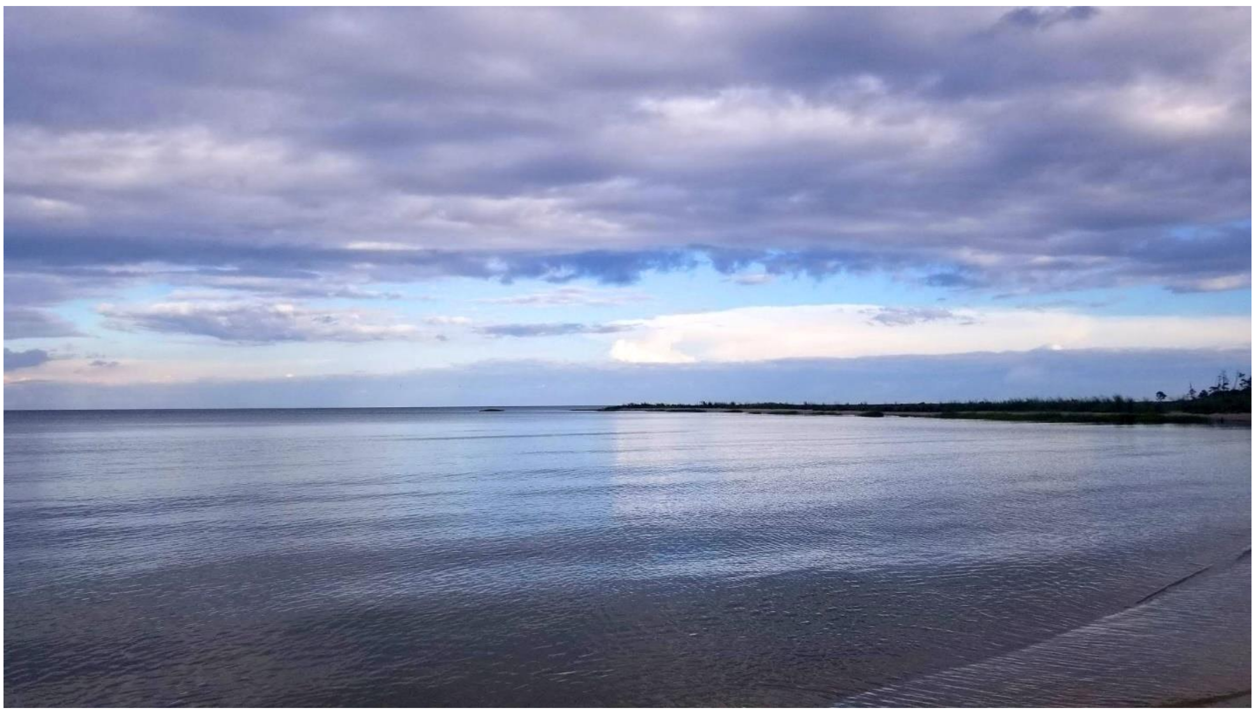
Boundary of the Deep Water Designated Use in Virginia's Chesapeake Bay Mainstem

Virginia Department of Environmental Quality



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Executive Summary

In 2003, the United States Environmental Protection Agency-Chesapeake Bay Program Office (CBPO) conceptualized five aquatic life designated uses for the Chesapeake Bay and its tidal tributaries. Four of these uses—the Migratory Fish Spawning Nursery, Open Water, Deep Water, and Deep Channel uses—are protected through dissolved oxygen (DO) criteria that were also recommended by the CBPO. The technical details of the proposed designated uses—including their defining physical characteristics, temporal application periods, and spatial extents—were published by the CPBO in a series of technical support documents. In 2005, Virginia incorporated these documents by reference into 9VAC25-260-185, along with the recommended criteria and description of designated uses. Since then, the CBPO's scheme of designated use boundaries has been used to determine where specific DO criteria should be applied for the purposes of criteria assessment and water quality modeling, including the modeling work underlying the Chesapeake Bay Total Maximum Daily Load.

The aforementioned designated uses are protected through a suite of DO criteria varying in terms of stringency, in accordance with the physiological tolerances of the aquatic life assemblages that are targeted by each use. For instance, the Migratory Fish Spawning Nursery use, which is established around optimal habitat for larval and juvenile aquatic life, is assessed using the most stringent DO criteria. The stringency of these criteria reflects the heightened sensitivity of larval/juvenile aquatic life to hypoxia. Pelagic aquatic life (e.g., forage fish) are the target assemblage of the Open Water use, which is protected by DO criteria that are less stringent than the criteria tailored to the needs of larval/juvenile aquatic life. The Deep Water and Deep Channel uses are protected by criteria that are less stringent than the Open Water use. The Deep Water use targets aquatic life—like oysters and the bay anchovy—that reside in moderately deep-water habitat and that are adapted to DO levels that are frequently less than 5.0 mg/L. The Deep Channel use targets aquatic life—like sediment-dwelling worms and small clams—that reside in very deep water habitat that are adapted to DO levels between 1 and 3 mg/L. While the Open Water use is presumed to exist in all tidal areas of the Bay and its tributaries, the Migratory Fish Spawning Nursery, Deep Water, and Deep Channel uses are designated only in specific waters.

The CBPO determined that the Deep Water and Deep Channel designated uses are necessary to account for the following natural conditions that collectively promote low DO concentrations: deep water bathymetry, water column stratification, and water circulation patterns that do not mitigate the negative effects of the first two conditions on DO concentrations. These three natural conditions occur most prominently in the Bay mainstem. Much of Maryland's portion of the Bay mainstem is designated for both the Deep Water and Deep Channel uses. However, most of Virginia's Bay mainstem is only designated for the Open Water use (Figure ES-A).

The two largest segments in Virginia's Bay mainstem have bifurcated designated uses (Figure ES-A). The northernmost portions of segments CB6PH and CB7PH are designated for the Open Water and Deep Water uses, while the remaining portions are only designated for the Open Water use. The EPA-CBPO 2003 technical support document describing the Chesapeake Bay designated uses provides supporting evidence of the defining physical characteristics of the Deep Water use in the upper portions of CB6PH and CB7PH and also includes a rationale for not including the lower portions in this designation. At the time, CBPO staff made the assumption that oxygen-rich inflow from the Atlantic Ocean precludes the need for the Deep Water use designation in the lower portions, despite the presence of deep water bathymetry and water column stratification characteristic of the Deep Water use. Virginia accepted this assertion when it incorporated the CBPO's technical support materials by reference into its water quality standards.

A reasonable inference from the CBPO's rationale for the designated uses in Virginia's Bay mainstem is that the influence of the Atlantic Ocean should foster high enough DO concentrations in CB6PH and CB7PH that attainment of the Open Water use should occur frequently, especially in the absence of excessive algal biomass. However, the CBPO's historical attainment analysis indicates that these two segments are frequently not attaining the Open Water 30-day DO mean criterion of 5 mg/L, while immediately adjacent segments CB5MH-VA and CB8PH typically attain this criterion. The segment CB5MH-VA to the north is designated in its entirety for the Deep Water and Deep Channel uses because it exhibits the characteristic natural conditions associated with these uses, and thus the hypoxic bottom waters of this segment are assessed against less stringent DO criteria than those used to assess the Open Water use. Segment CB8PH to the south is designated only for the Open Water use due to its close proximity to the Atlantic Ocean. The high amount of oceanic inflow this segment receives minimizes the occurrence of low DO in its bottom waters. While it is possible that the effects of eutrophication are simply more intense in CB6PH and CB7PH than in CB5MH and CB8PH, the attainment picture in Virginia's Bay mainstem begs the question of whether the assumptions governing the placement of the Deep Water boundary developed by the CBPO were technically sound.

A comprehensive examination of historical and contemporary monitoring data has led staff at the Virginia Department of Environmental Quality (DEQ) to the conclusion that the physical conditions characteristic of the Deep Water habitat (deep-water bathymetry, summertime water column stratification, and minimal inflow of oxygen-rich waters) are present in portions of Virginia's Bay mainstem that are not currently designated for the Deep Water use. Moreover, DEQ staff conclude that the monitoring data indicate that these physical conditions exacerbate the effects of anthropogenic nutrient pollution on DO concentrations to such a degree that these areas should be designated for the Deep Water use. As shown in Figure ES-B, the recommended expanded boundary of the Deep Water use includes all of CB6PH, almost all of CB7PH except for the area closest to the mouth of the Bay, and the deep-water channel cutting through Mobjack Bay (segment MOBPH).

The areas proposed for the Deep Water use designation would continue to be protected by Open Water DO criteria.[1] During the non-summer months, these criteria would apply from the surface to sediment-water interface. From June 1 to September 31, the Open Water criteria would apply to the portion of the water column above the observed pycnocline, while the Deep Water criteria[2] would apply to the portion of the water column from the top of the pycnocline to the sediment-water interface.

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[1] Open Water DO Criteria: 30-day mean DO criterion = 5 mg/L at a salinity greater than 0.5 ppt or 5.5 mg/L at a salinity less than or equal to 0.5 ppt, 7-day mean DO criterion = 4 mg/L, and instantaneous minimum DO criterion = 3.2 mg/L at temperatures less than or equal to 29°C, 4.3 mg/L at temperatures greater than 29°C.

[2] Deep Water DO Criteria: 30-day mean criterion = 3 mg/L, 1-day mean DO criterion = 2.3 mg/L, and instantaneous minimum DO criterion = 1.7 mg/L.

A.

B.

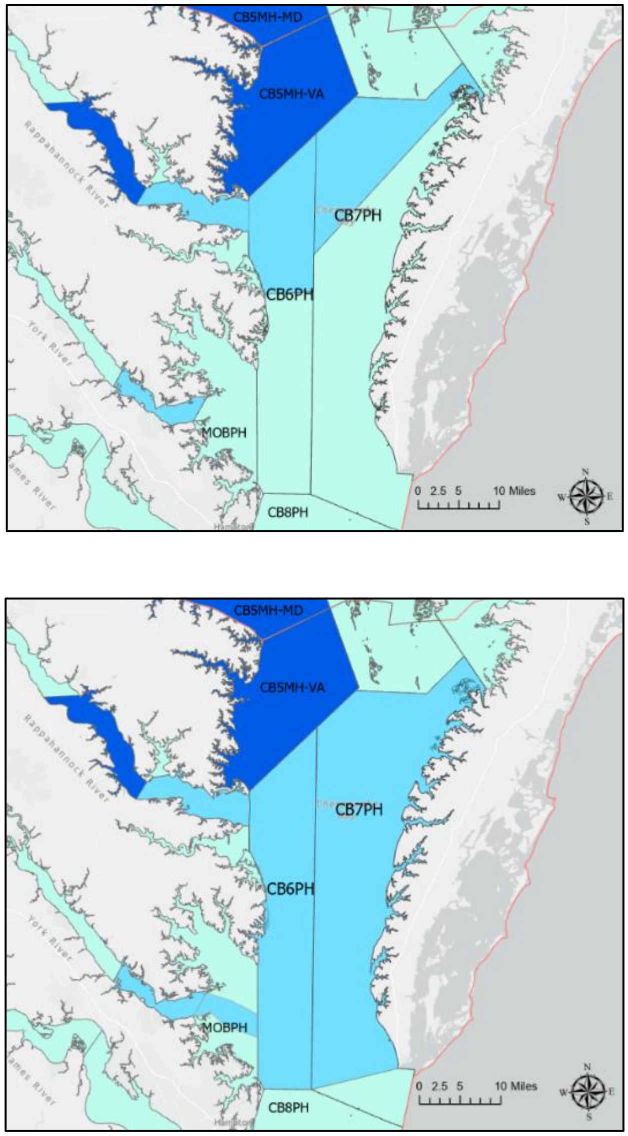

Figure ES. Maps of Virginia's Chesapeake Bay mainstem showing the current (A) and the DEQ staff-recommended (B) extents of the Deep Water designated use (shown in sky blue). The light blue areas are only designated for the Open Water use, while the dark blue areas are designated for the Deep Channel use. The red line corresponds to the state boundary.

1. Introduction

1.1. Chesapeake Bay Designated Uses and 2003 Use Attainability Analysis

In April 2003, the U.S. Environmental Protection Agency-Chesapeake Bay Program (CBPO) published the *Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll a for the Chesapeake Bay and Its Tidal Tributaries*, which was the foundation document establishing recommended Chesapeake Bay water quality criteria and implementation procedures for monitoring and assessment (U.S. EPA 2003a). In October 2003, the CBPO published the document entitled *Technical Support Document for Identification of Chesapeake Bay Designated Uses and Attainability*, which defined the following five tidal water designated uses to be protected through the recommended water quality criteria (U.S. EPA 2003b): Migratory Fish Spawning and Nursery, Open Water, Deep Water, Deep Channel Seasonal Refuge, and Shallow-Water Submerged Aquatic Vegetation (Figure 1).

Virginia adopted the recommended Chesapeake Bay water quality criteria and designated uses into its water quality regulation (9VAC25-260) in 2005. It also incorporated by reference the aforementioned technical documents as well as subsequent addendum documents published by the CBPO (USEPA 2004a, 2004b, 2005. 2007a, 2007b, 2008, 2010, 2017) that describe recommended implementation procedures for the Chesapeake Bay water quality criteria. These criteria are enumerated in 9VAC25-260-185. The Bay designated uses occupy different spaces (horizontally and vertically) at different times and target a diversity of aquatic life assemblages. Four of the five uses are assessed using dissolved oxygen (DO) criteria that are tailored to the physiological tolerances of their targeted aquatic life assemblages[3]. A description of these uses is provided in 9VAC25-260-10.

Only one use—the Open Water use—is presumed to exist in all areas of the Bay and its tidal tributaries[4.] The use is targeted to the aquatic life assemblages that reside in the well-mixed "open water" habitat. In all 92 Bay segments during the non-summer months and many of the segments during the summer, the Open Water use is the sole Bay designated use, extending shoreline to shoreline, surface to sediment-water interface year-round. However, in some segments during the summer months, the Open Water use extends shoreline to shoreline, surface to the upper boundary of the observed pycnocline—a water column layer marked by a steep change in water density (see Figure 2). These segments are designated for the Deep Water and/or Deep Channel uses in addition to the Open Water use. The Open Water use is protected by the following DO criteria: 1) a 30-day mean criterion of either 5 mg/L (salinity > 0.5 ppt) or 5.5 mg/L (salinity < 0.5 ppt), 2) a 7-day mean criterion of 4 mg/L, and 3) an instantaneous minimum criterion of either 3.2 mg/L (temperature $\leq$ 29°C) or 4.3 mg/L (temperatures > 29°C).

The Migratory Fish Spawning and Nursery use targets early life stages of populations of anadromous, semi-anadromous, catadromous and tidal fresh resident fish species inhabiting spawning and nursery grounds. It is designated in the upper reaches of the major Bay tributaries and only exists from February

[3] The four Bay designated uses that are protected through DO criteria will hereafter be referred to as "the Bay designated uses". The Shallow Water Bay Grass use, which is protected through submerged aquatic vegetation and water clarity goals, is not discussed in this technical support document.
[4] The Chesapeake Bay mainstem and its tidal tributaries will be referred to as the "Bay" hereafter, unless otherwise specified.

1 to May 31. The horizontal spatial extent of this use throughout the Bay is detailed in Table A-1 of U.S EPA (2004b). There are two DO criteria applicable to this use—a 7-day mean of 6 mg/L (salinity < 0.5 ppt) and an instantaneous minimum criterion of 5 mg/L. Out of all the criteria used to assess the Bay designated uses, these are the most stringent since they reflect the heightened sensitivity of larval and juvenile aquatic life to the effects of hypoxia. The Migratory Fish Spawning and Nursery use exists concurrently with the Open Water use in the areas that are designated for both.

The Deep Water use targets aquatic life like oysters and the bay anchovy that reside in deep-water habitats. In areas designated for the Deep Water use, the use exists from June 1 to September 30—when warmer temperatures result in the formation of a pycnocline. A pycnocline, which is a steep change in water density with depth, acts as a physical barrier to vertical water column mixing. A pycnocline occurring in waters overlaying deep-water bathymetry tends to promote the development of low DO concentrations in bottom waters. In half of the segments with the Deep Water use designation, the use extends from shoreline to shoreline and below the upper boundary of the pycnocline to the sediment-water interface. But the other half of segments designated for this use, there is also the designation of the Deep Channel use. In these segments, the Deep Water use extends from shoreline to shoreline and below the upper boundary of the pycnocline to the lower boundary of the pycnocline whenever a mixed layer below the pycnocline is observed (US. EPA 2008). The horizontal spatial extent of this use throughout the Bay is detailed in Table A-2 of U.S EPA (2004b). The Deep Water use is protected by the following three DO criteria: 1) a 30-day mean criterion of 3 mg/L, 2) a 1-day mean criterion of 2.3 mg/L, and 3) an instantaneous minimum criterion of 1.7 mg/L.

Finally, the Deep Channel use targets benthic infauna and epifauna inhabiting the deepest waters of the Chesapeake Bay. In areas designated for the Deep Channel use, the use exists from June 1 to September 30, when warmer temperatures result in the formation of a pycnocline overlaying a well-mixed bottom layer. All areas designated for the Deep Channel use are also designated for the Deep Water use. The Deep Channel use exists in designated areas shoreline to shoreline and below the lower boundary of the pycnocline to the sediment-water interface. The horizontal spatial extent of this use through the Bay is detailed in Table A-2 of U.S EPA (2004b). The Deep Channel use is protected by one DO criterion—an instantaneous minimum criterion of 1 mg/L. This criterion is the least stringent among the Bay DO criteria.

The CBPO's technical support document on the Chesapeake Bay designated uses (U.S. EPA 2003b) provides information to assist Chesapeake Bay jurisdictions in developing individual use attainability analyses (UAAs) for those waters of the Chesapeake Bay and its tidal tributaries not expected to meet the Open Water use due to low DO that is either naturally occurring or that cannot be feasibly remedied. This information laid the groundwork for the designation of the Deep Water and Deep Channel uses, which are held to less stringent criteria than the default Open Water use. The Open Water use is the Bay designated use most similar to the Bay jurisdiction's aquatic life use established at the time of the 2003 publication.

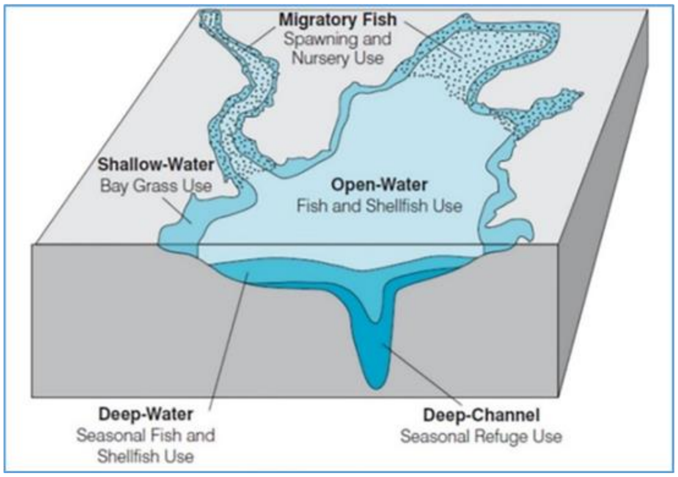

Figure 1. The Chesapeake Bay designated uses.

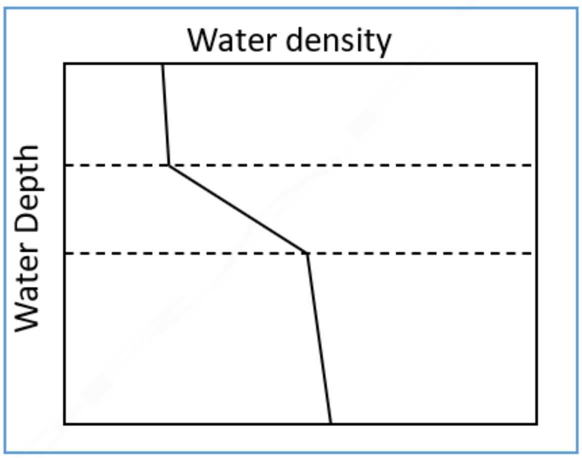

Figure 2. An example of a vertical density profile characteristic of a water column exhibiting a pycnocline, the layer contained within the two dashed lines.

