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Derivation of habitat-specific dissolved oxygen criteria for Chesapeake Bay and its tidal tributaries

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ABSTRACT

The Chesapeake 2000 Agreement committed its state and federal signatories to "define the water quality conditions necessary to protect aquatic living resources" in the Chesapeake Bay (USA) and its tidal tributaries. Hypoxia is one of the key water quality issues addressed as a result of the above Agreement. This paper summarizes the protection goals and specific criteria intended to achieve those goals for addressing hypoxia. The criteria take into account the variety of Bay habitats and the tendency towards low dissolved oxygen in some areas of the Bay. Stressful dissolved oxygen conditions were characterized for a diverse array of living resources of the Chesapeake Bay by different aquatic habitats: migratory fish spawning and nursery, shallow-water, open-water, deep-water, and deep-channel. The dissolved oxygen criteria derived for each of these habitats are intended to protect against adverse effects on survival, growth, reproduction and behavior. The criteria accommodate both spatial and temporal aspects of low oxygen events, and have been adopted into the Chesapeake Bay states – Maryland, Virginia, and Delaware – and the District of Columbia's water quality standards regulations. These criteria, now in the form of state regulatory standards, are driving an array of land-based and wastewater pollution reduction actions across the six-watershed.

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1. Introduction

Dissolved oxygen (DO) has been a major factor in both the ecology and evolution of aquatic organisms dependent on aerobic respiration. Oxygen drives vital metabolic processes and, when in short supply, can affect growth rates, spatial distributions, behavior, reproduction, and survival of aquatic organisms (Diaz and Rosenberg, 1995; Breitburg et al., 1997, 2009; Vaquer-Sunyer and Duarte, 2008). The result can be substantial changes in estuarine food webs affecting both microbial dominance (Baird et al., 2004) and upper trophic levels (Breitburg, 2002; Diaz and Rosenberg, 2008). There has been considerable scientific and management concern about the apparent increase in the severity and prevalence of low DO concentrations (hypoxia) in estuaries and coastal marine waters worldwide (Smith et al., 1987; Karlson et al., 2002; OSPAR, 2003; Diaz and Rosenberg, 2008).

The Chesapeake Bay and its tidal tributaries harbor diverse and productive communities of aquatic organisms that are supported by a complex and spatially varying food web (Baird and Ulanowicz, 1989; Kemp et al., 2005). In recognition of variation among Bay habitats in their use by ecologically and economically important species, as well as variation among habitats in their tendency towards development of low DO, the Chesapeake Bay Program partners (U.S. Environmental Protection Agency and the watershed states) and an advisory panel comprised of researchers and other stakeholders developed DO criteria that explicitly considered temporal and spatial aspects of both species' needs and drivers of hypoxia. This paper describes the process and results of synthesizing and applying a science-based approach to the derivation of DO criteria for managing water quality with the goal of protecting living resources and the food web upon which they depend. We considered both a wide variety of organisms ranging from plankton to finfish, and a variety of indicators of stress ranging from growth reductions to predicted mortality of all life stages.

1.1. Dissolved oxygen as a tool for estuary restoration

Unlike chemical contaminants or other more conventional pollutants, there were no clear, well established guidelines for deriving criteria for DO, particularly for estuarine waters inhabited by freshwater and marine species. The goal in setting Chesapeake DO criteria

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was to use the best science possible to define conditions that would improve or sustain the suitability of Chesapeake Bay habitats for finfish and invertebrates, with the states ultimately factoring in consideration of attainability in adopting the criteria as water quality standards. Thus, we developed criteria that would greatly increase the spatial and temporal extent of Bay waters in which oxygen concentrations were not major limitations to growth and survival of organisms dependent on particular Bay habitats. We did not, however, derive criteria that would require oxygen concentrations high enough at all times and in all locations such that no organism would be negatively affected in any location in the Bay. The states and U.S. Environmental Protection Agency (EPA) determined that such conditions would not be achievable either economically nor technologically (U.S. EPA, 2003d) and may not, in fact, reflect pre-historical conditions of Chesapeake Bay, which showed that low oxygen conditions, although not nearly as severe as today, may have been a historical feature in the deep channel of the bay (Cooper and Brush, 1991; Karlsen et al., 2000; Adelson et al., 2001; Zimmerman and Canuel, 2002; Bratton et al., 2003; Colman and Bratton, 2003; Cronin and Vann, 2003; Zheng et al., 2003).

DO criteria can play a central, defining role in reducing excessive nutrient loads and their negative effects in estuarine and coastal systems. Under EPA regulations, once adopted into states' water quality standards regulations, DO criteria define which waters are impaired and, thereby, require establishment of a total maximum daily load or TMDL. These TMDLs can then be used to establish numerical limits on loads discharged from municipal and industrial wastewater discharging facilities, regulated stormwater dischargers as well as from traditionally non-regulated sources (e.g., agricultural lands).

The DO criteria described herein were developed by a team of scientists and managers and then published by the EPA as regional Chesapeake Bay water quality criteria to protect a set of Chesapeake Bay-specific designated uses and aquatic life habitats (U.S. EPA, 2003a,d, 2004a,b, 2007, 2008). Along with similar water quality criteria for water clarity and chlorophyll *a*, the DO criteria were used as the basis for establishing caps on nutrient and sediment loads from the six states comprising the 164,480 km^2 Chesapeake Bay watershed (U.S. EPA, 2003c). These criteria have since been adopted into Maryland, Virginia, Delaware and the District of Columbia's state water quality standards regulations.

In defining what it means for the criteria to be attained, stressor magnitude, duration, return frequency, spatial extent and temporal assessment period were determined to be important (National Research Council, 2001). For the purpose of developing aquatic life criteria applicable under the Clean Water Act, stressor magnitude refers to how much of the pollutant or condition can be allowed (e.g., 5 mg L^{-1}) while still achieving the designated uses; duration refers to the period of time over which measurements of the pollutant or water quality parameter is to be averaged (e.g., the 30-day mean); and the allowable return frequency at which the criterion can be violated without a loss of the designated use also must be defined. It was determined that attainment of the Chesapeake Bay DO criteria, as well as criteria for water clarity and chlorophyll within the respective designated use habitats, would be assessed at the spatial scale of the 78 Chesapeake Bay segments (Chesapeake Bay Program, 2004). These segments are spatial units with both hydrographic and jurisdictional meaning, and with a more than 20-year record of water quality information. The temporal period for attainment assessment was set at the most recent three consecutive years of applicable water quality monitoring data (U.S. EPA, 2003a). Multi-year assessments were determined to be particularly important for shallow water habitat, which can be strongly influenced by inter-annual variation in rainfall and resulting interannual variation in nutrient loads (Paerl et al., 2006).

