chapter iii

Dissolved Oxygen Criteria

BACKGROUND

Of all life-supporting environmental constituents, oxygen is one of the most essential. In cells, oxygen stores and liberates the energy that drives vital processes of fish, crabs and shellfish such as feeding, growth, swimming and reproduction. Low dissolved oxygen concentrations can increase mortality, reduce growth rates and alter the distribution and behavior of aquatic organisms, all of which can produce significant changes in the overall estuarine food web (Breitburg 2002).

The Chesapeake Bay and its tidal tributaries harbor diverse and productive communities of aquatic organisms that are supported by a complex array of food webs. To establish dissolved oxygen criteria for these living resources and the food webs they depend upon, we must characterize the dissolved oxygen conditions that lead to stressful conditions for the living resources of the Chesapeake Bay, ranging from copepods to sturgeon.

CHESAPEAKE BAY SCIENCE

The development of the scientific underpinnings for Chesapeake Bay-specific criteria has been under way for decades. The first documentation of seasonal occurrence, low dissolved oxygen conditions in the Chesapeake Bay took place in the 1930s (Newcombe and Horne 1938; Newcombe et al. 1939), with low oxygen conditions documented in the lower Potomac River in the early 1900s (Sale and Skinner 1917). Chesapeake Bay dissolved oxygen dynamics, which are critical to deriving criteria that reflect the ecosystem process, first became understood during the research cruises of the Johns Hopkins Chesapeake Bay Institute during the 1950s through the late 1970s. A five-year, multidisciplinary research program established in the late 1980s, funded and coordinated by the Maryland and Virginia Sea Grant programs, yielded significant advances in the understanding of Chesapeake Bay oxygen dynamics, effects and ecosystem implications (Smith et al. 1992). The coordinated state-federal Chesapeake Bay Water Quality Monitoring Program, initiated

in 1984, provided decadal scale records of seasonal to interannual variability in dissolved oxygen conditions throughout the tidal waters. Building on the long-term baywide monitoring data record, a series of multi-investigator, multi-year National Science Foundation, NOAA and EPA-funded research programs provided new insights into Bay ecosystem processes and responses. These investigations laid the groundwork for management application of the resulting science.

NATURAL DISSOLVED OXYGEN PROCESSES

Dissolved oxygen in any natural body of water is primarily a function of atmospheric oxygen (which diffuses into the water at the surface), oxygen produced by plants (microscopic free-floating plants or phytoplankton) during photosynthesis and aquatic animals, plants and bacteria that consume dissolved oxygen through respiration. Oxygen also is consumed by chemical processes such as sulfide oxidation and nitrification. The reduction of dissolved oxygen stimulates sulfate reduction and results in hydrogen sulfide, a more toxic form of sulfur. Oxygen depletion also can inhibit nitrogen removal via coupled nitrification and denitrification and enhance the recycling of ammonia and phosphates as well as the release of heavy metals from bottom sediments into the overlying water column.

The amount of oxygen dissolved in the water changes as a function of temperature, salinity, atmospheric pressure and biological and chemical processes. Gill and integumentary respiration, which most Chesapeake Bay aquatic species use, is accomplished by extracting dissolved oxygen across a pressure gradient (rather than a concentration gradient). As the partial pressure of dissolved oxygen increases in the water (e.g., increasing temperature and salinity), it can more readily be extracted by an organism. Cold-blooded organisms, however, have much higher metabolic rates and oxygen requirements at higher temperatures, which more than offsets the oxygen gained at the higher temperature. The interactions among metabolism, temperature and salinity clearly are complex, but they must be considered in deriving Chesapeake Bay dissolved oxygen criteria.

Biological processes such as respiration and photosynthesis can affect the concentration of dissolved oxygen before a new equilibrium can be reached with the atmosphere. As a result, for relatively short periods of time, or under sustained conditions of reduced physical mixing (i.e., the stratification of the water column), dissolved oxygen concentrations can be driven well below the point of saturation. They can decrease to zero (a condition known as anoxia), especially in deep or stratified bodies of water, or increase to a concentration of 20 mg liter^{-1} (a condition known as supersaturation) during dense algal blooms.

CHESAPEAKE BAY OXYGEN DYNAMICS

It is critical to take into account the natural processes that control oxygen dynamics in order to establish criteria that reflect natural conditions and protect different habitats. The Chesapeake Bay tends to have naturally reduced dissolved oxygen

conditions in its deeper waters because of its physical morphology and estuarine circulation. As in other estuarine systems (e.g., Boynton et al. 1982; Nixon 1988; Caddy 1993; Cloern 2001), the Chesapeake's highly productive waters, combined with sustained stratification, long residence times, low tidal energy and its tendency to retain and recycle nutrients, set the stage for lower dissolved oxygen conditions. The mesohaline mainstem Chesapeake Bay and lower reaches of the major tidal rivers have a stratified water column, which essentially prevents waters near the bottom from mixing with oxygenated surface waters. The recycling of nutrients and water-column stratification lead to severe reductions in dissolved oxygen concentrations during the warmer months of the year in deeper waters within and below the pycnocline layer.

This reduction in dissolved oxygen generally results from a host of additional biological and physical factors (e.g., Kemp and Boynton 1980; Kemp et al. 1992; Sanford et al. 1990; Boynton and Kemp 2000). The annual spring freshet delivers large volumes of fresh water to the Bay. The contribution of significant quantities of nutrients in the spring river flows, 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 broken down by bacteria over a period of days or weeks (e.g., Malone et al. 1986; Tuttle et al. 1987; Malone et al. 1988). This loss of oxygen due to bacterial metabolism is exacerbated by restricted mixing with surface waters because of the onset of increased water-column stratification.

The Chesapeake Bay's nearshore shallow waters periodically experience episodes of low to no dissolved oxygen, in part because bottom water has been forced into the shallows by a combination of internal lateral tides and sustained winds (Carter et al. 1978; Tyler 1984; Seliger et al. 1985; Malone et al. 1986; Breitburg 1990; Sanford et al. 1990). Low dissolved oxygen conditions in the shallow waters of tidal tributaries are more often the result of local production and respiration than the incursion of bottom waters. Climatic conditions such as calm winds and several continuous cloudy days in a row can contribute to oxygen depletion in these shallow-water habitats. They can be exposed to episodes of extreme and rapid fluctuations in dissolved oxygen concentrations (Sanford et al. 1990). In depths as shallow as 4 meters, dissolved oxygen concentrations may decline to 0.5 mg liter^{-1} for up to 10 hours (Breitburg 1990).

Diel cycles of low dissolved oxygen conditions often occur in nonstratified shallow waters where water-column respiration at night temporarily reduces dissolved oxygen levels (D'Avanzo and Kremer 1994). In nearshore waters of the mesohaline mainstem Chesapeake Bay, near-bottom dissolved oxygen concentrations are characterized by large diel fluctuations and daily minima during the late night and early morning hours of July and August (Breitburg 1990).

The timing and extent of reduced dissolved oxygen conditions in the Chesapeake Bay vary from year to year, driven largely by local weather patterns, the timing and

magnitude of freshwater river flows, the concurrent delivery of nutrients and sediments into tidal waters and the corresponding springtime phytoplankton bloom (Officer et al. 1984; Seliger et al. 1985; Boynton and Kemp 2000; Hagy 2002). In the Chesapeake Bay's mesohaline mainstem, these conditions generally occur from June through September but have been observed to occur as early as May. They may persist through early October, until the water column is fully mixed in the fall. The deeper waters of several Chesapeake Bay major tidal tributaries also can exhibit hypoxic and anoxic conditions (Hagy 2002).

Anoxia is the absence of oxygen. Because most field dissolved oxygen meters are only precise to ± 0.1 or 0.2 mg liter^{-1}, areas with measured oxygen concentrations of 0.2 mg liter^{-1} or less are sometimes classified as anoxic. There is no accurate consensus on the scientific definition of hypoxia, but it is often defined as oxygen concentrations below 2 mg liter^{-1} (U.S. scientific literature) or 2 ml liter^{-1} (European scientific literature). These specific concentration-based definitions are problematic when applied in an effects context, because many species show reduced growth and altered behavior at oxygen levels above 2 mg liter^{-1}, and sensitive species experience mortality during prolonged exposure at these low concentrations. As an operational definition, hypoxia should be considered to be oxygen concentrations reduced from full saturation that impair living resources.

LOW DISSOLVED OXYGEN: HISTORICAL AND RECENT PAST

Dissolved oxygen levels vary naturally in lakes, estuaries and oceans over varying temporal and spatial scales due to many biological, chemical and physical processes. In estuaries such as the Chesapeake Bay, freshwater inflow that influences water-column stratification; nutrient input and cycling; physical processes such as density-driven circulation; and tides, winds, water temperature and bacterial activity are among the most important factors. These processes can lead to large natural seasonal and interannual variability in oxygen levels in many parts of the Chesapeake Bay and its tidal tributaries.

Superimposed on this natural dissolved oxygen variability is a progressive increase in the intensity and frequency of hypoxia and anoxia over the past 100 to 150 years, most notably since the 1960s. This human-induced eutrophication is evident both from instrumental data and geochemical and faunal/floral 'proxies' of dissolved oxygen conditions obtained from the sedimentary record.

The instrumental record, while incomplete prior to the inception of the multi-agency Chesapeake Bay Monitoring Program in 1984, suggests that as early as the 1930s (Newcombe and Horne 1938) and especially since the 1960s (Taft et al. 1980), summer oxygen depletion has been recorded in the Chesapeake Bay. Officer et al. (1984), Malone (1992), Harding and Perry (1997) and Hagy (2002) provide useful

discussions of the instrumental record of dissolved oxygen and related parameters such as chlorophyll *a* across this multi-decade data record.

At issue is whether, and to what degree, dissolved oxygen reductions are a naturally occurring phenomenon in the Chesapeake Bay. Long sediment core records (17 meters to greater than 21 meters in length) indicate that the Chesapeake Bay formed about 7,500 years ago (Cronin et al. 2000; Colman et al. 2002) when the rising sea level after the final stage of Pleistocene deglaciation flooded the Susquehanna channel. The modern estuarine circulation and salinity regime probably began in the mid- to late Holocene epoch, about 4,000-5,000 years ago (in the regional climate of the early Holocene, Chesapeake Bay's salinity differed from that of the late Holocene). This is based on the appearance of 'pre-colonial' benthic foraminiferal, ostracode and dinoflagellate assemblages. It is against this mid- to late Holocene baseline that we can view the post-European settlement and modern dissolved oxygen regime of the Chesapeake Bay.

During the past decade, studies of the Chesapeake Bay's late Holocene dissolved oxygen record have been carried out using several proxies of past dissolved oxygen conditions, which are preserved in sediment cores that have been dated using the most advanced geochronological methods. These studies, using various indicators of past dissolved oxygen conditions, are reviewed in Cronin and Vann (2003) and provide information that puts the monitoring record of the modern Chesapeake Bay into a long-term perspective and permits an evaluation of natural variability in the context of restoration targets. The following types of measurements of oxygen-sensitive chemical and biological indicators have been used: nitrogen isotopes (Bratton et al. 2003); biogenic silica and diatom communities (Cooper and Brush 1991; Cooper 1995; Colman and Bratton 2003); molybdenum and other metals (Adelson et al. 2000; Zheng et al., in press); lipid biomarkers; acid volatile sulfur (AVS)/chromium reducible sulfur (CRS) ratios; total nitrogen and total organic carbon (Zimmerman and Canuel 2000); elemental analyses (Cornwell et al. 1996) and paleo-ecological reconstructions based on dinoflagellate cysts (Willard et al. 2003); and benthic foraminiferal assemblages (Karlsen et al. 2000). Although space precludes a comprehensive review of these studies, and the time period studied and level of quantification vary, several major themes emerge, which are summarized here.

First, the 20th century sedimentary record confirms the limited monitoring record of dissolved oxygen, documenting that there has been a progressive decrease in dissolved oxygen levels, including the periods of extensive anoxia in the deep-channel region of the Chesapeake Bay that have been prominent during the last 40 years. Most studies provide strong evidence that there was a greater frequency or duration of seasonal anoxia beginning in the late 1930s and 1940s and again around 1970, reaching unprecedented frequencies or duration in the past few decades in the mesohaline Chesapeake Bay and the lower reaches of several tidal tributaries. Clear evidence of these low dissolved oxygen conditions has been found in all geochemical and paleo-ecological indicators studied principally through their great impact on benthic and phytoplankton (both diatom and dinoflagellate) communities.

Second, extensive late 18th and 19th century land clearance also led to oxygen reduction and hypoxia, which exceeded levels characteristic of the previous 2,000 years. Best estimates for deep-channel mid-bay seasonal oxygen minima from 1750 to around 1950 are 0.3 to 1.4-2.8 mg liter^{-1} and are based on a shift to dinoflagellate cyst assemblages of species tolerant of low dissolved oxygen conditions. This shift is characterized by a four- to fivefold increase in the flux of biogenic silica, a greater than twofold (5-10 millileter^{-1}) increase in nitrogen isotope ratios (^{15}N) and periods of common (though not dominant) *Ammonia parkinsoniana*, a facultative anaerobic foraminifer. These patterns are likely the result of increased sediment influx and nitrogen and phosphorous runoff due to extensive land clearance and agriculture.

Third, before the 17th century, dissolved oxygen proxy data suggest that dissolved oxygen levels in the deep channel of the Chesapeake Bay varied over decadal and interannual time scales. Although it is difficult to quantify the extremes, dissolved oxygen probably fell to 3 to 6 mg liter^{-1}, but rarely if ever fell below 1.4 to 2.8 mg liter^{-1}. These paleo-dissolved oxygen reconstructions are consistent with the Chesapeake Bay's natural tendency to experience seasonal oxygen reductions due to its bathymetry, freshwater-driven salinity stratification, high primary productivity and organic matter and nutrient regeneration (Boicourt 1992; Malone 1992; Boynton et al. 1995).

In summary, the main channel of the Chesapeake Bay most likely experienced reductions in dissolved oxygen before large-scale post-colonial land clearance took place, due to natural factors such as climate-driven variability in freshwater inflow. However, this progressive decline in summer oxygen minima, beginning in the 18th century and accelerating during the second half of the 20th century, is superimposed on interannual and decadal patterns of dissolved oxygen variability. Human activity during the post-colonial period has caused the trend towards hypoxia and most recently (especially after the1960s) anoxia in the main channel of the Chesapeake Bay and some of its larger tidal tributaries. The impact of these patterns has been observed in large-scale changes in benthos and phytoplankton communities, which are manifestations of habitat loss and degradation.

APPROACH FOR DERIVING DISSOLVED OXYGEN CRITERIA

Against this backdrop, a set of dissolved oxygen criteria have been derived to protect Chesapeake Bay estuarine species living in different habitats that are influenced by the Bay's natural processes. The Chesapeake Bay dissolved oxygen criteria directly reflect natural oxygen dynamics. For example, instantaneous minimum to daily mean criterion values reflect short-term variations in oxygen concentrations, and seasonal application of deep-water and deep-channel criteria account for the natural effects of water-column stratification on oxygen concentrations. Oxygen dynamics and natural low- to no-oxygen conditions also were taken into account in developing

Chesapeake Bay Dissolved Oxygen Criteria Team member Dr. Thomas Cronin, of the U.S. Geological Survey (USGS), (surveyed five scientists[1] who have studied the history of anoxia and hypoxia in the Chesapeake Bay over decadal and centennial time scales, using geochemical and biological proxies from sediment cores and instrumental and historical records. The consensus of the five scientists is that the Chesapeake Bay was seasonally anoxic between 1900 and 1960. The seasonal anoxia was extensive in the deep channel and probably lasted several months. Similarly, between 1600 and 1900, the near-unanimous consensus is that the Bay was seasonally anoxic for probably weeks to months in the deep channel. One researcher had reservations about his group's earlier conclusion on definitive evidence of anoxia prior to 1900, but cannot exclude the possibility of anoxia during this period. Anoxia during the 1900–1960 period was probably geographically less extensive in the Bay and perhaps occurred less frequently (i.e., not every year) than after the 1960s. In addition to the geochemical and faunal proxies of past trends in oxygen depletion, experts cite the Sale and Skinner (1917) instrumental documentation of hypoxia and probable anoxia in the lower Potomac in 1912.

For the period prior to European colonization (~1600 AD), the consensus is that the deep channel of the Bay may have been briefly hypoxic (< 2 mg liter^{-1}), especially during relatively wet periods (which did occur, based on the paleoclimate record). Anoxia probably occurred only during exceptional conditions. It should be noted that the late 16th and much of the 17th century was an extremely dry period which was not conducive to oxygen depletion.

In sum, hypoxia, and probably periodic spatially-limited anoxia, occurred in the Bay prior to the large-scale application of fertilizer, but since the 1960s oxygen depletion has become much more severe.

These experts also unanimously believe that restoring the Bay to mid-20th century, pre-1960 conditions might be possible but very difficult (one expert suggested an 80 percent nitrogen reduction was necessary), in light of remnant nutrients in sediment in the Bay and behind dams, likely increased precipitation as the climate changes, population growth and other factors. Most researchers believe that restoring the Bay to conditions prior to 1900 is either impossible, or not realistic, simply due to the fact that the temporal variability (year-to-year and decadal) in 'naturally occurring' hypoxia renders a single target dissolved oxygen level impossible to define.

[1]T. M. Cronin (USGS, Reston, Virginia), S. Cooper (Bryn Athyn College), J. F. Bratton (USGS, Woods Hole, Massachusetts), A. Zimmerman (Pennsylvania State University), G. Helz (University of Maryland, College Park).

the refined tidal-water designated uses (see Appendix A; U.S. EPA 2003a), which factor in natural conditions leading to low dissolved oxygen concentrations.

The derivation of these regional criteria followed the methodologies outlined in the EPA's *Guidelines for Deriving Numerical National Water Quality for the Protection of Aquatic Organisms and their Uses* (U.S. EPA 1985), the risk-based approach used in developing the *Ambient Aquatic Life Water Quality Criteria for Dissolved Oxygen*

(Saltwater): Cape Cod to Cape Hatteras (U.S. EPA 2000) and the *Biological Evaluation on the CWA 304(a) Aquatic Life Criteria as part of the National Consultations, Methods Manual* (U.S. EPA, U.S. Fish and Wildlife Service and NOAA National Marine Fisheries Service, in draft). The resulting criteria factored in the physiological needs and habitats of the Chesapeake Bay's living resources and are designed to protect five distinct tidal-water designated uses (Appendix A; U.S. EPA 2003a).

Criteria for protecting the migratory fish spawning and nursery, shallow-water bay grass and open-water fish and shellfish designated uses were set at levels to protect the growth, recruitment and survival ecologically, recreationally and commercially important fish and shellfish species. Criteria applicable to deep-water seasonal fish and shellfish designated uses were set at levels to protect shellfish and juvenile and adult fish, and to foster the recruitment success of the bay anchovy. Criteria for deep-channel seasonal refuge designated uses were set to protect the survival of bottom sediment-dwelling worms and clams. These summer deep-water and deep-channel designated uses take into account the natural historic presence of low oxygen in these habitats and the likelihood that such conditions may persist (U.S. EPA 2003a).

CHESAPEAKE BAY DISSOLVED OXYGEN RESTORATION GOAL FRAMEWORK

The Chesapeake Bay dissolved oxygen restoration goal was published in 1992 in response to the Chesapeake Executive Council's commitment to "develop and adopt guidelines for the protection of water quality and habitat conditions necessary to support the living resources found in the Chesapeake Bay system and to use these guidelines" (Chesapeake Executive Council 1987). The 1992 goal contained specific target dissolved oxygen concentrations for application over specified averaging periods and locations (Table III-1; Jordan et al. 1992).