EPA's Water Quality Standards Regulation (at Title 40 of the Code of Federal Regulation §131.3) defines a UAA as ". . . a structured scientific assessment of the factors affecting the attainment of a use which may include physical, chemical, biological, and economic factors as described in 40 CFR 131.10[g]." 40 C.F.R. 131.3 requires a state to conduct a UAA when it designates uses that do not include those specified in Section 101(a)(2) of the Federal Water Pollution Control Act. A state must also conduct a UAA when it wishes to remove a specified designated use of the Federal Water Pollution Control Act or adopt subcategories of those specified uses that require less stringent criteria. When conducting a UAA, a state must demonstrate that attaining the designated use is not feasible due to one or more of six factors specified in Section 131.10(g). These factors are:

1. Naturally occurring pollutant concentrations prevent the attainment of the use;

2. Natural, ephemeral, intermittent, or low-flow conditions or water levels prevent the attainment of the use, unless these conditions may be compensated for by the discharge of a sufficient volume of effluent without violating state water conservation requirements to enable uses to be met;

3. Human-caused conditions or sources of pollution prevent the attainment of the use and cannot be remedied or would cause more environmental damage to correct than to leave in place;

4. Dams, diversions or other types of hydrologic modifications preclude the attainment of the use, and it is not feasible to restore the water body to its original condition or to operate such modifications in a way that would result in the attainment of the use;

5. Physical conditions related to the natural features of the water body, such as the lack of a proper substrate, cover, flow, depth, pools, riffles and the like, unrelated to chemical water quality, preclude attainment of aquatic life protection uses; and

6. Controls more stringent than those required by sections 301(b) and 306 of the Act would result in substantial and widespread economic and social impact.

40 C.F.R. 131.3 also specifies that any change in designated uses must show that the existing uses are still being protected. An existing use is one attained in the water body on or after November 28, 1975, whether or not they are included in the water quality standards (40 CFR 131.3[e]). Federal regulations require state anti-degradation policies to protect existing water quality. Therefore, any recommendations regarding refined designated uses for the Chesapeake Bay and its tidal tributaries must ensure that existing aquatic life uses continue to be protected.

U.S. EPA (2003b) documented the CBPO's findings that attainment of the designated uses in place at the time of the publication was not feasible in all of the Bay due to two of the six factors listed above—natural conditions (Factor 1) and human-caused conditions that cannot be remedied (Factor 3). The CBPO performed a demonstration of these factors by evaluating the percent nonattainment of simulated DO observations with respect to a monthly DO average of 5 mg/L—a criterion that U.S. EPA (2003a) had recommended for the protection of the Bay Open Water use—under three model scenarios: all-forested Bay watershed, pristine Bay watershed, and limit of pollutant control technology in "everything, everywhere by everybody" within the Bay watershed. The first two scenarios presented the best quantitative estimate of where and when naturally occurring pollutant[5] concentrations prevent the attainment of the use. High percent nonattainment in all three scenarios was found in areas that had been tentatively identified as meeting the conditions for Deep Water and Deep Channel habitat. This modeling work was used to support a refinement of the designated uses that were established by the Bay jurisdictions at the time. The uses defined in regulation at the time did not account for natural conditions that can promote low DO.

In addition to providing the technical justification for refining Bay designated uses with respect to natural conditions, U.S. EPA (2003b) also provided the technical basis for the spatial delineation of these refined designated uses. The CBPO's analyses of monitoring and modeling data led to the creation of spatial boundaries for the Migratory Fish Spawning and Nursery (presented in U.S. EPA 2004b) and Deep Water and Deep Channel uses (presented in U.S. EPA 2003b and U.S. EPA 2004b). The Bay jurisdictions

[5] While dissolved oxygen is not a pollutant in the conventional sense of the word, EPA considers dissolved oxygen to be a naturally occurring pollutant when its depletion can be tied to factors besides human-caused pollution.

incorporated by reference into their water quality standards regulations U.S. EPA (2003a), U.S. EPA (2003b), and U.S. EPA (2004b). The decisions laid out in these documents became effective in 2005. Since 2005, the CBPO's scheme of designated use boundaries has been used to determine where DO criteria should be applied for the purposes of criteria assessment and water quality modeling, including the modeling work underlying the Chesapeake Bay Total Maximum Daily Load (U.S. EPA 2010).

While the designated use delineations were made independent of the segmentation scheme described in the publication entitled *The Chesapeake Bay Program Segmentation Scheme Revisions, Decisions and Rationales: 1983-2003* (U.S. EPA 2004b), the segmentation scheme serves as a useful reference for the location of the Deep Water and Deep Channel designated uses since the segment boundaries were designed to encapsulate areas with similar natural conditions, like salinity and geographic features. In most segments where the Deep Water and Deep Channel uses are designated, the uses are designated over the entirety of a segment's extent. There are three notable exceptions to this, and they are all located in Virginia. First, the mesohaline segment of the Rappahannock River is unique in that it has three "subsegments", each one with a unique set of designated uses—1) Shallow Water, Migratory Fish Spawning and Nursery, and Open Water uses in the northernmost subsegment, 2) Shallow Water, Open Water, Deep Water, and Deep Channel uses in the central subsegment, and 3) Shallow Water, Open Water, and Deep Water uses in the southernmost subsegment. The other two segments with "subsegmented" water quality standards are in the Bay mainstem—CB6PH and CB7PH. For these two segments, the northern portions are designated for Shallow Water, Open Water, and Deep Water uses, while the southern portions are only designated for the Shallow Water and Open Water uses. The technical rationale for partitioning these segments in such a way is provided in U.S. EPA (2003b).

The purpose of this document is to present a technical rebuttal to the rationale presented in U.S. EPA (2003b) for the Deep Water boundary in Virginia's Bay mainstem. The information presented here provides support for the finding that the natural conditions which necessitate a Deep Water use designation in the northern portion of segments CB6PH and CB7PH occur throughout their southern extents and the channel of Mobjack Bay as well. Staff at the Virginia Department of Environmental Quality (DEQ) are recommending that the Deep Water boundary published in U.S. EPA (2004b) be expanded to properly account for the natural conditions occurring in Virginia's Bay mainstem.

1.2 Current Delineation of the Deep Water Use in Virginia's Bay Mainstem

1.2.1 Vertical Extent of the Deep Water Use

Stratification occurs in the Chesapeake Bay whenever there is a vertical gradient in water density, usually arising from warmer, less saline surface water overlaying much cooler, more saline bottom water. In a stratified water column, these two layers are separated from each other by another layer, the pycnocline—where water density changes rapidly with depth. Vertical mixing is reduced in the pycnocline (Figure 2), limiting downward transport of DO and upward transport of nutrients and organic material. As a result, Bay segments characterized by strong seasonal stratification are more susceptible than other segments to developing extended periods of low dissolved oxygen concentrations in their deep waters. U.S. EPA (2003b) outlines the conditions that define the Deep Water habitat and assigns this use to specific waters of the Bay. The procedure for determining pycnocline depths pertinent to the Deep Water and Deep Channel designated uses was published in U.S. EPA (2004a) with updates in U.S. EPA (2008) and U.S. EPA (2010). Most of the Chesapeake Bay mainstem and the lower reaches of several major tributaries are designated for the Deep Water use.

The waters inside the Deep Water boundaries can experience prolonged hypoxia (DO concentrations less than 3.0 mg/L) during the warmest months of the year. The spatial distribution and seasonal development of hypoxia in the Chesapeake Bay are indicative of oxygen depletion arising from interactions between biological and physical processes (Taft et. al. 1980, Kemp et. al. 1992, Kemp et. al 2005). While nearshore waters of Chesapeake Bay can experience episodic hypoxia and anoxia, prolonged hypoxia is an annual event in the deep waters associated with areas experiencing 1) strong stratification resulting from natural bathymetric features, water flow patterns, water circulation patterns coupled with 2) the oxygen-consuming effects of nutrient enrichment on increased plankton biomass, algal bloom deposition and decomposition (Kemp et. al 2005).

For deep waters subject to summertime stratification which were not recommended for the Deep Water or Deep Channel designation in U.S. EPA (2003b), EPA maintains that certain circulation patterns can provide adequate oxygen replenishment to offset net oxygen consumption resulting from the decomposition of organic matter deposition from plankton and other organic input sources (e.g. storm delivered debris, wetland erosion, etc.). These circulation patterns presumably can maintain oxygen levels high enough to support pelagic aquatic life assemblages, even in the presence of water column stratification. This is made clear in EPA's rationale for the Open Water designated use:

> *"Clear evidence from the Chesapeake Bay as well as other estuarine and coastal systems, including Long Island Sound (Howell and Simpson 1994), Albemarle Pamlico Sound (Eby 2001) and the Gulf of Mexico (Craig et al. 2001), indicates that the fish and other organisms inhabiting open-water habitats will use deeper within pycnocline and below-pycnocline habitats, given suitable dissolved oxygen conditions. It is the lack of sufficient oxygen, not the presence of stratification, that limits the use of these deeper habitats. Therefore, the open-water designated use applies to transitional pycnocline and bottom mixed-layer below-pycnocline habitats where these below-pycnocline and pycnocline waters are sufficiently reoxygenated by oceanic or riverine waters."* (U.S. EPA 2003b)

In waters designated for the Deep Water use, the Deep Water habitat occurs during the summer months within the portion of the water column that is either between the upper and lower boundaries of the pycnocline (if the waters are also designated for the Deep Channel use) or between the upper boundary of the pycnocline and the sediment-water interface (U.S. EPA 2003a). In waters designated for the Deep Water use, the summertime Open Water use exists in the portion of the water column above the upper boundary of the observed pycnocline (U.S. EPA 2003a). Without the Deep Water designation, it is presumed that the summertime Open Water habitat exists from the surface to the sediment-water interface in waters, even at times when the water column is stratified. The Open Water habitat is protected through more stringent dissolved oxygen criteria than the Deep Water habitat during the summer (U.S. EPA 2003a) since the target species of the Deep Water use are able to tolerate lower DO concentrations than more pelagic assemblages. For the period October 1-May 31, Open Water criteria apply as protection for deep water habitats (U.S. EPA 2003a).

Both Open Water and Deep Water uses are protected with 30-day mean DO criteria—5 mg/L at a salinity greater than 0.5 ppt or 5.5 mg/L at a salinity less than or equal to 0.5 ppt[6] for the Open Water use and 3 mg/L for the Deep Water use (USEPA, 2003a). While criteria with shorter durations also apply to these uses, there has not been adequate data to date to determine attainment of those shorter duration criteria. Therefore, the attainment of these uses has only been routinely determined using 30-day mean criteria. Chesapeake Bay waters that frequently have monthly average DO concentrations less than 5 mg/L in a significant portion of their water column are assumed to have chronically low DO due to anthropogenic cause(s) like nutrient enrichment unless they are designated for the Deep Water use, or the depressed DO has been linked to the drainage of adjacent wetlands, as in the case with the segments of the Pamunkey and Mattaponi Rivers.

The Deep Water use is protected with the 30-day mean DO criterion of 3 mg/L. This concentration is lower than the Open Water 30-day mean DO criterion to account for naturally depressed DO levels that have been determined to occur in association with summertime stratification and in the absence of other sources of ventilation that offset net oxygen consumption from organic matter decomposition and plankton respiration in the enriched waters of Chesapeake Bay. Wherever there is a designation of the Deep Water use, 5 mg/L (the Open Water 30-day mean criterion) is the applicable criterion above the monthly averaged upper boundary of the pycnocline, while 3 mg/L (the Deep Water criterion) is the applicable criterion below this depth. The Deep Water use only exists in the summer months (June 1 through September 30), when stratification combines with high oxygen consumption rates that deplete oxygen levels. As illustrated in Figure 1, a Chesapeake Bay segment can have up to five designated uses, all characterized by their own specific spatial and temporal extents as outlined in U.S. EPA (2003a).

1.2.2 Horizontal Extent of the Deep Water Use in Virginia's Bay Mainstem

The Chesapeake Bay Program Partnership's original delineation of the Deep Water use is presented in U.S. EPA (2003b), along with its delineation of the Deep Channel use. As described in U.S. EPA (2003b), the boundary lines were drawn using bottom bathymetry data and spatial distribution maps based on average bottom dissolved oxygen concentrations 1-3 mg/L for the Deep Water use and less than 1 mg/L for the Deep Channel use. Following the 2003 publication, water quality modeling was conducted to inform the Bay jurisdictions of the level of effort needed to restore Bay uses. Multiple segments were evaluated for possible designated use boundary adjustments. Decisions to retain the original boundary decisions or to make adjustments to a segment boundary were based on 1) monitoring data, 2) modeling analysis, or 3) a combination of monitoring and modeling results.

For Virginia, the 2003 Bay model predicted Open Water DO criteria nonattainment for Virginia mainstem segment CB6PH under the nutrient and sediment cap loads established at the time (USEPA, 2004b). In light of these results, at Virginia's request the boundary of the mainstem Bay Deep Water use was shifted southward. Figure 3 shows the designated use boundaries developed in 2003 and 2004. The decision-making process undertaken by the Partnership to select the 2004 mainstem Deep Water boundary is shown in Figure 4. Since the adoption of the Bay DO water quality standards in 2005, the

[6] For the remainder of this document, 5 mg/L will be used to represent the Open Water 30-day mean criterion since the water bodies being discussed always experience salinities greater than 0.5 ppt.

2004 scheme has been used to determine where Deep Water DO criteria should be applied for the purposes of criteria assessment and water quality modeling, including the modeling work underlying the Chesapeake Bay Total Maximum Daily Load (U.S. EPA, 2010). Both the original U.S. EPA (2003b) technical support document and the U.S. EPA (2004) addendum are referenced in the water quality standards regulations of Maryland and Virginia.

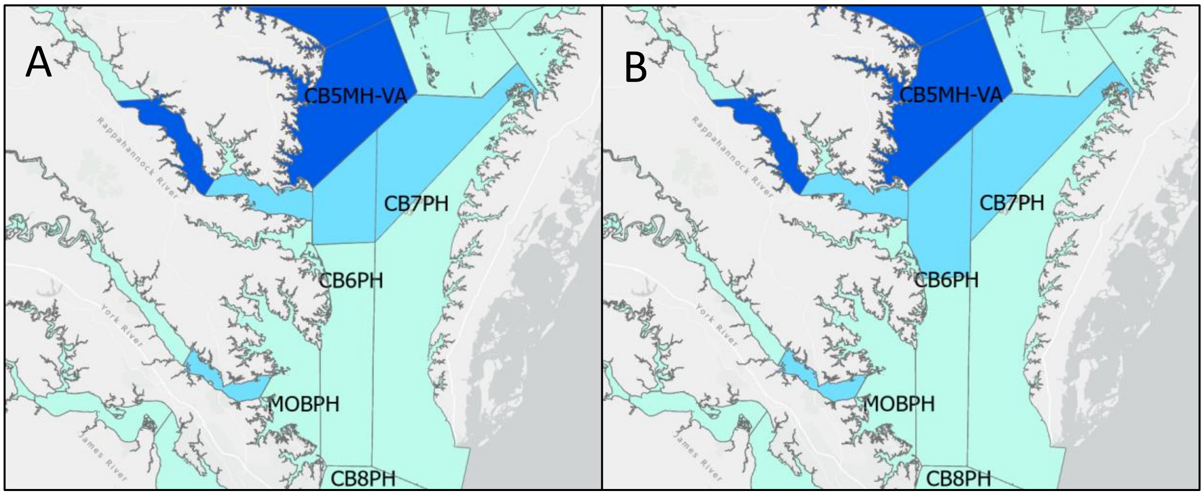

Figure 3. Maps showing the Open Water-only (light blue), Deep Water (sky blue), and Deep Channel (dark blue) designated uses of the Chesapeake Bay and its tidal tributaries. A) The original scheme published in U.S. EPA (2003b). B) The refined scheme published in U.S. EPA (2004b).

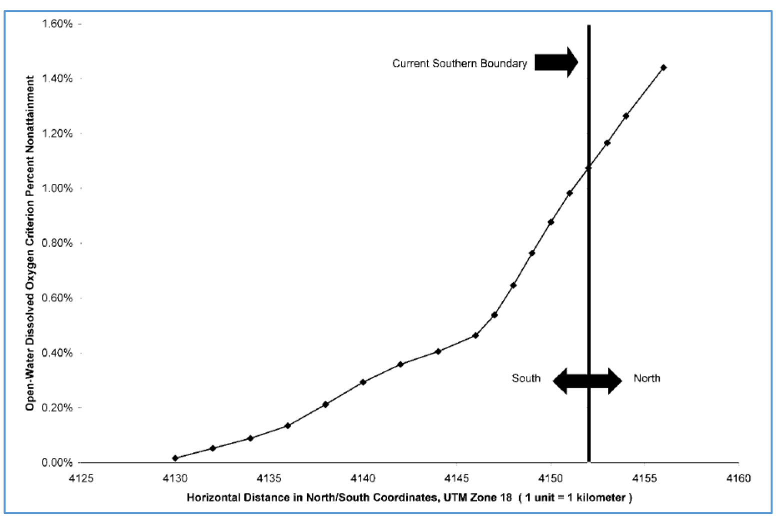

Figure 4. Illustration of the Open Water DO criteria percent nonattainment within the segment CB6PH under model simulated summer (June-September) water quality conditions upon basin wide achievement of nutrient and sediment cap load allocations established in 2003. Percent criteria nonattainment estimates are provided at one-kilometer increments north and south of the boundary between the Open Water/Deep Water and the Open Water-only designated uses originally published in U.S. EPA (2003b) The refined boundary selected by the Partnership was predicted to confer an acceptable percent nonattainment of 0.5%.

Chesapeake Bay segments CB6PH and CB7PH are the largest segments by area and volume in Virginia's portion of the Chesapeake Bay. The northernmost portions of these segments are designated for both Open Water and Deep Water uses, while the latter use is absent from the remaining portions (Figure 3). The bifurcated water quality standards of these two segments makes them unique among the Bay mainstem segments. U.S. EPA (2003b) acknowledges that the portions of these segments excluded from the Deep Water use boundary contain the bottom bathymetry and water column stratification characteristic of Deep Water habitat.

But as shown in the excerpt below, U.S. EPA (2003b) asserts that water circulation patterns obviate the need for the Deep Water designation in the lower portions of these segments:

> *"As ocean water flows into the Chesapeake Bay mouth along the bottom, the Coriolis force swings this flow northward along the lower eastern shore of the Chesapeake Bay. This water flow pattern carries ocean water directly into the trench in segment CB7PH and provides a steady supply of oxygenated water to the below-pycnocline habitats. Ocean water similarly replenishes the below-pycnocline waters of segment CB6PH.*
>
> *Only the very northern portions of segments CB6PH and CB7PH appear to have a chronic dissolved oxygen depletion problem related to the pycnocline and local bottom bathymetry."* U.S. EPA (2003b)

Thus, while areas designated for the Deep Water use have deep bottom bathymetry and persistent summertime stratification, these features are not sufficient alone to support the designation of the Deep Water use. Water circulation patterns enabling below-pycnocline low DO is the most important condition of the Deep Water designation. Based on an analysis of monitoring data, the CBPO concluded that the lower portions of CB6PH and CB7PH do not meet this condition (USEPA 2003b). However, it is important to note that "low DO" in this context was defined as DO concentrations less than 3 mg/L as opposed to less than 5 mg/L—the magnitude of the 30-day mean criterion of the Open Water use.

