A Methodology for Evaluating Dissolved Oxygen Requirements of Species in the Delaware Estuary

Final Report

Submitted to

The Delaware River Basin Commission

By

The Patrick Center for Environmental Research
Academy of Natural Sciences of Drexel University

March 2018

BACKGROUND

Oxygen is necessary for sustaining life for most aquatic biota with variation in tolerances of oxygen concentrations existing among species and life stages. Fluctuations in dissolved oxygen (DO) occur both spatially and temporally and may be a determining factor in the presence and distribution of fauna found throughout waterbodies. Assessment of DO sensitivity is important in determining effects on the aquatic fauna and ultimately for establishing appropriate water quality standards. For this reason, the identification of DO needs of sensitive species at different life stages within the Delaware Estuary is a key component of the Delaware River Basin Commission's (DRBC) Aquatic Life Use and Estuary Eutrophication Modeling effort. Under Task Order 1, DRBC has directed the Academy of Natural Sciences of Drexel University (ANSDU), to develop a methodology for evaluating the DO requirements of sensitive species in the Delaware River Estuary.

OBJECTIVE

The objective of Task Order 1 was to propose a methodology for evaluating DO requirements of multiple sensitive Delaware Estuary species at multiple life stages. To achieve this objective we:

1. Outlined a proposed methodology that includes a key species list;
2. Identified candidate key species, and their relevant life stages and spatial distribution, where possible;
3. Proposed a methodology for determining if any species are currently absent due to DO limitations;
4. Identified potential experts for the execution of our proposed methodology;
5. Reviewed secondary pathways of oxygen sensitivity (e.g., geochemical).

1. PROPOSED METHODOLOGY

The proposed methodology uses literature assessments to identify key sensitive species in the Delaware River Estuary and their associated dissolved oxygen requirements in support of the development of new dissolved oxygen criteria for the estuary. Steps for the proposed methodology are outlined below.

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.

2. IDENTIFY CANDIDATE KEY SPECIES SENSITIVE TO LOW DISSOLVED OXYGEN

2.1. Methods for Identifying Candidate Key Species

A literature review was conducted to obtain a comprehensive list of species within the Delaware Estuary (1, 38, 45, 49, 54, 69, 87, 108, 139). For flora and fauna other than fishes, the most common species belonging to certain groups (e.g., chironomids, polychaetes, oligochaetes, copepods, etc.) were chosen as representatives to increase the probability of finding relevant DO literature. For fish fauna, each species was further broken down into life stage (i.e., egg, larva, juvenile, adult).

Preliminary literature searches were conducted to identify sources of DO information and thresholds for these species, or similar species, using keywords: "DO", "oxygen", "threshold", "criteria", "anoxia", "hypoxia", "Delaware Estuary", and/or the species/genus/family names. From the search results, a comprehensive database of sources (the references of this report) was created using Mendeley citation software.

As this was the first step in an ongoing process of literature review, some additional sources were identified and collected, which will be analyzed in more detail in the next phase of this work. The goal of this step was to begin identifying literature sources and availability of information and data to aid in the next phase of a more in-depth, comprehensive review of all existing literature. Additionally, this step of the methodology was used as a way to preliminarily narrow the list of potential candidate species so that subsequent literature searches can be more directed and comprehensive.

Literature collected in this step was then preliminarily examined to identify where gaps in information exist and to aid in the determination of species that are likely to be sensitive to low DO. Species were deemed "sensitive", "tolerant", or "likely to be" either of the two. The "likely to be" category was created for those species where data is not readily available, where data exists for other species in the same genus or family therefore likely to apply to that species, or where some information was found but more is needed. A species was classified as "Tolerant" if the literature stated that they were: oxygen regulators, tolerant of low DO (<3.5 mg/l), able to become anaerobic, and/or had a relatively low chronic or acute oxygen requirement. A species was classified as "sensitive" if the literature stated that they were: sensitive to low DO, had high mortality or behavioral changes in lowered DO, and/or had relatively high chronic or acute DO requirements (typically >3.5 mg/l). The DO criterion for sensitivity may be lower than that commonly used, but it provides a conservative evaluation to generate a candidate list, which may be reduced in subsequent steps.

Additionally, a draft of the methodology was circulated among various stakeholders for review. Suggestions for additional literature sources and species sensitivity were received and incorporated into this step of the process. Specifically, comments were received in support of the inclusion of Atlantic Sturgeon in the list of key species and for the further investigation of freshwater mussels as sensitive taxa.

2.2. Results for Identifying Candidate Key Species

From the literature results, 36 species of fish and 16 invertebrate species were identified as sensitive or likely to be sensitive (Tables 1 and 2). These species will go on for recommendation for evaluation of specific oxygen requirements in Step 5 of the proposed methodology.

The 36 sensitive fish species span 18 families, including species that inhabit fresh, marine, or mixed (i.e., oligohaline, mesohaline, polyhaline, or some combination) waters (Table 1). Seven of these species are anadromous and one is catadromous, and therefore use different areas of the estuary at different life stages. Most of these species (29) are known to be sensitive through data encountered in the literature; the remaining seven species are suspected to be sensitive. These seven species were assigned this ranking either because the literature described them as generally sensitive to oxygen without providing numerical data or because a closely related species was found to be sensitive. Literature for all 36 sensitive fish species will be reviewed more closely for specific oxygen requirements in subsequent steps of the proposed methodology.

Of the 16 invertebrate species, one is a clam, two are copepods, two are amphipods, two are mysid shrimp, two are shrimp, one is a lobster, four are crabs, one is a mussel, and one is a sand dollar (Table 2). Eight of these are known to be sensitive to low DO through a search of the literature and eight are likely to be sensitive. Of those that are "likely", three (*Acartia tonsa, Eurytemora affinis,* and *Echinarachnius parma*) were classified as such because more information is needed to corroborate literature sources, and four (*Neomysis Americana*,*Mysidopsis bigelowi*, *Palaemonetes paludosus*, and *Ovalipes ocellatus*) were classified as such because literature was found pertaining to surrogate species either in the same genus or family. *Elliptio complanata*, was added to this list after suggestions from reviewers which identified potential chronic low dissolved oxygen sensitives.Other species of fresh water mussel may also be added upon review of information on sensitivity of this group. All 16 taxa are recommended to be examined in further detail for specific oxygen requirements in the next step of the proposed methodology.

Table 1. List of fish species deemed sensitive to low dissolved oxygen based upon a primary literature search, their sensitivity by life stage, location within the estuary, and list of references.