Information on the effects of low dissolved oxygen concentrations was compiled for 14 target species of fish, mollusks and crustaceans, as well as for other benthic and planktonic communities in the Bay food web. These species were selected from a larger list of important species reported in *Habitat Requirements for Chesapeake Bay Living Resources, Second Edition* (Funderburk et al. 1991). The selection of target dissolved oxygen concentrations and their temporal and spatial applications followed an analysis of dissolved oxygen concentrations that would provide the levels of protection needed to achieve the restoration goal. Where data gaps existed, best professional judgment was used.

The original Chesapeake Bay dissolved oxygen restoration goal and its supporting framework made three significant breakthroughs for the derivation and management application of the Bay-specific dissolved oxygen criteria. First, the 1992 dissolved oxygen target concentrations varied with the vertical depth of the water column and horizontally across the Chesapeake Bay and its tidal tributaries, reflecting variations in the levels of water quality required for the protection of different habitats (see

Table III-1. 1992 Chesapeake Bay dissolved oxygen goal for restoration of living resource habitats.

The Chesapeake Bay dissolved oxygen goal for the restoration of living resource habitats is to provide for sufficient dissolved oxygen to support the survival, growth and reproduction of anadromous, estuarine and marine fish and invertebrates in the Chesapeake Bay and its tidal tributaries by achieving, to the greatest spatial and temporal extent possible, the following target concentrations of dissolved oxygen, and by maintaining the existing minimum concentration of dissolved oxygen in areas of the Chesapeake Bay and its tidal tributaries where dissolved oxygen concentrations fall above the recommended targets.

Target Dissolved Oxygen Concentrations	Time and Location
Dissolved oxygen 1 mg liter $^{-1}$	All times, everywhere.
1.0 mg liter^{-1} ≥ dissolved oxygen ≤ 3 mg liter^{-1}	For no more than 12 hours, interval between excursions at least 48 hours, everywhere.
Monthly mean dissolved oxygen ≥ 5 mg liter^{-1}	All times, throughout above-pycnocline[1] waters.
Dissolved oxygen ≥ 5 mg liter^{-1}	All times, throughout above-pycnocline waters in spawning reaches, spawning rivers, and nursery areas.

[1]The pycnocline is the portion of water column where density changes rapidly because of salinity and temperature.
Source: Jordan et al. 1992

Appendix A; U.S. EPA 2003a). Second, the averaging period for each target concentration was tailored to each habitat, understanding that short-term exposures to concentrations below the target concentrations were tolerable and could still protect living resources (see "Chesapeake Bay Dissolved Oxygen Criteria Derivation," page 40). Finally, the 1992 dissolved oxygen restoration goal contained a methodology through which water quality monitoring data and model scenario outputs, collected over varying time periods, could be assessed to calculate the percentage of time that areas of bottom habitat or volumes of water-column habitat would meet or exceed the applicable target dissolved oxygen concentrations (see Chapter VI).

REGIONALIZING THE EPA VIRGINIAN PROVINCE SALTWATER DISSOLVED OXYGEN CRITERIA

The EPA's *Ambient Water Quality Criteria for Dissolved Oxygen (Saltwater): Cape Cod to Cape Hatteras* (U.S. EPA 2000), here referred to as the Virginian Province criteria document, involved the development of an extensive database on dissolved

oxygen effects (Miller et al. 2002) and a close evaluation and synthesis of earlier data, published in peer-reviewed literature. Ultimately the criteria were derived using both traditional methodologies and a new biological risk-assessment framework. A mathematical model was used to integrate effects over time, replacing the concept of an averaging period, and protection limits were established for different life stages (i.e., larvae versus juveniles and adults). Where practical, data were selected and analyzed to conform to *Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and their Uses* (or *EPA Guidelines*, U.S. EPA 1985).

The Virginian Province criteria document addressed three areas of protection: 1) juvenile and adult survival, 2) growth effects and 3) larval recruitment effects. In doing so, it segregated effects on juveniles and adults from those on larvae. To address cumulative effects of low dissolved oxygen on larval recruitment to the juvenile life stage (i.e., larval survival time), a new biological approach using a mathematical model was taken. The model evaluated the effects of dissolved oxygen conditions on larvae by tracking the intensity and duration of low dissolved oxygen effects across the larval recruitment season (U.S. EPA 2000). Criteria to protect larvae were derived using data based on varying dissolved oxygen exposures for larval stages of nine sensitive estuarine and coastal organisms.

The juvenile and adult survival and growth criteria presented in the Virginian Province document set boundaries for judging the dissolved oxygen status of a given site. If dissolved oxygen concentrations are above the Virginian Province chronic growth criterion (4.8 mg liter^{-1}), then the site meets the objectives for protection. If the dissolved oxygen conditions remain above the Virginian Province juvenile/adult survival criterion (2.3 mg liter^{-1}) over a 24-hour period, the site meets the objectives. When the dissolved oxygen conditions fall between these two values, then the site requires further evaluation.

The Virginian Province criteria document supported the derivation of region-specific dissolved oxygen criteria tailored to the species, habitats and dissolved oxygen exposure regimes of varying estuarine, coastal and marine waters. The segregation by life stage allows the criteria to be tailored to protect the individual refined Chesapeake Bay tidal-water designated uses, which reflect the use of different habitats by different life stages (Appendix A). This segregation by life stage differs significantly in approach from traditional aquatic life water quality criteria. However, the Virginian Province criteria were not designed to address natural variations in dissolved oxygen concentrations from surface waters to greater water-column depths. If Chesapeake Bay-specific dissolved oxygen criteria had been derived using only a strict application of this criteria methodology, they would not be flexible enough to tailor each set of criteria to the refined tidal-water designated uses presented in Appendix A. The resulting criteria would be driven solely by larval effects data, irrespective of depth and season.

Therefore, the dissolved oxygen criteria specific to the Chesapeake Bay were derived through the regional application of the Virginian Province criteria and the application of both EPA published traditional toxicological and new EPA biological-based methodologies. Chesapeake Bay-specific science was factored into each step of the process. The extensive Virginian Province data base was supplemented with additional Chesapeake Bay-specific data from the scientific literature. The Virginian Province larval recruitment model parameters were adjusted to better reflect Chesapeake Bay conditions, data and species. Finally, steps were taken to ensure protection of species listed as threatened or endangered in Chesapeake Bay tidal waters following both national EPA guidelines and joint U.S. EPA, U.S. Fish and Wildlife and National Marine Fisheries Service national Endangered Species Act consultation methodologies. The Chesapeake Bay-specific dissolved oxygen criteria were derived with the full support of and technical assistance from the U.S. EPA Office of Research and Development's Atlantic Ecology Division and the U.S. EPA Office of Water's Office of Science and Technology.

Chesapeake Bay Species

A total of 36 species of fish, crustaceans and mollusks were included in the Virginian Province criteria data base (U.S. EPA 2000). Only four are not resident Chesapeake Bay species (Table III-2, U.S. EPA 1998), including the green crab and the mysid *Americamysis bahia*. Both the American lobster and Atlantic surf clam have been observed in the Chesapeake Bay, but only near the Bay mouth, in high salinities. American lobster larvae require relatively low temperatures (20ºC) and high salinities (30 ppt) for successful development, and these conditions do not normally occur in the Chesapeake Bay.

The EPA guidelines on criteria recalculation, which allow regional and site-specific criteria derivation, state that species should be deleted from the effects data base only if the class is absent (U.S. EPA 1994). Emphasis is placed on deriving criteria using an effects data base that represents the range of sensitivity of tested and untested species from, in this case, the Chesapeake Bay and its tidal tributaries. As described below, including these four non-Chesapeake Bay species in the effects data base does not change the Bay-specific dissolved oxygen criteria. To ensure consistency with national EPA guidelines, no species were dropped from the original Virginian Province effects data base when deriving these Chesapeake Bay-specific criteria.

Juvenile and Adult Survival Criteria

The criterion minimum concentration, or CMC, provides a lower limit for a 24-hour averaged concentration to protect juvenile and adult survival. The CMC for juvenile and adult survival was recalculated using a Chesapeake Bay-specific effects data base of 32 species of fish, crustaceans and mollusks (Table III-2). Dropping the four non-Chesapeake Bay species from the original Virginian Province data base resulted in a recalculated Chesapeake Bay-specific juvenile/adult survival CMC value of

Table III-2. U.S. EPA Virginian Province criteria data base species found in the Chesapeake Bay.

Common Name	Scientific Name	Found in the Chesapeake Bay		Notes
		Species	Genus Only	
American lobster	*Homarus americanus*	(Yes)	-	1
Amphipod	*Ampelisca abdita*	Yes	-	
Atlantic menhaden	*Brevoortia tyrannus*	Yes	-	
Atlantic rock crab	*Cancer irroratus*	Yes	-	
Atlantic silverside	*Menidia menidia*	Yes	-	
Atlantic surfclam	*Spisula solidissima*	(Yes)	-	2
Blue crab	*Callinectes sapidus*	Yes	-	
Burry's octopus	*Octopus burryi*	No	Yes	4
Daggerblade grass shrimp	*Palaemonetes pugio*	Yes	-	
Eastern oyster	*Crassostrea virginica*	Yes	-	
Flatback mud crab	*Eurypanopeus depressus*	Yes	-	
Fourspine stickleback	*Apeltes quadracus*	Yes	-	
Green crab	*Carcinus maenas*	No	No	6
Hard clam	*Mercenaria mercenaria*	Yes	-	
Harris mud crab	*Rhithropanopeus harrisii*	Yes	-	
Inland silverside	*Menidia beryllina*	Yes	-	
Longfin squid	*Loligo pealeii*	(Yes)	-	3
Longnose spider crab	*Libinia dubia*	Yes	-	
Marsh grass shrimp	*Palaemonetes vulgaris*	Yes	-	
Mysid shrimp	*Americamysis bahia*	No	No	7
Naked goby	*Gobiosoma bosc*	Yes	-	
Northern sea robin	*Prionotus carolinus*	Yes	-	
Pipe fish	*Syngnathus fuscus*	Yes	-	
Rock crab	*Cancer irroratus*	Yes	-	
Sand shrimp	*Crangon septemspinosa*	Yes	-	

continued

Table III-2. U.S. EPA Virginian Province criteria data base species found in the Chesapeake Bay *(continued).*

Common Name	Scientific Name	Found in the Chesapeake Bay		Notes
		Species	Genus Only	
Say mud crab	*Dyspanopeus sayi*	Yes	–	5
Scup	*Stenotomus chrysops*	Yes	–	
Sheepshead minnow	*Cyprinodon variegatus*	Yes	–	
Skillet fish	*Gobiesox strumosus*	Yes	–	
Striped bass	*Morone saxatilis*	Yes	–	
Striped blenny	*Chasmodes bosquianus*	Yes	–	
Spot	*Leiostomus xanthurus*	Yes	–	
Summer flounder	*Paralichthys dentatus*	Yes	–	
Tautog	*Tautoga onitis*	Yes	–	
Windowpane flounder	*Scophthalmus aquosus*	Yes	–	
Winter flounder	*Pleuronectes americanus*	Yes	–	

Notes:
1. Occasionally found in the Chesapeake Bay mouth region outside of the Bay Bridge/tunnel during blue crab winter dredge surveys.
2. Found near the Chesapeake Bay mouth at high salinities.
3. Found in the region around the Chesapeake Bay mouth.
4. *Octopus americanus* is found in the higher salinity reaches of the Chesapeake Bay.
5. Genus *Dyspanopeus* supercedes genus *Neopanope* (See Weiss, H. 1995. *Marine Animals of Southern New England and New York*, State Geological and Natural History Survey of Connecticut).
6. If found in the Chesapeake Bay, *Carcinus maenas* would be at the extreme southern edge of its range (See Gosner, K. 1979. *Field Guide to the Atlantic Seashore : Invertebrates and Seaweeds of the Atlantic Coast from the Bay of Fundy to Cape Hatteras*, Houghton Mifflin. Boston.). This species has not been documented in the Comprehensive List of Chesapeake Bay Basin Species (U.S. EPA 1998).
7. *Americamysis bahia* supercedes *Mysidopsis bahia*. (See Price W. W., R. W. Heard, L. Stuck 1994. Observations on the genus *Mysidopsis Sars*, 1864 with the designation of a new genus, *Americamysis*, and the descriptions of *Americamysis alleni* and *A. stucki* (Peracarida: Mysidacea: Mysidae), from the Gulf of Mexico. *Proceedings of the Biological Society of Washington* 107:680-698).

Sources: U.S. EPA 1998, 2000.

2.24 mg liter^{-1}, very close to the EPA Virginian Province criterion value of 2.27 mg liter^{-1} (U.S. EPA 2000). To maintain consistency with EPA Virginian Province criteria and national EPA guidelines, no changes were made to the Virginian Province criteria value of 2.27 mg liter^{-1} (rounded off to 2.3 mg liter^{-1} for purposes of this criteria document), applied as a 1-day mean concentration.

Larval and Juvenile Growth Criteria

The criterion value protecting against adverse effects on growth under continuous exposures, called the criterion continuous concentration (or CCC), when recalculated for only Chesapeake Bay species, increased 0.2 mg liter^{-1} to a Chesapeake Bay-specific value of 5.0 mg liter^{-1}. To maintain consistency with EPA Virginian Province criteria and the national EPA criteria derivation guidelines, no changes were made to the Virginian Province criteria value of 4.8 mg liter^{-1}.

Larval Recruitment Model Application

The Virginian Province criteria larval recruitment model was used only to confirm that the criterion values selected for the migratory fish spawning and nursery, shallow-water and open-water criteria fully protected larval recruitment. Only in the case of the deep-water criteria was application of the larval recruitment model central to deriving Chesapeake Bay-specific dissolved oxygen criteria values.

Virginian Province Larval Recruitment Model. The recruitment model is a discrete time, density-independent model consisting of several equations that allow the cumulative impact of low dissolved oxygen to be expressed as a proportion of the potential annual recruitment of a species. The model is run by inputting the necessary bioassay and biological information, selecting dissolved oxygen durations to model, and then, through an iterative process, assessing various dissolved oxygen concentrations until the desired percent recruitment impairment is obtained. The resulting pairs of duration and dissolved oxygen concentration become the recruitment curve. The process has been incorporated in a spreadsheet for simplicity. The model can be set up to handle unlimited and various life history stages. Its application for dissolved oxygen effects is to model larval recruitment to the juvenile stage.

The model's equations and the major assumptions used in its application are explained in Appendix E of the Virginian Province document (U.S. EPA 2000). The life history parameters in the model include larval development time, larval season, attrition rate and spatial distribution (e.g., vertical distribution). The magnitude of effects on recruitment is influenced by each of the four life history parameters. For instance, larval development time establishes the number of cohorts that entirely or partially co-occur within the interval of low dissolved oxygen stress. The second parameter, the length of the larval season, is a function of the spawning period, and also influences the relative number of cohorts that fall within the window of hypoxic

stress. The third life history variable, natural attrition rate, gauges the impact, if any, of slower growth and development of the larvae in response to low dissolved oxygen by tracking the associated increase in natural mortality (e.g., predation). The model assumes a constant rate of attrition, so increased residence time in the water column due to delayed development translates directly to decreased recruitment. Finally, the distribution of larvae in the water column determines the percentage of larvae from each cohort that would be exposed to reduced dissolved oxygen under stratified conditions.

The recruitment model assumes that the period of low dissolved oxygen occurs within the larval season (hypoxic events always begin at the end of the development time of the first larval cohort), and that hypoxic days are contiguous. Use of the current model also assumes that a new cohort occurs every day of the spawning season, and that each cohort is equal in size. Use of the model, however, does not require that a fresh cohort be available every day. Successful calculation of recruitment impairment only requires knowing the total number of cohorts available during a recruitment season (i.e., it does not matter whether they were created daily, weekly, monthly, etc.) and whether a cohort is exposed to hypoxia. The application of the model is further simplified by assuming that none of the life history parameters change in response to hypoxia.

Chesapeake Bay Larval Recruitment Model Refinements. A series of refinements were made to the Virginian Province criteria parameters for length of recruitment season and duration of larval development. These values were revised to reflect Chesapeake Bay-specific conditions (Table III-3).

Crustaceans. The Virginian Province criteria document states that the larval model for crustaceans includes all larval stages and the transition from larval to megalopal (post-larval) stage, but not the megalopal stage in its entirety (U.S. EPA 2000). Therefore, the duration used in the model was based on the duration of larval development, plus one day for molting to the megalopal stage. The following Chesapeake Bay-specific estimates of the duration of larval development are rounded to the nearest whole day: rock crab—22 days; say mud crab—17 days; lobster—15 days; spider crab—6 days; and grass shrimp—15 days. These estimates also are supported by a wide array of literature (Anger et al. 1981a; Anger et al. 1981b; Broad 1957; Chamberlain 1957; Costlow and Bookhout 1961; Johns 1981; Logan and Epifanio 1978; Maris 1986; Ryan 1956; Sandifer 1973; Sandifer and Van Engel 1971; Sasaki et al. 1986; Sastry 1970; Sastry 1977; Sastry and McCarthy 1973; Sulkin and Norman 1976; Wass 1972; Williams 1984).

The literature supports a larval release season (here termed the reproductive season) of 120 days or more for rock crab, say mud crab and spider crab, based on the presence of gravid females and larvae in field collections (Anger et al. 1981a; Anger et al. 1981b; Broad 1957; Chamberlain 1957; Costlow and Bookhout 1961; Johns 1981; Logan and Epifanio 1978; Maris 1986; Ryan 1956; Sandifer 1973; Sandifer

Table III-3. Original U.S. EPA Virginian Province saltwater dissolved oxygen criteria larval recruitment values and the revised recruitment season and larval development values reflecting Chesapeake Bay-specific conditions.

Species	Length of Recruitment Season (days)[1]	Duration of Larval Development (days)[1]	Attrition Rate (percent per day)	Percentage Population Exposed to Hypoxic Event
Rock crab	65/100	35/22	5%	20%
Say mud crab	66/90	21/17	5%	75%
Flatback mud crab	66/90	21/17	5%	75%
Lobster	95	35/15	5%	20%
Spider crab	66/80	21/6	5%	50%
Silverside	42/150	14	5%	50%
Striped bass	49/70	28	5%	50%
Grass shrimp	100/120	12/15	5%	50%
Red drum	49/140	21	5%	50%

[1] First value is the original Virginian Province-wide value; the second value following the slash is the Chesapeake Bay-specific value.

and Van Engel 1971; Sasaki et al. 1986; Sastry 1970; Sastry 1977; Sastry and McCarthy 1973; Sulkin and Norman 1976; Wass 1972; Williams 1984). Lobster larvae and adults are rarely found in the Chesapeake Bay, therefore, collection data were not available.

Grass shrimp have an extremely long reproductive season that extends even longer than the brachyurans. The Virginian Province criteria document implies that the actual period over which most of these crustaceans release larvae is only 30 to 40 days (except for grass shrimp). This was not supported in the literature for the Chesapeake Bay. However, given the interest in capturing "the period of predominant recruitment, rather than observance of the first and last dates for zoeal presence in the water column" (U.S. EPA 2000), one could reasonably state that brachyuran larvae are released over a 75-day period in the Chesapeake Bay. Grass shrimp larvae are released over a period of at least 100 days due to their greater reproductive flexibility. These reproductive season values, added to the duration of the larval development, provided the following values for the length of the recruitment season in the Chesapeake Bay: rock crab—100 days; mud crab—90 days; spider crab—80 days; and grass shrimp—120 days (Table III-3).