1.3 Use Attainment History of CB6PH and CB7PH

A Bay segment's criterion attainment status with respect to applicable designated uses is determined through the defined, published procedures supporting assessment of water quality criteria (U.S. EPA 2003a, 2004, 2007, 2008, 2010, 2017). The assessment of Bay DO criteria involves an evaluation of DO concentrations in three-dimensional space within a three-year period, specific to the applicable season, and resulting in a determination of attainment or nonattainment for each designated use-season (U.S. EPA 2003a). There are three aspects to the Bay DO criteria assessment method that make it stand out from other DO criteria assessment approaches: 1) the concentrations that are compared against a DO criterion are not observed DO concentrations but rather are estimates derived from observed DO concentrations, 2) monitoring data collected outside of a segment can be used to inform the DO estimates within that segment, and 3) criteria exceedance is measured over space (i.e., habitat volume) and through space-time rather than just in time (U.S. EPA 2003a, 2004, 2007a, 2008, 2010, 2017). Appendix A provides a more detailed description of the current Bay DO criteria assessment procedure.

As shown in Table 1, the CBPO's analysis of historical and recent monitoring datasets reveals that the Open Water 30-day mean criterion (5 mg/L) is often not attained in CB6PH for the summer season and has never been attained in CB7PH. These results are a striking contrast to those for the adjacent segments CB5MH-VA (to the north, see Figure 3) and CB8PH (to the south), both which almost always attain this criterion. One important difference between CB5MH-VA and CB6PH/CB7PH is that the entirety of the former is designated for the Open Water and Deep Water use, while the Deep Water use applies only to the northern portion of the latter, with the remainder designated only as Open Water. DO concentrations less than 5 mg/L in CB5MH-VA typically occur below the upper boundary of the pycnocline in the summer and thus are evaluated against the summer season Deep Water 30-day mean criterion (3 mg/L)[7]. However, in waters not designated for the Deep Water use, the more stringent Open Water criterion is applied to all DO measurements from surface to bottom, even when the water column is stratified. Thus, below-pycnocline DO less than 5 mg/L in the portions of CB6PH and CB7PH excluded from the 2004 Deep Water boundary is treated the same as low DO occurring in shallower areas with well-mixed water columns.

As shown in Table 1, CB8PH (shown in Figure 3) has almost always attained the Open Water 30-day mean DO criterion. One may expect CB6PH and CB7PH to have a similar attainment history as their southern neighbor, which—like the lower portions of CB6PH and CB7PH—is not designated for the Deep Water use. However, this is not the case. The near-perfect attainment of the Open Water use in CB8PH is likely due to the high amount of oxygen replenishment from the Atlantic Ocean as this segment is closer to the ocean than CB6PH and CB7PH. Though it is possible that CB6PH and CB7PH experience more intense eutrophication than CB8PH, the lack of consistent Open Water attainment in CB6PH and CB7PH suggests that this replenishment may be more limited in degree and/or spatial extent in these segments. The assessment results for Virginia's mainstem Bay segments invite the question of whether the 2004 Deep Water boundary fully encompasses those areas within CB6PH and CB7PH that have naturally depressed DO concentrations. This concern has prompted a review of long-term monitoring datasets, with the goal of better understanding the spatial and temporal dynamics of low DO in these segments. The outcome of this review, which is detailed in the following section, demonstrates that the low DO-promoting natural conditions found in the northern portions of these segments also occur in their southern portions.

[7] CB5MH-VA is also designated for the Deep Channel use. If there is a mixed bottom layer present below the pycnocline during the summer, the Deep Water criterion is applied to the portion of the water column between the upper and lower boundaries of the pycnocline and the Deep Channel instantaneous criterion (1 mg/L) is applied to the portion of the water column within and below the lowermost pycnocline boundary to the sediment-water interface. If there is no discernable mixed layer below the pycnocline, the Deep Water criterion is applied to the portion of the water column from the top of the pycnocline to the sediment-water interface.

Table 1. Attainment history of the Open Water 30-day mean DO criterion for selected Bay segments, as reported by the CBPO (CBPO, 2025). 1 = criterion was attained for a three-year period. 0=criterion was not attained for a three-year period. This analysis is primarily based on DO data acquired from monthly vertical profiles taken at CBPO stations.

Year Range	CB5MH-VA	CB6PH	CB7PH	CB8PH
1985-1987	1	0	0	1
1986-1988	1	0	0	1
1987-1989	1	0	0	0
1988-1990	1	0	0	0
1989-1991	1	0	0	0
1990-1992	1	0	0	1
1991-1993	1	0	0	1
1992-1994	1	0	0	1
1993-1995	1	0	0	1
1994-1996	1	0	0	1
1995-1997	1	0	0	1
1996-1998	1	0	0	1
1997-1999	1	1	0	1
1998-2000	1	0	0	1
1999-2001	1	1	0	1
2000-2002	1	1	0	1
2001-2003	1	1	0	1
2002-2004	1	0	0	1
2003-2005	1	0	0	1
2004-2006	1	1	0	1
2005-2007	1	1	0	1
2006-2008	1	1	0	1
2007-2009	1	1	0	1
2008-2010	1	0	0	1
2009-2011	1	0	0	1
2010-2012	1	0	0	1
2011-2013	0	0	0	1
2012-2014	1	1	0	1
2013-2015	1	1	0	1
2014-2016	1	1	0	1
2015-2017	1	1	0	1
2016-2018	1	1	0	1
2017-2019	1	1	0	1
2018-2020	0	0	0	1
2019-2021	0	0	0	1
2020-2022	0	0	0	1

2. Supporting Evidence of Natural Conditions in the Lower Portions of CB6PH and CB7PH

The Deep Water designated use includes the tidally influenced waters between the measured upper and lower boundaries of the pycnocline where, in combination with bottom bathymetry and water circulation patterns, the pycnocline limits oxygen replenishment of deeper waters (U.S. EPA 2003b). In Deep Water areas not designated for the Deep Channel use, such as the upper portions of CB6PH and CB7PH, the Deep Water designated use extends from the measured depth of the upper boundary of the pycnocline down through the water column to the bottom of the sediment-water interface (U.S. EPA 2003b). Historical and contemporary monitoring data show that the bottom bathymetry, water column stratification, and below-pycnocline low DO that are the defining features of the Deep Water use according to U.S. EPA (2003b) are present in the lower portions of CB6PH and CB7PH, as well as the channel of Mobjack Bay. While there is empirical evidence that water circulation patterns of the Lower Bay mainstem result in some reoxygenation of deeper waters, current information indicates that this reoxygenation is less than what was assumed by the CBPO in 2003. The following subsections review 1) long-term (1985-2021) patterns in stratification and low DO revealed by Chesapeake Bay water quality monitoring datasets, 2) bathymetric considerations, 3) statistical relationships assessing drivers of conditions, and 4) inferences about water circulation patterns drawn from monitoring data. This information collectively provides technical support for an expansion of the Deep Water use in Virginia's mainstem Bay.

2.1 Bottom Bathymetry of CB6PH and CB7PH

Deep bottom bathymetry (>30 m) is an important feature of the Deep Water designated use in the tidal waters of Chesapeake Bay. Bottom waters in trenches and holes are isolated from oxygenated waters at the surface and thus are especially prone to oxygen depletion (U.S. EPA 2003b). However, there is no minimum depth requirement for the Deep Water designation. As shown in Figure 5, the 2004 Deep Water boundary in CB6PH and CB7PH includes areas with deep bottom bathymetry (>30 m) but it also includes shoreline areas with bathymetry less than 6-m deep that are in close proximity to deeper areas and thus potentially prone to the effects of wind-driven upwelling, as described by Breitburg (1990) in the Choptank River. The portions of CB6PH and CB7PH that were excluded from the 2004 Deep Water designated use boundary are no less deep, on average, than the designated portions. The long-term CBPO stations located in the excluded portions have average depths that are within the range of depths for the stations within the designated portions. Most of the deep trench that runs along the axis of CB7PH is within the portion of CB7PH that is not designated for the Deep Water use. This trench is approximately 40-m deep at its deepest point. U.S. EPA (2003b) recognized that the bottom bathymetry characteristic of the Deep Water designation is present in the excluded portions of CB6PH and CB7PH, however, the best available science at that time suggested water circulation patterns in the Lower Bay mainstem obviate the need for extending the Deep Water designation boundaries further south than the present-day boundaries.

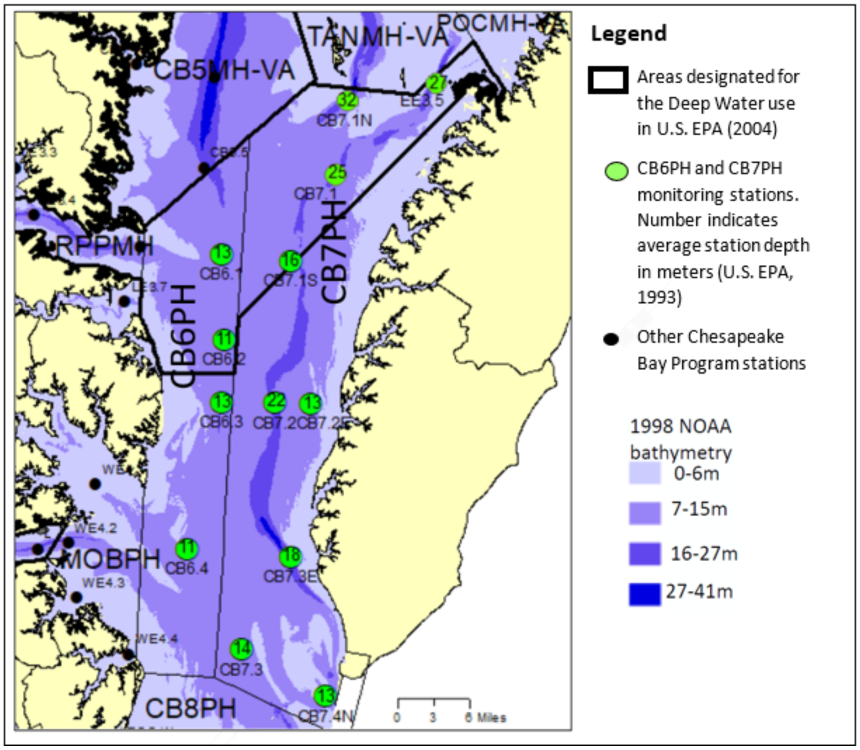

Figure 5. Map of the Deep Water designation in Virginia's Chesapeake Bay mainstem adopted by the Chesapeake Bay Program Partnership in 2004, with bottom bathymetry.

2.2 Stratification in CB6PH and CB7PH

U.S. EPA (2003b) recognized that the lower portions of CB6PH and CB7PH are capped by a pycnocline during the summer. The vertical structure of water density (expressed as sigma-T) can be examined graphically to evaluate the degree to which the water column at a particular site is stratified, on average (see Figure 6). At Deep Water station CB6.2, the shape of the average density profile is characteristic of partially stratified shallow estuaries, reflecting a well-mixed surface layer followed by a distinct pycnocline (i.e., the portion of the profile that deviates the most from a vertical line) and a thin bottom layer. A similar profile is evident at CB6.3, though the mixed bottom layer appears to be more substantial in size. Among all the CB6PH and CB7PH stations not included in the 2004 Deep Water boundary, the most pronounced average pycnoclines are found at CB7.2 and CB7.3. At CB7.4N, where more vertical mixing is expected due to the high proportional volume of seawater present there, the pycnocline is quite weak. The southwesterly position of CB7.3 relative to the other CB7PH stations means that it receives more freshwater flow at the surface while simultaneously receiving more seawater inflow at the bottom, supporting relatively strong stratification at this station. A quantitative evaluation of the magnitude of stratification for CB6PH and CB7PH stations indicates neither proximity to the 2004 Deep Water horizontal boundary nor the mouth of the bay are reliable predictors of where the physical conditions of the Deep Water use are likely to occur in the segments. However, CB7.4N, which is closest to the ocean boundary in the segments, shows the weakest stratification among the stations in the study area(see Appendix A).

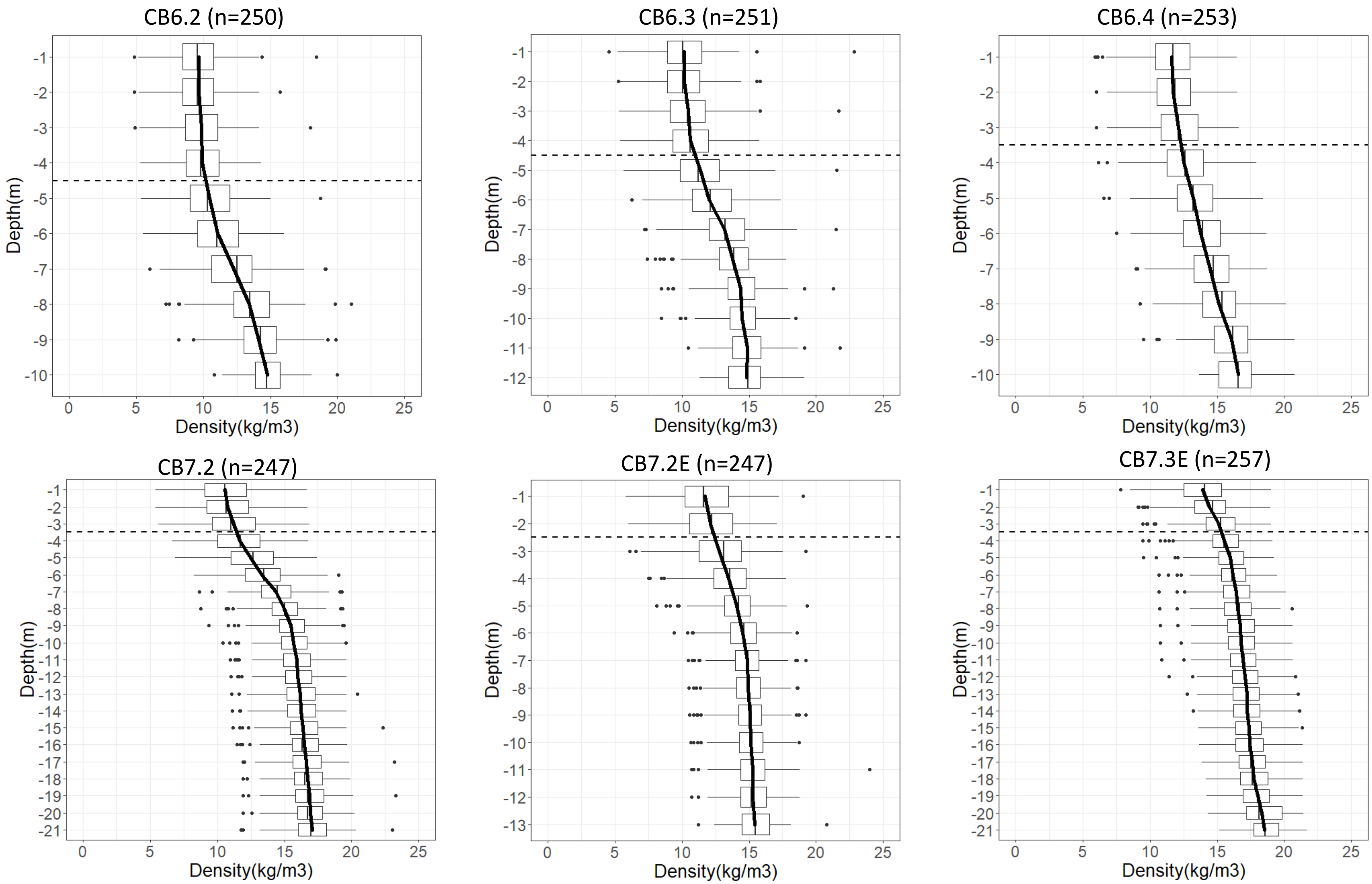

Figure 6. Boxplots of water density (expressed as sigma-T) with depth at select CB6PH and CB7PH stations, developed from monitoring datasets collected June-September 1985-2021. The black curve is the average density profile, and the dashed horizontal line corresponds to the median upper boundary of the uppermost pycnocline. Density and pycnocline depths were calculated according to the procedure described in Chapter III of U.S. EPA (2008). n = number of monitoring events. Station locations are shown in Figure 5.

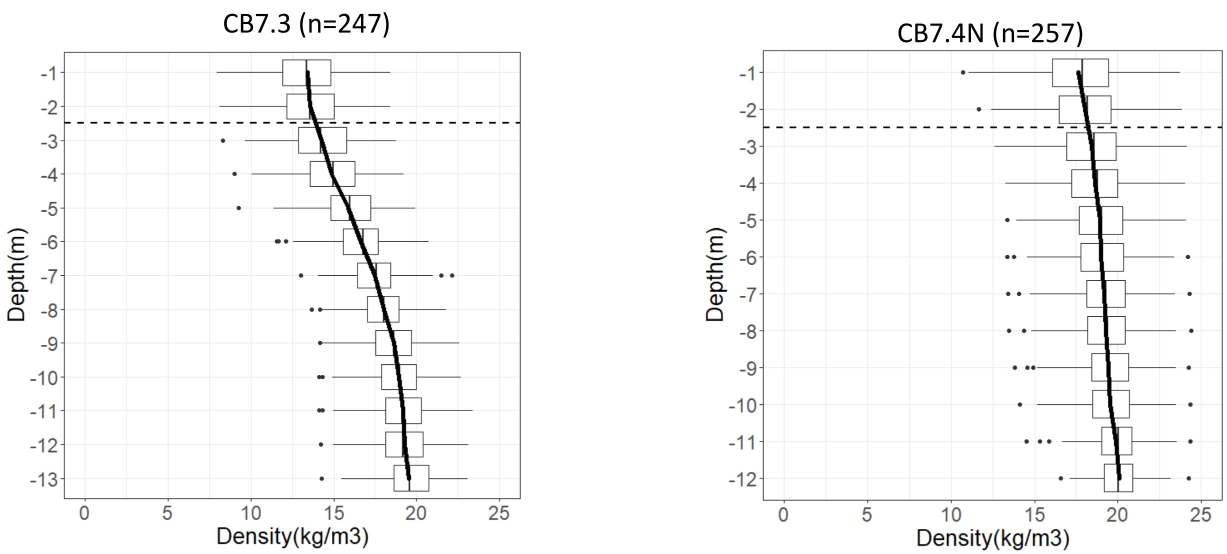

Figure 6 (continued). Boxplots of water density (expressed as sigma-T) with depth at select CB6PH and CB7PH stations, developed from monitoring datasets collected June-September 1985-2021. The black curve is the average density profile, and the dashed horizontal line corresponds to the median upper boundary of the uppermost pycnocline. Density and pycnocline depths were calculated according to the procedure described in Chapter III of U.S. EPA (2008). n = number of monitoring events. Station locations are shown in Figure 5.

2.3 Deep-Water Low DO in CB6PH and CB7PH

The Deep Water use was designated wherever the measured pycnocline, in combination with bottom bathymetry and water circulation patterns, presents a barrier to oxygen replenishment of deeper waters (USEPA 2003b). Waters that tend to be either weakly stratified or "recharged" by oceanic inflow can be expected to attain Open Water dissolved oxygen criteria and thus do not require the Deep Water designation. The original Deep Water and Deep Channel boundaries were developed using spatial distribution maps of bottom DO concentrations observed in 1997 (U.S. EPA 2003b). This year was selected because it was considered the best year out of a 17-year record for DO concentrations in the Bay, with dry weather conditions minimizing the amount of anthropogenic nutrient inputs. DO concentrations of 1-3 mg/L were used to flag Deep Water habitats, while DO concentrations less than 1 mg/L were used to identify Deep Channel habitats. Open water criteria protective of living resources in the polyhaline waters of the Bay include a 30-day mean criterion of 5 mg/L. Bottom waters that have depressed DO concentrations due to natural conditions may have been captured more comprehensively if bottom concentrations less than 5 mg/L were used as a filter coincident with deep bottom bathymetry and stratification.

