segment-atlantic-sturgeon-5-year-review.
[20] *Ibid*. See Section 2.3.2, "Five-Factor Analysis (threats, conservation measures, and regulatory mechanisms)."
[21] Dunton, K.J., Jordaan, A., Conover, D.O., McKown, K.A., Bonacci, L.A., and Frisk, M.G. (2015). Marine Distribution and Habitat Use of Atlantic Sturgeon in New York Lead to Fisheries Interactions and Bycatch. Marine and Coastal Fisheries 7:18-32. https://doi.org/10.1080/19425120.2014.986348;
Atlantic Sturgeon Bycatch Working Group. (2022). Action Plan to Reduce Atlantic Sturgeon Bycatch in Federal Large Mesh Gillnet Fisheries. NOAA National Marine Fisheries Service. https://media.fisheries.noaa.gov/2022-09/Final-Action-Plan-to-Reduce-Atlantic-Sturgeon-Bycatch.pdf.
[22] Secor and Waldman (1999).
[23] White, S.L., Sard, N.M., Brundage, H.M., Johnson, R.L., Lubinski, B.A., Eackles, M.S., Park, I.A., Fox, D.A., and Kazyak, D.C. (2022). Evaluating Sources of Bias in Pedigree-Based Estimates of Breeding Population Size. Ecological Applications 32(5): e2602. https://doi.org/10.1002/eap.2602.

In addition to being listed as endangered under the ESA, available evidence suggests that Shortnose Sturgeon and Atlantic Sturgeon are the most oxygen-sensitive species in the specified zones of the Delaware River. In general, all sturgeon species share common physiological traits,[24] which include being relatively more sensitive to low dissolved oxygen levels than other co-occurring fish.[25,26] Sturgeon are considered unusually sensitive to hypoxia (i.e., low oxygen) given their documented metabolic and behavioral responses and limited ability to oxyregulate.[27] Juvenile Atlantic Sturgeon are particularly sensitive to low dissolved oxygen levels, especially at high water temperatures,[28] such as those typically present at the peak of summer in the Delaware River. A literature review across oxygen-sensitive species in the Delaware River indicates that Atlantic Sturgeon, particularly the juveniles, have the highest documented dissolved oxygen requirements for growth and survival when compared to other oxygen-sensitive species in the specified zones of the Delaware River.[29] In its five-year review of the listing of the New York Bight DPS of Atlantic Sturgeon, NMFS observed a continuation of low dissolved oxygen conditions in known Atlantic Sturgeon juvenile rearing habitat in the Delaware River.[30] Juvenile Atlantic Sturgeon seeking relief from areas with low oxygen may move to waters that limit their growth due to other factors, such as reduced prey availability.[31] NMFS also noted studies showing fewer juvenile Atlantic Sturgeon captured in the Delaware River in the fall when the preceding summer dissolved oxygen levels were low, providing further evidence that low dissolved oxygen levels are a contributor to the mortality of juvenile Atlantic Sturgeon.[32]

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[24] Federal Register, Vol. 82, No. 158. August 17, 2017. 50 CFR Part 226. pp. 39161-39163. https://www.federalregister.gov/documents/2017/08/17/2017-17207/endangered-and-threatened-species-designation-of-critical-habitat-for-the-endangered-new-york-bight.

[25] *Ibid*. p. 39162, see Dees (1961), Sulak and Clugston (1999), Billard and Lecointre (2001), Secor and Niklitschek (2002), and Pikitch et al. (2005), cited therein.

[26] Stoklosa et al. (2018); Secor, D.H. and Niklitschek, E.J. (2001). Hypoxia and Sturgeons: Report to the Chesapeake Bay Program Dissolved Oxygen Criteria Team. March 29, 2001.Reference Number: [UMCES] CBL 01-0080.
https://www.researchgate.net/publication/277065759_Hypoxia_and_Sturgeons_report_to_the_Chesapeake_Bay_Program_Dissolved_Oxygen_Criteria_Team.

[27] Secor and Niklitschek (2001). Oxyregulation refers to an organism's ability to maintain metabolic rates as the oxygen level in the water declines.

[28] Secor, D., and T. Gunderson. (1998). Effects of hypoxia and temperature on survival, growth, and respiration of juvenile Atlantic sturgeon, Acipenser oxyrinchus. Fishery Bulletin 96:603-613;
Niklitschek, E. (2001). Bioenergetics modeling and assessment of suitable habitat for juvenile Atlantic and shortnose sturgeons (Acipenser oxyrinchus and A. brevirostrum) in the Chesapeake Bay. University of Maryland at College Park.

[29] Stoklosa et al. (2018).

[30] National Marine Fisheries Service (2022). See Section 2.3.2.1, "Present or threatened destruction, modification, or curtailment of its habitat or range."

[31] *Ibid*. See Allen et al. (2014), cited therein.

[32] *Ibid*. See Moberg and DeLucia (2016), Stetzar et al. (2015), and Park (2020), cited therein.

1.1.3 Dissolved Oxygen Trends in the Specified Zones of the Delaware River

Dissolved oxygen levels in the relevant zones of the Delaware River mirror trends in historic pollutant loading and recent pollution control efforts in the river. Average summer dissolved oxygen levels in the Delaware River near Chester, Pennsylvania (Zone 4) declined from near saturation in the late 1880s to near zero (i.e., anoxia) in the 1950s and 1960s.[33] Starting in 1970, dissolved oxygen levels began to increase steadily following reductions in carbonaceous biological oxygen demand from wastewater treatment plants.[34] Ammonia nitrogen concentrations in the Delaware River declined contemporaneously while nitrate concentrations increased,[35] which likely reflects increased nitrification rates in the river, enabled by increased dissolved oxygen concentrations. Reductions in nutrient concentrations, including ammonia nitrogen, have been documented across the Delaware River watershed through at least 2018.[36] However, dissolved oxygen levels in the summer are not yet high enough and therefore continue to limit the growth and survival of oxygen-sensitive species, such as juvenile Atlantic Sturgeon.[37] Recent modeling studies have shown that further reductions in pollutant loading, including enhanced treatment of ammonia nitrogen discharges and, to a lesser extent, a reduction in the volume and frequency of CSOs, could significantly improve the dissolved oxygen conditions in the relevant zones of the Delaware River.[38] Accordingly, this could better support the growth and survival of oxygen-sensitive species.

1.2 Scope of the EPA's Final Rule

The EPA's rule applies to the mainstem Delaware River in Zone 3, Zone 4, and the upper portion of Zone 5 (in total, river miles 108.4 to 70.0), for the states of Delaware, New Jersey, and Pennsylvania (Table 1, Figure 1).

Table 1. Zones Corresponding with the Mainstem Delaware River Covered by the EPA's Rule

Segment of the Delaware River	River Miles	States Affected
Zone 3	108.4 to 95.0	New Jersey, Pennsylvania
Zone 4	95.0 to 78.8	New Jersey, Pennsylvania
Zone 5 – Upper Portion	78.8 to 70.0	Delaware, New Jersey

[33] Sharp, J. (2010). Estuarine oxygen dynamics: What can we learn about hypoxia from long-time records in the Delaware estuary? Limnology and Oceanography, 55(2), 535-548.
[34] Albert, R. C. (1988). The Historical Context of Water-Quality Management for the Delaware Estuary. Estuaries 11(2): 99-107.
[35] Sharp (2010).
[36] Shoda, M.E., and Murphy, J.C. (2022). Water-quality trends in the Delaware River Basin calculated using multisource data and two methods for trend periods ending in 2018. U.S. Geological Survey Scientific Investigations Report 2022–5097. https://doi.org/10.3133/sir20225097.
[37] Delaware River Basin Commission (2024a); Stoklosa et al. (2018); Niklitschek, E., and D. 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. https://doi.org/10.1016/j.jembe.2009.07.018.
[38] Delaware River Basin Commission (2024a, 2024b).

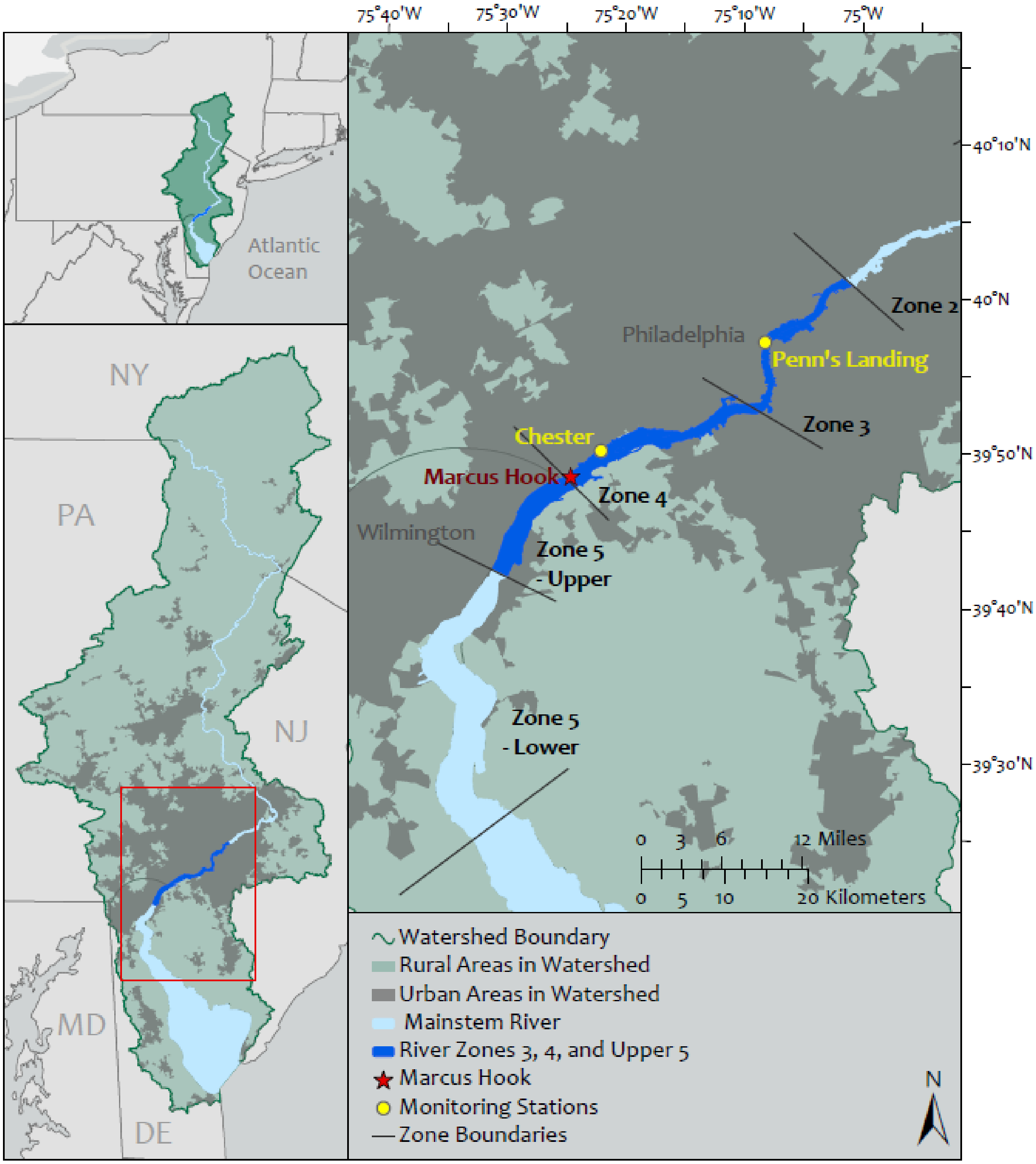

Figure 1: Map of the Delaware River Watershed and Zones Covered by the EPA's Final Rule. The EPA's final rule applies to the urban stretch of the mainstem Delaware River in Zone 3, Zone 4, and the upper portion of Zone 5 (in total, river miles 108.4 to 70.0). There are two relevant continuous monitoring stations in these zones, one at Penn's Landing (Zone 3) and one at Chester (Zone 4). Atlantic Sturgeon spawning and juvenile development has been frequently documented near Marcus Hook, PA. Sources: The watershed boundary, zone boundaries, and river shapefiles were provided by the Delaware River Basin Commission. The EPA obtained data on urban areas from the U.S. Census Bureau. The location coordinates for the monitoring stations are from the U.S. Geological Survey. Service Layer Credit: ESRI Light Gray Basemap.

2 Water Quality Conditions in the Delaware River

This section provides a description of selected water quality characteristics (dissolved oxygen, temperature, and salinity) in the specified zones of the Delaware River using recent observed data and projections of water quality conditions under a restored scenario.

2.1 Observed Conditions

Daily water quality data for the relevant zones of the Delaware River are available from two continuous water quality monitoring stations jointly maintained by the United States Geological Survey (USGS) and the Delaware River Basin Commission (DRBC). Measurements from the Delaware River at Penn's Landing include data from several locations near the monitoring station in Zone 3 (Figure 1).[39] Measurements from the Delaware River at Chester, PA include data from several locations near the monitoring station in Zone 4 (Figure 1).[40] The water quality record at both sites begins in the early 1960s and data collection is ongoing.

The EPA obtained data on daily average, daily minimum, and daily maximum values for water temperature, specific conductivity, and dissolved oxygen that were measured every 15 minutes at both the Penn's Landing and Chester monitoring sites. Data availability varied across seasons and years, with larger gaps in the record during winter months in many years when data were not collected. For the summer months, the EPA filled small gaps in the data by interpolating from available observations; the EPA did not interpolate data to fill large gaps in the winter months. Data from 2010 were not included in further analyses because a substantial period of missing data was present in early July at both the Chester and Penn's Landing locations. Daily means and data gaps for July to October for the years 2002 – 2022 are presented in Appendix 1.

From 2002 to 2022, water temperature was often greater than 20°C by June 1st and remained above that level until early October. Water temperatures reached a seasonal maximum in mid-August, with daily averages typically near 27°C and in some years reaching over 30°C (Figure 2). During winter, water temperature was always less than 18°C, with daily averages typically near 9°C.

The EPA calculated salinity from measurements of specific conductivity and water temperature.[41] The relevant zones of the Delaware River are freshwater to oligohaline. Median salinity was less than 0.5 parts per thousand (ppt) at both Chester and Penn's Landing monitoring stations during each season. At Chester, salinity increased in some years during late summer to fall, but was always less than 2 ppt.

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[39] USGS 01467200 Delaware River at Penn's Landing, Philadelphia, PA. (39°56'47.0", 75°08'23.1") Retrieved March 9, 2023. https://waterdata.usgs.gov/nwis/inventory/?site_no=01467200&agency_cd=USGS.
[40] USGS 01477050 Delaware River at Chester PA. (39°50'44", 75°21'03") Retrieved January 31, 2023. https://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_no=01477050.
[41] Using ec2pss function in wql package in R. Source: Jassby, A., Cloern, J., and Stachelek, J. wql: Exploring Water Quality Monitoring Data. R package version 1.0.0. https://cran.r-project.org/web/packages/wql/index.html.

The EPA calculated percent oxygen saturation from dissolved oxygen concentrations, salinity, and water temperature using the following equation:

$$Percent\ Oxygen\ Saturation = \frac{100 \cdot [DO]}{[DO]_s} \qquad \text{(eq. 1)}$$

where $[DO]_s$ is the calculated concentration of oxygen in water at equilibrium with the atmosphere at sea level at the observed salinity and water temperature.[42] Dissolved oxygen concentrations quantify the amount of oxygen in the water, most often using units of milligrams per liter (mg/L). Percent oxygen saturation quantifies the amount of oxygen in water in relation to the oxygen concentration in the water when at equilibrium with the atmosphere.

There are two main reasons why percent saturation is the EPA's preferred metric when evaluating aquatic life requirements for the final rule. First, as noted by Niklitschek and Secor (2009a), percent oxygen saturation or partial pressure are the most biologically relevant measures of oxygen level. This reflects the fact that these measures determine the maximum gradient in partial pressure across biological membranes, such as the gill lamellae of fish, and therefore the maximum rate at which aquatic organisms may obtain oxygen from the water.[43] Dissolved oxygen concentrations, on the other hand, vary with water temperature and salinity even if the partial pressure or percent oxygen saturation does not vary. Thus, physiological effects of oxygen levels are *directly* related to percent oxygen saturation and *indirectly* related to dissolved oxygen concentration.

Second, water temperature influences dissolved oxygen concentration via both physical effects associated with changes in oxygen solubility and biological effects resulting from the effect of temperature on rates of oxygen consuming processes. As a result, dissolved oxygen concentrations are more strongly influenced by water temperature than percent oxygen saturation (Figure 2). The strong negative relationship between dissolved oxygen concentration and temperature can complicate interpretation of seasonal dissolved oxygen patterns. For example, in the Delaware River, dissolved oxygen concentrations increase quickly during autumn as temperatures decrease, even though percent saturation increases more slowly (Figure 2). In this example, the increasing oxygen concentration gives the appearance that oxygen availability to aquatic organisms is increasing more rapidly than it is. For Atlantic Sturgeon and other oxygen-sensitive species, this means that low levels of percent oxygen saturation may continue to impact growth and survival even though dissolved oxygen concentrations may appear to be protective. Given this relationship between temperature and dissolved oxygen concentration, criteria expressed as concentration will result in higher or lower maximum oxygen availability for absorption at various times of the year, whereas criteria expressed as percent oxygen saturation reflect consistent oxygen availability throughout the year.

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[42] Using gas_O2sat function in the marelac package in R. Source: Soetaert, K., Petzoldt, T., Meysman, F., Meire, L. marelac: Tools for Aquatic Sciences. R package version 2.1.10. https://cran.r-project.org/web/packages/marelac/index.html.

[43] Also see review by Roman et al. (2019): Roman, M. R., S. B. Brandt, E. D. Houde and J. J. Pierson (2019). Interactive Effects of Hypoxia and Temperature on Coastal Pelagic Zooplankton and Fish. *Frontiers in Marine Science* **6**.

Therefore, for this final rule the EPA is evaluating oxygen requirements and thresholds in terms of percent oxygen saturation, rather than as oxygen concentration.

Percent oxygen saturation was lowest from late July to early August, reaching a typical seasonal low of 64% at Chester and 58% at Penn's Landing. Minimum values for the daily mean saturation levels were 46% at Chester and 38% at Penn's Landing, with the lowest values distributed from mid-July to late August at Chester and from mid-June to mid-September at Penn's Landing (Figure 2). During November through February, oxygen levels remained at or above 66% at Chester and 69% at Penn's Landing, with median values of 85% and 88%, respectively.

The importance of dissolved oxygen for defining Atlantic Sturgeon habitat suitability within the relevant zones of the Delaware River reflects the fact the salinity and water temperature are generally in a suitable range for juveniles, even if water temperatures are often higher than optimal. Salinity is consistently low, and though water temperature varies seasonally, spatial variability is subtle. Water temperatures are slightly lower in the upstream end of the relevant zones (e.g., Penn's Landing or landward), compared with the more estuary-adjacent region of the river (Chester or seaward; Figure 2). In the Delaware River, as would be expected in most natural waters, the lowest oxygen levels mostly coincided with the highest water temperatures.

