A Review of Dissolved Oxygen Requirements for Key Sensitive Species in the Delaware Estuary

Final Report

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Summary

Dissolved oxygen (DO) is necessary for sustaining aquatic life with variation in tolerances of oxygen concentrations existing among species and life stages. Fluctuations in DO concentrations occur both spatially and temporally in natural systems, and deleterious effects on fauna are seen in areas that experience lowered DO and hypoxia. DO concentrations may therefore be a determining factor in the presence and distribution of fauna. Consequently, the evaluation of DO requirements for sensitive species is important in establishing appropriate water quality standards to protect aquatic life. The Delaware River Basin Commission (DRBC) has tasked the Academy of Natural Sciences of Drexel University (ANSDU) with examining these requirements for the Delaware Estuary. ANSDU has narrowed the species in the estuary to a list of key sensitive species that are intolerant, at either the lethal or sub-lethal level, to DO concentrations that are equal to or higher than the standards in place since 1967. This report summarizes available literature and data on DO sensitivity for 14 fish and invertebrates at different life stages, locations, and seasons within the Delaware Estuary.

Background

The Delaware River's past has been beset by bouts of water quality problems, including hypoxia, since the late 1800s. By the mid-1900s, population growth and increased wastewater discharge created deleterious conditions in the Delaware River Estuary (Trenton, NJ to the bay) that affected both wildlife and human health (Federal Water Pollution Control Administration 1966). The pollution problems culminated in the creation of the Delaware Estuary Comprehensive Study under the provisions of the Federal Water Pollution Control Act in 1961 to "provide a blueprint for the enhancement of the waters of the Delaware"(Federal Water Pollution Control Administration 1966) as well as the establishment of the Delaware River Basin Commission. The comprehensive study, coupled with amendments to the Federal Water Pollution Control Act (Federal Water Pollution Control Administration 1968), resulted in the establishment of DO criteria for the Delaware Estuary in 1967. DO standards for the Delaware River Estuary were set at a 24-hour average concentration of 3.5 mg/l for Zones 3, 4, and the upper portion of 5; 5.0 mg/l for Zone 2; 4.5 mg/l for Zone 5 at River Mile 70.0; and 6.0 mg/l for the lower portion of Zone 5 and Zone 6. Seasonal averages were set for the periods of April 1 to June 15 and September 16 to December 31 at 6.5 mg/l for Zones 2 through 5. Zone 6 was set not to drop below 5.0 mg/l at any time "unless due to natural conditions" (Delaware River Basin Commission 2013). No seasonal averages were set for June 15 through September 16 or January 1 through March 31. The establishment of these water quality standards in 1967 began the process of increasing the health of the Delaware Estuary which is reflected today in increased aquatic populations and improved water quality. However, these standards have yet to be reexamined and updated to reflect the current scientific knowledge available.

The Federal Water Pollution Control Administration (1968) had defined a standard as "a plan that is established by governmental authority as a program for water pollution prevention and abatement", and criteria as "a scientific requirement on which a decision or judgement may be based concerning the suitability of water quality to support a designated use". As such, ANSDU has been tasked with identifying DO requirements, apart from any achievability concerns, that may be used by the DRBC to create future standards.

For the purpose of this report, "sensitive" refers to a species that exhibits deleterious effects, either lethal or sub-lethal (e.g., reduced growth, lowered reproduction, increased respiration rates, etc.), when exposed to concentrations of DO that are equal to or greater than the current criteria. Note that "failure to spawn" is treated in this report as a lethal effect. Failure to spawn does not involve direct mortality but has demographic consequences analogous to egg or larval mortality and may therefore be implicit of lethal effects.

In this report, "key" refers to species that have been determined to be representative of an area spatially and temporally with oxygen demands that are greater than or equal to those of other species found within the same spatial and temporal locality. Protection of key sensitive species encompasses the protection of those which are more tolerant to lower DO concentrations. Therefore, refining the list allows for a more in-depth examination of the key species without disregarding the needs of others.

Under the DRBC's Aquatic Life Use and Estuary Eutrophication Modeling effort, ANSDU was tasked with the development of a methodology for evaluating and reviewing the DO requirements of key sensitive species in the Delaware River Estuary. A comprehensive review of the current available literature and data on DO requirements for key sensitive species within the Delaware Estuary is found within this report.

Objective

The objective of this report was to narrow a candidate species list for DO sensitivity to key sensitive species, both spatially and temporally, within the Delaware Estuary and provide information on oxygen requirements at different life stages to serve as a scientific basis for potential future standards, apart from any achievability concerns.

Methodology

Under Task Order 1 (ANSDU 2018), a literature and data search was conducted to obtain a comprehensive list of species that occur within the Delaware Estuary. For flora and fauna other than fishes, searches were conducted at the genus, species, and family level. For fish fauna and appropriate invertebrates, each species was further broken down by life stage (i.e., egg, larval, juvenile, adult). An attempt was made to primarily include native species; however, non-native species were included when they support important recreational fisheries within the estuary.

Literature searches were conducted in Google Scholar, Web of Science, Academy of Natural Sciences Archives, and Drexel University libraries to identify sources of DO information and thresholds for these species using combinations of the keywords: "dissolved oxygen", "threshold", "criteria", "anoxia", "hypoxia", "Delaware Estuary", and/or the species/genus/family names. Literature was also obtained by finding references within found literature and by finding literature that has since cited primary literature. From the search results, a comprehensive database of sources (the references of this report and ANSDU 2018 Task Order 1) was created using Mendeley citation software.

Data collected from this step were then examined to identify where gaps in information exist and to determine which species are likely to be sensitive to low DO concentrations. As part of Task Order 1 (ANSDU 2018), a species was classified as "tolerant" if the literature stated that they were: oxygen regulators, tolerant of low DO concentrations (<3.5 mg/l), able to become anaerobic, and/or had a relatively low lethal or sub-lethal oxygen requirement. A species was classified as "sensitive" if the literature stated that they were: sensitive to low DO concentrations, had high mortality or behavioral changes in lowered DO, and/or had relatively high lethal or sub-lethal DO requirements (typically >3.5 mg/l). From these primary literature results, 36 species of fish and 16 invertebrate species were identified as sensitive or likely to be sensitive (tables presented in Appendix A). These species were then advanced to the next steps in the methodology (i.e., this Task Order).

At that time, a draft of the methodology in Task Order 1 was circulated among various stakeholders for review. Suggestions for additional literature sources and species sensitivity were received and incorporated into the next step of the process. Specifically, comments were received in support of the inclusion of Atlantic Sturgeon, *Acipenser oxyrhynchus*, in the list of key species and for the further investigation of freshwater mussels as sensitive taxa.

To meet the objective of this Task Order, which is subsequent to Task Order 1, the list of candidate species suspected to be sensitive to low DO was narrowed to key species; their seasonal and spatial occurrences within the Delaware Estuary at different life stages were determined; and DO thresholds and/or associated endpoints for the key species were compiled.

To narrow the candidate list to key species, an additional search for existing literature and data was conducted using the preliminary findings from Task Order 1. In some instances, additional data and reports were found by contacting scientific researchers studying the species of interest.

The literature, information, and data sought throughout the methodology were from appropriate scientific or published sources, and special effort was made to identify and obtain the most recent and reliable studies and reports. Unpublished data were used where available, relevant, and of high technical quality. All sources consulted have been appropriately documented and listed in this report.

All values found for candidate species were then compiled in spreadsheets and sorted to determine which candidate species had values equal to or exceeding the current DO standards (typically at least 3.5 mg/l). Additionally, data, in some cases, are absent for some species and a key species may have been selected as a representative on the basis that adequate scientific knowledge was available. When this was the case, gaps in the existing data were noted. The available DO values were then further broken down into lethal and sub-lethal effect categories. The species were examined for spatial and temporal occurrence in the estuary. Significant figures for values were presented as given in the primary literature in the text and Tables 1 and 2. Tables 3-6 have had the significant figures rounded for comparability among studies and ease of reading. The DRBC designated water quality zones of the Delaware Estuary were used in this report for species occurrence. Additionally, the seasons for this report were classified based on solstices and equinoxes and are as follows: Spring (March 20 to June 20), Summer (June 20 to September 20), Fall (September 20 to December 20), and Winter (December 20 to March 20). It is recognized that seasons could have been designated in other ways; however, this classification was chosen as it aligns with many of the key species' life histories. It is to be noted, however, that for some species being included in one season may in reality only represent presence for a small portion of that season. More in-depth details on species occurrences within the estuary are provided in the text and the seasonal requirements should serve as a general guideline and not an absolute. Additionally, data on the temperatures and salinities for each zone and season were provided by the DRBC's monitoring program and it should be noted that data is lacking for portions of the winter months, so lower temperature values may not be well represented.

Where several sensitive species overlapped in time and space, the least tolerant species was selected as the primary sensitive species. Species in which literature and data were lacking were identified as areas where data gaps exist. Data gaps were also highlighted where the found data was highly variable or anecdotal.

In terms of data gaps, there exists a common problem in assessing lethal sensitivity and a secondary problem assessing life stage distribution. Many toxicological studies report lethality as LC50 concentrations and do not calculate, or cite, no-effect concentrations. Since a standard producing mortality much less than 50% is likely to be adopted, some method of determining more sensitive endpoints may frequently be necessary, such as the methodology employed by the US Environmental Protection Agency (See Appendix B). Secondly, many taxa may occur, at least in small numbers, in zones outside of their primary areas of occurrence. This leads to one question about where to define the limits of the species distribution and a second question of how much data to compile to document rare occurrences. In this report, we list primary areas of occurrence, and note other occurrences where information was available.

From the reduction of the sensitive species list, 14 species of fish and invertebrates were determined to be the key oxygen sensitive species for the Delaware Estuary. Those species are: Shortnose Sturgeon (*Acipenser brevirostrum*), Atlantic Sturgeon (*Acipenser oxyrhynchus*), American Shad (*Alosa sapidissima*), Blue Crab (*Callinectes sapidus*), Atlantic Rock Crab (*Cancer irroratus*), Eastern Elliptio (*Elliptio complanata*), Scud (*Gammarus spp.*), Channel Catfish (*Ictalurus punctatus*), Largemouth Bass (*Micropterus salmoides*), White Perch (*Morone americana*), Striped Bass (*Morone saxatilis*), Summer Flounder (*Paralichthys dentatus*), Yellow Perch (*Perca flavescens*), and Bluefish (*Pomatomus saltatrix*).

Final DO values were placed into tables summarizing the species requirements, such that the aggregate spatial and temporal DO needs may be defined in support of development of new DO criteria for the Delaware Estuary.

Delaware Estuary Zones

Note: The following information has been compiled from information provided by the DRBC website (http://www.state.nj.us/drbc).

The Delaware Estuary has been designated into five zones, numbered 2 through 6, by the DRBC (Figure 1). Zone 2 extends from the head of tidewater at river mile 133.4 to 108.4 (~Trenton, NJ to Tacony, PA) and has salinities in the range of 0.06 to 0.25‰. Zone 3 extends from river mile 108.4 to 95.0 (~ Tacony to South Philadelphia, PA) and exhibits similar salinities. Zone 4 extends from river mile 95.0 to 78.8 (~South Philadelphia to Marcus Hook, PA) and has fresh and oligohaline waters with salinities ranging from 0.10 to 1.30‰. Zone 5 extends from river mile 78.8 to 48.2 (~Marcus Hook to Odessa, DE) and has salinities in the range of 0.10 to 14.7‰. Zone 6 extends from river mile 48.2 to 0.0 (~Odessa, DE to Atlantic Ocean) and ranges in salinity from 0.14 to 31.6‰. The Atlantic Ocean has a salinity of 35+ ‰. The salt line, which is defined as the location of the seven-day average chloride concentration of 250 mg/l, for the estuary is tied closely to river discharge and varies by day and season. As discharge in the river is regulated upstream of the estuary by several reservoirs, the salt line is typically found just south of Wilmington, DE in Zone 5. With periods of severe drought, however, the salt line moves upstream and was at a record of river mile 102, north of Philadelphia, in 1963.

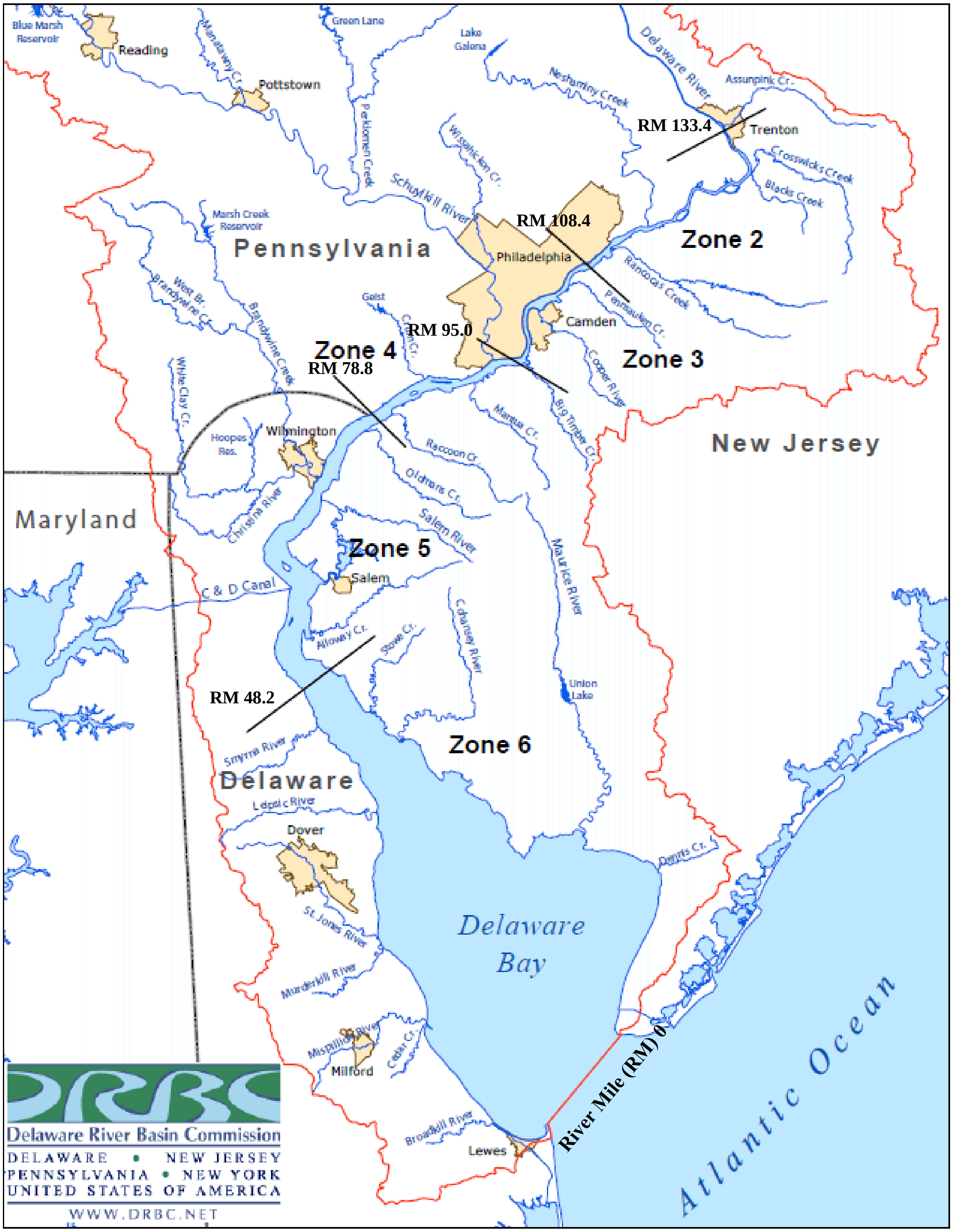

Figure 1. Map of the Delaware Estuary and Delaware River Basin Commission Water Quality Zones. (From: http://www.state.nj.us/drbc/basin/map/)

Table 1. Summarized dissolved oxygen requirements, temperatures, and salinities associated with lethal effects for sensitive stages of key oxygen sensitive species in the Delaware Estuary which are equal to or exceeding current DO standards.