Chesapeake Bay waters that consistently have monthly DO concentrations less than 5 mg/L in a significant portion of their water column, from surface to bottom, are assumed to have chronic low DO due to anthropogenic cause(s) (U.S. EPA 2003a), unless they are designated for the Deep Water use. Waters designated for the Deep Water use are protected by three criteria that must be met simultaneously in the summer: 1) the 30-day mean DO criterion of 3 mg/L, 2) 1-day mean criterion of 2.3 mg/L, and 3) an instantaneous minimum criterion of 1.7 mg/L (U.S. EPA 2003a) to account for naturally depressed DO levels occurring below a pycnocline. Wherever there is a designation of the Deep Water use, 5 mg/L (the Open Water 30-Day mean criterion for mesohaline and polyhaline waters of the Bay) is the applicable criterion above the monthly averaged upper boundary of the uppermost pycnocline, while 3 mg/L (the Deep Water criterion) is the applicable 30-day mean criterion applicable for waters below the monthly averaged upper boundary of the uppermost pycnocline. Thus, it is expected that in waters designated for the Deep Water use, there is a high likelihood of summertime DO concentrations less than 5 mg/L within and below the pycnocline during the summer. Summer season 30-day mean DO concentrations that are consistently less than 3 mg/L would only be expected in impaired Deep Water habitats or areas with very deep bottom bathymetry (i.e., the Deep Channel habitat).

With the exception of one station, DO concentrations less than 5 mg/L below the upper boundary of the pycnocline (hereafter referred to as a "deep-water low DO layer") have been observed historically at all CB6PH and CB7PH stations excluded from the 2004 Deep Water boundary; however, the frequency, magnitude, and vertical extent of the low DO does vary across the stations, as shown in Figure 7. Among these stations, the most frequently occurring deep-water low DO layers can be found at CB6.3, occurring 56% of the time during the summer (compared to 67% of the time at Deep Water station CB6.2). While a deep-water low DO layer occurs less frequently at CB7.2, the vertical thickness of the layer is much

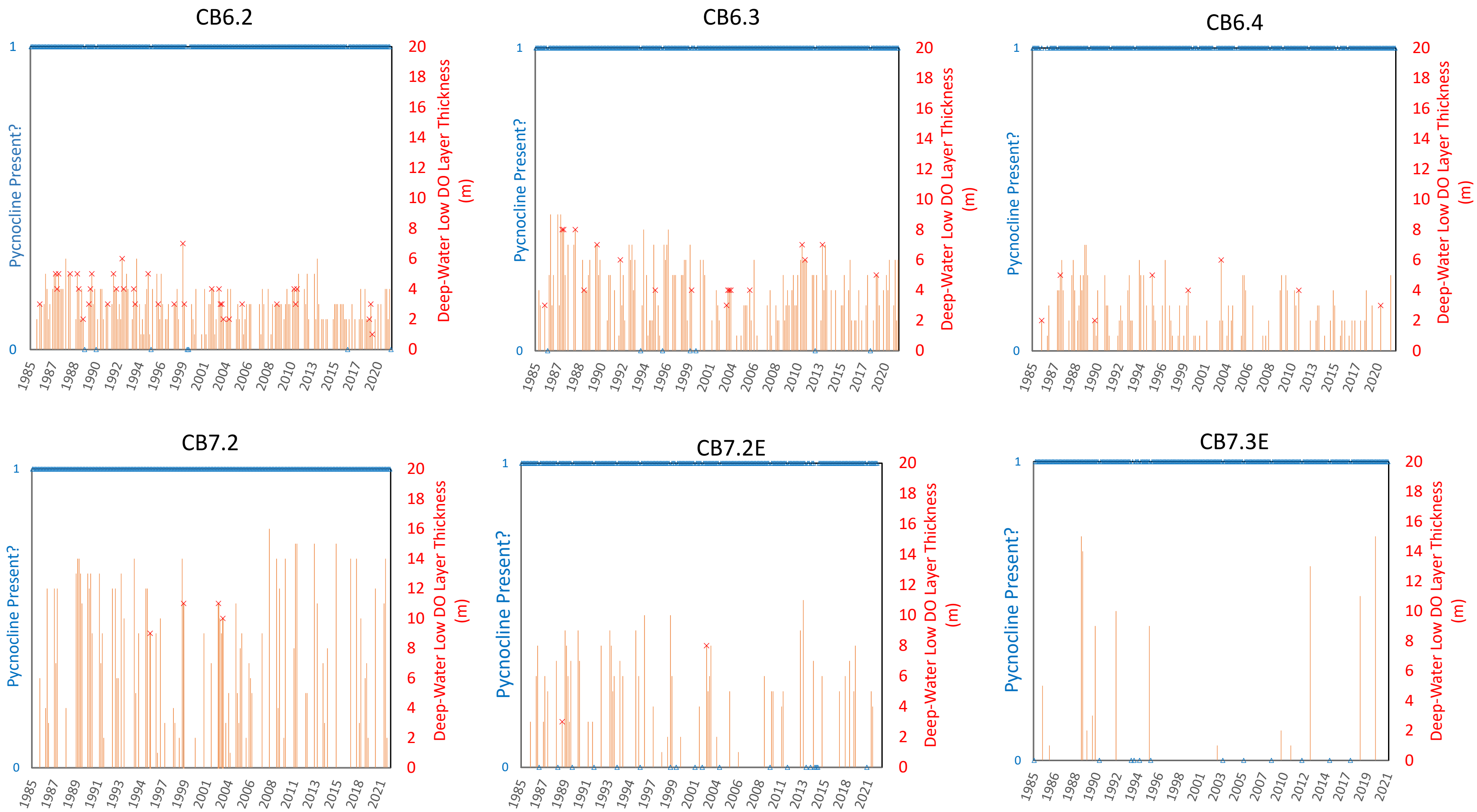

Figure 7. Pycnocline occurrence and thickness of the low DO layer (DO concentration less than 4.5 mg/L) below the upper boundary of the pycnocline computed from vertical profile data collected June-September 1985-2021. A pycnocline value of 0 signifies that no pycnocline was present at a particular monitoring event. "X" indicates those low DO events for which a DO concentration less than 2.5 mg/L was recorded at one or more depths. Station locations are shown in Figure 5.

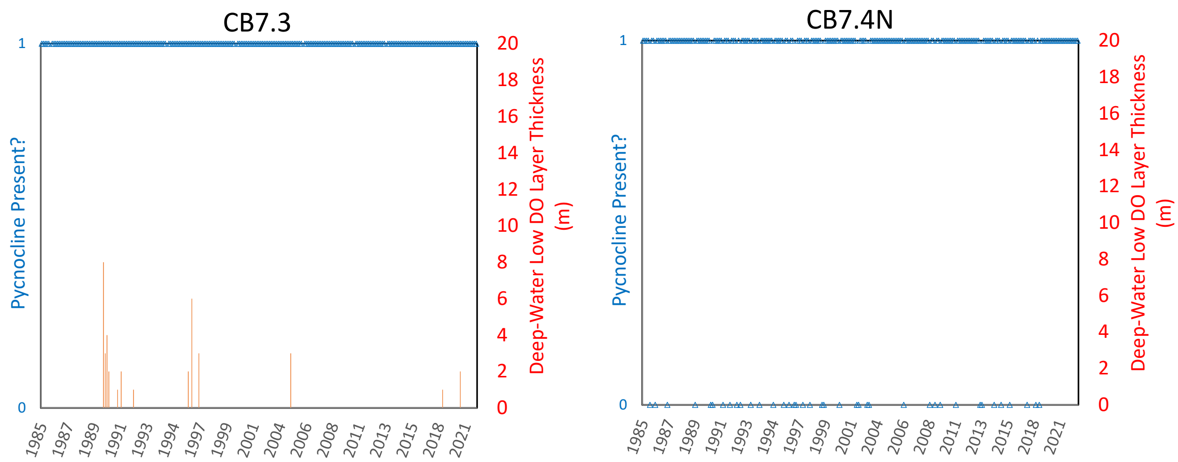

Figure 7 (continued). Pycnocline occurrence and thickness of the low DO layer (DO concentration less than 4.5 mg/L) below the upper boundary of the pycnocline computed from vertical profile data collected June-September 1985-2021. A pycnocline value of 0 signifies that no pycnocline was present at a particular monitoring event. "X" indicates those low DO events for which a DO concentration less than 2.5 mg/L was recorded at one or more depths. Station locations are shown in Figure 5.

greater at this station, on average. The median thickness of the low DO layers at CB6.2, CB6.3, and CB6.4 is 3, 3, and 4 m, respectively, while it is 8 m thick at CB7.2. The frequency and magnitude of deep-water low DO diminish as one moves closer to the Bay mouth. Low DO has only occurred sporadically at CB7.3 despite this station having a strongly stratified water column relative to some of the other stations (Figures 6 and 7). The data suggest the mitigating influence of oceanic inflow. DO concentrations less than 5 mg/L have never been reported at CB7.4N.

Finally, the Chesapeake Bay Program has supported a living resource monitoring program for summer benthic macroinvertebrate community integrity assessment. Probabilistic bottom DO measurements are collected simultaneously with summer benthic infauna sampling. Results show that bottom low DO can be encountered throughout much of CB6PH and CB7PH, as shown in Figure 8, further supporting southward extension of the Deep Water boundary to include CB6PH and CB7PH from the original 2004 Deep Water boundary.

In the portions of CB6PH and CB7PH not included in the 2004 Deep Water boundary, the average DO concentration below the summertime pycnocline when low DO is present is 3.8 mg/L, slightly higher than the Deep Water 30-day mean criterion of 3 mg/L. However, because this value is a long-term average reflecting both low and high nutrient enrichment conditions, it is not accurate to conclude that this is the highest attainable 30-day mean concentration. To approximate this concentration, an analysis of DO data collected at stations in the area of interest during the three years when chlorophyll-a concentrations were at their lowest recorded levels (i.e., "best years") was performed (see Appendix D). For each station, the minimum DO concentration at each summertime monitoring event during these

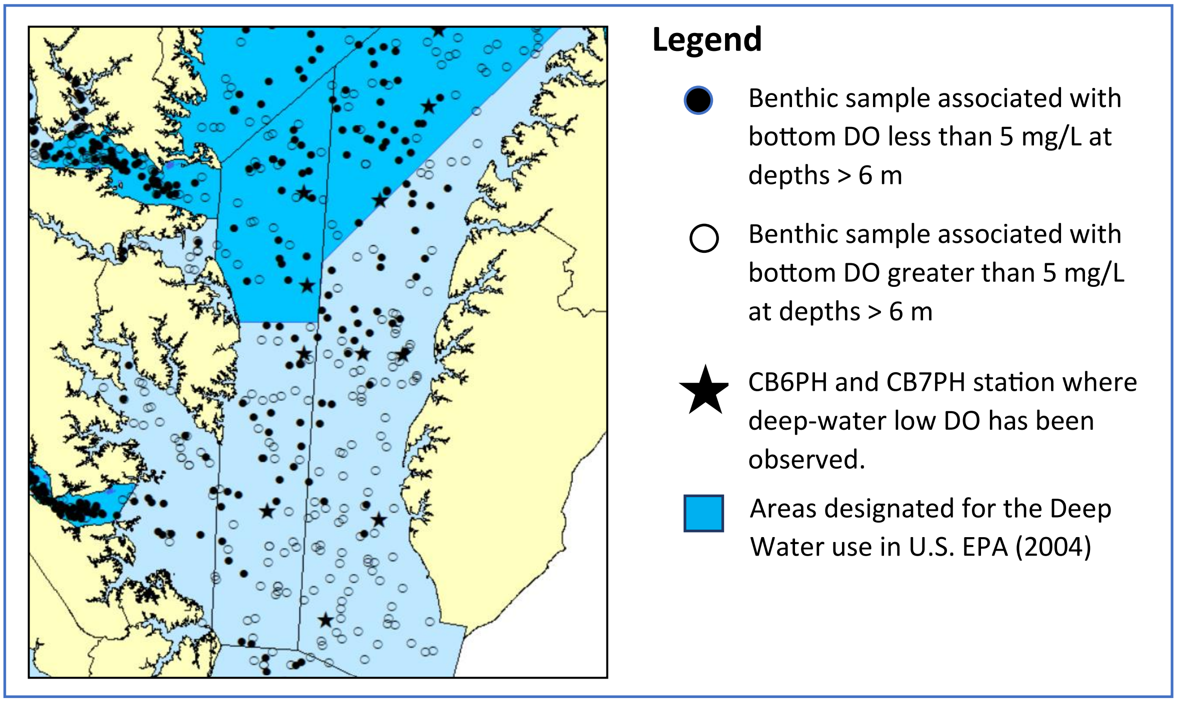

Figure 8. Map of bottom DO measurements taken in CB6PH and CB7PH from 1985-2019 by Old Dominion University's probabilistic benthic monitoring program.

"best" years was recorded, and the 20th percentile of these values was then calculated (Table D-1). The mean of the 20th percentiles—4.3 mg/L—represents the highest attainable deep-water 30-day mean DO concentration for the area of interest during the summer. Out of all the 19,417 summertime DO measurements that have been recorded in this area at the long-term CBPO stations from 1985-2021, only approximately 0.4% are less than 2.3 mg/L and 0.09% are less than 1.7 mg/L—the magnitude of the Deep Water 1-day mean and instantaneous minimum criteria, respectively. These findings indicate that the Deep Water use is the highest attainable use for this portion of Virginia's Bay mainstem.

2.4 Water Circulation Patterns in the Lower Bay Mainstem

U.S. EPA (2003b) defines the Deep Water use as "[t]idally influenced waters located…. where the measured pycnocline, in combination with bottom bathymetry and water circulation patterns, presents a barrier to oxygen replenishment of deeper waters." The exclusion of most of CB6PH and CB7PH from the Deep Water use designation is justified on the original decision that the continual inflow of highly oxygenated seawater prevents the occurrence of deep-water low DO in CB6PH and CB7PH (U.S. EPA 2003b).

Stratification, bottom bathymetry, and deep-water low DO can be measured directly and definitively. One must draw an inference from the last metric to conclude whether a site experiences water circulation patterns that potentiate or mitigate development of low DO below a pycnocline. The mitigating influence of the Atlantic Ocean is evident from vertical profiles taken at stations in segment CB8PH, located at the mouth of the Bay. Like the mainstem segments to the north, CB8PH has a persistent pycnocline during the summer. However, as shown in Figure 9, the average summertime DO vertical profiles at the CB8PH stations show the absence of an oxycline, the DO analog to the pycnocline, while the profiles for stations in CB6PH, CB7PH, and one station from Mobjack Bay (MOBPH) exhibit an oxycline. This can potentially be explained by the geographic variability of the Atlantic's influence on DO concentrations, with the waters of CB8PH experiencing much greater ocean-induced mixing than upbay waters.

The data further show that bottom waters of the northern portions of CB6PH and CB7PH consistently have summertime DO concentrations less than 3 mg/L, which is why these waters were designated for the Deep Water use. The bottom waters of the downbay portions often have DO concentrations higher than 3 mg/L during the summer. The greater mitigating influence of the Atlantic Ocean on the southern end relative to the northern end of CB6PH and CB7PH explains these geographical differences in DO concentrations. This influence can be seen in the inverted and "zig zag" DO profiles that can be observed at the downbay stations (Figure B-2, Appendix B). But while this replenishment is sufficient to maintain

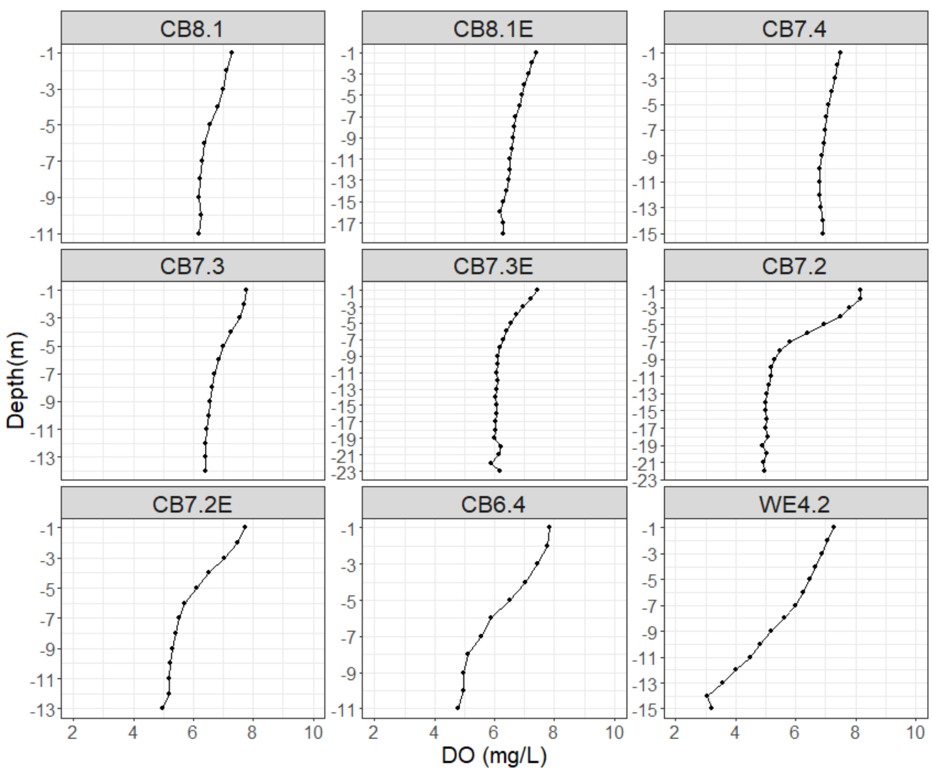

Figure 9. Average DO profiles for stations in CB8PH (top row) and selected stations in CB6PH, CB7PH, and MOBPH (WE4.2). Profiles are based on summertime DO measurements taken from 1985 to 2021. The points indicate the median of DO measurements for each depth.

Open Water habitat from surface to bottom in CB8PH, it is insufficient in CB6PH and CB7PH. DO concentrations in the southern end of CB6PH and CB7PH are frequently low enough that they do not meet the Open Water 30-day mean criterion of 5 mg/L, indicating that water circulation patterns of the Lower Bay mainstem do not completely mitigate the potential for low oxygen.

MOBPH is sandwiched between CB6PH and YRKPH, a segment that is designated for the Deep Water use in its entirety (U.S. EPA 2004b). While much of MOBPH is relatively shallow, at approximately 13 meters deep, the channel extending from the mouth of the York River into MOBPH is deep enough to be a candidate for the Deep Water designation.

The deep-water low DO layers observed at the long-term CBPO stations in MOBPH were examined to determine if expansion of the Deep Water boundary into MOBPH is warranted, as shown in Figure 10. Low DO below the upper boundary of the pycnocline has been observed at the MOBPH stations, but only at WE4.2—located at the mouth of the York—does stratification occur frequently and in conjunction with thick deep-water low DO layers with no concurrent surface layer low DO.