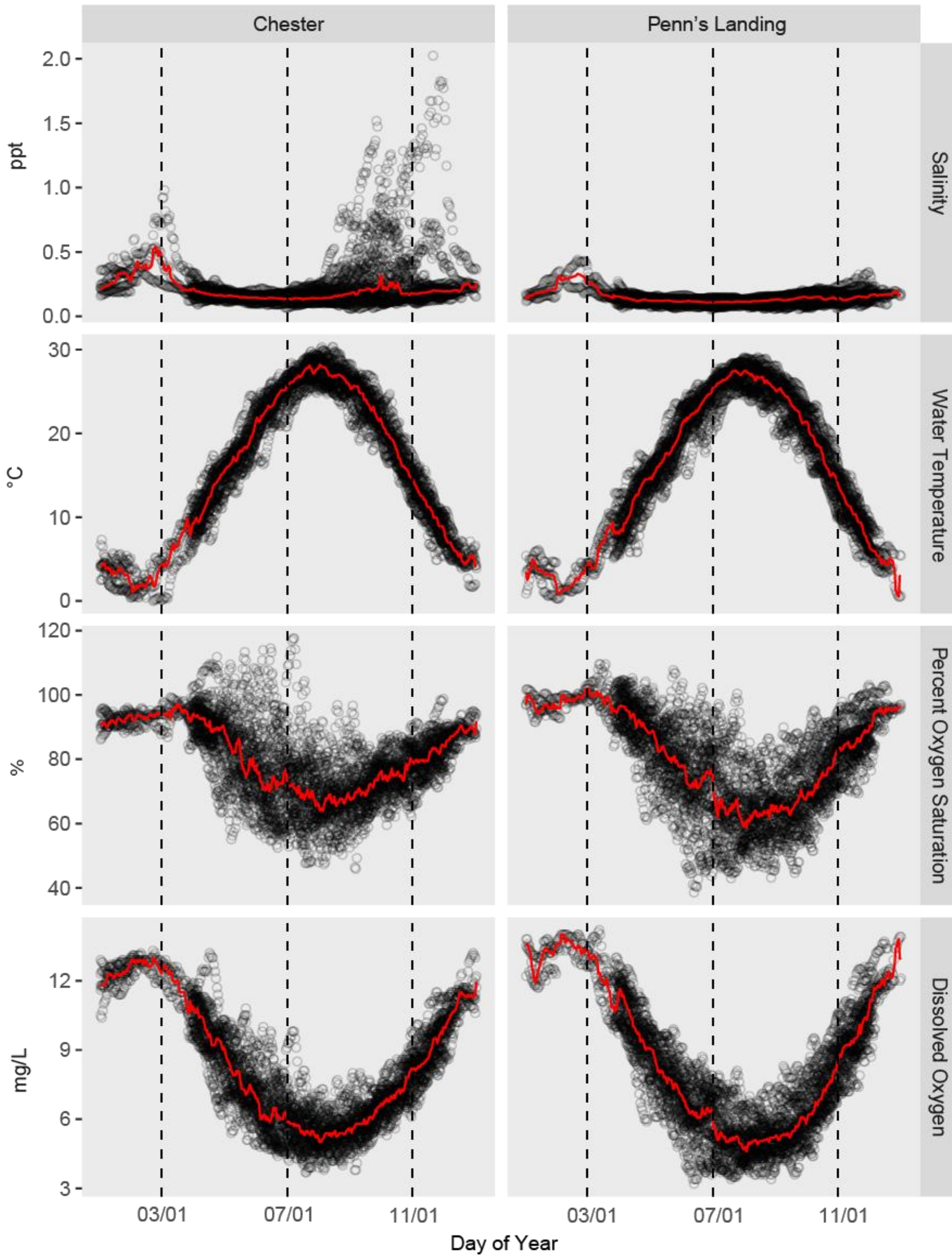

Figure 2: Seasonal Distributions of Selected Water Quality Parameters at the Chester and Penn's Landing Monitoring Stations. Each measurement taken between 2002 to 2022 is represented by a grey circle. Red lines indicate the typical seasonal pattern for the period of record. Vertical dashed lines indicate the seasons corresponding with the EPA's dissolved oxygen criteria.

2.2 Projected Future (Restored) Conditions

The EPA expects that future pollution treatment and controls – including reductions in effluent ammonia nitrogen discharge and increases in effluent dissolved oxygen concentrations – will significantly improve dissolved oxygen levels in the specified zones of the Delaware River.[44] The DRBC modeled the effect of pollution reduction on dissolved oxygen levels in the Delaware River using an Environmental Fluid Dynamics Code (EFDC) hydrodynamic model coupled with a water quality analysis simulation program (WASP) eutrophication model.[45] The DRBC provided the EPA with vertically averaged water quality simulation results at a 2-hour interval under restored conditions for the years 2012, 2018, and 2019.[46]

The EPA estimated a time series of restored dissolved oxygen concentrations for July through October from 2002 to 2022 for the Chester and Penn's Landing monitoring stations using a generalized additive model (GAM).[47] The GAM relates observed daily mean dissolved oxygen at the monitoring stations to daily means of restored scenario predictions for those locations from the DRBC's EFDC-WASP model (Appendix 2). The GAM has the form:

$$DO_{res} \sim s(DO_{obs}) + s(Q) \qquad \text{(eq. 2)}$$

where DO_{res} is the daily mean dissolved oxygen under the restored scenario, $s(DO_{obs})$ is a smooth function of the observed daily average dissolved oxygen (mg/L), and $s(Q)$ is a smooth function of the daily discharge (m^3/s) of the Delaware River measured at the USGS monitoring station at Trenton, NJ. GAMs were fitted separately for the Chester and Penn's Landing monitoring locations (Appendix 2).

Percent oxygen saturation during the *Juvenile Development* season (July 1 - October 31) was projected to increase by an average of 9.3% across both sites, with a 2.3% larger increase at Chester compared to Penn's Landing. Dissolved oxygen levels closer to the lower end of the seasonal distribution were projected to increase more than higher values. For example, the 10th percentile of percent oxygen saturation across both sites was projected to increase by 12.6%, while the median percent oxygen saturation was projected to increase by 9.6%, similar to the average change.

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[44] More information is available in the associated rule document, *Economic Analysis for the Final Rule: Water Quality Standards to Protect Aquatic Life in the Delaware River*.
[45] Delaware River Basin Commission (2024b).
[46] In this analysis, "restored conditions" or "restored scenario" refer to dissolved oxygen levels in the specified zones following implementation of existing and expected CSO long-term control plans, reductions in effluent ammonia nitrogen, and increases in effluent dissolved oxygen at certain wastewater treatment plants. More information is available in the associated rule document, *Economic Analysis for the Final Rule: Water Quality Standards to Protect Aquatic Life in the Delaware River*.
[47] Although the DRBC provided modeled data for the full area of the specified zones, the EPA chose to evaluate conditions at the two monitoring stations (Chester and Penn's Landing) for consistency with the available observed data.

3 Methodology for Deriving Dissolved Oxygen Criteria

This section describes the EPA's approach for developing dissolved oxygen criteria for the mainstem Delaware River in Zone 3, Zone 4, and the upper portion of Zone 5. Section 3.1 discusses the applicability and use of the EPA's existing guidance documents for dissolved oxygen criteria derivation. Section 3.2 explains how the EPA selected three distinct seasons for criteria development. Section 3.3 outlines the EPA's modeling approach used to calculate dissolved oxygen criteria during the *Juvenile Development* season (July – October). Section 3.4 describes the criteria development process for the remaining two seasons, *Overwintering* (November – February) and *Spawning and Larval Development* (March – June).

3.1 The EPA's Existing Guidance Documents on Dissolved Oxygen

Under Clean Water Act section 304(a), the EPA publishes, from time to time, national recommended aquatic life criteria for a variety of pollutants and parameters. The EPA's 1986 *Quality Criteria for Water* ("Gold Book")[48] and the 2000 *Ambient Aquatic Life Water Quality Criteria for Dissolved Oxygen (Saltwater): Cape Cod to Cape Hatteras* ("Virginian Province Document")[49] contain the EPA's Clean Water Act section 304(a) national recommended criteria for dissolved oxygen in freshwater and saltwater environments, respectively. The relevant zones of the Delaware River include a freshwater to oligohaline tidally-influenced reach.

The Gold Book recommends different freshwater dissolved oxygen criteria for protection of coldwater versus warmwater species. Coldwater values are recommended for waters with salmonids or other coldwater or coolwater fish species with similar sensitivities. Water temperature and species composition indicate that the relevant zones of the Delaware River support warmwater species. The EPA's national recommended dissolved oxygen criteria for early life stages[50] in warmwater environments are 6.0 mg/L as a 7-day mean and 5.0 mg/L as a 1-day minimum. For all other life stages, the EPA's national recommended dissolved oxygen criteria are 5.5 mg/L as a 30-day mean, 4.0 mg/L as a 7-day mean minimum, and 3.0 mg/L as a 1-day minimum. The Gold Book recommendations are intended to protect a wide range of aquatic organisms nationally. Given the site-specific nature of the EPA's rule, presence of oxygen-sensitive endangered species, and abundance of site-specific water quality and species-specific data, the EPA chose to derive site-specific criteria to protect the oxygen-sensitive species in the specified zones of the Delaware River and not rely on the national recommendations in the Gold Book in this instance.

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[48] United States Environmental Protection Agency. (1986). Quality Criteria for Water 1986. Document ID: EPA 440/5-86-001. May 1, 1986. https://www.epa.gov/sites/default/files/2018-10/documents/quality-criteria-water-1986.pdf.
[49] United States Environmental Protection Agency. (2000). Ambient Aquatic Life Water Quality Criteria for Dissolved Oxygen (Saltwater): Cape Cod to Cape Hatteras. Document ID: EPA-822-R-00-012. November 2000. https://www.epa.gov/sites/default/files/2018-10/documents/ambient-al-wqc-dissolved-oxygen-cape-code.pdf.
[50] "Early life stages" includes all embryonic and larval stages and all juvenile forms to 30-days following hatching.

The Virginian Province Document recommends acute and chronic dissolved oxygen criteria for marine waters and a recommended approach for deriving dissolved oxygen criteria given required data on acute and chronic effects of low oxygen on resident species. There are several reasons why the criteria and recommended approach from the Virginian Province Document cannot be applied to determine dissolved oxygen criteria for the relevant zones of the Delaware River. First, the test data included in the Virginian Province Document and used for criteria derivation are for marine species tested under salinity levels much higher than the levels that occur in the relevant zones of the Delaware River. Most of the tested taxa do not occur in the tidal-fresh Delaware River, where salinity is typically less than 0.5 ppt and always less than 2 ppt (Figure 2). Second, in part due to the intended application to saltwater taxa, the recommended criteria in the Virginian Province Document are far lower than levels that protect freshwater species. The recommended acute criterion (2.3 mg/L) is less than both the existing 24-hour average criterion for the specified zones of the Delaware River (3.5 mg/L)[51] and oxygen levels observed in recent years, when juvenile Atlantic Sturgeon were observed only intermittently (Figure 2). The chronic criterion recommended in the Virginian Province Document for application to the 30-day average (4.8 mg/L) is likewise below the Gold Book freshwater criterion for the 30-day average for warmwater fisheries (5.5 mg/L) and is too low to protect Atlantic Sturgeon (section 4). Finally, the Virginian Province Document recognizes the potential limitations of the approach recommended within, noting that "in cases where a threatened or endangered species occurs at a site, and sufficient data exist to suggest that it is more sensitive at concentrations above the criteria, it is appropriate to consider development of site-specific criteria based on this species." Recognizing that this situation applies to the specified zones of the Delaware River, the EPA separately evaluated the dissolved oxygen requirements of juvenile Atlantic Sturgeon, as detailed in section 3.3.

3.2 Delineating Seasons for Criteria Derivation

The EPA defined three distinct seasons for criteria derivation based largely on Atlantic Sturgeon early life history. Atlantic Sturgeon are a federally endangered species and are found throughout the specified zones.[52] As explained above (sections 1.1 and 3.1), available evidence relating dissolved oxygen levels to the critical endpoints of growth and survival of juveniles suggests that Atlantic Sturgeon are the most oxygen-sensitive species in the specified zones of the Delaware River. Deriving dissolved oxygen criteria based on the requirements of sensitive and important species, which can include threatened or endangered species, to ensure protection

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[51] More information on the dissolved oxygen criteria in the specified zones prior to the promulgation of the EPA's final rule is available in section II(D) of the rule preamble.

[52] Section 1.1 of this document; Stoklosa et al. (2018); Moberg, T. and DeLucia. M. (2016). Potential Impacts of Dissolved Oxygen, Salinity and Flow on the Successful Recruitment of Atlantic Sturgeon in the Delaware River. The Nature Conservancy. https://conservationgateway.org/ConservationPractices/Freshwater/HabitatProtectionandRestoration/Documents/DelawareAtlanticSturgeonReport_TNC5172016.pdf;
Federal Register, Vol. 82, No. 158. August 17, 2017. 50 CFR Part 226. (pp. 39161-39163). https://www.federalregister.gov/documents/2017/08/17/2017-17207/endangered-and-threatened-species-designation-of-critical-habitat-for-the-endangered-new-york-bight.

of the applicable aquatic life designated use is consistent with prior EPA guidance and actions.[53] Additionally, several laboratory studies (detailed in section 3.3) provided the EPA with sufficient data to evaluate quantitative relationships between water quality parameters and juvenile sturgeon growth and mortality. Thus, the EPA concluded that deriving criteria largely based on juvenile Atlantic Sturgeon would ensure that the applicable aquatic life designated uses are protected.

Atlantic Sturgeon return from marine habitats to spawn in the Delaware River in the spring, generally during May and June, with egg and larval development occurring during May through July and growth and development of young-of-the-year juveniles increasing during July.[54] The dates of major phases of the life history of Atlantic Sturgeon can vary between years and are difficult to quantify because Atlantic Sturgeon are rare in the Delaware River.[55] Research that might provide more evidence is limited by the protected status of the species.[56] The EPA focused on the period from July 1 to October 31 as the period of interest for modeling juvenile growth and development in the Delaware River because available data suggest that juveniles are present during this period and that dissolved oxygen and water temperatures that occur during this period are likely to affect their growth and survival.[57] By November, oxygen levels are relatively high and not expected to limit growth and survival, a characteristic of the overwintering period.[58] Therefore, while data show that juveniles in the Delaware River continue to grow in November and December, the EPA selected October 31 to mark the transition from the juvenile development period to the overwintering period.

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[53] Stephen, C.E., Mount, D.I., Hansen, D.J., Gentile, J.R., Chapman, G.A., and Brungs, W.A. (1985). Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses. United States Environmental Protection Agency. Document ID: PB85-227049. https://www.epa.gov/sites/default/files/2016-02/documents/guidelines-water-quality-criteria.pdf ; United States Environmental Protection Agency (2000); United States Environmental Protection Agency. (2003). Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll a for the Chesapeake Bay and its Tidal Tributaries. April 2003. Document ID: EPA 903-R-03-002. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100YKPQ.PDF?Dockey=P100YKPQ.PDF.

[54] Moberg and DeLucia (2016).

[55] *Id*. Because fish spawning is often largely dependent on water temperature, there is variation in the timing of early life history and migration between years and between populations of the same species that are in different geographic locations. For example, the timing of Atlantic Sturgeon spawning in the Delaware River may occur later than the Atlantic Sturgeon spawning in Virginia rivers. Thus, to determine an appropriate date to mark the transition between larval development and juvenile rearing, the EPA relied on the limited studies evaluating the timing of Delaware River Atlantic Sturgeon early life history.

[56] Federal Register, Vol. 77, No. 24. February 6, 2012. 77 FR 5879. https://www.federalregister.gov/documents/2012/02/06/2012-1946/endangered-and-threatened-wildlife-and-plants-threatened-and-endangered-status-for-distinct.

[57] Sections 2.1 and 3.2.2 of this document; Moberg and DeLucia (2016); Stoklosa et al. (2018); Delaware River Basin Commission. (2022). Linking Aquatic Life Uses with Dissolved Oxygen Conditions in the Delaware River Estuary. November 2022. Draft. https://www.nj.gov/drbc/library/documents/AnalysisAttainability/LinkingALDU-DO_DRAFTnov2022.pdf.

[58] Sections 3.3.3 and 4.1.2 of this document.

The endangered Atlantic Sturgeon and Shortnose Sturgeon are not the only oxygen-sensitive species present in the specified zones of the Delaware River. A comprehensive literature review identified additional species that likely face lethal and sub-lethal effects during their early life histories due to low levels of dissolved oxygen in the Delaware River Estuary.[59] While the life histories of various fish and aquatic invertebrates differ, general groupings can be developed that cover a range of species. For example, spawning generally occurs from March through June for the American Shad, Channel Catfish, Striped Bass, Largemouth Bass, White Perch, and Yellow Perch.[60] This period overlaps with the spawning period of Atlantic Sturgeon. Therefore, while the EPA defined seasons generally based on the life history of Atlantic Sturgeon, these seasons are likely to be protective of early life histories of other oxygen-sensitive species in the specified zones of the Delaware River. By developing criteria that are protective of Atlantic Sturgeon throughout their life history, the EPA concluded that the criteria are also protective of other resident and migratory aquatic species in the specified zones of the Delaware River.

Thus, the EPA derived dissolved oxygen criteria for the following three seasons that are intended to protect Atlantic Sturgeon throughout their life history, while also protecting a range of other aquatic species during their sensitive early life histories. The *Spawning and Larval Development* season occurs from March 1 to June 30.[61] The *Juvenile Development* season occurs from July 1 to October 31. Finally, the *Overwintering* season occurs from November 1 to February 28/29.

3.3 Ecological Modeling to Derive Criteria for the *Juvenile Development* Season

The EPA developed an Atlantic Sturgeon cohort model that describes the effects of temperature, salinity, and dissolved oxygen on the potential growth and mortality of a hypothetical cohort or group of juvenile fish spawned during a single year (section 3.3.1). The cohort model predicts the maximum fraction of the cohort that survives through October 31 and the maximum relative change in biomass from July 1 to October 31.[62] As part of the cohort model, the EPA developed a mortality model (section 3.3.2) and a growth model (section 3.3.3) to predict the minimum daily instantaneous mortality rate and the potential growth rate, respectively, for members of the cohort. Lastly, the EPA defined an index of habitat suitability based on selected water quality parameters to evaluate dissolved oxygen levels that would provide suitable habitat for juvenile Atlantic Sturgeon (section 3.3.4). The EPA's data and R code used to implement the modeling are available on GitHub.[63]

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[59] Stoklosa et al. (2018).

[60] Stoklosa et al. (2018); Delaware River Basin Commission. (2015). Existing Use Evaluation for Zones 3, 4, & 5 of the Delaware Estuary Based on Spawning and Rearing of Resident and Anadromous Fishes. September 30, 2015. https://www.nj.gov/drbc/library/documents/ExistingUseRpt_zones3-5_sept2015.pdf.

[61] The EPA defined the *Spawning and Larval Development* season as starting on March 1st to encompass the spawning period of several oxygen-sensitive species in the specified zones. Although Atlantic Sturgeon spawning typically occurs beginning in May, defining the season as starting in March ensures that the criteria are protective of a broader range of species, including the Atlantic Sturgeon.

[62] The cohort model cannot predict the absolute number of individuals surviving because the initial number of individuals resulting from spawning and larval development is not known.

[63] https://github.com/USEPA/DelawareRiverDO

3.3.1 Atlantic Sturgeon Cohort Model

The EPA followed the approach of Niklitschek and Secor (2005) and expressed production (*P*) of an annual cohort of juvenile Atlantic Sturgeon over an interval of *t* days as the product of the change in average weight of individuals and the number of surviving individuals, using the following formula:

$$P = \frac{W_0 e^{(\overline{G_{max}} t)} N_0 e^{-(\overline{Z_{min}} t)}}{W_0 N_0} \quad \text{(eq. 3)}$$

where:

- G_{max} is the potential growth rate (d^{-1}), or the growth rate that a fish would achieve on a given day at a particular location at the prevailing temperature, salinity, and oxygen conditions averaged over 24 hours and assuming food supply is not limiting (i.e., *ad libitum* feeding), and
- Z_{min} is the minimum mortality rate (d^{-1}), or the mortality rate that the fish population would experience on a given day at a particular location at the prevailing temperature, salinity, and oxygen conditions, averaged over 24 hours, neglecting causes of mortality other than stress due to high temperature and/or low oxygen.

Bar notation (e.g., $\overline{G_{max}}$) denotes an average of the parameter across a period of t days. In all cases, t=123 days, which is the number of days from July 1 to October 31. The initial weight of individuals in the cohort (W_0) and the initial cohort abundance (N_0) appear in both the numerator and denominator and can be eliminated from equation 3, leaving:

$$P = e^{(\overline{G_{max}} - \overline{Z_{min}})t} = e^{\varphi_{pp} t} \quad \text{(eq. 4)}$$

where

$$\varphi_{pp} = \overline{G_{max}} - \overline{Z_{min}} \quad \text{(eq. 5)}$$

defines the instantaneous production potential, φ_{pp} (d^{-1}, or the rate of change in the biomass of the cohort per day.[64] The EPA defined habitat suitability index (HSI) as the seasonal average value of the instantaneous production potential for July 1 through October 31. Further discussion of HSI is provided in Section 3.3.4.

The EPA calculated Z_{min} for each day from a regression model relating published estimates of juvenile Atlantic Sturgeon mortality under experimental treatments of water temperature and percent oxygen saturation or oxygen concentration (Table 2).[65] Next, the EPA calculated G_{max} for each day using a bioenergetics model that depends on salinity (ppt), water

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[64] Niklitschek, E. J., and Secor, D.H. (2005). Modeling spatial and temporal variation of suitable nursery habitats for Atlantic sturgeon in the Chesapeake Bay. Estuarine, Coastal and Shelf Science 64:135-148. https://doi.org/10.1016/j.ecss.2005.02.012.

[65] Niklitschek and Secor (2009a); United States Environmental Protection Agency (2003); Campbell, J., and Goodman, L. (2004). Acute sensitivity of juvenile shortnose sturgeon to low dissolved oxygen concentrations. Transactions of the American Fisheries Society 133:722-776. https://doi.org/10.1577/T02-070.1.

temperature (°C), percent oxygen saturation, and fish size (g).[66] Descriptions of the regression model and the bioenergetics model are provided below in sections 3.3.2 and 3.3.3, respectively.