Species	Common Name	General	Egg	Larvae	Juvenile	Adult	References
Acipenser brevirostrum	Shortnose Sturgeon	-	-	-	P, F	-	16, 58, 102
Acipenser oxyrhynchus	Atlantic Sturgeon	-	-	-	S, C	-	80, 81, 101, 102
Anguilla rostrata	American Eel	P, C	-	-	-	-	82
Anchoa mitchilli	Bay Anchovy	S, C	-	-	-	-	78
Alosa aestivalis	Blueback Herring	P, C	-	-	-	-	38, 86
Alosa mediocris	Hickory Shad	-	S, F	-	-	-	52
Alosa pseduoharengus	Alewife	-	S, F	S, F	S, C	S, M	38, 86
Alosa sapidissima	American Shad	-	S, F	-	S, C	S, M	38, 117
Brevoortia tyrannus	Atlantic Menhaden	P, M	-	-	-	-	15, 38
Semotilus atromaculatus	Creek Chub	-	S, F	-	-	-	71
Ictalurus punctatus	Channel Catfish	S, F	-	-	-	-	72
Esox lucius	Northern Pike	-	-	-	S, F	-	56
Esox masquinongy	Muskellunge	-	P, F	P, F	-	-	24
Fundulus heteroclitus	Mummichog	-	S, C	-	-	-	29
Menidia beryllina	Inland Silverside	S, C	-	-	-	-	140
Pogonias cromis	Black Drum	-	-	-	S, C	-	38
Micropogonias undulatus	Atlantic Croaker	-	-	-	P, M	-	38
Cynoscion regalis	Weakfish	-	-	-	S, C	-	38, 74
Leiostomus xanthurus	Spot	-	-	-	S, M	S, M	38, 46, 51, 116
Bairdiella chrysoura	Silver Perch	S, C	-	-	-	-	46
Pomatomus saltatrix	Bluefish	-	-	-	S, C	-	84, 106
Morone americana	White Perch	-	S, C	S, C	S, C	S, C	38, 110
Morone saxatilis	Striped Bass	-	S, F	S, F	S, C	P, M	8, 38
Perca flavescens	Yellow Perch	-	-	-	-	S, F	64
Sander vitreus	Walleye	-	S, F	-	S, F	-	73
Stenotomus chrysops	Scup	-	-	-	S, C	-	113
Lagodon rhomboides	Pinfish	S, M	-	-	-	-	46
Lepomis auritus	Redbreast Sunfish	P, F	-	-	-	-	3
Lepomis cyanellus	Green Sunfish	P, F	-	-	-	-	119
Lepomis macrochirus	Bluegill	-	-	-	-	S, F	120
Micropterus dolomieu	Smallmouth Bass	S, F	S, F	-	-	-	39
Micropterus salmoides	Largemouth Bass	S, F	-	-	-	-	121
Pomoxis annularis	White Crappie	S, F	-	-	-	-	42
Pomoxis nigromaculatus	Black Crappie	S, F	-	-	-	-	41
Pseudopleuronectes americanus	Winter Flounder	-	-	-	S, M	-	118
Paralichthys dentatus	Summer Flounder	-	-	-	S, M	-	7, 34, 38, 118

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

Table 2. List of invertebrate species deemed sensitive to low dissolved oxygen based upon a primary literature search, their location within the estuary, and list of references.

Taxon	Species	Common Name	Sensitivity	Location	References
Mussel	*Elliptio complanata*	Eastern Elliptio	P	F	1, 20, 27, 129, 131
Clam	*Mercenaria mercenaria*	Hard Clam/Quahog	S	M	7, 22, 35, 38, 45, 50, 66, 67, 114, 129, 130, 131, 143
Copepod	*Acartia tonsa*	-	P	C	7, 22, 26, 38, 91, 95, 104, 109, 114, 129
Copepod	*Eurytemora affinis*	-	P	C	7, 22, 26, 38, 129
Amphipod	*Gammarus daiberi*	Scud	S	C	2, 26, 53, 68, 108, 129, 130, 139
Amphipod	*Corophium spp.*	-	S	C	7, 26, 50, 68, 130, 139
Mysid Shrimp	*Neomysis americana*	Opossum Shrimp	P	C	7, 22, 26, 38, 55, 69, 104, 108, 129, 130
Mysid Shrimp	*Mysidopsis bigelowi*	-	P	C	7, 22, 38, 104, 129, 130
Shrimp	*Palaemonetes paludosus*	Grass Shrimp	P	C	7, 22, 38, 75, 114, 115, 130, 131
Shrimp	*Crangon septemspinosa*	Sand Shrimp	S	C	7, 22, 26, 35, 38, 50, 61, 108, 114, 129, 130, 131
Lobster	*Homerus americanus*	American lobster	S	M	22, 45, 50, 75, 129, 130, 131
Crab	*Cancer irroratus*	Atlantic Rock Crab	S	M	7, 22, 36, 75, 129, 131, 134
Crab	*Callinectes sapidus*	Blue Crab	S	M	22, 26, 28, 30, 36, 45, 50, 90, 114, 130, 131, 115
Crab	*Ovalipes ocellatus*	Lady Crab	P	M	36, 38, 108
Crab	*Dyspanopeus sayi*	Mud Crab	S	M	22, 38, 114, 130, 131
Sand Dollar	*Echinarachnius parma*	Sand Dollar	P	M	35, 38

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

Additionally, 19 fish species or families and 34 non-fish species were classified as tolerant, or likely to be tolerant, of low DO (Tables 3 and 4). These species will not be recommended for evaluation of oxygen requirements in the proposed methodology for the next Task Order.

Of the non-sensitive fishes, 14 represent species of fish and the remaining five represent groups of fish (Table 3). *Fundulus* spp. are generally considered tolerant, although there is information indicating sensitivity of eggs of *Fundulus heteroclitus. Gambusia affinis* is listed as tolerant. Literature pertaining to *G. affinis* may pertain to *G. holbrooki* as well, since the two were formerly treated as conspecific. *G. holbrooki* is native to the Delaware drainage and may occur in tributaries of Delaware Bay. *G. affinis* has been introduced into the Delaware drainage and is probably now more widespread within the estuary. Three groups denoted with ND (no data) represent groups of fish for which information sought, without finding specific lacked literature on oxygen sensitivity. This group includes small minnow species, which includes a number of species occurring in fresh water. Some of these are common in fresh water parts of the estuary and may stray into oligohaline water. *Rhinichthys* spp. are in Cyprinidae and are part of the group of small minnow species. Of the tolerant species/groups, five were considered tolerant and 11 were considered likely to be tolerant. Those regarded as likely to be tolerant lacked specific data on oxygen requirements, but are generally referred to as tolerant of low oxygen or hypoxic conditions.

The 34 non-fish taxa classified as tolerant ranged from plants to chironomids (Table 4). Of these, 11 were deemed tolerant because literature was found directly stating the tolerance of that species or genus to low DO. 23 species were deemed likely to be tolerant due to evidence in the literature of other species in that family having tolerance of low DO, evidence citing the ability to become anaerobic, or because there was a substantial lack of research on that species in regards to oxygen.