Fishes. In the Chesapeake Bay, striped bass spawn over a 30- to 40-day period. By adding in the duration of larval development of 28 to 50 days, a reasonable estimate for the recruitment season is 70 days (Grant and Olney 1991; McGovern and Olney 1996; Olney et al. 1991; Rutherford and Houde 1995; Secor and Houde 1995; Ulanowicz and Polgar 1980). It should be noted that most spawning in a given tributary may occur over a much shorter period of 7 to 21 days (Rutherford 1992; Olney et al. 1991). However, given the inability to predict which portion of the reproductive season will result in recruitment, it is important to provide water quality conditions that support recruitment for the duration of spawning season (Secor 2000; Secor and Houde 1995).

Silversides, along with other East Coast estuarine-dependent species, tend to show differences in the date of initiation of spawning and spawning duration from north to south (e.g., southern sites have longer durations). Silversides are serial batch spawners that spawn over a less than two-month period in the northern regions of the east coast, from two to three months around New York, and from three to four months in the Maryland portion of the Chesapeake Bay (Conover and Present 1990; Conover 1992; Gleason and Bengston 1996). A 140-day recruitment season factors in a 90-day reproductive season and a 50-day duration of larval development.

Red drum also are serial batch spawners. Documentation of the red drum spawning season is mostly for southern systems and varies between two months (Wilson and Neiland 1994; Rooker and Holt 1997) and three months (McMichael and Peters 1987). The 140-day recruitment season applied here factors in a 90-day reproductive season and a 50-day duration of larval development.

Impairment Percentage. Population growth of estuarine and coastal organisms may be more affected by mortality of the juvenile and adult stages than the larval stage. In nature only a small fraction of a season's larvae will make it to the juvenile/adult stage. Thus, removal of a single larva from exposure to low dissolved oxygen (which has a high probability of being removed naturally) is not nearly as important as the loss of a single juvenile (at each successive life stage—from egg to larva to juvenile to adult—the probability of survival to the next stage increases). Juveniles are much closer to the reproductive stage and represent the loss not only of the individual, but also of the potential larvae from that individual for the next season. In this regard, an individual larvae is not as important to the population as an individual juvenile or adult. Therefore, populations can tolerate different levels of impact at different stages of individual development (U.S. EPA 2000). At the same time, the criteria need to protect members of a species at all life stages so they can develop from an egg to an adult.

Protection against a greater than 5 percent cumulative reduction in larval seasonal recruitment due to exposure to low oxygen conditions was applied in the Chesapeake Bay-specific larval recruitment effects models, consistent with the level of protection selected for the Virginian Province criteria (U.S. EPA 2000). The selection of a 5 percent impairment of early life stages accords the same level of protection as that

set for adult and juvenile life stages through the CMC criteria. The 5 percent impairment also is consistent with EPA guidelines for deriving ambient aquatic life water quality criteria (U.S. EPA 1985). The 5 percent impairment sets the potential reduction in seasonal recruitment of affected species due to low dissolved oxygen exposure at a low level, relative to the cumulative effects of other natural and anthropogenic factors.

The EPA's criteria derivation guidelines and technical support documents do not state that the purpose of criteria is to prevent any losses; the purpose of the criteria is to prevent "unacceptable" losses. The EPA has acknowledged throughout the history of the criteria development process that criteria may allow some adverse effects to occur, e.g., the use of 95th percentile means that there is the possibility that 5 percent of the communities' genera will experience some impact (U.S. EPA 1985).

The EPA recognizes that large losses of larval life stages occur naturally. Some species may be able to withstand a greater than 5 percent loss of larvae from exposure to low dissolved oxygen or other causes without an appreciable effect on juvenile recruitment. However, this may not be the case for certain highly sensitive species or populations that already are highly stressed, such as threatened/endangered species where the 5 percent impairment is not applied.

In the absence of data showing how much impairment may be caused by low dissolved oxygen conditions alone and still have a minimal effect on natural larval recruitment to the juvenile stage for all species protected, a conservative level of acceptable impairment has been applied. The goal is to provide a level of protection from exposure to low dissolved oxygen that will not cause unacceptable loss to the juvenile recruitment class above what is expected to occur naturally.

Regional Species Effects

The same species from different regions may react differently to low dissolved oxygen conditions. For example, populations from traditionally warmer waters may be less sensitive because they have adapted to lower concentrations of oxygen associated with native warmer temperatures. Alternatively, higher temperatures may cause warmer-water populations to need more dissolved oxygen and thereby make them more sensitive to lower concentrations.

Most of the effects data in the EPA Virginian Province saltwater dissolved oxygen criteria document were from EPA-sponsored laboratory tests conducted with species collected in the northern portion of the province. To determine whether such geographic differences exist, northern (Rhode Island) and southern populations (Georgia or Florida) of two invertebrates, the mud crab and the grass shrimp, and one fish, the inland silverside, were tested in the laboratory at non-stressful temperatures. Exposure-response relationships were similar for northern and southern populations of each species, supporting the use of data from one region to help develop safe dissolved oxygen limits for other regions (Coiro et al., unpublished data; see Appendix B).

Temperature/Dissolved Oxygen Interactions

This document includes effects data collected at temperatures that are greater than 20ºC and many greater than 25ºC. Where there are data for the same species at multiple temperatures, for example, grass shrimp larvae tested at temperatures ranging from 20ºC to 30ºC (see Appendix B), there is no evidence for a temperature effect on sensitivity to hypoxia over the range of temperatures tested.

The findings reported in detail in Appendix B indicate that the low dissolved oxygen effects data were gathered over a range of different temperatures that did not influence the resulting effects findings. These findings further confirmed that test organisms from the northern portion of the Virginian Province were no more or less sensitive than organisms collected well south of the province boundaries. (See "Strengths and Limitations of the Criteria Derivation Procedures," p. 34, for a description of the potential interaction between dissolved oxygen effects and stressful temperatures.)

APPLYING THE EPA FRESHWATER DISSOLVED OXYGEN CRITERIA

The Virginian Province saltwater criteria were derived largely from laboratory-based effects data using test conditions with salinities ranging from oligohaline to oceanic. Although a majority of the tests were run at salinities of greater than 15 ppt, data from the literature included tests whose estuarine species were exposed to salinities as low as 5 ppt. Many of the estuarine species tested tolerate a wide range of salinities, but the location of the U.S. EPA Office of Research and Development Atlantic Ecology Division laboratory at Narragansett Bay, Rhode Island, dictated that the tests be run at higher salinities. With extensive tidal-fresh (0-0.5 ppt) and oligohaline (> 0.5-5ppt) habitats in the upper Chesapeake Bay and upper reaches of most tidal tributaries, criteria established for these less saline habitats must protect resident species. To bridge this gap, the applicable EPA freshwater dissolved oxygen criteria were applied to ensure that the Chesapeake Bay-specific criteria protected freshwater species inhabiting tidal waters.

Freshwater Dissolved Oxygen Criteria

The EPA freshwater criteria document, published in 1986, stipulated five limits for dissolved oxygen effects on warm-water species (Table III-4**,** U.S. EPA 1986). To protect early life stages, the criteria include a 7-day mean of 6 mg liter^{-1} and an instantaneous minimum of 5 mg liter^{-1}. To protect other life stages, additional criteria were derived. These are a 30-day mean of 5.5 mg liter^{-1}, a 7-day mean of 4 mg liter^{-1} and an instantaneous minimum of 3 mg liter^{-1}. Some of the most sensitive survival and growth responses reported for warm-water species in the freshwater criteria document were for early life stages of channel catfish and largemouth bass, both of which are present in tidal-fresh habitats throughout the Chesapeake Bay and its tidal tributaries (Murdy et al. 1997).

Table III-4. U.S. EPA freshwater dissolved oxygen water quality criteria (mg liter^{-1}) for warm-water species.

Duration	Early Life Stages[1]	Other Life Stages
30-day mean	NA[2]	5.5
7-day mean	6	NA
7-day mean minimum	NA	4
1-day minimum[3]	5	3

[1]Includes all embryonic and larval stages and all juvenile forms to 30 days following hatching.
[2]Not applicable.
[3]All minima should be considered as instantaneous concentrations to be achieved at all times.
Source: U.S. EPA 1986.

The freshwater dissolved oxygen criteria documentation contains data for effects on an extensive array of fish species. In addition, the freshwater document focuses on growth effects to early life stages, which are the more sensitive stages. Recognizing that the 1986 freshwater dissolved oxygen criteria were not derived following the EPA's 1985 criteria derivation guidelines, the EPA conducted a preliminary survey of the literature since the 1986 freshwater document was published and did find additional data that were consistent with the 1985 EPA guidelines. However, the effects data that were found (additional field observations and short-term [several hours] laboratory exposures), most of which focused on respiratory effects, indicated that the 1986 freshwater criteria were protective. Therefore, the EPA believes that its existing freshwater criteria accurately portray the expected effects of low dissolved oxygen on freshwater aquatic species.

Early Life Stages

The EPA freshwater early life stage criteria were based on embryonic and larval data for the following eight species: largemouth bass, black crappie, white sucker, white bass, northern pike, channel catfish, walleye and smallmouth bass (U.S. EPA 1986). *Fishes of Chesapeake Bay* (Murdy et al. 1997) documents smallmouth bass as "occasional to common in Chesapeake Bay tributaries from Rappahannock northward, rare to occasional south of the Rappahannock, and absent from Eastern Shore streams and rivers." Regarding white suckers: "Found in all tributaries to Chesapeake Bay throughout the year, the white sucker occurs in nearly every kind of habitat..." The largemouth bass is "common to abundant in all tributaries of Chesapeake Bay." Black crappie were reported to be "occasional to abundant inhabitants in major tributaries of Chesapeake Bay." Finally, channel catfish were "common in all tributaries of Chesapeake Bay." (All references Murdy et al. 1997.)

Given that five of these species—largemouth bass, black crappie, white sucker, channel catfish and smallmouth bass—are resident in Bay tidal-fresh waters, the freshwater early life stage criteria are fully applicable to Chesapeake Bay tidal-fresh habitats. (See Figure 1 on page 14 and the text on pages 17-18 in the EPA's *Ambient Water Quality Criteria for Dissolved Oxygen [Freshwater]* for more details; U.S. EPA 1986.) No efforts were made to recalculate the national freshwater criteria using only Chesapeake Bay species, given the limited number of species used in deriving the 1986 criteria. Dropping any of the eight species would not provide an effects data set meeting the EPA's guidelines for criteria recalculation to address site-specific conditions (U.S. EPA 1994).

Other Life Stages

The warm-water freshwater criteria that protect other life stages were derived from a much wider array of fish and invertebrate species, many of which occur in Chesapeake Bay tidal-fresh habitats (U.S. EPA 1998). These criteria apply to Chesapeake Bay habitats with salinities of less than 0.5 ppt. The national EPA freshwater criteria protecting other warm-water species life stages were not recalculated using only Chesapeake Bay species, for the same reasons described above.

Given the differences in the available effects data, the methodologies followed in deriving the freshwater dissolved oxygen criteria differed from those used in developing the Virginian Province dissolved oxygen criteria. In-depth descriptions of both methodologies can be found in each respective criteria document (U.S. EPA 1986, 2000).

SPECIES LISTED AS THREATENED OR ENDANGERED

When a threatened or endangered species occurs at a site and sufficient data indicate that it is sensitive at concentrations above the recommended criteria, site-specific dissolved oxygen criteria may be derived (U.S. EPA 2000). Based on a review of all federal and Chesapeake Bay tidal water state lists of threatened or endangered species (U.S. Fish and Wildlife Service; National Oceanic and Atmospheric Administration; the states of Maryland, Virginia and Delaware and the District of Columbia), the only federally listed endangered species found to need protection from the effects of low dissolved oxygen conditions was shortnose sturgeon (U.S. EPA 2003b).

Shortnose sturgeon occur in the Chesapeake Bay and several tidal tributaries (Skjeveland et al. 2000; Mangold 2003; Spells 2003). Genetic evidence suggests that the shortnose captured in the Chesapeake Bay share the same gene pool with Delaware Bay shortnose sturgeon, and movement has been documented between the two bays through the C & D Canal (Welsh et al. 2002; Wirgin et al., in review).

Shortnose sturgeon have been federally protected since 1967 (National Marine Fisheries Service 1998). Chesapeake Bay shortnose sturgeon are listed as a Distinct Population Segment in the National Oceanic and Atmospheric Administration's National Marine Fisheries Service Shortnose Sturgeon Recovery Plan. Since 1996, 50 sub-adult and adult shortnose sturgeon have been captured in the upper Chesapeake Bay, Potomac River and Rappahannock River (Skjeveland et al. 2000). Mitochondrial DNA analysis indicated that these were a subset of the Delaware population's gene pool.

Currently two views are held on the status of shortnose sturgeon in the Chesapeake Bay. One view holds that shortnose sturgeon may continue to reproduce in the Bay, arguing that the genetic evidence is inconclusive or that the Delaware Bay and Chesapeake Bay populations may share the same gene pool. The other opinion is that the C & D Canal serves as an important migration corridor, and shortnose occurrences in the Chesapeake Bay result from immigration from the Delaware Bay.

Further, due to salinity preferences it is conceivable that their immigration (and recent occurrences) has been favored by the recent series of wet years. Several sturgeon population geneticists, ecologists and icthyologists favor this latter view (Secor 2003; Wirgin et al. in review; I. Wirgin, personal communication; J. Waldman, personal communication; J. Musick, personal communication). Regardless of whether shortnose sturgeon populations remain in the Chesapeake Bay, the Chesapeake Bay dissolved oxygen criteria have been derived to be protective of all life stages of both shortnose and Atlantic sturgeon.

Sturgeon Dissolved Oxygen Sensitivity

Sturgeon in Chesapeake Bay and elsewhere are more sensitive to low dissolved oxygen conditions than most other fish. In comparison with other fishes, sturgeon have a limited behavioral and physiological capacity to respond to hypoxia (multiple references reviewed and cited by Secor and Niklitschek 2003). Sturgeon basal metabolism, growth, consumption and survival are all very sensitive to changes in oxygen levels, which may indicate their relatively poor ability to oxyregulate. In summer, temperatures greater than 20°C amplify the effect of hypoxia on sturgeon and other fishes due to a temperature-oxygen 'habitat squeeze' (Coutant 1987). Deep waters with temperatures that sturgeon prefer tend to have dissolved oxygen concentrations below the minimum that they require. Sturgeon are therefore either forced to occupy unsuitable habitats or have a reduction in habitat.

Several studies have directly addressed the lethal effects of hypoxia on sturgeon species important to the Chesapeake Bay. Jenkins et al. (1993) examined the effects of different salinities and dissolved oxygen levels on juveniles of the shortnose sturgeon *Acipenser brevirostrum.* The dissolved oxygen tests were all conducted at a mean temperature of 22.5°C. The authors state:

> Due to various constraints including limitations of facilities and test animals, strictly controlled and standardized methods could not be followed in all tests. The findings reported should be considered as preliminary until such time as more rigorous testing can be accomplished.

In addition, the authors report nominal[2] oxygen levels rather than those specific dissolved oxygen concentrations experienced during each replicate experiment. All experiments were conducted in freshwater. Still, strong evidence was presented that younger fish were differentially susceptible to low oxygen levels in comparison to older juveniles. Fish older than 77 days experienced minimal mortality at nominal levels 2.5 mg liter^{-1}, but at 2 mg liter^{-1} experienced 24 to 38 percent mortality.

[2]The authors report that dissolved oxygen levels were monitored every 30 minutes throughout the 6-hour tests, and state that each parameter remained at "satisfactory levels." The dissolved oxygen values reported are 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0 and 7.5 mg liter^{-1}. Since up to five replicates were used with as many as 12 measurements, it seems unlikely that these exact dissolved oxygen concentration values were maintained consistently throughout all the tests.

Younger fish experienced 18 to 38 percent mortality in the 3 mg liter^{-1} treatment and >80 percent mortality in the 2.5 mg liter^{-1} treatment. Mortality of juveniles 77 days or older at treatment levels 3.5 mg liter^{-1} was not significantly different than control levels. Because only nominal dissolved oxygen concentrations were reported, the EPA could not derive LC_{50} values for criteria derivation purposes based upon responses reported by Jenkins et al. (1993).

Criterion Protective of Sturgeon

More rigorous tests with shortnose sturgeon were recently performed using young-of-the-year fish 77 to 134 days old (Campbell and Goodman 2003). Campbell and Goodman (2003) present four 24-hr LC_{50} values for shortnose sturgeon (*Acipenser brevirostrum*). Three of these are from tests with non-stressful temperatures (22–26°C) for this species. The fourth test was conducted at 29°C and was considered to be a stressful temperature by the authors (Larry Goodman, personal communication). Fish from this fourth test also were exposed to temperatures as high as 31°C during the acclimation period immediately preceding their exposure to hypoxia. Since the data from the fourth test also include an effect due to temperature stress, they should be considered separately from data from the other three tests.

The current draft (December 2002) of the "National Consultation" on threatened and endangered species (being negotiated between the U.S. EPA, the U.S. Fish and Wildlife Service and the NOAA National Marine Fisheries Service) states:

> Where acute toxicity data are available for the species of interest, only these data will be used for designating the LC_{50} for this species. If these data include more than one test, the geometric mean of the LC_{50}s of these tests will be used in risk calculations. If only one toxicity test has been conducted, the lower 95% confidence interval of the LC_{50} from this test will be used.

Following this guidance the final LC_{50} for shortnose sturgeon under ambient conditions of non-stressful temperatures would be the geometric mean of 2.2, 2.2 and 2.6 mg liter^{-1}, or 2.33 mg liter^{-1}. Under stressful temperatures, the LC_{50} value that should be used would be 3.1 mg liter^{-1} (this is the LC_{50} of the 29°C test, since the 3.1 mg liter^{-1} treatment resulted in exactly 50 percent mortality there was no 95 percent confidence interval) (Campbell and Goodman 2003).

Long-term exposures (10 days) of Atlantic sturgeon, *Acipenser oxyrinchus*, young-of-the-year (150 to 200 days old) to 2.8 to 3.3 mg liter^{-1} at 26°C resulted in complete mortality over a 10-day period in three of four replicates (Secor and Gunderson 1998). The fourth replicate experienced 50 percent mortality. At 19°C and 2.3 to 3.2 mg liter^{-1}, only 12 to 25 percent mortality was recorded. There was insufficient data to calculate an LC_{50} for 19°C (it was less than 2.70 mg liter^{-1} [3], but could not determine how much less). However, based on survival data present in Secor and

[3]Based on daily dissolved oxygen data provided by the lead author, Dr. David Secor, University of Maryland Center for Environmental Science, Chesapeake Biological Laboratory, Solomons, Maryland.

Gunderson (1998), a 96-hour LC_{50} of 2.89 mg liter^{-1} [3] was estimated for Atlantic sturgeon at 26°C. This value is very similar to the "high temperature" value of 3.1 mg liter^{-1} calculated for shortnose sturgeon by Campbell and Goodman (2003). Data from Secor and Niklitschek (2001) show that shortnose sturgeon are more tolerant of higher temperatures than Atlantic sturgeon, which could explain why 26°C is not a stressful temperature for shortnose sturgeon (Campbell and Goodman 2003), but is for Atlantic sturgeon (Secor and Gunderson 1998). Alternatively, the temperature difference between the two species could be because the shortnose sturgeon were from Savannah River progeny and were held at higher temperatures than the Atlantic sturgeon, which came from Hudson River progeny.