The DO criteria were not developed with the unrealistic assumption that acceptable attainment would be defined as fully achieving all criteria in all locations at all times. Instead, cumulative frequency distribution methodology was adopted for measuring criteria attainment and to allow for a small, but allowable percentage of instances in which criteria were not met and yet the biological communities were not impaired. The cumulative frequency distribution calculations integrate the five elements of criteria definition and attainment: magnitude, duration, return frequency, space and time (National Research Council, 2001). The methodology summarizes the frequency of instances in which the water quality threshold (e.g., DO concentration) is exceeded, as a function of the volume affected at a given place and over a defined period of time. The assessment methodology first evaluates how much of a spatial region is in exceedence of the threshold (e.g., 10% of open water designated use area) for every measurement period (e.g., a summer month in 2005). Then, each of these temporal snapshots of % exceedences are ranked among measurement periods (e.g., all summer months across all assessed years). The resultant plot shows percent of exceedences in time against percent of exceedences in space (Fig. 1). Acceptable and protective combinations of the frequency and spatial extent of such instances are defined using a biologically based reference curve (U.S. EPA, 2003a). Using this approach to define criteria attainment, one must quantify the spatial extent (volume) to which the water quality criterion has been achieved or exceeded for each monitoring event. This brings to fore issues of spatial interpolation in both two- and three-dimensions, which has required developments in software capabilities and increased geostatistical capabilities (Secor et al., 2006).

1.2. General considerations for criteria derivation

In deriving the DO criteria, the team needed to ensure that the criteria reflected the wide variety of Chesapeake Bay tidal water habitats and the seasonal movements of species across these different habitats. The criteria needed to also account for the spatial and seasonal variations in DO. Finally, the criteria needed to ensure protection of these species across an array of adverse effects – survival, growth, larval recruitment – fully factoring in the duration of the exposures leading to these adverse effects.

2. Chesapeake Bay oxygen dynamics — spatial and seasonal variation

Our goal was to consider habitat- and season-specific variations in processes that control oxygen dynamics in Chesapeake Bay in setting habitat- (i.e., designated use; see below) and temporal-specific DO criteria. The mesohaline mainstem Chesapeake Bay and lower reaches of the major tidal rivers have a stratified water column, which limits

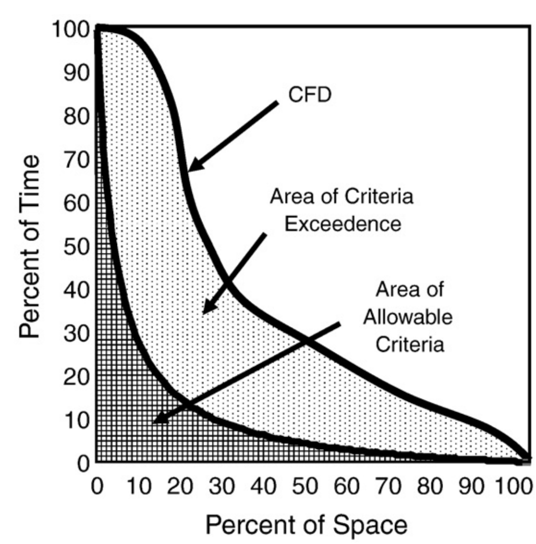

Fig. 1. Cumulative Frequency Diagram (CFD) for attainment assessment of exceedences of water quality criteria. Area of allowable criteria exceedence is determined by a reference curve representing a pristine or healthy condition (U.S. EPA, 2003a).

mixing of bottom waters with oxygenated surface waters during late spring through early autumn (Officer et al., 1984; Seliger et al., 1985; Boynton and Kemp, 2000; Hagy et al., 2004). Hypoxia and anoxia are seasonally persistent in the mesohaline mainstem Bay, but stratification and bottom-layer hypoxia can be disrupted by wind and tidal mixing in tributaries (Haas, 1977; Breitburg, 1992).

Physical and biological factors contribute to the seasonal reduction in bottom layer DO (e.g., Kemp and Boynton, 1980; Sanford et al., 1990; Kemp et al., 1992; Boynton and Kemp, 2000). The spring freshet delivers large volumes of fresh water and nutrients to the Bay, and combined with increasing temperatures and light, produces a large increase in phytoplankton biomass. Phytoplankton not consumed by suspension feeders (such as zooplankton, oysters and menhaden) sink to the subpycnocline waters, where they are decomposed by microbes over a period of days or weeks (e.g., Malone et al., 1986, 1988; Tuttle et al., 1987). The loss of oxygen due to bacterial metabolism is exacerbated because the timing coincides with the onset of increased stratification.

The timing and extent of low DO conditions in the Chesapeake Bay vary from year to year, driven largely by local weather patterns, the timing and magnitude of freshwater river flows, variation in the concurrent delivery of nutrients and sediments into tidal waters and variation in the corresponding springtime phytoplankton bloom (Officer et al., 1984; Seliger et al., 1985; Boynton and Kemp, 2000; Hagy et al., 2004). In the Chesapeake Bay's mesohaline mainstem, hypoxic conditions generally occur from June through September but have been observed to occur as early as May and extend into October.

The surface layer and much of the nearshore shallow water habitat are not subjected to low DO. However, areas of Chesapeake Bay's nearshore shallow waters periodically experience episodes of low DO through upwelling of bottom waters. In areas along the western shore of the mainstem Bay, hypoxic bottom water is advected into the shallows by a combination of internal lateral tides and winds (Carter et al., 1978; Breitburg, 1990; Sanford et al., 1990). The result can be episodes of extreme and rapid fluctuations in DO concentrations (Sanford et al., 1990). In depths as shallow as 4 m, DO concentrations may decline to 0.5 mg L^{-1} for up to 10 h (Breitburg, 1990). Diel cycling hypoxia may also occur in some small tidal systems and is related to high rates of hererotrophic metabolism driven by eutrophication (Verity et al., 2006; Tyler and Targett, 2007). Physical conditions such as calm winds and several continuous cloudy days can contribute to oxygen depletion in these shallow habitats.

3. Spatial and temporal variation in living resource use

Habitat use for many Bay species varies by season and life stage. Thus, both spatial and temporal patterns of species habitat requirements and spatial patterns in system susceptibility to develop low oxygen were considered in zoning the Bay into five designated use categories: migratory spawning and nursery habitat, shallow-water bay grass, open-water fish and shellfish, deep-water fish and shellfish and deep-channel seasonal refuge (Fig. 2). These five categories are described in detail in U.S. EPA (2003d) and reflect the habitats of an array of recreationally, commercially and ecologically important species and biological communities.

The migratory spawning and nursery designated use was designed to protect the eggs, larvae and early juveniles of migratory (anadromous) and resident tidal freshwater fish during the late winter (February 1) to late spring (May 30) spawning and nursery seasons in tidal freshwater to low-salinity (0 to 5 psu) habitats. Located primarily in the upper reaches of many Bay tidal rivers and creeks and the upper mainstem Chesapeake Bay, this use is designated to protect several species including striped bass (*Morone saxatilis*), white perch (*Morone americana*), American shad (*Alosa sapidissima*), alewife (*Alosa pseudoharengus*), blue back herring (*Alosa aestivalis*), Atlantic (*Acipenser oxyrinchus*) and shortnose (*Acipenser brevirostrum*) sturgeons, and largemouth bass (*Micropterus salmoides*).

The shallow-water bay grass designated use protects submerged aquatic vegetation (SAV) and the many fish and crab species that utilize vegetated shallow-water habitat provided by underwater grass beds. Such habitats are critical nursery habitats for many Chesapeake Bay fishes and blue crab (Ruiz et al., 1993; Wagner and Austin, 1999; Wingate and Secor, 2008). The shallow-water designated use is a seasonally designated use, and converges with the open-water designated use during the SAV growing season of April–October. Therefore, the open-water DO criteria described below apply to these shallow-water habitats (Table 1).