Table 3. List of fish species or families deemed tolerant of low dissolved oxygen based upon a primary literature search, their location within the estuary, and list of references.

Species	Common Name	Sensitivity	Location	References
Catostomus commersoni	White Sucker	P	F	126
Cyprinus carpio	Common Carp	T	F	5
Cyprinidae	Small minnow species	ND	F	124
Rhinichthys spp.	Dace	ND	F	40
Ameiurus spp.	Bullheads	ND	F	37, 79
Gobiesox strumosus	Skilletfish	P	M	100
Fundulus spp.	Killifish	P	C	79
Lucania parva	Rainwater Killifish	P	C	46
Cyprinodon variegatus	Sheepshead Minnow	T	C	10, 46
Gambusia affinis	Mosquitofish	T	C	46, 59
Menidia menidia	Atlantic Silverside	P	C	44
Gasterosteus aculeatus	Threespine Stickleback	T	C	129
Apeltes quadracus	Fourspine Stickleback	P	C	77
Syngnathus fuscus	Northern Pipefish	P	C	77
Prionotus carolinus	Northern Sea Robin	P	C	46
Gobiosoma bosc	Naked Goby	P	C	100
Chasmodes bosquianus	Striped Blenny	P	M	100
Tautoga onitis	Tautog	T	M	112
Trinectes maculatus	Hogchoker	P	M	38

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 4. List of non-fish species deemed tolerant of low oxygen based upon a primary literature search, their location within the estuary, and list of references.

Taxon	Species	Common Name	Sensitivity	Location	References
Plant	*Zostera marina*	Seawrack	T	M	88
Coral	*Astrangia poculata*	Northern Coral	P	M	38
Snail	*Ilyanassa obsoleta*	Eastern Mudsnail	P	C	38, 131
Whelk	*Busycotypus canaliculatum*	Channeled Whelk	P	M	67, 129, 131
Whelk	*Busycotypus carica*	Knobbed Whelk	P	M	67, 131
Mussel	*Mytilus edulis*	Blue Mussel	T	C	35, 38, 50, 61, 67, 69, 96, 108, 129, 131
Oytser	*Cassostrea virginica*	American oyster	T	M	14, 22, 50, 67, 87, 103, 107, 114, 115, 129, 130, 131
Clam	*Nucula proxima*	Nut Clam	P	M	38, 66, 69
Clam	*Gemma gemma*	Amethyst Gem Clam	P	M	38, 66, 69
Clam	*Spisula solidissima*	Atlantic Surfclam	T	M	22, 35, 38, 50, 66, 67, 129, 130, 131
Clam	*Tellina agilis*	Northern Dwarf Tellin	P	M	38, 50, 66, 69, 129
Clam	*Ensis directus*	Atlantic Jackknife Clam	P	M	38, 50, 66, 69, 108
Clam	*Mya arenaria*	Soft Shell Clam	T	C	22, 38, 50, 61, 67, 114, 129, 131
Clam	*Mulina lateralis*	Dwarf Surf Clam	P	M	38, 69, 129
Polychaete	*Glycera dibranchiata*	Bloodworms	P	M	38, 50, 66, 69
Polychaete	*Heteromastus filiformis*	-	T	C	35, 38, 61, 66, 69, 96
Polychaete	*Sabellaria spp.*	-	T	M	38, 98
Polychaete	*Hydroides spp.*	-	P	M	38
Oligochaete	*Limnodrilus spp.*	-	P	M	27, 65, 66, 129
Horsehoe Crab	*Limulus polyphemus*	Horseshoe Crab	T	M	1, 17, 38, 45, 50, 87, 108, 129
Water Flea	*Daphnia spp.*	Water Flea	P	C	22, 129
Copepod	*Halicyclops fosteri*	-	P	M	26
Copepod	*Acartia hudsonica*	-	P	M	26
Copepod	*Pseudodiaptomus pelagicus*	-	P	M	26
Barnacles	*Balanus spp.*	-	T	M	26, 38, 50, 98, 129
Crayfish	*Orconectes limosus*	Spinycheek Crayfish	P	F	27, 50, 70, 129, 141
Crayfish	*Cambarus bartonii*	Appalachian Brook Crayfish	P	F	50, 70, 141
Hermit Crab	*Pagurus spp.*	Hermit Crab	P	M	38, 50, 69, 129
Sea Squirt	*Molgula spp.*	-	T	M	38, 99
Chironomid	*Prodadius culiciformis*	-	P	F	27, 50, 57, 66
Chironomid	*Polypedilum spp.*	-	P	F	50, 57, 65, 66
Chironomid	*Cryptochironomus spp.*	-	P	F	27, 50, 57, 66
Chironomid	*Cladotanytarso spp.*	-	P	F	50, 57, 66

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

3. SPECIES ABSENT DUE TO DISSOLVED OXYGEN LIMITATIONS

If species are currently not found in the estuary because of existing DO conditions, their inclusion would be critical in establishing criteria. This assessment needs to be considered tentative, since it represents interpretation of causes of events that do not occur. Criteria for consideration as candidate species are:

a. Species occurring in parts of the Delaware drainage which do not occur in the estuary; or
b. Species formerly occurring in the estuary, but not currently known; or
c. Species occurring in nearby estuaries; and
d. Likelihood that DO is or was a primary factor in the current absence of this species.

For task I, we assessed species formerly occurring in the estuary or occurring in the drainage but not in the estuary. Investigation of species present in nearby estuaries would need to be done in subsequent steps.

No candidate species were defined by criteria a or b, and d. Species meeting criteria a or b include:

Longnose Gar *Lepisosteus osseus*. This species appears to have been extirpated from the Delaware drainage. It formerly occurred in at least freshwater portions of the estuary. However, since the gar is an air-breather, DO limitation is presumably not the cause of its extirpation.

Rainbow Smelt *Osmerus mordax*. This anadromous species occurred in the Delaware estuary, although we have no evidence of a smelt fishery in the drainage analogous to that occurring in other parts of its range. It was probably extirpated from the drainage in the 19th Century. Rainbow Smelt has been reported relatively recently, but there is no evidence of an established population in the estuary. Reduced DO has not been suggested as a cause of its extirpation from the drainage.

Bridle Shiner *Notropis bifrenatus*. There are a few records of this species in the estuary, including oligohaline areas. These occurrences have been attributed to fish straying from populations in the Delaware River. This species was once common in fresh water parts of the drainage, but is currently restricted to a few sites, none near the estuary. Its decrease has been attributed to loss of aquatic vegetation, decrease in water clarity and possibly by introduction of predators. Therefore, DO sensitivity is not considered likely as a base cause of loss of this species from the estuary.