Using the above data, the EPA calculated acute criteria for the protection of sturgeon survival in the Chesapeake Bay under both non-stressful and stressful temperatures. The only LC_{50} value available for non-stressful temperatures that meets the requirements for criteria derivation based on the EPA's 1985 guidelines (U.S. EPA 1985) is the 24-hour 2.33 mg liter^{-1} calculated above from Campbell and Goodman (2003). To be consistent with EPA guidelines, this value was used with the original Virginian Province criteria acute data set to recalculate the Final Acute Value (FAV). The new FAV, 2.12 mg liter^{-1}, is more protective than the 1.64 mg liter^{-1} from the Virginia Province document, but still substantially lower than the 2.33-3.5 mg liter^{-1} derived directly from the empirical study on shortnose sturgeon. Therefore, the EPA defaulted to the 2.33 mg liter^{-1} value, multiplying it by 1.38[4] to arrive at a new CMC, 3.2 mg liter^{-1} (rounded to two significant figures). This value is expected to be protective of sturgeon survival at non-stressful temperatures. Campbell and Goodman (2003) indicate that most of the mortality for shortnose sturgeon occurs within the first 2 to 4 hours of a test. Therefore, using this value as an instantaneous value should protect sturgeon under most conditions.

A higher dissolved oxygen criterion would be needed in areas and times of the year where sturgeon are to be protected and temperatures are likely to be considered stressful (e.g., 29°C and above for shortnose sturgeon). The simplest approach is to use the LC_{50} value of 3.1 mg liter^{-1} from the fourth test of Campbell and Goodman (2003). Multiplying this by 1.38 results in a high temperature CMC for shortnose sturgeon of 4.3 mg liter^{-1}.

To determine a criterion value that would also protect sturgeon from nonlethal effects, bioenergetic and behavioral responses were considered which had been derived from laboratory studies conducted on juvenile Atlantic and shortnose sturgeon (Niklitschek 2001; Secor and Niklitschek 2001). Growth was substantially reduced at 40 percent oxygen saturation compared to normal oxygen saturation

[4] This value is the geometric mean of the LC_5/LC_{50} ratios from the Virginian Province document (U.S. EPA 2000). The ratio for the shortnose sturgeon tests from Campbell and Goodman (2003) was 1.30 based on an analysis of raw data provided by the co-author, Larry Goodman, U.S. Environmental Protection Agency, office of Research and Development, Gulf Ecology Division, Gulf Breeze, Florida. To be consistent with the Virginian Province document, EPA applied the 1.38 ratio.

conditions (greater than or equal to 70 percent saturation) for both species at temperatures of 20ºC and 27ºC. Metabolic and feeding rates declined at oxygen levels below 60 percent oxygen saturation at 20ºC and 27ºC. In behavior studies, juveniles of both sturgeon species actively selected 70 percent or 100 percent oxygen saturation levels over 40 percent oxygen saturation levels. Based on these findings, a 60 percent saturation level was deemed protective for sturgeon. This corresponds to 5 mg liter^{-1} at 25ºC. Therefore, a 5 mg liter^{-1} Chesapeake Bay criterion protecting against adverse growth effects would protect sturgeon growth as well.

In accordance with Section 7 of the Endangered Species Act, the EPA is continuing consultation with the NOAA National Marine Fisheries Service to promote the recovery and protection of the endangered shortnose sturgeon in the Chesapeake Bay and its tidal tributaries.

Historical and Potential Sturgeon Tidal Habitats in Chesapeake Bay

Atlantic and shortnose sturgeon probably most recently colonized the Chesapeake Bay 5,000–8,000 years ago after the last glaciation, when climate and the watershed's hydraulic regime became more stable (Custer 1986; Miller 2001; also see page 11). The Chesapeake Bay during this period already exhibited the two-layer circulation pattern. Thus, we should expect that deep-channel habitats during periods of strong stratification were hypoxic during the past 5,000 years, albeit not at the same spatial extent or severity that has occurred over the past 50 years (Officer et al. 1984; Cooper and Brush 1991). Atlantic sturgeon in other estuarine and coastal systems will use habitats greater than 15 meters in depth (see below), but these other systems do not exhibit the same characteristics of estuarine circulation, watershed areal extent and bathymetry that contribute to natural deep-water and deep-channel hypoxia in the mesohaline Chesapeake Bay.

The geochemical, paleo-ecological and instrumental record of the 20th century indicates that deep-channel regions have not served as potential habitats for sturgeon because seasonal (summer) anoxia and hyopxia have occurred most years, reaching levels below those required by sturgeon. Hypoxia, and probably periodic, spatially-limited anoxia occurred in the Chesapeake Bay prior to the large-scale application of fertilizer, but since the 1960s oxygen depletion has become much more severe (Hagy 2002), prohibiting sturgeon use of this habitat during summer months. Analysis of recent U.S. Fish and Wildlife Service sturgeon capture location data showed absence of sturgeon occurrences in deep-channel habitats during summer months (June 1 through September 30), but substantial numbers of occurrences in these same habitats during other seasons (U.S. EPA 2003b). In summary, based upon the recent relevant history of the Chesapeake Bay ecosystem, deep-channel regions in summer are not considered sturgeon habitats.

Deeper water-column regions may continue to provide temperature refuges, migration corridors and foraging for sturgeon in the absence of strong water-column

stratification (which results in dissolved oxygen concentrations well below saturation levels, due to restricted mixing with the well-oxygenated surface waters.) Recent fisheries-dependent data did not show overlap during summer months (June 1–September 30) between deep-water regions and sturgeon occurrences, but most gear deployed were for shallow waters (i.e., pound nets). During other months (October–May), deeper fishing gill nets captured sturgeon in both deep-channel and deep-water regions (U.S. EPA 2003b). Fishery-independent gill netting in the upper Chesapeake Bay above the Bay Bridge resulted in several Atlantic sturgeon captured in June and July at one station in pycnocline waters.

In other systems where strong water-column stratification does not occur to the degree observed in the Chesapeake Bay and its tidal tributaries, both sturgeon species are known to use deep-water habitats in summer months as thermal refuges. During the period of 1990–1999, very little summer deep-water habitat was predicted to support sturgeon production based on a bioenergetics model, due principally to pervasive hypoxia (Secor and Niklitschek, in press). Further, sturgeons are able to respond behaviorally to favorable gradients in dissolved oxygen (Secor and Niklitschek 2001).

Based on this evidence, pycnocline deep-water habitat does not comprise 'potential' habitats for sturgeon during periods of strong water-column stratification limiting exchange with overlying, more oxygenated waters. In the absence of strong water-column stratification, these deeper water-column habitats are considered open-water habitat and comprise 'potential' habitats for sturgeon.

Atlantic sturgeon occur at depths between 1 meter to more than 25 meters; shortnose sturgeon occur at depths between 1 and 12 meters (Kieffer and Kynard 1993; Savoy and Shake 2000: Welsh et al. 2000). In winter, Atlantic sturgeon select deeper habitats occurring in the Chesapeake Bay's deep channel (Secor et al. 2000; Welsh et al. 2000).

Distribution studies and laboratory experiments support the view that shortnose sturgeon prefer riverine and estuarine habitats over marine ones (e.g., Secor 2003). Shortnose adults have been reported occasionally in coastal waters up to 31 ppt, but typically occur within several kilometers of their natal estuaries (Dadswell et al. 1984; Kynard 1997). This contrasts with the sympatric Atlantic sturgeon, which are considered true *anadromous* fish that must migrate into coastal waters to complete their life cycles (Kynard 1997). In general, shortnose sturgeon do not invade salinities greater than 15 ppt, with centers of concentrations at less than 5 ppt for all life history stages during summer months (Dadswell et al. 1984; Brundage and Meadows 1982; Dovel et al. 1992; Geoghegan et al. 1992; Collins and Smith 1996; Bain 1997; Haley 1999). Atlantic sturgeon older than one year fully tolerate marine salinities and are expected to be distributed across all salinities, depending on season, reproduction and foraging conditions after their first year of life (Dovel and Berggen 1983; Dovel et al. 1992; Kieffer and Kynard 1993; Colligan et al. 1998; Secor et al. 2000).

Thus, Atlantic sturgeon are not limited by bathymetry and salinity in the Chesapeake Bay and would be expected to inhabit all tidal waters, including pycnocline and sub-pycnocline waters, if water quality conditions permitted. Shortnose sturgeon habitats would overlap those of Atlantic sturgeon for salinities less than 15 ppt. But there is strong evidence that both species historically have not used deep-water and deep-channel designated use habitats during the summer months (U.S. EPA 2003b) due to naturally pervasive low dissolved oxygen conditions (see above and the prior section titled "Low Dissolved Oxygen: Historical and Recent Past").

SCIENTIFIC LITERATURE FINDINGS

For each tidal-water designated use-based set of Chesapeake Bay dissolved oxygen criteria, a review was conducted of the relevant dissolved oxygen effects literature beyond those data contained in the Virginian Province criteria document, to include recent published findings and Chesapeake Bay-specific data. These findings were used to confirm the derived criteria values and support the adoption of criteria with instantaneous minimum durations. In the case of the deep-channel designated use, the scientific literature formed the basis for the seasonal-based Chesapeake Bay deep-channel criterion value.

INSTANTANEOUS MINIMUM VERSUS DAILY MEAN

The scientific literature provides clear evidence that mortality occurs rapidly from short-term exposure (less than 6 to 12 hours) to low oxygen concentrations (Magnusson et al. 1998; Breitburg 1992; Jenkins et al. 1993; Chesney and Houde 1989; Campbell and Goodman 2003). In a recent comprehensive review of the effects of hypoxia on coastal fishes and fisheries, Breitburg (2002) stated:

> Oxygen concentrations below those that result in the standardly calculated 50% mortality in 24 to 96 h exposure test can lead to mortality in minutes to a few hours. For example, in the case of naked gobies, exposure to dissolved oxygen concentrations of 0.25 mg liter^{-1} leads to death in a matter of a few minutes (Breitburg 1992). As exposure time increases, the oxygen saturation that causes death approaches the saturation level that results in reduced respiration—typically a saturation level 2 to 3 times higher than found to be lethal in 24 h tests (Magnusson et al. 1998).
>
> Temperature is often an important cofactor determining when lethal conditions are reached because it can affect both the amount of oxygen that can dissolve in water, and the metabolic requirements of fish. Studies to date indicate that fish require higher oxygen saturations and higher dissolved oxygen concentrations for survival at higher temperatures.... The effects of exposure duration and temperature are thus very important to consider in setting water quality standards for dissolved oxygen concentration, highlighting the need to set absolute minima, instead of time-averaged minima, and the need to consider geographic variation in maximum water temperatures.

Data on laboratory tests of asphyxia and field data on fish kills associated with intrusions of hypoxic bottom water indicate that mortality rapidly occurs from short-term exposure to very low dissolved oxygen concentrations. Asphyxia occurs at about half the dissolved oxygen concentration resulting in reductions in respiration (Magnusson et al. 1998). For the species illustrated, respiration declines at dissolved oxygen concentrations of about 85 percent of the LC_{50} concentration (see Figure 2 in Magnusson et al. 1998).

Asphyxia, as stated above, has been reported at dissolved oxygen concentrations well below the reported LC_{50} concentrations. To ensure full protection of each of the five designated uses, an instantaneous minimum criterion has been recommended. In addition, a daily mean criterion value has been recommended for the deep-water use to ensure full protection of the open-water juvenile and adult fish that use deep-water habitats for short periods in summer to forage for food.

STRENGTHS AND LIMITATIONS OF THE CRITERIA DERIVATION PROCEDURES

As with any science-based set of criteria, the approach used in deriving these criteria has its strengths and limitations. The dissolved oxygen criteria are designed to protect the five proposed designated uses under the conditions in which the underlying effects data were generated. Elevated temperatures, for example, will stress organisms regardless of the dissolved oxygen concentrations. The proposed conditions will protect the designated uses along with the application of other appropriate water quality criteria that protect against temperature, chemical contaminant and other related stresses.

The EPA recognizes that interactions among other stressors and dissolved oxygen exist. Conservative assumptions, documented in this chapter and associated appendices, were made to reflect these remaining uncertainties with regard to interactions with other stressors. Incorporation of arbitrary ‘margins of safety’ were not part of the Chesapeake Bay criteria derivation process, consistent with national EPA guidelines (U.S. EPA 1985). The EPA believes that the criteria provided in this document are protective under water quality conditions in which aquatic organism are not otherwise unduly stressed by other factors.

Salinity Effects

The Virginian Province criteria document is geared toward >15 ppt salinities, with a subset of tests run at much lower salinities (e.g., striped bass larvae). However, low dissolved oxygen effects synthesized from the science literature used in deriving the EPA criteria included tests run at salinities lower than 15 ppt salinity (e.g., Burton et al. 1980, research on menhaden and spot). All tests were run at salinities found to be nonstressful to the respective organisms. These results and a review of the literature indicated that nonstressful salinity levels do not influence an organism’s sensitivity to low dissolved oxygen.

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 dissolved oxygen. The amount of available dissolved oxygen 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 dissolved oxygen conditions.

High temperatures and low dissolved oxygen concentrations often appear together. Generally, low dissolved oxygen concentrations would be more lethal at water temperatures approaching the upper thermal limit for a species. Surface or shoal regions of high temperature will cause fish to seek cooler habitats, yet these deeper habitats are more likely to contain hypoxic waters. The resulting 'habitat squeeze' (Coutant 1985) curtails summertime habitats and production (Brandt and Kirsch 1993; Secor and Niklitschek 2001). A number of species have shown heightened sensitivity to low dissolved oxygen concentrations at higher, yet nonlethal, temperatures (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) to fully quantify and build temperature and dissolved oxygen interactions into a set of Chesapeake Bay-specific dissolved oxygen criteria. Clearly, given the well-documented role of temperature and dissolved oxygen interactions in constraining the potential habitats of striped bass, sturgeon and other Chesapeake Bay fishes, more research and model development are needed.

The EPA does not think that a margin of safety for temperature effects is needed. Although having more data specific to an issue is always desirable, the available data are sufficient to derive dissolved oxygen criteria for the Chesapeake Bay that are protective of most species most of the time (which was the original intent of the EPA's 1985 national aquatic life criteria derivation guidelines). The data in Appendix B show that high, but nonstressful temperatures will not alter the dissolved oxygen criteria (some of these temperatures were as high as 30°C). The only rigorous data that are available for a single Chesapeake Bay species using nonstressful and stressful temperatures are for shortnose sturgeon (Campbell and Goodman 2003). These data have been used in the revised the Chesapeake Bay open-water dissolved oxygen criteria to derive protection limits specifically aimed at shortnose sturgeon in higher, stressful temperature waters.

pH Effects

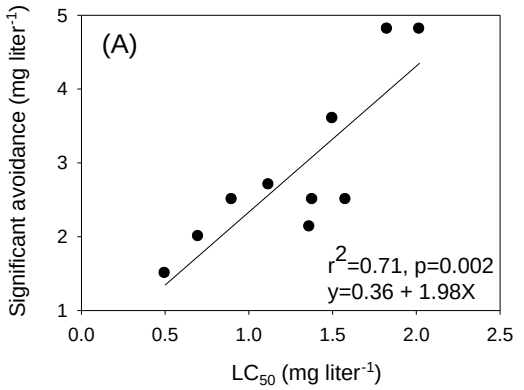
The interaction between pH levels and dissolved oxygen concentrations is more of an issue in laboratory experimentation and the analysis of laboratory-based effects data than in deriving and applying the dissolved oxygen criteria themselves. Given the great buffering capacity of seawater, pH, although a potentially important factor, is unlikely to change much in seawater. Existing pH water quality criteria, along with the application of the appropriate dissolved oxygen criteria, should be protective of the use.

Behavioral Effects

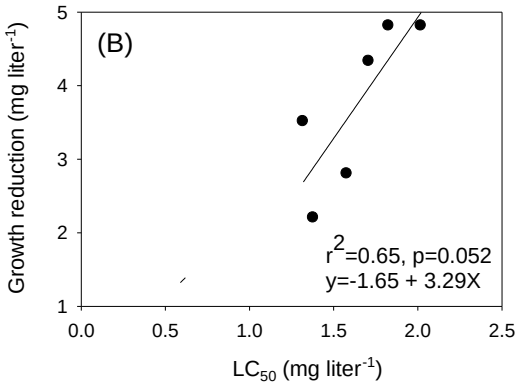
As Breitburg (2002) concluded from a recent extensive review of the scientific literature, clear evidence exists of behavioral responses to low dissolved oxygen conditions.

> Field studies have repeatedly shown that as oxygen concentrations decline, the abundance and diversity of demersal fishes decrease (e.g., Howell and Simpson 1994; Baden and Pihl 1996; Eby 2001; Breitburg et al. 2001). Bottom waters below approximately 2 mg liter^{-1} have extremely depauperate fish populations. Some individual species appear to have threshold concentrations below which their densities decline precipitously (Howell and Simpson 1994; Baden and Pihl 1996; Eby 2001). However, because fish species vary in both physiological tolerance and behavior, total fish abundance and fish species richness tend to decline gradually with declining oxygen concentrations.
>
> Longer duration exposures to low oxygen and more severe hypoxia lead to avoidance of and emigration from affected habitat. All larval, juvenile and adult fishes that have been tested to date respond to oxygen gradients by moving upwards or laterally away from waters with physiologically stressful or potentially lethal dissolved oxygen towards higher oxygen concentrations (e.g., Deubler and Posner 1963; Stott and Buckley 1979; Breitburg 1994; Wannamaker and Rice 2000). Mortality from direct exposure to hypoxic and anoxic conditions is less than might otherwise occur because of this potential capacity for behavioral avoidance.
>
> Habitat loss due to hypoxia in coastal waters is, however, far greater than would be calculated based on the spatial extent of lethal conditions, because most fish avoid not only lethal oxygen concentrations but also those that would reduce growth and require greatly increased energy expenditures for ventilation. Field and sampling and laboratory experiments indicate that oxygen concentrations that are avoided tend to be 2 to 3 times higher than those that lead to 50 percent mortality in 24-to 96-hour exposures, and approximately equal to concentrations that have been shown to reduce growth rates in laboratory experiments.
>
> The net result of emigration and mortality is reduced diversity, abundance and production of fishes within the portion of the water column affected by low dissolved oxygen. Emigration leading to reduced densities of fishes even at oxygen concentrations approaching 40 to 50 percent saturation (3 to 4 mg liter^{-1}) is supported by the pattern of increasing number of species in trawl samples with increasing dissolved oxygen concentration in Long Island Sound (Howell and Simpson 1994) and Chesapeake Bay (Breitburg et al. 2001) and the increasing number of finfish individuals caught per trawl hour within increasing bottom dissolved oxygen off the Louisiana Coast in the Gulf of Mexico (Diaz and Solow 1999).