In cohort model simulations, the EPA assumed initially that the weight of juvenile Atlantic Sturgeon on July 1 was 20 g, based on the 6 to 48 g size of young-of-the-year juveniles included in laboratory studies by Niklitschek and Secor (2009a). Initial fish weight was subsequently evaluated and adjusted as a calibration parameter to match observed fish weights, resulting in a final value of 27 g for the initial weight. Fish weight (g) was calculated daily as

$$W_t = W_{t-1} e^{G_{max,t}} \qquad \text{(eq. 6)}$$

where $G_{max,t}$ is the calculated value of G_{max} on day t considering the water quality conditions and the fish size on day t. Similarly, the number of surviving individuals from the cohort on day t was calculated as

$$N_t = N_{t-1} e^{-Z_{min}} \qquad \text{(eq. 7)}$$

The EPA ran simulations using observed dissolved oxygen, water temperature, and salinity at the Chester and Penn's Landing monitoring stations for 2002-2022. Simulations were also run using the estimates of restored dissolved oxygen – along with observed water temperature and salinity – for the same stations. The EPA computed average G_{max}, Z_{min}, and φ_{pp} for the *Juvenile Development* season in each scenario after the seasonal simulations were completed.

3.3.2 Mortality Model

Results of experimental studies illustrate that juvenile Atlantic Sturgeon and Shortnose Sturgeon are sensitive to moderately low dissolved oxygen levels and their sensitivity to low dissolved oxygen increases at high (i.e., stressful) water temperature,[67] a pattern that occurs in other estuarine and marine fish species and can be predicted based on principles of fish physiology.[68] To meet the requirements of the cohort model used in this study, the EPA combined data for both species addressing mortality due to low oxygen and high water temperature and used them to fit a regression model that predicts mortality resulting from low dissolved oxygen given any temperature and dissolved oxygen level. Juvenile Atlantic Sturgeon and Shortnose Sturgeon are both recognized as sensitive to oxygen and temperature stress, with Shortnose Sturgeon generally recognized to be slightly more tolerant than Atlantic Sturgeon. Combining data for both species is justified to reduce uncertainty based on the similarity of the species and the small amount of data available for each.

Secor and Gunderson (1998) describe results of experiments in which Atlantic Sturgeon experienced "Low" (~3 mg/L) and "High" (~7 mg/L) dissolved oxygen concentrations at

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[66] Niklitschek, E. J., and Secor, D.H. (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. https://doi.org/10.1016/j.jembe.2009.07.019.

[67] Secor and Gunderson (1998), Campbell and Goodman (2004), Niklitschek and Secor (2009a).

[68] Portner, H.O., and Knust, R. (2007). Climate change affects marine fishes through the oxygen limitation of thermal tolerance. Science 315:95-97. https://doi.org/10.1126/science.1135471; Kraus, R.T., Secor, D.H., and Wingate, R.L. (2015). Testing the thermal-niche oxygen-squeeze hypothesis for estuarine striped bass. Environmental Biology of Fishes 98:2083-2092. https://doi.org/10.1007/s10641-015-0431-3.

temperatures of 19°C and 26°C and in tanks that were either sealed, limiting access of experimental fish to the water surface, or unsealed. In sealed tanks at 26°C and with low dissolved oxygen, 100% mortality occurred within 24 hours. Most individuals survived 10 days at high dissolved oxygen regardless of temperature and whether the tanks were sealed or not. At 19°C, most fish survived at both "low" and "high" dissolved oxygen, but 25% died in the low dissolved oxygen treatment, generally between 3 and 6 days. In the unsealed tanks at 26°C, fish survived low dissolved oxygen for 2 to 9 days, but all fish eventually died, with most fish succumbing between 3 and 6 days.[69] Although the results characterized a pattern of response, this study did not estimate instantaneous mortality rates or dissolved oxygen levels causing a specified fraction of mortality (e.g., LC50), and therefore did not provide a basis for the EPA to use when quantifying the effect of low dissolved oxygen on survival.

Campbell and Goodman (2004) provide estimates of the 24-hour LC50 for juvenile Shortnose Sturgeon in four water temperature ranges between 22°C and 29°C. Reported experimental temperature and salinity was used to convert their estimates of 24-hour LC50 expressed as dissolved oxygen concentration (mg/L) to equivalent levels as percent oxygen saturation. The EPA calculated the instantaneous daily mortality rate for a 24-hour LC50 by recognizing that at the LC50 threshold, the fraction of individuals surviving 24-hours (S) is 0.5, and the instantaneous mortality rate is therefore $-\ln(S) = 0.6931$. This provided four estimates that can be used in a regression model (Table 2). Using an average LC5:LC50 ratio of 1.38,[70] EPA (2003) estimated that the 24-hour LC5 (i.e., the dissolved oxygen level causing 5% mortality in 24 hours) for Shortnose Sturgeon at 29°C was 4.3 mg/L,[71] which was converted to 56.53% oxygen saturation associated with a daily mortality rate of $-\ln(0.95) = 0.0513$ (Table 2).

Niklitschek and Secor (2009a) reported estimates of daily instantaneous mortality rates observed in a partial factorial experimental design involving >20-day exposures of a total of 172 fish to 30%, 70%, and 100% oxygen saturation at 20°C and 28°C. No mortality occurred at 100% saturation, but measurable mortality occurred at 70% saturation and rates appeared to increase approximately exponentially with declining dissolved oxygen levels. Some variability may relate to differences caused by salinity because the experimental design had an unequal number of fish assigned to each treatment and did not have any fish assigned to some treatment combinations within the factorial experimental design. The EPA obtained mean estimates of daily mortality rates for each treatment from the upper panel of Figure 7 in Niklitschek and Secor (2009a) (Table 2).

[69] Table 2 in Secor and Gunderson (1998).
[70] United States Environmental Protection Agency (2000).
[71] United States Environmental Protection Agency (2003).

Table 2. Daily Instantaneous Mortality Rates of Juvenile Atlantic Sturgeon Used to Predict Mortality Across the Observed Range of Water Temperature and Dissolved Oxygen Levels

Percent Oxygen Saturation	Water Temperature (°C)	Mortality Rate (/d)	Source
33.04	24.8	0.6931	Campbell and Goodman (2004)[1,2]
40.76	28.8	0.6931	Campbell and Goodman (2004)[1,2]
25.58	22.1	0.6931	Campbell and Goodman (2004)[1,2]
27.62	26.2	0.6931	Campbell and Goodman (2004)[1,2]
100.00	20	0.0000	Niklitschek and Secor (2009a)
100.00	28	0.0000	Niklitschek and Secor (2009a)
70.00	20	0.0100	Niklitschek and Secor (2009a)
70.00	28	0.0400	Niklitschek and Secor (2009a)
40.00	20	0.0180	Niklitschek and Secor (2009a)
40.00	28	0.0250	Niklitschek and Secor (2009a)
30.00	20	0.0400	Niklitschek and Secor (2009a)
56.53	28.8	0.0513	EPA (2003)[2,3]

[1] Experiments used juvenile Shortnose Sturgeon
[2] Daily instantaneous mortality rate was computed from LC5 or LC50 as -ln(S), where S is the fraction of individuals surviving 24-hour exposure (S=0.95 for LC5; S=0.5 for LC50).
[3] Estimate is based on interspecies estimate of LC5:LC50 ratio.

To model the approximately exponential increase in mortality rates with decreasing percent oxygen saturation, while including observations with zero mortality, the EPA transformed mortality rate estimates using $Z'_{min} = \ln(Z + 0.001)$, then fitted a linear model to the transformed values (Figure 3) using

$$Z'_{min} = \beta_0 + \beta_1 T + \beta_2(POSAT) + \beta_3(T \cdot POSAT) + \varepsilon \qquad \text{(eq. 8)}$$

where $\beta_{0..3}$ are the estimated coefficients of the regression model, T is water temperature (°C), $POSAT$ is percent oxygen saturation, and ε is a normally distributed random variable. Predicted values from the regression, $\hat{Z}'_{min}$ were back-transformed to compute estimates of minimum instantaneous mortality Z'_{min} using

$$\hat{Z}_{min} = e^{\widehat{Z'}_{min}} - 0.001 \qquad \text{(eq. 9)}$$

The EPA used daily average water quality conditions observed between 2002-2022 at the Chester and Penn's Landing monitoring stations (Figure 2, section 2.1) in equations 8 and 9 to calculate the Z_{min} (d^{-1}) for each day. Daily values were averaged to compute a seasonal average mortality rate and predicted relative abundance of the Atlantic Sturgeon young-of-the-year cohort on October 31. Predicted relative abundance was compared with catch per unit effort (CPUE) in 2009-2022 from juvenile Atlantic Sturgeon abundance surveys conducted by the Delaware Department of Natural Resources and Environmental Control (Appendix 3).

3.3.3 Growth Model

Niklitschek and Secor (2009b) developed a bioenergetics model to model the relationship between water quality conditions that control, limit, or otherwise impact metabolic rates and measurements of those rates from a series of laboratory experiments (Niklitschek and Secor 2009a). These metabolic rates (kJ/d) are terms of a balanced energy equation in which growth (G) results from the balance of inputs (FC = food consumption) less energetic costs (RM = routine metabolism, SDA = postprandial metabolism or specific dynamic action, and ACT = activity cost) and waste or loss (EG = egestion, U = excretion).

$$G = FC - (RM + SDA + ACT) - (EG + U) \quad \text{(eq. 10)}$$

Instantaneous growth rate G_{max} (d^{-1}) for each day was calculated as the log of the ratio of the increased (or decreased) weight (g) to initial weight, with the net energy allocated to growth converted to its equivalent in weight via the energy content, E (kJ/g)

$$G_{max} = \log\left(\frac{W + G/E}{W}\right) \quad \text{(eq. 11)}$$

where the energy content was computed from weight using an empirical relationship (Niklitschek and Secor 2009b).

In this bioenergetic framework, water temperature controls the potential or maximum bioenergetic rates, while percent oxygen saturation limits the maximum oxygen delivery rate and therefore may limit bioenergetic rates to less than their temperature-driven potential. Salinity may impose an additional metabolic cost associated with osmoregulation, which causes a proportional increase in routine metabolism when salinity is higher or lower than optimal.[72] For juvenile Atlantic Sturgeon, potential bioenergetic rates are maximized when water temperature is 20°C, while the osmoregulation costs (i.e., energetic costs imposed by salinity) are minimized when salinity is 9.3 ppt. As shown by Niklitschek and Secor (2009b), a decrease in oxygen saturation from 100% to 40% limits food consumption to 60% of the maximum, which by itself would be expected to limit growth. The model also predicts that gross growth efficiency (i.e., the proportion of food consumption allocated to growth) decreases from 31% to 24%, reflecting a 2% increase in the relative allocation to routine metabolism and a 6% increase in the fraction of the diet not assimilated (i.e., egestion). Thus, low oxygen levels both limit overall metabolic rates and cause a shift in the allocation of available energy away from growth.

The EPA obtained code for the bioenergetics model from the original authors and tested it to ensure that it replicated the results shown in relevant figures from Niklitschek and Secor (2009b). The EPA's initial evaluation showed that the code did not replicate the published results. When comparing the code to the equations reported in the Supplemental Information for the peer-reviewed manuscript, the EPA noted several differences, including differences in reported values of the model parameters vs. parameter values included in the code. Therefore, to produce working code, the EPA edited the provided code so that the equations were faithful to the formulations presented in the Supplemental Information. The model was then re-optimized to select parameters resulting in a best fit to the experimental measurements using a genetic optimization algorithm coded in R. The EPA used parameter values included in the original code as starting values for the optimization and then varied randomly, with parameter sets resulting in

[72] Niklitschek and Secor (2009b).

the lowest residual error selected and used in subsequent optimization, narrowing the magnitude of random variations until the parameter values stabilized. The resulting sub-models were optimized starting with routine metabolism as follows: routine metabolism (*RM*) → food consumption (*FC*) → egestion (*EG*) → specific dynamic action (*SDA*) → excretion (*U*) → activity cost (*ACT*), following Niklitschek and Secor (2009b). The EPA reproduced key figures from the original manuscript to ensure that the model was reproducing the observed responses to water temperature, salinity, and percent oxygen saturation (Appendix 4). The EPA then compared model-predicted bioenergetic rates to averages of measured values to ensure that the model provided an unbiased prediction. The estimates of model parameters derived from experimental measurements, those included in the code as obtained from the authors, and the final optimized values are included in Appendix 4.

Finally, the EPA compared computed estimates of daily fish weight for 2002-2022 to the distribution of fish weights for young-of-the-year individuals that were captured or recaptured during fall on the Delaware River (Figure 6).[73]

[73] Park, Ian. (2020). Final Report. Section 6 Species Recovery Grants Program. Award Number: NA16NMF4720072. Conservation and Recovery of Juvenile Atlantic Sturgeons in the Delaware River. Delaware Department of Natural Resources and Environmental Control. Division of Fish and Wildlife.

3.3.4 Relating Habitat Suitability to Indicators of Dissolved Oxygen Status

The EPA followed Niklitschek and Secor (2005) in defining a Habitat Suitability Index (HSI) which is equivalent to the instantaneous daily production potential (equation 5). Although habitat suitability has been defined in a variety of ways in the context of fish-habitat relationships, conservation management, and habitat evaluation,[74] the EPA defined habitat suitability exclusively in terms of water quality for this analysis. For this analysis, suitable habitat is defined as habitat with water quality that supports the potential for increasing biomass of the annual cohort, which occurs when HSI is greater than zero. The EPA inferred that other characteristics that potentially affect habitat suitability for Atlantic Sturgeon and other migratory fish species, such as water depth or sediment characteristics, are adequate in these habitats because juvenile Atlantic Sturgeon have successfully utilized this habitat in recent years when water quality was unusually good (e.g., Moberg and DeLucia 2016). The EPA quantified relationships between computed values of HSI and corresponding percentiles of percent oxygen saturation using quantile generalized additive models (QGAMs).[75] QGAMs can model the non-linear relationship between oxygen levels and HSI as well as predict the expected median HSI, rather than the expected mean. Although the dissolved oxygen percentiles quantify a single reference point on the seasonal distribution, HSI is affected by every oxygen value that occurs during the *Juvenile Development* season. Therefore, each relationship between a dissolved oxygen percentile and HSI is predicated on a certain distribution of dissolved oxygen values over the season. QGAMs were fitted to model the simple curvature of the relationship and to avoid overfitting. The EPA computed estimates for the lowest value of the dissolved oxygen percentile for which the expected median HSI > 0.

3.4 Criteria Development for the *Spawning and Larval Development* and *Overwintering* Seasons

The Atlantic Sturgeon cohort model described in the previous section relies on experimental studies that were conducted using juvenile Atlantic Sturgeon and therefore provides information that is most relevant to juvenile growth and survival. Additionally, the underlying studies allocated most experimental treatments to water temperatures between 12°C and 28°C, with only a single experimental treatment at 6°C and none at lower water temperatures.[76] The EPA's cohort modeling approach therefore does not apply to the *Spawning*

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[74] E.g., Woodland, R.J., Secor, D.H., and Niklitschek, E.J. (2009). Past and Future Habitat Suitability for the Hudson River Population of Shortnose Sturgeon: A Bioenergetic Approach to Modeling Habitat Suitability for an Endangered Species. American Fisheries Society Symposium 69: 589-604;
Collier, J.J., Chiotti, J.A., Boase, J., Mayer, C.M., Vandergoot, C.S., and Bossenbroek, J.M. (2022). Assessing habitat for lake sturgeon (Acipenser fulvescens) reintroduction to the Maumee River, Ohio using habitat suitability index models. Journal of Great Lakes Research. 48(1): 219-228. https://doi.org/10.1016/j.jglr.2021.11.006;
Brown, S.K., Buja, K.R., Jury, S.H., Monaco, M.E., and Banner, A. (2000). Habitat Suitability Index Models for Eight Fish and Invertebrate Species in Casco and Sheepscot Bays, Maine. North American Journal of Fisheries Management, 20(2): 408-435, https://doi.org/10.1577/1548-8675(2000)020%3C0408:HSIMFE%3E2.3.CO;2.
[75] Fasiolo, M., Wood, S.N., Zaffran, M., Nedellec, R., and Goude, Y. (2020). Fast Calibrated Additive Quantile Regression. Journal of the American Statistical Association 116:1402-1412. https://doi.org/10.1080/01621459.2020.1725521;
Fasiolo, M., Wood, S.N., Zaffran, M., Nedellec, R., and Goude, Y. (2021). qgam: Bayesian Nonparametric Quantile Regression Modeling in R. Journal of Statistical Software 100. https://doi.org/10.18637/jss.v100.i09.
[76] Niklitschek and Secor (2009a).

and Larval Development season and has minimal relevance to the *Overwintering* season. Accordingly, the EPA did not use the cohort model to derive criteria for the *Spawning and Larval Development* or the *Overwintering* seasons.

To derive criteria for the *Spawning and Larval Development* and *Overwintering* seasons, the EPA considered evidence compiled in the Virginian Province Document that larvae of many species are as sensitive or more sensitive to low dissolved oxygen than juveniles. The effects of low oxygen on juvenile Atlantic Sturgeon are greater at high water temperatures;[77] water temperatures in the Delaware River peak during the *Juvenile Development* season, typically in July and August (section 2.1; Figure 2). Water temperatures in the Delaware River are lower during the Atlantic Sturgeon larval development period; therefore, larvae are unlikely to be more sensitive to low dissolved oxygen than juveniles because the larvae generally experience non-stressful water temperature. Similarly, overwintering Atlantic Sturgeon juveniles have temperature-limited metabolism and therefore have similar or slightly lower oxygen requirements than juveniles during summer. Thus, considering the available evidence, the EPA concluded that the percent oxygen saturation threshold that is protective for juveniles experiencing stressful water temperatures during the *Juvenile Development* season would also be protective for larvae and overwintering juveniles experiencing non-stressful water temperatures.

The *Juvenile Development* season criteria consist of two criteria derived from the Atlantic Sturgeon cohort model that together ensure a protective seasonal distribution of dissolved oxygen values is maintained (section 4.2). Since the cohort model is not directly used to derive criteria for the *Spawning and Larval Development* and *Overwintering* seasons, protectiveness does not depend on the existence of the same overall dissolved oxygen distribution as is the case for the *Juvenile Development* season. The EPA therefore determined that a single protective criterion limiting the frequency and severity of low dissolved oxygen conditions that could impact sturgeon would protect aquatic organisms and the designated uses of the waterbody during the *Spawning and Larval Development* and *Overwintering* seasons.

4 Results

4.1 Ecological Modeling Results

4.1.1 Atlantic Sturgeon Mortality

A regression model using estimates of mortality from three studies (Table 2; Campbell and Goodman 2004, EPA 2003, Niklitschek and Secor 2009a) showed that mortality rates of sturgeon increased with declining dissolved oxygen levels and increasing water temperature. A multiple regression fitted to log-transformed mortality rates suggested that the log of mortality rate increased linearly with decreasing percent oxygen saturation and increasing water temperature, such that back-transformed rates increased exponentially with increasing stress due to interacting effects of low oxygen and high water temperature (Figure 3). The mortality rates calculated from estimates of LC50, which were derived from experiments using Shortnose Sturgeon (Campbell and Goodman 2004), all have the same instantaneous mortality rate (i.e., -

[77] Secor and Gunderson (1998), Campbell and Goodman (2004).

ln(0.5)), but the dissolved oxygen level causing 50% mortality in 24 hours increased with increasing water temperature (Figure 3). Although the regression model explains a substantial fraction of the uncertainty (adjusted $r^2 = 0.75$, $p = 0.0025$), the small number of experimental estimates of mortality resulted in wide limits of uncertainty. Additional statistical details are provided in Appendix 5.

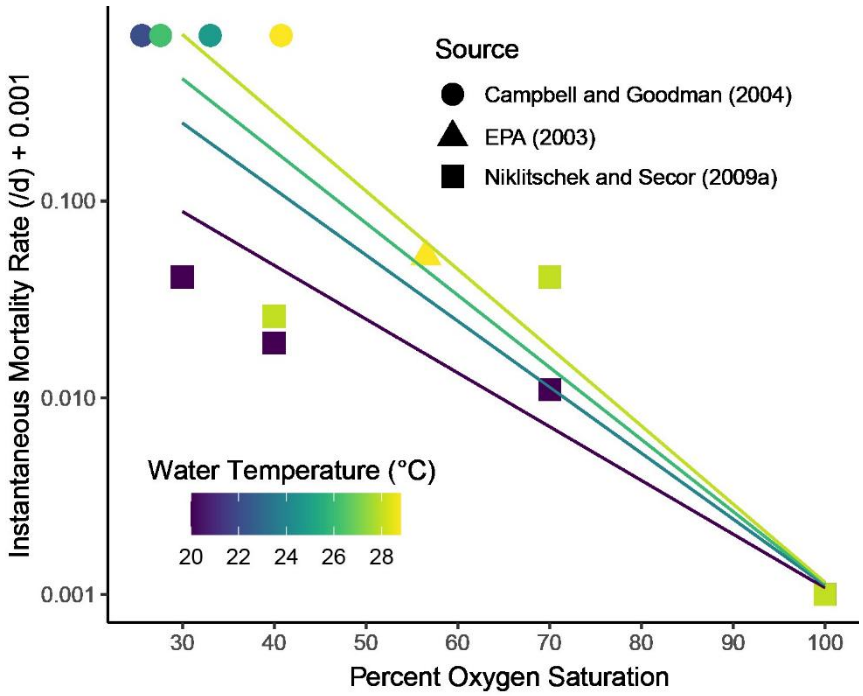

Figure 3: Relationship between Instantaneous Mortality Rates, Percent Oxygen Saturation, and Water Temperature. Oxygen saturation levels were as reported for experimental tests or as calculated from reported dissolved oxygen concentrations (Table 2).