Other fresh water fishes. A number of species occur in fresh waters of the drainage. There may be historical records of some of these in the estuary, especially in the upper estuary. Many of these occurrences probably represent strays from established populations and are reasons for inclusion in the candidate sensitive species list. As with the Bridle Shiner, some of these species have decreased in abundance, further reducing the change for current occurrence in the estuary.

When determining the distribution of sensitive species in the estuary, limitation by current DO conditions will need to be considered. A similar analysis of possible changes in distribution resulting from changes in DO would need to be done, although that might require a detailed analysis of current spatial patterns of DO.

4. POTENTIAL EXPERTS FOR THE EXECUTION OF PROPOSED METHODOLOGY

During this phase of the proposed methodology, experts for collaboration were not sought but were identified for potential future collaboration as authors of published research. In the next steps of the proposed methodology, these experts may be contacted if a significant lack of information is found after the literature is extensively reviewed. One gap in the data is likely to be related to the spatial and temporal distributional patterns of species in the Delaware Estuary, which may require input from other researchers in the estuary for information. A second likely gap is contradictory information on sensitivity, e.g., for unionid mussels. A third likely gap is extrapolating information on some life stages to other life stages which have not been studied.

5. SECONDARY PATHWAYS OF OXYGEN SENSITIVITY

A number of geochemical processes occur under low oxygen concentrations that can indirectly and directly affect the health of aquatic estuarine species. The effect of these secondary pathways on oxygen concentrations in benthic sediments and overlying water should be considered when determining the oxygen requirements of both fresh and marine estuarine species, particularly benthic species.

Oxygen deficiency may affect nutrient concentrations in the water column by altering the cycling of phosphorus, nitrogen and carbon. Phosphorus fluxes from benthic sediments to the overlaying water can increase under hypoxic conditions in both fresh (149) and coastal marine systems (147, 151). The efficiency of nitrogen removal and organic carbon remineralization via denitrification and anaerobic ammonium oxidation may decline under hypoxic conditions (146, and references therein). These changes in nutrient

dynamics can accelerate primary productivity, furthering eutrophication and associated declines in oxygen concentrations. Somewhat conversely, it has been proposed that under low oxygen concentrations, CO_2 concentrations my inhibit respiration by aerobic marine organisms (144), effectively raising the oxygen concentration threshold for hypoxia.

When benthic sediments and overlying water becomes anoxic, benthic metabolism shifts to anaerobic pathways (ex. sulfate reduction), increasing the concentrations of reduced metabolites (ex. sulfide) in the sediment and overlying water (152, and references therein). Sulfide, in particular, has been shown to be toxic to aerobic organisms (150) and to decrease the survival times of marine benthic communities under hypoxia by, on average, 30% (153). This effect is greater on eggs and juveniles. Sulfate-reducing bacteria have also been shown to be the principal methylators of Hg^{2+} in anoxic sediments (145), although iron-reducing bacteria and methanogens may also play a role (148). Methylmercury is the most toxicologically important species in regards to aquatic species and human health risks and is the predominant form of mercury that biomagnifies in the aquatic food chain (148, and references therein).

NEXT STEPS

Under Task Order 1, steps 1-4 of the proposed methodology have been completed. From the results of the primary literature search, 50 species have been deemed candidate key sensitive species and are being recommended for inclusion in the next step (Step 5) of the proposed methodology.

Narrowing this candidate list in Step 6 may be accomplished by choosing species with the highest DO requirements in different places and times to determine the most stringent requirements. Protection of these key species would likely protect other species with higher tolerances. Alternately, the list may be narrowed by changing the criteria for inclusion, by deleting species where definitive information is lacking, or based on other species characteristics (e.g., uncommon or limited occurrence in the estuary or non-native status).

Steps 7 and 8 will then be executed by additional literature searches and potential collaboration with experts to determine the spatial and temporal species patterns within the Delaware Estuary. Additionally, information for each of the key species on appropriate exposure and averaging periods for DO will be identified to the greatest extent possible based on current literature and data to complete Step 9 of the proposed methodology.

At this point, any persistent data gaps will be identified (Step 10). We anticipate likely areas of data gaps are:

1) Resolution of contradictory information on DO sensitivity;
2) Extrapolation of rigorous studies to other life stages or to different environmental conditions (e.g., salinity);
3) Providing more quantitative information on some taxa for which existing information is not adequate to determine sensitivity;
4) Providing more detailed information on spatial and temporal occurrence of different species and life stages; such information may be especially important where recent changes in environmental conditions have led to changes in spatial distribution or temporal occurrence which are not well documented in the published literature;
5) Determination of important data needs which are likely to require additional study.

Methods for investigating these issues include: a) targeted literature searches, e.g., on specific taxa without limitation to those explicitly discussing DO sensitivity; b) discussion of unpublished, relevant information, e.g., on spatial and temporal distribution, with personnel from academic, governmental, non-governmental and private entities; c) discussion of specific issues with outside experts; d) and feedback from review of draft versions of the final report.

The primary literature, information, and data sought throughout the proposed methodology will be from appropriate scientific or published sources and special effort will be made to identify and obtain the most recent studies and reports. Unpublished data will be used where available, relevant and of high technical quality. All sources consulted will be appropriately documented and listed.

The primary deliverable of this evaluation of DO needs would be the set of tables (Step 11) and a report listing the DO requirements for each key species, such that the aggregate spatial and temporal DO need may be defined in support of development of new DO criteria for the Delaware Estuary. This may include consideration, description, and recommendations regarding appropriate exposure and averaging periods (e.g., instantaneous minimum, daily averages, seasonal averages, etc.), or that step might be considered as part of setting criteria rather than reviewing literature. The report may also include discussion of specific cases where existing information is either inadequate or sufficiently contradictory that precise quantitative DO requirements cannot be made. These cases would be especially important where estimates of DO requirements of a taxon exceed those of other taxa occurring at the same time and place, since these would have significant impact on water quality standards for DO.

