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Dissolved Oxygen Trends in the Chesapeake Bay (1984-1990)

Chesapeake Bay Program

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CSC

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Executive Summary

Low dissolved oxygen is one of the most important problems facing managers and scientists in the restoration of Chesapeake Bay. Oxygen is critical to the health and survival of the Bay's aquatic life. Faced with decreasing levels of dissolved oxygen associated with rising nutrient levels (e.g., nitrogen, phosphorus), managers adopted a basinwide nutrient reduction goal in 1987, to achieve at least a 40 percent reduction of nitrogen and phosphorus entering the mainstem Chesapeake by the year 2000. To track the progress toward this goal and to extablish long-term trends, an analysis of current and historical dissolved oxygen data was conducted.

Since 1984, the Chesapeake Bay Program has overseen a comprehensive water quality monitoring program in which the Bay's water is sampled throughout the year at fixed stations. Water quality data collected prior to 1984 were not comparable to that of the current Monitoring Program and were thus inadequate in determining historical baywide trends unequivacably.

Dissolved oxygen was examined in several ways to determine trends through time. Using a volumetric "interpolator," dissolved oxygen was analyzed over the entire Bay and regionally over segments. This interpolator also has the capability of dealing with missing data and variable sampling locations, and weights the influence of individual stations by the size region they represent. Long-term trends (1950-1990) in dissolved oxygen were determined by examining changes in the volume of water containing under 5 mg/l of dissolved oxygen and that under 1 mg/l as estimated by the interpolator. Trends since 1984 were determined by examining changes in:

1) dissolved oxygen concentration;
2) the volume of water under certain target concentrations; and
3) oxygen deficit mass.

Dissolved oxygen in the upper Chesapeake Bay appears to be generally related to water flow into the Bay from the Susquehanna River, the largest source of freshwater to the Bay. The volume of hypoxic water decreased during the drought years of the 1960s, then increased with the higher flows of the early 1970s, and decreased again in the latter half of the decade although flow was high.

Since 1984, a gradual downward trend in the average concentration of dissolved oxygen was observed in the Bay with minima occuring in July 1986 and July 1989, and the volume of hypoxic/anoxic water fluctuated widely. Under the hydrologic conditions of1984-1990, anoxic waters have appeared each summer. This finding contrasts with the higher levels found in the 1950s under similar hydrologic conditions. The volume of water under 1 mg/l increased in segments CB4 and CB5. The volume of water under 5 mg/l has generally decreased in the upper Bay segments through CB5 and has increased in lower Bay segments. The plot of dissolved oxygen deficit for the entire Bay showed no definitive trend through time (Figure 10) nor did the majority of plots for the individual segments. However, three small segments of the Bay did show trends in dissolved oxygen through the period of Monitoring Program data (1984-1990). The causes of the apparent trends are not clear.

Although significant reductions in phosphorus levels have been achieved, corresponding improvements in dissolved oxygen have not yet been seen.

Introduction

Oxygen in the Bay's waters, like oxygen in the air, is critical for the survival of its living resources. Thus, the levels of dissolved oxygen found in the Bay are an important indicator of its water quality. The EPA Chesapeake Bay Program (CBP), in its initial characterization of the Bay's water quality, estimated that the amount of water with low or no dissolved oxygen had increased between 1950 and 1980 (CBP, 1983). The reductions in dissolved oxygen were linked to nutrient enrichment from phosphorus and nitrogen.

Based on the EPA report and other findings, a basinwide nutrient reduction goal was adopted in 1987 to achieve at least a 40 percent reduction of nitrogen and phosphorus entering the mainstem of the Bay by the year 2000. It is expected that dissolved oxygen levels will rise as nutrient levels decrease.

This summary of trends in dissolved oxygen is one in a series of reports on the progress toward and reevaluation of the 40 percent nutrient reduction goal. Reports describing trends in phosphorus and nitrogen in Chesapeake Bay are companion documents to this report (CBP, 1991a, b).