Species Common Name	Stage	DO (mg/l)	Temp. (°C)	Salinity (‰)	Description	Reference
Shortnose Sturgeon	Juvenile	3.0	23	0-5	Significant decrease in percent survival.	Jenkins et al. 1993
Shortnose Sturgeon	Juvenile	2.2-3.1	22-30	2-4.5	LC50.	Campbell and Goodman 2004
Atlantic Sturgeon	Juvenile	6.3	20	1	Optimal for survival.	Niklitschek and Secor 2009a
Atlantic Sturgeon	Juvenile	4.3	12	1	Optimal for survival.	Niklitschek and Secor 2009a
Atlantic Sturgeon	Juvenile	4.3	26	-	Higher than this needed to protect survival (S. Atlantic DPS).	Federal Register 2017
American Shad	Juvenile	2.0-4.0	-	-	Surival possible with limited exposure.	Tagatz 1961
American Shad	Egg/Larval	2.5-2.9	-	-	LC50.	Stier and Crance 1985
American Shad	All	5.0	-	-	Required for spawning.	Stier and Crance 1985; Walburg and Nichols 1967
Blue Crab	Juvenile	4.1	20	10	LC50.	Stickle et al. 1989
Blue Crab	Juvenile	4.6	30	30	LC50.	Stickle et al. 1989
Blue Crab	Juvenile	5.0	24	22	28-day LC50.	Das and Stickle 1993
Blue Crab	Juvenile	5.2	30	20	LC50.	Stickle et al. 1989
Blue Crab	Juvenile	5.6	30	10	LC50.	Stickle et al. 1989
Blue Crab	Juvenile	6.0	20	30	LC50.	Stickle et al. 1989
Blue Crab	Juvenile	6.4	20	20	LC50.	Stickle et al. 1989
Atlantic Rock Crab	Larval	4.2-6.0	30	30	LC50.	Vargo and Sastry 1977
Atlantic Rock Crab	Larval	3.8	20	28-32	LC10.	Miller, Poucher, and Coiro 2002
Atlantic Rock Crab	Megalops	4.7	30	30	LC50.	Vargo and Sastry 1977
Scud (G. fasciatus)	Adult	4.3	20	-	24-hour LC50.	Sprague 1963
Scud (G. psuedolimnaeus)	Adult, Female	4.1	20	0*	Lowest DO resulting in significant mortality.	Hoback and Barnhart 1996
Channel Catfish	Egg/Larval	4.2	25	-	Decreased hatching success and survival.	Carlson, Siefert, and Herman 1974
Striped Bass	Egg	2.0-3.5	-	-	Complete absence.	Chittenden 1971
Striped Bass	Egg	4.0	-	-	Reduced survival.	Turner and Farley 1971
Striped Bass	Egg/Larval	5.0	18	-	Decreased hatching success and survival.	Turner and Farley 1971
Striped Bass	Juvenile	5.0	-	-	Threshold for high survival.	Krouse 1968 as in Bain and Bain 1982
Yellow Perch	Juvenile/Adult	4.3	26	-	Lowest DO for 100% survival.	Moore 1942
Yellow Perch	Juvenile/Adult	4.8	4	-	Lowest DO for 100% survival.	Moore 1942
Yellow Perch	Juvenile/Adult	5.1	19	-	Lowest DO for 100% survival.	Moore 1942

Where: "-" indicates absence of a temperature or salinity given in the reference; and * means test was done in "freshwater" and salinity is likely close to 0

Table 2. Summarized dissolved oxygen requirements, temperatures, and salinities associated with sub-lethal effects for sensitive stages of key oxygen sensitive species in the Delaware Estuary.

Species Common Name	Stage	DO (mg/l)	Temp. (°C)	Salinity (‰)	Description	Reference
Shortnose Sturgeon	Juvenile	3.5	20	8	Chose 8.7 mg/l over 3.5 mg/l in controlled experiment.	Niklitschek and Secor 2010
Atlantic Sturgeon	Larval	3.0	15	0	Prey consumption reduced at this concentration.	Wirgin and Chambers 2018
Atlantic Sturgeon	Juvenile	3.5	20	8	Chose 8.7 mg/l over 3.5 mg/l in controlled experiment.	Niklitschek and Secor 2010
Atlantic Sturgeon	Juvenile	6.3	20	1	Optimal for growth.	Niklitschek and Secor 2009a
Atlantic Sturgeon	Juvenile	4.3	12	1	Optimal for growth.	Niklitschek and Secor 2009a
Atlantic Sturgeon	Juvenile	6.0	-	-	Needed for rearing habitat (NY Bight).	Federal Register 2017
Atlantic Sturgeon	Juvenile	5.0	25	-	Less likely to support rearing (S. Atlantic DPS).	Federal Register 2017
Atlantic Sturgeon	Juvenile	4.3	26	-	Higher than this needed to support growth (S. Atlantic DPS).	Federal Register 2017
American Shad	Juvenile	4.0	-	-	Respiration rates and distress increase.	Tagatz 1961
American Shad	Adult	2.8-4.0	-	-	Median sublethal threshold (as found in review by authors).	Vaquer-Sunyer and Duarte 2008
Eastern Elliptio	Juvenile	4.0	23-25	-	Increase in behavioral responses.	Sparks and Strayer 1998
Eastern Elliptio	Juvenile	4.0	16.5-24.5	-	Increased succinic acid in gills.	Chen 1998
Channel Catfish	Juvenile	4.0	-	-	Increased production.	Torrans, Ott, and Bosworth 2012
Channel Catfish	Juvenile	4.0	23	0*	First increase in ventilation.	Gerald and Cech 1970
Channel Catfish	Juvenile	5.0	-	-	Reduced feeding.	Randolph and Clemens 1976
Channel Catfish	Juvenile/Adult	5.0	-	-	Adequate for growth and survival.	McMahon and Terrell 1984
Channel Catfish	Adult	3.9-6.4	18	-	Doubled gill ventilation and lactic acidosis.	Burggren and Cameron 1980
Largemouth Bass	Juvenile	4.5	-	-	Avoidance reported.	Whitmore et al. 1960
Largemouth Bass	Juvenile	4.0-6.0	16-27	-	Growth reduced by 33%.	Brake 1972
Largemouth Bass	Juvenile	4.0	26	-	Growth substantially reduced.	Stewart et al. 1967
Largemouth Bass	Juvenile	5.0	15-17		Difficulty swimming through currents.	Katz et al. 1959
Largemouth Bass	Juvenile	5.0-6.0	25	-	Swimming speed and ability reduced.	Dahlberg et al. 1968, Katz et al. 1959
Largemouth Bass	Juvenile	8.0	26	-	Reduced growth begins.	Stewart et al. 1967
White Perch	Juvenile	3.6-6.3	20-28	-	Growth and consumption reduced, metabolism increased.	Hanks and Secor 2011
White Perch	Adult	3.0-4.6	8-21	3-6	Avoided areas at this level in favor of high DO waters.	Meldrim, Gift, and Petrosky 1974
Striped Bass	Juvenile	4.0	20	0*	Lowered consumption and growth.	Brandt et al. 2009
Summer Flounder	Juvenile	5.0	30	-	Growth reduced.	Stierhoff et al. 2006
Summer Flounder	Juvenile/Adult	4.3-5.0	22-30	30-34	Ventilation rates increase.	Capossela et al 2012
Summer Flounder	Juvenile/Adult	4.2	20	25	Swimming response begins/angular correlation increased.	Brady and Targett 2010
Summer Flounder	Juvenile/Adult	4.5	-	-	Chronic value for growth and survival.	Bailey et al. 2014
Yellow Perch	Juvenile	7.0	15-20	-	Normal activity restricted below this level.	Thorp 1977
Yellow Perch	Juvenile/Adult	5.0	-	-	Lowest DO for normal growth and development.	Auer 1982
Bluefish	Juvenile	4.5-7.3	24-30	-	Occur in these areas.	Smith 1971
Bluefish	Juvenile	5.0	-	-	Not found below this DO in Hudson or Chesapeake.	Shepherd and Packer 2006

Where: "-" indicates absence of a temperature or salinity given in the reference; and * means test was done in "freshwater" and salinity is likely close to 0

Table 3. Summarized dissolved oxygen concentration requirements for key oxygen sensitive species of the Delaware Estuary and seasonal salinities and temperatures summarized by zone of occurrence during the Spring (March 20 – June 20). Lethal effects are marked by bold font. For each species/life stage the highest reported DO requirement found was chosen for this summary. Additional information can be found in the accompanying text. Note that ranges for temperature and salinity may include outliers or anomalies, and as such, the 25th and 75th percentiles are also provided. Temperature and salinity data were provided by the DRBC.

	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Median Salinity (‰)	0.10	0.10	0.11	0.24	12.80
Salinity Range (‰)	0.06-0.16	0.07-0.16	0.07-0.30	0.09-14.70	0.12-31.42
25th -75th % Salinity (‰)	0.10-0.11	0.10-0.12	0.10-0.14	0.11-1.20	6.77-18.80
Median Temperature (°C)	16.06	15.88	15.70	15.82	14.78
25th -75th % Temp (°C)	12.80-19.23	12.65-18.93	12.30-18.54	12.32-19.14	11.77-18.52
Temperature Range (°C)	4.70-28.26	5.20-20.00	5.80-24.96	6.40-25.65	5.70-25.57

Common Name	Stage	DO Value (mg/l)					Notes	Reference
Shortnose Sturgeon	Juvenile	**3.0**	**3.0**	**3.0**	**3.0**	NA	Significant decrease in percent survival (23°C, 0-5‰).	Jenkins et al. 1993
Shortnose Sturgeon	Juvenile	NA	NA	NA	3.5	3.5	Chose 8.7 mg/l over 3.5 mg/l in controlled experiment (20°C, 8‰).	Niklitschek and Secor 2010
Atlantic Sturgeon	Larval	3.0	3.0	3.0	3.0	-	Prey consumption significantly reduced (15°C, 0 ‰).	Wirgins and Chambers 2018
Atlantic Sturgeon	Juvenile	**6.3**	**6.3**	**6.3**	**6.3**	**6.3**	Optimal for survival, low mortality rates, and growth (20°C, 1‰).	Niklitschek and Secor 2009a
American Shad	Egg	**5.0**	**5.0**	**5.0**	-	-	Required for spawning and survival.	Stier and Crance 1985
American Shad	Larval	**5.0**	**5.0**	**5.0**	-	-	Required for spawning and survival.	Stier and Crance 1985
American Shad	Juvenile	-	-	-	-	**4.0**	Respiration rates increase, survival is possible with limited exposure.	Tagatz 1961
American Shad	Adult	**5.0**	**5.0**	**5.0**	**5.0**	**5.0**	Required for spawning and migration.	Stier and Crance 1985
Atlantic Rock Crab	Larval	-	-	-	-	**3.8**	LC10 (20°C and 28‰).	Miller, Poucher, and Coiro 2002
Eastern Elliptio	Juvenile	4.0	4.0	4.0	4.0	-	Behavioral changes begin (23-25°C).	Sparks and Strayer 1998
Scud (G. fasciatus)	Adult	**4.3**	**4.3**	**4.3**	NA	NA	24 Hour LC50 (20°C and freshwater).	Sprague 1963
Scud (G. psuedolimnaeus)	Adult	**4.1**	**4.1**	**4.1**	NA	NA	Lowest DO resulting in significant mortality (20°C and freshwater).	Hoback and Barnhart 1996
Channel Catfish	Egg	NA	NA	NA	NA	-	NA at these conditions.	-
Channel Catfish	Larval	NA	NA	NA	NA	-	NA at these conditions.	-
Channel Catfish	Juvenile	5.0	5.0	5.0	5.0	-	Feeding reduced.	Randolph & Clemens 1976
Channel Catfish	Adult	3.9-6.4	3.9-6.4	3.9-6.4	3.9-6.4	3.9-6.4	Gill ventilation doubles and lactic acidosis occurs (18°C).	Burggren and Cameron 1980
Largemouth Bass	Juvenile	5.0	5.0	5.0	5.0	-	Difficulty swimming against currents (15-17°).	Katz et al. 1959
White Perch	Juvenile	3.6-6.3	3.6-6.3	3.6-6.3	3.6-6.3	3.6-6.3	Growth threshold effect seen between these ranges (20°C).	Hanks and Secor 2011
White Perch	Adult	NA	NA	NA	4.0	4.0	Avoided areas with this DO (21°C, 2.5-12.5‰).	Meldrim, Gift, and Petrosky 1974
Striped Bass	Egg	**5.0**	**5.0**	**5.0**	**5.0**	-	Egg hatching rates decreased (18.3°C).	Turner and Farley 1971
Striped Bass	Larval	**5.0**	**5.0**	**5.0**	**5.0**	-	Larval survival decreased (18.3°C).	Turner and Farley 1971
Summer Flounder	Juvenile	-	-	-	-	**4.5**	Chronic effects on survival and growth.	Bailey et al. 2014
Summer Flounder	Adult	-	-	-	-	**4.5**	Chronic effects on survival and growth.	Bailey et al. 2014
Yellow Perch	Juvenile	7.0	7.0	7.0	7.0	-	Level below which restrict normal activity (15-20°C).	Thorpe 1977
Yellow Perch	Adult	5.0	5.0	5.0	5.0	-	Normal growth and development/Optimal.	Auer 1982; Jones et al. 1988; Krieger et al. 1983
Bluefish	Juvenile	-	-	-	5.0	5.0	Typically not found in areas with DO less than this.	Shepherd and Packer 2006

Where: "-" indicates absence of a species from a Zone and "NA" indicates that a species is likely to inhabit that Zone but no DO data was found matching the temperature and salinity.

Table 4. Summarized dissolved oxygen concentration requirements for key oxygen sensitive species of the Delaware Estuary and seasonal salinities and temperatures summarized by zone of occurrence during the Summer (June 20 – September 20). Lethal effects are marked by bold font. For each species/life stage the highest reported DO requirement found was chosen for this summary. Additional information can be found in the accompanying text. Note that ranges for temperature and salinity may include outliers or anomalies, and as such, the 25th and 75th percentiles are also provided. Temperature and salinity data were provided by the DRBC.

	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Median Salinity (‰)	0.11	0.11	0.15	1.04	16.00
Salinity Range (‰)	0.10-0.22	0.10-0.20	0.10-0.80	0.10-12.00	0.40-31.40
25th -75th % Salinity (‰)	0.10-0.12	0.10-0.13	0.10-0.19	0.24-3.00	9.91-22.24
Median Temperature (°C)	25.61	25.65	25.62	26.00	24.83
25th -75th % Temp (°C)	23.98-27.31	24.54-26.60	24.09-26.40	24.77-26.80	23.62-26.01
Temperature Range (°C)	19.57-32.39	20.11-29.04	20.48-29.23	20.42-29.35	18.98-28.90

Common Name	Stage	DO Value (mg/l)					Notes	Reference
Shortnose Sturgeon	Juvenile	**3.0**	**3.0**	**3.0**	**3.0**	NA	Significant decrease in percent survival (23°C, 0-5‰).	Jenkins et al. 1993
Shortnose Sturgeon	Juvenile	NA	NA	NA	3.5	3.5	Chose 8.7 mg/l over 3.5 mg/l in controlled experiment (20°C, 8‰).	Niklitschek and Secor 2010
Atlantic Sturgeon	Larval	3.0	3.0	3.0	3.0	-	Prey consumption significantly reduced (15°C, 0‰).	Wirgins and Chambers 2018
Atlantic Sturgeon	Juvenile	**6.3**	**6.3**	**6.3**	**6.3**	**6.3**	Optimal for survival, low mortality rates, and growth (20°C, 1‰).	Niklitschek and Secor 2009a
American Shad	Larval	**5.0**	**5.0**	**5.0**	-	-	Required for spawning and survival.	Stier and Crance 1985
American Shad	Juvenile	4.0	4.0	4.0	4.0	4.0	Respiration rates increase, survival is possible with limited exposure.	Tagatz 1961
American Shad	Adult	**5.0**	**5.0**	**5.0**	**5.0**	**5.0**	Required for spawning and migration.	Stier and Crance 1985
Blue Crab	Juvenile	-	-	-	NA	**6.4**	LC50 (20°C, 20‰).	Stickle et al. 1989
Blue Crab	Juvenile	-	-	-	**4.1**	NA	LC50 (20°C, 10 ‰).	Stickle et al. 1989
Atlantic Rock Crab	Larval	-	-	-	-	**6.1**	LD50 (30°C, 30 ‰).	Vargo and Sastry 1977
Eastern Elliptio	Juvenile	4.0	4.0	4.0	4.0	-	Behavioral changes begin (23-25°C).	Sparks and Strayer 1998
Scud (G. fasciatus)	Adult	**4.3**	**4.3**	**4.3**	NA	NA	24-Hour LC50 (20°C, freshwater)	Sprague 1963
Scud (G. psuedolimnaeus)	Adult	**4.1**	**4.1**	**4.1**	NA	NA	Highest DO resulting in significant mortality (20°C, freshwater)	Hoback and Barnhart 1996
Channel Catfish	Egg	**4.4**	**4.4**	**4.4**	NA	-	Decrease in hatching success (25°C).	Carlson et al. 1974
Channel Catfish	Larval	**4.4**	**4.4**	**4.4**	NA	-	Decrease in larval survival (25°C).	Carlson et al. 1974
Channel Catfish	Juvenile	5.0	5.0	5.0	5.0	-	Feeding reduced.	Randolph & Clemens 1976
Channel Catfish	Adult	3.9-6.4	3.9-6.4	3.9-6.4	3.9-6.4	3.9-6.4	Gill ventilation doubles and lactic acidosis occurs (18°C).	Burggren and Cameron 1980
Largemouth Bass	Juvenile	8.0	8.0	8.0	8.0	-	Growth reduced (26°C).	Stewart et al 1967
White Perch	Juvenile	3.6-6.3	3.6-6.3	3.6-6.3	3.6-6.3	3.6-6.3	Growth threshold effect seen between these ranges (20°C).	Hanks and Secor 2011
White Perch	Adult	NA	NA	NA	4.0	4.0	Avoided areas with this DO (21°C, 2.5-12.5‰).	Meldrim, Gift, and Petrosky 1974
Striped Bass	Egg	**5.0**	**5.0**	**5.0**	**5.0**	-	Egg hatching rates decreased (18.3°C).	Turner and Farley 1971
Striped Bass	Larval	**5.0**	**5.0**	**5.0**	**5.0**	**5.0**	Survival decreases below this (18.3°C).	Turner and Farley 1971
Striped Bass	Juvenile	**5.0**	**5.0**	**5.0**	**5.0**	**5.0**	High survival.	Krouse 1968 in Bain and Bain 1982
Summer Flounder	Juvenile	-	-	-	-	5.0	Growth reduced (30°C, 25‰).	Stierhoff et al. 2006
Summer Flounder	Adult	-	-	-	-	**4.5**	Chronic effects on survival and growth.	Bailey et al. 2014
Yellow Perch	Juvenile	**5.1**	**5.1**	**5.1**	NA	-	Lowest concentration for 100% survival (19°C).	Moore 1942
Yellow Perch	Adult	**4.3**	**4.3**	**4.3**	**4.3**	-	Lowest concentration for 100% survival (26°C).	Moore 1942
Bluefish	Juvenile	-	-	-	5.0	5.0	Typically not found in areas with DO less than this.	Shepherd and Packer 2006

Where: "-" indicates absence of a species from a Zone and "NA" indicates that a species is likely to inhabit that Zone but no DO data was found matching the temperature and salinity.