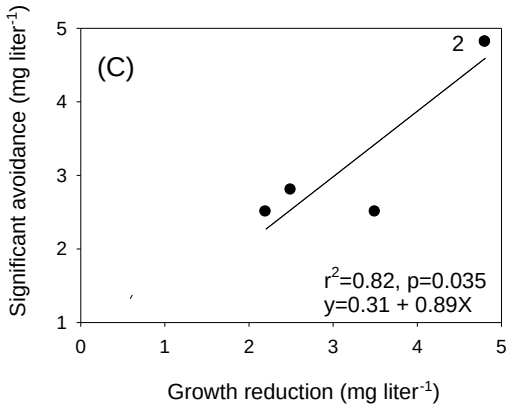
Concentrations associated with avoidance are very similar to those observed to result in adverse effects on growth (Breitburg 2002). Figure III-1 illustrates the relationship



Dissolved oxygen concentrations causing avoidance = 2.25*LC50



Dissolved oxygen concentrations causing growth reduction = 2.28*LC50



Dissolved oxygen concentrations causing avoidance = 0.98 * dissolved oxygen causing growth reduction

Figure III-1. Relationship between lethal dissolved oxygen 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. Two identical points in (c) are indicated by the number 2 next to the data point. Data sources are as follows. Avoidance vs. mortality: Burton et al. 1980; Coutant 1985; Petersen and Petersen 1990; Pihl et al. 1991; Scholz and Waller 1992; Schurmann and Steffensen 1992; Howell and Simpson 1994; Petersen and Pihl 1995; Poucher and Coiro 1997; Wannamaker and Rice 2000; U.S. EPA 2000; Eby 2001. Growth vs. mortality: Burton et al. 1980; Petersen and Petersen 1990; Pihl et al. 1991; Scholz and Waller 1992; Schurmann and Steffensen 1992; Petersen and Pihl 1995; Chabot and Dutil 1999; U.S. EPA 2000; McNatt 2002. Avoidance vs. growth: Couton 1985; Pihl et al. 1991; Scholz and Waller 1992; Howell and Simpson 1994; Petersen and Pihl 1995; Poucher and Coiro 1997; U.S. EPA 2000; Eby 2001; and McNatt 2002. Only studies utilizing a range of dissolved oxygen concentrations are included in figures. Data from multiple studies on the same species were averaged. If responses were tested at several temperatures, the temperature with the most dissolved oxygen effects tested was selected.

Source: Breitburg 2002.

between dissolved oxygen 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. Dissolved oxygen concentrations associated with avoidance were found to be 2.25 times the LC_{50} concentration (Figure III-1a). Dissolved oxygen concentrations causing growth reduction were 2.28 times the LC_{50} concentration (Figure III-1b). Dissolved oxygen concentrations causing avoidance were essentially the same as those concentrations causing growth reduction (Figure III-1c). 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.

The relationship between the average number of species per trawl across a range of dissolved oxygen concentrations provides additional evidence for a strong dissolved oxygen/behavioral connection that transcends individual estuarine and coastal systems (Figure III-2; Breitburg 2002). Using data from the Chesapeake Bay, Long Island Sound and Kattegat Sea, the number of species collected per trawl was shown to increase with increasing dissolved oxygen concentration in all three estuarine and coastal systems.

Individual species habitat requirements and the characteristics of habitats both determine the extent to which an ecosystem's habitats are used and contribute to the health and production of Chesapeake Bay living resources. Each species' behavioral responses, their predators and their prey can also be considered in deriving dissolved oxygen criteria. Based on the limited data on behavioral responses, we are not sure of the actual adverse effects that behavioral responses such as avoidance have on individuals, much less on whole populations. Although considerable data on behavioral avoidance of low oxygen habitats exist, we are unable to predict individual or population-level consequences of such avoidance.

Although it is true that we cannot directly evaluate the effects of avoidance in the same way that we can with effects on growth and survival, the EPA does not believe that a margin of safety for avoidance behavior is needed. The data reviewed by Breitburg (2002) clearly show that concentrations that have an effect on avoidance are nearly identical to those that affect growth. Therefore, criteria that protect growth should also be protective of habitat squeeze due to avoidance.

Larval Recruitment Model

The larval recruitment model was used only in the actual derivation of the deep-water criteria when it was applied specifically to bay anchovy egg and larval life stages. In deriving the migratory spawning and nursery and open-water criteria, the larval recruitment model results for nine different species were used to ensure that the criteria based on other effects data would be fully protective of larval life stages.

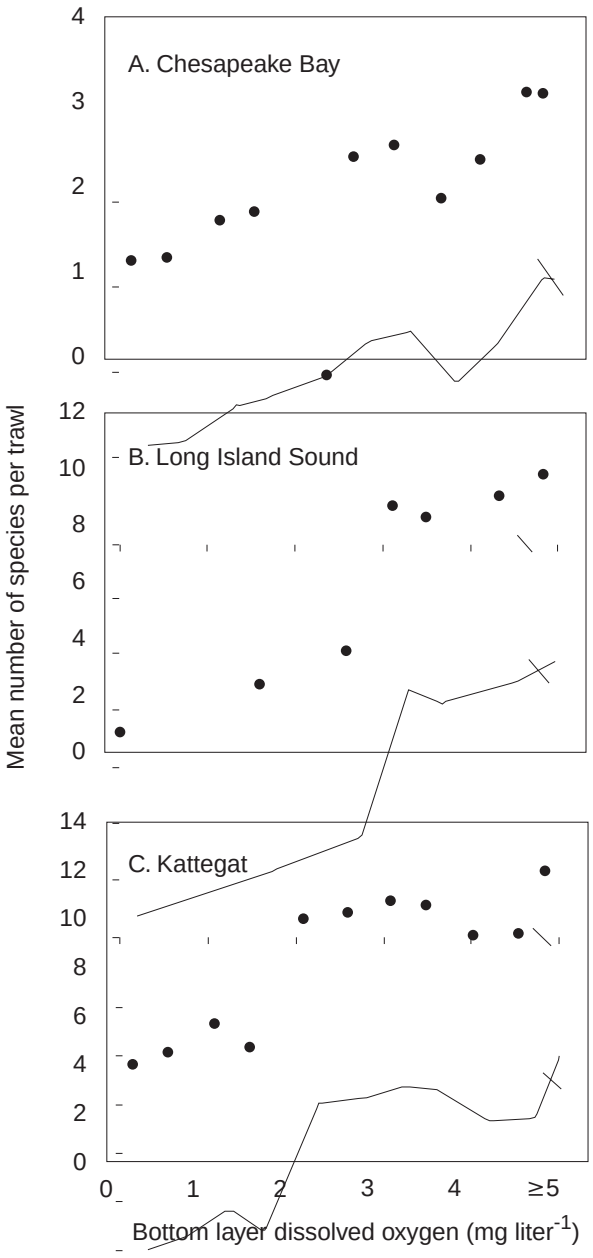


Figure III-2. Average number of species per trawl at a range of dissolved oxygen concentrations along the a) western shore of the Chesapeake Bay near the Calvert Cliffs Nuclear Power Plant (Breitberg and Kolesar, unpublished data), b) Long Island Sound (redrawn from Howell and Simpson 1994, figures 3 and 4), and c) Kattegat (Baden et al. 1990; Baden and Phil 1996). Data are averaged in approximately 0.5 mg liter^{-1} intervals and for all data >0.5 mg liter^{-1}. Note variation in scale of vertical axes.

Source: Breitburg 2002.

Uncertainties remain with respect to the percent of the population exposed to low dissolved oxygen, 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 is that all spawning days are equal.

Due to meteorological, food web and other influences, eggs hatched at different times during the spawning season are not expected to contribute equally to successful survival to juvenile and adult stages, nor are eggs produced continuously throughout the spawning season. In particular, species show spawning behaviors and early survival rates that depend on lunar tidal patterns, weather-driven changes to water quality (e.g., winds and temperature changes) and available forage for young. For example, it is well-documented that most striped bass survival can come from a relatively narrow period of time during the entire spawning period (Ulanowicz and Polgar 1980; Secor and Houde 1995; Secor 2000). Since we cannot predict when this smaller window may occur relative to specific hypoxic events, conservative assumptions must be made. These include always assuming in the recruitment model that hypoxia will occur during times of maximum offspring production.

A number of reports exist on the consequences of slow growth in terms of increased predation mortality. The model does not contain a variable for growth (it only deals with larval survival), however, it does increase the mortality (i.e., changes the sensitivity to hypoxia) with increasing exposure duration.

The EPA acknowledges uncertainties with the parameters in the larval recruitment model. This is why specific parameters within the model were chosen to be conservative. Specifically, spawning periods reflect when the bulk of spawning occurs, not just the first and last possible occurrence of a given species larvae in the water column. In addition, the model always assumes that a hypoxic event occurs during the spawning season of each species modeled. The percentages of each cohort that is exposed during a hypoxic event were also intended to be conservative.

CHESAPEAKE BAY DISSOLVED OXYGEN CRITERIA DERIVATION

Chesapeake Bay dissolved oxygen criteria were established to protect estuarine living resources inhabiting five principal habitats: migratory spawning and nursery, shallow-water, open-water, deep-water and deep-channel. These five categories are drawn from the refined designated uses for the Chesapeake Bay and its tidal tributary waters (Figure III-3). See Appendix A and U.S. EPA 2003a for more detailed descriptions of the refined designated uses.

The EPA's *Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and their Uses* (U.S. EPA 1985) is the primary source on how to establish numerical criteria. Consistent with the national guidelines provided, scientific judgment took precedence over the specifics of the guidelines,

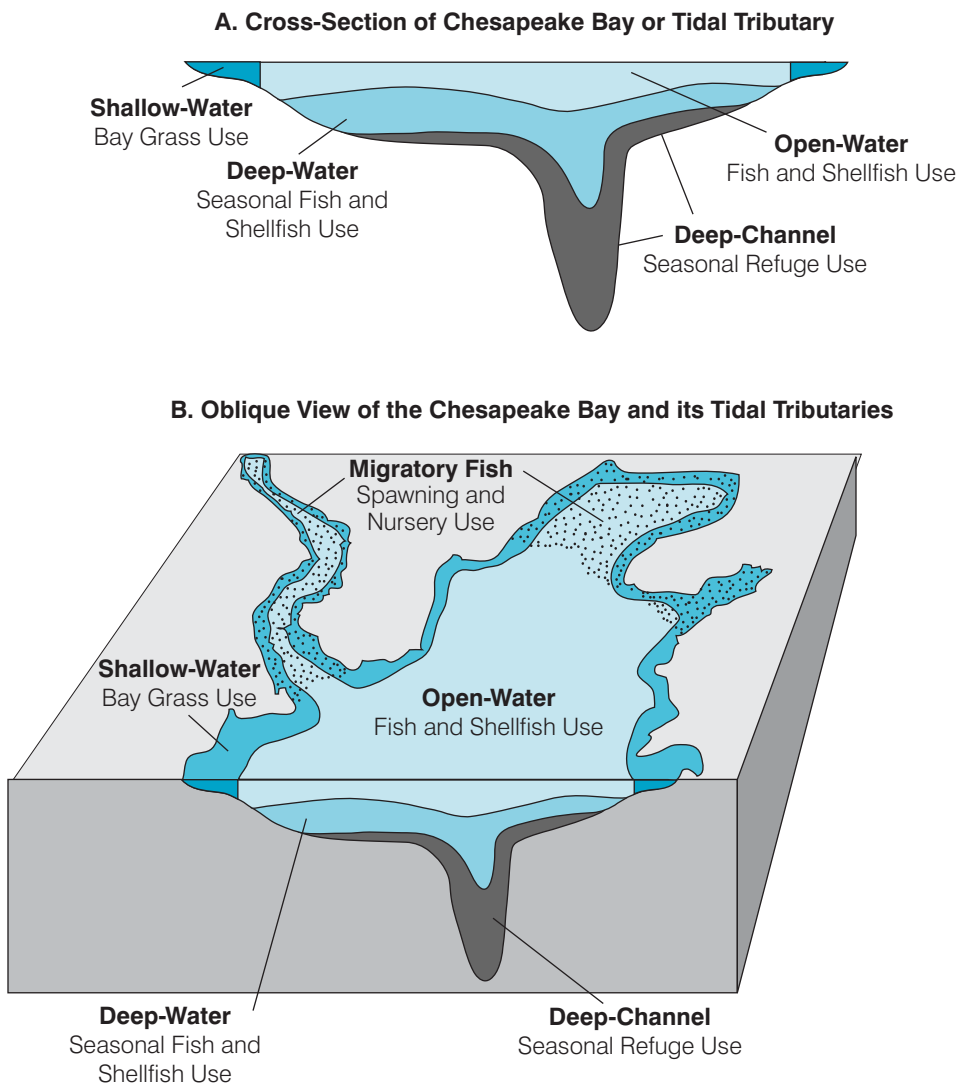


Figure III-3. Conceptual illustration of the five Chesapeake Bay designated use zones.

when warranted. A similar judgment was applied in the development of the 2000 EPA Virginian Province saltwater and the 1986 EPA freshwater dissolved oxygen criteria documents (U.S. EPA 1986, 2000).

The Chesapeake Bay dissolved oxygen criteria were derived using methodologies documented in the EPA Virginian Province saltwater criteria document and using criteria originally published in the EPA freshwater criteria document. The scientific rationale for modifications to the 1985 EPA guidelines for deriving the saltwater dissolved oxygen criteria for the Virginian Province and the national freshwater dissolved oxygen criteria are detailed in those peer-reviewed, EPA documents.

Criteria for migratory fish spawning and nursery, shallow-water bay grass and open-water fish and shellfish designated use habitats were set at levels to protect the survival, growth and reproduction of all species. Criteria that apply to deep-water seasonal fish and shellfish habitats in summer were set at levels to protect shellfish, the survival of juvenile and adult fish, and the recruitment success of the bay anchovy. Criteria for deep-channel seasonal refuge designated use habitats in summer were set to protect the survival of sediment-dwelling worms and clams.

MIGRATORY FISH SPAWNING AND NURSERY DESIGNATED USE CRITERIA

Criteria that support the migratory fish spawning and nursery designated use must fully 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" (Appendix A; U.S. EPA 2003a). This covers the survival and growth of all life stages—eggs, larvae, juveniles and adults—for a given number of species and their underlying food sources. As described below, the criteria are based on establishing dissolved oxygen concentrations to protect against losses in larval recruitment, growth effects on larvae and juveniles and the survival and growth effects on the early life stages of resident tidal-fresh species.

Criteria Components

Protection against Larval Recruitment Effects. Applying the Virginian Province criteria larval recruitment effects model generates a relationship illustrated as a curve, projecting the cumulative loss of recruitment caused by exposure to low dissolved oxygen (Figure III-4). The number of acceptable days of exposure to low dissolved oxygen decreases as the severity of the low oxygen conditions increases. The migratory fish spawning and nursery designated use criteria must ensure protection of larvae as they are recruited into the juvenile/adult population. The Virginian Province criteria larval recruitment curve levels out at approximately 4.6 mg liter^{-1} beyond 30 days of exposure (Figure III-4). By dropping non-Chesapeake Bay species and applying Chesapeake Bay-specific modifications to the larval recruitment model parameters, as described previously, a curve is generated that closely follows the original Virginian Province criteria curve but levels off just above 4.6 mg liter^{-1}. Dissolved oxygen concentrations and exposure durations falling above the Chesapeake Bay-specific curve, e.g., above 4.6 mg liter^{-1} for 30 days, 3.4-3.5 mg liter^{-1} for up to seven days and 2.7-2.8 liter^{-1} at all times, would protect against larval recruitment effects.

Protection for Early Life Stages for Resident Tidal-Fresh Species. The EPA freshwater dissolved oxygen criteria set a 7-day mean of 6 mg liter^{-1} and an instantaneous minimum of 5 mg liter^{-1} to protect early life-stage, warm-water, freshwater species (Table III-4) (U.S. EPA 1986).

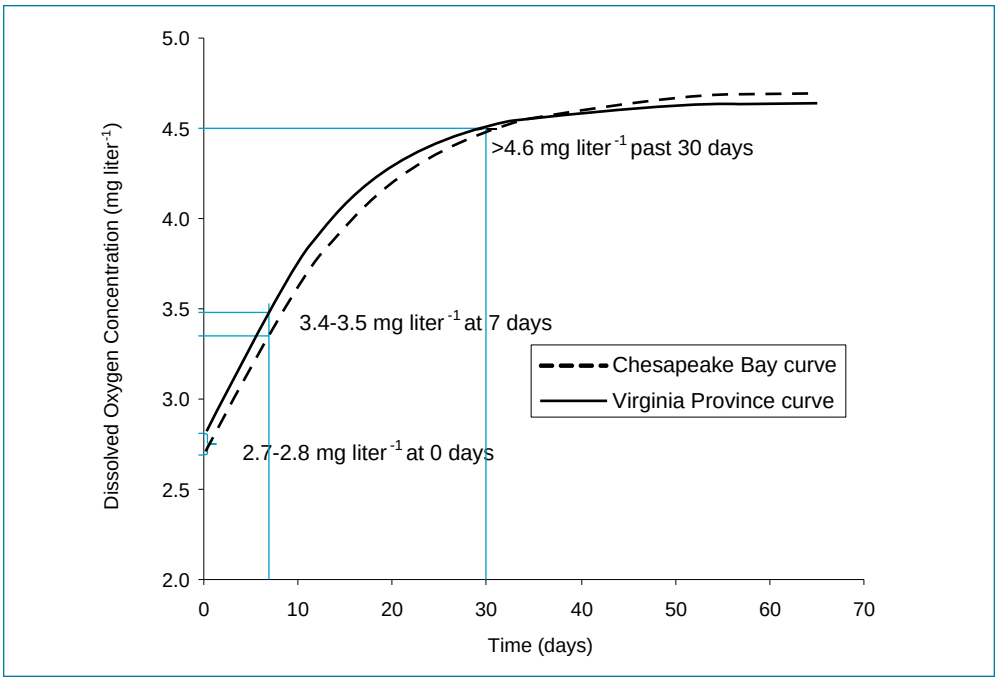


Figure III-4. Comparison of the Virginian Province-wide (—) and Chesapeake Bay-wide (---) larval recruitment effects.

Protection against Growth Effects. To ensure recruitment to the adult population, the Chesapeake Bay criteria must ensure protection against growth effects on rapidly developing larvae and juveniles. The Virginian Province criteria document recommends 4.8 mg liter^{-1} as the threshold above which long-term, continuous exposures should not cause unacceptable growth effects (U.S. EPA 2000). As described previously, if the non-Chesapeake Bay species were removed from the Virginian Province criteria dissolved oxygen growth effects data base, a recalculated Chesapeake Bay-specific criterion would be 5 mg liter^{-1}.

These values were derived by observing the effects of low dissolved oxygen on larval and early juvenile life stages. Growth effects on these stages served as the basis for the chronic criterion because: 1) growth is generally the more sensitive endpoint measure upon exposure to low dissolved oxygen compared with survival; 2) results for other sublethal endpoints such as reproduction were limited; 3) the limited data available indicated that thresholds protecting against growth effects are likely to protect against reproductive effects; and 4) larval and juvenile life stages were more sensitive to effects from low dissolved oxygen than were adults (U.S. EPA 2000). In addition to higher dissolved oxygen requirements, fish eggs and larvae also are more vulnerable to low dissolved oxygen because of limitations in behavioral avoidance (Breitburg 2002).

Protection against Effects on Threatened/Endangered Listed Species. As documented previously, short-term exposures to dissolved oxygen concentrations

of > 3.2 mg liter^{-1} on the order of several hours at nonstressful temperatures and longer-term exposures of 30 days or longer at > 5 mg liter^{-1} will not impair the survival or growth of Atlantic and shortnose sturgeon (Secor and Niklitschek 2001, 2003; Niklitschek 2001; Secor and Gunderson 1998; Campbell and Goodman 2003). At stressful temperatures above 29°C, short-term exposures to dissolved oxygen concentrations >4.3 mg liter^{-1} will not impair the survival of shortnose sturgeon.