Dissolved Oxygen in Estuarine Waters

The amount of oxygen in Bay waters is a function of several factors: 1) surface aeration and oxygen production processes; 2) physical and chemical processes affecting oxygen carrying capacity and transfer within the water 3) biological and chemical processes which use oxygen. Atmospheric oxygen enters the water through wind action and surface adsorption. When sunlight is sufficient in surface and shallow waters, plant photosynthesis generates oxygen. The total amount of oxygen that water can hold depends on both water temperature and salinity. The exchange of oxygenated surface water with waters below is dependent on the degree and extent of density stratification in the Bay, which, in turn, is a function of the temperature and salinity of the different water layers. Plant and animal respiration, bacterial decomposition, and abiotic chemical oxidation-reduction reactions all consume oxygen.

The addition of nutrients to the water fuels photosynthesis, locally increasing oxygen production initially, but also boosting plant production. Decomposition of excess organic matter, which takes place primarily in the Bay's bottom waters, remineralizes the nutrient constituents of the organic matter. It is an oxygen-consuming process which delivers phosphorus and nitrogen both to the sediments and the water.

The rates of these biological and chemical processes increase as temperature increases. With a temperature rise, however, the amount of oxygen water can hold (the saturation level) decreases. The saturation level is also decreased by increasing salinity, but to a lesser extent. In the summer, water temperatures rise and salinity generally increases, causing a reduction in dissolved oxygen potential. If the amount of unconsumed organic production exported to the bottom is sufficiently large and the Bay waters sufficiently stratified, then the transport of surface oxygen into lower depths is inhibited. The bottom waters gradually become depleted of oxygen until they have either minimal amounts of oxygen (hypoxia) or no oxygen (anoxia).

Determining Trends in Dissolved Oxygen

Determining long-term dissolved oxygen trends in the Bay is hindered by the dynamic interactions of these many factors and by an historical record that is inconsistent in space, time, and quality. These problems were recognized in the research phase of the Chesapeake Bay Program, so that in 1984 the CBP initiated a long-term baywide water quality monitoring program to evaluate the status and trends of a suite of water quality parameters, including dissolved oxygen.

In this analysis, the historical (pre-1984) record was included to the extent possible to provide a reference point to past conditions, but emphasis is on trends since the beginning of the Monitoring Program, from June 1984 through September 1990.

The Data

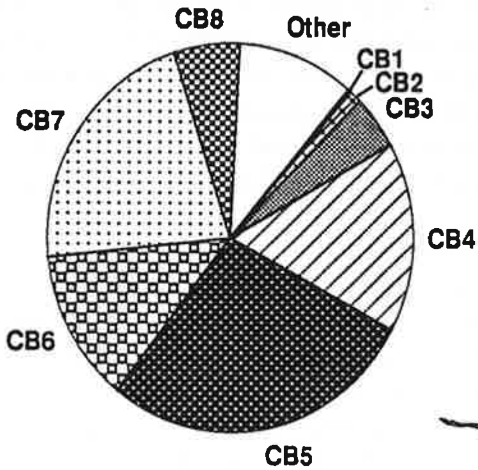
Chesapeake Bay Mainstem Water Quality Monitoring Program

The Chesapeake Bay Program, a cooperative effort between the federal government and the states surrounding Chesapeake Bay, provides funds to the states of Maryland and Virginia for the routine monitoring of 19 water quality parameters at 49 stations in the mainstem of Chesapeake Bay (Figure 1).

The Maryland Department of the Environment oversees the Program in the Maryland portion of the Bay. In the lower Bay, Virginia Institute of Marine Science and Old Dominion University (under contract to the Virginia Water Control Board) share responsibility for sample collection and analysis.