Table 5. Summarized dissolved oxygen concentration requirements for key oxygen sensitive species of the Delaware Estuary and seasonal salinities and temperatures summarized by zone of occurrence during the Fall (September 20 – December 20). Lethal effects are marked by bold font. For each species/life stage the highest reported DO requirement found was chosen for this summary. Additional information can be found in the accompanying text. Note that ranges for temperature and salinity may include outliers or anomalies, and as such, the 25th and 75th percentiles are also provided. Temperature and salinity data were provided by the DRBC.

		Zone 2	Zone 3	Zone 4	Zone 5	Zone 6		
Median Salinity (‰)		0.12	0.13	0.18	1.32	17.55		
Salinity Range (‰)		0.10-0.15	0.10-0.20	0.10-1.30	0.10-10.70	0.14-31.60		
25th -75th % Salinity (‰)		0.10-0.12	0.10-0.15	0.11-0.27	0.25-3.96	11.32-23.40		
Median Temperature (°C)		16.74	17.24	17.52	17.72	18.26		
25th -75th % Temp (°C)		14.30-19.34	14.79-19.82	14.74-20.65	14.94-21.16	15.59-21.18		
Temperature Range (°C)		6.77-26.41	8.00-24.22	9.21-24.85	9.43-24.83	9.46-23.94		
Common Name	**Stage**			**DO Value (mg/l)**			**Notes**	**Reference**
Shortnose Sturgeon	Juvenile	**3.0**	**3.0**	**3.0**	**3.0**	NA	Significant decrease in percent survival (23°C, 0-5‰).	Jenkins et al. 1993
Shortnose Sturgeon	Juvenile	NA	NA	NA	3.5	3.5	Chose 8.7 mg/l over 3.5 mg/l in controlled experiment (20°C, 8‰).	Niklitschek and Secor 2010
Atlantic Sturgeon	Larval	3.0	3.0	3.0	3.0	-	Prey consumption significantly reduced (15°C, 0‰).	Wirgins and Chambers 2018
Atlantic Sturgeon	Juvenile	**6.3**	**6.3**	**6.3**	**6.3**	**6.3**	Optimal for survival, low mortality rates, and growth (20°C, 1‰).	Niklitschek and Secor 2009a
American Shad	Juvenile	4.0	4.0	4.0	4.0	4.0	Respiration rates increase, survival is possible with limited exposure.	Tagatz 1961
Blue Crab	Juvenile	-	-	-	NA	**6.4**	LC50 (20°C, 20‰).	Stickle et al. 1989
Blue Crab	Juvenile	-	-	-	**4.1**	NA	LC50 (20°C, 10‰).	Stickle et al. 1989
Eastern Elliptio	Juvenile	4.0	4.0	4.0	4.0	-	Behavioral changes begin (23-25°C).	Sparks and Strayer 1998
Scud (G. fasciatus)	Adult	**4.3**	**4.3**	**4.3**	NA	NA	24 Hour LC50 (20°C, freshwater).	Sprague 1963
Scud (G. psuedolimnaeus)	Adult	**4.1**	**4.1**	**4.1**	NA	NA	Lowest DO resulting in significant mortality (20°C, freshwater).	Hoback and Barnhart 1996
Channel Catfish	Juvenile	5.0	5.0	5.0	5.0	-	Adequate for growth and survival.	McMahon and Terrell 1982
Channel Catfish	Adult	5.0	5.0	5.0	5.0	5.0	Adequate for growth and survival.	McMahon and Terrell 1982
Largemouth Bass	Juvenile	5.0	5.0	5.0	5.0	-	Difficulty swimming against current (15.5-17.0°C).	Katz et al. 1959
White Perch	Juvenile	3.6-6.3	3.6-6.3	3.6-6.3	3.6-6.3	3.6-6.3	Growth threshold effect seen between these ranges (20°C).	Hanks and Secor 2011
White Perch	Adult	NA	NA	NA	4.0	4.0	Avoided areas with this DO (21°C, 2.5-12.5‰).	Meldrim, Gift, and Petrosky 1974
Striped Bass	Juvenile	**5.0**	**5.0**	**5.0**	**5.0**	**5.0**	High survival .	Krouse 1968 as in Bain and Bain 1982
Striped Bass	Adult	-	-	-	-	NA	NA at these conditions.	-
Summer Flounder	Larval	-	-	-	-	NA	NA at these conditions.	-
Summer Flounder	Juvenile	-	-	-	-	**4.5**	Chronic effects on survival and growth.	Bailey et al. 2014
Summer Flounder	Adult	-	-	-	-	4.2	Swimming response to low DO begins (20°C, 25‰)	Brady and Targett 2010
Yellow Perch	Juvenile	7.0	7.0	7.0	7.0	-	Level below which restrict normal activity (15-20°C).	Thorpe 1977
Yellow Perch	Adult	5.0	5.0	5.0	5.0	-	Normal growth and development/Optimal.	Auer 1982; Jones et al. 1988; Krieger et al. 1983

Where: "-" indicates absence of a species from a Zone and "NA" indicates that a species is likely to inhabit that Zone but no DO data was found matching the temperature and salinity.

Table 6. Summarized dissolved oxygen concentration requirements for key oxygen sensitive species of the Delaware Estuary and seasonal salinities and temperatures summarized by zone of occurrence during the Winter (December 20 – March 20). Lethal effects are marked by bold font. For each species/life stage the highest reported DO requirement found was chosen for this summary. Additional information can be found in the accompanying text. Note that ranges for temperature and salinity may include outliers or anomalies, and as such, the 25th and 75th percentiles are also provided. Temperature and salinity data were provided by the DRBC.

		Zone 2	Zone 3	Zone 4	Zone 5	Zone 6		
Median Salinity (‰)		0.11	0.12	0.16	0.54	17.11		
Salinity Range (‰)		0.10-0.12	0.10-0.13	0.10-0.20	0.10-6.36	3.24-30.10		
25th -75th % Salinity (‰)		0.10-0.12	0.10-0.13	0.14-0.16	0.20-1.30	9.70-23.55		
Median Temperature (°C)		6.73	6.11	6.15	6.11	6.39		
25th -75th % Temp (°C)		5.85-8.37	5.15-6.75	5.89-7.30	5.91-6.87	5.78-6.82		
Temperature Range (°C)		2.81-10.68	2.80-7.60	3.64-7.40	3.38-7.50	2.61-7.48		
Common Name	**Stage**			**DO Value (mg/l)**			**Notes**	**Reference**
Shortnose Sturgeon	Juvenile	NA	NA	NA	NA	NA	NA at these conditions.	-
Atlantic Sturgeon	Larval	NA	NA	NA	NA	-	NA at these conditions.	-
Atlantic Sturgeon	Juvenile	NA	NA	NA	NA	NA	NA at these conditions.	-
American Shad	Juvenile	-	-	-	-	4	Respiration increases.	Tagatz 1961
Blue Crab	Juvenile	-	-	NA	NA	NA	NA at these conditions.	-
Eastern Elliptio	Juvenile	NA	NA	NA	NA	-	NA at these conditions.	-
Scud	Adult	NA	NA	NA	NA	NA	NA at these conditions.	-
Channel Catfish	Juvenile	NA	NA	NA	NA	-	NA at these conditions.	-
Channel Catfish	Adult	NA	NA	NA	NA	NA	NA at these conditions.	-
Largemouth Bass	Juvenile	4.5	4.5	4.5	4.5	-	Avoidance observed.	Whitmore et al. 1960
White Perch	Adult	NA	NA	NA	NA	NA	NA at these conditions.	-
Striped Bass	Adult	-	-	-	-	NA	NA at these conditions.	-
Summer Flounder	Larval	-	-	-	-	NA	NA at these conditions.	-
Summer Flounder	Juvenile	-	-	-	-	NA	NA at these conditions.	-
Summer Flounder	Adult	-	-	-	-	NA	NA at these conditions.	-
Yellow Perch	Juvenile	**4.8**	**4.8**	**4.8**	-	-	Lowest for 100% survival (4°C).	Moore 1942
Yellow Perch	Adult	**4.8**	**4.8**	**4.8**	**4.8**	-	Lowest for 100% survival (4°C).	Moore 1942

Where: "-" indicates absence of a species from a Zone; "NA" indicates that a species is likely to inhabit that Zone but no DO data was found matching the temperature and salinity.

Key Sensitive Species

Ten fish and four invertebrate species were chosen to be representative key oxygen sensitive species for the Delaware Estuary and are described in detail in the following sections and Tables 1 and 2.

The occurrence of species and stages varied by zone and season (Tables 3-6). Many of the DO requirements found were determined in controlled laboratory settings with a small range of temperatures and/or salinities tested. In some cases, no temperatures or salinities were provided at all. This makes it difficult to determine the precise DO requirements of each species by season, where natural water temperatures fluctuate and often drop below tested values. Given this, we have attempted to summarize the available data to the fullest extent possible by season and zone in the following section.

Seasonal Requirements

Differences in assemblages occur seasonally within the estuary in terms of life stage and species presence. Additionally, water temperature has a direct effect on DO concentrations as well as biological tolerances. Consequently, seasonal variation exists in terms of DO requirements for species within the estuary, and it is pertinent to examine available data in terms of seasonality within each zone and to align provided values with corresponding temperature and salinity regimes within the estuary. Therefore, the highest DO concentration requirement found for each sensitive species was organized by season and zone for the estuary in an attempt to summarize DO requirements that would objectively provide the highest levels of protection, apart from achievability concerns, for all species.

Spring, with water temperatures ranging between 4 and 28°C, has species' DO requirements between 3 and 7 mg/l, including both lethal and sub-lethal effects as well as high mortality (i.e., LC50) effects (Table 3). At the lethal level, the majority of DO requirements for survival are within the 5.0 to 6.8 mg/l range in all zones, with a modal value of 5.0 mg/l. American Shad spawning and survival requires 5.0 mg/l in all zones (Stier and Crance 1985), with the eggs and larvae constrained to Zones 2 through 4 and adult migration plausible within all zones during the season. 5.0 mg/l was also found to be the lower requirement for Striped Bass egg and larval survival (Turner and Farley 1971), which is applicable to Zones 2 through 5. At the sub-lethal level, 5.0 mg/l was also found to be a requirement for adult Yellow Perch growth and development (Auer 1982; Jones et al. 1988; Kreiger et al. 1983), Bluefish occurrence (Shepherd and Packer 2006), Channel Catfish feeding rates (Randolph and Clemens 1976), and Largemouth Bass swimming ability (Katz et al. 1959). The combination of these species covers all five zones. Juvenile Atlantic Sturgeon, however, have a higher DO requirement at 6.3 mg/l for survival, growth, and mortality rates (Niklitschek and Secor 2009a). Juvenile Atlantic Sturgeon can also be found within all zones of the estuary. Additionally, adult Channel Catfish and juvenile White Perch exhibit sub-lethal effects at 3.95-6.40 and 3.60-6.30 mg/l respectively within all zones (Burggren and Cameron 1980; Hanks and Secor 2011). The highest reported DO requirement found within spring temperatures was 7.0 mg/l for juvenile Yellow Perch and supports normal activity at the sub-lethal level (Thorp 1977). Adult Scud exhibit 50% mortality at 4.3 mg/l (Sprague 1963) and Summer Flounder have chronic negative effects on growth and survival at 4.52 mg/l (Bailey et al. 2014). These data suggest that a 4.0 mg/l DO concentration is likely the minimum requirement for some sensitive species, 5.0 mg/l may be adequate for many species, and 6.0-7.0 mg/l or higher would likely be protective of all species at both the lethal and sub-lethal level within all zones during Spring.

Summer, with water temperatures ranging between 18 and 32°C, has the most available data for species DO sensitivities which range from 3.0 to 8.0 mg/l (Table 4). At the lethal effect level, DO concentration requirements range from 4.08 to 6.44 mg/l with a modal value of 5.0 mg/l. At the lower end of lethal effect requirements are juvenile Blue Crab with an LC50 of 4.08 mg/l (Stickle et al. 1989), corresponding to Zone 5. However, this value corresponds to a high (50%) mortality. Adult Scud follow with a 24-hour LC50 of 4.3 mg/l (Sprague 1963) and a reported highest DO value with significant mortality of 4.09 mg/l (Hoback and Barnhart 1996). Scud may be found in all zones of the estuary. This is followed by adult Yellow Perch with a lowest reported concentration for survival of 4.3 mg/l (Moore 1942) and egg and larval Channel Catfish with decreases in survival at 4.4 mg/l (Carlson et al. 1974). These species are typically found among Zones 2 through 4. There are also sub-lethal effects found at concentrations below these values for Eastern Elliptio, larval Atlantic Sturgeon, and Juvenile Shortnose Sturgeon (see Table 4). At 5.0 mg/l, lethal effects are seen for the spawning and survival of American Shad (Stier and Crance 1985), and for survival of juvenile Yellow Perch (Moore 1942). Yellow Perch is likely to be found within Zones 2, 3, and 4, and American Shad may be found within all zones during the summer in varying life stages. The next highest concentration requirement is seen for larval Atlantic Rock Crab with an LC50 of 6.05 mg/l (Vargo and Sastry 1977) and juvenile Blue Crab with an LC50 of 6.44 mg/l (Stickle et al. 1989), both of which inhabit Zone 6. Juvenile Atlantic Sturgeon have similarly high DO requirements at 6.3 mg/l for survival and growth (Niklitschek and Secor 2009a) and may inhabit all zones of the estuary. At the sub-lethal level, high values are reported for adult Channel Catfish gill ventilation rates at 3.95-6.4 mg/l (Burggren and Cameron 1980); juvenile White Perch growth at 3.6-6.3 mg/l (Hanks and Secor 2011); juvenile Largemouth Bass growth at 8 mg/l (Stewart et al. 1967); and juvenile Striped Bass growth at 8 mg/l (Brandt et al. 2009). These data suggest that a DO concentration of 4.0 mg/l is likely the lower limit for some sensitive species; 5.0 mg/l may be adequate for the protection of several species within Zones 2 through 4; however, concentrations of 6.0-7.0 mg/l or higher would be protective of more species. A DO concentration higher than 6.4 mg/l appears necessary for Zones 5 and 6 during Summer to protect larval stages of crustaceans. Further still, 8.0 mg/l would be protective of ideal growth rates and success of all species in all zones, especially in the freshwater portions of the estuary.