The open-water fish and shellfish designated use encompasses water column habitats in tidal creeks, rivers, embayments and the mainstem Chesapeake Bay and is designed to protect diverse populations of sport fish, including striped bass, bluefish (*Pomatomus salatrix*), and weakfish (*Cynoscion regalis*), as well as important bait fish such as menhaden (*Brevoortia tyrannus*) and Atlantic silversides (*Menidia menidia*). The open-water designated use applies throughout the water column during the non-summer months of October through May when the entire water column is well mixed. During June through September, with the onset of a strong stratified water column in many parts of the mainstem Bay and lower tidal tributaries, the open-water designated use only applies to the upper mixed layer of the water column above the upper pycnocline boundary. At all times of the year, the open-water designated use applies up into the shallow-waters to the high tide line.

The deep-water seasonal fish and shellfish designated use is designed to protect animals inhabiting the deeper transitional water-column and bottom habitats between the well-mixed surface waters and the very deep channels during the summer months (June–September). This use protects many bottom-feeding fish, crabs and oysters, and other ecologically important species such as the bay anchovy (*Anchoa mitchilli*).

Finally, the deep-channel seasonal refuge designated use is intended to provide some protection for bottom sediment dwelling worms and small clams that bottom-feeding fish and crabs consume. Low to no DO conditions currently occur in this habitat zone during the summer. The deep-channel use applies only during the summer months of June through September in the waters below the lower pycnocline boundary in the mesohaline mainstem Chesapeake Bay and the lower mesohaline reaches of the larger tidal rivers (e.g., Potomac, Rappahannock rivers).

4. Matching temporal duration of exposure and protection targets

Temporal processes were also incorporated into criteria to provide protection against a variety of adverse effects including: (1) reduced growth of juveniles and adults from long-term chronic exposure, (2) reduced survival of adults and juveniles resulting from short-term acute exposure, (3) reduced survival rates of larvae predicted to be of sufficient magnitude to result in reduced recruitment, and (4) reduced survival of adults and juveniles of particularly susceptible threatened or endangered species.

The larval recruitment model employed to derive individual criteria is a discrete time, density-independent model that expresses the cumulative impact of low DO as a proportion of the potential annual recruitment of a species (U.S. EPA, 2000). The impact depends on both the magnitude and duration of the hypoxia event. The model calculates the number of days a species can be exposed to a given DO concentration without impairment of annual recruitment exceeding a predetermined maximum. For the purpose of the Chesapeake Bay this maximum negative effect was set at 5% — the same percentage used in deriving EPA's Virginian Province DO criteria (U.S. EPA, 2000).

4.1. Derivation of the Chesapeake Bay dissolved oxygen criteria

The Chesapeake Bay DO water quality criteria were derived for the protection of the five tidal water designated uses against adverse

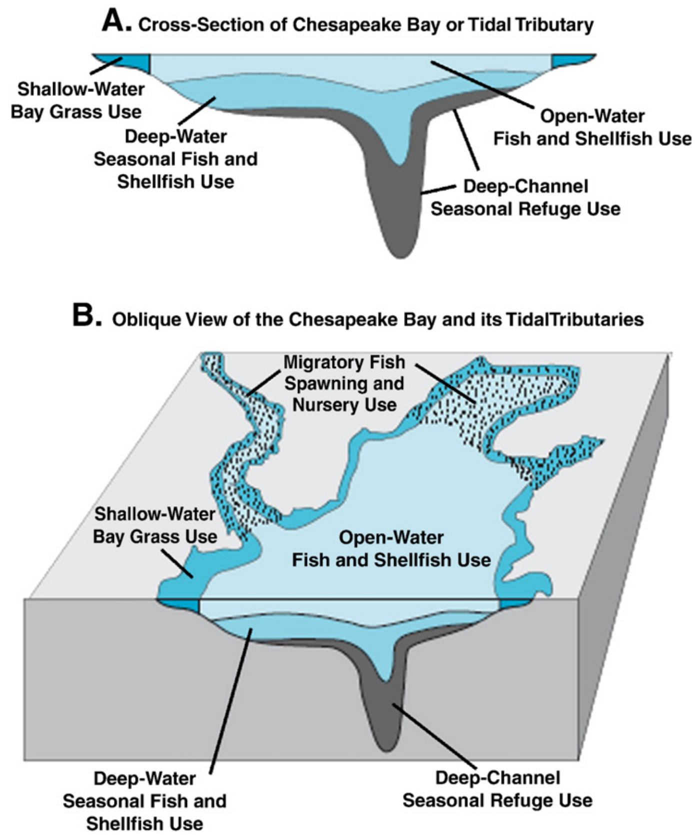

Fig. 2. Conceptual illustration of the five Chesapeake Bay tidal water designated uses zones (U.S. EPA, 2003d).

effects on survival, growth, larval recruitment, freshwater species and threatened/endangered species (Table 1). The criteria were structured so that every tidal water habitat has an applicable set of criteria protective of the unique species and communities inhabiting those tidal waters across the different seasons. Each criterion's concentration, duration and temporal application was derived to protect against specific adverse impacts within a respective designated use.

5. Migratory fish spawning and nursery criteria

Criteria that support the migratory fish spawning and nursery designated use were derived to protect the "survival, growth and propagation of balanced indigenous populations of ecologically, recreationally and commercially important anadromous, semi-anadromous and tidal-fresh resident fish species inhabiting spawning and nursery grounds from February 1 through May 31" (U.S. EPA, 2003d) (Table 1).

Table 1
Chesapeake Bay dissolved oxygen water quality criteria for the protection of tidal water designated uses against adverse effects on survival, growth, larval recruitment, freshwater species and threatened/endangered species.

Designated use	Criteria concentration/duration	Protection provided	Temporal application
Migratory fish spawning and nursery use	7-day mean ≥ 6.0 mg L^{-1} (tidal habitats with 0–0.5 salinity)	Survival/growth of larval/juvenile tidal-fresh resident fish; protective of threatened/endangered species	February 1–May 31
	Instantaneous minimum ≥ 5.0 mg L^{-1}	Survival and growth of larval/juvenile migratory fish; protective of threatened/endangered species	
	Open-water fish and shellfish designated use criteria apply		June 1–January 31
Shallow-water bay grass use	Open-water fish and shellfish designated use criteria apply		Year-round
Open-water fish and shellfish use	30-day mean ≥ 5.5 mg L^{-1} (tidal habitats with 0–0.5 salinity)	Growth of tidal-fresh juvenile and adult fish; protective of threatened/endangered species	Year-round
	30-day mean ≥ 5 mg L^{-1} (tidal habitats with >0.5 salinity)	Growth of larval, juvenile and adult fish and shellfish; protective of threatened/endangered species	
	7-day mean ≥ 4 mg L^{-1}	Survival of open-water fish larvae	
	Instantaneous minimum ≥ 3.2 mg L^{-1}	Survival of threatened/endangered sturgeon species[a]	
Deep-water seasonal fish and shellfish use	30-day mean ≥ 3 mg L^{-1}	Survival and recruitment of bay anchovy eggs and larvae	June 1–September 30
	1-day mean ≥ 2.3 mg L^{-1}	Survival of open-water juvenile and adult fish	
	Instantaneous minimum ≥ 1.7 mg L^{-1}	Survival of bay anchovy eggs and larvae	
	Open-water fish and shellfish designated-use criteria apply		October 1–May 31
Deep-channel seasonal refuge use	Instantaneous minimum ≥ 1 mg L^{-1}	Survival of bottom-dwelling worms and clams	June 1–September 30
	Open-water fish and shellfish designated use criteria apply		October 1–May 31

[a] At temperatures considered stressful to shortnose sturgeon (29 °C), DO concentrations above an instantaneous minimum of 4.3 mg L^{-1} will protect survival of this listed sturgeon species. Source: U.S. EPA, 2003a.