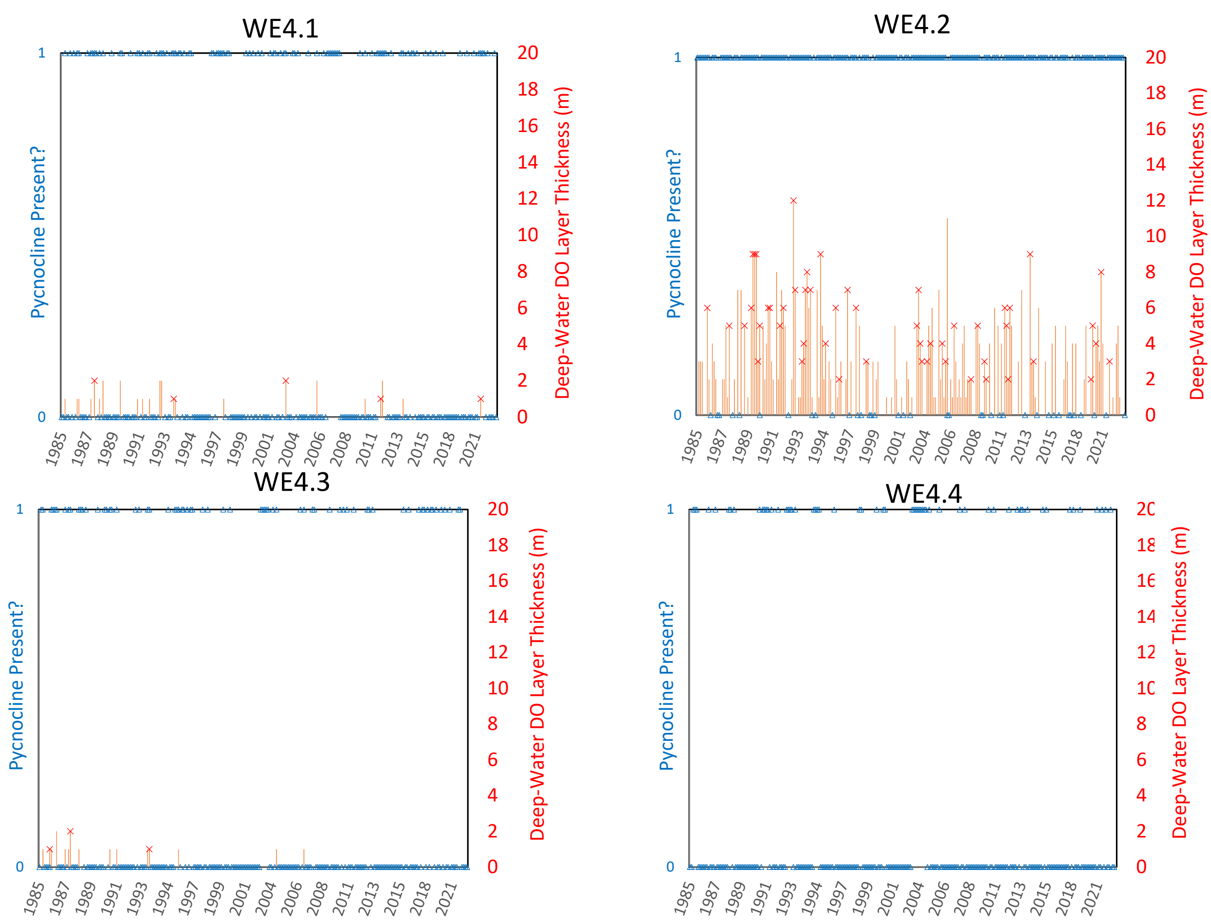

Figure 10. Pycnocline occurrence and thickness of the hypoxic layer (DO concentration less than 4.5 mg/L) below the upper boundary of the pycnocline computed from vertical profile data collected in Mobjack Bay (MOBPH) June-September 1985-2021. A pycnocline value of 0 signifies that no pycnocline was present at a particular monitoring event. "X" indicates those low DO events for which a DO concentration less than 2.5 mg/L was recorded at one or more depths.

Additionally, the mean depth at WE4.2 is 13 meters (U.S. EPA 1993), much deeper than WE4.1, WE4.3, and WE4.4 (6-m, 6-m, and 8-m deep on average, respectively). The Bay estuarine model's simulation of the DO gradient in the channel represented by WE4.2 is similar to its simulation of the DO gradient in areas designated for the Deep Water use (Figure 11). For these reasons, the channel starting from the mouth of the York and ending at the mouth of Mobjack Bay is recommended for revision to update the 2004 Deep Water designated use boundary.

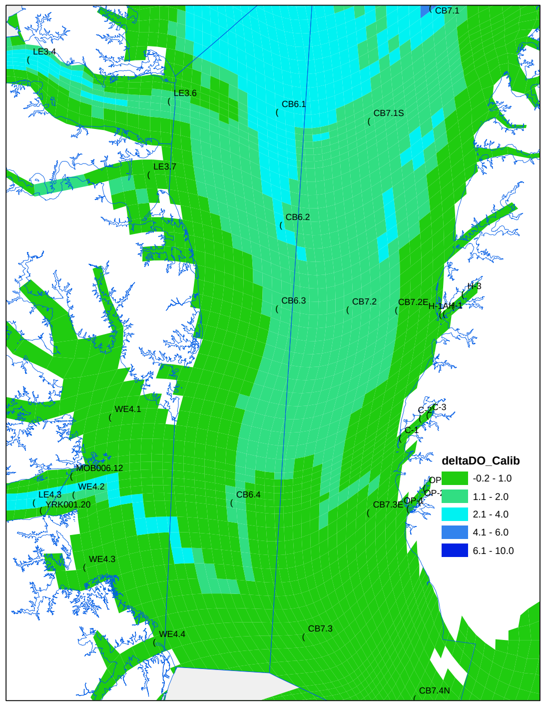

Figure 11. Average difference in surface and bottom DO concentrations under full implementation of the Bay TMDL simulated by the Phase 6 Bay estuarine model for the 1993-1995 period.

The Atlantic Ocean is not the only factor influencing DO concentrations in the Lower Bay mainstem. Despite the net northward transport of the bottom waters due to gravitational circulation, hypoxic waters can flow in from the north and west, thus negatively influencing concentrations in CB6PH and CB7PH. The interconnectedness of below-pycnocline hypoxia in the Bay mainstem is illustrated in Figure 12. Hypoxic deep waters in the Bay are pulsed out of trenches and holes in a lateral (landward) direction, especially by southerly winds (Li et al. 2015; Xie and Li 2018; and Li et al. 2020), and then propelled by tidal currents (Breitburg 1990). U.S. EPA (2003b) recognized the seaward movement of below-pycnocline hypoxic waters over the sill at the northern boundary of CB6PH and CB7PH, supporting the 2003 Deep Water Boundary being established south of the sill.

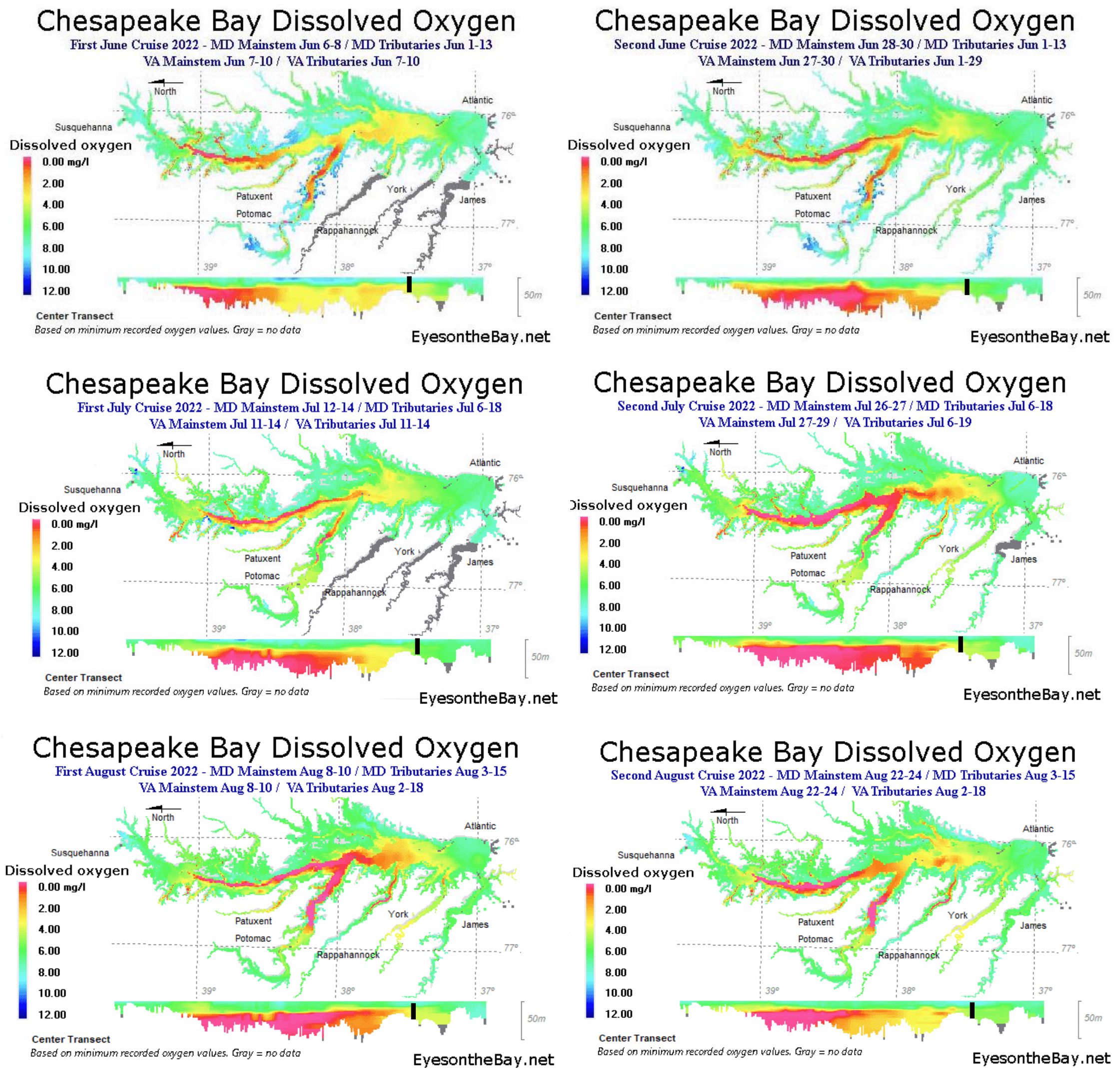

Figure 12. Maps of minimum Chesapeake Bay DO concentrations developed from monitoring data collected during the summer of 2022. The black vertical bar in the cross-sectional view corresponds to the southern edge of the 2004 Deep Water boundary. The Maryland Department of Natural Resources generated these maps using the Chesapeake Bay 3-D Interpolator, which is used by the CBPO for Bay DO criteria assessments. Strong, less southerly winds and with cooler temperatures may explain the reduced hypoxic volume observed in the latter part of August 2022 (VIMS, 2022).

3. DEQ Staff Recommendation for the Deep Water Use Boundary in Virginia's Bay Mainstem

Expansion of the Deep Water designated use in the tidal waters of the lower Chesapeake Bay is supported by updated analysis showing that the nonattainment of the Open Water use in CB6PH and CB7PH can be attributed to 1) stratification strong enough to impede vertical oxygenation throughout the water column, 2) long-term patterns of low DO at monitoring stations located within these segments and 3) inadequate replenishment of DO concentrations via lateral advection from oceanic inflow.

CB6PH and CB7PH

Boundary revisions are recommended for CB6PH, CB7PH and Mobjack Bay. A southward boundary revision is recommended to encompass the entirety of CB6PH and CB7PH excluding the area close to the mouth where no low DO has ever been observed but including all of the deep trench (Figure 13). Table 2 provides the coordinates for the expanded boundary.

Mobjack Bay

The channel starting from the mouth of the York and ending at the mouth of Mobjack Bay is recommended for revision to update the Deep Water designated use boundary.

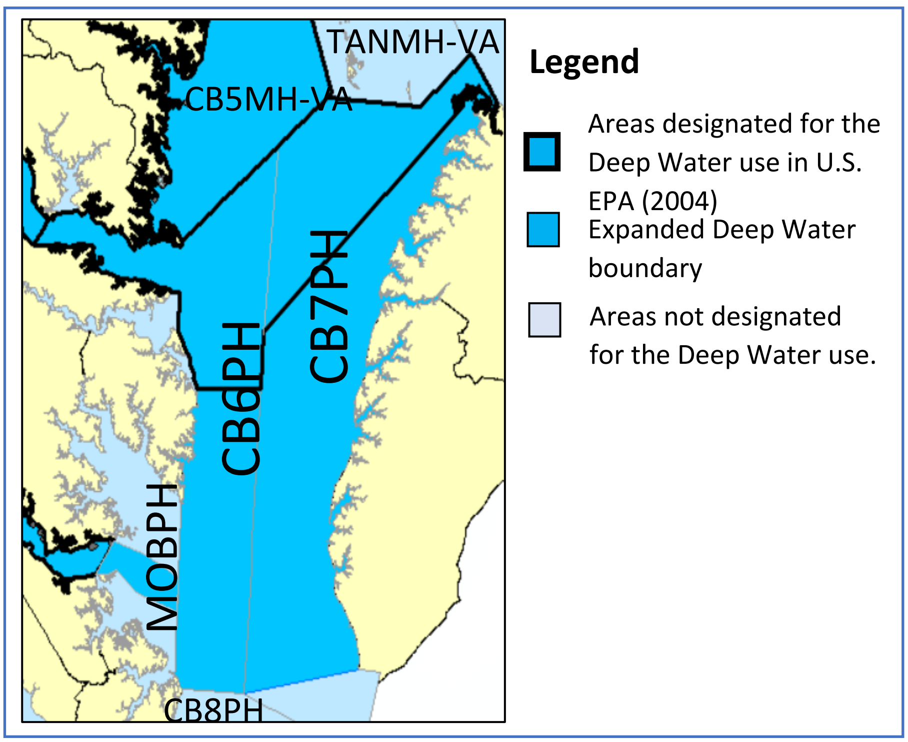

Figure 13. Expanded Deep Water boundary in Chesapeake Bay mainstem segments CB6PH, CB7PH, and MOBPH.

Table 2. Narrative descriptions and latitude/longitude coordinates for the expanded Deep Water boundary in the northern part of the lower Chesapeake Bay and lower Rappahannock River (referred to as Deep Water Zone 3 in Table A-2 of U.S. EPA (2004b).

Latitude/Longitude and Narrative Georeference Identifiers for End Coordinates			
Point 1	Lat/Long	37.2624	-76.39088
	Description	Northern corner of downstream boundary of YRKPH	
Point 2	Lat/Long	37.22316	-76.42016
	Description	Southern corner of downstream boundary of YRKPH	
Point 3	Lat/Long	37.223	-76.4
	Description	1 mile due east of Point 2	
Point 4	Lat/Long	37.229	-76.386
	Description	Tue Point	
Point 5	Lat/Long	37.202	-76.351
	Description	Approximately 2.7 miles SE of Point 4	
Point 6	Lat/Long	37.179	-76.28
	Description	Approximately 4 miles SE of Point 5	
Point 7	Lat/Long	37.105407	-76.283675
	Description	0.6 mile SE of Factory Point	
Point 8	Lat/Long	37.084687	-76.271124
	Description	Western corner of the downstream boundary of CB6PH	
Point 9	Lat/Long	37.087894	-76.268973
	Description	0.3 mile NE of Point 8	
Point 10	Lat/Long	37.083695	-76.165153
	Description	Eastern corner of the downstream boundary of CB6PH	
Point 11	Lat/Long	37.115576	-75.970391
	Description	0.05 mile due west of Lankford Jr. Memorial Highway	
Point 12	Lat/Long	37.78793	-75.7411
	Description	S of Webb I., between Deep Cr. and Doe Cr.	
Point 13	Lat/Long	37.84624	-75.7865
	Description	0.57 miles WSW of fl. red lt. at tip of Guilford Flats	
Point 14	Lat/Long	37.781960	-75.873726
	Description	1 mile SE of S tip of Watts I., just E of quad bound.	
Point 15	Lat/Long	37.797581	-76.025650
	Description	3 miles WNW of Tangier Sound Light	
Point 16	Lat/Long	37.619465	-76.280251
	Description	Fleets Island, at end of road north of Windmill Pt.	
Point 17	Lat/Long	37.613708	-76.280586
	Description	Windmill Pt.	
Point 18	Lat/Long	37.653767	-76.457794
	Description	0.5 mile NW of Orchard Pt.	
Point 19	Lat/Long	37.649799	-76.496513
	Description	Aprox. 0.25 miles S of Whitehouse Cr. Mouth	
Point 20	Lat/Long	37.642095	-76.509873
	Description	Towles Pt.	
Point 21	Lat/Long	37.612686	-76.533853
	Description	North of Christchurch, 0.75 miles west of Cooper	

Point 22	Lat/Long	37.558598	-76.297974
	Description	Stingray Pt.	
Point 23	Lat/Long	37.558395	-76.283516
	Description	0.8 miles east of Stingray Pt.	
Point 24	Lat/Long	37.512447	-76.285423
	Description	Gwynn Island, east side of northern end	
Point 25	Lat/Long	37.473808	-76.263008
	Description	Gwynn Island, 0.25 miles NE of Sandy Pt. tip	
Point 26	Lat/Long	37.462313	-76.257705
	Description	0.08 miles NNE from northern tip of Rigby I.	
Point 27	Lat/Long	37.22	-76.279
	Description	Approx. 6 miles SE of New Point Comfort Lighthouse	
Point 28	Lat/Long	37.223	-76.298
	Description	Approx. 3.6 miles NW of Point 27	
Point 29	Lat/Long	37.247	-76.336
	Description	Approx. 3.2 miles SE of Point 1	

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APPENDIX A

Bay DO Assessment Method

U.S. EPA (2003) describes the cumulative frequency diagram approach that is used by the Chesapeake Bay Program Office for Bay DO criteria assessments. The approach utilizes a spatially defined grid that is populated by estimates derived from DO data collected during a monitoring cruise. These estimates are calculated using an interpolation method called inverse distance weighting. The use of a data interpolation method allows for all waters of the Bay, tributaries and mainstem, to be assessed in three dimensions (i.e., shoreline-to-shoreline and surface-to-bottom) from the DO measurements collected at approximately 130 monitoring stations maintained by the Chesapeake Bay Program Office. The assessment begins with the calculation of pycnocline depths at monitoring stations where vertical profiles of salinity and temperatures were collected, using the steps outlined in US. EPA (2004) and below:

1. From the water surface downward, the first density slope observation that is greater than 0.1 kg/m^3 is designated as the upper pycnocline boundary provided that: a. That observation is not the first observation in the water column and b. The next density slope observation is positive.

2. From the bottom sediment-water interface upward, the first density slope observation that is greater than 0.2 kg/m^3 is designated as the lower pycnocline depth provided that:

   a. An upper pycnocline depth exists,

   b. There is a bottom mixed layer, defined by the first or second density slope observation from the bottom sediment-water interface being less than 0.2 kg/m^3, and

   c. The next density slope observation is positive.

Pycnocline depths and DO observations are spatially interpolated so that the 3-dimensional grid of a segment is populated with estimates. The estimated pycnocline depths are used to partition the segment into its appropriate designated uses for a particular monitoring cruise. For each designated use, the proportion of space not attaining a criterion is quantified. This measure of criteria exceedance is then compiled over the entire three-year assessment period to develop a cumulative frequency diagram, or CFD. A reference CFD is used to evaluate whether the assessment CFD indicates excessive criteria exceedance occurred over the assessment period. “Excessive exceedance” can be the result of too much space not meeting the criterion, a localized area experiencing criteria exceedance too frequently over time, or a combination of both. For the Open Water 30-day mean and Deep Channel instantaneous minimum criteria, a default 10% CFD curve is used as a reference. For the Deep Water 30-day mean criterion, the reference curve is a CFD based on DO criterion violation rates matched with the integrity of co-occurring benthic assemblages (USEPA, 2010).