Fall, with water temperatures ranging between 6 and 26°C, has similar reported DO concentration requirements as Spring at 3.0 to 7.0 mg/l, with a modal value of 5.0 mg/l (Table 5). At the lethal level, juvenile Blue Crab exhibit the highest DO requirement with an LC50 of 6.44 mg/l in Zone 6 and 4.08 in Zone 5 (Stickle et al. 1989). Juvenile Atlantic Sturgeon follow with survival and growth rates at 6.3 mg/l in all zones (Niklitschek and Secor 2009a). Juvenile Striped Bass have high survival at 5.0 mg/l (Krouse 1968 as in Bain and Bain 1982) and may likewise be found in all zones of the estuary during Fall. Summer Flounder, Scud, and Shortnose Sturgeon follow within the 3.0-4.0 mg/l range (see Table 5). At the sub-lethal effect level, juvenile Yellow Perch have the highest requirement at 7.0 mg/l that is supportive for normal activity (Thorp 1977). Channel Catfish, Largemouth Bass, and adult Yellow Perch follow at the sub-lethal level with requirements of 5.0 mg/l (see Table 5). These data suggest that a 5.0 mg/l DO concentration may be adequate for many species and 6.0-7.0 mg/l or higher would likely be protective of all species at both the lethal and sub-lethal level within all zones during Fall.

Winter, exhibiting water temperatures between 2 and 10°C, has substantial data gaps in terms of available DO requirements at comparable temperatures (Table 6). It is likely that requirements seen in Fall and Spring are also adequate for Winter. However, direct assessment of species' requirements at low temperatures could not be made in many instances. Where data do exist, a DO concentration between 4.0 and 5.0 mg/l is required for at least one species in each zone. Juvenile and adult Yellow Perch were shown to have a minimum requirement of 4.8 mg/l at 4°C for 100% survival (Moore 1942) and are likely be found within Zones 2 through 5 during these months. Juvenile Largemouth Bass have been shown to avoid any area where DO concentrations drop to 4.5 mg/l (Whitmore et al. 1960), and this species is likely to inhabit Zones 2 and 3. Additionally, American Shad have been shown to have increased distress and respiration rates when DO concentrations drop to 4.0 mg/l (Tagatz 1961) and juveniles may still be present in Zone 6 for a portion of the winter. Unfortunately, no other studies tested species at winter temperatures and the true DO criteria may be higher than this. This may be especially true for more sensitive species, such as Atlantic Sturgeon, that are present in winter months but that have yet to be tested at low temperatures.

Shortnose Sturgeon (*Acipenser brevirostrum*)

In 1967, Shortnose Sturgeon were first listed as endangered under the Endangered Species Act and remain listed under federal protection (Federal Register 1967). Shortnose Sturgeon are found in the Delaware River and are considered amphidromous as their life cycle includes some degree of mixohaline use for non-breeding purposes. Based on tracking of 28 telemetered adults (54.4 cm to 87.1 cm FL), O'Herron et al. (1993) found no evidence suggesting that the Delaware River population of Shortnose Sturgeon utilized the freshwater-saltwater transition zone during the summer and little evidence of them using this zone at any time of the year. However, juvenile and larval stages may use higher saline waters, and the occurrence of a Shortnose Sturgeon in mixohaline waters would not be unusual given the species' behavior in other estuaries (Bain 1997; Brundage and O'Herron 2009). In the Delaware River, adult Shortnose Sturgeon overwinter in the freshwater tidal estuary between Torresdale, PA and Trenton, NJ, whereas, juveniles overwinter in an area between Artificial Island and Philadelphia, PA (Bochenek et al. 2014; Brundage and O'Herron 2009; O'Herron, Able, and Hastings 1993). In other estuaries, Shortnose Sturgeon overwinter in lower portions that have higher salinity waters (Bain 1997; Dadswell et al. 1984) and, in some cases, make inter-riverine movements that are poorly understood (Federal Register 2015).

Adults spawn in late-March through early-May when temperatures reach 9 to 12°C in the non-tidal river above Trenton, NJ (O'Herron, Able, and Hastings 1993; Dadswell et al.1984). Post-spawn individuals travel downriver to the Philadelphia area until mid-Spring before returning to the tidal section near Trenton, NJ in late-spring, where they reside through winter (O'Herron et al. 1993). In the Hudson River estuary, adult Shortnose Sturgeon reach sexual maturity at 50 cm FL (55 cm TL) and ≥ three years for males and ≥ six years for females (Bain 1997).

Eggs are adhesive and incubate for one to two weeks (Dadswell et al. 1984). The egg stage occurs in the spring during the spawning period and one to two weeks following the spawning period, presumably in the non-tidal river and areas downstream including tidal portions (where currents may carry eggs). In the Hudson River estuary, after hatching, Shortnose Sturgeon larvae disperse downstream and throughout much of the Hudson River estuary (Hoff et al. 1988 as cited in Bain 1997). After hatching, the larvae grow for <0.08 years (~4 weeks) before metamorphosing into juveniles around 2 cm TL (Bain 1997; Dadswell et al. 1984).

In the Delaware River estuary, juveniles have been documented from the mesohaline waters of the Delaware Bay (at approximately river kilometer 70) to Trenton, NJ (Brundage and O'Herron 2009). In the Hudson River estuary, juvenile Shortnose Sturgeon use fresh and brackish waters during the summer, brackish waters during the winter and spring, and there is no evidence that they leave the estuary (Bain 1997). In the Delaware River, juvenile Shortnose sturgeon occur in the Wilmington, DE to Marcus Hook, PA area year-round (Brundage and O’Herron 2009). Additionally, juvenile Shortnose Sturgeon and Atlantic Sturgeon co-occur in the tidal Delaware River and appear not to segregate based upon salinity (Brundage and O’Herron 2009).

At the lethal effect level, juvenile Shortnose Sturgeon show sensitivity to low DO concentrations. Juvenile mortality was not observed for 13-day old (described by authors as juvenile stage) Shortnose Sturgeon exposed to ≥4.0 mg/l DO (Jenkins et al. 1993). Shortnose Sturgeon juveniles may be sensitive to DO concentrations of 3.5 to 4.0 mg/l; however, a significant difference for 19-day old (26 mm TL) fish was not found between these concentrations (Jenkins et al. 1993). There was, however, a significant decrease in percent survival between 3.5 and 3.0 mg/l DO for fish 22-77 days of age (Jenkins et al. 1993). DO experiments conducted by Jenkins et al. (1993) were conducted at a mean temperature of 22.5°C and mostly in freshwater. Jenkins et al. (1993) states that their juvenile fish were obtained from a hatchery and were 11 to 310 days old (17-365 mm TL). According to size and age information provided by Dadswell et al. (1984), some of these fish could have been in the larval stage. It is unclear if Jenkins et al. (1993) included some larval fish for his experiments. In addition, using various temperature, DO, and salinity combinations (2.0 to 4.5‰) in 24-hour exposures, Campbell and Goodman (2004) estimated the LC50 of 77 to 104 day old fish to be 2.7 mg/l (32% DO saturation, 22°C, 4‰), 2.2 mg/l (28% DO saturation, 26°C, 4.5‰), and 3.1 mg/l (42% DO saturation, 30°C, 2‰). Lastly, when given a choice of 40% or 100% DO saturation at 20°C with salinity 8 ‰ (3.5 and 8.7 mg/l DO, respectively) in a controlled experiment, juvenile Shortnose Sturgeon chose the 100% DO saturation condition for a significantly higher percentage of the trials (Niklitschek and Secor 2010).

There are no reported DO sensitivities for Shortnose Sturgeon adults, eggs, or larvae. Future studies on the sensitivity of these life stages would greatly aid the scientific knowledge used for setting DO standards.

Shortnose Sturgeon were selected as a key oxygen sensitive species because of their sensitivity to low DO at the juvenile stage and broad range throughout benthic habitats, primarily in the fresh and oligohaline waters of the Delaware River estuary.

Atlantic Sturgeon (*Acipenser oxyrhynchus*)

In 2012, the New York Bight distinct population segment (DPS) of Atlantic Sturgeon was listed as endangered under the Endangered Species Act, and the Delaware River estuary was listed as containing critical habitat (Federal Register 2012; Federal Register 2017). Atlantic Sturgeon are anadromous, with spawning migrations in the spring and summer to freshwaters above the salt-line and below the fall-line of large rivers (Bain 1997; Federal Register 2017; Pennsylvania Commison of Fisheries 1897; Scott and Crossman 1973). Atlantic Sturgeon spawn in water ranging from 13 to 26°C (Greene et al. 2009; Federal Register 2017). Summer time (i.e., September) spawning has been documented in the Roanoke River, NC, in waters ranging from 24.3 to 25.3°C (Smith et al. 2015).

Balazik et al. (2012) documented evidence of spawning in summer and fall (August to early-October) in the James River, VA, and spawning in the Hudson River estuary occurred in freshwaters in the spring (Van Eenennaam et al. 1996; Bain 1997).

Atlantic Sturgeon eggs are adhesive, benthic, cannot tolerate high salinity, and hatch 94-140 hours after deposition at temperatures of 18 to 20°C (Bain 1997; Greene et al. 2009; Federal Register 2017; Van Eenennaam et al. 1996). In the Hudson River estuary, larvae were ≤ 3 cm TL and < 0.08 years old (~4 weeks) (Bain 1997). Presumably, the egg and larval stages occur in the vicinity of spawning and any location where currents may take the eggs before they adhere to plants or substrate. Bath et al. (1981) collected sturgeon larvae in the Hudson River estuary in salinities ranging from 0 to 2.2‰. The egg and larval stages occur in the spring and, in some populations, in the summer and fall following spawning (Bain 1997; Balazik et al. 2012; Smith et al. 2015).

In the Hudson River estuary, juveniles range from 2 to 134 cm FL and 0.08 to 11 years old (Bain 1997). In the Delaware River estuary, during all seasons, juvenile Atlantic Sturgeon occur from Trenton, NJ to the lower Delaware Bay (Brundage and O'Herron 2009; Hale et al. 2016; Lazzari, O’Herron, and Hastings 1986) and some leave the estuary for marine waters and coastal movements (Bochenek et al. 2014; Brundage and O’Herron 2009). Bochenek et al. (2014) found that older juveniles (> 80 cm FL) left the estuary in the fall and were present only from May to October. Allen et al. (2014) demonstrated that juvenile Atlantic Sturgeon (43.7 cm mean FL) can move into salinities of 33‰.

Overall, there is little information on larval Atlantic Sturgeon (Greene et al. 2009). Wirgin and Chambers (2018) found DO to be a significant predictor for prey consumption and percent survival of hatchery raised larval to juvenile (1.94 cm to 5.08 cm SL) Atlantic Sturgeon originating from an Atlamaha River, Georgia stock. Although, post hoc tests revealed prey consumption was significantly reduced at 3 mg/l DO when compared to treatments of 4, 6, 8, and 10 mg/l DO at 15°C and 0.01 ‰ salinity, percent survival did not differ among treatments (Wirgin and Chambers 2018). Wirgin and Chambers (2018) did not find a significant effect for average fish velocity (i.e., activity), percent survival of larval to juvenile (1.09 cm to 8.01 cm SL) hatchery fish originating from Canada, or a consistent pattern for the effect of DO on prey consumption of the Canada stock used in their experiments.

Juvenile survival is significantly affected by DO, temperature, and salinity (Niklitschek and Secor 2009a). At 70% DO saturation and salinity of 8‰, Niklitschek and Secor (2009a) determined the instantaneous mortality rate of juveniles to be 0.01 d-1 at 20°C and approximately 0.04 d-1 at 28°C (at 20°C, 70% DO saturation equates to 6.3 mg/l). At 20°C and 70% DO saturation, instantaneous mortality rates increased from 0 to 3.5% with increasing salinity (1 to 29‰) (Niklitschek and Secor 2009a). Note that Niklitschek and Secor (2009a) used juvenile Atlantic Sturgeon < 1 year of age that weighed 6-48 g to evaluate survival response to salinity and that these size fish remain in fresh waters of the Delaware estuary and do not appear to use higher salinity waters (Desmond Kahn, personal comments). In addition, Niklitschek and Secor (2009a) did not employ freshwater for their experiments. According to Niklitschek and Secor (2009a):

> “For illustration purposes, if optimal growth or survival rates were used as criteria to set a hypoxia threshold for juvenile Atlantic sturgeon, that value would rise from 40 to 70% DO

saturation if temperature increased from 12 to 20°C. At salinity 1 these values would correspond to concentrations of 4.3 and 6.3 mg^{-1}, respectively. At salinity 29, on the other hand, the same thresholds would correspond to concentrations of 3.6 and 5.4 mg^{-1}, respectively".

As an example of features needed to support growth, development, and recruitment, the National Marine Fisheries Service (NMFS) stipulates 6.0 mg/l DO or greater is needed for juvenile rearing habitat in the New York Bight DPS (Federal Register 2017). In the South Atlantic DPSs, "Appropriate temperature and oxygen values will vary interdependently, and depending on salinity in a particular habitat. For example, 6.0 mg/l DO or greater likely supports juvenile rearing habitat, whereas DO less than 5.0 mg/l for longer than 30 days is less likely to support rearing when water temperature is greater than 25°C. In temperatures greater than 26°C, DO greater than 4.3 mg/l is needed to protect survival and growth" (Federal Register 2017). When given a choice of 40% or 100% DO saturation (at 20°C with salinity 8‰, 3.5 and 8.7 mg/l DO respectively) in a controlled experiment, juvenile Atlantic Sturgeon chose the 100% DO saturation for a significantly higher percentage of the trials (Niklitschek and Secor 2010).

In the Hudson River estuary, after two to six years, juveniles migrate to marine waters and may frequent riverine habitats during warmer months (Bain 1997). Adults are ≥ 135 cm FL, ≥ 12 years old, and migrate to marine waters after spawning (Bain 1997). Greene et al. (2009) found no information on adult DO requirements.

Atlantic Sturgeon were selected as a key oxygen sensitive species because of their sensitivity to low dissolved oxygen at both the lethal and sub-lethal levels at the juvenile and larval stages and broad range throughout benthic habitats in the Delaware Estuary. There are no available data on DO requirements for adults and little data for larvae, presenting a gap in the current scientific knowledge. Additional studies would greatly improve the current understanding of Atlantic Sturgeon DO sensitivity at those stages.

American Shad (*Alosa sapidissima*)

American Shad is an important anadromous species distributed along the Atlantic Coast of the United States and is also the largest species in the Clupeid, or Herring, family (Stier and Crance 1985). The Delaware River is important for the continued success of the American Shad population and supports both commercial and recreational shad fisheries. The health of the river is often reflected in the American Shad population. Severe decreases in the population were seen in the early 1900s for a variety of anthropogenic reasons (Miller 1995). By the mid-20th Century, low seasonal DO formed a block severely limiting down-migration of juvenile American Shad (Miller 1995). With improved water quality, American Shad have returned to and increased in the Delaware River.

As an anadromous species, American Shad migrate from the Atlantic Ocean into freshwater rivers and their tributaries to spawn before returning to the ocean. Spawning adults typically return to the same rivers in which they are born, with timing of migrations linked to water temperature (Miller 1995). In the Delaware River and its tributaries, American Shad males will reach freshwater spawning grounds before females, when water temperatures reach or exceed 12°C (Able and Fahay 2010; Scott and Crossman 1973), and spawning occurs from March through May (Greene et al. 2009). After spawning up to five times, adults make their way back downstream towards the ocean, although many may experience mortality brought on by spawning stress (Able and Fahay 2010; Scott and Crossman 1973). The proportion of surviving spawners varies latitudinally and has varied over time in the Delaware River. Survival may be linked to length of the spawning migration and water temperatures, which affect energetic costs of migration and spawning (Richard Horwitz, personal communication, May 2018).

Eggs are carried by currents as they slowly sink, either remaining at or just downstream of the spawning area until hatching (Stier and Crance 1985). Hatching takes place within 2 to 17 days (Able and Fahay 2010). Larvae are initially planktonic and are carried downstream by currents (Green et al. 2009). This stage is found almost exclusively in freshwater but has been shown to drift into brackish areas (Greene et al. 2009). After 4-5 weeks, larvae transform into juveniles and display schooling behavior as they swim downstream to nursery areas in brackish water (Stier and Crance 1985) or fresh water. Juveniles in fresh water nursery areas migrate downstream into the estuary in fall (Richard Horwitz, personal communication, May 2018). Some juvenile American Shad will overwinter in the estuary while others emigrate from estuaries to nearshore waters throughout October and November (Greene et al. 2009). Adult American Shad are found off the Atlantic Coast and make seasonal migrations along the Atlantic coastal waters in the winter and spring (Stier and Crance 1985).