SOURCES & REFERENCE LIST - SPECIES

1. Adkins J (2008) State of the Delaware Estuary 2008. Estuary News 18:1–36
2. Agnew DJ, Jones MB (1986) Metabolic adaptations of Gammarus duebeni Liljeborg (Crustacea, Amphipoda) to hypoxia in a sewage treatment plant. Comp Biochem Physiol 84A:475–478
3. Aho JM, Anderson CS, Terrell JW (1986) Habitat suitability index models and instream flow suitability curves: redbreast sunfish. US Fish Wildl Rep 82(10.119):23 pp
4. Albert RC (1988) The historical context of water quality management for the Delaware Estuary. Estuaries 11:99–107
5. Allen AW (1982) Habitat suitability index models: common carp. USDI Fish Wildl Serv Rep FWS/OBS-82:27 pp
6. Allen PJ, Mitchell ZA, Devries RJ, Aboagye DL, Ciaramella MA, Ramee SW, Stewart HA, Shartau RB (2014) Salinity effects on Atlantic sturgeon (Acipenser oxyrinchus oxyrinchus Mitchill, 1815) growth and osmoregulation. J Appl Ichthyol 1–8
7. Bailey H, Curran C, Pucher S, Sutula M (2014) Science supporting dissolved oxygen objectives for Suisun Marsh. South Calif Coast Water Res Proj Tech Rep 830:33 pp
8. Bain MB, Bain JL (1982) Habitat suitability index models: coastal stocks of striped bass. US Fish Wildl Serv Rep FWS/OBS-82:29 pp
9. Batiuk RA, Breitburg DL, Diaz RJ, Cronin TM, Secor DH, Thursby G (2009) Derivation of habitat-specific dissolved oxygen criteria for Chesapeake Bay and its tidal tributaries. J Exp Mar Bio Ecol 381:S204–S215
10. Bennett WA (1994) Responses of selected Texas fishes to abiotic factors, and an evaluation of the mechanisms controlling thermal tolerance of the sheephead minnow. University of North Texas
11. Breitburg D (2002) Effects of hypoxia, and the balance between hypoxia and enrichment, on coastal fishes and fisheries. Estuaries 25:767–781
12. Breitburg DL, Adamack A, Rose KA, Kolesar SE, Decker B, Purcell JE, Keister JE, Cowan JH (2003) The pattern and influence of low dissolved oxygen in the Patuxent River, a seasonally hypoxic estuary. Estuaries 26:280–297
13. Brundage HMI, Herron JCOI (2009) Investigations of juvenile shortnose and Atlantic sturgeons in the lower tidal Delaware River. Bull New Jersey Acad Sci 54:1–8
14. Buroker NE (1982) Oxygen consumption in the American oyster Crassostrea virginica. Mar Ecol Prog Ser 9:59–68
15. Burton, D.T; Richardson, L.B., Moore CJ (1980) Effect of oxygen reduction rate and constant low dissolved oxygen concentrations on two estuarine fish. Trans Am Fish Soc 109:552–557
16. Campbell JG, Goodman LR (2004) Acute sensitivity of juvenile shortnose sturgeon to low dissolved oxygen concentrations. Trans Am Fish Soc 133:772–776
17. Carlsson KH, Gade G (1986) Metabolic adaptation of the horseshoe crab, Limulus polyphemus, during exercise and environmental hypoxia and subsequent recovery. Biol Bull 171:217–235
18. Cech JJ, Mitchell SJ, Wragg TE (1984) Comparative growth of juvenile white sturgeon and striped bass: effects of temperature and hypoxia. Coast Estuar Res Fed 7:12–18
19. Chapman G (1986) Ambient water quality criteria for dissolved oxygen. US Environ Prot Agency 440/5-86-0:46 pp
20. Chen L-Y, Heath AG, Neves RJ (2001) Comparision of oxygen consumption in freshwater mussels (Unionidae) from different habitats during declining dissolved oxygen concentration. Hydrobiologia 450:209–214
21. Chesapeake Bay Program (2003) New Chesapeake Bay water quality criteria: dissolved oxygen. Backgrounder 1 pp
22. Chesapeake Bay Program (2002) Dissolved Oxygen Criteria. pp 7–79

23. Ciccotto P, Stranko S (2011) Patterns of shield darter, Percina peltata, distribution in the Eastern Piedmont of Maryland, USA. Environ Biol Fishes 92:141–150
24. Cook MF, Soloman RC (1987) Habitat suitability index models: muskellunge. US Fish Wildl Rep 82(10.148):33 pp
25. Crance J (1986) Habitat suitability index models and instream flow suitability curves: shortnose sturgeon. US Fish Wildl Rep 82(10.129):31 pp
26. Cronin LE, Daiber JC, Hulburt EM (1962) Quantitative aspects of zooplankton in the Delaware River estuary. Chesap Sci 3:63–93
27. Crumb SE (1977) Macrobenthos of the Tidal Delaware River between Trenton and Burlington, New Jersey. Chesap Sci 18:253–265
28. Das T, Stickle WB (1993) Sensitivity of crabs Callinectes sapidus and C. similis and the gastropod Stramonita haemastoma to hypoxia and anoxia. Mar Ecol Prog Ser 98:263–274
29. Davis JC (1975) Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review. J Fish Res Board Canada 32:2295–2332
30. Delaware River Basin Commission (1979) Dissolved oxygen requirements of a “fishable” Delaware River Estuary.
31. Delaware River Basin Commission (2013) Administrative Manual – Part III Water Quality Regulations. Water Qual Regul 18 CFR Par:136 pp
32. Delaware River Basin Commission (2015) Existing Use Evaluation for Zones 3, 4, & 5 of the Delaware Estuary.
33. Delaware River Basin Commission (2008) Delaware River: State of the basin report.
34. Deubler Jr. EE, Posner GS (1963) Response of Postlarval Flounders, Paralicthys lethostigma, to Water of Low Oxygen Concentrations. Copeia 1963:312–317
35. Diaz RJ, Rosenberg R (1995) Marine benthic hypoxia: A review of its ecological effects and the behavioural responses of benthic macrofauna. Oceanogr Mar Biol 33:245–303
36. Dittel AI, Epifanio CE (1982) Seasonal abundance and vertical-distribution of crab larvae in Delaware Bay. Estuaries 5:197–202
37. Doudoroff P, Shumway DL (1970) Dissolved oxygen requirements of freshwater fishes. FAO Fish Tech Pap 86:1–292
38. Dove LE, Nyman RM (eds) (1995) Living resources of the Delaware Estuary. The Delaware Estuary Program
39. Edwards EA, Gebhart G, Maughan OE (1983) Habitat suitability index models: smallmouth bass. US Dept Int Fish Wildl Serv Rep FWS/OBS-82:47 pp
40. Edwards EA, Hiram L, Schreck CB (1983) Habitat suitability index models: longnose dace. USDI Fish Wildl Serv Rep FWS/OBS-82:13 pp
41. Edwards EA, Krieger DA, Bacteller M, Maughn OE (1982) Habitat suitability index models: black crappie. USDI Fish Wildl Serv Rep FWS/OBS-82:25 pp
42. Edwards EA, Krieger DA, Gebhart G, Maughan OE (1982) Habitat suitability index models: white crappie. USDI Fish Wildl Serv Rep FWS/OBS-82:22 pp
43. Elshout PMF, Dionisio Pires LM, Leuven RSEW, Wendelaar Bonga SE, Hendriks AJ (2013) Low oxygen tolerance of different life stages of temperate freshwater fish species. J Fish Biol 83:190–206
44. Fay CW, Neves RJ, Pardue GB (1983) Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Mid-Atlantic): Atlantic silverside. US Fish Wildl Serv Rep FWS/OBS-82:24
45. Frithsen JB, Killam K, Young M (1991) An assessment of key biological resources in the Delaware River Estuary. Delaware Estuary Biol Assess 193 pp
46. Gelwick FP, Senol A, Arrington DA, Winemiller KO (2001) Fish assemblage structure in relation to environmental variation in a Texas Gulf coastal wetland. Estuaries 24:285–296