These criteria were designed to be protective of the survival and growth of all life stages – eggs, larvae, early juveniles and spawning adults –for a given number of species and their underlying food sources. The criteria were based on establishing DO concentrations to protect against losses in larval recruitment, growth effects on larvae and early juvenile stages, and the survival and growth effects on the early life stages of resident tidal-fresh species. Data on the effects of low DO on larval and/or spawning adult behavior were not available for factoring into the criteria derivation. Later stage juveniles and adults were protected by the open-water criteria which apply year-round and bay-wide.

To ensure protection not only of survival and recruitment of larvae into the juvenile population but also to eliminate any potential for adverse effects on growth during the critical larval and early juvenile life stages, an instantaneous minimum criterion of 5 mg L^{-1} was selected. Instantaneous minimum is defined here as exposure to a concentration for durations less than an hour. A concentration of 5 mg L^{-1} was determined to be protective of published effects on larval survival and recruitment, as well as survival and growth effects on juveniles spawning adults (Table 2). The Virginian Province saltwater criteria document states that exposures to DO concentrations above 4.8 mg L^{-1} should not result in any adverse effects on growth (U.S. EPA, 2000).

Given the lack of information on the population level consequences of short- versus long-term reductions in growth on the survival of larvae and juveniles, a specific averaging period was not recommended in the Virginian Province saltwater criteria. In the case of anadromous species, a narrow set of conditions (e.g., salinity, temperature) is required and a narrow time window exists for a successful spawn. Natural mortalities for larvae are extremely high and even short-term reductions in growth could influence advancement to the next stage through the impairment of survival and the ability to avoid predators (Houde, 1987). Therefore, the criterion value designed to protect against growth effects was applied as an instantaneous minimum (Table 1).

Setting the criterion duration of exposure as an instantaneous minimum was consistent with the instantaneous minimum duration for the 5 mg L^{-1} concentration criterion value from the EPA freshwater DO criteria for ensuring full protection of warm-water freshwater species' early life stages against short-term exposures (Table 3; U.S. EPA, 1986). As indicated below, the instantaneous minimum of the 5 mg L^{-1} criterion value also protects the survival and growth of shortnose and Atlantic sturgeons (Table 2).

Table 3
EPA freshwater dissolved oxygen water quality criteria (mg L^{-1}) for warm-water species (U.S. EPA, 1986) used to ensure the derived migratory fish spawning and nursery and open-water dissolved oxygen criteria were protective of freshwater species inhabiting Chesapeake Bay tidal water habitats.

Duration	Early life stages[a]	Other life stages
30-day mean	NA[b]	5.5
7-day mean	6	NA
7-day mean minimum	NA	4
1-day minimum[c]	5	3

[a] Includes all embryonic and larval stages and all juvenile forms to 30 days following hatching.
[b] Not applicable.
[c] All minima should be considered as instantaneous concentrations to be achieved at all times.

The migratory spawning and nursery designated use criteria were also designed to ensure protection for warm-water freshwater species' egg, larval and juvenile life stages, which co-occur with the tidal-fresh and low-salinity migratory spawning and nursery habitats (Table 1). To ensure protection for resident tidal-fresh warm-water species' early life stages, a 7-day mean criterion of 6 mg L^{-1} and an instantaneous minimum criterion of 5 mg L^{-1} were selected, consistent with the EPA freshwater criteria (Table 3) (U.S. EPA, 1986).

6. Open-water fish and shellfish criteria

DO criteria that support open-water habitats were designed to protect the "survival, growth and propagation and growth of balanced, indigenous populations of ecologically, recreationally and commercially important fish and shellfish inhabiting open-water habitats" (U.S. EPA, 2003d) (Table 1). The DO requirements for the species and communities inhabiting open- and shallow-water habitats were similar enough to ensure protection of both the open-water and shallow-water designated uses with a single set of criteria. Selected criteria values included a 30-day mean of 5.5 mg L^{-1} applied to tidal-fresh habitats (salinity 0–0.5 psu); a 30-day mean of 5 mg L^{-1} applied to all other open-water habitats (salinity>0.5 psu); a 7-day mean of 4 mg L^{-1}; and an instantaneous minimum of 3.2 mg L^{-1} (Table 4). At temperatures stressful to shortnose sturgeon (>29 °C), a 4.3 mg L^{-1} instantaneous minimum criterion was applied.

Table 2
Dissolved oxygen effects data used in the derivation of the migratory fish spawning and nursery designated use dissolved oxygen criteria to ensure protection against adverse effects on survival, growth and larval recruitment.

Criteria components	Concentration (mg L^{-1})	Duration	Source
Protection against growth effects	>4.8	–	U.S. EPA (2000)
Protection against larval recruitment effects	>4.6	30 to 40 days	U.S. EPA (2000)
	>3.4–3.8	7 days	U.S. EPA (2000)
	>2.7–2.8	Instantaneous minimum	U.S. EPA (2000)
Protection of early life stages for resident tidal freshwater species	>6	7-day mean	U.S. EPA (1986)
	>5	1-day min.	U.S. EPA (1986)
Protection against effects on threatened/ endangered species (shortnose sturgeon)	>5	30 days	Secor and Niklitschek (2001, 2002); Niklitschek (2001);
	>3.5	6 h	Secor and Gunderson (1998); Jenkins et al. (1993);
	>3.2[a]	2 h	Campbell and Goodman (2004)
	>4.3[b]	2 h	Campbell and Goodman (2004)
Additional published findings			
Growth effects on striped bass	<3 to 4	–	Brandt et al. (1998); Chittenden (1971b)
Protect eggs hatching	>5	–	Bradford et al. (1968); O'Malley and Boone (1972); Marcy and Jacobson (1976); Harrell and Bayless (1981); Jones et al. (1988)
Survival/growth of larvae, juveniles	>5	–	Tagatz (1961); Bogdanov et al. (1967); Krouse (1968); Bowker et al. (1969); Chittenden (1969, 1971a,b, 1973); Meldrim et al. (1974); Rogers et al. (1980); Miller et al. (1982); Coutant (1985); Jones et al. (1988)
Intermediate striped bass survival	>3	72 h	Krouse (1968)
Full survival	>5	72 h	Krouse (1968)
Preferred concentrations	>6	–	Hawkins (1979); Christie et al. (1981); Rothschild (1990)

[a] Protective of shortnose sturgeon at non-stressful temperatures.
[b] Protective of shortnose sturgeon at stressful temperatures (>29 °C).

Table 4
Dissolved oxygen effects data used in the derivation of the open-water fish and shellfish designated use dissolved oxygen criteria to ensure protection against adverse effects on survival, growth, behavior, larval recruitment, freshwater species and threatened/endangered species.