While water quality has been proven to be important for American Shad reproductive success and distribution, available information on DO requirements is scarce. Lethal effects of low DO have been documented for eggs, larvae, and juveniles; however, the identification of upper lethal limits has not been documented. DO concentrations less than 1.0 mg/l have been shown to cause 100% mortality of American Shad eggs and 2.5 to 2.9 mg/l has been shown to cause 50% mortality (Stier and Crance 1985). Mortality in juveniles has been documented at 1.2 mg/l, but survival is possible with limited exposure to DO concentrations between 2.0 and 4.0 mg/l (Tagatz 1961). A DO concentration of 5.0 mg/l has been reported necessary to support spawning success (Stier and Crance 1985).

Although the available data on lethal effects do not strongly indicate this species' sensitivity to low DO, several sub-lethal effects have been documented in the literature at higher oxygen concentrations. For example, respiration rates and distress increase in juvenile American Shad when DO levels drop to 4.0 mg/l (Tagatz 1961). The median sublethal threshold for adult American Shad is reported at 2.75 to 4.0 mg/l in a review by Vaquer-Sunyer and Duarte (2008). Additionally, American Shad spawn in areas with DO concentrations greater than or equal to 5.0 mg/l, and migration into or out of spawning grounds can be blocked by unsuitable conditions, including low DO concentrations (Walburg and Nichols 1967).

The susceptibility of American Shad to low DO during migration, spawning, and at the juvenile life stage has indicated this species as a key oxygen sensitive species. It is necessary to be mindful that reported lethal values for American Shad are for 50 or 100% mortality, and the no-effect levels are not indicated in the literature. This is an existing data gap and more research on the lethality of DO concentrations on different life stages of American Shad would greatly benefit the assessment of their sensitivity.

While ample literature and data are wanting, American Shad has the most available data on DO sensitivities within the Clupeids, and American Shad plays an important role in the Delaware River.

Therefore, American Shad were further selected as a key species to represent other Clupeids within the Delaware River that occupy similar niches and may be similarly affected by low DO.

Blue Crab (*Callinectes sapidus*)

The Blue Crab is the most valuable commercial species of crab in the Delaware Estuary, with commercial values reaching over $6 million annually and landings exceeding 7 million lbs. (Santoro 2004; Wong et al. 2012). The adults of the species are found almost exclusively in estuaries (Dittel and Epifanio 1982). Mating occurs in lower salinity areas in the upstream portions of the estuary, followed by female migration downstream for spawning (Santoro 2004). Gravid females are typically concentrated in shallow areas within 15 km of the bay mouth and hatching occurs on ebbing tides (Santoro 2004). Adult abundances are high at all depths in the water column in June and show a decline in abundance in the fall (Pihl et al. 1991). In the western portion of the Delaware Bay, adult abundances reached a peak in August (Wong et al. 2012).

Following hatching, Stage 1 larvae are most abundant in surface waters and ebbing tidal currents (Dittel and Epifanio 1982; Epifanio, Masse, and Garvine 1989; Epifanio, Valenti, and Pembroke 1984). Larvae are most abundant in late-July through early-August with a second peak typically seen in early-September (Dittel and Epifanio 1982; Epifanio et al. 1984, 1989). By the third week in September, the earliest larval stages decline (Epifanio et al. 1984, 1989). Megalops are then recruited in mid-September through mid-October (Dittel and Epifanio 1982; Epifanio et al. 1984; Wong et al. 2012). Megalops exhibit swarming behavior and sink on ebb tides and rise on flood tides (Epifanio et al. 1984). It is believed that zoeal development takes place on the continental shelf, with a flushing of early stage larvae from the bay correlated with tidal currents and recruitment of megalops and adults observed (Epifanio et al. 1984). Juvenile Blue Crabs are found at all depths in the water column, with a greater abundance near the bottom (Dittel and Epifanio 1982; Wong et al. 2012).

Adult Blue Crabs are generally tolerant of low DO, with a mean acute LC50 of less than 1.0 mg/l (Thursby et al. 2000) and an LT50 (time for 50% mortality) of 2.56 days in 0.5 mg/l at 20 to 26°C and salinities of 16 to 23‰ (Sagasti et al. 2001). Larval and juvenile Blue Crabs are more sensitive than their adult counterparts. Juvenile Blue Crabs had an LC50 between 4.08 and 6.44 mg/l that varied with temperatures from 20 to 30°C and salinities of 10 to 30‰ in an experiment by Stickle et al. (1989). A similar experiment by Das and Stickle (1993) showed a 28-day LC50 for juveniles of 5.02 mg/l. Juvenile Blue Crabs, unlike adults, cannot survive brief anoxic periods and have an LT50 of less than one day in anoxia (Stickle et al. 1989).

In addition to lethal effects, several sub-lethal effects of low DO were also observed in juveniles. Das and Stickle (1993) found a significant feeding rate decline at 2.31 mg/l as well as decreased and longer molting at 1.16 to 2.31 mg/l.

Due to the larval and juvenile susceptibility to low DO at the lethal level, Blue Crab has been included as a key sensitive species for the Delaware Estuary and is a representative for oxygen sensitive benthic invertebrates.

Atlantic Rock Crab (*Cancer irroratus*)

Unlike the Blue Crab, which spends most of its life cycle in the estuary, the Atlantic Rock Crab is only in the estuary during spawning (Dittel and Epifanio 1982). Adults reside in the Atlantic Ocean but are found in the Delaware Estuary in early spring for spawning in open areas in the lower bay with fine to medium sandy substrates (Maurer et al. 1978; Dittel and Epifanio 1982). The larval stages are found in the surface waters of the bay from March through June, with peak abundances in May (Dittel and Epifanio 1982).

Like the Blue Crab, the larval stages of the Atlantic Rock Crab are sensitive to low DO. The DO sensitivity of larval stages 1 through 5 is correlated with temperature and in 30‰ salinity LC50s range from 0.47 to 3.80 mg/l at 10-22°C and 4.2 to 6.05 mg/l at 30°C (Vargo and Sastry 1977). An experiment conducted by Miller, Poucher, and Coiro (2002) reported a larval LC10 of 3.8 mg/l, LC50 of 2.6 mg/l, and LC90 of 2.1 mg/l at 20°C and salinities of 28 to 32‰.

Megalops are similarly sensitive to low DO with reported LC50s ranging from 1.58 to 4.70 mg/l at 10 to 30°C and salinity of 30‰ (Vargo and Sastry 1977). No information on adult Atlantic Rock Crab DO sensitivity was found. However, adults are only in the bay briefly for spawning, so protection of DO for larvae is likely to be sufficient for adults during that time.

Atlantic Rock Crab larvae are sensitive at the lethal effect level and occur in the Delaware Estuary earlier in the year than Blue Crab, occupying a different seasonal niche for benthic invertebrates. For this reason, Atlantic Rock Crab has been included as a key sensitive species as a representative for oxygen sensitive benthic invertebrates.

Eastern Elliptio (*Elliptio complanata)*

Freshwater Unionid mussels provide important ecosystem services and have declined or been extirpated from many of their natural habitats over the years (IUCN 2017; Kreeger, Gatenby, and Bergstrom 2017; Strayer 1999; Strayer et al. 1999; Thomas et al. 2011; Williams et al. 1993). Due to their current status and recognized importance, Unionids have warranted consideration for DO criteria.

Unionids are generally considered tolerant to hypoxic conditions and able to withstand even anoxic conditions; however, similar to other invertebrates and fish, tolerances vary by species and life stage (Byrne et al. 1995; Chen 1998; Sparks and Strayer 1998; McMahon and Bogan 2001; Strayer 2008). Considered to be oxygen regulators, adult mussels can withstand anoxia for hours to days by slowing their metabolism (McMahon and Bogan 2001, Strayer 2008). Adult mussels are considered to be more tolerant than juveniles (Sparks and Strayer 1998; Strayer 2008), and McMahon and Bogan (2001) found that adult mussels do not exhibit acute stress under low DO for up to several weeks. While much of the oxygen consumption in mussels exhibits natural seasonal and temporal variation (Kreeger 2011), oxygen tolerances also vary by species. For instance, *Villosa iris* was found to be a poor oxygen regulator with short-term DO requirements reported at 6 mg/L at 24.5°C, where others have been reported at 2 mg/l (Chen 1998). *Villosa iris* is not found within the Delaware Estuary; however, this study suggests that there may be other native species with similar oxygen sensitivities that have yet to be tested.

While there are several Unionids that occur in the freshwater portion of the Delaware Estuary, there exists a significant data gap on almost all of them regarding DO requirements. Literature on DO sensitivity was only found for two species native to the Delaware Basin: *Elliptio complanata* (Eastern Elliptio) and *Pyganodon cataracta* (Eastern Floater).

Adult Eastern Elliptio are generally regarded as tolerant to hypoxia (Chen 1998; Chen et al. 2001). Adults exhibit oxygen regulation below 2 mg/l (Chen 1998) and can maintain normal oxygen content without stress at 2 to 3 mg/l (Chen et al. 2001). Juvenile (<4 years old) Eastern Elliptio are more sensitive to low DO than adults, exhibiting behavior changes starting at 4.0 mg/l in 23 to 25°C and 67% mortality after a week at 1 mg/l (Sparks and Strayer 1998). Sparks and Strayer (1998) conclude that juveniles may be sensitive to low DO at a chronic level by exposing themselves to predation through behavior changes.

Eastern Floater adults exhibit a 55% decrease in heart rate in anoxia and are unable to maintain a constant rate of oxygen consumption at DO concentrations less than 3.3 mg/l (Tankersley and Dimock 1993; Polhill and Dimock 1996). Juvenile Eastern Floater were similarly found to be more sensitive than their adult counterparts with a 70% decrease in heart rate under anoxic conditions and 100% mortality within 24 hours of complete anoxia (Dimock and Wright 1993; Tankersley and Dimock 1993; Polhill and Dimock 1996). Both adults and juveniles were found to be more sensitive to temperature than DO (Polhill and Dimock 1996).

While freshwater Unionid mussels are important components of the aquatic ecosystem in the Delaware River, a large data gap exists on DO requirements for many species. The available literature on *V. iris* does indicate a potential for the discovery of higher DO demands for species in the Delaware that have not previously been studied, and studies on Eastern Elliptio juveniles indicate deleterious behavioral changes with lowered DO concentrations.

Scud (*Gammarus spp.*)

Several species of amphipods, commonly referred to as Scuds, are found throughout the Delaware Estuary, with the most common historically being *Gammarus fasciatus* (Cronin et al. 1962). Amphipods are important food sources in estuarine systems for fish, birds, and other invertebrates. *G. fasciatus* is most abundant in the estuary in spring and summer but is present year round (Cronin et al. 1962). While this species is typically found in fresh, oligohaline, or mesohaline waters, it can occasionally be found in salinities as high as 26.8‰ (Cronin et al. 1962). High abundance has been specifically documented in the estuary near Wilmington, DE (Cronin et al. 1962).

There was one report found on *G. fasciatus* oxygen sensitivity which states that a 24-hour LC50 at 20°C in freshwater is 4.3mg/l for the species; however, there were problems with their control during this experiment and conclusions may not be credible (Sprague 1963).

Adequate data do exist for *Gammarus pseudolimnaeus*, though, which can be used as a surrogate species for others in the genus (U.S. Environmental Protection Agency 2012).

G. pseudolimnaeus varies in DO sensitivity among life stages and sexes, with the highest tolerance seen in juveniles with LC50s ranging from 0.35 to 2.49 mg/l, and the lowest observed in females with LC50s ranging from 1.41 to 4.09 mg/l at 10 to 20°C in freshwater (Hoback and Barnhart 1996). Males appear to have an intermediate tolerance, with LC50s ranging from 0.91 to 3.19 mg/l in 10 to 20°C. Vaquer-Sunyer and Duarte (2008) similarly reported in their review that the mean LC50 was 0.91 to 3.26 mg/L for adults and 0.35 to 1.91 mg/l for juveniles.

While adult males and juveniles have low sensitivity to reduced DO concentrations, the sensitivity of adult, female amphipods may have implications for reproduction if DO levels are not adequate.

Because of the sensitivity for this sex and life stage, *Gammarus spp.* are included on the key sensitive species list. Additionally, *Gammarus spp.* occupies a wide range of the Delaware Estuary in all seasons and has a higher oxygen requirement than other invertebrates within the same range, making them representative for other species and an important consideration for DO criteria.

Channel Catfish (*Ictalurus punctatus*)

The Channel Catfish, native to the Mississippi/Ohio Drainage, has been introduced to the Delaware River Basin on numerous occasions since the late 1800s (Pennsylvania Commission of Fisheries 1897). Channel Catfish are currently the most abundant catfish species in the freshwater Delaware River (O'Herron, Lloyd, and Laidig 1994; Keller 2011).Their populations continue to be stocked as a sport fish by both the NJDEP and PAFBC in the Delaware River basin (Lorantas et al. 2005; NJ Division of Fish and Wildlife 2017). Channel Catfish spawn in the Delaware River from May through July (Keller 2011; McMahon and Terrell 1982) when water temperatures reach 20°C or higher (Keller 2011). Males will build nests for spawning in areas protected by woody debris, undercut banks, or boulders (Scott and Crossman 1973). Males then protect and care for the eggs which hatch within ten days, on average (Scott and Crossman 1973). After hatching, larvae are benthic for about a week and then can be found near surface waters (Scott and Crossman 1973). Eggs, larvae, and juveniles are residents of freshwater and oligohaline portions of the river whereas adults can tolerate slightly higher salinities, entering mesohaline environments (McMahon and Terrell 1982; O'Herron et al. 1994). Channel Catfish can be found during all seasons within the freshwater and oligohaline zones of the Delaware Estuary and may venture into the upper mesohaline zones in salinities as high as 11‰ (Perry 1967, Keller 2011). During the day, Channel Catfish often take cover in available habitat in clear waters and feed at night (Scott and Crossman 1973).

Data on the sub-lethal impacts of low DO on Channel Catfish are widely available in the literature. Eggs, larvae, and juveniles are the most sensitive life stages. Eggs and larvae were reported to have decreased hatching success and survival at 3.6 to 4.4 mg/l DO at 25ºC and at 3.6 to 4.2 mg/l DO at 28ºC (Carlson et al. 1974). Juvenile Channel Catfish have been documented to have reduced feeding at 5.0 mg/l and higher production at 4.0 mg/l DO (Randolph and Clemens 1976; McMahon and Terrell 1982; Torrans et al. 2012). Another study found that the first increase in ventilation rates due to decreasing DO occurred at 4.0 mg/l (Gerald and Cech 1970). General statements that 5.0 mg/l DO is adequate for growth and survival while 7.0 mg/l is optimum for growth and survival have been made in studies of the association between Channel Catfish and oxygen (Andrews et al. 1973; Carlson et al. 1974). Burggren and Cameron (1980) found that adult fish of weights 520 to 1069 g exposed to 3.95 to 6.4 mg/l DO resulted in doubled gill ventilation and lactic acidosis.

Lethal effects of low DO are less readily available and indicate a tolerance to low DO at a lethal level. Channel Catfish > 100 g (estimated to be a juvenile) had an LC50 of 0.85 mg/l DO (Scott and Rogers 1980). Lethal concentrations have also been reported at 0.95 to 1.08 mg/l at 25 to 35°C (Scott and Crossman 1973).

These data indicate that Channel Catfish are sensitive to low DO concentrations at a sub-lethal level. Eggs, larvae, and juveniles have the greatest sensitivities in terms of growth and survival, but one study (Burggren and Cameron 1980) did document the sub-lethal sensitivity of adults. As a widespread, resident benthic species of the Delaware River and important sport fish, Channel Catfish with sub-lethal DO sensitivity was included here as a key oxygen sensitive species.

Largemouth Bass (*Micropterus salmoides*)

Largemouth Bass is nonindigenous to the Delaware River Basin but has been prevalent since it was first introduced in 1870 (Pennsylvania Commission of Fisheries 1897). Largemouth Bass is a popular freshwater game species in ponds, lakes, pool habitat in rivers and streams, and backwaters (IUCN 2017). Largemouth Bass are typically found in the mid- to surface-levels of warm, fresh or oligohaline waters and are often associated with habitat such as woody debris and submerged vegetation (Scott and Crossman 1973).