47. Gilbert CR (1989) Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Mid-Atlantic): Atlantic and shortnosed sturgeons. US Fish Wildl Rep 82(11.122):28 pp
48. Gilbert CR (1986) Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (South Florida): southern, gulf, and summer Flounders. US Dept Int Fish Wildl Serv Rep 82(11.54):27 pp
49. Gosner KL (1978) A field guide to the Atlantic seashore. Houghton Mifflin Company, Boston, MA
50. Grieshaber MK, Hardewig I, Kreutzer U, Pörtner H-O (1994) Physiological and metabolic responses to hypoxia in invertebrates. Rev Physiol Biochem Pharmacol 125:43–147
51. Hales LS, Van Den Avyle MJ (1989) Species profiles: Life histories and environmental requirements of coastal fishes and invertebrates (South Atlantic): spot. US Fish Wildl Serv Rep 82(11.91):24 pp
52. Harris JE, Hightower JE (2011) Spawning habitat selection of hickory shad. North Am J Fish Manag 31:495–505
53. Hoback WW, Barnhart MC (1996) Lethal limits and sublethal effects of hypoxia on the amphipod Gammarus pseudolimnaeus. J North Am Benthol Soc 15:117–126
54. Horwitz RJ (1986) Fishes of the Delaware Estuary in Pennsylvania. In: Majumdar SK, Brenner FJ, Rhoads AF (eds) Endangeed Threat. species programs Pennsylvania other states Causes, issues, Manag. The Pennsylvania Academy of Science, pp 177–201
55. Hulburt EM (1957) The distribution of Neomysis americana in the estuary of the Delaware River. Am Soc Limnol Oceanogr 2:1–11
56. Inskip PD (1982) Habitat suitability index models: northern pike. US Dept Int Fish Wildl Serv FWS/OBS-82:40 pp
57. Irving EC, Liber K, Culp JM (2004) Lethal and sublethal effects of low dissolved oxygen condition on two aquatic invertebrates, Chironomus tentans and Hyalella azteca. Environ Toxicol Chem 23:1561–1566
58. Jenkins WE, Smith TIJ, Heyward LD, Knott DM (1993) Tolerance of shortnose sturgeon, Acipenser brevirostrum, juveniles to different salinity and dissolved oxygen concentrations. Proc Annu Conf Southeast Assoc Fish Wildl Agencies 47:476–484
59. Johnson L (2008) Pacific Northwest aquatic invasive species profile: Western mosquitofish (Gambusia affinis).
60. Johnson TB, Evans DO (1991) Behavior, energetics, and associated mortality of young-of-the-year white perch (Morone americana) and yellow perch (Perda flavescens) under simulated winter. Can J Fish Aquat Sci 48:672–680
61. Jørgensen BB (1980) Seasonal oxygen depletion in the bottom waters of a Danish Fjord and its effect on the benthic community. Oikos 34:68–76
62. Jørgensen BB, Revsbech NP (1985) Diffusive boundary layers and the oxygen uptake of sediments and detritus. Limnol Oceanogr 30:111–122
63. Kemp WM, Sampou PA, Garber J, Tuttle J, Boynton WR (1992) Seasonal depletion of oxygen from bottom waters of Chesapeake Bay: roles of benthic and planktonic respiration and physical exchange processes. Mar Ecol Prog Ser 85:137–152
64. Krieger DA, Terrell JW, Nelson PC (1983) Habitat suitability information: yellow perch. US Fish Wildl Rep FWS/OBS-83:37 pp
65. Lenat DR (1993) A biotic index for the Southeastern United States: derivation and list of tolerance values, with criteria for assigning water-quality ratings. J North Am Benthol Soc 12:279–290
66. Llansó RJ, Scott LC, Dauer DM, Hyland JL, Russell DE (2002) An estuarine benthic index of biotic integrity for the Mid-Atlantic region of the United States. I. Classification of assemblages and habitat definition. Estuaries 25:1219–1230

67. MacKenzie CLJ, Burrell VGJ, Rosenfield A, Hobart WL (1997) The history, present condition, and future of the molluscan fisheries of North and Central America and Europe. NOAA Tech Rep NMFS 127:234 pp
68. Maltby L (1995) Sensitivity of the crustaceans Gammarus pulex (L.) and Asellus aquaticus (L.) to short-term exposure to hypoxia and unionized ammonia: observations and possible mechanisms. Water Res 29:781–787
69. Maurer D, Watling L, Kinner P, Leathem W, Wethe C (1978) Benthic invertebrate assemblages of Delaware Bay. Mar Biol 45:65–78
70. McMahon BR, Burggren WW, Wilkens JL (1974) Respiratory responses to long-term hypoxic stress in the crayfish Orconectes virilis. J Exp Biol 60:195–206
71. McMahon TE (1982) Habitat suitability index models: creek chub. USDI Fish Wildl Serv Rep FWS/OBS-82:23 pp
72. McMahon TE, Terrell JW (1982) Habitat suitability index models: channel catfish. USDI Fish Wildl Serv Rep FWS/OBS-82:29 pp
73. McMahon TE, Terrell JW, Nelson PC (1984) Habitat suitability information: walleye. US Fish Wildl Rep FWS/OBS-82:43 pp
74. Mercer LP (1989) Species Profiles: life histories and environmental requirements of coastal fishes and invertebrates (Mid-Atlantic): weakfish. US Fish Wildl Serv Rep 82(11.109):17 pp
75. Miller DC, Poucher SL, Coiro L (2002) Determination of lethal dissolved oxygen levels for selected marine and estuarine fishes, crustaceans, and a bivalve. Mar Biol 140:287–296
76. Moore WG (1942) Field studies on the oxygen requirements of certain fresh-water fishes. Ecology 23:319–329
77. Moran D (1986) Life Histories and Environmental Requirements of Coastal Fishes Fish and Invertebrates (North Atlantic) American Shad. Biol. Rep.
78. Morton T (1989) Species Profiles: life histories and environmental requirements of coastal fishes and invertebrates (Mid-Atlantic): bay anchovy. US Fish Wildl Serv Rep 82 (11.97):13 pp
79. Moss, D.D.; Scott DC (1989) Dissolved-oxygen requirements of three species of fish. Trans Am Fish Soc 90:377–393
80. National Marine Fisheries Service, National Oceanic and Atmospheric Administration (2017) Endangered and threatened species; designation of critical habitat for the endangered New York Bight, Chesapeake Bay, Carolina and South Atlantic distinct population segments of Atlantic Sturgeon and the threatened Gulf of Maine distinct population segmen. 82:39160–39274
81. Niklitschek EJ, Secor DH (2009) Dissolved oxygen, temperature and salinity effects on the ecophysiology and survival of juvenile Atlantic sturgeon in estuarine waters: II. Model development and testing. J Exp Mar Bio Ecol 381:S161–S172
82. NYCDEP (2015) Consolidated assessment and listing methodology section 305(b) assessment methodology.
83. O'Herron JCII, Lloyd T, Laidig K (1994) A survey of fish in the Delaware estuary from the area of the Chesapeake and Delaware Canal to Trenton. Delaware Estuary Progr Rep 94–1:42 pp
84. Oliver JD, Van Den Avyle MJ, Bozeman ELJ (1989) Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (South Atlantic): bluefish. US Fish Wildl Serv Rep 82(11.96):13 pp
85. PA Department of Environmental Protection (1996) Rationale for the development of ambient water quality criteria for dissolved oxygen.
86. Pardue GB (1983) Habitat suitability index models: alewife and blueback herring. US Dept Int Fish Wildl Serv Rep FWS/OBS-82:22 pp
87. Partnership for the Delaware Estuary (2012) Technical report for the Delaware Estuary and Basin. PDE Rep No 12–1:255 pp