Additional Scientific Literature Findings. Results from Brandt et al. (1998) indicate that striped bass food consumption and growth decline as oxygen levels decline. Continuous exposure to dissolved oxygen concentrations of 4 mg liter^{-1} or less caused striped bass to lose weight, even though food was always unlimited. Previous experiments on the effects of oxygen levels on striped bass also have shown that dissolved oxygen concentrations of less than 3 to 4 mg liter^{-1} adversely affect feeding (Chittenden 1971).

Jordan et al. (1992) summarized the literature supporting the adoption of the Chesapeake Bay restoration goal target concentration protecting anadromous spawning and nursery areas as follows.

> This target DO concentration (>5 mg liter^{-1} at all times) was selected to protect the early life stages of striped bass, white perch, alewife, blueback herring, American shad, hickory shad and yellow perch. This concentration of DO will allow eggs to hatch normally (Bradford et al. 1968; O'Malley and Boone 1972; Marcy and Jacobson 1976; Harrell and Bayless 1981; Jones et al. 1988), as well as allow survival and growth of larval and juvenile stages of all anadromous target species (Tagatz 1961; Bogdanov et al. 1967; Krouse 1968; Bowker et al. 1969; Chittenden 1969, 1972, 1973; Meldrim et al. 1974; Rogers et al. 1980; Miller et al. 1982; Coutant 1985; ASMFC 1987; Jones et al. 1988). For example, concentrations of DO below 5 mg liter^{-1} for any duration will not support normal hatching of striped bass eggs (O'Malley and Boone 1972). Although one hatchery operation was able to maintain striped bass fingerlings at DO concentrations of 3 to 4 mg liter^{-1} (Churchill 1985). Bowker et al. (1969) found DO > 3.6 mg liter^{-1} was required for survival of juveniles.

Across an array of temperatures (13–25°C) and salinities (5–25 ppt), Krouse (1968) observed complete mortality of striped bass at 1 mg liter^{-1}, 'minimal mortality' at 5 mg liter^{-1} and 'intermediate survival' at 3 mg liter^{-1} upon exposure of 72 hours. Some field observations have indicated that juveniles and adults of anadromous species prefer dissolved oxygen concentrations ≥ 6 mg liter^{-1} (Hawkins 1979; Christie et al. 1981; Rothschild 1990). However, no lethal or sublethal effects other than possible avoidance have been documented for dissolved oxygen concentrations between 5 and 6 mg liter^{-1}.

Rationale

The migratory spawning and nursery designated use criteria must ensure full 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 III-5). To ensure full protection for resident tidal-fresh warm-water species' early life stages, a 7-day mean criterion of 6 mg liter^{-1} and an instantaneous minimum criterion of 5 mg liter^{-1} were selected, consistent with the EPA freshwater criteria (U.S. EPA 1986).

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 larvae and early juvenile life stages, an instantaneous minimum criterion of 5 mg liter^{-1} was selected. The Virginian Province saltwater criteria document states that exposures to dissolved oxygen concentrations above this concentration 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

Table III-5. Migratory fish spawning and nursery designated use dissolved oxygen criteria components.

Criteria Components	Concentration	Duration	Source
Protection against growth effects	> 4.8 mg liter^{-1}	-	U.S. EPA 2000
Protection against larval recruitment effects	> 4.6 mg liter^{-1} > 3.4-3.5 mg liter^{-1} > 2.7-2.8 mg liter^{-1}	30 to 40 days 7 days instantaneous minimum	U.S. EPA 2000
Protection of early life stages for resident tidal freshwater species	> 6 mg liter^{-1} > 5 mg liter^{-1}	7-day mean instantaneous minimum	U.S. EPA 1986
Protection against effects on threatened/endangered species (shortnose sturgeon)	> 5 mg liter^{-1} > 3.5 mg liter^{-1} > 3.2 mg liter^{-1} [1] > 4.3 mg liter^{-1} [2]	30 days 6 hours 2 hours 2 hours	Secor and Niklitschek 2003; Niklitschek 2001; Secor and Gunderson 1998; Jenkins et al. 1993; Campbell and Goodman 2003
Additional published findings - Growth effects on striped bass - Protect early life stages - Intermediate striped bass survival - Full survival - Preferred concentrations	 < 3 to 4 mg liter^{-1} > 5 mg liter^{-1} > 3mg liter^{-1} >5 mg liter^{-1} ≥ 6 mg liter^{-1}	 - - 72 hours 72 hours -	 Brandt et al. 1998; references in text Krouse 1968 Krouse 1968 Hawkins 1979; Christie et al. 1981; Rothschild 1990

[1] Protective of survival at nonstressful temperatures.

[2] Protective of shortnose sturgeon at stressful temperatures (>29°C).

period was not recommended in the Virginian Province saltwater criteria. In the case of anadromous species, a narrow set of natural conditions (e.g., salinity, temperature) is required and a narrow time window exists for a successful spawn. Natural mortalities for larvae already are extremely high. As even short-term reductions in growth could influence advancement to the next stage through the impairment of survival and the ability to avoid predators, the criterion value that protects against growth effects is applied as an instantaneous minimum.

Setting the criterion duration of exposure as an instantaneous minimum is consistent with the instantaneous minimum duration for the 5 mg liter^{-1} concentration criterion value from the EPA freshwater dissolved oxygen criteria for ensuring full protection of warm-water freshwater species' early life stages against short-term exposures (Table III-4; U.S. EPA 1986). The instantaneous minimum of the 5 mg liter^{-1} criterion value also protects the survival and growth of shortnose sturgeon (Table III-5).

Migratory Spawning and Nursery Criteria

The following dissolved oxygen criteria fully support the Chesapeake Bay migratory fish spawning and nursery designated use when applied from February 1 through May 31: a 7-day mean $\geq$ 6 mg liter^{-1} applied to tidal-fresh waters with long-term averaged salinities up to 0.5 ppt; and an instantaneous minimum $\geq$ 5 mg liter^{-1} applied across all the migratory fish spawning and nursery designated use habitats, regardless of salinity. See U.S. EPA 2003a for details on the selection of February 1 through May 31 as the time period for applying the migratory spawning and nursery designated use.

OPEN-WATER FISH AND SHELLFISH DESIGNATED USE CRITERIA

Criteria that support the open-water designated use must fully 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" (Appendix A; U.S. EPA 2003a). The dissolved oxygen requirements for the species and communities inhabiting open- and shallow-water habitats are similar enough to ensure protection of both the open-water and shallow-water designated uses with a single set of criteria. The open-water criteria were based on establishing dissolved oxygen concentrations to protect against losses in larval recruitment, growth effects on larvae and juveniles and the survival of juveniles and adults in tidal-fresh to high-salinity habitats.

Criteria Components

Protection against Larval Recruitment Effects. Applying the Virginian Province criteria model generates a relationship illustrated as a curve that projects the cumulative loss of recruitment caused by exposure to low dissolved oxygen. The number of acceptable days of exposure to low dissolved oxygen decreases as the

severity of the low oxygen conditions increases. The open-water designated use criteria must ensure protection of larvae as they recruit into the juvenile/adult population.

The Virginian Province larval recruitment effects curve levels out at approximately 4.6 mg liter^{-1} beyond 30 days' exposure (Figure III-5). Dropping the non-Chesapeake Bay resident species and then applying a series of Chesapeake Bay-specific modifications to the larval recruitment model parameters, as described previously, yields a curve that follows the original Virginian Province criteria curve and also levels out around 4.6 mg liter^{-1} beyond 30 days exposure (Figure III-5). Setting the larval exposure level to 100 percent[5] results in a curve that levels out at 4.8 mg liter^{-1}. The effects curves illustrated in Figure III-5 reflect the combined dissolved oxygen concentration and duration of exposure protective against a five percent or greater impact, thereby protecting 95 percent or greater of the seasonally produced offspring. Dissolved oxygen concentrations/exposure durations falling above the curve, e.g., above 2.7-2.9 mg liter^{-1} at all times, above 3.4-3.6 mg liter^{-1} for up to seven days, and above 4.6-4.8 mg liter^{-1} for 30 days, would protect against larval recruitment effects greater than five percent in open-water designated use habitats.

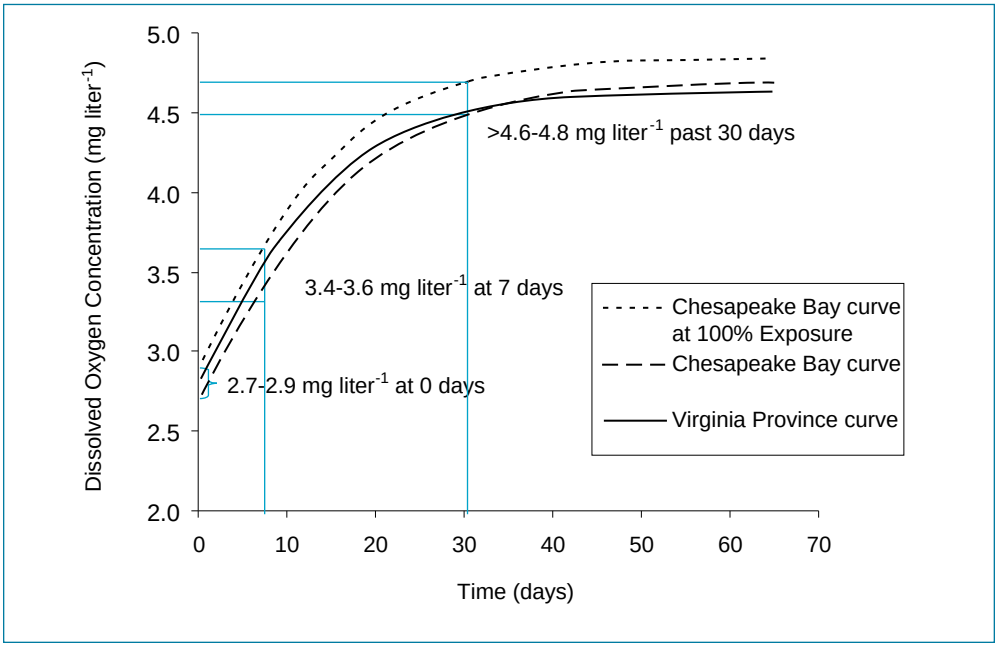


Figure III-5. Comparison of the Virginian Province-wide (—) and Chesapeake Bay specific larval recruitment effects at variable (---) and 100 percent (. . .) exposures.

[5] The larval recruitment model has a parameter for what percentage of a given cohort is exposed to low dissolved oxygen conditions.

Protection of Juvenile/Adult Survival. The Virginian Province criteria document recommends 2.3 mg liter^{-1} as the threshold above which long-term, continuous exposures should not cause unacceptable lethal conditions for juvenile and adult fish and shellfish. As described below, this value does not protect the survival of shortnose sturgeon.

Protection against Growth Effects. To ensure recruitment to the adult population, the open-water designated use dissolved oxygen criteria must protect against growth effects on rapidly developing larvae and juveniles. The Virginian Province document recommends 4.8 mg liter^{-1} as the threshold above which long-term, continuous exposures should not cause unacceptable growth effects. If the non-Chesapeake Bay species were to be removed from the Virginian Province growth effects data base, the recalculated Bay-specific criterion protective against growth effects would be 5 mg liter^{-1}.

This chronic criterion value was derived from laboratory evaluations of the effects of low dissolved oxygen on growth, principally with larval and early juvenile life stages. Growth effects on these early life stages were used as the basis of the chronic criterion because: 1) growth is generally the more sensitive endpoint measure upon exposure to low dissolved oxygen compared with survival; 2) results for other non-mortality related endpoints such as reproduction were very limited; 3) the limited data indicated that thresholds protecting against growth effects are likely to protect against negative reproductive effects; and 4) larval life stages were more sensitive to effects from low dissolved oxygen than were juveniles/adults (U.S. EPA 2000). The derivation of a dissolved oxygen criterion value of 5 mg liter^{-1} to protect against growth effects is consistent with findings reported by Breitburg (2002) that dissolved oxygen concentrations causing growth reductions were 2.28 times the LC_{50} concentration (2.28 x 1.64 = 3.7 mg liter^{-1}, where 1.64 is the Final Acute Value from the EPA Virginian Province document).

Protection of Resident Tidal-Fresh Species. The open-water fish and shellfish designated use criteria must also fully protect warm-water freshwater species that co-occur in tidal-fresh and low-salinity open- and shallow-water habitats. The EPA freshwater dissolved oxygen criteria set a 30-day mean of 5.5 mg liter^{-1}; a 7-day mean minimum of 4.0 mg liter^{-1}, and an instantaneous minimum of 3.0 mg liter^{-1} to protect life stages for warm-water species beyond early life stages (Table III-4) (U.S. EPA 1986).

Protection against Effects on Threatened/Endangered Listed Species. As documented previously, short-term exposures of several hours to dissolved oxygen concentrations of > 3.2 mg liter^{-1} at nonstressful temperatures and longer-term exposures of 30 days or more at > 5 mg liter^{-1} would protect the survival and growth of Atlantic and shortnose sturgeon (Secor and Niklitschek 2001, 2003; Niklitschek 2001; Secor and Gunderson 1998; Campbell and Goodman 2003). At

stressful temperatures above 29°C, short-term exposures to dissolved oxygen concentration > 4.3 mg liter^{-1} will not impair the survival of shortnose sturgeon.

Additional Scientific Literature Findings. As striped bass larvae begin their metamorphoses to the juvenile stage, they move into shallow-water habitats near shore and in shoal areas less than 2 meters deep (Boreman and Klauda 1988; Boynton et al. 1981; Setzler-Hamilton et al. 1981). Nursery areas for juvenile striped bass with dissolved oxygen concentrations greater than 5 mg liter^{-1} are preferable, given findings that concentrations below 4 mg liter^{-1} can adversely affect juvenile growth rates, feeding rates, habitat use and susceptibility to predation (e.g., Kramer 1987; Breitburg et al. 1994). Mortality of juvenile striped bass has been observed at dissolved oxygen concentrations < 3 mg liter^{-1} (Chittenden 1972; Coutant 1985; Krouse 1968).

Results from trawls in Long Island Sound showed significant reductions in both species diversity and abundance at sites with dissolved oxygen < 2 mg liter^{-1} (Howell and Simpson 1994). At open water-column sites with dissolved oxygen concentrations > 3 mg liter^{-1}, 15 of the 18 target species caught occurred with greater frequency compared with sites with concentrations < 2 mg liter^{-1}. Further research indicated that the total abundance of fish was relatively insensitive to low dissolved oxygen conditions, reaching normal levels at 1.5 mg liter^{-1}. However, total fish biomass and species richness were particularly sensitive, declining at dissolved oxygen concentrations of 3.7 mg liter^{-1} and 3.5 mg liter^{-1}, respectively (Simpson 1995).

Rationale

To ensure the full protection of survival and recruitment of larvae into the juvenile population, reduce the potential for adverse effects on growth and protect threatened or endangered species across tidal-fresh to high-salinity habitats, dissolved oxygen criteria values of a 30-day mean of 5.5 mg liter^{-1} applied to tidal-fresh habitats with long- term averaged salinities up to 0.5 ppt; a 30-day mean of 5 mg liter^{-1} applied to all other open-water habitats (> 0.5 ppt salinity); a 7-day mean of 4 mg liter^{-1}; and an instantaneous minimum of 3.2 mg liter^{-1} were selected (Table III-6). At temperatures stressful to shortnose sturgeon (>29°C), a 4.3 mg liter^{-1} instantaneous minimum criteria should apply.

The 5 mg liter^{-1} value is based on the Virginian Province criterion protecting against growth effects (U.S. EPA 2000). The Virginian Province criteria document states that exposures to dissolved oxygen 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 liter^{-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 Chesapeake Bay habitats. The 30-day mean averaging

Table III-6. Open-water fish and shellfish designated use dissolved oxygen criteria components.

Criteria Components	Concentration	Duration	Source
Protection against larval recruitment effects	> 4.6-4.8 mg liter^{-1} > 3.4-3.6 mg liter^{-1} > 2.7-2.9 mg liter^{-1}	30 to 40 days 7 days < 24 hours	U.S. EPA 2000
Protection against growth effects	> 4.8 mg liter^{-1}	-	U.S. EPA 2000
Protection of juvenile/adult survival	> 2.3 mg liter^{-1}	24 hours	U.S. EPA 2000
Protection for resident tidal freshwater species	> 5.5 mg liter^{-1} > 4 mg liter^{-1} > 3 mg liter^{-1}	30 days 7 days instantaneous minimum	U.S. EPA 1986
Protection against effects on threatened/endangered species (shortnose sturgeon)	> 5 mg liter^{-1} > 3.5 mg liter^{-1} > 3.2 mg liter^{-1} [1] > 4.3 mg liter^{-1} [2]	30 days 6 hours 2 hours 2 hours	Secor and Niklitschek 2003; Niklitschek 2001; Secor and Gunderson 1998; Jenkins et al. 1994; Campbell and Goodman 2003
Additional published findings			
– Preferred striped bass juvenile habitat	> 5 mg liter^{-1}	-	Kramer 1987; Breitburg et al. 1994
– Juvenile striped bass growth, feeding effects	< 4 mg liter^{-1}	-	Kramer 1987; Breitburg et al. 1994
– Juvenile striped bass mortality	< 3 mg liter^{-1}	-	Chittenden 1972; Coutant 1985; Krouse 1968
– Total fish biomass declining	< 3.7 mg liter^{-1}	-	Simpson 1995
– Total fish species richness	< 3.5 mg liter^{-1}	-	Simpson 1995

[1] Protective of survival at nonstressful temperatures.
[2] Protective of shortnose sturgeon at stress temperatures (> 29°C).

period is consistent with and fully protects against effects on larval recruitment (see Figure III-5 and text below) and is consistent with the duration protection of freshwater species.

The criterion values of a 30-day mean of 5 mg liter^{-1}, a 7-day mean of 4 mg liter^{-1} and an instantaneous minimum of 3.2 mg liter^{-1} fully protect larval recruitment. Depending on an assumption of partial or 100 percent exposure to low dissolved oxygen concentrations, larval recruitment would be protected at concentrations ranging between 4.6 and 4.8 mg liter^{-1} beyond 30 days of exposure (Figure III-5). At seven days of exposure, concentrations between 3.4 and 3.6 mg liter^{-1}, extracted from the range of larval recruitment curves protects against effects. The 7-day mean, 4 mg liter^{-1} concentration criterion value, therefore, protects recruitment. The instantaneous minimum 3.2 mg liter^{-1} criterion would protect larval recruitment, given that the instantaneous minimum exposure level concentrations are between 2.7 to 2.9 mg liter $^{-1}$.

The instantaneous minimum 3.2 mg liter^{-1} criterion will also protect the survival of juvenile and adult fish and shellfish species inhabiting shallow- and open-water habitats, given it has a higher value than the Virginian Province value of 2.3 mg liter^{-1} (U.S. EPA 2000).

The 30-day mean 5.5 mg liter^{-1} criterion value is consistent with the EPA freshwater dissolved oxygen 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 liter^{-1} and instantaneous minimum of 3.2 mg liter^{-1}—are also consistent with the EPA warm-water freshwater criteria (Table III-4).

The instantaneous minimum 3.2 mg liter^{-1} criterion protects against lethal effects from short-term exposures to low dissolved oxygen for both Bay species of sturgeon. A 30-day mean 5 mg liter^{-1} criterion protects against growth effects for longer-term exposures (Secor and Niklitschek 2001, 2003; Niklitschek 2001; Secor and Gunderson 1998). Application of the 3.2 mg liter^{-1} criterion as an instantaneous minimum concentration is justified on the basis that effects on shortnose sturgeon were observed after just two hours' exposure (Campbell and Goodman 2003).