Males begin building nests in sandy and silty substrates when water temperatures reach 15.6°C and spawning occurs from late-spring through summer (Scott and Crossman 1973). Males guard the nests, eggs hatch within five days, and larvae remain in or near the nest for up to 31 days after hatching (Scott and Crossman 1973). Juveniles remain in fresh or oligohaline waters with salinities up to 1.5‰ (Stuber et al. 1982).

The available reports suggest that lethal DO concentrations for Largemouth Bass are relatively low at 0.92 to 1.5 mg/l (Boyd and Lichtkoppler 1979; Moss and Scott 1961). The same is true for the threshold for egg survival and hatching which is reported at 2.8 mg/l (Jones, Martin, and Hardy 1978). Largemouth Bass juveniles, however, exhibit many sub-lethal deleterious effects from low DO. At 5.0 to 6.0 mg/l at 25°C, swimming speed begins to reduce (Dahlberg, Shumway, and Doudoroff 1968) and difficulty swimming through currents is documented below 5.0 mg/l at 15.5 to 17.0°C (Katz et al. 1959). Juveniles will also actively avoid areas with 4.5 mg/l (Whitmore et al. 1960). Reduced growth for juveniles is reported to begin at 8.0 mg/l (Stewart et al. 1967), is reduced by 33% between 4.0 and 6.0 mg/l (Brake 1972), and is substantially reduced below 4.0 mg/l (Stewart et al. 1967).

While Largemouth Bass are not sensitive to low DO at the lethal level, juvenile Largemouth Bass exhibit growth and behavioral effects even when DO is at a much higher level. Growth and success of juveniles affects the overall health and success of the population within the Delaware Estuary and has implications for the recreational fishery. For this reason, Largemouth Bass is included as a key oxygen sensitive species in the Delaware Estuary at the sub-lethal effect level.

White Perch (*Morone americana*)

White Perch is a species in the temperate bass family, Moronidae, and is an important recreational species in the Delaware Estuary. White perch are semi-anadromous, meaning they migrate short distances from brackish water to fresh or nearly-fresh water to spawn. The spawning season extends from May through June (Able and Fahay 2010; Stanley and Danie 1983) from the lower- to mid-estuary through the upstream tidal freshwater portions (Mansueti 1961). Males and females congregate in large groups, and eggs and sperm are spread randomly throughout the water column (Stanley and Danie 1983). Spawning for this species is prolonged and may continue for up to two weeks with two to three separate spawning acts (Scott and Crossman 1973). No nest is made and eggs are laid without preference on bottom substrates (Scott and Crossman 1973). Eggs hatch in 3-5 days, and larvae remain near the spawning area until they grow large enough to move downstream (Stanley and Danie 1983). Juvenile White Perch utilize nearshore habitats as nursery areas (Stanley and Danie

1983) and may either move into more brackish waters several months after metamorphosis or stay in tidal freshwater areas (Kraus and Secor 2004). Adults then remain in these areas as a resident species (Stanley and Danie 1983) with a minor fall migration to deeper waters downstream observed in the fall (Mansueti 1961).

Data on DO sensitivities of White Perch are well documented for juveniles. Hanks and Secor (2011) exposed juvenile White Perch to several experimental treatments with varied DO and temperature. The authors found that at 3.6 mg/l DO, growth rate (0.020 g/d) and consumption rate (0.11 g/g fish weight) of the juvenile fish were significantly lower than those at 6.3 mg/l DO (0.032 g/d and 0.17 g/g fish weight) (Hanks and Secor 2011). Depressed DO levels resulted in increased metabolic costs for juvenile White Perch, illustrating the potential impact of hypoxic conditions on habitat suitability (Hanks and Secor 2011).

Fewer data on other life stages of White Perch and their DO requirements are available. At the lethal level, an LC40 of 0.5 to 1.0 mg/l was reported for juveniles (Dorfman and Westman 1970). Other studies have documented that White Perch abundance is associated with oxygen gradients in estuarine systems (O'Herron et al. 1994; Able et al. 2009) and that adult White Perch avoided areas between 3.0-4.6 mg/l DO concentration in favor of more oxygenated water (Meldrim et al. 1974).

Despite the lack of robust data on the sensitivity of White Perch to low DO, the data that do exist indicate that this species' distribution is related to DO gradients and there are several sub-lethal effects of low DO that inhibit the success of this species. White Perch are an estuarine resident, utilizing all areas of the Delaware Estuary throughout its life. For these reasons, White Perch was selected as a key oxygen sensitive species.

Striped Bass (*Morone saxatilis*)

Striped Bass is a popular recreational estuarine species, with annual landings reported at over 18 million pounds along the east coast (asmfc.org). Striped Bass is a migratory species, and is sometimes described as semi-anadromous, meaning it spawns in fresh and oligohaline waters but matures and lives in coastal bays or the ocean, with migrations north in the summer and south in the winter (Bain and Bain 1982). Adults typically live in the lower bay or offshore in polyhaline waters (Bain and Bain 1982) but can be found over the summer in oligohaline portions of the estuary (Wingate et al. 2011). Adults will begin their migration to spawning grounds, located 107-231km from the mouth of the bay (Fay et al. 1983), in April through July (Bain and Bain 1982; Fay et al. 1983). Spawning typically takes place in fresh or oligohaline waters with salinities up to 1.5‰ (Bain and Bain 1982). Eggs are then laid and start to float downstream, often hatching in fresh or oligohaline waters but have been documented to hatch in mesohaline waters (Bain and Bain 1982). Eggs typically hatch in two to three days (Scott and Crossman 1973). Striped Bass larvae are most abundant in surface waters with salinities of 3 to 7‰, but may tolerate ranges of 0 to 15‰ (Bain and Bain 1982; Nemerson and Able 2003). Juveniles will then move to nearshore areas and gradually make their way into higher salinity waters and towards the ocean (Bain and Bain 1982).

Striped Bass eggs require a DO concentration equal to, or greater than, 4.0 to 5.0 mg/l (Turner and Farley 1971) with reports of reduced egg survival at 4.0 mg/l and complete absence of eggs between 2.0 and 3.5 mg/l (Chittenden 1971). Larvae and post-larvae have reported lethal thresholds at 3.0 mg/l (Chittenden 1971; Westin and Rogers 1978), with decreased survival observed between 4.0 and 5.0

mg/l (Turner and Farley 1971) and LC50s ranging from 1.96 to 3.46 mg/l at 18.5 to 20.6°C and salinities of 4 to 7‰ (Poucher and Coiro 1997). In other reports, juvenile Striped Bass will experience no growth or consumption below 2.0 mg/l at 20 to 30°C, and decreased growth and consumption below 4.5 mg/l at 20 to 28°C (Brandt et al. 2009).

Juvenile Striped Bass have reported minimum DO requirements of 3.0 mg/l with intermediate survival (Coutant 1985) and high survival at 5.0 mg/l (Bain and Bain 1982). Juveniles have reported LC50s between 1.5 and 1.89 mg/l at 18.2 to 21.8°C and salinities of 30 to 32‰ (Poucher and Coiro 1997).

Oxygen data were less available for adult Striped Bass, but an optimum DO concentration of at least 6.0 mg/l has been suggested for high survival, growth, and reproduction (Fay et al. 1983). Additionally, adults have been documented to avoid areas with 3 mg/l (Meldrim et al. 1974).

While more data on adult Striped Bass would improve the understanding of DO requirements for that stage, adequate data exists for all other life stages demonstrating the sensitivity of this species to low DO and warranting inclusion as a key oxygen sensitive species.

Summer Flounder (*Paralichthys dentatus*)

Summer Flounder is a benthic, marine flatfish that resides in the inshore and offshore waters of the Atlantic Ocean. Summer Flounder is an important species for recreational fishing in the Delaware Bay with adults being present in small numbers in the bay throughout the year (Able and Fahay 2010, Packer et al. 1999) and spawning offshore in the fall and winter (Buckley 1989). Eggs hatch offshore and larvae move into the estuaries to mature to juveniles from October through May (Buckley 1989). Juveniles typically spend one to two years in the estuary before moving back offshore (Buckley 1989).

Summer Flounder are relatively tolerant to low DO at the lethal effect level. LC50s have been reported at 1.1 to 1.6 mg/l for juveniles at 20 to 25°C and 28 to 32‰ salinity (Poucher and Coiro 1997; Miller et al. 2002). A study by Poucher and Coiro (1997) reported 100% mortality in newly metamorphized juveniles in less than 1.50 mg/l at 23.5 to 25°C and 29 to 30‰ salinity. Adults are reported to have similarly high tolerances to low DO at the lethal level with a mean LC50 of 1.62 mg/l reported in a review by Vaquer-Sunyer and Duarte (2008).

While the lethal DO level for Summer Flounder is low, this species is sensitive to sub-lethal effects at higher DO concentrations. An active avoidance of waters below 3.0 mg/l has been observed (Bell and Eggleston 2005; Miller 2010), with increased angular correlation and swimming responses beginning at 4.2 mg/l at 20°C and salinity of 25‰ (Brady and Targett 2010). Ventilation rates increase between 4.3 and 5.0 mg/l at 22 to 30°C and 30 to 34‰ and bradycardia set in at 1.9 mg/l at 22°C and 30-34‰ (Capossela et al. 2012). Growth was found to be reduced at 5.0 mg/l at 30°C and 3.5 mg/l at 20 to 25°C (Stierhoff et al. 2006). Bailey and others (2014) similarly determined that the chronic value below which effects on survival and growth are seen was 4.52 mg/l.

The sub-lethal sensitivity of Summer Flounder to low DO warrants consideration for DO criteria as it affects the continued growth and success of the species in the Delaware Bay. Additionally, high growth rates and survival are important components for a prosperous recreational fishery in the bay. Like many other benthic species, Summer Flounder are more tolerant to low DO than their pelagic counterparts, but they occupy an important spatial niche in the bay and are included as a representative for the polyhaline, benthic fish community.

Yellow Perch (*Perca flavescens*)

Yellow Perch are a common freshwater fish species found in much of North America. Native to the Delaware River Basin, this species is recreationally important and widespread. While typically a fresh water species, adult Yellow Perch can inhabit waters with salinities up to 13‰ (Krieger et al. 1983), and they have been reported as far downstream as the C&D Canal in DRBC Zone 5 (O'Herron, Lloyd, and Laidig 1994). While adults are tolerant of brackish waters, spawning is limited to fresh water and occurs mainly between April and June (Krieger et al. 1983), but has been reported to extend into July (Scott and Crossman 1973). Adults that are found in brackish waters typically start their migration upstream into shallow freshwater areas in late-February through early-March (Mansueti 1964). Males move to spawning grounds before females and often stay longer (Scott and Crossman 1973). Eggs are semi-buoyant, usually attaching to rocks or submerged logs. Eggs are unguarded and hatch, on average, within ten days, but may take up to 27 days (Scott and Crossman 1973). Yellow Perch larvae will stay in shallow freshwater habitats as they mature (www.fws.gov). Adults and juveniles are gregarious and are typically found in shallow water areas, but become inactive at night and rest on bottom substrate (Scott and Crossman 1973). Larval stages are typically pelagic, but juveniles shift to demersal habitats with growth.

Adult Yellow Perch are sensitive to low DO with mortalities occurring between 3.1 and 5.1 mg/l at 11 to 26°C (Moore 1942; Krieger et al. 1983). The lower optimal DO limit for Yellow Perch is typically set at 5.0 mg/l (Auer 1982; Jones et al. 1988; Kreiger et al. 1983).

Data on DO sensitivity of juvenile Yellow Perch are less available and more variable than those on other stages. Juvenile sensitivity ranges from mortality criteria of 7.0 mg/l in Lake Erie (Thorpe 1977) to lowered growth and consumption at 2.0 mg/l in 20 to 26°C freshwater (Roberts et al. 2011).

Moore (1942) found that the lowest concentrations for 100% survival were 4.3 mg/l at 26°C, 4.8 mg/l at 4°C, and 5.1 mg/l at 19°C. The study did not specify life stages used, and likely both juveniles and adults were included.

The DO sensitivity of adult Yellow Perch coupled with their large range in distribution warrant this species eligible as a key oxygen sensitive species in the Delaware Estuary. More studies and data on larval and juvenile Yellow Perch would significantly improve the understanding of oxygen criteria and DO sensitivity for those stages.

Bluefish (*Pomatomus saltatrix*)

Bluefish is a migratory, marine pelagic fish common on the East Coast of North America (mafmc.org). Bluefish is also an important recreational and commercial species in the Delaware Bay. Bluefish travel the Atlantic in schools, moving south from the Mid-Atlantic Bight in the fall (Fahay et al. 1999). Adults are generally oceanic but are also found in bays and estuaries with polyhaline waters (Fahay et al. 1999) and move offshore for spawning from June through August (Juanes et al. 1996; Shepherd and Packer 2006). Eggs and larvae occur offshore within the Atlantic Ocean (Able and Fahay 1998; Juanes et al. 1996; Shepherd and Packer 2006). A bimodal distribution of size classes suggests a possibility of two spawning events, spring and summer; however, it is debated whether spawning is in fact continuous (Able and Fahay 2010; Fahay et al. 1999). Juveniles recruit into estuaries from late-May through mid-June with another recruitment typically seen in late-August (McBride and Conover 1991; Cowen et al. 1993). Juveniles are typically found in salinities ranging between 23 and 33‰ but may be found in salinities as low as 3‰ (Fahay et al. 1999). By October, juveniles leave the estuary to migrate south for overwintering (Fahay et al. 1999; Juanes et al. 1996; Shepherd and Packer 2006).

Bluefish eggs and larvae require salinities > 30-32‰ and occur in the Atlantic Ocean (Fahay et al. 1999), rendering these stages ineligible for DO criteria considerations in the Delaware Estuary. Juveniles have been reported to occur in areas of the estuary where the DO concentration is between 4.5 to 7.3 mg/l at 24.5 to 30°C (Smith 1971) and 5 to 9 mg/l (Shepherd and Packer 2006). Bluefish are 74% less abundant in areas where DO reaches 2 mg/l (Howell and Simpson 1994) and show complete avoidance in areas of extreme hypoxia (Oliver et al. 1989). The DO requirement for juveniles has been suggested at 4.5 to 7.3 mg/l (Shepherd and Packer 2006). No information was found on oxygen tolerances of adult Bluefish.

The small amount of DO data for juvenile Bluefish, presents a serious data gap in the scientific knowledge for this species. With that in mind, the reported values that are available and have been published suggest that the Delaware Estuary is an important location for nursery and juvenile habitat and that Bluefish is a species sensitive to low DO. Therefore, Bluefish has been included as a key oxygen sensitive species.

Discussion

Literature was reviewed for 36 fish and 16 invertebrate species that were deemed likely to be sensitive to low DO in the Delaware Estuary under Task Order 1 (Appendix A). This list was narrowed to a key species list of ten fish and four invertebrates under the current Task Order. These key oxygen sensitive species are: Shortnose Sturgeon (*Acipenser brevirostrum*), Atlantic Sturgeon (*Acipenser oxyrhynchus*), American Shad (*Alosa sapidissima*), Blue Crab (*Callinectes sapidus*), Atlantic Rock Crab (*Cancer irroratus*), Eastern Elliptio (*Elliptio* complanata), Scud (*Gammarus spp.*), Channel Catfish (*Ictalurus punctatus*), Largemouth Bass (*Micropterus salmoides*), White Perch (*Morone americana*), Striped Bass (*Morone saxatilis*), Summer Flounder (*Paralichthys dentatus*), Yellow Perch (*Perca flavescens*), and Bluefish (*Pomatomus saltatrix*). The DO sensitivity information for these species found in available literature was summarized and organized by stage and temporal and spatial occurrence to provide broad coverage of the Delaware Estuary.

Data gaps were often discovered during the compiling of DO requirement information. In many instances data gaps were seen for entire species, automatically removing them from the candidate species list. This was especially true for several species of amphipods, aquatic insects, copepods, Lady Crab (*Ovalipes ocellatus*), several species of herring, American Eel, sharks, Pinfish (*Lagodon rhomboides*), several species of sunfish, and many species of minnows. Additionally, data were absent for many species of Unionid mussels that are important for ecosystem health. It is possible that some of these species that occur in the Delaware Estuary may be as, or more, sensitive to low DO than the key species reviewed in this report, but little to no data exist.

Data gaps were also seen in some instances for the key sensitive species in this report for certain life stages and/or at certain temperatures. For many species, only one life stage is frequently tested in laboratory studies. Additionally, DO requirements are often found through laboratory experiments where a small range of temperatures and/or salinities is used. In natural systems, the temperatures fluctuate and often drop below tested values. Consequently, the need for additional laboratory and in situ testing exists to determine requirements of additional species, life stages, and under differing temperature and salinity regimes.