DO estimates for a segment are derived from DO observations taken both outside and within a segment’s boundaries, in acknowledgment of the fact that each segment essentially represents a portion of a singular, tidally connected water body. The designated uses of the surrounding areas are not taken into account when computing DO estimates within a segment. This means that DO data collected in the Deep Channel-designated waters of CB5MH-VA and the Deep Water-designated portions of CB6PH and CB7PH are used to inform estimates in the lower portions of CB6PH and CB7PH.

The steps of the CFD approach are illustrated in Figure A-1.

Appendix A

Step 1. Collect DO data at monitoring stations

Step 2. Interpolate the DO data to grid cells.

Steps 3-4. Determine attainment status of each cell within a segment (indicated by bold border).

Date 1

6			5
		5	
		2	

6	6	5	5
6	5	5	5
5	3	3	4
4	3	2	3

meets	meets	meets	meets
meets	meets	meets	meets
meets	fails	fails	meets
fails	fails	fails	meets

Date 2

5			1
		6	
		5	

5	4	3	1
5	5	6	3
5	5	5	4
5	5	5	4

meets	fails	fails	fails
meets	meets	meets	meets
meets	meets	meets	meets
meets	meets	meets	meets

Date 3

3			2
		5	
		5	

3	3	3	2
3	4	5	3
4	4	4	4
4	5	5	4

fails	fails	fails	fails
fails	fails	meets	meets
fails	fails	fails	meets
fails	meets	meets	meets

Step 5: Determine percent attainment by date

Date	% non-attainment in space
Date 1	50%
Date 2	25%
Date 3	62.5%

Step 6. Rank the percent of space values and assign percent of time as (100*R/(N+1)), where R is rank and N is sample size.

Date	Ranked % space	% time
	100%	0%
Date 3	62.5%	25%
Date 1	50%	50%
Date 2	25%	75%
	0%	100%

Figure A-1. An illustration of the steps of the CFD method. In this hypothetical example, a segment (the portion of the grid in the bold border) is assessed using a criterion of 5. The area to its right has a different designated use and is assessed using a criterion of 3.

The coordinate pairs in Step 6 are evaluated against the 10% reference curve shown in Figure A-2. The segment is judged as failing the criterion because it extends to the right of the reference curve at one point or more. A CFD for a summertime 30-day mean assessment would have 12 points (four summer months x 3 years).

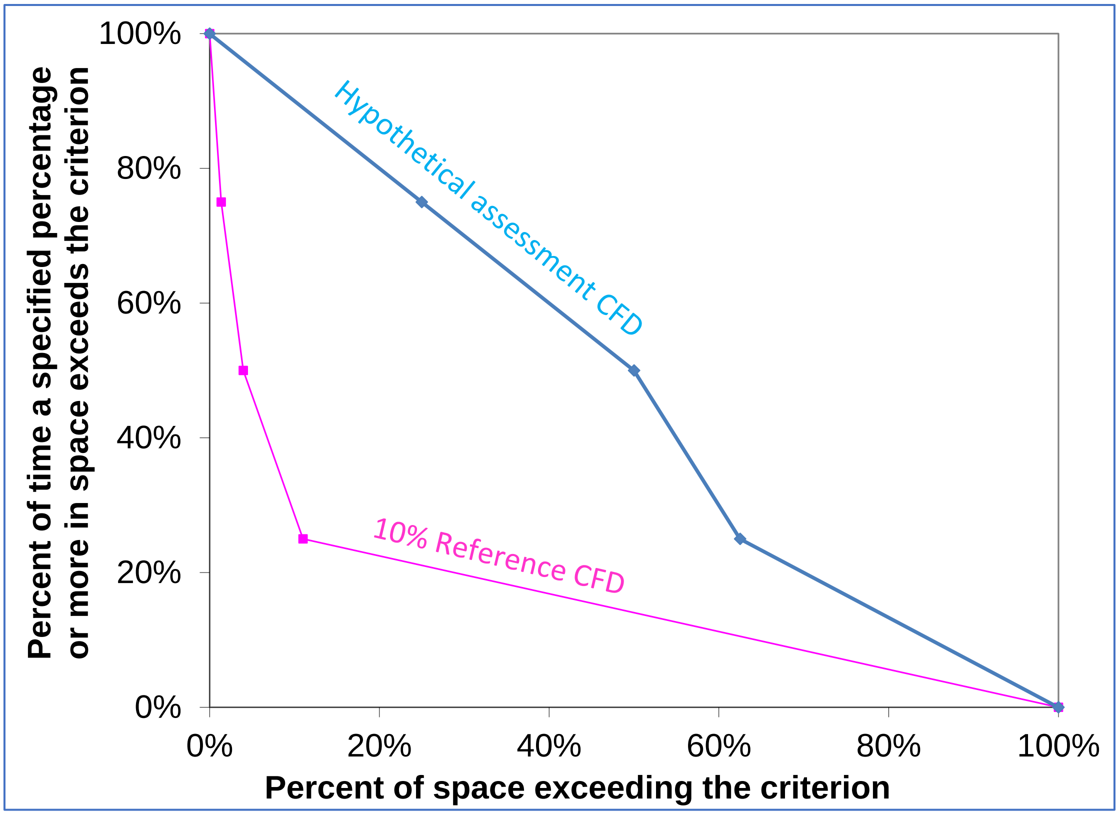

Figure A-2. Graphical representation of the CFD from the above theoretical example assessment curve with a 10% reference curve.

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APPENDIX B

Analyses to Support Deep Water Boundary Delineation

Magnitude of Stratification

Magnitude of stratification can be quantified by examining density gradients (the difference between bottom and surface density) and slopes (the largest magnitude of density change within the water column) observed at the CB6PH and CB7PH stations outside of the 2004 Deep Water boundary (see Figure B-1). The distributions of these two metrics can be compared statistically and visually across the stations, including the Deep Water station CB6.2, to discern patterns in stratification as one moves from north to south. It is not surprising that the water column at CB7.2 tends to show the strongest stratification out of all the selected stations, given its depth and proximity to the 2004 Deep Water boundary. However, it is surprising that the stratification in the water column of CB7.2's closest neighbor, CB7.2E, tends to be relatively weak and the stratification observed at its second farthest downstream neighbor, CB7.3, tends to be just as strong as what occurs at CB7.2. These findings indicate that neither proximity to the 2004 Deep Water boundary nor the mouth of the Bay are reliable predictors of where the physical conditions of the Deep Water use are likely to occur in CB6PH and CB7PH. That said, the station farthest from the 2004 Deep Water boundary and closest to the mouth, CB7.4N, stands out as the station with the weakest stratified water column, on average.

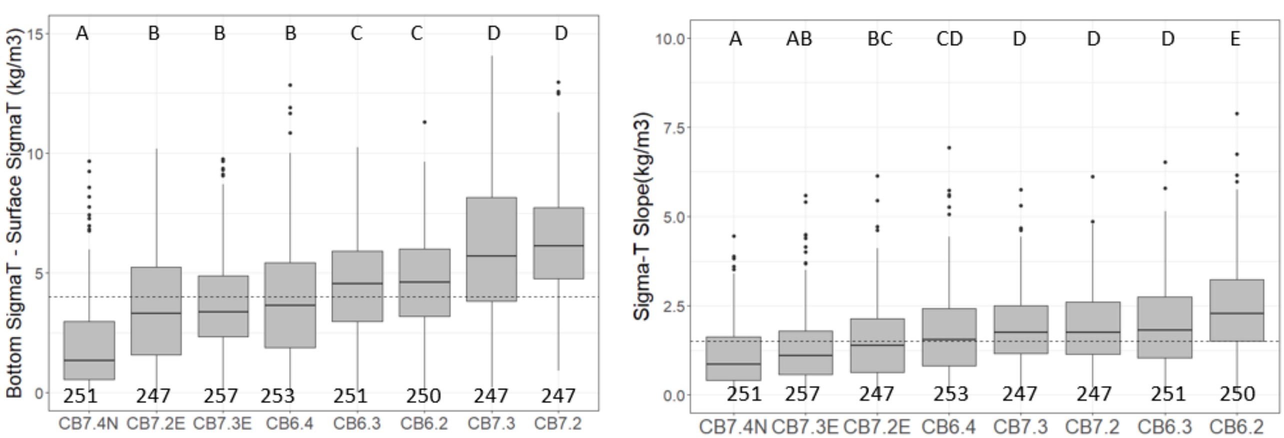

Figure B-1. Boxplots of the difference between bottom and surface water density (left) and density slopes (right) computed from vertical profile data collected June-September 1985-2021. Letters represent statistically different groups ($p<0.05$, Kruskal-Wallis test, post-hoc Conover-Iman test). Dashed line represents the median of all observations. Number of monitoring events is shown at the bottom of boxplots.

Appendix B

Low DO is Decoupled from Nutrients in CB6PH, CB7PH, and MOBPH

The Bay waters designated for the Deep Water use were designated under the assumption that their deep-water hypoxic volumes are not primarily driven by anthropogenic pollutants like total nitrogen, total phosphorus, or suspended solids. Thus, it is important to verify that the deep-water low DO observed in CB6PH and CB7PH outside the 2004 Deep Water boundary conforms to this expectation. DEQ staff performed two analyses to obtain this verification.

The first examination takes inspiration from the "single best year" approach used by the Partnership in 2003 to delineate the original Bay designated uses (USEPA, 2003). Rather than selecting a single best year for the entire Bay based on precipitation, three sets of three best years were selected for each station and segment in the study area, along with the entire Lower Bay mainstem--with surface chlorophyll-a as the indicator. Chlorophyll-a is considered a reliable indicator of phytoplankton biomass and thus nutrient enrichment/eutrophication (Harding et al. 2014). For each station in the study area, the three summer-years over the 1985-2021 period with the lowest median chlorophyll-a concentrations were identified. The maximum thickness of the deep-water low DO layer observed at that station over each of those three years was measured. This was repeated using the best three summer-years for the segment the station is located in and the entire Lower Bay mainstem (CB5MH, CB6PH, CB7PH, MOBPH, CB8PH, and the mouths of the Rappahannock, Piankatank, York, and James rivers). Different spatial scales were chosen to account for the fact that the best water quality at a station may not necessarily mean that conditions for the surrounding area were the "best". It would be reasonable to conclude that deep-water low DO in the area of interest is being driven primarily by nutrient enrichment if deep-water low DO was found to be absent or minimal during periods of relatively low phytoplankton biomass and thus low chlorophyll-a concentrations.

As shown in Table B-1, deep-water low DO layers of considerable thickness occurred during all the "best" years at CB6.3, CB6.4, CB7.2, and WE4.2 (located in Mobjack Bay). Layers were present during two of three of the "best" years at CB7.2E. CB7.3 stands out as the station with no low DO during most of its best years. But even CB7.3 experienced six meters worth of deep-water low DO during a summer when CB7PH had its lowest ever recorded chlorophyll concentration and the Lower Bay mainstem had its second lowest chlorophyll concentration. While this analysis does not conclusively rule out anthropogenic pollution as a primary cause of low DO in CB6PH and CB7PH, it strongly suggests it has a secondary role.

For the second investigation, statistical models were used to determine how predictive pollutant variables (surface chlorophyll-a and bottom total suspended solids [TSS]) and physical variables (surface temperature and density gradient) are to the presence and thickness of deep-water low DO in the area of interest. Logistic and negative binomial regression were the modeling approaches chosen for this analysis. The station datasets were individually modeled. Predictor variables were a median of observations recorded over the 30 days prior to when the DO observation was made to account for the potential lagging effect of these variables[8]. Possible interactions of these variables were also examined. The detailed model

[8] Support for a 1-month lag (as opposed a shorter or longer lag) is provided by Boicort (1992), who found that there is a 1-month lag response of Middle Bay stratification to the springtime influx of freshwater into the Bay. Additionally, Harding and Perry (2017) found that in the area of interest, the 1-month lagged average temperature is a stronger predictor of chlorophyll-a concentration than temperature lagged over longer durations. The findings of Yu et al. (2020) also suggest a 1-month response lag between chlorophyll-a concentration and hypoxia.

Appendix B

Table B-1 Summary of "Best Chlorophyll-a Years" Analysis

CB6.3

CB6.3 average median summer chlorophyll = 9.1 ug/L		CB6PH average median summer chlorophyll = 8.4 ug/L		Lower Bay Mainstem average median summer chlorophyll = 8.0 ug/L	
Three best years at station	Max thickness (m) of low DO layer observed at station	Three best years in segment	Max thickness (m) of low DO layer observed at station	Three best years for Lower Bay	Max thickness (m) of low DO layer observed at station
1995 (4.9 ug/L)	7	1991 (5.7 ug/L)	5	1985 (5.2 ug/L)	3
2008 (5.6 ug/L)	3	1995 (6.4 ug/L)	7	1992 (5.9 ug/L)	6
2016 (5.9 ug/L)	6	2016 (5.7 ug/L)	3	1995 (5.5 ug/L)	5

CB6.4

Station average median summer chlorophyll = 7.9 ug/L		CB6PH average median summer chlorophyll = 8.4 ug/L		Lower Bay Mainstem average median summer chlorophyll = 8.0 ug/L	
Three best years at station	Max thickness (m) of low DO layer observed at station	Three best years in segment	Max thickness (m) of low DO layer observed at station	Three best years for Lower Bay	Max thickness (m) of low DO layer observed at station
1985 (3.7 ug/L)	2	1991 (5.7 ug/L)	5	1985 (5.2 ug/L)	2
1991 (5.0 ug/L)	5	1995 (6.4 ug/L)	5	1992 (5.9 ug/L)	3
2016 (4.7 ug/L)	2	2016 (5.7 ug/L)	2	1995 (5.5 ug/L)	5

CB7.2

Station average median summer chlorophyll = 7.9 ug/L		CB7PH average median summer chlorophyll = 6.5 ug/L		Lower Bay Mainstem average median summer chlorophyll = 8.0 ug/L	
Three best years at station	Max thickness (m) of low DO layer observed at station	Three best years in segment	Max thickness (m) of low DO layer observed at station	Three best years for Lower Bay	Max thickness (m) of low DO layer observed at station
1985 (3.8 ug/L)	6	1985 (4.5 ug/L)	6	1985 (5.2 ug/L)	6
1995 (4.1 ug/L)	12	1995 (4.0 ug/L)	12	1992 (5.9 ug/L)	12
1997 (4.3 ug/L)	3	1997 (4.4 ug/L)	3	1995 (5.5 ug/L)	12

CB7.2E

Station average median summer chlorophyll = 6.6 ug/L		CB7PH average median summer chlorophyll = 6.5 ug/L		Lower Bay Mainstem average median summer chlorophyll = 8.0 ug/L	
Three best years at station	Max thickness (m) of low DO layer observed at station	Three best years in segment	Max thickness (m) of low DO layer observed at station	Three best years for Lower Bay	Max thickness (m) of low DO layer observed at station
1985 (3.6 ug/L)	3	1985 (4.5 ug/L)	3	1985 (5.2 ug/L)	3
1995 (3.3 ug/L)	9	1995 (4.0 ug/L)	9	1992 (5.9 ug/L)	2
2016 (4.3 ug/L)	0	1997 (4.4 ug/L)	4	1995 (5.5 ug/L)	9

CB7.3E

Station average median summer chlorophyll = 6.6 ug/L		CB7PH average median summer chlorophyll = 6.5 ug/L		Lower Bay Mainstem average median summer chlorophyll = 8.0 ug/L	
Three best years at station	Max thickness (m) of low DO layer observed at station	Three best years in segment	Max thickness (m) of low DO layer observed at station	Three best years for Lower Bay	Max thickness (m) of low DO layer observed at station
1985 (3.2 ug/L)	5	1985 (4.5 ug/L)	6	1985 (5.2 ug/L)	6
1997 (4.0 ug/L)	0	1995 (4.0 ug/L)	9	1992 (5.9 ug/L)	10
2016 (3.9 ug/L)	0	1997 (4.4 ug/L)	0	1995 (5.5 ug/L)	9

Table B-1 Summary of "Best Chlorophyll-a Years" Analysis (continued)

CB7.3

Station average median summer chlorophyll = 5.7 ug/L		CB7PH average median summer chlorophyll = 6.5 ug/L		Lower Bay Mainstem average median summer chlorophyll = 8.0 ug/L	
Three best years at station	Max thickness (m) of low DO layer observed at station	Three best years in segment	Max thickness (m) of low DO layer observed at station	Three best years for Lower Bay	Max thickness (m) of low DO layer observed at station
1988 (3.2 ug/L)	0	1985 (4.5 ug/L)	0	1985 (5.2 ug/L)	0
1997 (3.7 ug/L)	0	1995 (4.0 ug/L)	6	1992 (5.9 ug/L)	0
2001 (3.8 ug/L)	0	1997 (4.4 ug/L)	0	1995 (5.5 ug/L)	6

WE4.2

Station average median summer chlorophyll = 10.5 ug/L		MOBPH average median summer chlorophyll = 9.2 ug/L		Lower Bay Mainstem average median summer chlorophyll = 8.0 ug/L	
Three best years at station	Max thickness (m) of low DO layer observed at station	Three best years in segment	Max thickness (m) of low DO layer observed at station	Three best years for Lower Bay	Max thickness (m) of low DO layer observed at station
1992 (6.6 ug/L)	12	1992 (6.6 ug/L)	12	1985 (5.2 ug/L)	6
1995 (6.4 ug/L)	6	1995 (6.2 ug/L)	6	1992 (5.9 ug/L)	12
2008 (7.3 ug/L)	5	2013 (6.8 ug/L)	9	1995 (5.5 ug/L)	6

results are shown in Appendix C and a summary is presented in Table B-2. Anthropogenic pollution cannot be completely ruled out as a factor contributing to deep-water low DO in CB6PH and CB7PH, since pollutant variables were found to be predictive of either the presence of deep-water low DO or deep-water low DO layer thickness at two of the stations (CB7.2E and CB7.3). However, the importance of the density gradient is quite evident.

At CB7.3, the density gradient has almost 9 times the effect that chlorophyll-a concentration has on the odds of a deep-water hypoxic layer occurring. At CB7.2E, the density gradient has 4.90E+08 times the effect that surface chlorophyll-a concentration has on the thickness of the deep-water low DO layer.

Table B-2. Summary of the logistic and negative binomial regression models developed from anthropogenic pollutant and physical variables, with deep-water low DO layer presence and thickness used as the outcome variables, respectively.

Station	Predictors of deep-water low DO layer presence with greatest effect sizes (p<0.05 and + β's only)	Predictors of deep-water low DO layer thickness with greatest effect sizes (p<0.05 and + β's only)
WE4.2	none	none
CB6.3	none	none
CB6.4	none	none
CB7.2	none	none
CB7.2E	1. Density Gradient (β = 18.470) 2. Chlorophyll x TSS x Density Gradient (β = 0.095)	1. Density Gradient (β = 31.62) 2. Chlorophyll (β = 11.61)
CB7.3E	none	none
CB7.3	1. Density Gradient (β = 34.74) 2. Chlorophyll (β = 32.67)	1. Density Gradient (β = 38.27) 2. Temperature (β = 10.42)

Signs of Limited Oceanic Inflow in CB6PH, CB7PH, and MOBPH

Areas that are not designated for the Deep Water use are presumed to have water columns that are relatively well-mixed from surface to bottom. They may experience a pycnocline, but typically the stratification is weak, with some vertical exchange occurring across the pycnocline. For these reasons, it is not that unusual to observe DO concentrations less than 5 mg/L in the surface layer or above the pycnocline, if one is present, in waters where the Open Water use is frequently not attained. For instance, low DO occurred in the surface layer in the mesohaline portion of the York River (at station LE4.1) 4% of the summertime during the 1985-2021 period. According to the CBP attainment indicator, this segment has never attained the Open Water use. Thus, it is interesting that the deep-water low DO documented at the CB6PH and CB7PH has never been paired with low DO occurring above the pycnocline. Furthermore, there have only been a couple of events for which low DO has been observed in the absence of a pycnocline—one event out of a total of 253 for CB6.4 (6/15/1987) and one event out of a total of 247 for CB7.2E (7/6/1999). These observations strongly suggest that the area of interest is more similar to waters where physical conditions are the primary driver of low DO than waters where eutrophication is the primary driver of low DO. Despite frequently failing to meet the Open Water use, the CB6PH and CB7PH mainstem has never shown signs of this impairment in the portion of the water column most emblematic of the Open Water use.

