Task Orders 1 and 5 : Dissolved Oxygen Concentration Requirements of Key Oxygen Sensitive Species in the Delaware Estuary

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Background

Mid-1900’s (and earlier?):
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

1961:
Delaware Estuary Comprehensive Study under Federal Water Pollution Control Act “provide a blueprint for the enhancement of the waters of the Delaware”

1967:
Establishment of DO criteria for the Delaware Estuary

1972:
Under the Clean Water Act (and subsequent amendments), water quality criteria are tied to attaining designated uses. Designated uses of the Delaware Estuary were originally established for migration.

Currently:
DO standards have not been updated. The maintenance of aquatic life has since been included as an appropriate designated use of the estuary. Subsequently, the DRBC has been interested in updating the scientific knowledge for key sensitive species’ criteria that support the DO standards.

Definitions

Standard: “a plan that is established by governmental authority as a program for water pollution prevention and abatement” (Federal Water Pollution Control Administration) – *DRBC to decide*

Criteria: “a scientific requirement on which a decision or judgement may be based concerning the suitability of water quality to support a designated use” (Federal Water Pollution Control Administration) – *ANSDU to provide*

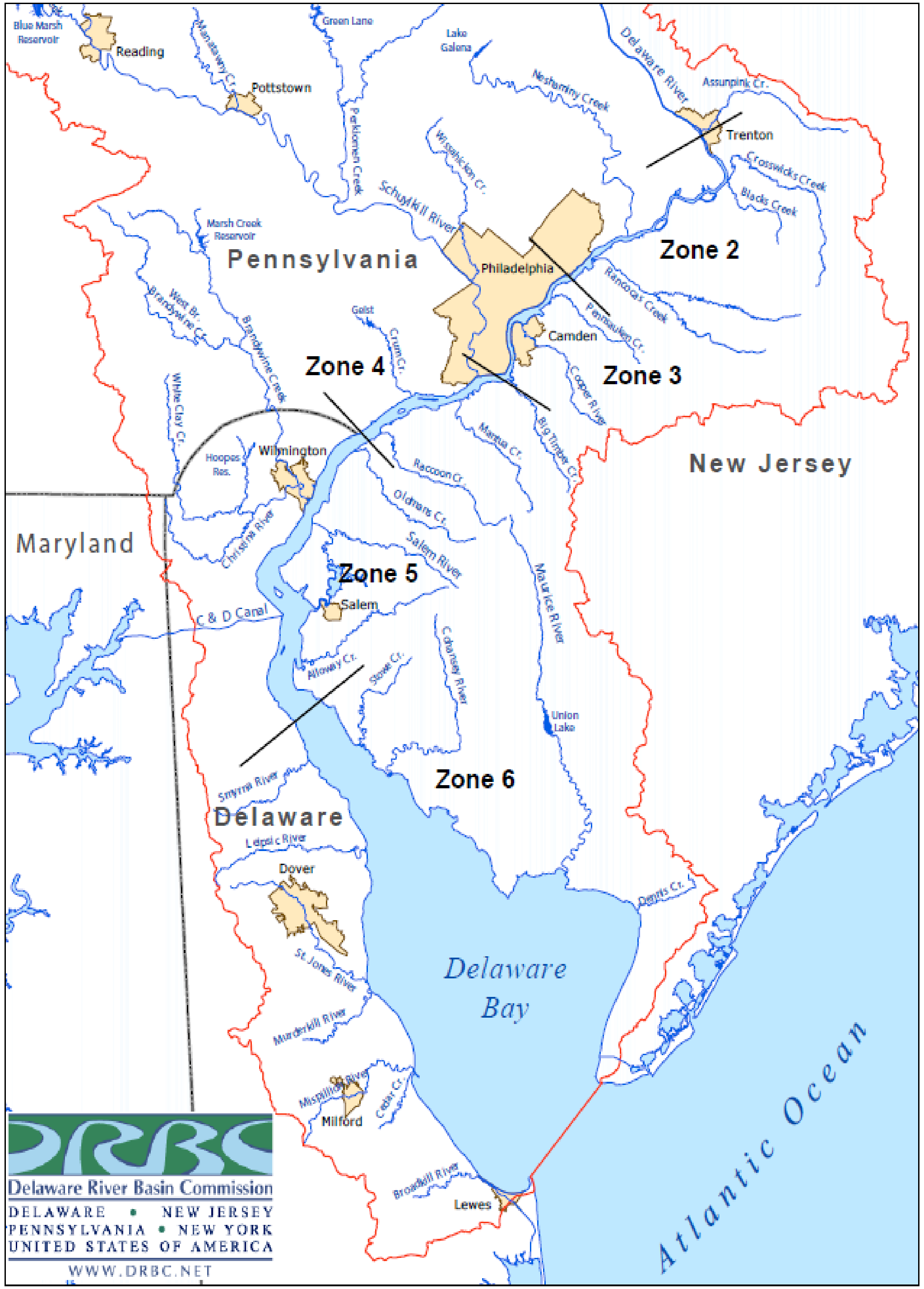
Sensitive (to low DO): refers to a species that exhibits deleterious effects, either lethal or sublethal when exposed to concentrations of DO that are equal to or greater than the current criteria

Lethal: resulting in direct mortality (LC50s, observed mortality, first onset of mortality)

Sublethal: indirect mortality or other deleterious effects (e.g., reduced growth, lowered reproduction, increased respiration rates, etc.). Note that “failure to spawn” is treated in this report as a sublethal effect; however, this has demographic consequences analogous to egg or larval mortality and may therefore be implicit of lethal effects.

Key: representative species of an area spatially and temporally with oxygen demands that are greater than or equal to those of other species found within the same locality. Protection of key sensitive species encompasses the protection of those which are more tolerant to lower DO concentrations

Current Standards and Zones



24-hour average concentration of 3.5 mg/l and a seasonal average of 6.5 mg/l from the periods of April 1 to June 15 and September 16 to December 31 in Zones 2-5, and a 24-hour average of 6.0 mg/l in Zone 6. No seasonal averages were set for June 15 to September 16

Zones 2, 3, and 4 are classified as fresh water to oligohaline (salinity of 0.5 to 5.0‰).

Zone 5 is transitional oligohaline to mesohaline in the upper portion and is classified as mesohaline (5.0 to 18.0‰).

Zone 6 contains a transitional mesohaline to polyhaline zone in the upper portion and is classified as polyhaline (18.0 to 30.0‰) in the middle and lower portions.

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Task Order 1

Objective:

Propose **methodology** for evaluating dissolved oxygen (DO) requirements of multiple sensitive Delaware Estuary (Trenton to mouth) species at several life stages.

Expected Tasks:

- Identify key Delaware Estuary species, their relevant life stages, and their spatial distribution.
- Determine if any species are currently absent from the Delaware Estuary due to DO limitation.
- Review secondary (md. geochemical) pathways of oxygen sensitivity.
- Identify potential experts to participate in execution of proposed methodology.
- **Outline proposed methodology**, including key species list, in a report and presentation to DRBC.
- Revise proposed methodology, based on reviewer and DRBC comments.