At each station, measurements are taken for dissolved oxygen, water temperature, conductivity, salinity, and pH. These measurements are sampled from surface to bottom at 1 to 2 meter intervals using either a Hydrolab probe or a Seabird Conductivity-Temperature-Depth (CTD) metering system. Water samples for chlorophyll and nutrient analyses are collected with a submersible pump and taken at surface and bottom at all stations and at 1 meter above and below the pycnocline at stratified stations (or at one-third and two-thirds the distance between surface and bottom if no pycnocline exists).

Mainbay Monitoring Segments and Stations



Relative Volume of Water in Bay Segments

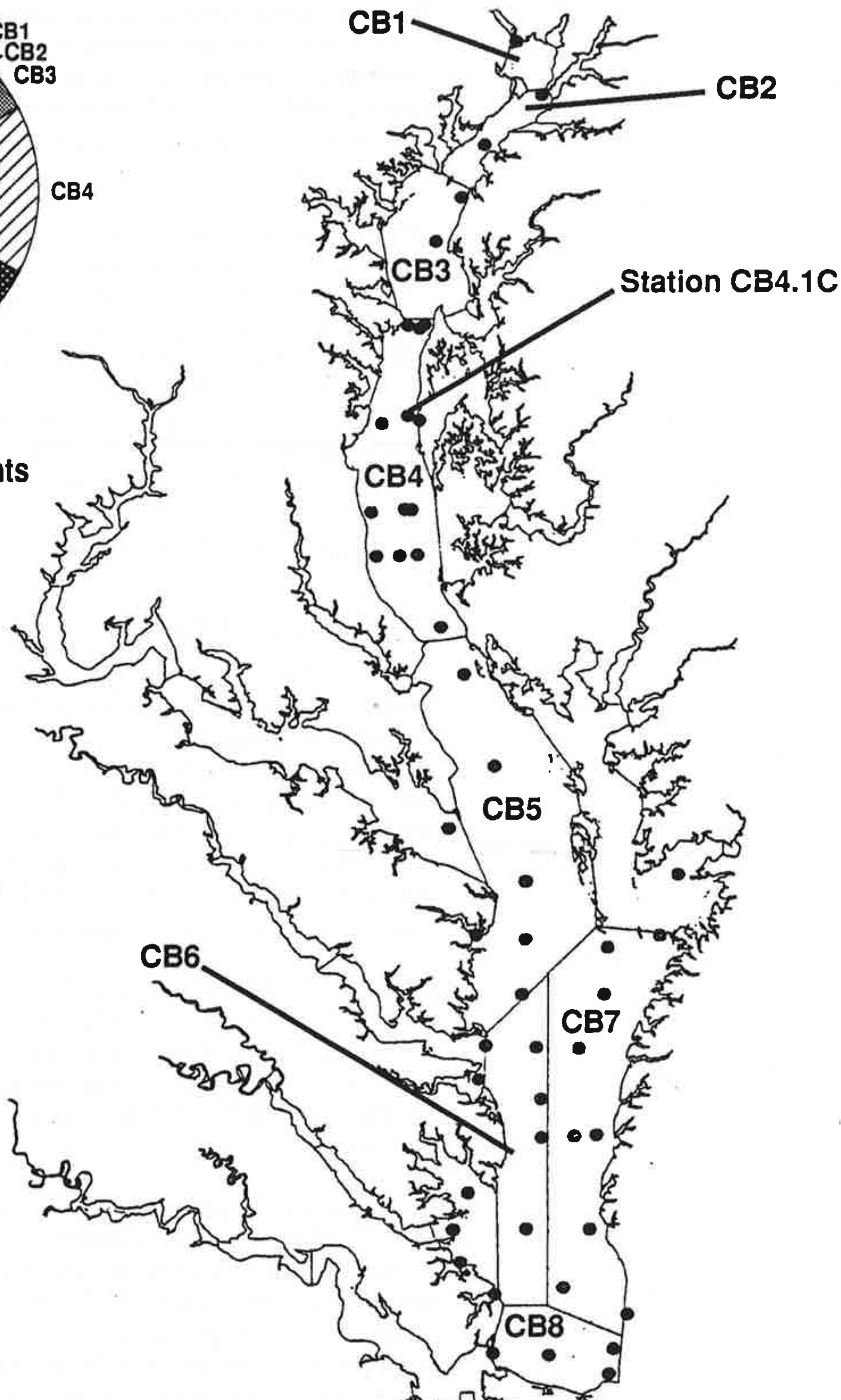


Figure 1. Chesapeake Bay stations and segments.