It is recognized that temperature, salinity, and other water quality variables (e.g., ammonia concentrations) interact with, and influence, DO concentrations in the estuary. Similarly, these parameters also affect species' survival, health, and tolerances and at times become cumulatively hazardous with low DO. However, the objectives of this report were to provide DO requirements for oxygen sensitive species without delving into these interactions and without concern over the feasibility of achieving found DO concentration requirements. Extrapolating between tested and untested salinities and temperatures from the literature is a difficult task, so to address this issue, DO requirements were matched to the greatest extent possible within seasons and zones which include the tested parameters. Care was given not to assume that a found DO concentration value at one temperature and/or salinity could be transferred to other regimes. Consequently, some seasons and zones are lacking data for some of the key species and/or life stages. This is especially true for the winter months (December 20 – March 20) when water temperatures drop below values tested in laboratory experiments. Despite these limitations, summarizing the data provided a suggestion of the DO requirements for the key oxygen sensitive species of the Delaware Estuary (Tables 3-6). 4 mg/l appears to be the lower limit for the less sensitive of the key species in all seasons but is not protective of most of the key species. 5 mg/l was the modal value among key species in Spring, Summer, and Fall providing protection for several key species at either the lethal or sub-lethal level at all zones, except for Zones 5 and 6 in the summer months when larval crustaceans are present and require higher than 6 mg/l for survival. 6.3 mg/l or higher is also required by Atlantic Sturgeon which may be found in any zone of the estuary at any time of the year. Additionally, 7 or 8 mg/l is optimal for high growth rates, survival, and reproduction success of some species. Thus, DO concentration values of 6-8 mg/l would be optimal for the protection of key species survival and success within the Delaware Estuary, and concentrations between 4 and 5 mg/l may provide protection for some species, but exclude the most sensitive species and life stages.

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NOTE: References listed here include all references consulted during both Task Order 1 and Task Order 5 and are not limited to those used solely to support the 14 key fish and invertebrate species. This is a comprehensive list of all literature consulted during the process of narrowing the species list to oxygen sensitive species.

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Appendix A: Tables of Candidate Species for Dissolved Oxygen Sensitivity from Task Order 1

The following tables were taken from the ANSDU 2018, Task Order 1 report: "A Methodology for Evaluating Dissolved Oxygen Requirements of Species in the Delaware Estuary". Additional information and supporting references can be found in that report at www.state.nj.us/drbc/library/documents/Methodology_Eval-Species-DO-Needs_ANStoDRBC_Mar2018.pdf

Table A1. List of invertebrate species deemed sensitive to low dissolved oxygen based upon a primary literature search, and their location within the estuary. From ANSDU 2018, Task Order 1. Note: This table has not been updated with information collected in Task Order 5.

Taxon	Species	Common Name	Sensitivity	Location
Mussel	*Elliptio complanata*	Eastern Elliptio	P	F
Clam	*Mercenaria mercenaria*	Hard Clam/Quahog	S	M
Copepod	*Acartia tonsa*	-	P	C
Copepod	*Eurytemora affinis*	-	P	C
Amphipod	*Gammarus daiberi*	Scud	S	C
Amphipod	*Corophium spp.*	-	S	C
Mysid Shrimp	*Neomysis americana*	Opossum Shrimp	P	C
Mysid Shrimp	*Mysidopsis bigelowi*	-	P	C
Shrimp	*Palaemonetes paludosus*	Grass Shrimp	P	C
Shrimp	*Crangon septemspinosa*	Sand Shrimp	S	C
Lobster	*Homerus americanus*	American lobster	S	M
Crab	*Cancer irroratus*	Atlantic Rock Crab	S	M
Crab	*Callinectes sapidus*	Blue Crab	S	M
Crab	*Ovalipes ocellatus*	Lady Crab	P	M
Crab	*Dyspanopeus sayi*	Mud Crab	S	M
Sand Dollar	*Echinarachnius parma*	Sand Dollar	P	M

Where: S = sensitive, P = likely to be sensitive, M = Marine, C = combination (oligohaline, polyhaline, mesohaline, or multiple), and F = freshwater.

Table A2. List of fish species deemed sensitive to low dissolved oxygen based upon a primary literature search, their sensitivity by life stage, and location within the estuary. From ANSDU 2018, Task Order 1. Note: This table has not been updated with information collected in Task Order 5.

Species	Common Name	General	Egg	Larvae	Juvenile	Adult
Acipenser brevirostrum	Shortnose Sturgeon	-	-	-	P, F	-
Acipenser oxyrhynchus	Atlantic Sturgeon	-	-	-	S, C	-
Anguilla rostrata	American Eel	P, C	-	-	-	-
Anchoa mitchilli	Bay Anchovy	S, C	-	-	-	-
Alosa aestivalis	Blueback Herring	P, C	-	-	-	-
Alosa mediocris	Hickory Shad	-	S, F	-	-	-
Alosa pseduoharengus	Alewife	-	S, F	S, F	S, C	S, M
Alosa sapidissima	American Shad	-	S, F	-	S, C	S, M
Brevoortia tyrannus	Atlantic Menhaden	P, M	-	-	-	-
Semotilus atromaculatus	Creek Chub	-	S, F	-	-	-
Ictalurus punctatus	Channel Catfish	S, F	-	-	-	-
Esox lucius	Northern Pike	-	-	-	S, F	-
Esox masquinongy	Muskellunge	-	P, F	P, F	-	-
Fundulus heteroclitus	Mummichog	-	S, C	-	-	-
Menidia beryllina	Inland Silverside	S, C	-	-	-	-
Pogonias cromis	Black Drum	-	-	-	S, C	-
Micropogonias undulatus	Atlantic Croaker	-	-	-	P, M	-
Cynoscion regalis	Weakfish	-	-	-	S, C	-
Leiostomus xanthurus	Spot	-	-	-	S, M	S, M
Bairdiella chrysoura	Silver Perch	S, C	-	-	-	-
Pomatomus saltatrix	Bluefish	-	-	-	S, C	-
Morone americana	White Perch	-	S, C	S, C	S, C	S, C
Morone saxatilis	Striped Bass	-	S, F	S, F	S, C	P, M
Perca flavescens	Yellow Perch	-	-	-	-	S, F
Sander vitreus	Walleye	-	S, F	-	S, F	-
Stenotomus chrysops	Scup	-	-	-	S, C	-
Lagodon rhomboides	Pinfish	S, M	-	-	-	-
Lepomis auritus	Redbreast Sunfish	P, F	-	-	-	-
Lepomis cyanellus	Green Sunfish	P, F	-	-	-	-
Lepomis macrochirus	Bluegill	-	-	-	-	S, F
Micropterus dolomieu	Smallmouth Bass	S, F	S, F	-	-	-
Micropterus salmoides	Largemouth Bass	S, F	-	-	-	-
Pomoxis annularis	White Crappie	S, F	-	-	-	-
Pomoxis nigromaculatus	Black Crappie	S, F	-	-	-	-
Pseudopleuronectes americanus	Winter Flounder	-	-	-	S, M	-
Paralichthys dentatus	Summer Flounder	-	-	-	S, M	-

Where: S = sensitive, P = likely to be sensitive, M = Marine, C = combination (oligohaline, polyhaline, mesohaline, or multiple), and F = freshwater.

Table A3. List of fish species or families deemed tolerant of low dissolved oxygen based upon a primary literature search, and their location within the estuary. From ANSDU 2018, Task Order 1. Note: This table has not been updated with information collected in Task Order 5.

Species	Common Name	Sensitivity	Location
Catostomus commersoni	White Sucker	P	F
Cyprinus carpio	Common Carp	T	F
Cyprinidae	Small minnow species	ND	F
Rhinichthys spp.	Dace	ND	F
Ameiurus spp.	Bullheads	ND	F
Gobiesox strumosus	Skilletfish	P	M
Fundulus spp.	Killifish	P	C
Lucania parva	Rainwater Killifish	P	C
Cyprinodon variegatus	Sheepshead Minnow	T	C
Gambusia affinis	Mosquitofish	T	C
Menidia menidia	Atlantic Silverside	P	C
Gasterosteus aculeatus	Threespine Stickleback	T	C
Apeltes quadracus	Fourspine Stickleback	P	C
Syngnathus fuscus	Northern Pipefish	P	C
Prionotus carolinus	Northern Sea Robin	P	C
Gobiosoma bosc	Naked Goby	P	C
Chasmodes bosquianus	Striped Blenny	P	M
Tautoga onitis	Tautog	T	M
Trinectes maculatus	Hogchoker	P	M

Where T = tolerant, P = likely to be tolerant, ND = no data was found, M = marine, C = combination (oligohaline, polyhaline, mesohaline, or multiple), and F = freshwater.

Table A4. List of non-fish species deemed tolerant of low oxygen based upon a primary literature search, and their location within the estuary. From ANSDU 2018, Task Order 1. Note: This table has not been updated with information collected in Task Order 5.

Taxon	Species	Common Name	Sensitivity	Location
Plant	*Zostera marina*	Seawrack	T	M
Coral	*Astrangia poculata*	Northern Coral	P	M
Snail	*Ilyanassa obsoleta*	Eastern Mudsnail	P	C
Whelk	*Busycotypus canaliculatum*	Channeled Whelk	P	M
Whelk	*Busycotypus carica*	Knobbed Whelk	P	M
Mussel	*Mytilus edulis*	Blue Mussel	T	C
Oytser	*Cassostrea virginica*	American oyster	T	M
Clam	*Nucula proxima*	Nut Clam	P	M
Clam	*Gemma gemma*	Amethyst Gem Clam	P	M
Clam	*Spisula solidissima*	Atlantic Surfclam	T	M
Clam	*Tellina agilis*	Northern Dwarf Tellin	P	M
Clam	*Ensis directus*	Atlantic Jackknife Clam	P	M
Clam	*Mya arenaria*	Soft Shell Clam	T	C
Clam	*Mulina lateralis*	Dwarf Surf Clam	P	M
Polychaete	*Glycera dibranchiata*	Bloodworms	P	M
Polychaete	*Heteromastus filiformis*	-	T	C
Polychaete	*Sabellaria spp.*	-	T	M
Polychaete	*Hydroides spp.*	-	P	M
Oligochaete	*Limnodrilus spp.*	-	P	M
Horsehoe Crab	*Limulus polyphemus*	Horseshoe Crab	T	M
Water Flea	*Daphnia spp.*	Water Flea	P	C
Copepod	*Halicyclops fosteri*	-	P	M
Copepod	*Acartia hudsonica*	-	P	M
Copepod	*Pseudodiaptomus pelagicus*	-	P	M
Barnacles	*Balanus spp.*	-	T	M
Crayfish	*Orconectes limosus*	Spinycheek Crayfish	P	F
Crayfish	*Cambarus bartonii*	Appalachian Brook Crayfish	P	F
Hermit Crab	*Pagurus spp.*	Hermit Crab	P	M
Sea Squirt	*Molgula spp.*	-	T	M
Chironomid	*Prodadius culiciformis*	-	P	F
Chironomid	*Polypedilum spp.*	-	P	F
Chironomid	*Cryptochironomus spp.*	-	P	F
Chironomid	*Cladotanytarso spp.*	-	P	F

Where: T = tolerant, P = likely to be tolerant, M = marine,C = combination (oligohaline, polyhaline, mesohaline, or multiple), and F = freshwater.

Appendix B: List of Toxicological Results for Species Found Within the Delaware Estuary

During the process of data collection and key oxygen sensitive species determination for the Delaware Estuary, toxicological laboratory experiments were often found listing results in terms of lethal doses (i.e., LC50s, LC90s, etc.). While this information was included in this report as appropriate, some data exist for species not included (mainly because these species were determined to be less sensitive than the 14 fish and invertebrates chosen). However, it is recognized that other methods of determining oxygen requirements exist that include calculations using LC50 endpoints. For this reason, the found data is reported here as a summary should a potential use arise in the future.

Species	Common Name	Stage	DO (mg/l)	Temperature (°C)	Salinity (‰)	Description	Reference
Acipenser brevirostrum	Shortnose Sturgeon	-	2.3	-	-	LC50	Bailey et al 2014
Alosa sapidissima	American Shad	Egg/Larval	2.5-2.9	-	-	LD50	Stier et al. 1985
Anchoa mitchilli	Bay Anchovy	Egg	2.7	-	-	Mean LC50	Vaquer-Sunyer and Duarte 2008
Anchoa mitchilli	Bay Anchovy	Adult	1.6-2.5	-	-	Mean LC50	Vaquer-Sunyer and Duarte 2008
Bairdiella chrysoura	Silver Perch	Juvenile	0.5	28	30	LC90	Hanke and Smith 2011
Bairdiella chrysoura	Silver Perch	Juvenile	1.1	28	30	LC50	Hanke and Smith 2011
Bairdiella chrysoura	Silver Perch	Juvenile	2.4	28	30	LC10	Hanke and Smith 2011
Brevoortia tyrannus	Atlantic Menhaden	-	0.9	25	-	LC50	Shimps et al 2005
Brevoortia tyrannus	Atlantic Menhaden	Juvenile	1.0	19	28-32	LC90	Miller et al 2002
Brevoortia tyrannus	Atlantic Menhaden	-	1.0	30	-	12 hr LC50	Shimps et al 2005
Brevoortia tyrannus	Atlantic Menhaden	-	1.0	28	6.9	96 hr LC50	Burton et al 1980
Brevoortia tyrannus	Atlantic Menhaden	Juvenile	1.1	18-20	29-31	24 hr IC50	Poucher and Coiro 1997
Brevoortia tyrannus	Atlantic Menhaden	Juvenile	1.2	19	28-32	LC50	Miller et al 2002
Brevoortia tyrannus	Atlantic Menhaden	Juvenile	1.2	18-20	29-31	72 hr LC50	Poucher and Coiro 1997
Brevoortia tyrannus	Atlantic Menhaden	-	1.6	28	6.9	96 hr LC50	Burton et al 1980
Brevoortia tyrannus	Atlantic Menhaden	Juvenile	1.7	19	28-32	LC10	Miller et al 2002
Fundulus heteroclitus	Mummichog	Adult	0.2	24.5	-	LD50	Nordlie 2006
Ictalurus punctatus	Channel Catfish	Juvenile/Adult	0.9	18	-	LC50	Scott and Rogers 1980
Leiostomus xanthurus	Spot	-	0.7	28	6.9	96 hr LC50	Burton et al 1980
Leiostomus xanthurus	Spot	-	0.8	28	6.9	96 hr LC5	Burton et al 1980
Leiostomus xanthurus	Spot	-	1.1	30	-	12 hr LC50	Shimps et al 2005
Menidia beryllina	Inland Silverside	Egg	2.4	24	29-32	8 day LC50	Poucher and Coiro 1997
Menidia beryllina	Inland Silverside	Egg	3.6	24-25	30-32	LC25	Poucher and Coiro 1997
Menidia beryllina	Inland Silverside	Larval	1.3	28	29-31	24 hr IC50	Poucher and Coiro 1997
Menidia beryllina	Inland Silverside	Larval	1.3	20-28	28-32	LC90	Miller et al 2002
Menidia beryllina	Inland Silverside	Larval	1.4	20-28	28-32	LC50	Miller et al 2002