Criteria components	Concentration (mg L^{-1})	Duration	Source
Protection against larval recruitment effects	>4.6–4.8	30 to 40 days	U.S. EPA (2000, 2003a)
	>3.4–3.6	7 days	U.S. EPA (2000, 2003a)
	>2.7–2.9	<24 h	U.S. EPA (2000, 2003a)
Protection against growth effects	>4.8	–	U.S. EPA (2000)
Protection of juvenile/adult survival	>2.3	24 h	U.S. EPA (2000)
Protection for resident tidal freshwater species	>5.5	30 days	U.S. EPA (1986)
	>4	7 days	U.S. EPA (1986)
	>3	Instantaneous minimum	U.S. EPA (1986)
Protection against effects on threatened/endangered	>5	30 days	Secor and Niklitschek (2002); Niklitschek (2001);
species (Atlantic and shortnose sturgeons)	>3.5	6 h	Secor and Gunderson (1998); Jenkins et al. (1993);
	>3.2[a]	2 h	Campbell and Goodman (2004)
	>4.3[b]	2 h	Campbell and Goodman (2004)
Additional published findings			
Preferred striped bass juvenile habitat	>5	–	Kramer (1987); Breitburg (1994)
Juvenile striped bass growth, feeding effects	<4	–	Kramer (1987); Breitburg (1994)
Juvenile striped bass mortality	<3	–	Chittenden (1971a,b); Coutant (1985); Krouse (1968)
Total open water fish biomass declining	<3.7	–	Simpson (1995)
Total open water fish species richness declines	<3.5	–	Simpson (1995)

[a] Protective of survival at non-stressful temperatures.
[b] Protective of shortnose sturgeon at stress temperatures (>29 °C).

The 5 mg L^{-1} value was based on the Virginian Province criterion protecting against growth effects (U.S. EPA, 2000). The Virginian Province criteria document states that exposures to DO concentrations above this concentration will not result in any adverse effects on growth. However, the document recommended no specific duration. The extensive open-water habitats provide better opportunities for avoiding predators and seeking food than the more confined, geographically limited migratory spawning and nursery habitats. The 30-day mean averaging period for the 5 mg L^{-1} criterion value was selected to reflect current uncertainties over how much impact growth reduction has on juvenile and adult survival and reproduction in the shallow- and open-water Bay habitats. The 30-day mean averaging period protects against effects on larval recruitment (Fig. 3), and is consistent with the duration for protection of freshwater species (Table 3).

The criterion values of a 30-day mean of 5 mg L^{-1}, a 7-day mean of 4 mg L^{-1} and an instantaneous minimum of 3.2 mg L^{-1} protect larval recruitment. Depending on an assumption of partial or 100% exposure to low DO concentrations, larval recruitment would be protected at concentrations greater than 4.6 to 4.8 mg L^{-1} beyond 30 days of exposure (Fig. 3). At 7 days of exposure, concentrations between 3.4 and 3.5 mg L^{-1}, extracted from the range of larval recruitment curves, protects against reduced recruitment effects. The 7-day mean, 4 mg L^{-1} concentration criterion value, therefore, should protect recruitment. The instantaneous minimum 3.2 mg L^{-1} criterion should protect larval recruitment, given that 1-day exposure level concentrations are between 2.7 and 2.8 mg L^{-1}. The instantaneous minimum 3.2 mg L^{-1} criterion will also protect the survival of juvenile and adult fish and shellfish species inhabiting shallow- and open-water habitats, and is a higher value than the Virginian Province value of 2.3 mg L^{-1} (U.S. EPA, 2000).

The 30-day mean 5.5 mg L^{-1} criterion value is consistent with the EPA freshwater DO criteria to protect warm-water freshwater species (U.S. EPA, 1986). The other two components of the proposed open-water criteria – 7-day mean of 4 mg L^{-1} and instantaneous minimum of 3.2 mg L^{-1} – are also consistent with the EPA warm-water freshwater criteria (Table 3).

These derived open-water DO criteria are also protective of molluscan and crustacean shellfish. Adverse effects due to exposure to low DO are observed at lower concentrations for shellfish compared with finfish species that occur in Chesapeake Bay (Funderburk et al., 1991).

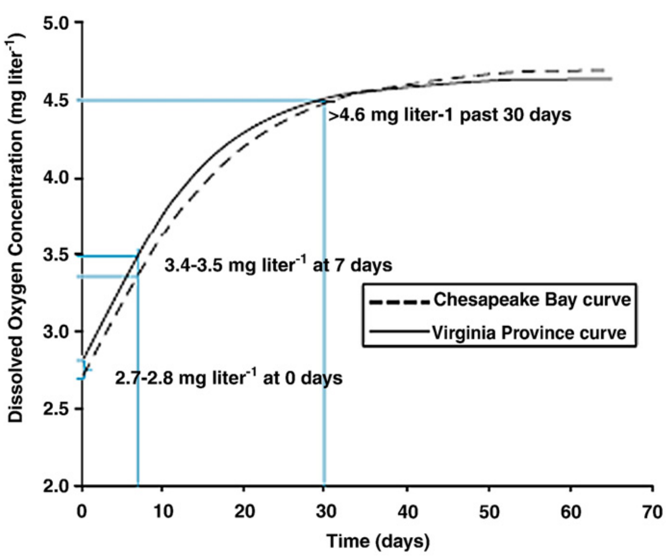

Fig. 3. Comparison of the Virginian Province-wide and Chesapeake Bay-specific larval recruitment effects curves (U.S. EPA, 2000, 2003a). Each line indicates concentrations reducing larval recruitment by 5% of the total population. Plots were generated using the larval recruitment model described in the Virginian Province document (U.S. EPA, 2000). The model is a discrete time, density-independent model that expresses the cumulative impact of low DO as a proportion of the potential annual recruitment of a species. The model accounts for both the magnitude and duration of a hypoxic event.

7. Species of concern

All U.S. water quality criteria are required to protect any aquatic species listed as threatened or endangered (U.S. EPA, 1985) — the shortnose sturgeon is the only listed species resident in the Chesapeake Bay requiring protection from exposure to low DO conditions. In addition, the Atlantic sturgeon is at risk of extinction (NOAA 2007). Both sturgeon species are particularly vulnerable to the summertime habitat squeeze phenomenon (i.e., synergism between temperature and low DO effects on habitat availability; Coutant and Benson, 1990; Collins et al., 2000) due to their demersal lifestyle and unique bioenergetic sensitivity to hypoxia. As reviewed previously, low DO conditions occur at greater frequency in demersal habitats particularly during the summer–fall production season for sturgeons. Although sturgeons do occasionally surface, they depend almost exclusively on benthic substrates and bottom waters for spawning, feeding, migration, and refuge from predation or stressful environments (e.g., using bottom waters for flow and temperature refugia).

In comparison to other estuarine-associated fishes, sturgeons show heightened sensitivity of metabolism to low oxygen levels due to physiological traits such as less efficient gill ventilation, low cardiac performance and lower affinity of hemoglobin to oxygen (Klyashtorin, 1982; Agnisola et al., 1999). In experiments on the two species endemic to the Chesapeake Bay, Niklitschek (2001) and Niklitschek and Secor (2009-this issue) observed substantial reductions in routine metabolism, consumption, feeding metabolism, growth, and survival by juveniles at 40% versus 70% DO. Mortality of juveniles of both sturgeon species is particularly sensitive to hypoxic conditions (<40% DO) in concert with temperatures >25 °C (Secor and Gunderson, 1998; Campbell and Goodman, 2004). To better predict lost potential production of sturgeons due to summer–fall habitat squeezes, Niklitschek and Secor (2005) developed a spatially explicit bioenergetics model for Chesapeake Bay Atlantic sturgeon. The bioenergetics model was supplied with Chesapeake Bay Program Monitoring data (1993–2002) and showed that during the first critical summer months of life, suitable habitat was restricted to 0% to 35% of total Bay bottom surface area.