88. Pedersen O, Binzer T, Borum J (2004) Sulphide intrusion in eelgrass (Zostera marina L.). Plant Cell Environ 27:595–602
89. Philadelphia Water Department (2011) Biological Resources. In: Delaware Direct Watershed River Conserv. Plan. pp 1–28
90. Pihl L, Baden SP, Diaz RJ (1991) Effects of periodic hypoxia on distribution of demersal fish and crustaceans. Mar Biol 108:349–360
91. Qureshi NA, Rabalais NN (2001) Distribution of zooplankton on a seasonally hypoxic continental shelf. In: Rabalais NN, Turner RE (eds) Coast. hypoxia consequences living Resour. Ecosyst. Coastal and Estuarine Studies 58, American Geophysical Union, Washington, D.C., pp 61–76
92. Rice JA, Thompson JS, Sykes JA, Water CT (2013) The role of metalimnetic hypoxia in striped bass summer kills: consequences and management implications. Am Fish Soc Symp 80:121–145
93. Robins CR, Ray GC (1986) A field guide to Atlantic coast fishes of North America. Houghton Mifflin Company, Boston, MA
94. Rogers SG, Van Den Avyle MJ (1989) Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Mid-Atlantic): Atlantic menhaden. US Fish Wildl Serv Rep 82:23 pp
95. Roman MR, Gauzens AL, Rhinehart WK, White JR (1993) Effects of low oxygen waters on Chesapeake Bay zooplankton. Limnol Oceanogr 38:1603–1614
96. Rosenberg R, Loo L, Möller P (1992) Hypoxia, salinity and temperatures as structuring factors for marine benthic comunities in eutrophic area. Netherlands J Sea Res 30:121–129
97. Rutherford LDJ, Thuesen E V. (2005) Metabolic performance and survival of medusae in estaurine hypoxia. Mar Ecol Prog Ser 294:189–200
98. Sagasti A, Schaffner LC, Duffy JE (2000) Epifaunal communities thrive in an estuary with hypoxic episodes. Estuaries 23:474–487
99. Sagasti A, Schaffner LC, Duffy JE (2001) Effects of periodic hypoxia on mortality, feeding and predation in an estuarine epifaunal community. J Exp Mar Bio Ecol 258:257–283
100. Saksena V, Joseph E (1972) Dissolved oxygen requirements of newly-hatched larvae of the striped blenny (Chasmodes bosquianus), the naked goby (Gobiosoma bosci), and the skilletfish (Gobiesox strumosus). Chesap Sci 13:23–28
101. Secor, D.H.; Gunderson TE (1998) Effects of hypoxia and temperature on survival, growth and respiration of juvenile Atlantic sturgeon, Acipencer oxyrinchus. Fish Bull 96:603–613
102. Secor DH, Niklitschek EJ (2001) Hypoxia and sturgeons: report to the Chesapeake Bay Program dissolved oxygen criteria team. Univ Maryl Cent Environ Sci Rep No TS-314-01-:26 pp
103. Sellers M a., Stanley JG (1984) Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (North Atlantic): American oyster. US Fish Wildl Rep FWS/OBS-82:15 pp
104. Sharp JH (1983) The Delaware estuary: research as background for estuarine management and development. Delaware River Bay Auth Rep 326 pp
105. Sharp JH (2010) Estuarine oxygen dynamics: What can we learn about hypoxia from long-time records in the Delaware Estuary? Limnol Oceanogr 55:535–548
106. Shepherd GR, Packer DB (2006) Essential fish habitat source document: bluefish, Pomatomus saltatrix, life history and habitat characteristics. NOAA Tech Memo NMFS-NE-19:89 pp
107. Shumway SE, Koehn RK (1982) Oxygen consumption in the American oyster Crassostrea virginica. Mar Ecol Prog Ser 9:59–68
108. Shuster Jr. CN (1959) A biological evaluation of the Delaware River Estuary, Informatio. University of Delaware Marine Laboratories
109. Stalder LC, Marcus NH (1997) Zooplankton responses to hypoxia: behavioral-patterns and survival of three species of calanoid copepods. Mar Biol 127:599–607