Task Orders 1 and 5: Proposed Methodology

T.O. 1

1. Identify common or characteristic aquatic species in the Delaware Estuary (Trenton to mouth).
2. Determine list of candidate key species that are suspected to be sensitive to low dissolved oxygen.
3. Determine where data gaps exist and identify sources and experts to fill in missing knowledge.
4. Review secondary pathways of oxygen sensitivity.
5. Compile literature data on dissolved oxygen requirements for candidate key sensitive species.
6. Narrow candidate species list to key sensitive species.
7. Determine the seasonal occurrence of key sensitive species’ life stages in the Delaware Estuary.
8. Determine the spatial distribution of key sensitive species’ life stages in the Delaware Estuary.
9. Compile dissolved oxygen concentration thresholds and/or associated endpoints for the key sensitive species and life stages.
10. Do additional targeted literature searches and conduct internal and external review to identify additional sources of information on species sensitivity and spatial and temporal patterns if data gaps still exist.
11. Develop a table (or tables) of dissolved oxygen requirements, such that the aggregate spatial and temporal dissolved oxygen need may be defined in support of development of new dissolved oxygen criteria for the Delaware Estuary.

T.O. 5

Approach

- Task Order 1
  - Lower sensitivity threshold (2 mg/l)
  - Identify large number of taxa for further study
  - Eliminate large number of taxa as tolerant

- Task Order 5
  - Restricted to a few species
  - Higher sensitivity threshold
  - Selection of key species

- Note: final list does not include every species which may benefit from increased DO concentrations

Task Order 1: Species Literature Searches

- Keywords: “dissolved oxygen”, “threshold”, “criteria”, “anoxia”, “hypoxia”, “Delaware Estuary”, and/or the species/genus/family names.
- Species groupings
    - **Sensitive**: 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 sublethal DO requirements (typically >3.5 mg/l).
    - **Tolerant**: 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 sublethal oxygen requirement.
    - **Likely to be either of the two:**
        - data are not readily available
        - data exist for other species in the same genus or family therefore likely to apply to that species
        - Some information was found but more is needed
    - 36 species of fish and 16 invertebrate species were identified as sensitive or likely to be sensitive and advanced to the next steps in the methodology.

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Task Order 1: Candidate Key Species

Lists of invertebrate and fish 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.

36 Fish & 16 Invertebrate Species

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.

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Task Order 1: Species Determined to be tolerant

Lists of invertebrate and 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.

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19 Fish & 34 Invertebrate Species

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.

Comments on Draft Report of Task Order 1

- Suggestion of some additional taxa for consideration as sensitive
  - Unionid mussels
  - Odonates

- Questions about
  - Adequacy of search
  - Adequacy of data
  - Use of conflicting data or data differing greatly in quality
  - Consideration of species not currently occurring in estuary
  - Also questions about eventual use of criteria to form standards

Task Order 5: Narrowing Key Oxygen Sensitive Species

- DO sensitivity
  - All data for candidate species were compiled identify candidate species had values equal to or exceeding the current DO standards
  - DO criteria divided into lethal and sublethal effect categories
- Species occurrence: spatial and temporal occurrence in the estuary
  - Spatial designations based on DRBC water quality zones of the Delaware Estuary
  - Standard astronomical seasons used (i.e., based on solstices and equinoxes)
    - 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).
- Selection of key species; where several sensitive species overlapped in time and space, selection based on the
  - Least tolerant species
  - Adequate data
- 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.

A Few Comments

- We **did not exclude** non-native species as key species
  - Well-established
  - Part of ecosystem
  - Often important for recreation and/or commercial use

- **Did not exclude** fresh water species
  - Widespread in Zone 2
  - Many occur in oligohaline water as well

- **Did not include** species mainly occurring locally at boundary of estuary, e.g., at falls of Trenton or near Art Museum Dam
  - E.g., Smallmouth Bass, Walleye

- **Included** Non-lethal effects
  - Legal decision whether these relevant to “maintenance”

Key Species: One or More Life Stage of:

- Lethal and Non-lethal
  - Shortnose Sturgeon: all zones
  - Atlantic Sturgeon: all zones
  - American Shad: all zones
  - Blue Crab: Zones 4-6
  - Rock Crab: Zone 6
  - *Gammarus fasciatus*: all zones
  - Striped Bass: all zones
  - Bluefish: Zone 6

- Non-Lethal Only
  - Yellow Perch: Zones 2-5
  - Channel Catfish: Zones 2-5
  - Largemouth Bass: Zone 2-3
  - White Perch: all zones
  - Summer Flounder: Zone 6

Zones where sensitive stage occurs

Sensitive stages of key oxygen sensitive species occurrence in the Delaware Estuary by stage and season

		Zone 2				**Zone 3**				**Zone 4**				**Zone 5**				**Zone 6**			
Species	**Stage**	**Winter**	**Spring**	**Summer**	**Fall**	**Winter**	**Spring**	**Summer**	**Fall**	**Winter**	**Spring**	**Summer**	**Fall**	**Winter**	**Spring**	**Summer**	**Fall**	**Winter**	**Spring**	**Summer**	**Fall**
Acipenser brevirostrum	Juvenile	-	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	-	-	-	-
Acipenser oxyrhynchus	Larval	-	S	-	S	-	S	-	S	-	S	-	S	-	S	-	S	-	-	-	-
Acipenser oxyrhynchus	Juvenile	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS
Alosa sapidissima	Egg	-	LS	-	-	-	LS	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Alosa sapidissima	Larval	-	LS	LS	-	-	LS	LS	-	-	LS	LS	-	-	-	-	-	-	-	-	-
Alosa sapidissima	Juvenile	-	-	LS	-	-	-	LS	-	-	-	LS	-	-	-	LS	LS	LS	LS	LS	LS
Alosa sapidissima	Adult	-	S	-	-	-	S	-	-	-	S	-	-	-	S	S	-	-	S	S	-
Callinectes sapidus	Larval	-	-	-	-	-	-	-	-	-	-	-	-	-	-	L	-	-	-	L	-
Callinectes sapidus	Megalops	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	L	-	-	-	L
Callinectes sapidus	Juvenile	-	-	-	-	-	-	-	-	L	-	-	L	L	-	-	L	L	-	-	L
Cancer irroratus	Larval	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	L	L	-
Gammarus fasciatus	Adult	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	RL	RL	RL	RL
Ictalurus punctatus	Egg	-	S	S	-	-	S	S	-	-	S	S	-	-	-	-	-	-	-	-	-
Ictalurus punctatus	Larval	-	S	S	-	-	S	S	-	-	S	S	-	-	-	-	-	-	-	-	-
Ictalurus punctatus	Juvenile	S	S	S	S	S	S	S	S	S	S	S	S	-	-	-	-	-	-	-	-
Ictalurus punctatus	Adult	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	-	-	-	-
Micropterus salmoides	Juvenile	S	S	S	S	S	S	S	S	-	-	-	-	-	-	-	-	-	-	-	-
Morone americana	Juvenile	-	S	S	S	-	S	S	S	-	S	S	S	-	S	S	S	-	S	S	S
Morone americana	Adult	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Morone saxatilis	Egg	-	L	L	-	-	L	L	-	-	-	-	-	-	-	-	-	-	-	-	-
Morone saxatilis	Larval	-	L	L	-	-	L	L	-	-	RL	RL	-	-	RL	RL	-	-	-	-	-
Morone saxatilis	Juvenile	-	-	LS	LS	-	-	LS	LS	-	-	LS	LS	-	-	LS	LS	-	-	LS	LS
Morone saxatilis	Adult	-	S	S	-	-	S	S	-	-	S	S	-	-	S	S	-	S	S	S	S
Paralichthys dentatus	Larval	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	S	S	-	S
Paralichthys dentatus	Juvenile	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	S	S	S	S
Paralichthys dentatus	Adult	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	S	S	S	S
Perca flavescens	Juvenile	LS	LS	LS	LS	LS	LS	LS	LS	-	-	-	-	-	-	-	-	-	-	-	-
Perca flavescens	Adult	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	-	-	-	-
Pomatomus saltatrix	Juvenile	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	LS	LS	LS