The mainstem stations are usually sampled within the same 3-day interval, with some exceptions due to extreme weather in winter and spring. Initially, stations were sampled twice monthly from March through October and once a month from November through February. However, in 1988, the once-monthly winter schedule was extended to include October and March in Virginia. At the same time, Maryland dropped the east and west lateral stations from the winter sampling schedule. These changes in sampling for Virginia and Maryland should have minimal effect on the dissolved oxygen analysis, since the period of concern extends from April through September, with dissolved oxygen levels usually becoming critically low between July and September.

The EPA Chesapeake Bay Program Office (EPA-CBPO) Computer Center in Annapolis, MD, compiles and maintains the Monitoring Program data. Prior to submission to CBPO, the data-collecting organizations check the data using a variety of quality assurance procedures. At the EPA-CBPO, values are rechecked against acceptable ranges and questionable entries are verified with the data originators. Some data are missing because of equipment failure during data collection and because of the lack of counterpart data. For example, data collected in Maryland during the second cruises in March and October 1987-1990 (cruises 75, 95, 109, and 115), were not used in the analysis due to the fact that no counterpart cruises took place in Virginia waters.

Before the Monitoring Program

Prior to 1984, the most extensive records of dissolved oxygen were collected by the Johns Hopkins University Chesapeake Bay Institute (CBI), the Virginia Institute of Marine Science, the U.S. Environmental Protection Agency's Annapolis Field Office (AFO), and by Maryland and Virginia as part of their state water quality monitoring programs. CBI and AFO data sets sometimes included baywide surveys. These data, however, were usually interrupted after one or more years once the objectives of the study were met. The other data sets were generally locally focused.

The method for determining dissolved oxygen changed over the 33-year record. Dissolved oxygen was originally determined using the Winkler titration method. Later, oxygen measurements were made by meter, as in the current monitoring program. The modern meters were usually calibrated against a Winkler titration. Therefore, a 1:1 comparability of methodologies was assumed.

The sampling designs of these studies differed according to individual scientific objectives. Often, dissolved oxygen was measured only at the surface or at several fixed depths. Vertical profiles at 1 to 2 meter intervals, as in the current program, were rare. The historical data most similar to those of the current program include once-monthly measurements for a year or more. More frequently, measurements were made once or twice each season. Some of the studies were designed to characterize oxygen levels in the Bay. Other studies focused on Bay circulation and physical models, nutrients and eutrophication, or were surveys of general water quality.

The historical data posed a variety of quality assurance problems. To check their quality, the original data were screened for outliers by comparing their values to the range of values observed in the Monitoring Program for the same season and segment. Any observation lying outside this range was defined as an outlier. Outliers were checked against field sheets or data reports and were omitted from the analysis if they could not be corrected or confirmed.

The historical dissolved oxygen data from 1950 to 1983 were evaluated for the suitability of their spatial and temporal coverage in this trend analysis. Data for each year and month were mapped to determine if the location and sample depth approximated that of the current Monitoring Program. Dissolved oxygen levels are most critical for the Bay's aquatic life between April and September, since this is when oxygen levels are at their lowest. There were many years for which no data were available, and only a few years where data were available for more than one or two of those months. Data for the Virginia portion of the Bay were especially sparse.