The instantaneous minimum 3.2 mg L^{-1} criterion is protective against lethal effects from short-term exposures to low DO for both Bay species of sturgeon (U.S. EPA, 2003a). A 30-day mean 5.0 mg L^{-1} criterion protects against growth effects for longer-term exposures (Table 4). Application of the 3.2 mg L^{-1} criterion as an instantaneous minimum concentration was justified on the basis that effects on shortnose sturgeon were observed after just two hours' exposure (Campbell and Goodman, 2004).

The DO Criteria Team undertook special efforts to develop criteria protective of sturgeon, which was not included in the Virginian Province DO criteria document's inventory of effects and models (U.S. EPA, 2000, 2003a). Published and research-in-progress data were reanalyzed by the Team to establish acute and chronic level criteria protective of survival and growth effects specific to sturgeons. The result was a unique instance where the summertime DO acute exposure criterion varied according to temperature (3.2 mg L^{-1} at <30 °C; 4.3 mg L^{-1} at >29 °C; Tables 1 and 4). In an analysis subsequent to development of these criteria, Niklitschek and Secor (2005) used their bioenergetics model to predict increases of juvenile sturgeon habitats to improvements in water quality. For the month of July, fully achieving the DO criteria across all Chesapeake Bay tidal waters was predicted to increase total suitable habitat by 13% over an average year.

Prior to EPA publication of the Chesapeake Bay water quality criteria, NOAA initiated a consultation under Section 7 of the Endangered Species Act (NOAA, 2004). At issue were the designated use zones applied to sturgeons. The Team proposed that during the critical summer months, recent and relevant sturgeon habitats occurred only in the spawning and nursery, shallow-water, and open-water habitats. This precluded application of DO criteria to deep-water and deep-channel habitats. In response to this consultation, the Team acknowledged that sturgeons would use these deep habitats in a normoxic system, but that the Chesapeake Bay's strong stratification and unique bathymetry indicated that summertime hypoxia was a historical feature that probably curtailed sturgeons to shoal habitats flanking channel areas (Cooper and Brush, 1993; U.S. EPA, 2003b). Incidence data of sturgeons captured in gill and pound nets supported this view (Secor et al., 2000; Welsh et al., 2000).

8. Deep-water seasonal fish and shellfish criteria

In the Chesapeake Bay, the bay anchovy is an abundant, ecologically significant fish likely to be affected by low DO conditions in these deep-water habitats, given its life history. Although it is not a commercial species, the bay anchovy is prey for bluefish, weakfish and striped bass (Hartman and Brandt, 1995), forms a link between zooplankton and predatory fish (Baird and Ulanowicz, 1989) and represents from 60 to 90% of piscivorous fish diets on a seasonal basis (Hartman, 1993). Criteria to support deep-water seasonal fish and shellfish habitats were designed to "protect the survival, growth and propagation of balanced, indigenous populations of ecologically, recreationally and commercially important fish and shellfish species inhabiting deep-water habitats" (U.S. EPA, 2003d) (Table 1).

Bay anchovy spawn from May to September in the Chesapeake Bay, with a peak in June and July (Olney, 1983; Dalton, 1987) across a broad range of temperatures and salinities throughout the Chesapeake Bay (Dovel, 1971; Houde and Zastrow, 1991). Their spawning and nursery periods coincide with the presence of low DO conditions in the Chesapeake Bay and its tidal tributaries.

Bay anchovy routinely inhabit waters within the pycnocline region. Bay anchovy eggs have been found throughout the water column regardless of bottom layer oxygen concentrations in mesohaline areas of tributaries (Keister et al., 2000), but tend to be retained in surface and pycnocline waters in the mesohaline mainstem Bay (North, 2005). MacGregor and Houde (1996) found that most bay anchovy eggs were distributed in water above the pycnocline when below pycnocline waters had DO concentrations of <2 mg L^{-1}. In contrast, Rilling and Houde (1999) observed bay anchovy eggs and larvae throughout the water column during June and July. Bay anchovy larvae are also found throughout the water column when bottom oxygen concentrations are above 2 mg L^{-1} (Keister et al., 2000). To derive a criteria to protect deep waters located within the pycnocline layer that are generally inhabited by bay anchovy and their eggs and larvae, a Chesapeake Bay-specific larval recruitment effects model was generated for the bay anchovy.

The hatchability of fish eggs is known to be influenced by the oxygen concentrations to which they are exposed during incubation (Rombough, 1988). Chesney and Houde (1989) observed that survival rates of bay anchovy eggs and larvae are likely affected when exposed to DO concentrations less than 3 mg L^{-1} and 2.5 mg L^{-1}, respectively. Breitburg (1994) found very similar effects for larvae, where 50% survival was observed at 2.1 mg L^{-1}.

Criteria to protect Bay anchovy eggs and larvae were derived using the larval recruitment model described in the Virginian Province criteria document (U.S. EPA, 2000), but with parameters specific to eggs or larvae of the anchovy (U.S. EPA, 2003a). The resulting two recruitment curves are shown in Fig. 4. DO concentrations and exposure durations lying above the combined Bay anchovy egg/larval recruitment curve – 3.0 mg L^{-1} for 30 days and 1.7 mg L^{-1} at all times – would protect against egg and larval recruitment effects. However, because larvae are more susceptible to low oxygen than eggs, the selection of the combined egg/larval curve for criteria derivation may lead to larvae subsequently experiencing >5% mortality even under conditions when the deep-water criteria are attained.

In addition to early life stages of bay anchovy, the instantaneous minimum of 1.7 mg L^{-1} protects juvenile and adult survival of those fish species commonly inhabiting water-column and bottom habitats within the pycnocline (e.g., spot (*Leiostomus xanthurus*), summer flounder (*Paralichthys dentatus*) and winter flounder (*Pleuronectes americanus*); Table 5) (U.S. EPA, 2003a). This criterion value also should protect zooplankton, the principal prey of the bay anchovy and many other fish during their early life stages (Table 5; Roman et al., 1993; Marcus, 2001). Application of the Virginian Province saltwater criteria for juvenile/adult survival, 2.3 mg L^{-1} as a 1-day mean, should provide the required level of protection to short-term exposures to low DO in deep-water habitats (U.S. EPA, 2000; Breitburg et al., 2001).

9. Deep-channel designated use criteria

Deep-channel habitats are principally channels in the lower reaches of the major tidal tributaries (e.g., the Potomac River) and along the spine of the upper and middle mainstem Chesapeake Bay. Seasonal severe hypoxia (<1 mg L^{-1} DO) to anoxia (<0.2 mg L^{-1} DO) routinely set in and persist for extended periods in these habitats. Under low DO conditions of 1 to 2 mg L^{-1}, these habitats are suitable only for survival of benthic infaunal and epifaunal organisms (Holland et al., 1987; Sagasti et al., 2001).