By applying the mortality model (equations 8 and 9) to the time series of percent oxygen saturation and water temperature at Chester and Penn's Landing, the EPA calculated the effect of these variables on potential survivorship (i.e., percentage of individuals surviving the effects of low dissolved oxygen and high water temperature) of a juvenile Atlantic Sturgeon cohort between July 1 and October 31. Between 2002-2022, potential survivorship at Chester and Penn's Landing varied from less than 1% to as high as 50%, with the highest calculated survivorship occurring at Chester in 2018, a year with above average river flow, below average temperature, and higher dissolved oxygen (Figure 4). Young-of-the-year catch per unit effort from the Delaware Department of Natural Resources and Environmental Control's (DNREC's) juvenile abundance surveys between 2009 and 2022 was positively correlated with modeled survivorship near Penn's Landing (r^2=0.56, p<0.01), but was not correlated with survivorship near Chester (Figure 4). Although the EPA cannot be certain of the reason for the difference in the correlation, one possible explanation is that Chester is located at the extreme seaward limit of the oxygen-sag and therefore experiences interannual variability that could differ from conditions across the specified zones of the river.

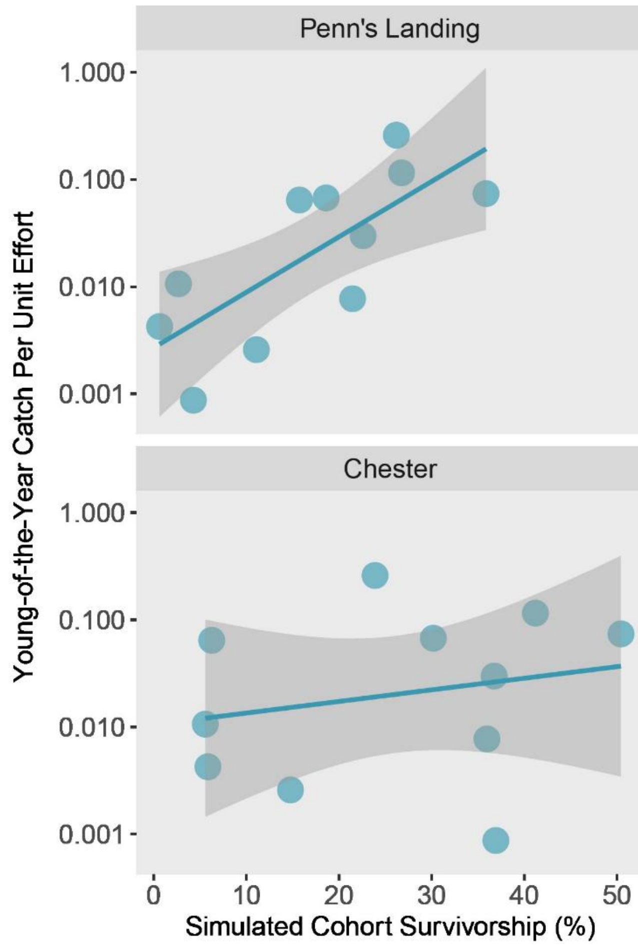

Figure 4: Relationship between Simulated Cohort Survivorship and Observed Annual Catch per Unit Effort Index for Young-of-the-Year Atlantic Sturgeon in the Delaware River during 2009-2022. The simulated cohort survivorship was calculated using the mortality model and water quality data from the Penn's Landing and Chester monitoring stations.

4.1.2 Atlantic Sturgeon Growth

Growth of juvenile Atlantic Sturgeon is maximal when water temperature is 20°C and salinity is 9 ppt.[78] At optimal values for water temperature and salinity, Niklitschek and Secor (2009a) observed higher growth rates in experimental treatments with percent oxygen saturation at 70% or 100%, compared to lower growth observed at 30% and 40% oxygen saturation. Between 2002 and 2022, water quality in the Delaware River was rarely optimal for early juvenile development of Atlantic Sturgeon (section 2.1, Figure 2).

Water temperature and percent oxygen saturation interact to affect the potential growth rate of juvenile Atlantic Sturgeon, as calculated using the bioenergetics model (Figure 5). Growth rates are slightly different from rates depicted in the comparable graph in the lower panel of Figure 1 in Niklitschek and Secor (2005), which shows predicted growth rates for a smaller fish (14.4 g) at a higher salinity (11 ppt), and with a lower maximum temperature (~28°C). In the

[78] Niklitschek and Secor (2009a).

relevant zones of the Delaware River, the lowest oxygen levels mostly coincided with the highest water temperatures, resulting in lower growth rates than either condition would cause alone. Predicted growth rates were negative under the most unfavorable conditions (Figure 5).

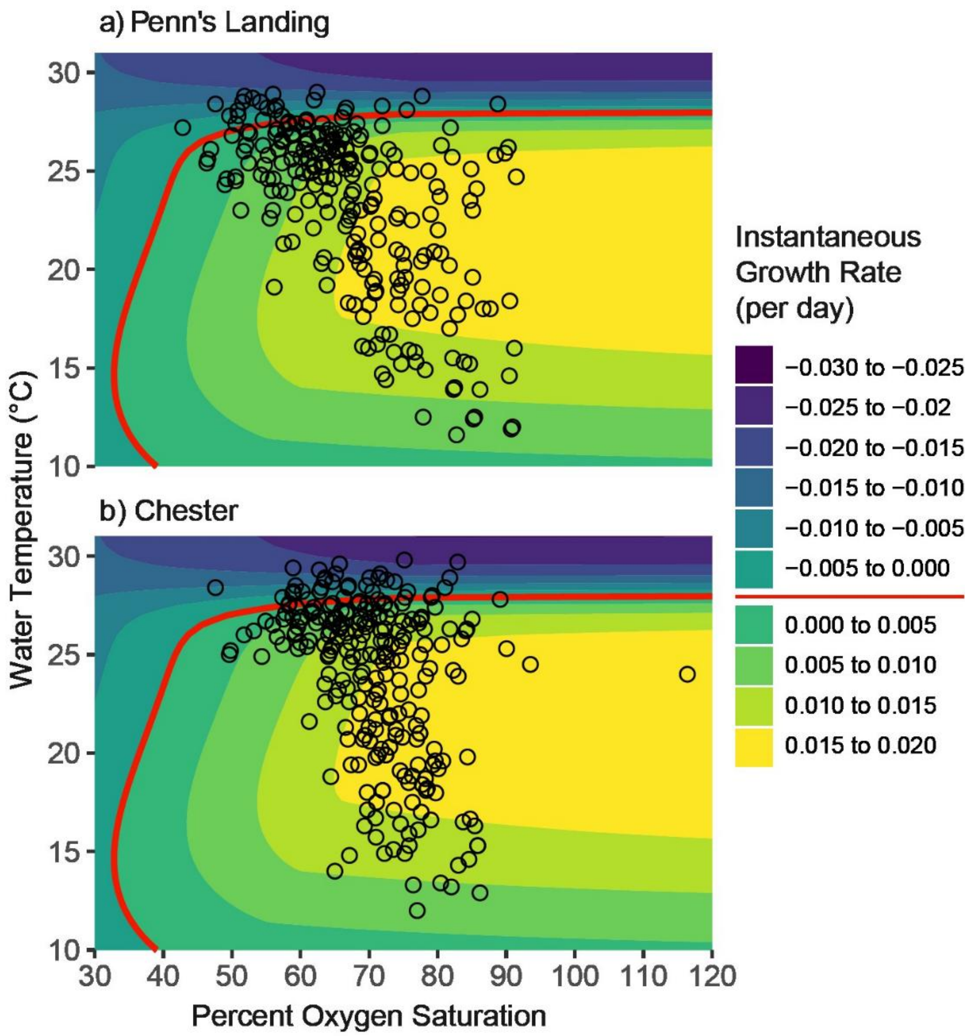

Figure 5: Response of Instantaneous Growth Rate of Juvenile Atlantic Sturgeon to Water Temperature and Percent Oxygen Saturation. Salinity was assumed to be 0.5 ppt (Figure 2) and fish size was assumed to be 50 grams for this figure. Black circles show the distribution of percent oxygen saturation and water temperature between July 1 and October 31 during 2002 to 2022 at the Chester and Penn's Landing monitoring stations. The red contour line delineates the region with positive growth from the region with negative growth.

The EPA simulated fish growth using water quality data at Chester to evaluate the otherwise poorly constrained estimate of initial size on July 1. Juvenile surveys provide benchmark data on juvenile weights in the late fall; however, fish size on July 1 has not been documented. An initial weight of 27 grams on July 1, which is well within the range of sizes suggested by Niklitschek and Secor (2009a), results in simulated fish weights that fall within the range of observed sizes from fish surveys (Calvo, 2010; Park, 2020) for years in which fish were captured (Figure 6).[79] The cohort model predicted reduced growth rates in many years in which no fish were captured; however, the EPA also ran simulations for years in which no fish surveys were conducted, resulting in both high and low growth rates that were not accompanied by observed fish sizes (Figure 6).

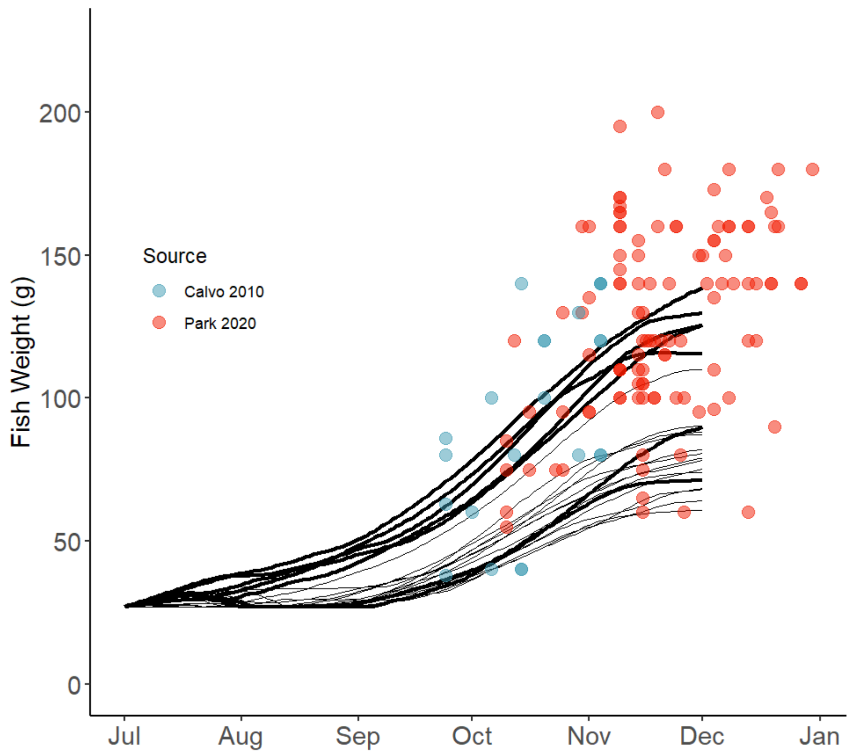

Figure 6: Simulated Fish Weight based on Water Quality at Chester for the Years 2002-2022 (lines) and Weights of Age-0 Juvenile Atlantic Sturgeon Captured in the Delaware River (circles). Fish size data are from Calvo (2010) and Park (2020). Captures and re-captures of fish were generally in the vicinity of Marcus Hook, near Chester, PA, on the date indicated on the x-axis. Darker black lines show model predictions for years in which fish were captured and their weights shown on the graph. Light grey lines show predictions for years where there are no data on fish sizes.

4.1.3 Intersection of Habitat Suitability and Dissolved Oxygen Thresholds

The Habitat Suitability Index quantifies the combined effect of percent oxygen saturation, water temperature, and salinity on juvenile Atlantic Sturgeon growth and survival at a seasonal time scale. HSI values for this analysis range from approximately -0.08 to 0.01. When HSI is

[79] Fish were captured in 2009 (Calvo 2010) and 2014 – 2018 (Park 2020).

greater than zero, the seasonal average potential growth rate is greater than seasonal average minimum mortality rate and the biomass of the cohort has the potential to increase.[80] Biomass decreases when HSI is negative; when HSI falls to -0.02 or lower, over 90% of the cohort biomass is lost (Figure 7).

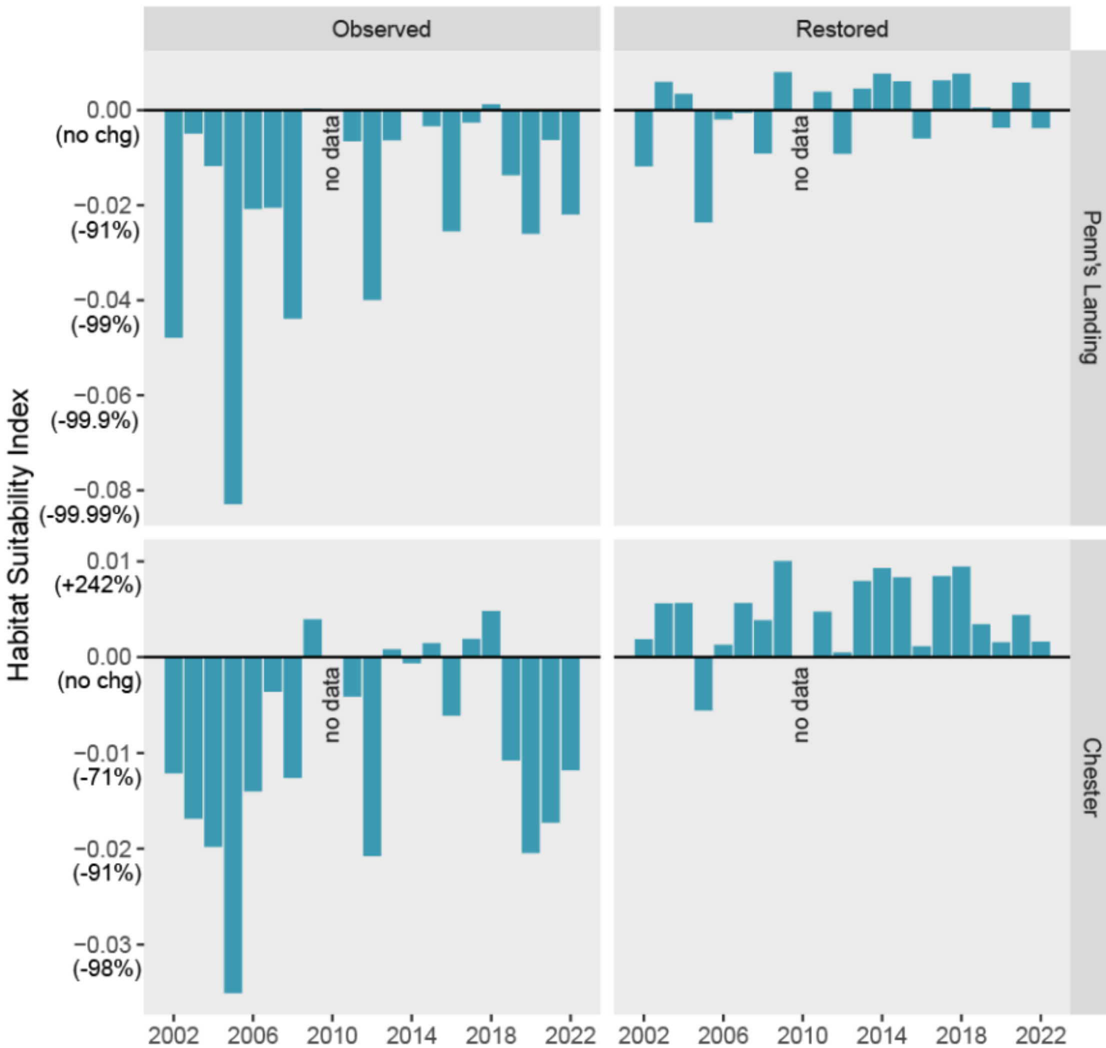

Figure 7: Habitat Suitability Index Computed for 2002-2022 using Observed Dissolved Oxygen Data or Estimates of Restored Dissolved Oxygen at the Penn's Landing and Chester Monitoring Stations. Due to missing water quality data, estimates were not computed for 2010 at either site. Y-axis values in parentheses are the seasonal percent change in biomass from July 1 to October 31 corresponding to the HSI value, computed as $100 \times \left(e^{(123 \times HSI)} - 1\right)$, where 123 is the number of days in the season. "no chg" signifies no change in biomass from July 1 – October 31.

[80] A positive HSI does not imply zero mortality in the cohort. Rather, it indicates the potential for the biomass (number of individuals multiplied by the weight of the individuals) of surviving fish to be greater than the initial biomass of the cohort on July 1.

HSI values computed from observed data varied from -0.082 at Penn's Landing in 2005 to 0.0056 at Chester in 2018 (Figure 7). The seasonal net cohort production associated with observed dissolved oxygen varied from a loss of nearly all biomass (i.e., more than 99% loss of biomass) to an 100% seasonal increase in cohort biomass, which occurred at Chester in 2018 (Appendix 6, Figure 7). HSI was 0.0094 higher at Chester, which generally had higher dissolved oxygen than Penn's Landing, and increased at a rate of 0.00084 each year during 2002-2022, with substantial interannual variability. The restored dissolved oxygen scenario resulted in a substantial increase in HSI of 0.031 – and in the best years, a 2- to 3- fold increase in biomass (Figure 7). Whereas HSI computed with observed dissolved oxygen was greater than zero in only a few years at either site, HSI computed using restored dissolved oxygen at Chester was greater than zero in every year except for 2005. Although several years had HSI less than zero at Penn's Landing under the restored scenario, the lower restored values were still much higher than the corresponding observed values. The overall positive shift in HSI values under the restored scenario indicates the expected positive effects of improvement in water quality conditions on sturgeon habitat suitability in the specified zones of the Delaware River.

QGAMs predicting the median HSI conditional on seasonal percentiles of percent oxygen saturation (POSAT) show that when dissolved oxygen levels were relatively low, expected median HSI increased nearly linearly with both the seasonal 10^{th} percentile and median (50^{th} percentile) POSAT. In general, as dissolved oxygen increased from moderate to high levels, the slope decreased toward an asymptote at high POSAT, reflecting a lack of mortality due to low POSAT and oxygen levels that maximized temperature-dependent growth rates (Figure 8). These relationships were similar for both Chester and Penn's Landing, thus justifying including data from the two stations together in a single relationship. Similar relationships were also found with both observed POSAT and the restored scenario (Figure 8). QGAMs fitted to only observed POSAT values were poorly constrained at relatively high POSAT because there were few observations at those levels, resulting in poor quantification of the threshold dissolved oxygen level required to attain HSI greater than zero. In contrast, QGAMs fitted to restored conditions, and the associated HSI, were well-constrained near HSI=0 and had a better-defined asymptote (Figure 8).