Where: L = Lethal Effect, S = Sublethal Effect, and R = Rare and indicates a possibility of occurrence

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Summarized dissolved oxygen requirements, temperatures, and salinities associated with lethal effects

Species	Stage	DO (mg/l)	Temperature (°C)	Salinity (‰)	Description	Reference
Acipenser brevirostrum	Juvenile	4.00	-	-	No mortality seen for 13-day olds	Jenkins et al. 1993
Acipenser brevirostrum	Juvenile	3.50	-	-	Mortality seen in 19-day olds	Jenkins et al. 1993
Acipenser brevirostrum	Juvenile	3.00	-	-	Decreased survival	Jenkins et al. 1993
Acipenser brevirostrum	Juvenile	2.2-3.1	22-30	2-4.5	LC50	Campbell and Goodman 2004
Acipenser oxyrhynchus	Juvenile	6.30	20	8	Instantaneous mortality rate of 1%/day	Niklitschek and Secor 2009a
Acipenser oxyrhynchus	Juvenile	6.30	20	29	Instantaneous mortality rate of 3.5%/day	Niklitschek and Secor 2009a
Acipenser oxyrhynchus	Juvenile	4.30	12	1	Optimal for survival	Niklitschek and Secor 2009a
Acipenser oxyrhynchus	Juvenile	6.30	20	1	Optimal for survival	Niklitschek and Secor 2009a
Acipenser oxyrhynchus	Juvenile	3.60	12	29	Optimal for survival	Niklitschek and Secor 2009a
Acipenser oxyrhynchus	Juvenile	5.40	20	29	Optimal for survival	Niklitschek and Secor 2009a
Alosa sapidissima	Juvenile	2.0-4.0	-	-	Surival possible with limited exposure	Tagatz 1961
Alosa sapidissima	Egg/Larval	2.5-2.9	-	-	LC50	Stier and Crance 1985
Callinectes sapidus	Juvenile/Larval	4.08-7.06	20-30	10-30	LC50	Stickle et al. 1989, VSD 2008
Cancer irroratus	Larval	0.66-6.05	10-30	30	LC50	VSD 2008, Vargo and Sastry 1977
Cancer irroratus	Larval	8.60	-	-	Median LC50	VSD 2008
Cancer irroratus	Megalops	2.70-4.70	25-30	30	LC50	Vargo and Sastry 1977
Gammarus pseudolimnaeus	Adult, Female	1.41-4.09	10-20	<5	LC50	Hoback and Barnhart 1996
Morone saxitilis	Egg	4.0-5.0	-	-	Required concentration for survival	Turner and Farley 1971
Morone saxitilis	Egg	4.00	-	-	Reduced survival	Bain and Bain 1982
Morone saxitilis	Egg	2.0-3.5	-	-	Complete absence	Bain and Bain 1982
Morone saxitilis	Larval	4.0-5.0	-	-	Decreased survival	Bain and Bain 1982
Morone saxitilis	Larval	1.96-3.46	18.5-20.6	4-7	LC50	Poucher and Coiro 1997
Morone saxitilis	Juvenile	3.00	-	-	Minimum requirement for intermediate survival	Coutant 1985
Morone saxitilis	Juvenile	5.00	-	-	Threshold for high survival	Bain and Bain 1982
Perca flavescens	Adult	3.1-5.1	11-26	-	Mortalities seen below this	Moore 1942, Kreiger et al. 1983
Perca flavescens	Adult	5.00	-	-	Lower Optimal Level	Auer 1982, Kreiger et al 1983
Perca flavescens	Juvenile	7.00	-	<5	Mortality criteria	Thorpe 1977
Pomatomus saltatrix	Juvenile	4.5-7.3	-	-	Suggested DO Requirement	Shepherd and Packer 2006

Where VSD = Vaquer-Sunyer and Duarte 2008

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Summarized dissolved oxygen requirements, temperatures, and salinities associated with sublethal effects

Species	Stage	DO (mg/l)	Temperature (°C)	Salinity (‰)	Description	Reference
Acipenser oxyrhynchus	Larval	3.00	-	-	Prey consumption reduced	Wirgin and Chambers 2018
Acipenser oxyrhynchus	Juvenile	6.30	20	-	Instantaneous growth rate reduced	Niklitschek and Secor 2009
Acipenser oxyrhynchus	Juvenile	6.00	-	-	Needed for rearing habitat (NY Bight)	Federal Register 2017
Acipenser oxyrhynchus	Juvenile	5.00	25	-	Less likely to support rearing (S. Atlantic DPS)	Federal Register 2017
Acipenser oxyrhynchus	Juvenile	4.30	26	-	Higher than this needed for rearing (S. Atlantic DPS)	Federal Register 2017
Alosa sapidissima	Juvenile	4.00	-	-	Respiration rates and distress increases	Tagatz 1961
Alosa sapidissima	Egg/Larval	5.00	-	-	Required for spawning	Stier et al. 1985
Alosa sapidissima	Adult	2.75-4.0	-	-	Median sublethal threshold	Vaquer-Sunyer and Duarte 2008
Ictalurus punctatus	Egg	3.6-4.4	28	-	Decreased hatching success	Carlson, Siefert, and Herman 1974
Ictalurus punctatus	Larval	3.6-4.4	28	-	Decreased survival success	Carlson, Siefert, and Herman 1974
Ictalurus punctatus	Juvenile	4.00	-	-	Increased production	Torrans, Ott, and Bosworth 2012
Ictalurus punctatus	Juvenile	4.00	-	-	First increase in ventilation	Gerald and Cech 1970
Ictalurus punctatus	Juvenile	5.00	-	-	Reduced feeding	Randolph and Clemens 1976
Ictalurus punctatus	Adult	3.95-6.4	-	-	Doubled gill ventilation and lactic acidosis	Burggren and Cameron 1980
Ictalurus punctatus	Juvenile/Adult	5.00	-	-	Adequate for growth and survival	McMahon and Terrell 1982
Ictalurus punctatus	Juvenile/Adult	7.00	-	-	Optimum for growth and survival	McMahon and Terrell 1982
Micropterus salmoides	Juvenile	5.0-6.0	25	-	Swimming speed and ability reduced	Dahlberg et al. 1968, Katz et al. 1959
Micropterus salmoides	Juvenile	4.50	-	-	Avoidance reported	Whitemore et al. 1960
Micropterus salmoides	Juvenile	8.00	-	-	Reduced growth begins	Stewart et al. 1967
Micropterus salmoides	Juvenile	4.0-6.0	-	-	Growth reduced by 33%	Brake 1972
Micropterus salmoides	Juvenile	<4.0	-	-	Growth substantially reduced	Stewart et al. 1967
Morone americana	Juvenile	3.6-6.3	20-28	-	Growth and consumption reduced, metabolism increased	Hanks and Secor 2011
Morone americana	Adult	3.0-4.6	8-21	2.5-6.0	Avoided areas at this level in favor of high DO waters	Meldrim, Gift, and Petrosky 1974
Morone saxatilis	Juvenile	4.50	20-28	-	Lowered consumption and growth	Brandt et al. 2009
Morone saxatilis	Juvenile	8.00	20-27	-	High levels of growth	Brandt et al. 2009
Morone saxitilis	Adult	6.0-12.0	-	-	Optimal for survival	Fay, Neeves, and Pardue 1983
Paralichthys dentatus	Juvenile/Adult	4.3-5.0	22-30	30-34	Ventilation rates increase	Capossela et al 2012
Paralichthys dentatus	Juvenile/Adult	5.00	30	-	Growth reduced	Stierhoff et al. 2006
Paralichthys dentatus	Juvenile/Adult	4.52	-	-	Chronic value for growth and survival	Bailey et al. 2014
Perca flavescens	Juvenile	2.00	20-26	-	Lowered consumption and growth	Roberts et al 2011
Pomatomus saltatrix	Juvenile	4.5-7.3	24.5-30	-	Occur in these areas	Smith 1971
Pomatomus saltatrix	Juvenile	5.0-9.0	-	-	Occur in these areas	Shepherd and Packer 2006