The approach chosen was to compare data collected in Maryland Chesapeake Bay for July of each year since it was the month most frequently sampled. If necessary, these data were supplemented by data from June or August, if July data were not available and the spatial coverage in June or August was adequate. Therefore, analysis of the 40-year (1950-1990) trend in dissolved oxygen was based on marginally sufficient July data (augmented by June or August for some years) for 26 of 40 years in Maryland Chesapeake Bay. Any trends found apply only to Maryland waters.

Data Analysis

There are several measures of dissolved oxygen which reveal various aspects of the Bay's water quality. Concentrations of dissolved oxygen are important since aquatic animals require minimum levels to survive. The volume of water at particular concentrations and the amount of time that oxygen deficient conditions persist are biologically significant and are also useful indicators of oxygen conditions from one year to the next. A good measure for analyzing trends is the total annual oxygen deficit, since it is an indicator that accounts for differences in temperature and salinity. For these reasons, several measures of dissolved oxygen were examined in this analysis:

1) average concentration (milligrams per liter) of dissolved oxygen;
2) volume (cubic meters) of water at particular concentrations;
3) volume days (cubic meter days) or the volume of water at particular concentrations on one sampling date multiplied by the number of days between that sampling date and the next, summed over time;
4) oxygen deficit (kilograms) or the difference between the mass of observed dissolved oxygen and the potential mass of dissolved oxygen in solution at saturation. In computing oxygen deficit, if the mass of oxygen in a cell was greater than saturation—which can occur in surface

waters during active photosynthesis—the oxygen mass was denoted as the saturation value for computation.

Several time scales were used: sampling date, monthly mean, and annual total. Water year (instead of calendar year) was used to define a year-long period. A water year begins on October 1 of one year and extends through September 30 of the following year. For example, water year 1985 extended from October 1, 1984 through September 30, 1985. Water year is often appropriate in environmental and biological contexts, as it best represents seasonal and annual hydrology. To compare complete water years, the partial water year 1984 was excluded since the Monitoring Program did not begin until late June.

For analytical purposes, the Chesapeake Bay basin is divided into segments. Salinity regimes, land use, and management areas all factor into the segmentation scheme (CBP, 1983). The main Bay is divided into eight segments (CB1 through CB8, Figure 1); the eastern and western embayments and areas at the mouths of tributaries are in separate segments. In this analysis, regional trends were examined in the eight CB segments. Baywide trends were derived for the entire region, including peripheral areas, as well as the main Bay segments. The piechart in Figure 1 shows the relative contributions of the segments to the total.

The Interpolator

The volumetric "interpolator" developed by Computer Sciences Corporation (Reynolds and Bahner, 1989), is an analytical tool that provides a way to look at the volume and mass of dissolved oxygen over a region rather than at particular locations. The interpolator is capable of handling missing data and variable sampling locations—a major consideration in the historical data—and also weights the influence of individual stations by the size region they represent.

Figure 2 illustrates how the interpolator works. The study area is divided into a three dimensional grid. The bathymetry or depth profile of the Bay determines the number of cell layers at any location. Actual sampling locations lie within the grid, and the values at the center of each cell are estimated by weighting measurements from nearby stations according to their distance from the center point. Mass or concentration within each cell is computed and the cells are averaged, totaled or grouped depending on the desired measurement (e.g., average concentration, total mass, or volume of water).

The Chesapeake Bay was divided into 57,871 cells, each cell measuring 1 kilometer long by 1 kilometer wide by 1 meter deep. At each station, vertical dissolved oxygen measurements were available at 1 or 2 meter intervals. Where measurements were missing, values were linearly interpolated from the closest measurements above and below the missing data point. A weighting method commonly applied in geostatistics—the inverse distance squared of the four nearest neighbors (Monmonier, 1982)—was used to interpolate cell values horizontally between stations (Figure 3).