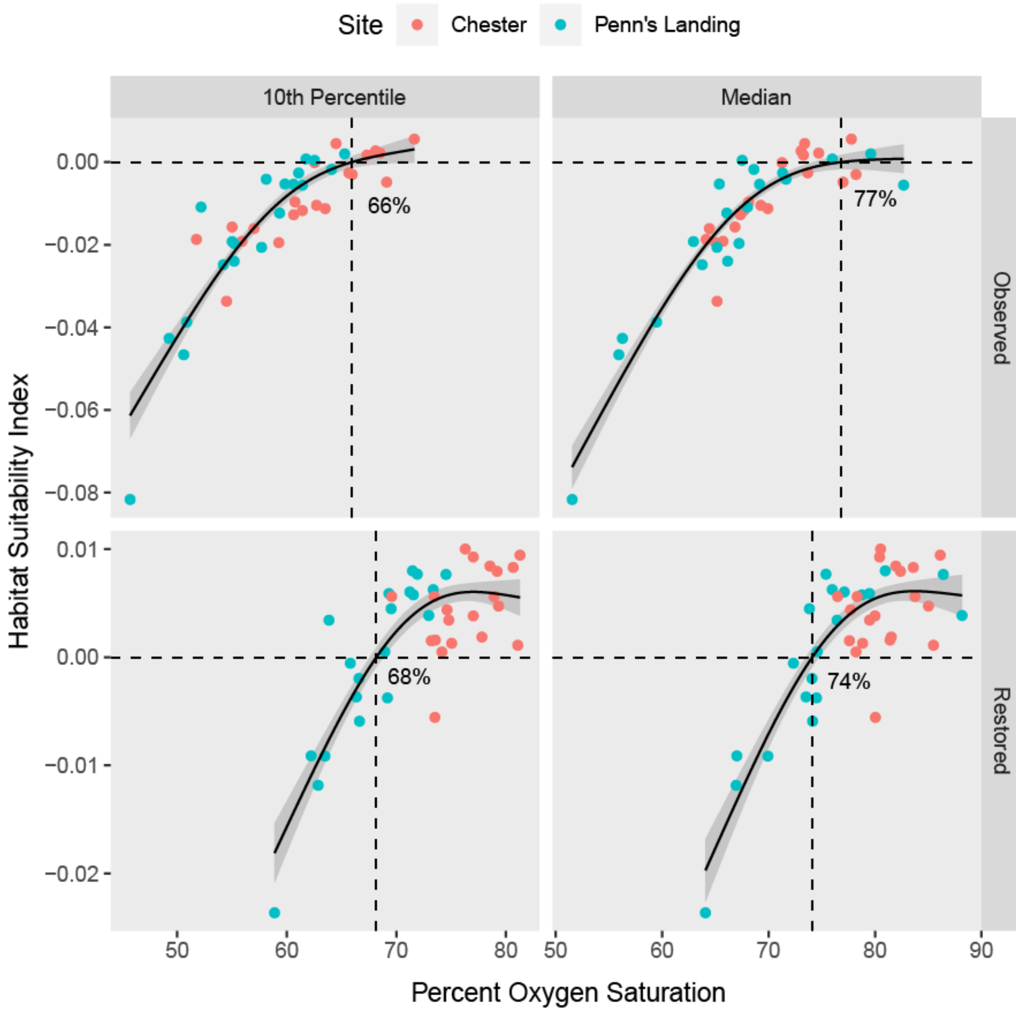

Figure 8: Relationship between Seasonal Percentiles of Percent Oxygen Saturation and Habitat Suitability Index at Chester and Penn's Landing from 2002-2022. Regression models are quantile generalized additive models predicting the median HSI conditioned on either the seasonal 10th percentile or median (50th percentile) percent oxygen saturation. Upper vs. lower panels show relationships between observed and restored dissolved oxygen levels and HSI calculated using the corresponding dissolved oxygen levels. Vertical dotted lines and associated labels (%) show the percent oxygen saturation level at which the median regression line intersects HSI=0.

The relationship between observed POSAT percentiles and HSI can be expected to quantify the seasonal relationship for water quality patterns as they currently exist. Since the seasonal distribution of POSAT could change with implementation of pollution controls, the relationship between percentiles of POSAT and HSI could also change, even though the effect of POSAT itself on growth and mortality does not change. However, the EPA's models show that if there is a difference, the difference is not apparent (Figure 8, Table 3). A QGAM fitted to the estimates based on both observed and restored dissolved oxygen together (Figure 9, Table 3) achieves improved fit associated with a larger range of POSAT values. The EPA believes this relationship to be relevant to the transition from the existing ecological conditions to a future state with improved water quality. Therefore, a combination approach using both observed and restored

POSAT data allows the EPA to evaluate QGAMs with the lowest uncertainty and the most relevant ecological conditions for the present and the expected future (Figure 9).

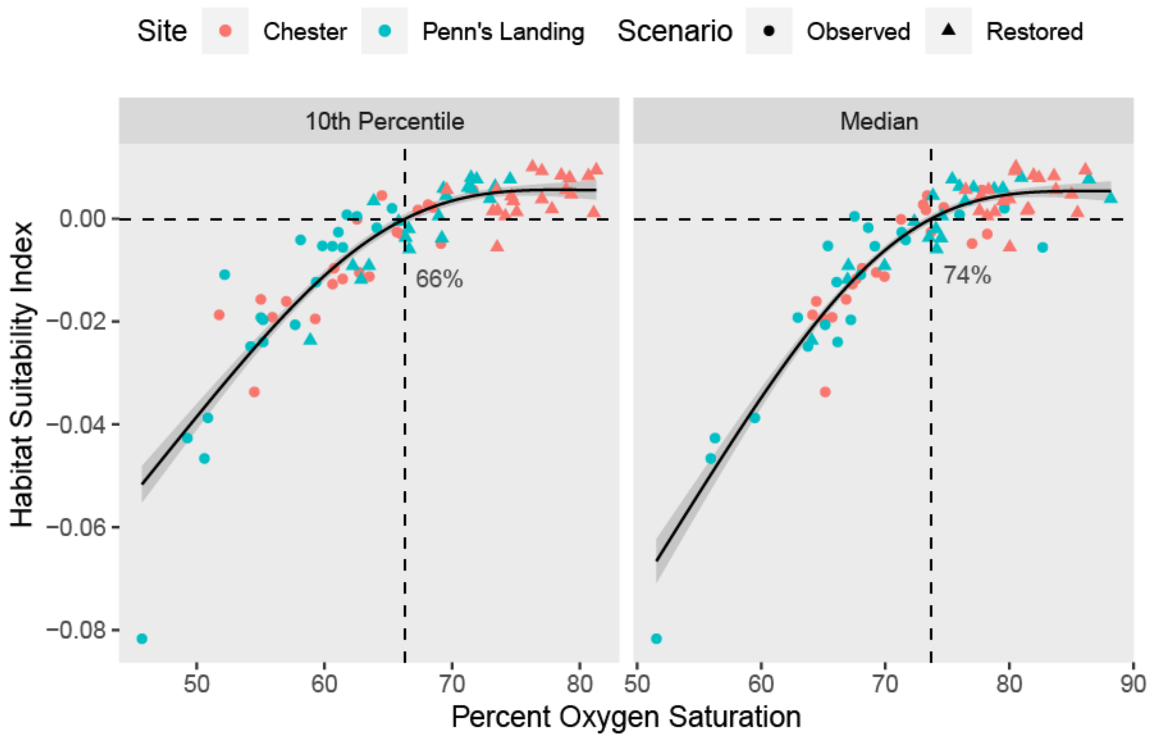

Figure 9: Relationship between Combined Seasonal Percentiles of Percent Oxygen Saturation and Habitat Suitability Index at Chester and Penn's Landing from 2002-2022. Regression models are quantile generalized additive models predicting the median HSI conditioned on either the seasonal 10th percentile or median (50th percentile) percent oxygen saturation. Models are fitted to the combined data including both observed and estimates of restored percent oxygen saturation levels and HSI calculated using the corresponding dissolved oxygen level. Vertical dotted lines and associated labels (%) show the percent oxygen saturation level at which the median regression line intersects HSI=0.

Table 3. Thresholds for Percent Oxygen Saturation Associated with Median HSI > 0.

Data	10th Percentile	Median (50th Percentile)
Observed	66%	77%
Restored	68%	74%
Combined	66%	74%

For this analysis, the EPA followed the approach of Niklitschek and Secor (2005) and defined suitable habitat for juvenile sturgeon growth and survival as habitat with water quality resulting in HSI greater than zero. When HSI is less than or equal to zero, seasonal average mortality rates are greater than or equal to seasonal average growth rates and the overall biomass of the cohort is likely to decrease. Maintaining a strong cohort through summer and into late fall is critical for propagation. After a period during winter when growth is limited by low water temperature, the cohort resumes growing when water temperature and oxygen are both favorable for growth and survival (Figure 2). However, these favorable conditions only benefit cohort members that survived the critical *Juvenile Development* season. A cohort of juveniles utilizing habitat with HSI greater than zero has the potential to increase its biomass during the *Juvenile Development* season, thus contributing to successful propagation. Therefore, to derive dissolved oxygen criteria protective of the juvenile Atlantic Sturgeon during the *Juvenile Developement* season, and going into the *Overwintering* season, the EPA evaluated seasonal percentiles of POSAT to find the lowest value at which the QGAMs predict expected median HSI is greater than 0 as the minimum thresholds for POSAT that would provide suitable habitat during that seasonal period.

Given the reliance of predicted HSI outcomes on the distribution of POSAT values throughout the season, the EPA selected two percent oxygen saturation percentiles as thresholds at or above which median HSI is expected to be greater than zero to maintain the expected distribution of percent oxygen saturation values. These two percentiles – the 10th percentile and the 50th percentile – characterize the low end and middle of the distribution of dissolved oxygen values that is protective of juvenile Atlantic Sturgeon and protect against a detrimental change in the lower half of the distribution that could result in a harmful effect on sturgeon. The 10th percentile is a reliable measure of the frequency of low dissolved oxygen values that may be especially harmful to aquatic life (section 4.2.1). Although the EPA could have selected a lower percentile to derive a criterion value, such extreme percentiles can be difficult to reliably assess. The 50th percentile represents the midpoint of the distribution and ensures that the center of the distribution does not become skewed towards low dissolved oxygen values. If the 10th percentile and the 50th percentile are attained, the EPA expects that the seasonal distribution of dissolved oxygen values will provide suitable habitat for juvenile Atlantic Sturgeon.

Overall, using the combined approach – which includes both observed and restored POSAT seasonal distributions – median HSI was predicted to be greater than zero when the 10th percentile of POSAT was greater than 66% and the 50th percentile POSAT was greater than 74% (Figure 9).

4.2 Final Dissolved Oxygen Criteria

The EPA's dissolved oxygen criteria cover three distinct seasons and are intended to protect all oxygen-sensitive species in the Delaware River. The *Spawning and Larval Development* season is March 1st to June 30th and captures a comprehensive range of resident aquatic species' spawning periods.[81] The *Juvenile Development* season is July 1st to October 31st and captures critical early growth and development for young-of-the-year Atlantic Sturgeon. The

[81] Stoklosa et al. (2018); Delaware River Basin Commission (2015).

Overwintering season is November 1st to February 28th (or 29th, in a leap year), when juvenile Atlantic Sturgeon growth is limited by low water temperatures.

Each season has water quality criteria that consist of three components: magnitude, duration, and exceedance frequency. The magnitude component indicates the required level of dissolved oxygen in the water, which in this rule is expressed as percent oxygen saturation. The duration component specifies the time period over which water quality is averaged before it can be compared with the criteria magnitude; in this rule, the duration is a daily average. The EPA selected a daily average duration because it is readily measurable using dissolved oxygen sensors and is protective in the relevant zones of the Delaware River because variations at time scales of less than one day are relatively small. Additionally, while the available science for Atlantic Sturgeon does not address the effect of low oxygen exposures lasting less than one day, calculations outlined in the Virginian Province Document suggest that to cause high mortality within a few hours, daily minimum oxygen concentrations would have to be lower than the minimum oxygen levels that the EPA expects would be likely in the specified zones if the EPA's criteria are attained.[82] The exceedance frequency component specifies how often each criterion magnitude can be exceeded while still ensuring that the use is protected. For this rulemaking, the exceedance frequency is determined based on the percentile of percent oxygen saturation from which the magnitude is derived. For example, the 10th percentile criterion magnitude can be exceeded on 10% of days in the season, which for a season consisting of 123 days is no more than 12 cumulative days of exceedance. For dissolved oxygen, an exceedance occurs when the daily average oxygen level in the water is below the criterion magnitude.

In this final rule, the *Spawning and Larval Development* and *Overwintering* seasons each have a single, identical dissolved oxygen criterion with a magnitude of 66% oxygen saturation, a daily average duration, and an exceedance frequency that allows for up to 12 days of cumulative exceedance during each of these two seasons (i.e., 10% of each 123-day season) (Table 4). The *Juvenile Development* season has two individually applicable dissolved oxygen criteria that together define a protective seasonal distribution of percent oxygen saturation. The criteria differ in both magnitude and exceedance frequency and both levels must be attained. The first *Juvenile Development* criterion defines the lower end of the distribution of oxygen levels and consists of a magnitude of 66% oxygen saturation, a daily average duration, and an exceedance frequency that allows for up to 12 days of cumulative exceedance during the season (i.e., 10% of the 123-day season). The second *Juvenile Development* criterion defines the center of the distribution of oxygen levels and consists of a magnitude of 74% oxygen saturation, a daily average duration, and an exceedance frequency that allows for up to 61 days of cumulative exceedance during the season (i.e., 50% of the 123-day season) (Table 4).

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[82] United States Environmental Protection Agency. (2000). Ambient Aquatic Life Water Quality Criteria for Dissolved Oxygen (Saltwater): Cape Cod to Cape Hatteras. Document ID: EPA-822-R-00-012. November 2000. https://www.epa.gov/sites/default/files/2018-10/documents/ambient-al-wqc-dissolved-oxygen-cape-code.pdf.

Table 4. The EPA's Final Dissolved Oxygen Criteria

Season	Magnitude (Percent Oxygen Saturation)	Duration	Exceedance Frequency
Spawning and Larval Development *(March 1 – June 30)*	66%	Daily Average	12 Days Cumulative *(10% of the 123-day season)*
Juvenile Development *(July 1 – October 31)*	66%	Daily Average	12 Days Cumulative *(10% of the 123-day season)*
	74%	Daily Average	61 Days Cumulative *(50% of the 123-day season)*
Overwintering *(November 1 – February 28/29)*	66%	Daily Average	12 Days Cumulative *(10% of the 123-day season)*

4.2.1 Expected Minimum Dissolved Oxygen Levels when the EPA's Criteria are Attained

During the public comment period, some commenters expressed concerns that very low dissolved oxygen levels could occur during the 12 days of allowable exceedance in each season for the 66% oxygen saturation criterion. The EPA's response to these comments is available in the associated response to public comments document, which is available in the docket for this rule. To better evaluate and explain the implications of the EPA's criteria, the EPA completed an informational analysis of seasonal minimum values for percent oxygen saturation that are expected to occur when the EPA's criteria are attained.

The EPA used data collected between 2002 and 2022 and projections of restored dissolved oxygen levels to evaluate the oxygen levels that could reasonably be expected to occur during the 12 days of allowable exceedance if the EPA's criteria are attained. A linear regression relating the seasonal 10th percentile and seasonal minimum value for the *Juvenile Development* season shows that when the 10th percentile of daily average oxygen saturation is 66%, the expected value for the minimum daily average oxygen saturation is 61% ($r^2 = 0.93$, 95% confidence interval: 60.6% to 61.7% saturation) (Figure 10).

Given the observed interannual variability in the 10th percentile level, the EPA expects that if the EPA's criteria are attained in all years, the 10th percentile of percent oxygen saturation will be higher than 66% in most years. The standard deviation of the seasonal 10th percentiles of percent oxygen saturation is 5.4% at both Chester and Penn's Landing for the observed oxygen levels and is 4.3% at Penn's Landing and 3.1% at Chester for restored percent oxygen saturation. The standard deviation of the 10th percentiles is lower in the restored scenario than the observed data because, compared to the observed data, the lowest values in the restored scenario increased more than the highest values. For the 10th percentile to be higher than 66% in 19 out of 20 years (i.e., 95% of the years), the lower 95% prediction interval for the future distribution should be 66%. Therefore, the expected mean can be computed as 66% minus the lower 95% quantile of the t-distribution (α=0.05, degrees of freedom=20) times the standard error for the restored oxygen scenarios. Accordingly, the mean value for the seasonal 10th percentile is expected to be in the range of 71% to 73% saturation (Figure 10). These values were computed for the restored scenarios because the 10th percentile criterion is not attained in the current condition. Based on the relationship between the seasonal 10th percentile and the seasonal minimum, the seasonal minimum percent oxygen saturation is likely to average 67% to 69% when the EPA's criteria are attained in all or nearly all years. As an example, restored data at Chester show that the expected lowest 10th percentile value is 70% saturation, which is higher than the EPA's 66% criterion. The mean of the seasonal 10th percentiles is 76% saturation, which is higher than the computed range for the mean (i.e., 71% to 73% saturation). Restored data at Chester also show the average of the seasonal minimums is 67% saturation.

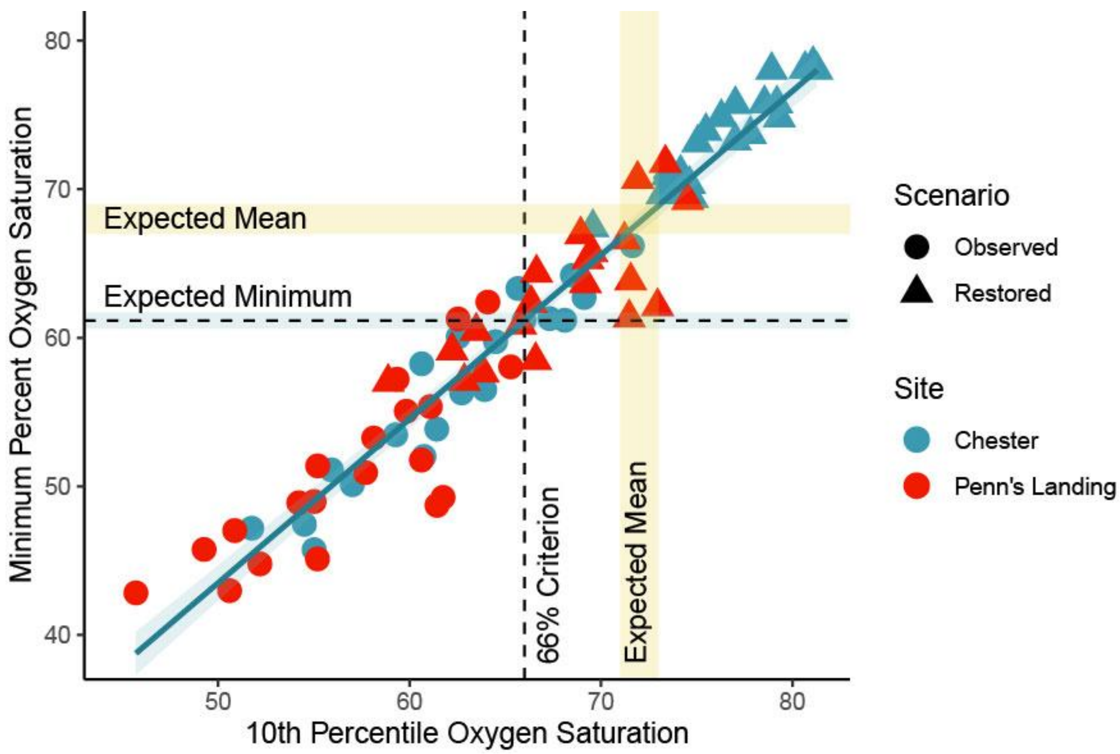

Figure 10: The relationship between the 10th percentile and minimum percent oxygen saturation during the *Juvenile Development* season at Chester and Penn's Landing for observed values (2002-2022) and restored values. A horizontal light blue band shows the expected minimum percent oxygen saturation (with 95% confidence interval) when the 10th percentile is 66% oxygen saturation. Yellow bands show the expected mean 10th percentile and minimum value if the 66% oxygen saturation criterion value is attained 95% of the time and variability is as expected in the restored scenario.

Whereas the expected value for the minimum percent oxygen saturation during the *Juvenile Development* season is 61% when the 10th percentile is 66%, the minimum and 10th percentile value are expected to be higher than 61% and 66%, respectively, in nearly all years to ensure attainment of the 66% oxygen saturation criterion in every year. Based on the EPA's cohort modeling approach, if the 10th percentile criterion is attained, the oxygen saturation values that are expected to occur during the 12 days of potential exceedance will not be low enough to reduce expected HSI values to less than zero and therefore the propagation use will be protected.

5 Limitations and Uncertainties

5.1 Restored Dissolved Oxygen Condition

The EPA computed HSI in part using estimates of dissolved oxygen levels that may occur in the future if additional effluent treatment technologies are applied at selected wastewater treatment facilities, as described in section 2.2 and in the EPA's associated economic analysis.[83] These estimated dissolved oxygen values were derived using simulation results from the DRBC's EFDC-WASP model. The EPA's use of these estimates assumes that the DRBC's model reasonably approximates the pattern and direction of change in dissolved oxygen levels that would be expected after water quality management actions are implemented. However, the EPA recognizes that percent oxygen saturation values in the future could increase by more, or less, than projected by the DRBC's model.[84]

The EPA expects that error or uncertainty in the estimates of the restored dissolved oxygen condition would have a small effect, if any, on the EPA's calculated criteria magnitudes for the *Juvenile Development* season. Errors of this type would have a small effect because changes in the restored dissolved oxygen condition would affect both calculated dissolved oxygen percentiles and the computed values of HSI. If percent oxygen saturation were to increase by more than expected under the restored scenario, then the dissolved oxygen percentiles and HSI would both be higher. Conversely, if percent oxygen saturation increased by a smaller amount, the corresponding percentiles and computed HSI would both be lower. The EPA's modeled relationship between dissolved oxygen percentiles and HSI accommodates both observed and restored oxygen levels without a clear difference in the distribution of observations around the quantile regression line (Figure 8, Figure 9). Therefore, the EPA does not anticipate that the regression model would change if the effect of restoration actions on percent oxygen saturation was larger or smaller than predicted by the DRBC's model.