Juvenile Atlantic Sturgeon

- Derived from experimental and modeling of Niklischek and Secor (2 papers, 2009a and 2009b)

- 2009a: experimental results and regression modeling
  - Nonlethal and sublethal effects
  - DO, T and Sal important
  - No DO-Sal interaction

- 2009b: Bioenergetic models of growth rate
  - Better than regression models
  - Difficult to assess DO-salinity interactions in model

At salinity = 9

At DO 100% saturation

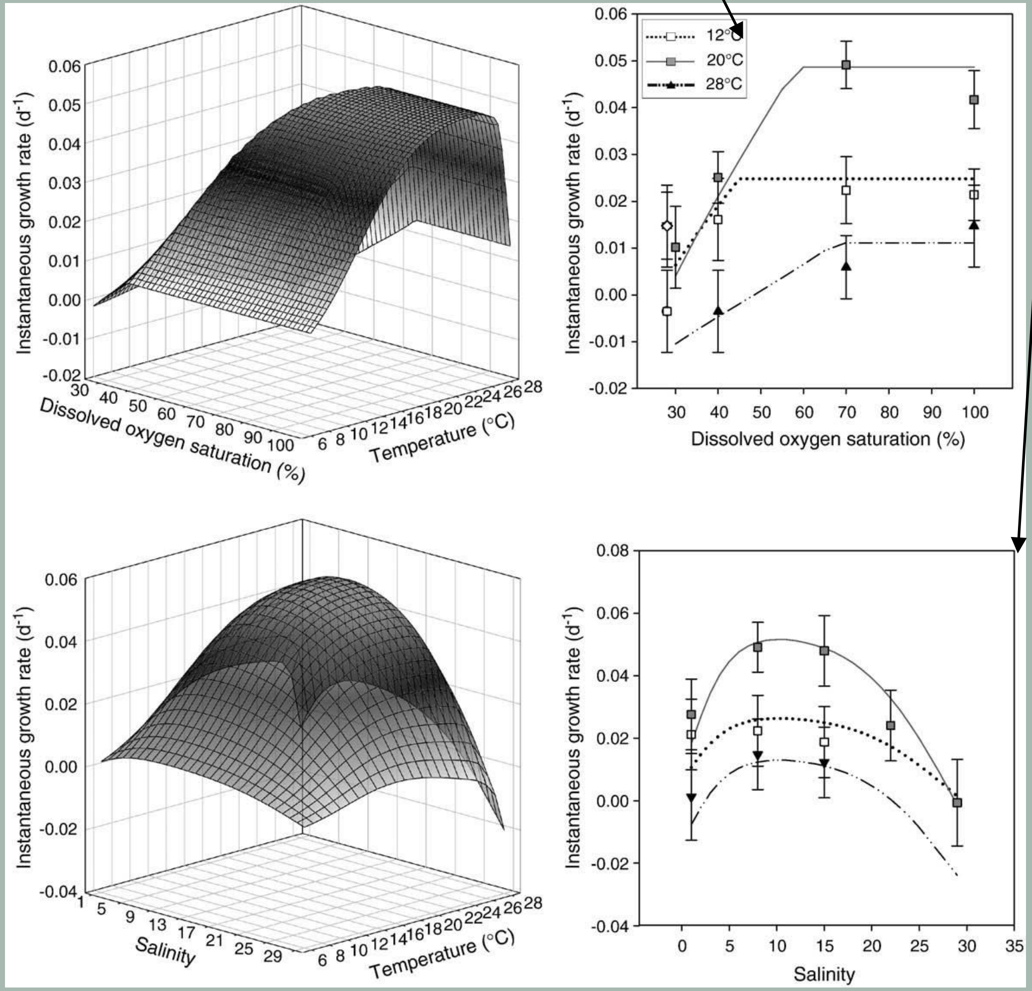

Fig. 8. Predicted (left panels) and mean observed ±SE (right panels) effects of temperature, dissolved oxygen saturation and salinity on instantaneous growth rate in juvenile Atlantic sturgeon. Figures show variability caused by two factors at a time, holding the third at fixed conditions (salinity 9 for top panels, 100% DOSAT for bottom panels). Predicted values are weight-normalized to represent a 20-g fish.

Niklischek, EJ and DH Secor, J Exp. Mar. Biology and Ecology 381(2009):S161-SD172

Atlantic Sturgeon (*Acipenser oxyrhynchus*)

Species	Stage	DO (mg/l)	Temperature (°C)	Salinity (‰)	Description	Reference
Acipenser oxyrhynchus	Larval	3.00	-	-	Prey consumption reduced	Wirgin and Chambers 2018
Acipenser oxyrhynchus	Juvenile	6.30	20	-	Instantaneous growth rate reduced	Niklitschek and Secor 2009
Acipenser oxyrhynchus	Juvenile	6.00	-	-	Needed for rearing habitat (NY Bight)	Federal Register 2017
Acipenser oxyrhynchus	Juvenile	5.00	25	-	Less likely to support rearing (S. Atlantic DPS)	Federal Register 2017
Acipenser oxyrhynchus	Juvenile	4.30	26	-	Higher than this needed for rearing (S. Atlantic DPS)	Federal Register 2017
Acipenser oxyrhynchus	Juvenile	6.30	20	8	Instantaneous mortality rate of 1%/day	Niklitschek and Secor 2009a
Acipenser oxyrhynchus	Juvenile	6.30	20	29	Instantaneous mortality rate of 3.5%/day	Niklitschek and Secor 2009a
Acipenser oxyrhynchus	Juvenile	4.30	12	1	Optimal for survival	Niklitschek and Secor 2009a
Acipenser oxyrhynchus	Juvenile	6.30	20	1	Optimal for survival	Niklitschek and Secor 2009a
Acipenser oxyrhynchus	Juvenile	3.60	12	29	Optimal for survival	Niklitschek and Secor 2009a
Acipenser oxyrhynchus	Juvenile	5.40	20	29	Optimal for survival	Niklitschek and Secor 2009a

Atlantic Sturgeon were selected as a key oxygen sensitive species because of their sensitivity to low dissolved oxygen at both the lethal and sublethal levels at the juvenile and larval stages and broad range throughout benthic habitats in Delaware River estuary.

Photo Credit: CaviarExpress.com

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 and information on these stages would greatly improve the current understanding of Atlantic Sturgeon DO sensitivity.

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Task Order 5: Unionid Mussels

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, and the existing information places the lethal and sublethal effects below the requirements for the key species list in this report. 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. However, more data are needed to make any claims on DO criteria for the estuary.

Photo Credit: Texas A&M

Task Order 5: Data Gaps

- Entire species:
    - Several species of amphipods
    - Copepods
    - Lady Crab (*Ovalipes ocellatus*)
    - Several species of herring
    - Sharks
    - Pinfish (*Lagodon rhomboides*)
    - Several species of sunfish
    - Many species of minnows.

Task Order 5: Data Gaps

- Some life stages or at various temperatures for the key sensitive species
- Complete data gaps on DO sensitivities
  - adult, egg, and larval Shortnose Sturgeon
  - egg and adult Atlantic Sturgeon
  - egg and larval American Shad
  - egg and larval White Perch
  - egg and larval Yellow Perch
- Some data, but higher precision data desirable
  - larval Atlantic Sturgeon
  - all stages of American Shad
  - adult White Perch
  - adult Striped Bass
  - juvenile Yellow Perch
  - all stages of Bluefish.