If a persistent pycnocline, bottom bathymetry, and low DO in the deeper waters are present in a segment, then one can reasonably surmise that the water circulation patterns in that segment enable the formation of Deep Water habitat. If only the first two conditions are met, then one can conclude that the water circulation patterns do not pose a barrier to oxygen replenishment and thus the existence of Open Water habitat from surface to bottom can be assumed. Thus, it is important to understand how water circulation patterns influence DO concentrations in CB6PH and CB7PH before forming a conclusion about whether these segments support Deep Water habitat.

Some understanding of the water circulation patterns in the lower portion of the Lower Bay can be obtained by comparing the individual vertical DO profiles documented in segment CB8PH, CB6PH, CB7PH, and MOBPH (Figure B-2). The CB8PH stations are more likely to exhibit zigzag and inverted DO vertical profiles than upbay stations. Zigzag profiles are those profiles for which an increase in DO concentration greater than or equal 0.2 mg/L between two consecutive depths occurred at least once within or below the observed pycnocline (Figure B-2). This kind of profile can result from the intrusion of hypoxic sub-pycnocline waters into a water column that is not as oxygen-depleted. More often in CB8PH, this kind of profile reflects the intrusion of oxygen-rich seawater into a water column that is not as oxygen-rich. Zigzag profiles occurred in 28% of the summertime monitoring events from 1985-2021 at CB8PH station CB8.1, while they are only documented in 9% of the events for CB6PH station CB6.4. Inverted DO vertical profiles arise when the intrusion of seawater is not just limited to a few depth layers, as is seen in zigzag profiles. They are inversions of the typical DO profile in the Bay. Rather than finding higher DO concentrations above the pycnocline than within and below the pycnocline, the reverse is observed. This kind of profile develops when the intrusion of seawater is so voluminous that undiluted seawater essentially dominates much of the water column, resulting in higher dissolved oxygen concentrations in the bottom than at the surface. Inverted DO profiles have been recorded at 13% of the summertime monitoring events at CB8PH station CB7.4, while they have only been recorded at 3% of the events at CB7PH station CB7.3. An inverted profile has only been observed once at station, CB6.4. Inverted profiles have not been documented during the summer at mainstem stations north of CB6.4.

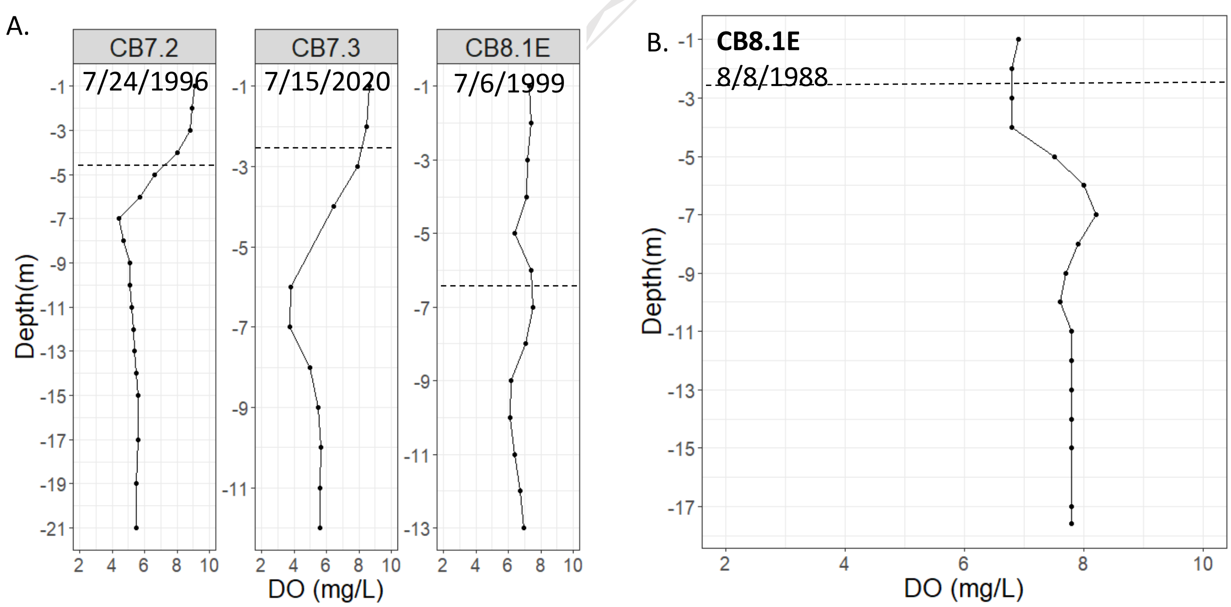

Figure B-2. Examples of zigzag and inverted-shaped vertical DO profiles. A) Zigzag DO profiles recorded at two stations in CB7PH and one station in CB8PH (CB8.1E). A profile is classified as "zigzag" if an increase in DO greater than or equal 0.2 mg/L occurs at least once below the observed upper boundary of the pycnocline between two consecutive depths. B) An inverted DO profile recorded at CB8PH station CB8.1E. A profile is classified as "inverted" when the mean DO concentration above the observed pycnocline is lower than the mean DO concentration below the upper boundary of the pycnocline, which is indicated by the dashed horizontal line.

These findings indicate that the Lower Bay mainstem does experience water circulation patterns that generate the oxygen replenishment that is asserted in U.S. EPA (2003). But while this replenishment is sufficient to maintain Open Water habitat from surface to bottom in CB8PH, it is insufficient for CB6PH and CB7PH.

This discussion of oceanic inflow closes with an acknowledgement that more ocean-induced oxygen replenishment occurs in CB7PH than in CB6PH. DEQ staff's review of historical and contemporary monitoring datasets reveals that the water columns of stations along the lower Eastern Shore (EE3.5, CB7.2E, and CB7.4N) are more likely to be—compared to the CB6PH and CB7PH stations to the west—fully oxygenated in the bottom mixed layer with stratification or well-mixed from surface to bottom with no stratification. These patterns are illustrated by the descriptions of water quality conditions occurring during two separate monitoring cruises:

<u>7/24/1995 - 7/25/1995</u>

- Deep-water low DO was observed at all stations in CB6PH, CB7PH and CB8PH, with the exception of the easternmost stations EE3.5, CB7.4N, and CB7.4.
- Stratified water columns were present at all CB6PH, CB7PH, and CB8PH stations except for EE3.5.
- The deep-water low DO layer at CB7.2E was 9-m thick, with a DO concentration of 2.9 mg/L at the bottom. The deep-water hypoxic layers due north at CB7.1 and due south at CB7.3E were also both 9-m thick, with bottom DO concentrations of 1.8 mg/L and 3.4 mg/L, respectively.

These observations are consistent with a water circulation pattern characterized by 1) oceanic inflow closely hugging the Eastern Shore due to the Coriolis effect, while bringing only marginal oxygen replenishment at and west of CB7.2E, and 2) increased water column mixing at the mouth of Tangier Sound due to tidal currents and bathymetric features (U.S. EPA 2003).

<u>7/14/2020 – 7/16/2020</u>

- The very large dead zone in the Chesapeake Bay mainstem recorded in July 2020 has been attributed to weak winds and very high temperatures (VIMS 2020). The average temperature for July 2020 was the highest ever recorded July average in Maryland and Virginia (NOAA 2023).
- Deep-water low DO was observed at all stations in CB6PH and CB7PH with the exception of CB7.2E and CB7.4N. It was not observed in CB8PH.
- The magnitudes of the density gradients at CB6.1, CB6.2, CB6.3, CB6.4, CB7.1, CB7.1N, CB7.1, CB7.2, CB7.3E, and CB7.3 were all above the summer average gradient for each station, while the magnitudes of the density gradients at EE3.5, CB7.2E, and CB7.4N were below their respective summer averages. Although CB7.2 and CB7.2E are located in close proximity to each other and were monitored within 30 minutes of each other, a thermocline was present at CB7.2 but not at CB7.2E.

These observations are consistent with a water circulation pattern characterized by turbulent mixing along the Eastern Shore induced by tidal currents, as described by U.S. EPA (2003).

Appendix B

Seaward Movement of Hypoxic Deep Water into the Lower Bay

There is an interconnectedness of below-pycnocline hypoxia in the Bay mainstem. Hypoxic deep waters in the Bay are pulsed out of trenches and holes in a lateral (landward) direction, especially by southerly winds (Li et al. 2015, Xie and Li, 2018, and Li et al. 2020), and then propelled by tidal currents (Breitburg, 1990). As these hypoxic waters flow seaward, they do not become fully reoxygenated the instant they move into the lower portions of CB6PH and CB7PH. The replenishment is gradual.

The southward flow of oxygen-depleted bottom waters is discussed in U.S. EPA (2003b) in the context of the northern portions of CB6PH and CB7PH:

> *"A shipping channel cuts through the sill, connecting the trench in segment CB7PH to the trench in the middle Chesapeake Bay (Figure IV-22). The channel enables an exchange of oxygen-depleted bottom waters from the mainstem trench with water in the northern portions of segments CB6PH and CB7PH.*
>
> *Although the overall direction of flow in the bottom layer is northward in this region, the smaller-scale actions of the outgoing tide can pulse bottom waters down-estuary (Figure IV-22). Oxygen-deficient water intrudes on the bottom and as lenses into mid-water depths. This effect can be intensified during a strong north-westerly wind event (see sidebar, "Tides Affected by Moon and Sun" on page 100). The deep- water designated use, therefore, extends below the sill in these two segments. Its lower boundary runs along a line more or less parallel to, but south of, the northern segment line (Figure IV-23). The delineation of the boundary was determined by examining maps of contemporary dissolved oxygen concentration distributions and the anecdotal historical dissolved oxygen concentration data record."* (U.S. EPA, 2003)

By drawing the southern edge of the 2004 Deep Water boundary where it did, the CBPO made the assumption that there is minimal seaward flow of hypoxic subpycnocline waters from the northern portions of CB6PH and CB7PH to their lower portions.

In search of evidence supporting this assumption, DEQ staff performed a series of "experiments" on the 1985-2021 monitoring dataset. The relative risk of deep-water low DO was computed for each station in the area of interest with respect to the conditions of another station—called the "condition" station. For each "event" and "condition" station pair, two conditional probabilities were calculated: 1) the probability of a deep-water low DO layer at the "event" station when one is present at the "condition" station during the same cruise and 2) the probability of a deep-water low DO layer at the "event" station when one is not present at the "condition" station during the same cruise. The relative risk the ratio of these two probabilities. If low DO deep water moves solely in a northward direction, the relative risk of deep-water low DO at the "event" stations should be consistently higher when downbay "condition" stations are used in the experiment versus upbay "condition" stations. One would also expect to see non-statistically significant relative risks when upbay stations are used in the experiment, since a statistically significant relative risk would suggest there is a good chance deep-water low DO occasionally has an upbay origin.

As shown in Table B-3, the results contradict these expectations. First, only one experiment generated a non-statistically significant relative risk—the one computed for WE4.2 as the "event" station and CB8.1E as the "condition" station. This result means there is not enough evidence to say that the low DO

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Table B-3. Relative risk results. The relative risk of low DO occurring at “event” stations given the specified conditions at selected “condition” stations are shown.

"Event" Station	"Condition" Station	Probability of deep water low DO at "event" station when it is present at "condition" station		Probability of deep water low DO at event" station when it is not present at "condition" station		Relative Risk[2]	95% CI
		Probability	No. of recorded low DO events at "condition" station[1]	Probability	No. of recorded non-low DO events at "condition" station[1]		
CB6.2	CB6.1 (upbay)	0.818	192	0.196	56	**4.2**	2.4 - 7.1
	CB7.2 (downbay)	0.932	59	0.561	107	1.6	1.4 - 1.9
CB6.3	*CB6.1 (upbay)*	0.701	194	0.073	55	9.6	3.7 - 24.9
	CB6.2 (upbay)	0.777	166	0.120	83	**6.5**	3.6 - 11.6
	CB7.2 (due east)	0.878	90	0.372	156	2.4	1.9 - 2.9
CB6.4	CB6.3 (upbay)	0.598	132	0.168	101	3.6	2.3 - 5.6
	CB7.3 (downbay)	0.846	13	0.373	228	2.3	1.7 - 3.0
	WE4.2 (due west)	0.561	148	0.152	99	3.7	2.3 - 6.0
CB7.2	*CB6.3 (due west)*	0.577	137	0.109	110	5.3	3.0 - 9.2
	CB6.4 (downbay)	0.639	97	0.188	144	3.7	2.3 - 4.9
	CB7.1S (upbay)	0.553	152	0.079	89	7.0	3.4 -14.5
	CB7.2E (due east)	0.873	55	0.200	180	4.4	3.2 - 5.9
CB7.2E	*CB7.2 (due west)*	0.571	84	0.046	151	**12.3**	5.8 - 26.0
	CB7.3E (downbay)	0.867	15	0.190	232	**4.6**	3.3 - 6.4
	EE3.5 (upbay)	0.319	91	0.177	147	1.8	1.1 - 2.9
CB7.3E	*CB7.2E (upbay)*	0.228	57	0.011	190	21.7	5.0 - 93.2
	CB7.3 (downbay)	0.385	13	0.039	233	10.0	3.9 - 25.5
CB7.3	*CB7.3E (upbay)*	0.385	13	0.040	150	9.7	3.6 - 25.9
	CB6.4 (upbay)	0.115	95	0.014	145	8.3	1.9 - 36.7
WE4.2	*CB6.4 (due east)*	0.847	98	0.436	149	1.9	1.5 - 2.3
	LE4.3 (due west)	1.000	15	0.567	238	1.8	1.6 - 2.0
	CB8.1E (downbay)	0.500	6	0.602	242	0.8	0.4 - 1.9

[1] For all tests, the “event” and “condition” stations were observed during the same cruises. For instance, over the 1985-2021 period, there were a total of 248 summertime cruises when CB6.1 and CB6.2 were both monitored—192 when CB6.1 experienced deep-water low DO and 56 when CB6.1 did not experience deep-water low DO. Italicized “condition” stations are those that were usually sampled on the same day as their paired “event” station.

[2] Relative risks in bold are statistically different from the relative risk immediately beneath it and matched to the same “event” station ($p<0.05$, test of interaction as described by Altman and Bland, 2003).

occurring at CB8.1E increases the likelihood of low DO at WE4.2. So, it is interesting that the other relative risks were all statistically significant (i.e., the lower 95% confidence interval does not overlap with 1). This strongly suggests the high likelihood of deep-water low DO at upbay stations being pushed to downbay stations, even when the distances are relatively large, as is the case between CB7.2E (the “event” station) and EE3.5 (the “condition” station). Deep-water low DO occurring at CB7.2E is 1.8 times more likely to occur when deep-water low DO is present at EE3.5 than when it is not present there. Secondly, the experiments involving upbay “event” stations tended to result in higher relative risks than those involving downbay “event” stations. In four cases, like the pairing for the “event” station CB6.2, these are statistically significant differences. The influence that CB6.1 has on CB6.2 is 2.6 times the influence that CB7.2 exerts on this station.

There are two other interesting observations from this analysis. First, WE4.2 appears to be affected by CB6.4 and LE4.3—the station just within the Deep Water boundary in the lower York—in equal measure. This suggests that WE4.2 is influenced by deep-water low DO from both the lower York River and the Chesapeake Bay mainstem. However, the relatively low relative risks in the WE4.2 experiments suggest that a deep-water low DO layer frequently occurs at WE4.2 even when it is absent in the adjacent areas. Secondly, the results for CB6.3-CB7.2-CB7.2E suggest that a site in the Bay mainstem is more likely to experience deep-water low DO when this condition is present in the waters to the west than in waters to the east. Deep-water low DO is 4.4 times more likey to be observed at CB7.2 when it is present at CB7.2E (due east) than when it is not present. This is in contrast to the finding that deep-water low DO is 12.3 times more likely to be observed at CB7.2E when it is present at CB7.2 (due west) than when it is not present. The relative risks between these two scenarios are statistically different, along with the results for the same scenarios involving CB6.3 and CB7.2.

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APPENDIX C

Appendix C

Empirical Relationships of Pollutant and Physical Variables to Deep-Water Low DO

Logistic regression was used to determine which pollutant and physical variables predict the occurrence of a deep-water low DO layer (i.e., the portion of the water column within and below the pycnocline where the DO concentration is less than 5 mg/L). Negative binomial regression was used to determine which pollutant and physical variables predict the thickness of the deep-water low DO layer. Predictor variables were a median of observations recorded over the 30 days prior to when the DO observation was taken to account for the potential lagging effect of these variables. Possible interactions of these variables were also examined.

The following tables are the model output for each station in the study area. P-values indicating statistical significance ($p<0.05$) are shown in bold.