From October 1 through May 31, when the open-water fish and shellfish designated use extends through the water column into the seasonally defined deep-water seasonal fish and shellfish and deep-channel seasonal refuge designated use habitats, these habitats are important both to blue crabs and larger finfish species seeking refuge in deeper, warmer waters (e.g., striped bass, white perch, Atlantic croaker, shortnose sturgeon and Atlantic sturgeon) during the cooler months of the year (see Appendix A; U.S. EPA 2003a). The criterion values described above will provide the necessary levels of protection for all of these species, for both juvenile and adult life stages.

Open-Water Criteria

The following criteria fully support both the Chesapeake Bay open-water fish and shellfish and shallow-water bay grass designated uses when applied year-round: a

30-day mean $\geq$ 5.5 mg liter^{-1} applied to tidal-fresh habitats only with long-term averaged salinities of up to 0.5 ppt; a 30-day mean $\geq$ 5 mg liter^{-1}; a 7-day mean $\geq$ 4 mg liter^{-1}; and an instantaneous minimum $\geq$ 3.2 mg liter^{-1}. At temperatures stressful to shortnose sturgeon (>29°C), a 4.3 mg liter^{-1} instantaneous minimum criteria should apply.

DEEP-WATER SEASONAL FISH AND SHELLFISH DESIGNATED USE CRITERIA

In deep-water habitats, where the physical exchange of higher oxygenated waters in the upper water-column habitats is much reduced by density stratification and pycnocline waters are not reoxygenated by riverine or oceanic bottom waters, dissolved oxygen concentrations will naturally be lower during the warmer months of the year. Criteria to support the deep-water seasonal fish and shellfish designated use must fully "protect the survival, growth and propagation of balanced, indigenous populations of ecologically, recreationally and commercially important fish and shellfish species inhabiting deep-water habitats" (Appendix A; U.S. EPA 2003a).

In the Chesapeake Bay, the bay anchovy is an abundant, ecologically significant fish likely to be affected by low dissolved oxygen conditions, 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 percent of piscivorus fish diets on a seasonal basis (Hartman 1993). 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 dissolved oxygen conditions in the Chesapeake Bay and its tidal tributaries.

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) conducted laboratory experiments to test the effects of low dissolved oxygen conditions on the hatchability and survival of bay anchovy eggs and yolk-sac larvae. Their findings demonstrated that survival rates of bay anchovy eggs and larvae are likely to be affected when exposed to dissolved oxygen concentrations less than 3 mg liter^{-1} and 2.5 mg liter^{-1}, respectively. Breitburg (1994) found very similar effects for 3- to 13-day post-hatch bay anchovy larvae, where 50 percent survival was observed at 2.1 mg liter^{-1}.

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 were retained in surface and pycnocline waters in the mesohaline mainstem Bay (North 2001; Breitburg et al., unpublished data; Figure III-6). MacGregor and Houde (1996) found that most bay anchovy eggs were distributed in water above the

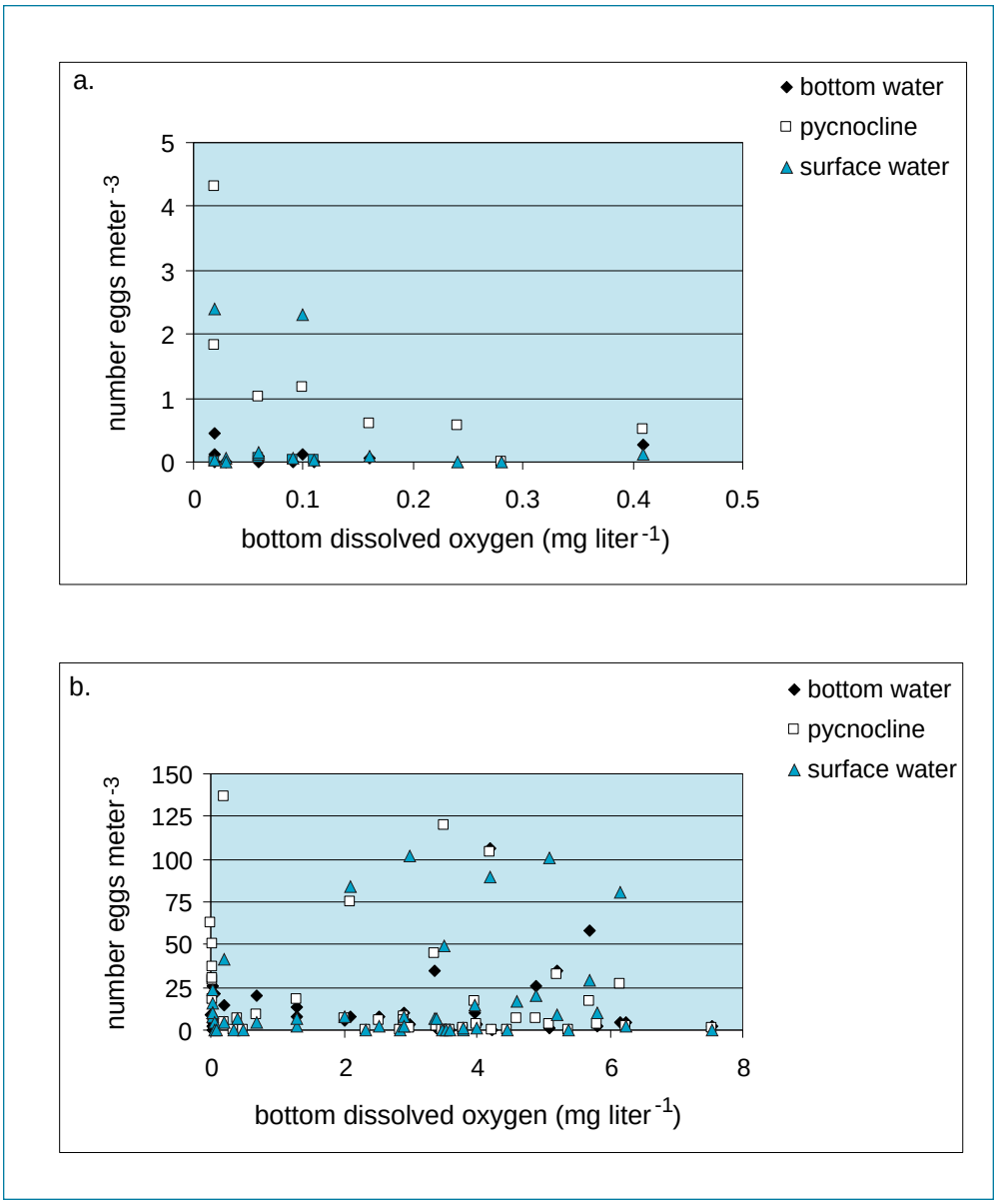


Figure III-6. Illustration of bay anchovy egg densities observed in the surface mixed layer, within pycnocline and below pycnocline waters in the mesohaline portion of the Chesapeake Bay (a) and the mesohaline portion of the Patuxent River (b).

NOTE: one surface value of 45 eggs meter^{-3} for the Chesapeake Bay and two bottom values of 274 and 413 eggs meter^{-3} for Patuxent River deleted for clarity.

Sources: Breitburg et al. 2003; Breitburg et al., unpublished data; Keister et al. 2000.

pycnocline when below pycnocline waters had dissolved oxygen concentrations of < 2 mg liter^{-1}. Rilling and Houde (1999) observed bay anchovy eggs and larvae throughout the water column during June and July. Bay anchovy larvae are found throughout the water column when bottom oxygen concentrations are above 2 mg liter^{-1} (Keister et al. 2000).

Environmental conditions present during the egg, larval or juvenile life stages strongly influence fish population dynamics. Key among these are changes in food supply for first-feeding larvae and factors that modify predation mortality for the highly vulnerable larval life stages. The majority of the species for which larval effects data are available within the Virginian Province criteria document do not routinely inhabit waters in the pycnocline layer. 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.

Criteria Components

Protection against Egg/Larval Recruitment Effects. Two larval recruitment effect models were derived that are specific to the Chesapeake's bay anchovy, based on the original Virginian Province larval recruitment effects model (U.S. EPA 2000). The bay anchovy eggs effects model was based on a 5 percent impairment of eggs hatching to yolk-sac larvae, assuming a 100-day recruitment period and 1-day development period (Chesney and Houde 1989). The larvae-based recruitment effects model, also based on a 5 percent impairment, assumed that yolk-sac larvae and post-yolk larvae or feeding larvae had the same sensitivity.

A development period of 32 days was applied, based on Houde's work (1987), which documented an egg-to-larval duration of 33 days. One day was subtracted to reflect the egg stage (Chesney and Houde 1989), yielding the 32-day development period. A 132-day recruitment period was calculated by adding the 32-day development period to the 100-day recruitment period mentioned above.

A 50 percent exposure[6] to low dissolved oxygen concentrations was built into both the egg and larvae recruitment effects models. Field-based observations have indicated widespread distributions of bay anchovy eggs and larvae across the Bay's mainstem waters and throughout the water column except in subpycnocline waters with extremely low dissolved oxygen concentrations (MacGregor and Houde 1996; Rilling and Houde 1999; Keister et al. 2000; Breitburg et al. 2003).

The final separate survival curves for both the egg and larval recruitment effect models, illustrated in Figure III-7, were based on comparing the effects data from

[6] The larval recruitment model has a parameter for what percentage of a given cohort is exposed to low dissolved oxygen conditions.

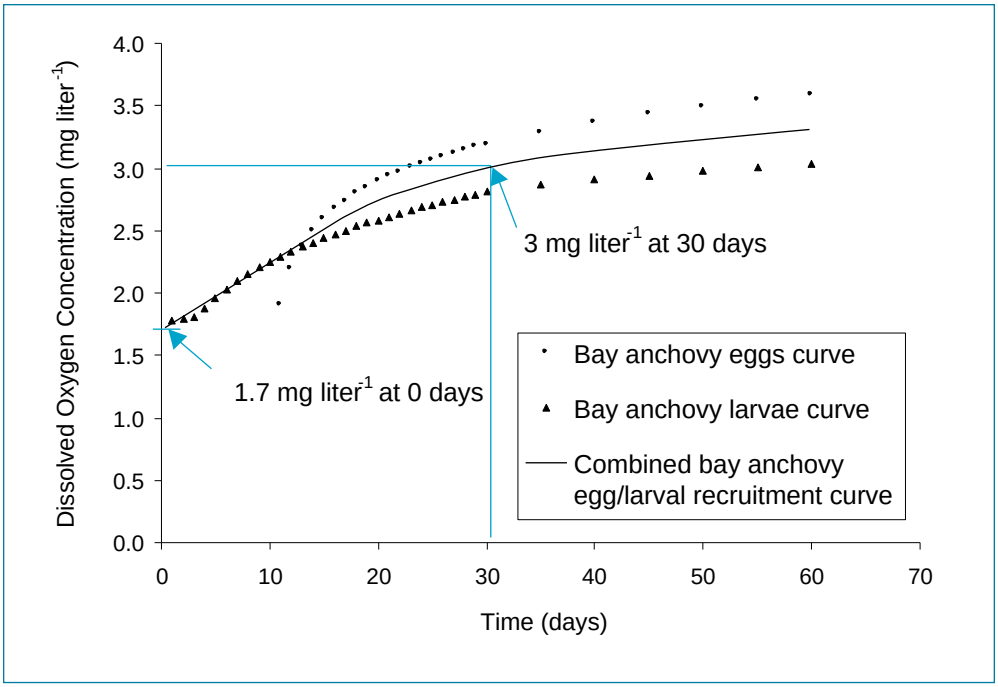


Figure III-7. Chesapeake Bay bay anchovy egg and larval recruitment effects curves.

Chesney and Houde (1989) with the final survival curve from Figure 5 in the Virginian Province saltwater criteria document (U.S. EPA 2000). A single combined egg/larval recruitment effects curve, based on the midpoint between the two individual effects curves, also is illustrated in Figure III-7. The effects curves illustrated in Figure III-7 reflect the combined dissolved oxygen concentration and duration of exposure protective against a 5 percent or greater impact, thereby protecting 95 percent of the seasonally produced offspring. Dissolved oxygen concentrations and exposure durations falling above the combined bay anchovy egg/larval recruitment curve—3 mg liter^{-1} for 30 days and 1.7 mg liter^{-1} at all times—would protect against egg and larval recruitment effects greater than 5 percent.

Protection of Juvenile/Adult Survival. The Virginian Province document recommends 2.3 mg liter^{-1} as the threshold above which long-term, continuous exposures should not cause lethal conditions for juvenile and adult fish and shellfish (U.S. EPA 2000).

Additional Scientific Literature Findings. Breitburg et al. (2001) provide a synthesis of the acute sensitivities of an array of species that may inhabit the water column or near-bottom habitats in the deep-water designated use habitats.

> Adults and juveniles of most Chesapeake Bay species that have been tested have 24 hr LC_{50} values near 1 mg l^{-1} (i.e., approximately 13% saturation at 25ºC and 18 psu). Acute toxicity tests have yielded 50% mortality rates with 24-hr exposures at 0.5-1.0 mg l^{-1} for species such as

hogchoker (*Trinectes maculatus*), northern sea robin (*Prionotus carolinus*), spot (*Leiostomus xanthurus*; but LC_{50} reported as >1 mg l^{-1} by Phil et al. 1991) tautog (*Tautoga onitis*), windowpane flounder (*Scopthalmus aquosus*), and fourspine stickleback (*Apeltes quadracus*), and 50% mortality rates between 1.1 and 1.6 mg l^{-1} for Atlantic menhaden (*Brevoortia tyrannus*), scup (*Stenotomus chrysops*), summer flounder (*Paralichthyus dentatus*), pipefish (*Syngnathus fuscus*) and striped bass (*Morone saxatilis*) (Pihl et al. 1991; Poucher and Coiro, 1997; Thursby et al. 2000 [cited here as U.S. EPA]). Thus, for nearly all species tested, the range of tolerances is quite low; only a 1.0 mg l^{-1} difference separates the most and least sensitive species described above.

Although fewer species have been tested during the larval stage, larvae of species that occur in Chesapeake Bay appear to be somewhat more sensitive to low oxygen exposure than are most adults and juvenile. For example, 50% mortality with 24-h exposure occurs between 1.0 and 1.5 mg l^{-1} for skilletfish (*Gobiesox strumosus*), naked goby (*Gobiosoma bosc*), and inland silverside (*Menidia beryllina*) larvae, while 50% mortality occurs at 1.8 to 2.5 mg l^{-1} for larval red drum (*Sciaenops ocellatus*), bay anchovy (*Anchoa mitchilli*), striped blenny (*Chasmodes bosquianus*) and striped bass (Saksena and Joseph 1972; Breitburg 1994; Poucher and Coiro 1997). Field and laboratory observations indicate that lethal dissolved oxygen concentrations for skilletfish, naked goby and striped blenny adults are 1.0 mg l^{-1} (Breitburg, unpublished data).

Embryo tolerances vary inconsistently in relation to tolerances of later stages; 50% mortality in 12-96 h occurs at a higher dissolved oxygen concentration than that for larval mortality for bay anchovy (2.8 mg l^{-1}), at a similar oxygen concentration as for larvae for inland silverside (1.25 mg l^{-1}), and at lower concentrations than that leading to larval mortality for winter flounder (*Pleuronectes americanus*; 0.7 mg l^{-1}) and naked goby (approximately 0.6 mg l^{-1}) (Chesney and Houde 1989; Poucher and Coiro 1997).

Roman et al. (1993) examined the distribution of two species of zooplankton copepods—*Acartia tonsa* and *Oithona colcarva*—through the water column in the Chesapeake Bay. *Acartia tonsa*, which regularly migrate from open water down to subpycnocline waters, were not found in bottom waters when oxygen concentrations were < 1 mg liter $^{-1}$. The highest concentration of zooplankton were found at the pycnocline level.

In a recent review of zooplankton responses to and ecological consequences of zooplankton exposure to low dissolved oxygen, Marcus (2001) synthesized the following literature findings.

Vargo and Sastry (1977) reported that 2-h LD_{50} values for *Acartia tonsa* and *Eurytemora affinis* adults collected from the Pettaquamscutt River Basin, Rhode Island ranged from dissolved oxygen concentrations of 0.36 to 1.40 mg l^{-1} and 0.57 to 1.40 mg l^{-1} respectively. Roman et al. (1993) tested the oxygen tolerance of adults of *Acartia tonsa* and *Oithona*

colcarva from Chesapeake Bay. Survival was considerably less after 24 h in < 2.0 mg l^{-1} oxygenated water.

Stalder and Marcus (1997) examined the 24-h survival of three coastal copepod species in response to low oxygen. *Acartia tonsa* showed excellent survival at concentrations as low as 1.43 mg l^{-1}. Between 1.29 and 0.86 mg l^{-1} survival declined markedly and at 0.71 mg l^{-1} mortality was 100%. *Labidocera aestiva* and *Centropages hamatus* were more sensitive to reduced dissolved oxygen concentrations. The survival of these species was significantly lower at 1.43 mg l^{-1}. The survival of nauplii of *Labidocera aestiva* and *Acartia tonsa* at low dissolved oxygen concentrations was generally better than adult survival.

Rationale

Protecting the recruitment of bay anchovy eggs and larvae into the juvenile and adult population is crucial to the integrity of the Chesapeake Bay ecosystem. The bay anchovy is a primary food source for many fish species. To protect bay anchovy recruitment, criteria values of a 30-day mean of 3 mg $liter^{-1}$ and an instantaneous minimum of 1.7 mg $liter^{-1}$ were selected to best reflect the shape of the final combined bay anchovy egg and larval recruitment effects curve illustrated in Figure III-7.

This approach to criteria derivation is consistent with the approach to derive criteria protective against larval effects in open-water habitats. These approaches followed the guidelines published by the EPA in the Virginian Province dissolved oxygen criteria document (U.S. EPA 2000). The bay anchovy 12- to 24-hour post larvae hatch values from Chesney and Houde (1989) place bay anchovy larvae within the upper range of larval life stage sensitivities for all 17 fish and invertebrate species documented in the Virginian Province document (see Figure 4 on page 13 and Appendix D). The criteria derived to protect bay anchovy early life stages should be protective of other species that routinely inhabit deeper, pycnocline habitats.

The 1.7 mg $liter^{-1}$ criterion value was derived as the dissolved oxygen concentration where the combined egg/larval recruitment effects curve intercepted the y-axis (Figure III-7). Given that the y-axis intercept reflects 'time zero,' an instantaneous minimum duration was applied to the 1.7 mg $liter^{-1}$ criterion value. The 3 mg $liter^{-1}$ criterion value was derived as the approximate point where the combined egg/larval recruitment effects curve levels out. The flattening of the curve beyond this point indicates that dissolved oxygen concentrations much greater than 3 mg $liter^{-1}$ should not cause increased impairment of egg/larval recruitment over longer periods of exposure. The 3 mg $liter^{-1}$ concentration corresponded with 30 days on the x-axis (Figure III-7).