Species	Common Name	Stage	DO (mg/l)	Temperature (°C)	Salinity (‰)	Description	Reference
Menidia beryllina	Inland Silverside	Larval	1.4	25	30-31	24 hr IC50	Poucher and Coiro 1997
Menidia beryllina	Inland Silverside	Larval	1.4	25	30-31	96 hr IC50	Poucher and Coiro 1997
Menidia beryllina	Inland Silverside	Larval	1.7	20-28	28-32	LC10	Miller et al 2002
Menidia beryllina	Inland Silverside	Adult	1.2-1.4	-	-	Mean LC50	Vaquer-Sunyer and Duarte 2008
Morone americana	White Perch	Juvenile	0.5-1.0	-	-	19 hr LC40	Dorfman and Westman 1970
Morone saxatilis	Striped Bass	Larval	2.34	18-19	4-5	96 hr LC50	Poucher and Coiro 1997
Morone saxatilis	Striped Bass	Juvenile	1.5	20-21	30	24 hr LC50	Poucher and Coiro 1997
Morone saxatilis	Striped Bass	Juvenile	1.53	20-21	30	96 hr LC50	Poucher and Coiro 1997
Morone saxatilis	Striped Bass	Juvenile	1.62	18-19	32	24 hr LC50	Poucher and Coiro 1997
Morone saxatilis	Striped Bass	Juvenile	1.63	18-19	32	96 hr LC50	Poucher and Coiro 1997
Morone saxatilis	Striped Bass	Juvenile	3.2	18-19	4-7	24 hr LC50	Poucher and Coiro 1997
Morone saxatilis	Striped Bass	Juvenile	3.5	18-19	4-7	96 hr LC50	Poucher and Coiro 1997
Paralichthys dentatus	Summer Flounder	juvenile	0.9	20	28-32	LC10	Miller et al 2002
Paralichthys dentatus	Summer Flounder	juvenile	1.1	20	28-32	LC50	Miller et al 2002
Paralichthys dentatus	Summer Flounder	new metamorph	1.1	20.5	31-32	24 hr LC50	Poucher and Coiro 1997
Paralichthys dentatus	Summer Flounder	new metamorph	1.1	20.5	31-32	96 hr LC50	Poucher and Coiro 1997
Paralichthys dentatus	Summer Flounder	juvenile	1.3	20	28-32	LC90	Miller et al 2002
Paralichthys dentatus	Summer Flounder	na	1.35	-	-	LC50	Bailey et al 2014
Paralichthys dentatus	Summer Flounder	juvenile	1.4	24	28-32	LC10	Miller et al 2002
Paralichthys dentatus	Summer Flounder	new metamorph	1.59	23.5-25	29-30	24 hr IC50	Poucher and Coiro 1997
Paralichthys dentatus	Summer Flounder	juvenile	1.6	24	28-32	LC50	Miller et al 2002
Paralichthys dentatus	Summer Flounder	juvenile	1.8	24	28-32	LC90	Miller et al 2002
Pseudopleuronectes americanus	Winter Flouder	new metamorph	1.3	19-20	29-30	24 hr IC 50	Poucher and Coiro 1997
Pseudopleuronectes americanus	Winter Flouder	new metamorph	1.3	19-20	29-30	96 hr IC50	Poucher and Coiro 1997
Pseudopleuronectes americanus	Winter Flouder	-	1.4	-	-	LC50	Bailey et al 2014
Pseudopleuronectes americanus	Winter Flouder	juvenile	1.4	19.7-20.5	31-32	24 hr IC50	Poucher and Coiro 1997
Pseudopleuronectes americanus	Winter Flouder	juvenile	1.5	19.7-20.5	31-32	96 hr IC50	Poucher and Coiro 1997
Stenotomus chrysops	Scup	juvenile	1.3	19.8-20.5	30-31	24 hr IC50	Poucher and Coiro 1997
Gammarus psuedolimnaeus	Scud	Female Adult	1.4	10	"fresh"	LC50, 24 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Female Adult	1.6	15	"fresh"	LC50, 24 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Female Adult	2.7	20	"fresh"	LC50, 24 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Female Adult	1.7	10	"fresh"	LC50, 48 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Female Adult	2.0	15	"fresh"	LC50, 48 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Female Adult	3.2	20	"fresh"	LC50, 48 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Female Adult	1.8	10	"fresh"	LC50, 72 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Female Adult	1.9	15	"fresh"	LC50, 72 hours	Hoback & Barnhart 1996

Species	Common Name	Stage	DO (mg/l)	Temperature (°C)	Salinity (‰)	Description	Reference
Gammarus psuedolimnaeus	Scud	Female Adult	3.3	20	"fresh"	LC50, 72 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Juvenile	0.4	10	"fresh"	LC50, 24 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Juvenile	0.9	15	"fresh"	LC50, 24 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Juvenile	1.3	20	"fresh"	LC50, 24 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Juvenile	0.8	10	"fresh"	LC50, 48 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Juvenile	1.1	15	"fresh"	LC50, 48 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Juvenile	1.8	20	"fresh"	LC50, 48 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Juvenile	0.9	10	"fresh"	LC50, 72 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Juvenile	1.2	15	"fresh"	LC50, 72 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Juvenile	1.9	20	"fresh"	LC50, 72 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Male Adult	0.9	10	"fresh"	LC50, 24 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Male Adult	1.1	15	"fresh"	LC50, 24 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Male Adult	2.1	20	"fresh"	LC50, 24 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Male Adult	1.2	10	"fresh"	LC50, 48 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Male Adult	1.3	15	"fresh"	LC50, 48 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Male Adult	2.8	20	"fresh"	LC50, 48 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Male Adult	1.5	10	"fresh"	LC50, 72 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Male Adult	1.3	15	"fresh"	LC50, 72 hours	Hoback & Barnhart 1996
Gammarus psuedolimnaeus	Scud	Male Adult	3.2	20	"fresh"	LC50, 72 hours	Hoback & Barnhart 1996
Callinectes sapidus	Blue Crab	na	4.1	20	10	LC50. (74Torr)	Stickle et al 1989
Callinectes sapidus	Blue Crab	na	6.4	20	20	LC50, (124 Torr)	Stickle et al 1989
Callinectes sapidus	Blue Crab	na	6.0	20	30	LC50. (133 Torr)	Stickle et al 1989
Callinectes sapidus	Blue Crab	na	5.6	30	10	LC50, (121 Torr)	Stickle et al 1989
Callinectes sapidus	Blue Crab	na	5.2	30	20	LC50, (119 Torr)	Stickle et al 1989
Callinectes sapidus	Blue Crab	na	4.6	30	30	LC50, (111 Torr)	Stickle et al 1989
Cancer irroratus	Atlantic Rock Crab	Larvae	2.1 +/- 0.9	20		LC90	Miller, Poucher, & Coiro 2002
Cancer irroratus	Atlantic Rock Crab	Larvae	2.6 +/- 0.4	20		LC50	Miller, Poucher, & Coiro 2002
Cancer irroratus	Atlantic Rock Crab	Larvae	3.8 +/- 2.7	20		LC10	Miller, Poucher, & Coiro 2002
Cancer irroratus	Atlantic Rock Crab	Megalops	1.3-1.8	10-20	30	LC50, 120 mins,	Vargo & Sastry 1977
Cancer irroratus	Atlantic Rock Crab	Megalops	2.7	25	30	LC50 120 mins,	Vargo & Sastry 1977
Cancer irroratus	Atlantic Rock Crab	Megalops	4.7	30	30	LC50 120 mins,	Vargo & Sastry 1977
Cancer irroratus	Atlantic Rock Crab	Megalops	1.58-2.2	10-20	30	LC50, 240 mins,	Vargo & Sastry 1977
Cancer irroratus	Atlantic Rock Crab	Megalops	3.4	25	30	LC50, 240 mins,	Vargo & Sastry 1977
Cancer irroratus	Atlantic Rock Crab	Megalops	4.7	30	30	LC50, 240 mins,	Vargo & Sastry 1977
Cancer irroratus	Atlantic Rock Crab	Stage 1-5	2.1	10-20	30	LC50, 120 mins,	Vargo & Sastry 1977

Species	Common Name	Stage	DO (mg/l)	Temperature (°C)	Salinity (‰)	Description	Reference
Cancer irroratus	Atlantic Rock Crab	Stage 1-5	0.57-1.3	10	30	LC50, 240 mins,	Vargo & Sastry 1977
Cancer irroratus	Atlantic Rock Crab	Stage 1-5	0.45-1.19	15	30	LC50, 240 mins,	Vargo & Sastry 1977
Cancer irroratus	Atlantic Rock Crab	Stage 1-5	1.07-2.29	20	30	LC50, 240 mins,	Vargo & Sastry 1977
Cancer irroratus	Atlantic Rock Crab	Stage 1-5	2.09-3.80	25	30	LC50, 240 mins,	Vargo & Sastry 1977
Cancer irroratus	Atlantic Rock Crab	Stage 1-5	4.2-6.05	30	30	LC50, 240 mins,	Vargo & Sastry 1977
Cancer irroratus	Atlantic Rock Crab	Stages 1-5	4.2-6.05	30	30	LC50. 120 mins,	Vargo & Sastry 1977
Cancer irroratus	Atlantic Rock Crab	To Post-Larvae	3.0 +/- 0.6	20	28-32 g/kg	Lc50	Miller, Poucher, & Coiro 2002
Dyspanopeus sayi	Mud Crab	Adult	5+	20-26	16-23	LT50 in 1.0 mg/l	Sagasti, Schaffner, Duffy 2001
Dyspanopeus sayi	Mud Crab	Adult	1.3	20-26	16-23	LT50 in 0.5mg/L	Sagasti, Schaffner, Duffy 2001
Dyspanopeus sayi	Mud Crab	Larvae	1.4 +/- 0.2	20-26	28-32 g/kg	LC90	Miller, Poucher, & Coiro 2002
Dyspanopeus sayi	Mud Crab	Larvae	1.9 +/- 0.7	20-26	28-32 g/kg	LC50	Miller, Poucher, & Coiro 2002
Dyspanopeus sayi	Mud Crab	Larvae	3.4 +/- 2.6	20-26	28-32 g/kg	LC10	Miller, Poucher, & Coiro 2002
Dyspanopeus sayi	Mud Crab	To Post-Larvae	2.4 +/- 1.4	25	28-32 g/kg	LC90	Miller, Poucher, & Coiro 2002
Dyspanopeus sayi	Mud Crab	To Post-Larvae	3.7 +/- 1.0	25	28-32 g/kg	LC50	Miller, Poucher, & Coiro 2002
Dyspanopeus sayi	Mud Crab	To Post-Larvae	1.7 +/- 2.4	25	28-32 g/kg	LC10	Miller, Poucher, & Coiro 2002
Dyspanopeus sayi	Mud Crab	To Post-Larvae	1.7 +/- 2.4	20	28-32 g/kg	LC90	Miller, Poucher, & Coiro 2002
Dyspanopeus sayi	Mud Crab	To Post-Larvae	2.5 +/- 0.8	20	28-32 g/kg	LC50	Miller, Poucher, & Coiro 2002
Dyspanopeus sayi	Mud Crab	To Post-Larvae	3.0 +/- 0.4	20	28-32 g/kg	LC10	Miller, Poucher, & Coiro 2002
Homerus americanus	American Lobster	Juvenile	0.8 +/- 0.1	20	28-32 g/kg	LC90	Miller, Poucher, & Coiro 2002
Homerus americanus	American Lobster	Juvenile	1.0 +/- 0.1	20	28-32 g/kg	LC50	Miller, Poucher, & Coiro 2002
Homerus americanus	American Lobster	Juvenile	1.4 +/- 0.5	20	28-32 g/kg	LC10	Miller, Poucher, & Coiro 2002
Homerus americanus	American Lobster	Larvae	2.2 +/- 1.0	18-20	28-32 g/kg	LC90	Miller, Poucher, & Coiro 2002
Homerus americanus	American Lobster	Larvae	3.1 +/- 2.1	18-20	28-32 g/kg	LC50	Miller, Poucher, & Coiro 2002
Homerus americanus	American Lobster	Larvae	4.1 +/- 3.2	18-20	28-32 g/kg	LC10	Miller, Poucher, & Coiro 2002
Homerus americanus	American Lobster	Post Larvae	1.2 +/- 0.1	19	28-32 g/kg	LC90	Miller, Poucher, & Coiro 2002
Homerus americanus	American Lobster	Post Larvae	1.4 +/- 0.3	19	28-32 g/kg	LC50	Miller, Poucher, & Coiro 2002
Homerus americanus	American Lobster	Post Larvae	1.8 +/- 0.3	19	28-32 g/kg	LC10	Miller, Poucher, & Coiro 2002
Homerus americanus	American Lobster	To Post-Larvae	1.2 +/- 0.1	19-20	28-32 g/kg	LC90	Miller, Poucher, & Coiro 2002
Homerus americanus	American Lobster	To Post-Larvae	2.8 +/- 1.4	19-20	28-32 g/kg	LC50	Miller, Poucher, & Coiro 2002
Homerus americanus	American Lobster	To Post-Larvae	3.4 +/- 9.0	19-20	28-32 g/kg	LC10	Miller, Poucher, & Coiro 2002
Americamysis bahia	Mysid Shrimp	Juvenile	1.0 +/- 0.2	26	28-32 g/kg	LC90	Miller, Poucher, & Coiro 2002
Americamysis bahia	Mysid Shrimp	Juvenile	1.2 +/- 0.2	26	28-32 g/kg	LC 50	Miller, Poucher, & Coiro 2002
Americamysis bahia	Mysid Shrimp	Juvenile	1.9 +/- 1.9	26	28-32 g/kg	LC10	Miller, Poucher, & Coiro 2002
Americamysis bahia	na	Juvenile	1.27			mean actue value, LC50	USEPA 2000
Americamysis bahia	na	Juvenile	1.5			mean acute value, LC5	USEPA 2000

Species	Common Name	Stage	DO (mg/l)	Temperature (°C)	Salinity (‰)	Description	Reference
Cragon septemspinosa	Sand Shrimp	All	1.0			mean acute value LC50	USEPA 2000
Cragon septemspinosa	Sand Shrimp	All	1.6			mean acute value LC5	USEPA 2000
Cragon septemspinosa	Sand Shrimp	Juvenile	1.0 +/- 0.3	20	28-32 g/kg	LC50	Miller, Poucher, & Coiro 2002
Cragon septemspinosa	Sand Shrimp	Juvenile	1.4 +/- 0.6	20	28-32 g/kg	LC10	Miller, Poucher, & Coiro 2002
Palaemonetes pugio	Daggerblade Grass Shrimp	Juvenile	0.6 +/- 0.1	20	28-32 g/kg	LC90	Miller, Poucher, & Coiro 2002
Palaemonetes pugio	Daggerblade Grass Shrimp	Juvenile	0.7 +/- 0.1	20	28-32 g/kg	LC 50	Miller, Poucher, & Coiro 2002
Palaemonetes pugio	Daggerblade Grass Shrimp	Juvenile	0.9 +/- 0.1	20	28-32 g/kg	LC10	Miller, Poucher, & Coiro 2002
Palaemonetes pugio	Daggerblade Grass Shrimp	Juvenile	0.7			mean acute value LC50	USEPA 2000
Palaemonetes pugio	Daggerblade Grass Shrimp	Juvenile	1.1			mean acute value LC5	USEPA 2000
Palaemonetes pugio	Daggerblade Grass Shrimp	Larvae	1.1 +/- 1.7	25	28-32 g/kg	LC90	Miller, Poucher, & Coiro 2002
Palaemonetes pugio	Daggerblade Grass Shrimp	Larvae	1.7 +/- 1.6	25	28-32 g/kg	LC 50	Miller, Poucher, & Coiro 2002
Palaemonetes pugio	Daggerblade Grass Shrimp	Larvae	2.2 +/- 2.8	25	28-32 g/kg	LC10	Miller, Poucher, & Coiro 2002
Palaemonetes pugio	Daggerblade Grass Shrimp	na	2.1	30	10	28 day LC50, (46T0rr)	Stickle et al 1989
Palaemonetes vulgaris	Marsh Grass Shrimp	Juvenile	1.0			mean acute value LC50	USEPA 2000
Palaemonetes vulgaris	Marsh Grass Shrimp	Juvenile	1.4			mean acute value LC5	USEPA 2000
Palaemonetest vulgaris	Marsh Grass Shrimp	Juvenile	0.7 +/- 0.1	24	28-32 g/kg	LC90	Miller, Poucher, & Coiro 2002
Palaemonetest vulgaris	Marsh Grass Shrimp	Juvenile	1.0 +/- 0.0	24	28-32 g/kg	LC 50	Miller, Poucher, & Coiro 2002
Palaemonetest vulgaris	Marsh Grass Shrimp	Juvenile	1.4 +/- 0.3	24	28-32 g/kg	LC10	Miller, Poucher, & Coiro 2002
Palaemonetest vulgaris	Marsh Grass Shrimp	Larvae	1.6 +/- 0.4	21-30	28-32 g/kg	LC90	Miller, Poucher, & Coiro 2002
Palaemonetest vulgaris	Marsh Grass Shrimp	Larvae	2.1 +/- 0.4	21-30	28-32 g/kg	LC 50	Miller, Poucher, & Coiro 2002
Palaemonetest vulgaris	Marsh Grass Shrimp	Larvae	2.7 +/- 1.3	21-30	28-32 g/kg	LC10	Miller, Poucher, & Coiro 2002
Palaemonetest vulgaris	Marsh Grass Shrimp	Post Larvae	0.6 +/- 0.1	18	28-32 g/kg	LC90	Miller, Poucher, & Coiro 2002
Palaemonetest vulgaris	Marsh Grass Shrimp	Post Larvae	1.0 +/- 0.1	18	28-32 g/kg	LC 50	Miller, Poucher, & Coiro 2002
Palaemonetest vulgaris	Marsh Grass Shrimp	Post Larvae	1.4 +/- 0.2	18	28-32 g/kg	LC10	Miller, Poucher, & Coiro 2002