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	CB6.3 (n= 237)							
	Presence of Deep Water Hypoxia				Thickness of Deep Water Hypoxic Layer			
	β	SE	*p-value*	% change	β	SE	*p-value*	% change
30-Day Median Surface Chlorophyll-a (Chl)	1.21	3.104	0.697	235.35	0.61177	2.473836	0.805	84.37
30-Day Median Bottom TSS (TSS)	0.7372	1.123	0.512	109.01	0.348423	0.85895	0.685	41.68
30-Day Median Surface Temperature (Temp)	-0.1049	0.95	0.912	-9.96	-0.451947	0.765379	0.555	-36.36
30-Day Median Density Gradient (Grad)	-5.196	5.152	0.313	-99.45	-5.663109	4.311394	0.189	-99.65
Chl x TSS	-0.1471	0.1651	0.373	-13.68	-0.123493	0.122894	0.315	-11.62
Chl x Temp	-0.03426	0.1209	0.777	-3.37	-0.019992	0.09661	0.836	-1.98
TSS x Temp	-0.024	0.04342	0.58	-2.37	-0.011468	0.033376	0.731	-1.14
Chl x Grad	0.2497	0.644	0.698	28.36	0.212688	0.529214	0.688	23.70
TSS x Grad	0.03598	0.2207	0.871	3.66	0.015521	0.186084	0.934	1.56
Temp x Grad	0.2155	0.1989	0.279	24.05	0.23007	0.16662	0.167	25.87
Chl x TSS x Temp	0.005037	0.006397	0.431	0.50	0.004541	0.00477	0.341	0.46
Chl x TSS x Grad	0.004682	0.0327	0.886	0.47	0.010731	0.025643	0.676	1.08
Chl x Temp x Grad	-0.01102	0.02485	0.657	-1.10	-0.00877	0.020386	0.667	-0.87
TSS x Temp x Grad	-0.00198	0.00855	0.817	-0.20	-0.000978	0.007178	0.892	-0.10
Chl x TSS x Temp x Grad	-8.7E-05	0.001266	0.945	-0.01	-0.000369	0.000987	0.709	-0.04
Constant	-0.5886	24.43	0.981	-44.49	10.84331	19.55414	0.579	5.12E+06
X^2	66.54				55.21			
Degrees of freedom	15				15			
Nagelkerke Pseudo R^2	0.33				0.21			

Appendix C

	CB6.4 (n= 237)							
	Presence of Deep Water Hypoxia				Thickness of Deep Water Hypoxic Layer			
	β	SE	*p-value*	% change	β	SE	*p-value*	% change
30-Day Median Surface Chlorophyll-a (Chl)	-2.873	4.11	0.485	-94.35	-1.722	2.725	0.527	-82.13
30-Day Median Bottom TSS (TSS)	-1.083	3.319	0.744	-66.14	0.2402	1.804	0.894	27.15
30-Day Median Surface Temperature (Temp)	0.3327	1.385	0.81	39.47	0.535	0.9236	0.562	70.74
30-Day Median Density Gradient (Grad)	4.382	7.966	0.582	7899.79	3.493	5.742	0.543	3188.45
Chl x TSS	0.2573	0.3765	0.494	29.34	0.0932	0.2084	0.655	9.77
Chl x Temp	0.0866	0.1558	0.578	9.05	0.06194	0.1044	0.553	6.39
TSS x Temp	0.0242	0.1263	0.848	2.45	-0.01541	0.07046	0.827	-1.53
Chl x Grad	0.2396	0.9315	0.797	27.07	0.4134	0.6843	0.546	51.19
TSS x Grad	-0.2586	0.7317	0.724	-22.79	-0.2253	0.4483	0.615	-20.17
Temp x Grad	-0.2149	0.3099	0.488	-19.34	-0.1488	0.2239	0.506	-13.83
Chl x TSS x Temp	-0.00792	0.0142	0.577	-0.79	-0.002977	0.008057	0.712	-0.30
Chl x TSS x Grad	-0.01088	0.08231	0.895	-1.08	-0.01884	0.05239	0.719	-1.87
Chl x Temp x Grad	-0.003	0.03576	0.933	-0.30	-0.01348	0.02623	0.607	-1.34
TSS x Temp x Grad	0.0146	0.02827	0.606	1.47	0.01116	0.01762	0.526	1.12
Chl x TSS x Temp x Grad	-5.8E-05	0.003148	0.985	-0.01	0.000509	0.002032	0.802	0.05
Constant	-5.095	36.11	0.888	-99.39	-13.94	23.77	0.558	-100.00
X^2	75.28				81.8			
Degrees of freedom	15				15			
Nagelkerke Pseudo R^2	0.37				0.31			

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	CB7.2 (n= 235)							
	Presence of Deep Water Hypoxia				Thickness of Deep Water Hypoxic Layer			
	β	SE	*p-value*	% change	β	SE	*p-value*	% change
30-Day Median Surface Chlorophyll-a (Chl)	-3.69362	4.410545	0.402	-97.51	-5.444	5.113	0.287	-99.57
30-Day Median Bottom TSS (TSS)	0.017468	0.778961	0.982	1.76	-0.4866	0.905	0.591	-38.53
30-Day Median Surface Temperature (Temp)	-0.33854	1.151662	0.769	-28.72	-0.7939	1.305	0.543	-54.79
30-Day Median Density Gradient (Grad)	1.412022	4.864731	0.772	310.42	-4.092	5.434	0.452	-98.33
Chl x TSS	0.099219	0.112667	0.379	10.43	0.1357	0.1369	0.322	14.53
Chl x Temp	0.162622	0.173059	0.347	17.66	0.2155	0.2023	0.287	24.05
TSS x Temp	0.004561	0.029261	0.876	0.46	0.01935	0.03484	0.579	1.95
Chl x Grad	0.347095	0.589041	0.556	41.50	0.762	0.7072	0.281	114.26
TSS x Grad	-0.17521	0.167082	0.294	-16.07	-0.005376	0.1789	0.976	-0.54
Temp x Grad	-0.03715	0.185622	0.841	-3.65	0.1566	0.2114	0.459	16.95
Chl x TSS x Temp	-0.00484	0.00448	0.28	-0.48	-0.005568	0.005471	0.309	-0.56
Chl x TSS x Grad	-0.00559	0.016002	0.727	-0.56	-0.01484	0.02075	0.475	-1.47
Chl x Temp x Grad	-0.0163	0.023278	0.484	-1.62	-0.02985	0.02815	0.289	-2.94
TSS x Temp x Grad	0.005667	0.006246	0.364	0.57	-1.6E-05	0.006912	0.998	0.00
Chl x TSS x Temp x Grad	0.000394	0.00064	0.538	0.04	0.00063	0.000837	0.451	0.06
Constant	5.124064	29.901	0.864	1.67E+04	21.49	33.41	0.52	2.15E+11
X^2	67.45				50.14			
Degrees of freedom	15				15			
Nagelkerke Pseudo R^2	0.35				0.2			

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	CB7.2E (n= 247)							
	Presence of Deep Water Hypoxia				Thickness of Deep Water Hypoxic Layer			
	β	SE	*p-value*	% change	β	SE	*p-value*	% change
30-Day Median Surface Chlorophyll-a (Chl)	7.286481	4.678907	0.1194	1.46E+05	11.61	5.629	**0.03923**	1.10E+07
30-Day Median Bottom TSS (TSS)	2.263158	1.185357	0.0562	861.34	3.807	1.472	**0.00972**	4401.52
30-Day Median Surface Temperature (Temp)	2.817128	1.418224	0.047	1572.87	4.149	1.685	**0.01379**	6237.06
30-Day Median Density Gradient (Grad)	18.47066	8.048537	**0.0217**	1.05E+10	31.62	10.18	**0.00189**	5.40E+15
Chl x TSS	-0.23909	0.1262	0.0582	-21.27	-0.4251	0.1605	**0.00809**	-34.63
Chl x Temp	-0.29281	0.182785	0.1092	-25.38	-0.4528	0.2237	**0.04293**	-36.42
TSS x Temp	-0.09173	0.047577	0.0538	-8.77	-0.1553	0.06028	**0.00997**	-14.38
Chl x Grad	-2.24672	1.060941	**0.0342**	-89.43	-4.086	1.39	**0.00328**	-98.32
TSS x Grad	-0.75511	0.348041	**0.03**	-53.00	-1.51	0.4789	**0.00161**	-77.91
Temp x Grad	-0.71315	0.315287	**0.0237**	-50.99	-1.22	0.404	**0.00254**	-70.48
Chl x TSS x Temp	0.009967	0.005107	0.051	1.00	0.01754	0.006679	**0.00865**	1.77
Chl x TSS x Grad	0.095257	0.045548	**0.0365**	9.99	0.1988	0.06338	**0.00171**	21.99
Chl x Temp x Grad	0.088942	0.041462	**0.0319**	9.30	0.1594	0.05505	**0.00378**	17.28
TSS x Temp x Grad	0.029902	0.013801	**0.0303**	3.04	0.05996	0.01915	**0.00174**	6.18
Chl x TSS x Temp x Grad	-0.00379	0.00179	**0.0344**	-0.38	-0.007888	0.002517	**0.00172**	-0.79
Constant	-74.1896	36.32663	**0.0411**	-100.00	-107.8	42.41	**0.01102**	-100.00
X^2	52.34				40.58			
Degrees of freedom	15				15			
Nagelkerke Pseudo R^2	0.29				0.17			

Appendix C

	CB7.3 (n= 247)							
	Presence of Deep Water Hypoxia				Thickness of Deep Water Hypoxic Layer			
	β	SE	*p-value*	% change	β	SE	*p-value*	% change
30-Day Median Surface Chlorophyll-a (Chl)	32.67	13.21	**0.01341**	1.54E+16	33.46	16.82	0.0466	3.40E+16
30-Day Median Bottom TSS (TSS)	11.01	5.32	**0.0384**	6.05E+06	10.98	5.603	0.0501	5.87E+06
30-Day Median Surface Temperature (Temp)	9.233	3.475	**0.00788**	1.02E+06	10.42	4.259	**0.0144**	3.35E+06
30-Day Median Density Gradient (Grad)	34.74	13.39	**0.00945**	1.22E+17	38.27	15.39	**0.0129**	4.17E+18
Chl x TSS	-1.551	0.812	0.05615	-78.80	-1.414	0.8627	0.1012	-75.68
Chl x Temp	-1.229	0.519	**0.0179**	-70.74	-1.256	0.6647	0.0589	-71.52
TSS x Temp	-0.4314	0.2157	0.04546	-35.04	-0.4291	0.2271	0.0588	-34.89
Chl x Grad	-5.244	2.104	**0.01269**	-99.47	-5.268	2.494	**0.0347**	-99.48
TSS x Grad	-1.705	0.8817	0.05308	-81.82	-1.645	0.8775	0.0609	-80.70
Temp x Grad	-1.31	0.5149	**0.01097**	-73.02	-1.454	0.5934	**0.0143**	-76.64
Chl x TSS x Temp	0.0611	0.03308	0.06471	6.30	0.05572	0.03547	0.1161	5.73
Chl x TSS x Grad	0.249	0.1344	0.06399	28.27	0.2234	0.1352	0.0985	25.03
Chl x Temp x Grad	0.1986	0.08153	**0.01484**	21.97	0.2013	0.09744	**0.0389**	22.30
TSS x Temp x Grad	0.06651	0.035	0.05739	6.88	0.06486	0.03494	0.0634	6.70
Chl x TSS x Temp x Grad	-0.00972	0.005334	0.06838	-0.97	-0.008816	0.00541	0.1032	-0.88
Constant	-249.4	90.88	**0.00607**	-100.00	-281.3	111.1	**0.0114**	-100.00
X^2	25.809				36.165			
Degrees of freedom	15				15			
Nagelkerke Pseudo R^2	0.3				0.28			

Appendix C

	CB7.3E (n= 257)							
	Presence of Deep Water Hypoxia				Thickness of Deep Water Hypoxic Layer			
	β	SE	*p-value*	% change	β	SE	*p-value*	% change
30-Day Median Surface Chlorophyll-a (Chl)	11.91	7.494	0.1121	1.49E+07	44.95089	30.61156	0.142	3.33E+21
30-Day Median Bottom TSS (TSS)	3.054	2.76	0.2684	2020.00	20.67059	12.22345	0.0908	9.49E+10
30-Day Median Surface Temperature (Temp)	4.212	2.485	0.0901	6649.14	15.86769	8.61084	0.0654	7.78E+08
30-Day Median Density Gradient (Grad)	19.21	13.68	0.1605	2.20E+10	76.33646	50.49188	0.1306	1.42E+35
Chl x TSS	-0.3479	0.3642	0.3394	-29.38	-2.23546	1.76872	0.2063	-89.31
Chl x Temp	-0.4648	0.3046	0.127	-37.17	-1.68	1.20341	0.1627	-81.36
TSS x Temp	-0.1211	0.1122	0.2802	-11.41	-0.75906	0.47817	0.1124	-53.19
Chl x Grad	-2.083	1.835	0.2564	-87.54	-7.68783	7.02539	0.2738	-99.95
TSS x Grad	-0.6172	0.7927	0.4363	-46.05	-3.90747	2.98492	0.1905	-97.99
Temp x Grad	-0.722	0.5529	0.1916	-51.42	-2.7737	1.99094	0.1636	-93.76
Chl x TSS x Temp	0.01443	0.01513	0.3403	1.45	0.08369	0.06942	0.228	8.73
Chl x TSS x Grad	0.07001	0.1187	0.5553	7.25	0.39259	0.42538	0.3561	48.08
Chl x Temp x Grad	0.08143	0.07586	0.2831	8.48	0.28611	0.27908	0.3053	33.12
TSS x Temp x Grad	0.02424	0.03225	0.4523	2.45	0.1428	0.11752	0.2243	15.35
Chl x TSS x Temp x Grad	-0.00288	0.00484	0.5514	-0.29	-0.01465	0.0168	0.3833	-1.45
Constant	-113.8	63.22	0.0718	-100.00	-433.691	220.6628	0.0494	-100.00
X^2	12.24				12.659			
Degrees of freedom	15				15			
Nagelkerke Pseudo R^2	0.13				0.09			

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Appendix C

	WE4.2 (n= 238)							
	Presence of Deep Water Hypoxia				Thickness of Deep Water Hypoxic Layer			
	β	SE	*p-value*	% change	β	SE	*p-value*	% change
30-Day Median Surface Chlorophyll-a (Chl)	1.713176	1.699571	0.313	454.65	1.391481	0.925357	0.1327	302.08
30-Day Median Bottom TSS (TSS)	-0.54293	1.623471	0.738	-41.90	-0.178027	0.728672	0.807	-16.31
30-Day Median Surface Temperature (Temp)	0.022789	0.629469	0.971	2.31	0.105913	0.309305	0.732	11.17
30-Day Median Density Gradient (Grad)	3.851454	6.072371	0.526	4606.14	4.297203	2.433396	0.0774	7249.39
Chl x TSS	-0.07596	0.170954	0.657	-7.31	-0.095151	0.090313	0.2921	-9.08
Chl x Temp	-0.05988	0.064328	0.352	-5.81	-0.04985	0.034409	0.1474	-4.86
TSS x Temp	0.025982	0.062323	0.677	2.63	0.009917	0.027844	0.7217	1.00
Chl x Grad	-0.81749	0.653738	0.211	-55.85	-0.647531	0.328826	0.0489	-47.67
TSS x Grad	-0.10484	0.570703	0.854	-9.95	-0.205462	0.210894	0.3299	-18.57
Temp x Grad	-0.12484	0.234302	0.594	-11.74	-0.146921	0.092805	0.1134	-13.66
Chl x TSS x Temp	0.002238	0.006557	0.733	0.22	0.003257	0.003432	0.3426	0.33
Chl x TSS x Grad	0.041448	0.063123	0.511	4.23	0.043934	0.031308	0.1605	4.49
Chl x Temp x Grad	0.029915	0.025207	0.235	3.04	0.02397	0.012475	0.0547	2.43
TSS x Temp x Grad	0.002711	0.022114	0.902	0.27	0.007196	0.008149	0.3772	0.72
Chl x TSS x Temp x Grad	-0.0014	0.002445	0.567	-0.14	-0.001589	0.001201	0.1857	-0.16
Constant	-2.6546	16.5715	0.873	-92.97	-3.575796	8.256184	0.6649	-97.20
X^2	65.58				85.41			
Degrees of freedom	15				15			
Nagelkerke Pseudo R^2	0.33				0.31			

APPENDIX D

Appendix D

Minimum DO Observed in the Area of Interest During the “Best Three Years”

Table D-1. Minimum DO observed during summertime monitoring events during the three years when chlorophyll concentrations were at their lowest at each station over the 1985-2021 period (also refer to Table B-1).

CB6.3		
Summer Sample Dates Within Three "Best Years"	Minimum DO (mg/L) Observed	20th Percentile Min DO Across Three "Best Years"
6/7/1995	3.9	3.5
6/19/1995	4.4	
7/10/1995	3.3	
7/24/1995	2.1	
8/11/1995	4.8	
8/23/1995	2.8	
9/5/1995	4.4	
9/19/1995	5.4	
6/10/2008	4.8	
7/7/2008	3.5	
7/21/2008	3.7	
8/11/2008	4.4	
8/25/2008	5.0	
9/30/2008	5.7	
6/7/2016	6.2	
7/11/2016	3.9	
7/25/2016	3.6	
8/8/2016	4.4	
8/29/2016	5.2	
9/26/2016	4.1	

CB6.4		
Summer Sample Dates Within Three "Best Years"	Minimum DO (mg/L) Observed	20th Percentile Min DO Across Three"Best Years"
6/3/1985	6.5	4.0
6/17/1985	5.4	
7/8/1985	4.8	
7/22/1985	5.8	
8/6/1985	5.9	
8/20/1985	7.3	
9/10/1985	1.1	
9/30/1985	6.5	
6/6/1991	7.3	
6/18/1991	4.7	
7/11/1991	3.5	
7/23/1991	2.7	
8/6/1991	3.1	
8/21/1991	4.4	
9/4/1991	7.0	
9/16/1991	5.0	
6/7/2016	6.8	
6/29/2016	4.5	
7/13/2016	3.8	
7/26/2016	5.1	
8/9/2016	4.3	
8/31/2016	5.0	
9/26/2016	7.3	

CB7.2		
Summer Sample Dates Within Three "Best Years"	Minimum DO (mg/L) Observed	20th Percentile Min DO Across Three "Best Years"
6/4/1985	6.3	4.2
6/19/1985	5.1	
7/9/1985	4.7	
8/7/1985	5.1	
8/20/1985	5.6	
9/10/1985	3.4	
6/7/1995	5.1	
6/19/1995	5.1	
7/10/1995	4.0	
7/24/1995	2.8	
8/11/1995	5.3	
8/21/1995	2.2	
9/5/1995	4.5	
9/19/1995	5.4	
6/11/1997	6.4	
7/15/1997	4.2	
7/31/1997	5.5	
8/12/1997	4.9	
8/25/1997	5.4	
9/8/1997	4.9	

CB7.2E		
Summer Sample Dates Within Three "Best Years"	Minimum DO (mg/L) Observed	20th Percentile Min DO Across Three "Best Years"
6/4/1985	6.6	4.6
6/19/1985	5.9	
7/9/1985	4.7	
7/24/1985	5.1	
8/7/1985	5.5	
8/20/1985	6.0	
9/10/1985	3.7	
6/7/1995	5.0	
6/19/1995	6.1	
7/10/1995	4.5	
7/24/1995	2.9	
8/9/1995	4.6	
8/21/1995	4.1	
9/5/1995	5.5	
9/19/1995	5.3	
6/6/2016	6.7	
6/27/2016	5.6	
7/11/2016	5.1	
7/25/2016	4.8	
8/8/2016	5.6	
8/29/2016	6.0	
9/26/2016	6.2	

Table D-1. Minimum DO observed during summertime monitoring events during the three years when chlorophyll concentrations were at their lowest at each station over the 1985-2021 period (also refer to Table B-1) (continued)

CB7.3E		
Summer Sample Dates Within Three "Best Years"	Minimum DO (mg/L) Observed	20th Percentile Min DO Across Three "Best Years"
6/3/1985	7.0	5.5
6/17/1985	6.4	
7/8/1985	5.5	
7/22/1985	7.0	
8/6/1985	6.0	
8/20/1985	5.8	
9/10/1985	3.3	
9/30/1985	6.6	
6/11/1997	6.6	
7/15/1997	4.6	
7/31/1997	6.4	
8/12/1997	4.6	
8/25/1997	7.1	
9/8/1997	6.4	
6/6/2016	7.0	
6/27/2016	6.0	
7/11/2016	5.0	
7/25/2016	5.6	
8/8/2016	5.8	
8/29/2016	6.7	
9/19/2016	6.6	

CB7.3		
Summer Sample Dates Within Three "Best Years"	Minimum DO (mg/L) Observed	20th Percentile Min DO Across Three "Best Years"
6/7/1988	6.9	5.9
6/20/1988	5.8	
7/6/1988	6.4	
7/18/1988	5.9	
8/8/1988	5.7	
8/23/1988	6.8	
9/9/1988	6.4	
9/19/1988	5.9	
6/12/1997	8.1	
7/16/1997	7.0	
8/1/1997	6.4	
8/13/1997	6.3	
8/26/1997	6.9	
9/10/1997	6.4	
6/12/2001	6.5	
7/11/2001	7.4	
7/23/2001	7.9	
8/13/2001	5.4	
8/29/2001	6.6	
9/10/2001	6.9	

WE4.2		
Summer Sample Dates Within Three "Best Years"	Minimum DO (mg/L) Observed	20th Percentile Min DO Across Three "Best Years"
6/8/1992	5.9	2.4
6/22/1992	3.6	
7/13/1992	1.9	
7/20/1992	1.6	
8/10/1992	5.7	
8/24/1992	3.1	
9/8/1992	4.4	
9/21/1992	2.4	
6/5/1995	4.3	
6/19/1995	6.0	
7/10/1995	4.7	
7/24/1995	1.6	
8/9/1995	4.2	
8/21/1995	1.4	
9/5/1995	4.0	
9/19/1995	5.0	
6/10/2008	5.2	
7/9/2008	3.6	
7/23/2008	2.4	
8/13/2008	2.9	
9/2/2008	6.6	
9/18/2008	6.3	