Task Order 5: Data Gaps

- Species stages at different temperatures
- DO criteria often found through laboratory experiments using a small range of temperatures, or no temperature is given
- More information on temperature and oxygen relationships for each species would benefit the scientific understanding of DO requirements.

Questions?

- Next slides summarize information for individual species
- Will use in response to questions as needed, to allow sufficient time for questions

Shortnose Sturgeon (*Acipenser brevirostrum*)

Species	Stage	DO (mg/l)	Temperature (°C)	Salinity (‰)	Description	Reference
Acipenser brevirostrum	Juvenile	4.00	-	-	No mortality seen for 13-day olds	Jenkins et al. 1993
Acipenser brevirostrum	Juvenile	3.50	-	-	Mortality seen in 19-day olds	Jenkins et al. 1993
Acipenser brevirostrum	Juvenile	3.00	-	-	Decreased survival	Jenkins et al. 1993
Acipenser brevirostrum	Juvenile	2.2-3.1	22-30	2-4.5	LC50	Campbell and Goodman 2004

At the lethal effect level, juvenile Shortnose Sturgeon show sensitivity to low DO concentrations

There are no reported DO sensitivities for Shortnose Sturgeon adults, eggs, and 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.

Photo Credit: NOAA Fisheries

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American Shad (*Alosa sapidissima*)

Species	Stage	DO (mg/l)	Temp °C	Salinity ‰	Description	Reference
Alosa sapidissima	na	<0.6	-	-	immediate death	Chittenden 1969
Alosa sapidissima	egg/larvae	1	-	-	100% mortality	Stier et al 1985
Alosa sapidissima	juvenile	1.2	-	-	mortalities occur	Tagatz 1961
Alosa sapidissima	juvenile	1.4-2.4	-	-	left school	Tagatz 1961
Alosa sapidissima	na	<2	-	-	heavy mortality	Chittenden 1969
Alosa sapidissima	na	2	-	-	never found below this	Howell and Simpson 1994
Alosa sapidissima	na	2.9	-	-	39% less abundant	Howell and Simpson 1994
Alosa sapidissima	egg/larvae	2.5-2.9	-	-	LD50	Stier et al 1985
Alosa sapidissima	Adult	2.75-4.0	-	-	median sublethal threshold	Vaquer-Sunyer and Duarte 2008
Alosa sapidissima	juvenile	2-4	-	-	survive limited exposure	Tagatz 1961
Alosa sapidissima	na	3	-	-	equilibrium is lost	Chittenden 1969
Alosa sapidissima	juvenile	4	-	-	respiration increases	Tagatz 1961
Alosa sapidissima	adult	4.0-5.0	-	-	required for migration	No citation
Alosa sapidissima	Adult	5	-	-	required for spawning	Stier et al 1985

Available information on DO requirements for American Shad is scarce and variable. Lethal effects of low DO have been documented for eggs, larvae, and juveniles; however, the identification of upper lethal limits has not been documented (reported lethal limits are for 50 or 100% mortality).

Photo Credit: USFWS

The sublethal 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. Data on other Clupeids was not found. 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.

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Blue Crab (*Callinectes sapidus*)

Species	Stage	DO (mg/l)	Temp °C	Salinity ‰	Description	Reference
Callinectes sapidus	Adult	<1.0	-	-	mean acute value LC50	USEPA 2000
Callinectes sapidus	Juvenile	1.16-2.31	-	-	molted slower and less	Das & Stickle 1993
Callinectes sapidus	Juvenile	2.31	-	-	signficant feeding rate decline	Das & Stickle 1993
Callinectes sapidus	na	2.14	-	-	median sublethal LC50	Vaquer-Sunyer & Duarte 2008
Callinectes sapidus	Juvenile	4.08	20	10	LC50. (74Torr)	Stickle et al 1989
Callinectes sapidus	Juvenile	4.61	30	30	LC50, (111 Torr)	Stickle et al 1989
Callinectes sapidus	Juvenile	5.02	24	22	28-day LC50 (116ppm=25Torr)	Das & Stickle 1993
Callinectes sapidus	Juvenile	5.23	30	20	LC50, (119 Torr)	Stickle et al 1989
Callinectes sapidus	Juvenile	5.63	30	10	LC50, (121 Torr)	Stickle et al 1989
Callinectes sapidus	Juvenile	6.03	20	30	LC50. (133 Torr)	Stickle et al 1989
Callinectes sapidus	Juvenile	6.44	20	20	LC50, (124 Torr)	Stickle et al 1989
Callinectes sapidus	na	2.3-7.06	-	-	mean LC50	Vaquer-Sunyer & Duarte 2008
Callinectes sapidus	Juvenile	<1 Day	-	-	LT50, half died in less than 1 day in total anoxia	Stickle et al 1989
Callinectes sapidus	Adult	2.56 Days	20-26	16-23	LT50 in 0.5mg/L	Sagasti, Schaffner, Duffy 2001

Adult Blue Crabs are generally tolerant of low DO. Larval and juvenile Blue Crabs are more sensitive than their adult counterparts at both the lethal and sublethal effect levels.

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.

Photo Credit: NWF.org

Atlantic Rock Crab (*Cancer irroratus*)

Species	Stage	DO (mg/l)	Temp °C	Salinity ‰	Description	Reference
Cancer irroratus	1st stage	0.81-8.64	-	-	mean LC50	Vaquer-Sunyer & Duarte 2008
Cancer irroratus	2nd stage	0.66-7.23	-	-	mean LC50	Vaquer-Sunyer & Duarte 2008
Cancer irroratus	3rd stage	0.34-6.0	-	-	mean LC50	Vaquer-Sunyer & Duarte 2008
Cancer irroratus	4th stage	0.56-6.43	-	-	mean LC50	Vaquer-Sunyer & Duarte 2008
Cancer irroratus	5th stage	0.64-6.43	-	-	mean LC50	Vaquer-Sunyer & Duarte 2008
Cancer irroratus	Stage 1-5	0.45-1.19	15	30	LC50, 240 mins,	Vargo & Sastry 1977
Cancer irroratus	Stage 1-5	0.57-1.3	10	30	LC50, 240 mins,	Vargo & Sastry 1977
Cancer irroratus	Stage 1-5	1.07-2.29	20	30	LC50, 240 mins,	Vargo & Sastry 1977
Cancer irroratus	Megalops	1.3-1.8	10-20	30	LC50, 120 mins,	Vargo & Sastry 1977
Cancer irroratus	Megalops	1.58-2.2	10-20	30	LC50, 240 mins,	Vargo & Sastry 1977
Cancer irroratus	Larvae	2.1 +/- 0.9	20	28-32 g/kg	LC90	Miller, Poucher, & Coiro 2002
Cancer irroratus	Stage 1-5	2.11	10-25	30	LC50, 120 mins,	Vargo & Sastry 1977
Cancer irroratus	Stage 1-5	2.09-3.80	25	30	LC50, 240 mins,	Vargo & Sastry 1977
Cancer irroratus	Larvae	2.6 +/- 0.4	20	28-32 g/kg	LC50	Miller, Poucher, & Coiro 2002
Cancer irroratus	To Post-Larvae	3.0 +/- 0.6	20	28-32 g/kg	Lc50	Miller, Poucher, & Coiro 2002
Cancer irroratus	Larvae	3.8 +/- 2.7	20	28-32 g/kg	LC10	Miller, Poucher, & Coiro 2002
Cancer irroratus	Megalops	2.7	25	30	LC50 120 mins,	Vargo & Sastry 1977
Cancer irroratus	Megalops	3.35	25	30	LC50, 240 mins,	Vargo & Sastry 1977
Cancer irroratus	Megalops	4.7	30	30	LC50 120 mins,	Vargo & Sastry 1977
Cancer irroratus	Megalops	4.7	30	30	LC50, 240 mins,	Vargo & Sastry 1977
Cancer irroratus	Megalops	1.86-6.71	-	-	mean LC50	Vaquer-Sunyer & Duarte 2008
Cancer irroratus	Stage 1-5	4.2-6.05	30	30	LC50, 240 mins,	Vargo & Sastry 1977
Cancer irroratus	Stages 1-5	4.2-6.05	30	30	LC50. 120 mins,	Vargo & Sastry 1977
Cancer irroratus	Larvae	8.6	-	-	median LC50. Most sensitive species tested	Vaquer-Sunyer & Duarte 2008

Atlantic Rock Crab is only in the estuary during spawning. The larval stages are found in the surface waters of the bay from March through June, with peak abundances in May

Photo Credit: DayBreakFishing.com

Photo Credit: Oskar Sindri Gislason

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.