110. Stanley JG, Danie DS (1983) Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (North Atlantic): white perch. US Fish Wildl Serv Rep FWS/OBS-82:12 pp
111. Stauffer JR, Criswell RW, Fischer DP (2016) The fishes of Pennsylvania. Cichlid Press, El Paso, TX
112. Steimle FW, Shaheen PA (1999) Tautog (Tautoga onitis) Life History and Habitat Requirements. NOAA Tech Memo NMFS-NE-11:18 pp
113. Steimle F, Zetlin C, Berrien P, Johnson D, Chang S (1999) Essential fish habitat source document: Scup, Stenotomus chrysops, life history and habitat characteristics. NOAA Tech Memo NMFS-NE-14:48 pp
114. Steve KJ, Cynthia S, Marcia O, Richard B, Mountford (1992) Chesapeake Bay dissolved oxygen goal for restoration of living resource habitats. Chesap Bay Progr Rep CBP/TRS 88:80 pp
115. Stickle WB, Kapper M a, Liu L-L, Gnaiger E, Wang SY (1989) Metabolic adaptations of several species of crustaceans and molluscs to hypoxia: tolerance and microcalorimetric studies. Biol Bull 177:303–312
116. Stickney RR, Cuenco ML (1982) Habitat suitability index models: juvenile spot. US Dept Int Fish Wildl Serv Rep FWS/OBS-82:12 pp
117. Stier DJ, Crance, Johnie H (1985) Habitat suitability index models and instream flow suitability curves: American shad. US Fish Wildl Serv Rep 82(10.88):34 pp
118. Stierhoff KL, Targett TE, Miller K (2006) Ecophysiological responses of juvenile summer and winter flounder to hypoxia: experimental and modeling analyses of effects on estuarine nursery quality. Mar Ecol Prog Ser 325:255–266
119. Stuber RJ, Gebhart G, Maughan OE (1982) Habitat suitability index models: green sunfish. USDI Fish Wildl Serv Rep FWS/OBS-82:28 pp
120. Stuber RJ, Glebhart G, Maughan OE (1982) Habitat suitability index models: bluegill. USDI Fish Wildl Serv Rep FWS/OBS-82:26 pp
121. Stuber RJ, Gebhart G, Maughan OE (1982) Habitat suitability index models: largemouth bass. USDI Fish Wildl Serv Rep FWS/OBS-82:32 pp
122. Summers JK, Rose KA (1987) The role of interactions among environmental conditions in controlling historical fisheries variability. Estuaries 10:255–266
123. Sutton CC, O'Heron II JC, Zappalorti RT (1996) The scientific characterization of the Delaware estuary. The Delaware Estuary Program, DRBC Project No. 321; HA File No. 93.21
124. Trial JG, Wade CS, Stanley JG, Nelson PC (1983) Habitat suitability information: common shiner. USDI Fish Wildl Serv Rep FWS/OBS-82:22 pp
125. Truelson RL (1997) Dissolved oxygen criteria proposed for aquatic life in British Columbia.
126. Twomey KA, Williamson KL, Nelson PC (1984) Habitat suitability index models and instream flow suitability curves: white sucker. US Fish Wildl Serv Rep FWS/OBS-82:56 pp
127. U.S. Environmental Protection Agency (2010) Ambient water quality criteria for dissolved oxygen, water clarity and chlorophyll a for the Chesapeake Bay and its tidal tributaries. Off Water EPA 903-R-:41 pp
128. U.S. Environmental Protection Agency (2013) Revised deletion process for the site-specific recalculation procedure for aquatic life criteria. Off Water EPA-823-R-:1
129. U.S. Environmental Protection Agency (2012) Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses. PB85-22704:52 pp
130. U.S. Environmental Protection Agency (2000) Ambient aquatic life water quality criteria for dissolved oxygen (saltwater): Cape Cod to Cape Hatteras. Off Water EPA-822-R-:45 pp
131. Vaquer-Sunyer R, Duarte CM (2008) Thresholds of hypoxia for marine biodiversity. Proc Natl Acad Sci 105:15452–15457
132. Vaquer-Sunyer R, Duarte CM (2008) Thresholds of hypoxia for marine biodiversity supplemental data. Proc Natl Acad Sci. doi: 10.1073/pnas.0803833105
133. Vaquer-Sunyer R, Duarte CM (2008) Thresholds of hypoxia for marine biodiversity supporting information. Proc. Natl. Acad. Sci. 105:

134. Vargo SL, Sastry AN (1977) Acute temperature and low dissolved-oxygen tolerances of brachyuran crab (Cancer irroratus) larvae. Mar Biol 40:165–171
135. Walburg CH, Nichols PR (1967) Biology and management of the American shad and status of the fisheries, Atlantic coast of the United States, 1960. USFWS Spec Sci Rep - Fish No 550:112 pp
136. Walton WE, Wirth MC, Workman PD (2007) Environmental factors influencing survival of threespine stickleback (Gasterosteus aculeatus) in a multipurpose constructed treatment wetland in southern California. J Vector Ecol 32:90–105
137. Warren C, Doudoroff P, Shumway D (1973) Development of dissolved oxygen criteria for freshwater fish. EPA Ecol Res Ser EPA-R3-73-:1–107
138. Watling L, Bottom D, Pembroke A, Maurer D (1979) Seasonal variations in Delaware Bay phytoplankton community structure. Mar Biol 52:207–215
139. Watling L, Maurer D (1972) Marine shallow water amphipods of the Delaware Bay area, U.S.A. Crustac Suppl 3:251–266
140. Weinstein MP (1986) Habitat suitability index models: Inland silverside. US Fish Wildl Serv Biol Rep 82(10.120):25 pp
141. Wilkes PRH, McMahon BR (1982) Effect of Maintained Hypoxic Exposure on the Crayfish Orconectes rusticus. 1. Ventilatory, Acid - Base, and Cardiovascular Adjustments. J Exp Biol 98:119–137
142. Williamson KL, Nelson PC (1985) Habitat suitability index models and instream flow suitability curves: gizzard shad. US Fish Wildl Serv Rep 82(10.112):33 pp
143. Winn RN, Knott DM (1992) An evaluation of the survival of experimental populations expoosed to hypoxia in the Savannah River estuary. Mar Ecol Prog Ser 88:161–179

SOURCES & REFERENCE LIST - GEOCHEMISTRY

144. Brewer PG, Peltzer ET (2009) Limits to Marine Life. Science 324(5925): 347-348
145. Compeau GC and Bartha R (1985) Sulfate-Reducing Bacteria: Principal Methylators of Mercury in Anoxic Estuarine Sediment. Appl. and Environ. Microbiology 50(2): 498-502
146. Conley DJ, Carstensen J, Vaquer-Sunyer R, Duarte CM (2009) Ecosystem thresholds with hypoxia. Hydrobiologia 629: 21–29
147. Conley DJ., Humborg C, Rahm L, Savchuk OP, Wulff F (2002) Hypoxia in the Baltic Sea and basin-scale changes in phosphorus biogeochemistry. Environ. Sci. & Technol. 36: 5315–5320
148. Hsu-Kim H, Kucharzyk KH, Zhang T, Deschusses MA (2013) Mechanisms Regulating Mercury Bioavailability for Methylating Microorganisms in the Aquatic Environment: A Critical Review. Environ. Sci. Technol. 47(6): 2441-2456
149. Mortimer CH (1941) The exchange of dissolved substances between mud and water. J. of Ecology 29: 280–329
150. Nicholls P (1975) Inhibition of cytochrome-C oxidase by sulphide. Biochem. Soc. Trans. 3(2): 316–319
151. Nixon SW, Kelly JR, Furnas BN, Oviatt CA, Hale SS (1980) Phosphorus regeneration and the metabolism of coastal marine bottom communities. In K. R. Tenore & B. C. Coull (eds), Marine Benthic Dynamics. University of South Carolina Press, USA: 219–242
152. Steckbauer A, Duarte CM, Carstensen J, Vaquer-Sunyer R, Conley DJ (2011) Ecosystem impacts of hypoxia: thresholds of hypoxia and pathways to recovery. Environ. Res. Lett. 6
153. Vaquer-Sunyer R and Duarte CM (2010) Sulfide exposure accelerates hypoxia-driven mortality. Limnol. and Oceanogr. 55(3): 1075-1082