5.2 Water Temperature Changes

Air temperature in the Delaware River watershed has increased steadily since the early 1900s and at an accelerated rate during the past 30 years.[85] Previous studies have documented a relationship between increasing air temperature and increasing water temperature;[86] however, a rigorous estimate of expected changes in water temperature for the Delaware River does not exist in the published literature.[87] Therefore, when deriving dissolved oxygen criteria, the EPA

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[83] *Economic Analysis for the Final Rule: Water Quality Standards to Protect Aquatic Life in the Delaware River*.
[84] *Id.* (see section 2.1).
[85] Partnership for the Delaware Estuary. (2022). Technical Report for the Delaware Estuary and Basin. L. Haaf, L. Morgan, and D. Kreeger (eds). PDE Report No. 22-05. 445 pages. https://delawareestuary.s3.amazonaws.com/TREB+2022+Full+Report.pdf.
[86] E.g., Hinson, K.E., Friedrichs, M.A.M., St-Laurent, P., Da, F., and Najjar, R.G.. (2022). Extent and Causes of Chesapeake Bay Warming. Journal of the American Water Resources Association 58(6): 805–825. https://doi.org/10.1111/1752-1688.12916.
[87] Partnership for the Delaware Estuary (2022).

assumed that overall water temperature and the seasonal pattern of water temperature would not change from recent observations.

Evidence shows that increased water temperature during late summer, when water temperature is already stressful, would likely increase mortality rates of juvenile Atlantic Sturgeon and increase their sensitivity to low oxygen.[88] Similarly, growth rates already limited by high temperature could be further reduced, especially if oxygen levels limit growth potential, potentially causing growth rates to be negative. On the other hand, if juveniles survive the most stressful period during late summer, increased water temperature during late fall, combined with relatively high oxygen levels, could extend the period of optimal temperature and increase growth rates in late fall. Thus, a credible estimate of the net effect of any future water temperature changes on oxygen requirements would require additional information on the magnitude and seasonal distribution of water temperature changes.

5.3 Sturgeon Population Dynamics

For this final rule, the EPA followed Niklitschek and Secor (2005) in defining suitable habitat on a seasonal basis in terms of water quality that potentially allows for positive production potential of the annual juvenile cohort (i.e., HSI greater than 0).

The EPA recognizes uncertainty associated with this approach as it relates to preventing extinction and promoting recovery of threatened and endangered populations. Despite having the necessary data to model age-0 juvenile Atlantic Sturgeon growth and survival, the EPA lacks an estimate of growth and survival of both older juveniles and the adult population and corresponding changes in population size over time. To estimate full recovery of the population, the EPA would need additional information such as: (1) estimates of growth and mortality of new recruits after they join the adult population, including during the period that they reside in marine waters, (2) estimates of the frequency at which spawning adults return to the river to spawn, (3) estimates of the magnitude of their reproductive output, (4) estimates of hatching success and larval survival, and (5) estimates of a population size that, if attained, would adequately reduce the risk of population decline or extinction. Absent this information, it is possible that an HSI lower than zero could be protective or that an HSI higher than zero could be required to protect the Atlantic Sturgeon population as a whole and lead to recovery of a stable population.

In 1998, NMFS published a recovery plan for the Shortnose Sturgeon, which includes narrative descriptions of population recovery criteria (i.e., criteria that if met would indicate that the species no longer requires ESA protection).[89] A recovery plan is not yet available for the Atlantic Sturgeon, but an outline was published in 2018.[90] However, neither document includes a numeric target population for species recovery. Without a target population for recovery, the

[88] See section 3.3.
[89] National Marine Fisheries Service (1998).
[90] National Oceanic and Atmospheric Administration. (2018). Recovery Outline for the Atlantic Sturgeon Distinct Population Segments. March 1, 2018. https://media.fisheries.noaa.gov/dam-migration/ats_recovery_outline.pdf.

EPA could not evaluate how attainment of the final criteria might contribute to species recovery in the ESA context.

5.4 Atlantic Sturgeon Cohort Model

In addition to unquantified dynamics of the overall Atlantic Sturgeon population, there are sources of uncertainty associated with the EPA's cohort model. These include factors that could result in actual growth rates lower than the potential growth rate or mortality rates higher than the minimum mortality rate. Both factors could reduce actual production to less than potential production. Therefore, a higher oxygen level may be required to ensure a seasonal increase in biomass of the cohort.

Following Niklitschek and Secor (2005), the EPA quantified growth potential by assuming that fish eat as much food as their physiology permits given ambient water temperature and dissolved oxygen. This has been called "full ration." The EPA also assumed that the diet of Atlantic Sturgeon in the Delaware River had an energy density comparable to the rations provided in experimental treatments by Niklitschek and Secor (2009a). However, fish may consume less in the wild than in experimental settings[91] and their diet may have a lower energy density.[92] If actual production potential was lower than the modeled production potential used in the EPA's analysis, then a higher dissolved oxygen level might be required to ensure that the biomass of the cohort could increase during the juvenile growth season.

The EPA estimated mortality due to low oxygen and high water temperature based on rates observed for laboratory-reared fish exposed in a laboratory setting. In a natural setting, fish may experience additional mortality resulting from the cumulative effect of predation, disease, deprivation, or other causes. If mortality rates were higher than the minimum rate the EPA used in the cohort model, then the oxygen level needed to maintain a cohort production rate greater than zero (i.e., HSI > 0) could be higher than the EPA estimated.

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Appendix 1: Percent Oxygen Saturation Time Series for the *Juvenile Development* Season

Time series plots in Figures A1-1 and A1-2 show the available dissolved oxygen and water temperature data during the *Juvenile Development* season from July 1 – October 31. Gaps in the record are apparent in all years from 2002 through 2022.

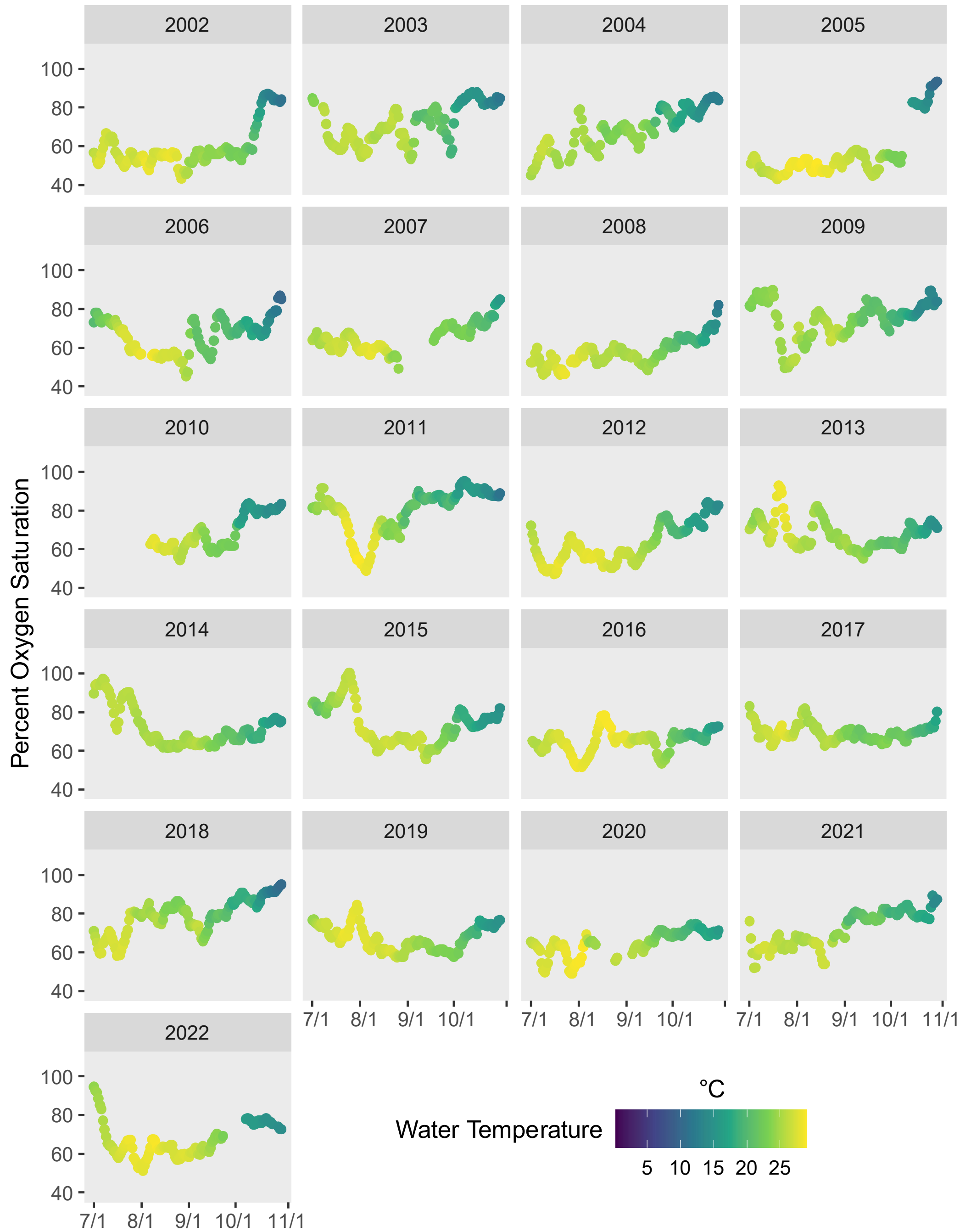


Figure A1-1: Daily Average Percent Oxygen Saturation and Water Temperature for 2002-2022 at Penn's Landing During the *Juvenile Development* Season. Gaps indicate where data are not available during the July 1 to October 31 period in each year.

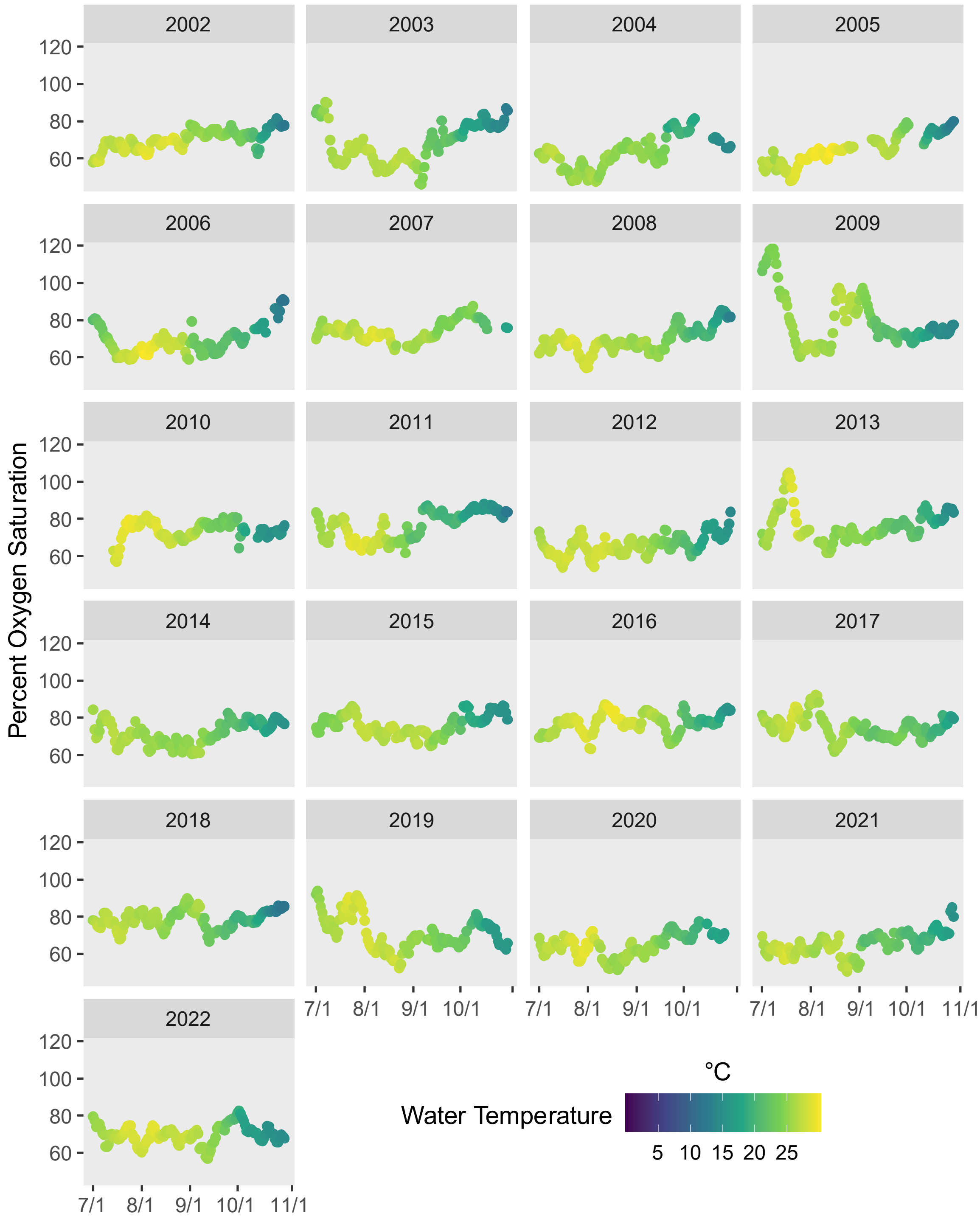


Figure A1-2: Daily Average Percent Oxygen Saturation and Water Temperature for 2002-2022 at Chester During the *Juvenile Development* Season. Gaps indicate where data are not available during the July 1 to October 31 period in each year.

Appendix 2: Modeling Restored Dissolved Oxygen Time Series

This appendix provides statistical details related to the generalized additive models (GAMs) relating observed dissolved oxygen time series at the Penn's Landing and Chester water quality monitoring stations to simulation model results for the same dates and locations from the DRBC's Environmental Fluid Dynamics Code – Water Analysis Simulation Program (EFDC-WASP) model predicting dissolved oxygen levels under a "restored" scenario.[93] The restored scenario predicts water quality responses to implementation of specified remedial actions, including reducing concentrations of ammonia nitrogen discharged by specified wastewater treatment plants, increasing effluent dissolved oxygen levels, and completing combined sewer overflow long-term control plans.[94] Model simulations of the restored scenario are available for 2012, 2018, and 2019.

Figures A2-1 and A2-3 show the relationship between observed dissolved oxygen and simulated dissolved oxygen in the restored scenario.

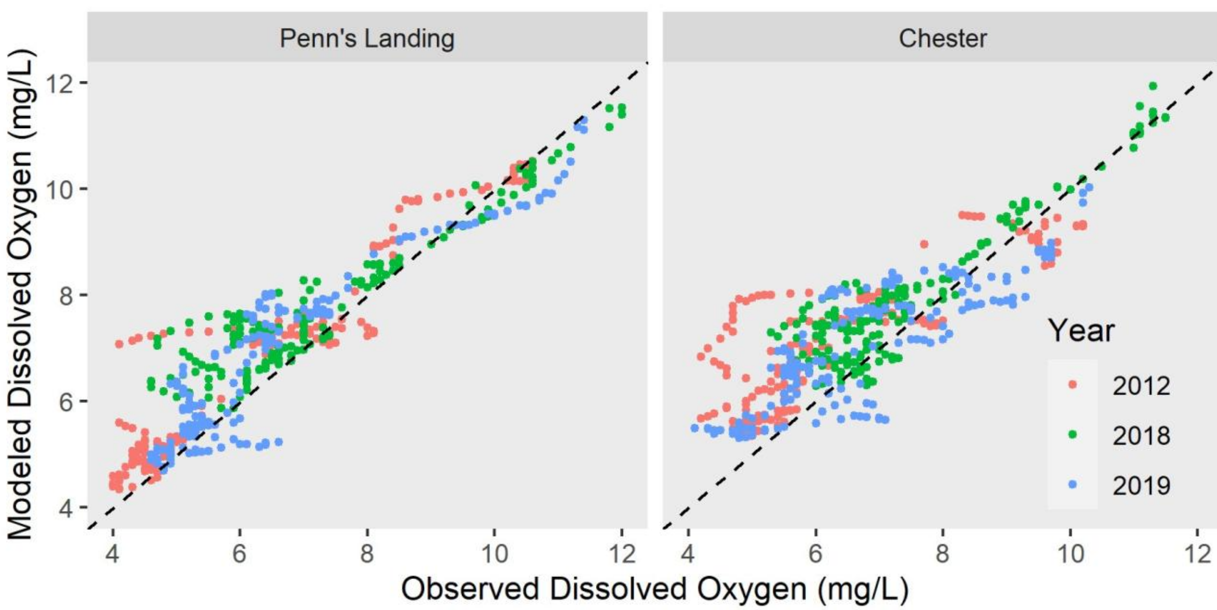


Figure A2-1: Relationship between Observed and Modeled Restored Dissolved Oxygen at the Penn's Landing (left) and Chester (right) Monitoring Stations. The modeled dissolved oxygen are results from the DRBC's EFDC-WASP model predicting restored conditions after a series of pollution controls. The black dashed line running diagonal through the plots is a 1:1 line.

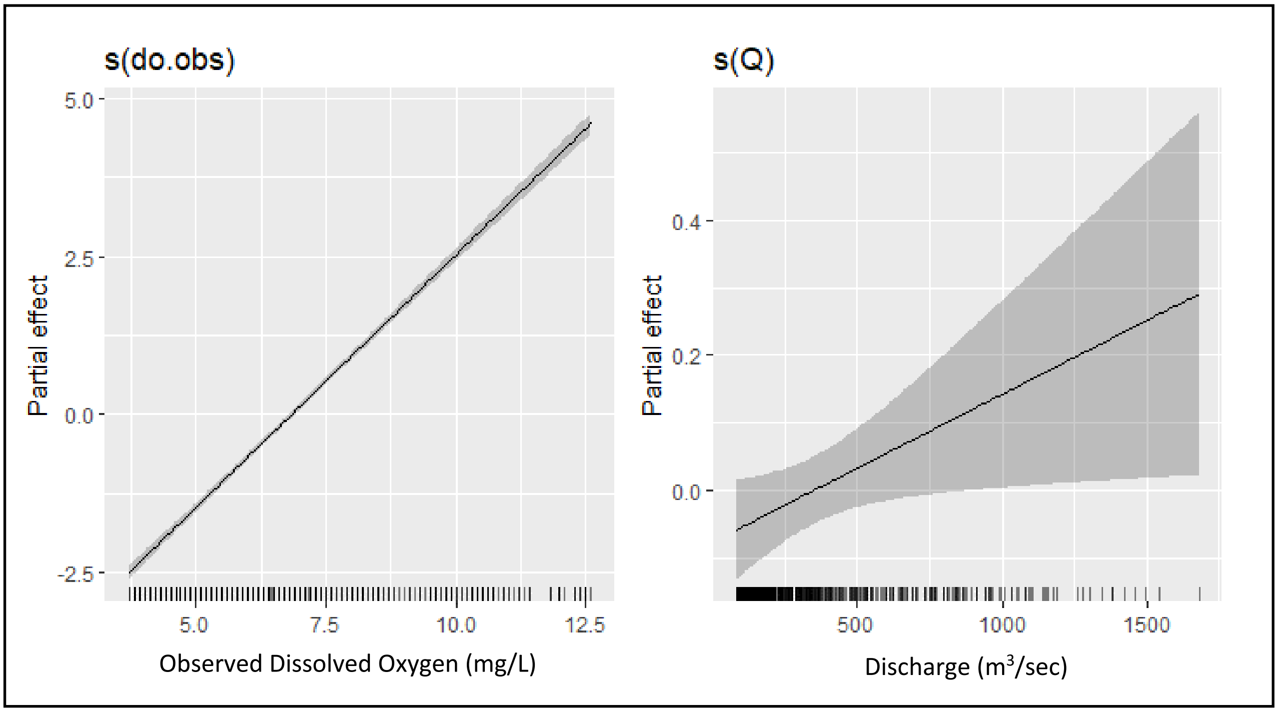
[93] Delaware River Basin Commission (2024a, 2024b).
[94] More information is available in the associated rule document, *Economic Analysis for the Final Rule: Water Quality Standards to Protect Aquatic Life in the Delaware River*.

```
Family: gaussian                                              Penn’s Landing
Link function: identity

Formula:
do.HADO ~ s(do.obs, k = 3) + s(Q, k = 4)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  7.30265    0.02554   285.9   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Approximate significance of smooth terms:
          edf Ref.df        F p-value
s(do.obs)   1      1 2989.518  <2e-16 ***
s(Q)        1      1    4.643  0.0316 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R-sq.(adj) =  0.889   Deviance explained = 88.9%
GCV = 0.36019  Scale est. = 0.35823   n = 549
```

```
Family: gaussian                                              Chester
Link function: identity

Formula:
do.HADO ~ s(do.obs, k = 3) + s(Q, k = 4)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  7.42631    0.02647   280.6   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Approximate significance of smooth terms:
            edf Ref.df      F  p-value
s(do.obs) 1.804  1.960 599.43  < 2e-16 ***
s(Q)      2.642  2.907  13.48 1.62e-06 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R-sq.(adj) =  0.774   Deviance explained = 77.6%
GCV = 0.38847  Scale est. = 0.38461   n = 549
```

Figure A2-2: Statistical details for the GAM Relating Observed Dissolved Oxygen at Penn’s Landing (top) and Chester (bottom) to EFDC-WASP Simulated Predictions for the Restored Scenario. In the code, “do.HADO” is the restored dissolved oxygen, “do.obs” is the observed dissolved oxygen, and “Q” is the discharge (river flow).