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Scud (*Gammarus* spp.)

Species	Stage	DO (mg/l)	Temp °C	Salinity ‰	Description	Reference
Gammarus pseudolimnaeus	Juvenile	0.35	10	"fresh"	LC50, 24 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Juvenile	0.66	10	"fresh"	highest DO resulting in significant mortality	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Juvenile	0.78	10	"fresh"	LC50, 48 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Juvenile	0.86	15	"fresh"	LC50, 24 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Male Adult	0.91	10	"fresh"	LC50, 24 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Juvenile	0.94	10	"fresh"	LC50, 72 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Juvenile	0.35-1.91	-	-	mean LC50	Vaquer-Sunyer & Duarte 2008
Gammarus pseudolimnaeus	Juvenile	1.05	15	"fresh"	LC50, 48 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Male Adult	1.11	15	"fresh"	LC50, 24 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Male Adult	1.22	10	"fresh"	LC50, 48 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Juvenile	1.23	15	"fresh"	LC50, 72 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Male Adult	1.27	15	"fresh"	LC50, 72 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Male Adult	1.28	15	"fresh"	LC50, 48 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Juvenile	1.31	20	"fresh"	LC50, 24 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Female Adult	1.41	10	"fresh"	LC50, 24 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Male Adult	1.45	10	"fresh"	LC50, 72 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Juvenile	1.47	15	"fresh"	highest DO resulting in significant mortality	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Male Adult	1.47	15	"fresh"	highest DO resulting in significant mortality	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Female Adult	1.6	15	"fresh"	LC50, 24 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Female Adult	1.66	10	"fresh"	LC50, 48 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Female Adult	1.77	10	"fresh"	LC50, 72 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Juvenile	1.81	20	"fresh"	LC50, 48 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Female Adult	1.87	10	"fresh"	highest DO resulting in significant mortality	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Male Adult	1.87	10	"fresh"	highest DO resulting in significant mortality	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Female Adult	1.89	15	"fresh"	LC50, 72 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Juvenile	1.91	20	"fresh"	LC50, 72 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Female Adult	2	15	"fresh"	LC50, 48 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Male Adult	2.14	20	"fresh"	LC50, 24 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Female Adult	2.4	15	"fresh"	highest DO resulting in significant mortality	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Juvenile	2.49	20	"fresh"	highest DO resulting in significant mortality	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Male Adult	2.49	20	"fresh"	highest DO resulting in significant mortality	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Female Adult	2.67	20	"fresh"	LC50, 24 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Male Adult	2.81	20	"fresh"	LC50, 48 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Male Adult	3.19	20	"fresh"	LC50, 72 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Female Adult	3.21	20	"fresh"	LC50, 48 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Female Adult	3.26	20	"fresh"	LC50, 72 hours	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Female Adult	4.09	20	"fresh"	highest DO resulting in significant mortality	Hoback & Barnhart 1996
Gammarus pseudolimnaeus	Adult	0.91-3.26	-	-	mean LC50	Vaquer-Sunyer & Duarte 2008

There were no reports or data found on G. fasciatus oxygen sensitivity. However, adequate data exists for Gammarus pseudolimnaeus, which can be used as a surrogate species for others in the genus

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.

Scud (*Gammarus* spp.)

- *Gammarus pseudolimnaeus*
- Hoback and Barnhart 1996
- Sensitivity greatest for adult female
- Sensitivity increases with temperature
- No temperature > 20^{o} C tested

Stage	Temp	LC50			Highest w sig mort
		24 hour	48 hour	72 hour	
Juvenile	10	0.35	0.78	0.94	0.66
Male Adult	10	0.91	1.22	1.45	1.87
Female Adult	10	1.41	1.66	1.77	1.87
Juvenile	15	0.86	1.05	1.23	1.47
Male Adult	15	1.11	1.28	1.27	1.47
Female Adult	15	1.60	2.00	1.89	2.40
Juvenile	20	1.31	1.81	1.91	2.49
Male Adult	20	2.14	2.81	3.19	2.49
Female Adult	20	2.67	3.21	3.26	4.09

Channel Catfish (*Ictalurus punctatus*)

Species	Stage	DO (mg/l)	Temp °C	Salinity ‰	Description	Reference
Ictalurus punctatus	juvenile	0.41-0.82	23-24	freshwater	breakdown in ventilation rhythm	Gerald and Cech 1970
Ictalurus punctatus	na	0.85	18	-	LC50	Scott and Rogers 1980
Ictalurus punctatus	na	0.5-2.0	18	-	tissues experienced necrosis and hyperaemia.	Scott and Rogers 1980
Ictalurus punctatus	na	0.95	25	-	lethal DO	Moss and Scott 1961
Ictalurus punctatus	na	1.03	30	-	lethal DO	Moss and Scott 1961
Ictalurus punctatus	na	1.08	35	-	lethal DO	Moss and Scott 1961
Ictalurus punctatus	juvenile	0.68-1.81	23-24	freshwater	maximum ventilation	Gerald and Cech 1970
Ictalurus punctatus	na	1.5	18	-	need at least this for consistent survival	Scott and Rogers 1980
Ictalurus punctatus	na	1.5	-	-	feed intake decreased by 36%	Torrans et al 2012
Ictalurus punctatus	juvenile	2	26.5	-	Stress. Increased mortality due to Edwardsiella ictaluri	Welker et al 2007
Ictalurus punctatus	na	2.5	-	-	feed intake decreased by 5%	Torrans et al 2012
Ictalurus punctatus	na	3	-	-	retards growth	McMahon and Terrell 1982
Ictalurus punctatus	egg and larvae	3.6-4.4	25	-	decrease in hatching success and survival of larvae	Carlson et al. 1974
Ictalurus punctatus	egg and larvae	3.6-4.2	28	-	decrease in hatching success and survival of larvae	Carlson et al. 1974
Ictalurus punctatus	520-1069g	3.95-6.4	18	-	gill ventilation doubles	Burggren and Cameron 1980
Ictalurus punctatus	520-1069g	3.95-6.4	18	-	lactic acidosis occurs and takes 2-6 hours to recover	Burggren and Cameron 1980
Ictalurus punctatus	juvenile	4	23-24	freshwater	first increase in ventilation	Gerald and Cech 1970
Ictalurus punctatus	na	4	-	-	gross and net production higher at this or more	Torrans et al 2012
Ictalurus punctatus	na	5	-	-	adequate for growth and survival	McMahon and Terrell 1982
Ictalurus punctatus	na	5	-	-	reduces feeding	McMahon and Terrell 1982
Ictalurus punctatus	na	7	-	-	optimum level for growth and survival	McMahon and Terrell 1982

Channel Catfish are sensitive to low DO concentrations at a sublethal level. Eggs, larvae, and juveniles have the greatest sensitivities in terms of growth and survival, but one did document the sublethal sensitivity of adults. As a widespread, resident benthic species of the Delaware River, Channel Catfish with sublethal DO sensitivity was included here as a key oxygen sensitive species.