These criteria values and durations are supported by findings published in the scientific literature. Chesney and Houde (1989) evaluated 12- to 14-hour-old yolk-sac bay anchovy larvae over 12 hours, yielding the effects data used in running the bay

anchovy egg/larval recruitment models. In deep-water habitats, field observations support the presence of effects at durations of less than 24 hours, which supports the selection of the instantaneous minimum versus a daily average criterion concentration (Breitburg 1992). Magnusson et al. (1998) have indicated that asphyxia, as described previously, has been reported at dissolved oxygen concentrations well below (> 50 percent) the reported LC_{50} concentrations. Given that the reported LC_{50} values for bay anchovy larvae range from 2.1 to 2.8 mg liter^{-1} (Chesney and Houde 1989; Breitburg 1994), an instantaneous minimum criteria value above 1.4 mg liter^{-1} (50 percent of 2.8 mg liter^{-1}) is required to prevent lethal conditions at exposures of less than 24-hour averaged conditions. Given that the reported laboratory and field effects were manifested in less than 12 hours, an instantaneous minimum concentration is further justified as the temporal period for application of the 1.7 mg liter^{-1} criterion value.

In addition to early life stages of bay anchovy, the instantaneous minimum of 1.7 mg liter^{-1} protects juvenile and adult survival of those fish species commonly inhabiting water-column and bottom habitats within the pycnocline (e.g., spot, summer flounder and winter flounder; Table III-7). See also Table 1, page 8 in U.S. EPA (2000) for additional supporting effects data. This criterion value also will protect zooplankton, the principal prey of the bay anchovy and many other fish during their early life stages (Table III-7; Marcus 2001; Roman et al. 1993). Application of the Virginian Province saltwater criteria for juvenile/adult survival, 2.3 mg liter^{-1} as a 1-day mean, will provide the required level of protection to short-term exposures to low dissolved oxygen in deep-water habitats (U.S. EPA 2000).

The open-water criteria that apply to the summer-only deep-water designated use habitats from October 1 through May 31 will protect Atlantic and shortnose sturgeon inhabiting these deep waters in the winter (Secor et al. 2000; Welsh et al. 2000). From June 1 to September 30, the deep-water designated use criteria will not fully protect Atlantic and shortnose sturgeon.

Historically, natural low dissolved oxygen conditions (< 3 mg liter^{-1}) in deep-water and deep-channel regions would have curtailed sturgeon access. Over the past several hundred years, sturgeon probably have not used deep-water and deep-channel designated use habitats during summer months due to ‘naturally’ pervasive hypoxia (see the sections above titled, “Low Dissolved Oxygen: Historical and Recent Past” and “Historical Potential Sturgeon Tidal Habitats”). Behavioral studies indicate that sturgeon are capable of avoiding these hypoxic regions (Niklitschek 2001) and probably have done so for centuries. On the other hand, deep-water and deep-channel designated use habitats do recover to normoxic conditions during the fall, winter and spring months. During these periods evidence supports a past and recent role for habitats as thermal refuge and migration corridors in the Chesapeake Bay.

This criterion also will protect open-water species with higher dissolved oxygen sensitivities that search for prey within these pycnocline habitats for short periods of time. Field data from other estuarine and coastal systems, such as Long Island Sound

Table III-7. Deep-water seasonal fish and shellfish designated use criteria components.

Criteria Components	Concentration	Duration	Source
Protection against egg/larval recruitment effects	3 mg liter^{-1} 1.7 mg liter^{-1}	30 days instantaneous minimum	Chesney and Houde 1989; Breitburg 1994; U.S. EPA 2000
Protection of juvenile/adult survival	> 2.3 mg liter^{-1}	24 hours	U.S. EPA 2000
Additional literature findings			
- 50 percent mortality for hogchoker, northern sea robin, spot	0.5-1 mg liter^{-1}	24 hours	Reviewed in Breitburg et al. 2001
- 50 percent mortality for tautog, windowpane flounder adults	> 1 mg liter^{-1}	24 hours	Reviewed in Breitburg et al. 2001; Pihl et al. 1991;
- 50 percent mortality for menhaden, summer flounder, pipefish, striped bass adults	1.1-1.6 mg liter^{-1}	24 hours	Reviewed in Breitburg et al. 2001; Pihl et al. 1991; Poucher and Coiro 1997; U.S. EPA 2000
- 50 percent mortality for skilletfish, naked goby, silverside larvae	1-1.5 mg liter^{-1}	24 hours	Breitburg 1994; Poucher and Coiro 1997
- 50 percent mortality for red drum, bay anchovy, striped blenny larvae	1.8-2.5 mg liter^{-1}	24 hours	Saksena and Joseph 1972; Breitburg 1994; Poucher and Coiro 1997
- Zooplankton habitat avoidance	< 1 mg liter^{-1}	-	Roman et al. 1993
- Reduced copepod nauplii abundance	< 1 mg liter^{-1}	-	Qureshi and Rabalais 2001
- 50 percent mortality for *Acartia tonsa* and *Eurytemora affinis*	0.36-1.4 mg liter^{-1}	2 hours	Vargo and Sastry 1977
- Mortality for *Acartia tonsa* and *Oithona colcarva*	< 2 mg liter^{-1}	24 hours	Roman et al. 1993
- 100 percent mortality for copepods	0.71 mg liter^{-1}	24 hours	Stalder and Marcus 1997
- Reduced survival for copepods	<.86-1.3 mg liter^{-1}	24 hours	Stalder and Marcus 1997
- *Acartia tonsa* survival	> 1.43 mg liter^{-1}	24 hours	Stalder and Marcus 1997

and Albemarle-Pamlico Sound, clearly indicate that open-water species will use pycnocline region habitats if dissolved oxygen concentrations are above levels that result in avoidance (e.g., Howell and Simpson 1994; Simpson 1995; Eby 2001).

Recommended Criteria

The following criteria fully support the seasonal-based Chesapeake Bay deep-water designated use when applied from June 1 through September 30: a 30-day mean 3 mg liter^{-1}, a 1-day mean 2.3 mg liter^{-1} and an instantaneous minimum 1.7 mg liter^{-1}.

DEEP-CHANNEL SEASONAL REFUGE DESIGNATED USE CRITERIA

Deep-channel habitats are defined as the very deep water-column and adjacent bottom surficial sediment habitats located principally in the river channel at the lower reaches of the major rivers (e.g., the Potomac River) and along the spine of the middle mainstem Chesapeake Bay at depths below which seasonal anoxic (< 0.2 mg liter^{-1} dissolved oxygen) to severe hypoxic conditions (< 1 mg liter^{-1} dissolved oxygen) routinely set in and persist for extended periods of time under current conditions (Appendix A; U.S. EPA 2003a). From late spring to early fall, many of these deep-channel habitats are naturally exposed to very low dissolved oxygen concentration conditions. Under low dissolved oxygen conditions of 1 to 2 mg liter^{-1}, these habitats are suitable only for survival of benthic infaunal and epifaunal organisms.

Criteria that support the deep-channel designated use must fully 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" (Appendix A; U.S. EPA 2003a). The seasonal-based deep-channel criteria are based on establishing dissolved oxygen concentrations to protect the survival of bottom sediment-dwelling worms and clams.

Components

The infauna of the deep-channel habitat are the most tolerant of all infaunal benthic organisms in the Chesapeake Bay. Even if there were no problems with low dissolved oxygen conditions, the benthic organisms inhabiting unconsolidated mud habitats in these deep-channel designated use habitats probably would not change. Looking at benthos from deep-channel habitats in the Chesapeake Bay that are not hypoxic or anoxic, one finds the same benthic community species. On an annual basis, productivity is about the same for hypoxic versus non-hypoxic deep unconsolidated mud bottom sediment habitats in the mesohaline Chesapeake Bay (Diaz and Schaffner 1990). The factors that control what is present in these mesohaline benthic habitats are salinity and sediment type. Hypoxic conditions run a distant third (Holland et al. 1977). Hypoxic conditions change the benthic community structure periodically, but the pool from which these low oxygen habitats are recolonized

after a severe low-oxygen to no-oxygen event is still the limiting factor for a benthic community.

Benthic infauna have high tolerances to low dissolved oxygen conditions (~1 mg liter^{-1}) and many macrofaunal species demonstrate behavioral reactions before they eventually die (Diaz and Rosenberg 1995). For the mesohaline zone of estuaries, the critical dissolved oxygen level appears to be around 0.6–1.0 mg liter^{-1} (Diaz and Rosenberg 1995; Table III-8). At the high end of this dissolved oxygen range, the bottom-dwelling community starts to lose moderately tolerant species, with more tolerant species dying off at the low end of the range. In estuaries and coastal systems exposed to seasonally varying low dissolved oxygen, the critical dissolved oxygen concentration is closer to 1 mg liter^{-1} (Llanso 1992), with subtle reductions in dissolved oxygen concentration from 1 to 0.5 mg liter^{-1} causing a full range of responses from behavioral to death (Llanso and Diaz 1994). In their synthesis of dissolved oxygen concentrations causing acute and chronic effects on Chesapeake Bay benthic infaunal organisms, Holland et al. (1989) found a similar range of oxygen concentrations that cause mortality or severe behavioral effects (Appendix C).

Table III-8. Deep-channel designated use criteria effects data.

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

In the deep channel of the Chesapeake Bay, communities of mud-burrowing worms and clams have a broad tolerance to a wide range of sediment types, salinities, dissolved oxygen concentrations and organic loadings. Several keystone Bay bottom-dwelling polychaete worm species—*Paraprionospio pinnata, Streblospio benedicti, Loimia medusa* and *Heteromastus filiformis*—are resistant to dissolved oxygen concentrations as low as 0.6 mg liter^{-1} (Llanso and Diaz 1994; Diaz et al. 1992; Llanso 1991).

Extensive mortality is likely only under persistent exposure to very low dissolved oxygen concentrations (< 1 mg liter^{-1}) at higher summer temperatures in the Chesapeake Bay (Holland et al. 1977). Similar findings have been reported for other

estuarine and coastal systems (Rosenberg 1977; Jorgensen 1980; Stachowitsch 1984; Gaston 1985).

While the macrobenthic community itself often is found to be insensitive to low dissolved oxygen concentrations around 2 mg liter^{-1}, exposure of these bottom habitats to brief periods of dissolved oxygen concentrations < 2 mg liter^{-1} affects behavior (resulting in decreased burrowing depth and exposure at the sediment surface), growth and production (Diaz et al. 1992). From a synthesis of 12 years of diverse observations and 5 years of remotely operated vehicle videotapes, Rabalais et al. (2001) reported stressed behavior, such as emergence from the sediments by burrowing invertebrates, at dissolved oxygen concentrations below 1.5 to 1 mg liter^{-1}. At dissolved oxygen concentrations of 1 to 1.5 mg liter^{-1}, they observed "even the most tolerant burrowing organisms, principally polychaetes, emerge partially or completely from their burrows and lie motionless on the bottom." Demersal feeding fish change their feeding habits quickly to take advantage of stressed macrobenthos that come to the sediment surface (Stachowitsch 1984; Jorgensen 1980), where they become more vulnerable to predation during or following a low dissolved oxygen event (Pihl et al. 1991, 1992).

Epifaunal communities living along the surfaces of bottom sediments in the Chesapeake Bay can persist with minimal changes in species composition and abundance under brief exposures to dissolved oxygen concentrations in the range of 0.5 to 2.0 mg liter^{-1} (Sagasti et al. 2000).

For the unconsolidated mud benthic infaunal community of the mesohaline Chesapeake Bay where the deep-channel designated use habitats are located, 1 mg liter^{-1} is protective of survival. The global scientific literature points towards 2 mg liter^{-1} as the protective dissolved oxygen value, but this is the oxygen tolerance for higher salinity, more structured benthic communities and species. Between 2 and 3.5 mg liter^{-1} there are definite behavioral changes for many species and mortality for sensitive species in these higher salinity habitats. For Chesapeake Bay species in similar higher salinity (polyhaline) habitats, 2 mg liter^{-1} would be the dissolved oxygen minimum requirement. Benthic communities in these polyhaline habitats in the Chesapeake Bay will be protected by applying the open-water dissolved oxygen criteria year-round. However, for the mesohaline Chesapeake Bay where the hypoxic and anoxic conditions are focused during the summer months, the scientific literature for unconsolidated mud mesohaline benthic communities supports 1 mg liter^{-1} as the bottom-line requirement. Dissolved oxygen concentrations of less than 1 mg liter^{-1} lead to mortality for even tolerant species.

Rationale

To ensure protection of the survival of bottom-dwelling worms and clams, an instantaneous minimum criterion of 1 mg liter^{-1} was selected (Table III-9). As documented through the extensive scientific literature reported here, this value will protect against lethal effects from exposure to low dissolved oxygen. However, behavioral

Table III-9. Response patterns of Chesapeake Bay benthic organisms to declining dissolved oxygen concentrations (mg liter^{-1}).

Response	Dissolved Oxygen	Species	Reference
Avoidance			
Infaunal swimming	1.1	*Paraprionospio pinnata*	Diaz et al. 1992
	0.5	*Nereis succinea*	Sagasti et al. 2001
Epifaunal off bottom	0.5	*Neopanope sayi*	Sagasti et al. 2001
	0.5	*Callinectes sapidus*	Sagasti et al. 2001
	1	*Stylochus ellipticus*	Sagasti et al. 2001
	1	*Mitrella lunata*	Sagasti et al. 2001
	0.5	*Dirodella obscura*	Sagasti et al. 2001
	1	*Cratena kaoruae*	Sagasti et al. 2001
Fauna, unable to leave or escape, initiate a series of sublethal responses			
Cessation of feeding	0.5	*Balanus improvisus*	Sagasti et al. 2001
	0.6	*Streblospio benedicti*	Llanso 1991
	1	*Loimia medusa*	Llanso and Diaz 1994
	1.1	*Capitella* sp.	Warren 1977; Forbes and Lopez 1990
Decreased activities not related to respiration	0.5	*Balanus improvisus*	Sagasti et al. 2001
	0.5	*Conopeum tenuissimum*	Sagasti et al. 2001
	0.5	*Membranipora tenuis*	Sagasti et al. 2001
	1	*Cratena kaoruae*	Sagasti et al. 2001
	1	*Stylochus ellipticus*	Sagasti et al. 2001
	1	*Streblospio benedicti*	Llanso 1991
Cessation of burrowing	1.1	*Capitella* sp.	Warren 1977

continued

Table III-9. Response patterns of Chesapeake Bay benthic organisms to declining dissolved oxygen concentrations (mg liter^{-1}) *(continued)*.

Response	Dissolved Oxygen	Species	Reference
Emergence from tubes or burrows	0.1-1.3	*Ceriathiopis americanus*	Diaz, unpublished data
	0.5	*Sabellaria vulgaris*	Sagasti et al. 2001
	0.5	*Polydora cornuta*	Sagasti et al. 2001
	0.7	*Micropholis atra*	Diaz et al. 1992
	1	*Hydroides dianthus*	Sagasti et al. 2001
	10% saturation	*Nereis diversicolor*	Vismann 1990
Siphon stretching into water column	0.1-1.0	*Mya arenaria, Abra alba*	Jorgensen 1980
Siphon or body stretching	0.5	*Molgula manhattensis*	Sagasti et al. 2001
	0.5	*Diadumene leucolena*	Sagasti et al. 2001
Floating on surface of water	0.5	*Diadumene leucolena*	Sagasti et al. 2001
Formation of resting stage	0.5	*Membranipora tenuis*	Sagasti et al. 2001
	0.5	*Conopeum tenuissimum*	Sagasti et al. 2001

Sources: Diaz and Rosenberg 1995; Sagasti et al. 2001.

changes leading to increased opportunities for predation are not protected by this criterion. These changes may benefit bottom-feeding fish and crabs, giving them direct access to food, albeit under potentially stressful water quality conditions.

The deep-channel criteria protect survival but not necessarily the growth of benthic infaunal and epifaunal species from June through September. However, Diaz and Schaffner (1990) reported that their evaluation of annual secondary productivity of hypoxic habitats in the Bay's deep-channel habitats indicated no significant reduction in productivity from low dissolved oxygen conditions. Therefore, the deep-channel criteria's failure to provide full protection against growth impairments is counteracted by growth during the rest of the year, when dissolved oxygen concentrations are naturally higher than 1 mg liter^{-1}, which leads to a net result of protection against growth impairment on an annual basis.

The instantaneous minimum value of 1 mg liter^{-1} is much more protective of benthic infaunal organisms than a 1- or 7-day average. In the case of bottom-dwelling organisms, it is not the average condition that is most detrimental to the organisms but the absolute minimum dissolved oxygen. When dissolved oxygen drops significantly below 1 mg liter^{-1} for even short periods of time (on the order of hours) mortality increases, even for tolerant species. Other deep-channel criteria with higher concentrations than 1 mg liter^{-1} and with 1-, 7- or 30-day averaging periods were not derived for deep-channel designated use habitats, since dissolved oxygen concentrations are not expected to exceed 2 mg liter^{-1} from June through September due to natural constraints.

Deep-Channel Criteria

The instantaneous minimum 1 mg liter^{-1} criterion fully supports the seasonal-based Chesapeake Bay deep-water designated use when applied from June 1 through September 30.

CHESAPEAKE BAY DISSOLVED OXYGEN CRITERIA

The Chesapeake Bay dissolved oxygen criteria are structured to protect the five tidal-water designated uses and reflect the needs and habitats of Bay estuarine living resources (Table III-10). Criteria for the migratory fish spawning and nursery, shallow-water bay grass and open-water fish and shellfish designated uses were set at levels to protect the reproduction and survival of all organisms and against impairments to their growth. Criteria for deep-water habitats during seasons when the water column is significantly stratified were set at levels to protect juvenile and adult fish, shellfish and the recruitment success of the bay anchovy. Criteria for deep-channel habitats in summer were set to protect the survival of bottom sediment-dwelling worms and clams.

Table III-10. Chesapeake Bay dissolved oxygen criteria.

Designated Use	Criteria Concentration/Duration	Protection Provided	Temporal Application
Migratory fish spawning and nursery use	7-day mean $\geq$ 6 mg liter $^{-1}$ (tidal habitats with 0-0.5 ppt salinity)	Survival/growth of larval/juvenile tidal-fresh resident fish; protective of threatened/endangered species.	February 1 - May 31
	Instantaneous minimum $\geq$ 5 mg liter $^{-1}$	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 $\geq$ 5.5 mg liter $^{-1}$ (tidal habitats with 0-0.5 ppt salinity)	Growth of tidal-fresh juvenile and adult fish; protective of threatened/endangered species.	Year-round
	30-day mean $\geq$ 5 mg liter $^{-1}$ (tidal habitats with >0.5 ppt salinity)	Growth of larval, juvenile and adult fish and shellfish; protective of threatened/endangered species.	
	7-day mean $\geq$ 4 mg liter $^{-1}$	Survival of open-water fish larvae.	
	Instantaneous minimum $\geq$ 3.2 mg liter $^{-1}$	Survival of threatened/endangered sturgeon species.[1]	
Deep-water seasonal fish and shellfish use	30-day mean $\geq$ 3 mg liter $^{-1}$	Survival and recruitment of bay anchovy eggs and larvae.	June 1 - September 30
	1-day mean $\geq$ 2.3 mg liter^{-1}	Survival of open-water juvenile and adult fish.	
	Instantaneous minimum $\geq$ 1.7 mg liter $^{-1}$	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 $\geq$ 1 mg liter $^{-1}$	Survival of bottom-dwelling worms and clams.	June 1 - September 30
	Open-water fish and shellfish designated use criteria apply		October 1 - May 31

[1] At temperatures considered stressful to shortnose sturgeon (>29°C), dissolved oxygen concentrations above an instantaneous minimum of 4.3 mg liter^{-1} will protect survival of this listed sturgeon species.

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