Penn's Landing



Chester

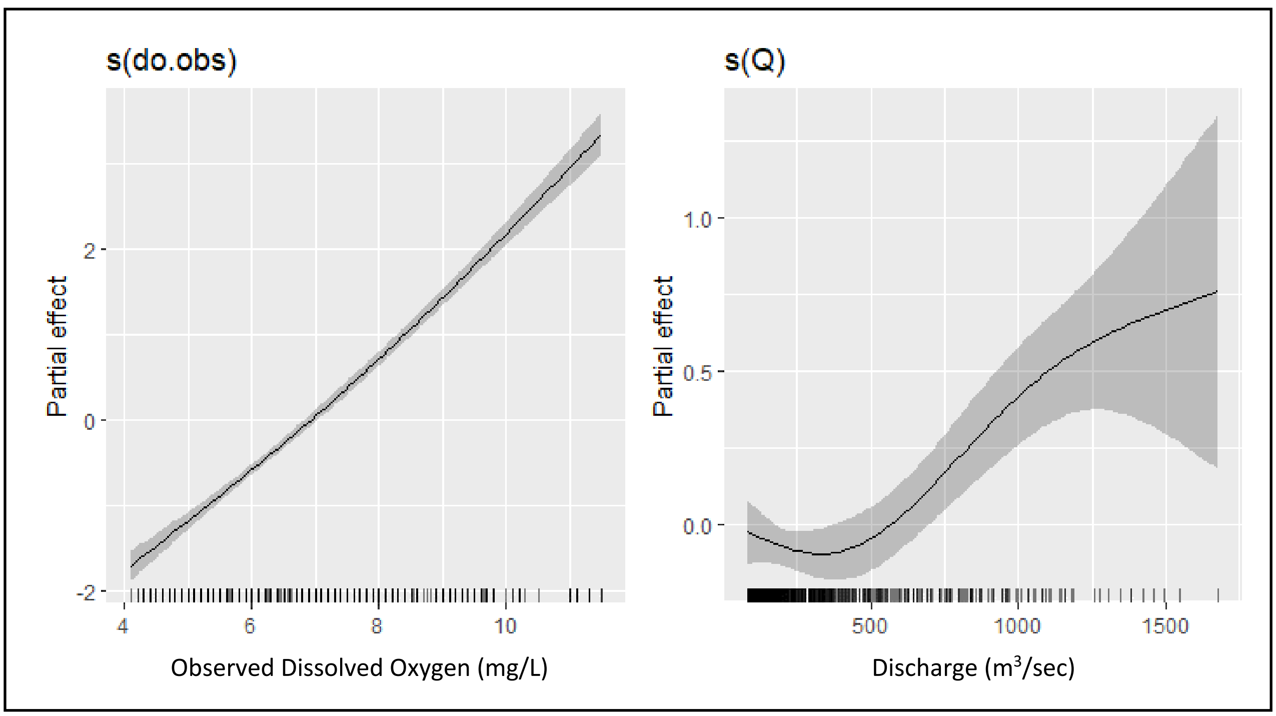


Figure A2-3: Partial Plots for GAMs Relating Observed Dissolved Oxygen at Penn's Landing (top) and Chester (bottom) to EFDC-WASP Simulated Predictions for the Restored Scenario Showing the Partial Effect of Observed Dissolved Oxygen (left) and Daily Discharge of the Delaware River Upstream at Trenton, NJ (right). Tick marks at the bottom of each graph show the distribution of observations; darker bars indicate a higher density of observations.

Appendix 3: Juvenile Atlantic Sturgeon Abundance Survey Data

The Delaware Department of Natural Resources and Environmental Control (DNREC) has conducted surveys of juvenile Atlantic Sturgeon abundance in the Delaware River since 1991.[95] The number of sampling days, hours of sampling, and the area of the net that was fished varied among years. Catch per unit effort (CPUE) is a measure of the relative abundance of juvenile Atlantic Sturgeon in each year. Surveys were conducted throughout the Delaware River in most years, but in some years was confined to the vicinity of the Marcus Hook anchorage. Data are reported separately for juvenile abundance (Tables A3-1 and A3-2) and young-of-the-year juvenile abundance (Tables A3-3 and A3-4). Additionally, data are reported for the juvenile abundance surveys river-wide (Tables A3-1 and A3-3) and separately for the vicinity of Marcus Hook (Tables A3-2 and A3-4). In 2016 and 2017, a project was undertaken to capture and relocate Atlantic Sturgeon away from the area of the Marcus Hook anchorage prior to implementing a project to deepen the anchorage, part of a larger channel deepening project in the Delaware River.[96] Abundance estimates are reported but may have been impacted by these activities.

Table A3-1. Data from Juvenile Atlantic Sturgeon River-wide Abundance Survey in the Delaware River, 2009 – 2021.

Year	Sample Days	Number Taken	Gill Net Hours	Net Area (m^2)	CPUE (catch/hour/m^2)	CPUE*1000
2009	13	34	37.41	7878	0.00012	0.11536
2010	9	0	25.13	8324	0.00000	0.00000
2011	16	50	47.16	15756	0.00007	0.06729
2012	8	1	28.61	8250	0.00000	0.00424
2013	0	0	0	0	0.00000	0.00000
2014(1)	15	184	52.67	13332	0.00026	0.26174
2015(1)	22	61	108.08	23998	0.00002	0.02352
2016	23	6	114.48	30219	0.00000	0.00173
2017	26	139	124.75	34663	0.00003	0.03214
2018	22	240	106.23	29330	0.00007	0.07703
2019	23	18	101.18	30664	0.00000	0.00580
2020(1)	16	69	79.5	21331	0.00004	0.04069
2021	16	107	79.61	20887	0.00006	0.06435

[1] Data only from Marcus Hook Sampling
CPUE = Catch Per Unit Effort

[95] DNREC survey data for 2009 - 2021 were provided to the EPA by the DRBC on February 9, 2023. Data prior to 2009 are not directly comparable to recent years due to differences in sampling method and locations. More information is available in: Park, Ian. (2020). Final Report. Section 6 Species Recovery Grants Program. Award Number: NA16NMF4720072. Conservation and Recovery of Juvenile Atlantic Sturgeons in the Delaware River. Delaware Department of Natural Resources and Environmental Control. Division of Fish and Wildlife.
[96] More information is available at https://www.nap.usace.army.mil/Missions/Civil-Works/Delaware-River-Main-Channel-Deepening/.

Table A3-2. Data from Atlantic Sturgeon Juvenile Abundance Surveys near Marcus Hook, PA, 2009 – 2021.

Year	Sample Days	Number Taken	Gill Net Hours	Net Area (m^2)	CPUE (catch/hour/m^2)	CPUE*1000
2009	9	33	30.77	6317	0.00017	0.16977
2010	1	0	1.92	1041	0.00000	0.00000
2011	9	50	26.95	10331	0.00018	0.17959
2012	6	1	21.43	6466	0.00001	0.00722
2013	0	0	0	0	0.00000	0.00000
2014	15	184	52.67	13332	0.00027	0.26677
2015	22	61	108.08	23998	0.00002	0.02352
2016	11	2	51.42	14221	0.00001	0.00274
2017(1)	9	88	43.77	11999	0.00017	0.16755
2017(2)	18	135	87.68	23998	0.00006	0.06416
2018	15	221	75.66	19998	0.00014	0.14606
2019	16	11	70.42	21331	0.00001	0.00732
2020	16	69	79.5	21331	0.00004	0.04069
2021	16	107	79.61	20887	0.00006	0.06435

[1] Data prior to relocation trawling efforts.
[2] After trawling commenced, DNREC sampled the anchorage an additional nine days and captured 47 sturgeon, resulting in a CPUE*1000 of only .09 during that period.
CPUE = Catch Per Unit Effort

Table A3-3. Data from Young-of-the-Year (YOY) Atlantic Sturgeon Abundance Surveys in the Delaware River, 2009 – 2021.

Year	Sample Days	Number Taken	Gill Net Hours	Net Area (m^2)	CPUE (catch/hour/ m^2)	CPUE*1000
2009	13	34	37.41	7878	0.00012	0.11536
2010	9	0	25.13	8324	0.00000	0.00000
2011	16	50	47.16	15756	0.00007	0.06729
2012	8	1	28.61	8250	0.00000	0.00424
2013	0	0	0	0	0.00000	0.00000
2014(1)	15	182	52.67	13332	0.00026	0.25919
2015(1)	22	20	108.08	23998	0.00001	0.00771
2016(2)	23	3	114.48	30219	0.00000	0.00087
2017(2)	26	129	124.75	34663	0.00003	0.02983
2018	22	230	106.23	29330	0.00007	0.07382
2019	23	8	101.18	30664	0.00000	0.00258
2020(1)	16	18	79.5	21331	0.00001	0.01061
2021(3)	16	105	79.61	20887	0.00006	0.06435

[1] Data only from Marcus Hook sampling
[2] Relocation project overlap
[3] Anchorage dredged during sampling season
CPUE = Catch Per Unit Effort

Table A3-4. Data from Young-of-the-Year (YOY) Atlantic Sturgeon Abundance Surveys near Marcus Hook, PA, 2009 – 2021.

Year	Sample Days	Number Taken	Gill Net Hours	Net Area (m^2)	CPUE (catch/hour/m^2)	CPUE*1000
2009	9	33	30.77	6317	0.00017	0.16978
2010	1	0	1.92	1041	0.00000	0.00000
2011	9	50	26.95	10331	0.00018	0.17958
2012	6	1	21.43	6466	0.00001	0.00722
2013	0	0	0	0	0.00000	0.00000
2014	15	182	52.67	13332	0.00026	0.25919
2015	22	20	108.08	23998	0.00001	0.00771
2016(1)	11	1	51.42	14221	0.00000	0.00137
2017(1)	18	126	87.68	23998	0.00006	0.05988
2018	15	215	75.66	19998	0.00014	0.14210
2019	16	6	70.42	21331	0.00000	0.00399
2020	16	18	79.5	21331	0.00001	0.01061
2021(2)	16	105	79.61	20887	0.00006	0.06435
2022	16	9	87.85	21331	0.00003	0.00480

[1] Relocation project overlap
[2] Anchorage dredged during sampling season
CPUE = Catch Per Unit Effort

Appendix 4: Atlantic Sturgeon Bioenergetics Model

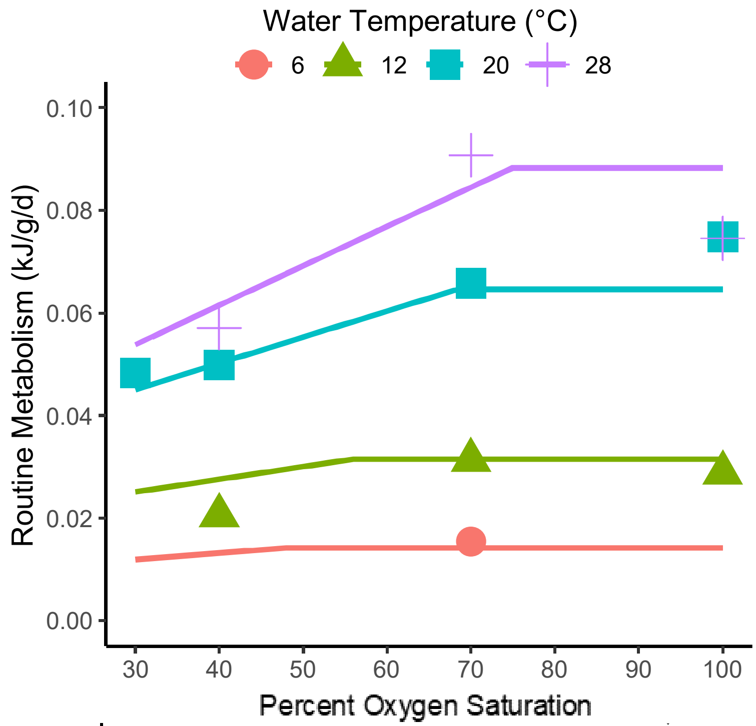
Table A4-1: Parameter Estimates for the Atlantic Sturgeon Bioenergetics Model

Column headers: (a) estimates from Niklitschek and Secor 2009a and Niklitschek 2001 experimental results or otherwise as reported in the supplemental information of Niklitschek and Secor 2009b, including the standard error (s.e.); (b) estimates in the unaltered SAS and R code provided to the EPA by Niklitschek and Secor; and (c) estimates used in the EPA's analysis following partial re-optimization of parameters to fit results shown in Niklitschek and Secor 2009b. Appendix S2 in Niklitschek and Secor 2009b contains the bioenergetics sub-model equations.

Parameter	Definition	(a) (± s.e.)	(b)	(c)
Routine Metabolism (RM)				
a_{RM}	Allometric intercept (scaling coefficient)	0.52 ± 0.092	0.522	0.500
b_{RM}	Allometric slope	-0.17 ± 0.022	-0.17	-0.159
TK1RM	Reaction rate multiplier at the lowest tested temperature (6°C)	0.14 ± 0.017	0.141	0.140
TL4RM	Reaction rate multiplier at the highest tested temperature (28°C)		0.796	0.796
TL98RM	Lower temperature threshold where f(T)RM ≥ 0.98	0.38 ± 0.094		
c_{RM}	Dissolved oxygen response shape parameter	1 ± 0.26	1.0	1.00
d_{RM}	Proportionally constant for reaction rate at lowest DOSAT	0.75 ± 0.097	1.048	0.991
g_{RM}	Proportionally constant for DOCRM	0.27 ± 0.051	0.748	0.6
h_{RM}	Hyperosmotic response coefficient	0.4 ± 0.14	0.268	0.268(1)
i_{RM}	Hyposmotic response coefficient	9 ± 3.2(2)	0.352	0.352(1)
SALMIN	Salinity at which minimum osmoregulation cost is predicted	0.52 ± 0.092(2)	9.166	9.166(1)
b1	Allometric exponent for specific gill surface area	-0.17 ± 0.022	-0.158	-0.158
Food Consumption (FC)				
a_{FC}	Allometric intercept (scaling coefficient)	1 ± 0.1	1.028	0.977
b_{FC}	Allometric exponent	-0.2 ± 0.019	-0.197	-0.213
TK1FC	Reaction rate multiplier at the lowest tested temperature (6°C)	0.2 ± 0.035	0.195	0.119
TK4FC	Reaction rate multiplier at the highest tested temperature (28°C)	0.6 ± 0.12	0.556	0.243
TL98FC	Lower temperature threshold where f(T)FC ≥ 0.98	2.61 ± 0.088	26.09	25.5
c_{FC}	Dissolved oxygen response shape parameter	1	1	1.15
d_{FC}	Proportionally constant for reaction rate at lowest DOSAT	2.5 ± 0.46	2.516	3.14

Parameter	Definition	(a) (± s.e.)	(b)	(c)
g_{FC}	Proportionally constant for DOCRM	0.73 ± 0.072	0.733	0.6
j_{FC}	Size-dependent intercept for reaction rate at the lowest salinity	0.358 ± 0.0087	0.359	0.359[1]
k_{FC}	Size-dependent intercept for reaction rate at the highest salinity	0.25 ± 0.045	0.247	0.247[1]
Postprandial Metabolism (SDA)				
a_{SDA}	Proportionality constant (to assimilated energy)	0.157 ± 0.0093	0.1657	0.1657
Active Metabolism (ACT)				
a_{ACT}	Proportionality constant (to food consumption)	0.29 ± 0.041	0.29	0.29
Egestion (EG)				
a_{EG}	Scale parameter for egestion	0.3 ± 0.12	0.335	0.2937
c_{EG}	Dissolved oxygen effect exponent	-0.8 ± 0.27	-0.75	-0.733
d_{EG}	Temperature effect exponent	-0.6 ± 0.24	-0.62	-0.484
g_{EG}	Ration size effect exponent	0	0	0
Excretion (U)				
a_{EX}	RNE, scaling factor	0.0557	0.0557	0.836
b_{EX}	RNE, exponent	-0.29	-0.29	-0.29
c_{EX}	XNE, FC proportionality coefficient	0.0392	0.0392	0.0588
Model Constants				
rt1	Lowest water temperature tested (°C)	6	6	6
rt4	Highest water temperature tested (°C)	28	28	28
s4	Highest salinity tested (ppt)	29	29	29
s1	Lowest salinity tested (ppt)	1	1	1
ox	Oxycalorific coefficient (kJ g-O_2^{-1})	13.55	13.55	13.55

[1] These parameters were not optimized because the optimization considered data with only one salinity value.
[2] The EPA assumed that these values were reported in the incorrect row in the table.



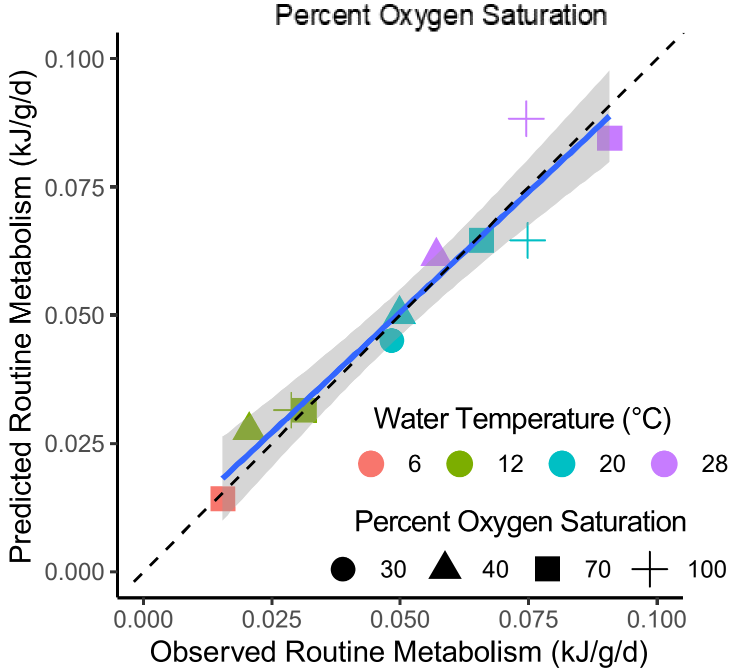


Figure A4-1: (Top) The relationship between routine metabolism calculated using the bioenergetics model from this study and percent oxygen saturation and water temperature. Points show mean rates from Niklitschek and Secor (2009b). (Bottom) The relationship between routine metabolism predicted by the bioenergetics model and measured routine metabolism.

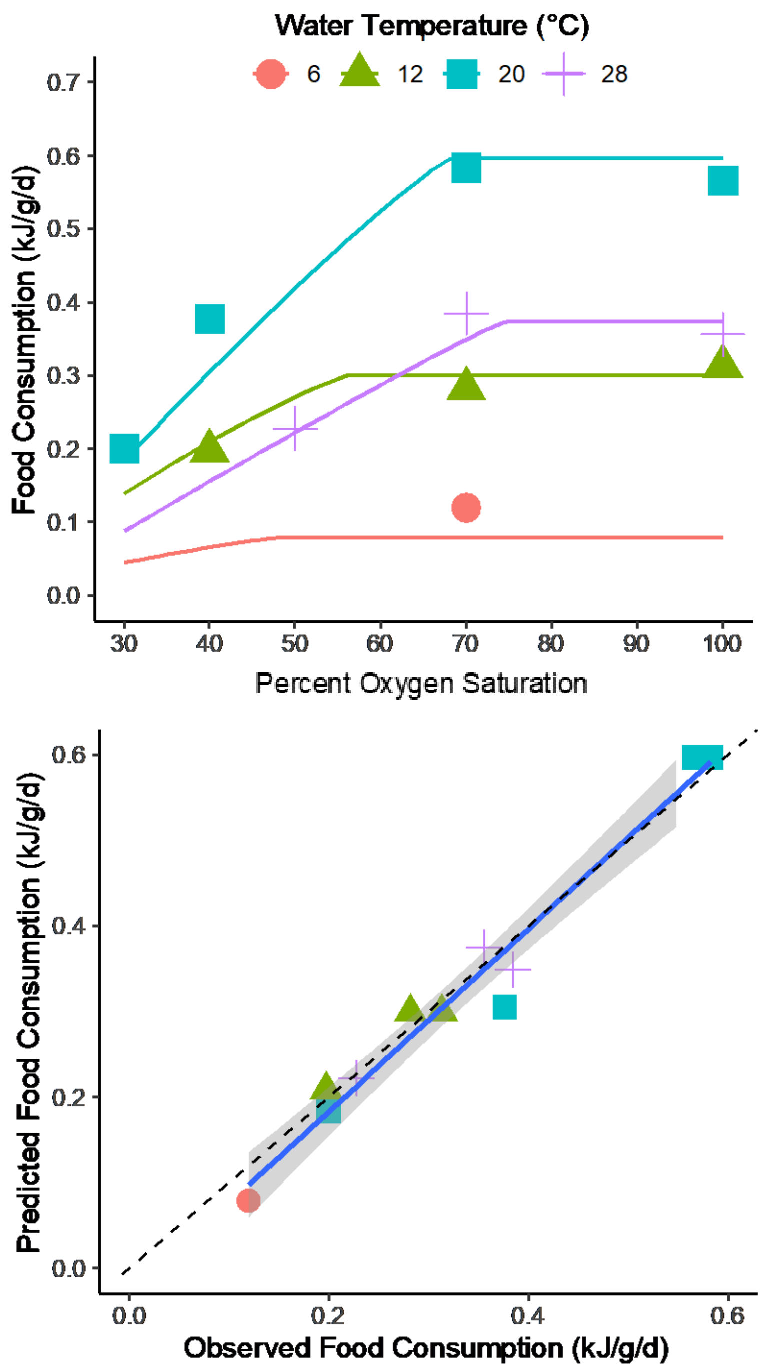


Figure A4-2: (Top) The relationship between food consumption calculated using the bioenergetics model from this study and percent oxygen saturation and water temperature. Points show mean rates from Niklitschek and Secor (2009b). (Bottom) The relationship between food consumption predicted by the bioenergetics model and measured food consumption.