Largemouth Bass (*Micropterus salmoides*)

Species	Stage	DO (mg/l)	Temp °C	Salinity ‰	Description	Reference
Micropterus salmoides	juvenile	0.92	25	-	critical DO	Moss and Scott 1961
Micropterus salmoides	juvenile	1.14	35	-	critical DO	Moss and Scott 1961
Micropterus salmoides	juvenile	1.19	30	-	critical DO	Moss and Scott 1961
Micropterus salmoides	na	1.5	-	-	threshold DO for rapid mortality	Boyd and Lichtkoppler 1979
Micropterus salmoides	adult	2	-	-	no large movements out of area	Gaulke et al 2015
Micropterus salmoides	Adult	2	-	-	after 6 hrs, no changes in hemoglobin, but saw anaerobic respiratioon	Gaulke et al 2015
Micropterus salmoides	Juv/adult	2.4	23.7	fresh	avoided areas, but DO not absolute barrier	Burleson et al 2001
Micropterus salmoides	eggs	2.8	-	-	threshold for low survival rates for newly hatched individuals	Jones, Martin, and Hardy 1978
Micropterus salmoides	juvenile	4	-	-	growth substanitally reduced	Stewart et al 1967
Micropterus salmoides	juvenile	4.5	-	-	slight avoidance behavior	Whitmore et al. 1960
Micropterus salmoides	juvenile	4-6	-	-	growth reduced by 33%	Brake 1972
Micropterus salmoides	juvenile	5-6	25	-	swimming speed reduced	Dahlberg, Shumway, and Doudoroff 1968
Micropterus salmoides	juvenile	5	15.5-17	-	difficulty completing a swim through tank with a current of 0.8ft/s	Katz et al. 1959
Micropterus salmoides	juvenile	8	-	-	growth reduced	Stewart et al. 1967
Micropterus salmoides	juvenile	range	-	-	low compared to high DO consistently resulted in lower growth	Stewart 1962

Credit: Georgia WRD

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 sublethal effect level.

White Perch (*Morone americana*)

Species	Stage	DO (mg/l)	Temp °C	Salinity ‰	Description	Reference
Morone americana	YOY	na	-	-	strongly associated with DO	Able et al 2009
Morone americana	adults	<35%	-	-	avoided DO conditions	Meldrim, Gift, and Petrosky 1974
Morone americana	juvenile	0.5-1.0	-	-	19 hr LC40	Dorfman and Westman 1970
Morone americana	YOY	1.8	20-28	-	decrease by 3x in growth, could increase predation on them	Hanks and Secor 2011
Morone americana	YOY	1.5-3.12	28	-	threshold for growth at 28	Hanks and Secor 2011
Morone americana	all	4.0-5.0	-	-	equal abundance for juveniles and adults	O'Herron, Lloyd, and Laidig 1994
Morone americana	all	>5.0	-	-	equal abundance for juveniles and adults	O'Herron, Lloyd, and Laidig 1994
Morone americana	YOY	3.6-6.3	20	-	threshold for growth at 20	Hanks and Secor 2011


Photo Credit: TulsaWorld.com

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 sublethal 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 were selected as a key oxygen sensitive species.

Striped Bass (*Morone saxatilis*)

Species	Stage	DO (mg/l)	Temp °C	Salinity ‰	Description	Reference
Morone saxatilis	juvenile	1	-	-	no survival	Bain and Bain 1982
Morone saxatilis	YOY	1.5	25	12	no mortality after 18 hours	Dixon et al 2017
Morone saxatilis	juvenile	1.5	20-21.8	30-30.5	24 hr IC50	Poucher and Coiro 1997
Morone saxatilis	juvenile	1.53	20-21.8	30-30.5	96 hr IC50	Poucher and Coiro 1997
Morone saxatilis	juvenile	1.62	18.2-19.6	32	24 hr IC50	Poucher and Coiro 1997
Morone saxatilis	juvenile	1.63	18.2-19.6	32	96 hr IC50	Poucher and Coiro 1997
Morone saxatilis	juvenile	1.89	18.2-19.6	32	mortality first observed	Poucher and Coiro 1997
Morone saxatilis	post larvae	1.96	19.8-20.6	5-6	24 hr IC50	Poucher and Coiro 1997
Morone saxatilis	post larvae	1.96	19.8-20.6	5-6	96 hr IC50	Poucher and Coiro 1997
Morone saxatilis	YOY	2	20-30	fresh	Consumption lowered	Brandt et al 2009
Morone saxatilis	YOY	2	-	fresh	growth occurs above this	Brandt et al 2009
Morone saxatilis	juvenile	2	20-21.8	30-30.5	mortality first observed	Poucher and Coiro 1997
Morone saxatilis	egg/larvae	2-3.5	-	-	absence in Delaware River	Bain and Bain 1982
Morone saxatilis	post larvae	2.22	18-19	4-5	24 hr IC50	Poucher and Coiro 1997
Morone saxatilis	larvae	2.34	18-19	4-5	96 hr IC50	Poucher and Coiro 1997
Morone saxatilis	post larvae	2.4	19.8-20.6	5-6	mortality first observed	Poucher and Coiro 1997
Morone saxatilis	egg/larvae	2.4-3.3	-	-	lethal threshold for pre- and post-yolk sac larvae	Westin and Rogers 1978
Morone saxatilis	juvenile	3	-	-	minimum DO requirement	Coutant 1985
Morone saxatilis	Adult	3	-	-	avoid areas	Bain and Bain 1982
Morone saxatilis	larvae	3	-	-	needed to survive	Bain and Bain 1982
Morone saxatilis	juvenile	3	-	-	intermediate survival	Bain and Bain 1982
Morone saxatilis	na	3	17	-	minimum o2 level for reasonably normal existence	Chittenden 1971
Morone saxatilis	post larvae	3.15	18.5-19	4-7	24 hr IC 50	Poucher and Coiro 1997
Morone saxatilis	post larvae	3.46	18.5-19	4-7	96 hr IC50	Poucher and Coiro 1997
Morone saxatilis	eggs	4	-	-	reduced egg survival	Bain and Bain 1982
Morone saxatilis	YOY	4.5	20-28	fresh	consumption and growth unaffected if this or higher	Brandt et al 2009
Morone saxatilis	juvenile	5	-	-	high survival	Bain and Bain 1982
Morone saxatilis	YOY	8	20-27	fresh	growth rate higher	Brandt et al 2009
Morone saxatilis	YOY	1-11	25	12	diel cycle, eradic swimming and lethargy	Dixon et al 2017
Morone saxatilis	eggs	4-5	-	-	egg hatch and larval survival decreased exposed to low DO	Turner and Farley 1971
Morone saxatilis	larvae	4-5	-	-	egg hatch and larval survival decreased exposed to low DO	Turner and Farley 1971
Morone saxatilis	all	6.0-12.0	-	-	optimum DO range	Fay, Neves, and Pardue 1983

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.