Macroinfauna tend to have higher tolerances to low DO than mobile fauna and can typically survive at DO concentrations around 1 mg L^{-1} (Diaz and Rosenberg, 1995) (Table 6). Around 2 to 3 mg L^{-1} DO, the benthic community starts to lose moderately tolerant species,

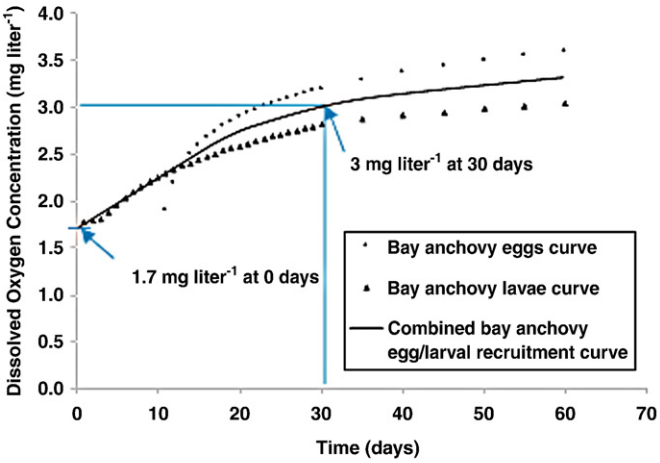

Fig. 4. Chesapeake Bay anchovy egg and larval recruitment response curves (U.S. EPA, 2000, 2003a). The same model was used as in Fig. 3 (U.S. EPA, 2000), but with parameters specific for Bay anchovy (U.S. EPA, 2003a).

with more tolerant species dying off at the low end of the range. In estuaries and coastal systems exposed to seasonal low DO, the critical DO concentration for survival is closer to 1 mg L^{-1} (Llansó, 1992), with subtle reductions in DO concentration from 1 to 0.5 mg L^{-1} causing a full range of responses from behavioral to death (Holland et al., 1989; Llansó and Diaz, 1994; Vaquer-Sunyer and Duarte, 2008).

Criteria for the deep-channel habitats were designed to protect the "survival of balanced, indigenous populations of ecologically important benthic infaunal and epifaunal worms and clams that provide food for bottom-feeding fish and crabs" (U.S. EPA, 2003d). To do this, an instantaneous minimum of 1 mg L^{-1} was selected (Table 1). In the case of bottom-dwelling organisms, it is not the average condition that is most detrimental to the organisms but the absolute minimum DO because many species lack the ability to avoid low oxygen events. When DO drops below 0.5 mg L^{-1} mortality increases, even for tolerant species (Diaz and Rosenberg, 1995; Vaquer-Sunyer and Duarte, 2008). However, behavioral changes by macroinfauna related to low DO can at times lead to increased opportunities for predation when bottom-feeding fish and crabs have access to prey stressed by low DO, albeit under potentially stressful water quality conditions (Pihl et al., 1991, 1992; Nestlerode and Diaz, 1998; Seitz et al., 2003).

Table 6
Dissolved oxygen effects data used in the derivation of the deep-channel designated use dissolved oxygen criteria to ensure protection against adverse effects on survival.

Effects observed	Concentration (mg L^{-1})	Source
Mesohaline community mortality of moderately tolerant species	1	Numerous references cited in Diaz and Rosenberg (1995)
Mesohaline community mortality of more tolerant species	0.6	Numerous references cited in Diaz and Rosenberg (1995)
Behavioral to lethal responses observed	0.5–1	Llansó (1992); Llansó and Diaz (1994); references cited in Holland et al. (1989)
Behavior, growth and production effects observed	<2	Diaz et al. (1992)
Epifaunal community survival	0.5–2	Sagasti et al. (2000)

10. Limitations of the criteria

As with any set of criteria, the approach used in deriving these criteria has its strengths and limitations. The DO criteria were designed to protect the five tidal water designated use habitats based on laboratory conditions in which the underlying effects data were generated. In many studies, data were not generated under stressful temperatures, conditions of insufficient prey, or other stressors such as the need to expend energy to swim against strong currents or avoid predators.

10.1. Salinity effects

The Virginian Province criteria document used as a starting point for deriving the Chesapeake Bay criteria was biased towards organisms occurring at salinities >15 psu, with a subset of tests run at much lower salinities (e.g., striped bass larvae). However, low DO effects synthesized from the scientific literature used in deriving the Chesapeake criteria included tests run at salinities <15 psu (e.g., Burton et al., 1980, research on menhaden and spot). All tests were run at salinities found to be non-stressful to the respective organisms. A review of the literature indicated that non-stressful salinity levels do not influence an organism's sensitivity to low DO (U.S. EPA, 2000, 2003a; Vaquer-Sunyer and Duarte, 2008).

Table 5
Dissolved oxygen effects data used in the derivation of the deep-water seasonal fish and shellfish designated use dissolved oxygen criteria to ensure protection against adverse effects on survival and larval recruitment.

Criteria components	Concentration (mg L^{-1})	Duration	Source
Protection against egg/larval recruitment effects	>3	30 days	Chesney and Houde (1989);
	>1.7	Instantaneous minimum	Breitburg (1994); U.S. EPA (2000)
Protection of juvenile/adult survival	>2.3	24 h	U.S. EPA (2000)
Additional literature findings			
50% mortality for hogchoker (*Trinectes maculatus*), northern sea robin (*Prionotus carolinus*) spot	0.5–1	24 h	Reviewed in Breitburg et al. (2001)
50% mortality for tautog (*Tautoga onitis*), windowpane flounder (*Scophthalmus aquosus*) adults	>1	24 h	Reviewed in Breitburg et al. (2001); Pihl et al. (1991)
50% mortality for menhaden, summer flounder, pipefish (*Syngnathus fuscus*), striped bass adults	1.1–1.6	24 h	Reviewed in Breitburg et al. (2001); Pihl et al. (1991); Miller et al. (2002); U.S. EPA (2000)
50% mortality for skilletfish (*Gobiesox strumosus*), naked goby, silverside (*Menidia menidia*) larvae	1–1.5	24 h	Breitburg (1994); Miller et al. (2002)
50% mortality for red drum (*Sciaenops ocellatus*), bay anchovy, striped blenny (*Chasmodes bosquianus*) larvae	1.8–2.5	24 h	Saksena and Joseph (1972); Breitburg (1994); Miller et al. (2002)
Zooplankton habitat avoidance	<1	–	Roman et al. (1993)
Reduced copepod nauplii abundance	<1	–	Qureshi and Rabalais (2001)
50% mortality for *Acartia tonsa* and *Eurytemora affinis*	0.36–1.4	2 h	Vargo and Sastry (1977)
Mortality for *Acartia tonsa* and *Oithona colcarva*	<2	24 h	Roman et al. (1993)
100% mortality for copepods	0.71	24 h	Stalder and Marcus (1997)
Reduced survival for copepods	<0.86–1.3	24 h	Stalder and Marcus (1997)
Acartia tonsa survival	>1.43	24 h	Stalder and Marcus (1997)

10.2. Temperature effects

With the exception of the criterion derived to protect shortnose sturgeon, Chesapeake Bay criteria do not explicitly address potential interactions between varying stressful temperature levels and the effects of low DO. The amount of available DO changes as temperature changes; and the metabolic rates of organisms increase as temperature increases. In both cases, temperature directly affects organisms and their responses to DO conditions.