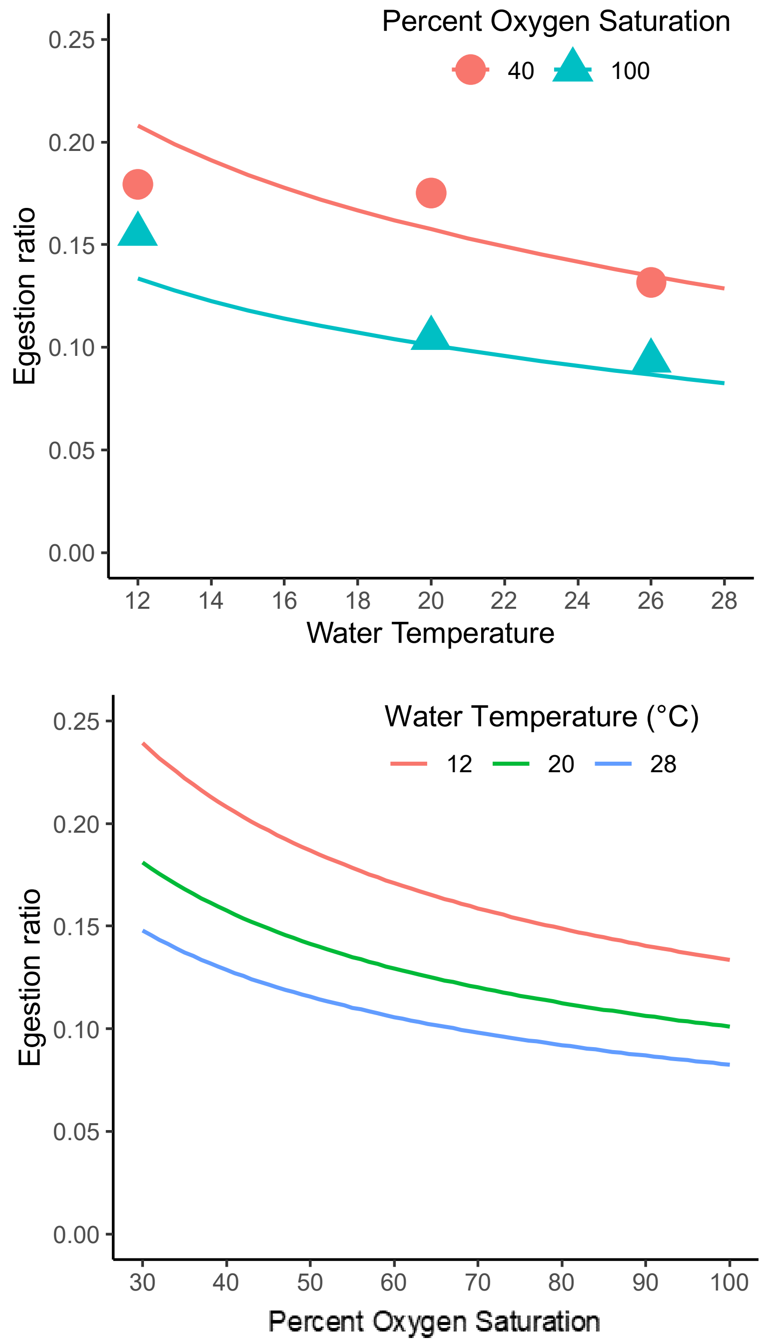


Figure A4-3: (Top) The relationship between egestion ratio calculated using the bioenergetics model from this study and water temperature at two levels of percent oxygen saturation. Points show mean ratios from Niklitschek and Secor (2009b). (Bottom) The relationship between egestion ratio and percent oxygen saturation predicted by the bioenergetics model at three water temperatures.

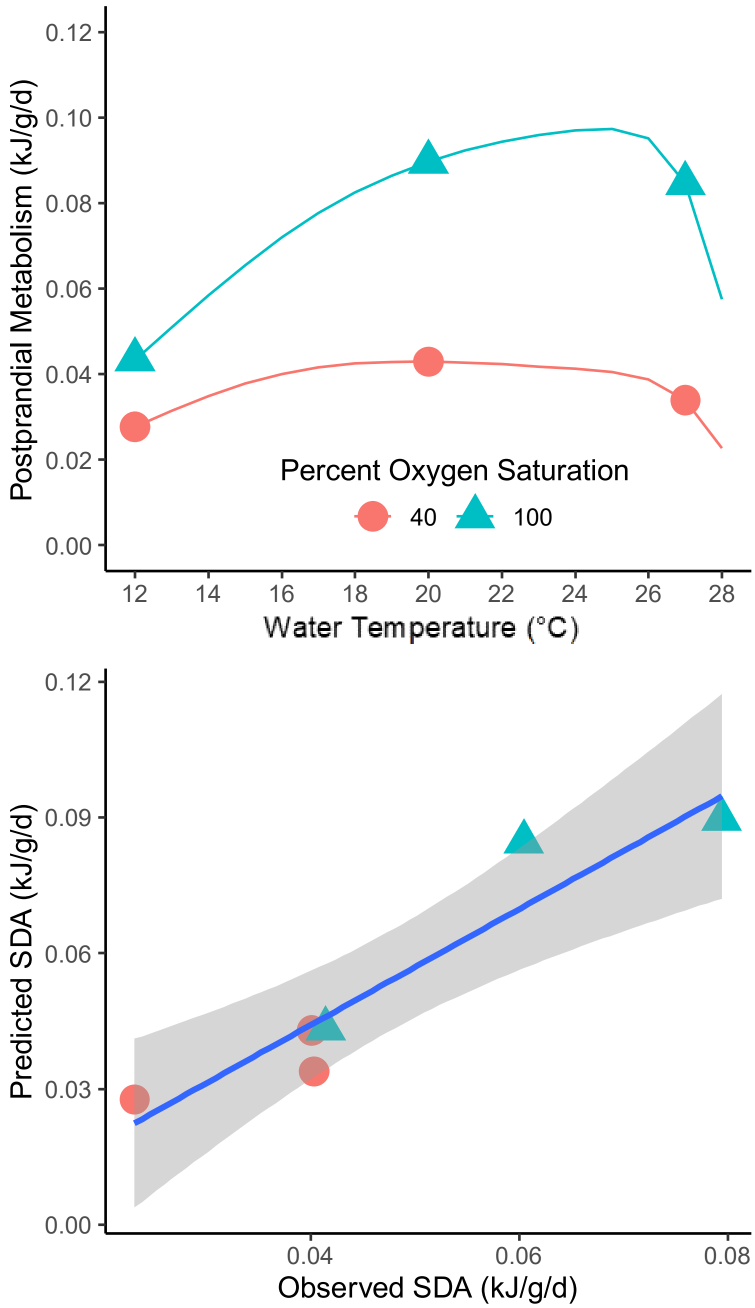


Figure A4-4: (Top) The relationship between specific dynamic action (SDA) (i.e., postprandial metabolism) and water temperature at two levels of percent oxygen saturation. Points show means of measurements as reported by Niklitschek and Secor (2009b). (Bottom) The relationship between predicted and observed SDA.

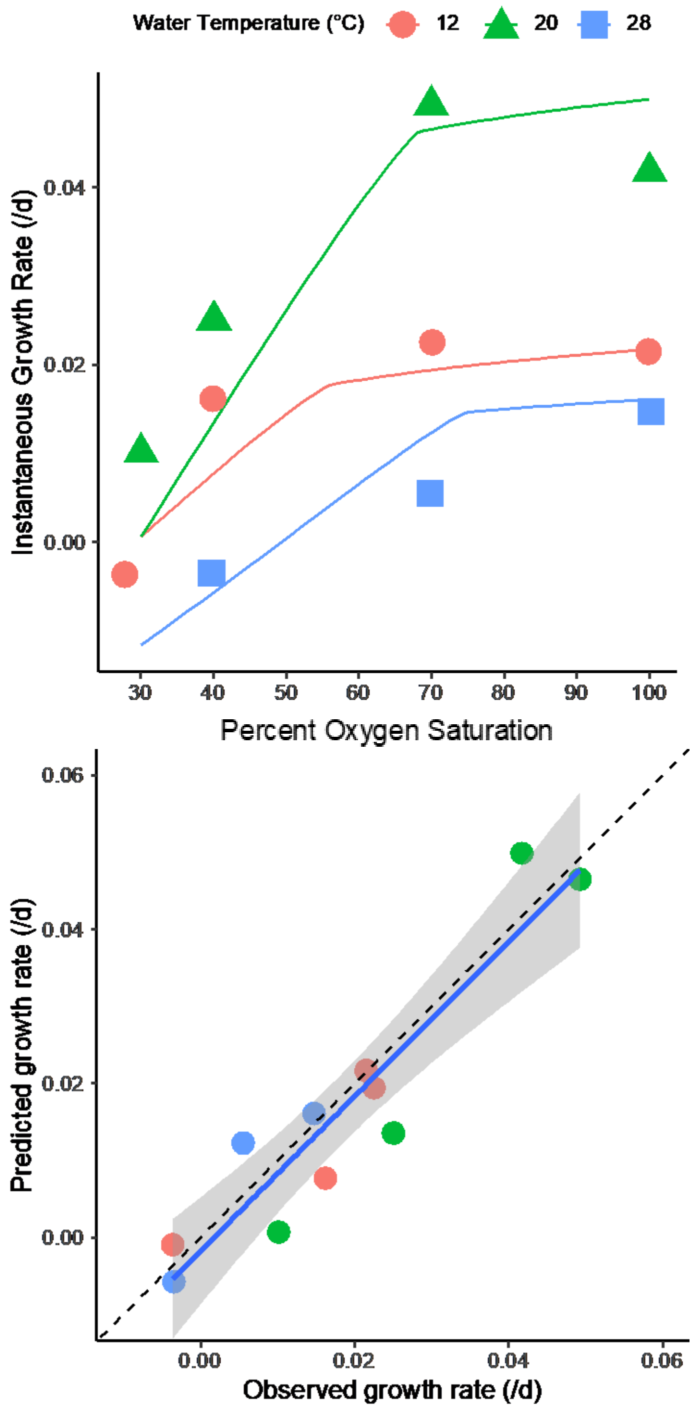


Figure A4-5: (Top) The relationship between instantaneous growth rate and percent oxygen saturation at three different temperatures. Points show means of measurements from Niklitschek and Secor (2009b). (Bottom) The relationship between predicted and observed growth rates.

Appendix 5: Statistical Summary for Mortality Model

This appendix contains a summary report for the linear model relating recoded and log-transformed instantaneous mortality rates to water temperature and percent oxygen saturation in experimental tests. A linear regression was fitted to the data in Table 2 (Section 3.3.2) using the *lm* function in R, which produced an object of class "lm" (i.e., linear model). The summary was produced using the summary function applied to the object.

```
Call:
lm(formula = log(Z + 0.001) ~ posat + t + posat * t, data = df)

Residuals:
     Min       1Q   Median       3Q      Max 
-2.37982 -0.41531  0.08754  0.80422  1.20570 

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) -7.868755   5.753160  -1.368    0.209
posat        0.008751   0.091078   0.096    0.926
t            0.366523   0.238039   1.540    0.162
posat:t     -0.003584   0.003777  -0.949    0.370


Residual standard error: 1.19 on 8 degrees of freedom
Multiple R-squared:  0.8171,     Adjusted R-squared:  0.7484 
F-statistic: 11.91 on 3 and 8 DF,  p-value: 0.002547
```

Figure A5-1: Statistical Summary for Linear Regression Relating Instantaneous Mortality Rates to Percent Oxygen Saturation and Water Temperature. In the code, "Z" is the instantaneous mortality rate, "posat" is the percent oxygen saturation, and "t" is the water temperature.

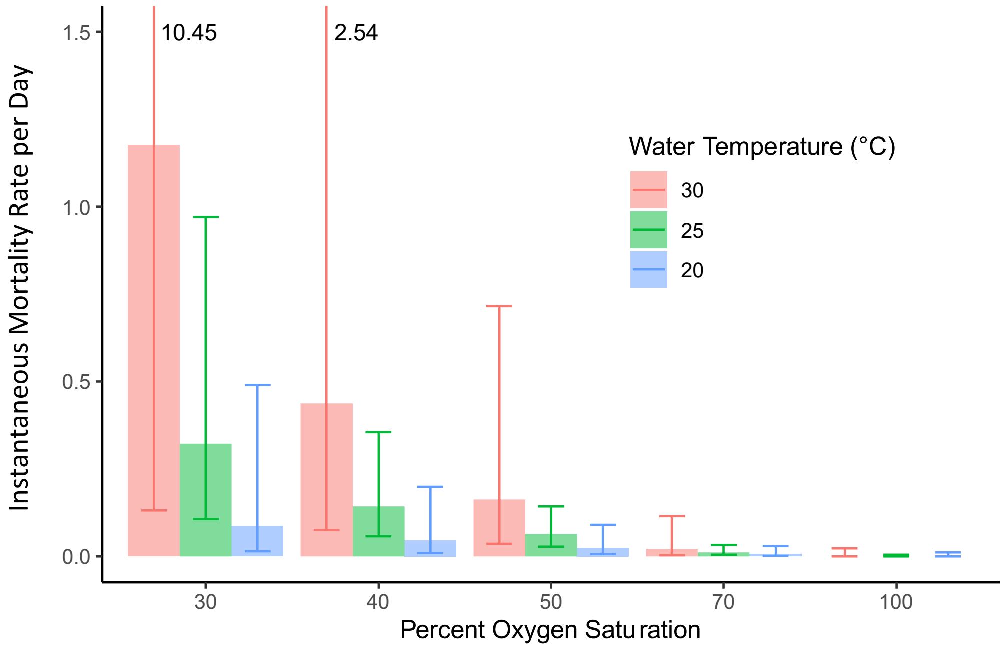


Figure A5-2: Predicted Instantaneous Mortality Rate Due to Low Dissolved Oxygen and Varying Water Temperature. Whiskers (thin lines) show the 95% confidence limits. The upper 95% confidence limit for 30% and 40% oxygen saturation at 30°C extend off the scale and are instead shown by the indicated values.

Appendix 6: Estimates of Seasonal Change in Cohort Biomass

In section 4.1.3, Figure 7 shows computed values of HSI for each year from 2002-2022, excluding 2010. The EPA defined HSI as the daily instantaneous production of the cohort (φ_{pp}). Following equation 4 ($P = e^{(G_{max} - Z_{min})t} = e^{\varphi_{pp} t}$), production of the cohort during the 123 day *Juvenile Development* season from July 1 to October 31 is $e^{123 \times \varphi_{pp}}$ and accordingly, the seasonal percent change in biomass is $100 \times (e^{123 \times \varphi_{pp}} - 1)$. Whereas Figure 7 best illustrates the negative range of production rate, Figure A6-1 illustrates how exponential growth contributes to clear distinctions between years when the cohort either fails almost entirely or is successful (i.e., biomass increased by the end of the season).

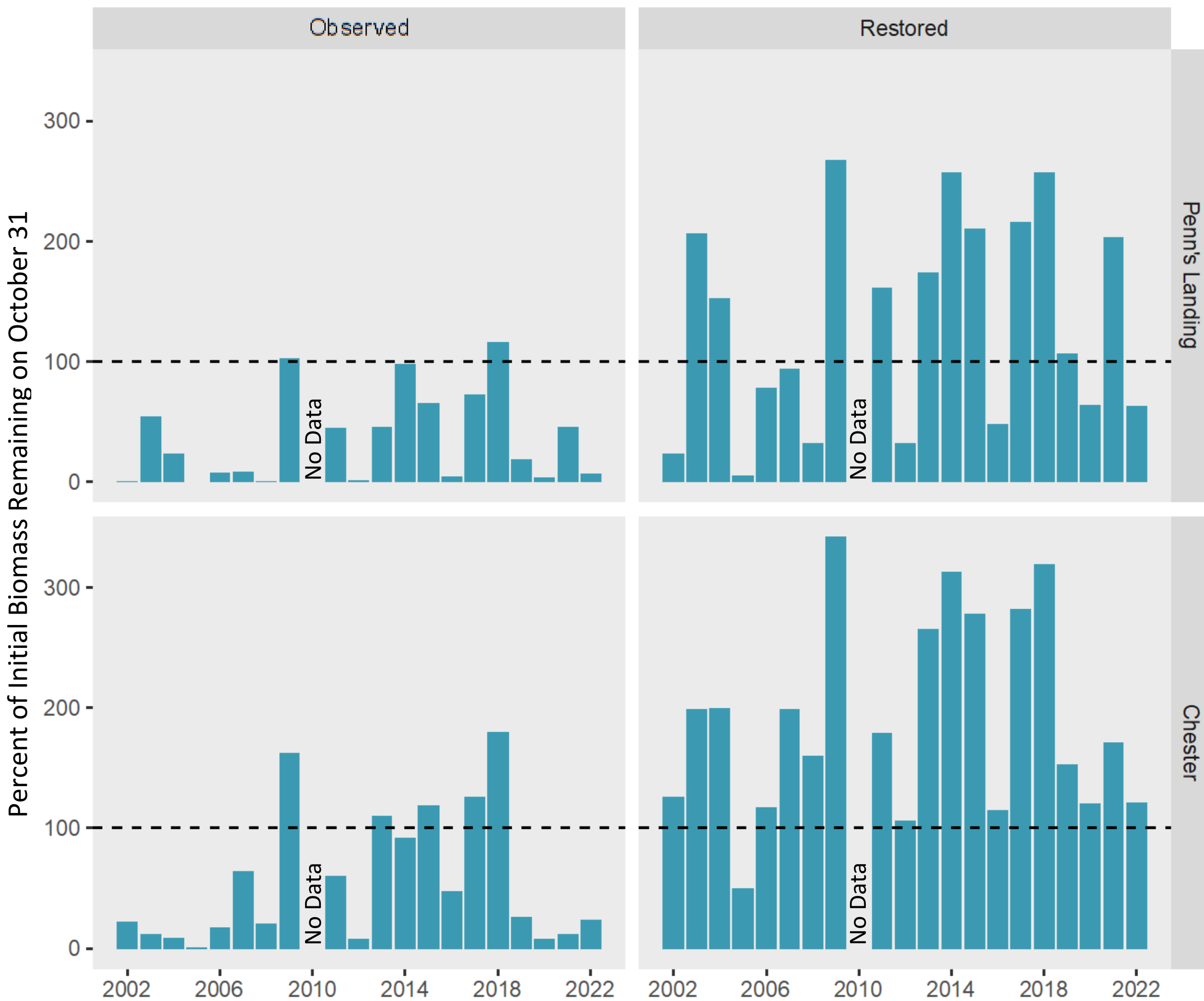


Figure A6-1: Seasonal Percent Change in Biomass for 2002-2022 using Observed Dissolved Oxygen or Estimates of Restored Dissolved Oxygen at the Penn's Landing and Chester Monitoring Stations. Due to missing water quality data, estimates were not computed for 2010 at either site. The dashed line at 100% indicates that biomass is maintained from July 1 to October 31 and corresponds to HSI = 0. Values below 100% biomass indicate that the cohort has lost biomass by the end of the season. Values greater than 100% indicate that the cohort has gained biomass by the end of the season.