Photo Credit: Missouri DOC

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Summer Flounder (*Paralichthys dentatus*)

Species	Stage	DO (mg/l)	Temp °C	Salinity ‰	Description	Reference
Paralichthys dentatus	juvenile	1-11	25	25	diel cycle, growth rate lowered	Davidson et al 2016
Paralichthys dentatus	juvenile	1-11	25	25	diel cycle, mortality after 15 days	Davidson et al 2016
Paralichthys dentatus	juvenile	0.9	20	28-32	LC10	Miller et al 2002
Paralichthys dentatus	juvenile	1.1	20	28-32	LC50	Miller et al 2002
Paralichthys dentatus	new metamorph	1.1	20.5	31-32	24 hr IC50	Poucher and Coiro 1997
Paralichthys dentatus	new metamorph	1.1	20.5	31-32	96 hr IC50	Poucher and Coiro 1997
Paralichthys dentatus	juvenile	1.1-1.61	-	-	Mean LC50	Vaquer-Sunyer and Duarte 2008
Paralichthys dentatus	juvenile	1.3	20	28-32	LC90	Miller et al 2002
Paralichthys dentatus	na	1.35	-	-	LC50	Bailey et al 2014
Paralichthys dentatus	na	1.4	20	25	swimming speed increased 248% (vs 7mg/L)	Brady and Targett 2010
Paralichthys dentatus	juvenile	1.4	24	28-32	LC10	Miller et al 2002
Paralichthys dentatus	new metamorph	<1.50	23.5-25	29-30	almost 100% mortality	Poucher and Coiro 1997
Paralichthys dentatus	new metamorph	1.59	23.5-25	29-30	24 hr IC50	Poucher and Coiro 1997
Paralichthys dentatus	juvenile	1.6	24	28-32	LC50	Miller et al 2002
Paralichthys dentatus	Adult	1.62	-	-	Mean LC50	Vaquer-Sunyer and Duarte 2008
Paralichthys dentatus	new metamorph	1.7	20.5	31-32	mortality first observed	Poucher and Coiro 1997
Paralichthys dentatus	juvenile	1.8	24	28-32	LC90	Miller et al 2002
Paralichthys dentatus	na	1.9	22	30-34	Bradycardia observed (original was 27% air)	Capossela et al 2012
Paralichthys dentatus	na	2-3.5	20-25	-	growth reduced	Stierhoff et al 2006
Paralichthys dentatus	na	<2-3	-	-	strong avoidance of waters	Bell and Eggleston 2005
Paralichthys dentatus	na	2.3	25-33	15-30	actively tried to avoid this and below	Miller 2010
Paralichthys dentatus	juvenile	2.3	-	-	positive relationship btw DO and RNA:DNA in situ	Stierhoff et al 2009
Paralichthys dentatus	na	4.2	20	25	Swimming response begins, angular correlation increased	Brady and Targett 2010
Paralichthys dentatus	na	4.3-5.0	22-30	30-34	ventilation increase (original was 77% air)	Capossela et al 2012
Paralichthys dentatus	na	4.52	-	-	Chronic Value (chronic effects on survival and growth of low DO)	Bailey et al 2014
Paralichthys dentatus	na	5	30	-	growth reduced	Stierhoff et al 2006

The sublethal 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*)

Species	Stage	DO (mg/l)	Temp °C	Salinity ‰	Description	Reference
Perca flavescens	na	1.5	-	-	this and below are lethal	Krieger et al 1983
Perca flavescens	na	1.5	4	-	highest concentration with mortality	Moore 1942
Perca flavescens	juvenile	2	20-26	-	lower consumption and growth	Roberts et al 2011
Perca flavescens	na	2	-	lake	consumed less, move vertically or horizontally to avoid	Roberts et al 2012
Perca flavescens	Adult	3.1	26	-	below this are lethal	Krieger et al 1983
Perca flavescens	na	3.1	15	-	highest concentration with mortality	Moore 1942
Perca flavescens	na	3.7	11	-	highest concentration with mortality	Moore 1942
Perca flavescens	na	4.3	26	-	lowest concentration for 100% survival	Moore 1942
Perca flavescens	na	4.8	4	-	lowest concentration for 100% survival	Moore 1942
Perca flavescens	na	5	-	-	lowest DO for normal growth and development	Auer 1982; Jones et al 1988
Perca flavescens	Adult	5	-	-	lower optimal limit	Krieger et al 1983
Perca flavescens	na	5.1	19	-	lowest concentration for 100% survival	Moore 1942
Perca flavescens	juvenile	7	-	-	lethal DO, Lake Erie	Thorpe 1977

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.

Photo Credit: NANFA

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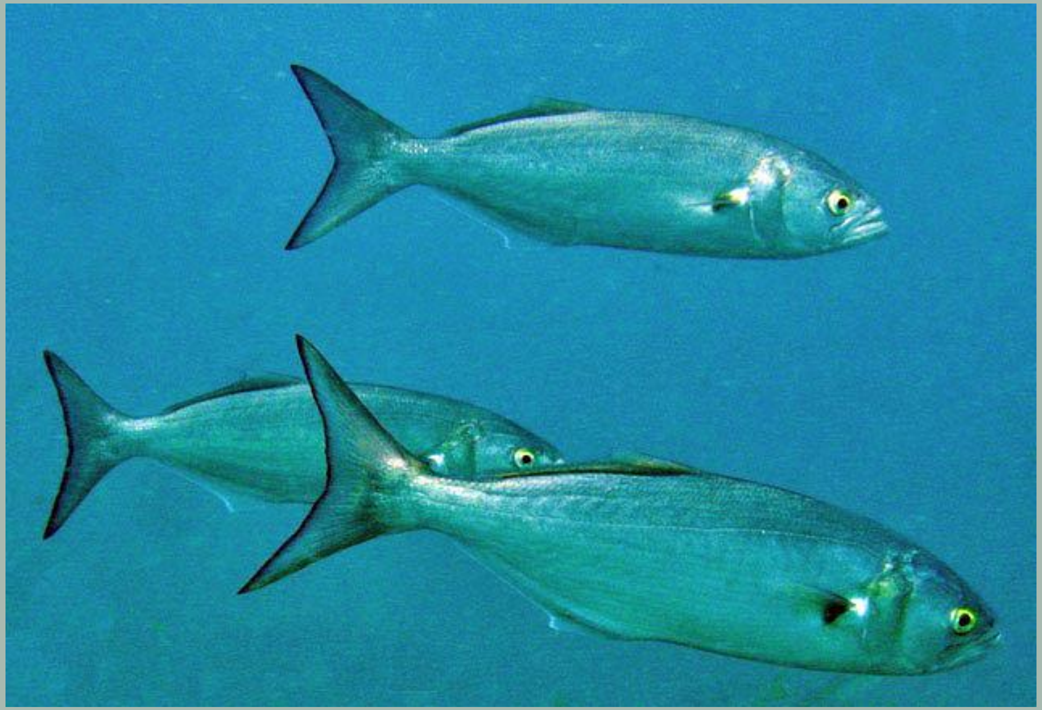
Bluefish (*Pomatomus saltatrix*)

Species	Stage	DO (mg/l)	Temp °C	Salinity ‰	Description	Reference
Pomatomus saltatrix	na	hypoxia	-	-	avoidance observed, absent from NY bight during hypoxia	Oliver et al 1989
Pomatomus saltatrix	na	2	-	-	74% less abundant	Howell and Simpson 1994
Pomatomus saltatrix	YOY/Juveniles	4.5-7.3	24.5-30	-	occurance	Smith 1971
Pomatomus saltatrix	juvenile	4.5-7.3	-	-	Do requirement	Shepherd and Packer 2006
Pomatomus saltatrix	juvenile	5-9	-	-	found here	Shepherd and Packer 2006

The small amount of DO criteria 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 are a species sensitive to low DO. Therefore, Bluefish has been included as a key oxygen sensitive species.



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