A number of species have shown heightened sensitivity to low DO concentrations at higher, yet nonlethal, temperatures (reviewed in Breitburg et al., 2001). At this time sufficient data exist only for specific life history stages of some species (i.e., juvenile shortnose and Atlantic sturgeon) currently or formerly found in Chesapeake Bay (Niklitschek and Secor, 2009-this issue) — too few to fully quantify and build temperature and DO interactions into the Chesapeake Bay-specific DO criteria. Clearly, given the well-documented role of temperature and DO interactions in constraining the potential habitats of striped bass, sturgeon and other Chesapeake Bay fishes, more research and model development are needed, and results of these should be incorporated into future criteria development efforts.

10.3. Behavioral effects

Clear evidence exists of behavioral responses to low DO conditions (e.g., Pihl et al., 1991; Breitburg et al., 1994; Robb and Abrahams, 2002; Vaquer-Sunyer and Duarte, 2008), and concentrations associated with avoidance tend to be very similar to those observed to result in adverse effects on growth (e.g., Breitburg, 2002). Fig. 5 illustrates the relationship between DO concentrations that are lethal and those resulting in reduced growth and behavioral avoidance of the affected habitat. Regressions, calculated from data from a variety of sources, included LC_{50} versus avoidance behavior, LC_{50} versus growth reduction and growth versus avoidance behavior. DO concentrations associated with avoidance were found to be 2.25 times the LC_{50} concentration (Fig. 5A). DO concentrations causing growth reduction were 2.28 times the LC_{50} concentration (Fig. 5B). DO concentrations causing avoidance were essentially the same as those concentrations causing growth reduction (Fig. 5C). Reduced growth and avoidance by fish occur at similar oxygen concentrations relative to lethal levels. Thus, protecting for one factor should protect for the other, if appropriate time durations are used. Therefore, criteria that protect growth should also be protective of habitat squeeze due to avoidance (Coutant, 1985).

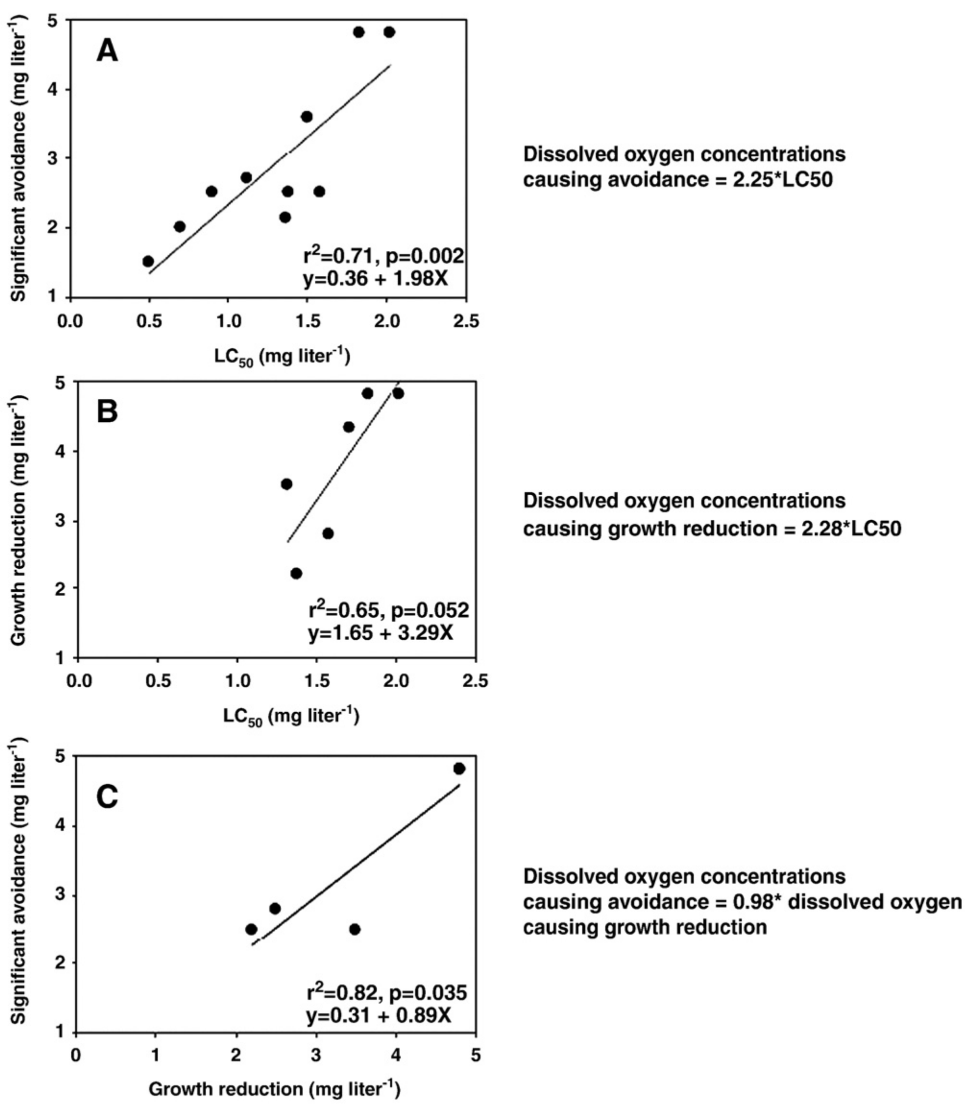

Fig. 5. Relationship between lethal DO concentrations and those resulting in reduced growth and behavioral avoidance of affected habitat. (A) LC_{50} vs. avoidance behavior, (B) LC_{50} vs. growth reduction, and (C) growth vs. avoidance behavior. There are two identical data points in (C) which overlap each other. Modified from Breitburg (2002).

10.4. Larval recruitment model

Uncertainties remain with respect to the percent of the population exposed to low DO, the length of the actual spawning period and the protection of spawning events concentrated over short periods of time. In addition, the assumption implicit in the larval recruitment model that was a considerable concern to the advisory panel was that all spawning days are equal. The larval recruitment model increases mortality with increasing duration of exposure; however, it does not contain a variable for growth. Although it does allow hypoxic conditions to increase larval duration, this component of the model was not used because of lack of sufficient data. Thus, as currently used, this may result in an underestimate of the indirect effect of hypoxia on larval mortality. Factors increasing larval duration are thought to strongly affect predation mortality during the larval stage (Houde, 1987).

11. Conclusions

The Chesapeake Bay DO criteria were developed by fully embracing the temporal and spatial complexity of both the biotic communities of Chesapeake Bay, and the susceptibility to oxygen depletion of its various habitats. Attainment of these criteria would require large increases in DO concentrations in some Bay habitats, and protects areas currently in attainment from future degradation. The complexity of the criteria requires substantial investment in monitoring at fine temporal and spatial scales that determine both current status and changes in water quality. Further, support of the novel cumulative frequency diagram or CFD attainment assessment approach (U.S. EPA, 2003a, 2004a, 2007, 2008) requires development of rigorous geostatistical procedures (Secor et al., 2006). Strategic water quality assessment and science is being used by Chesapeake Bay community managers and scientists to promote improved water quality at an ecosystem level scale, in addition to the narrower framework of TMDL. Still, water quality model simulations indicate that full attainment would require approximately a 50% reduction in nitrogen loads from 1985 loads (U.S. EPA, 2003c). Thus, despite rigorous water quality criteria and assessment procedures introduced here, improvements to water quality will largely be determined by strong public policy, regulations, and enforcement.**[SS]**

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