Inputs to the Interpolator

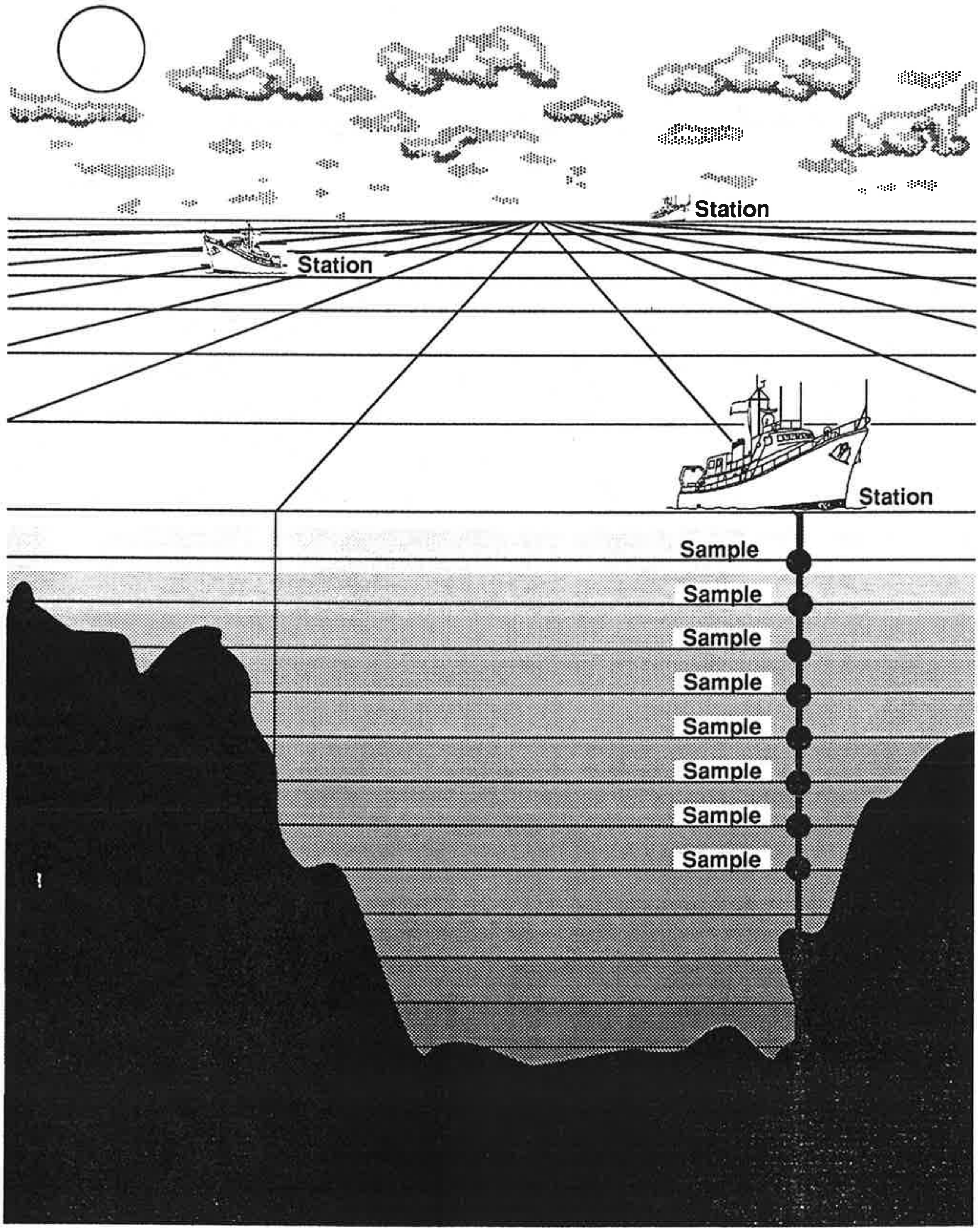


Figure 2. Interpolator three-dimentional grid.

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How the Interpolator Works

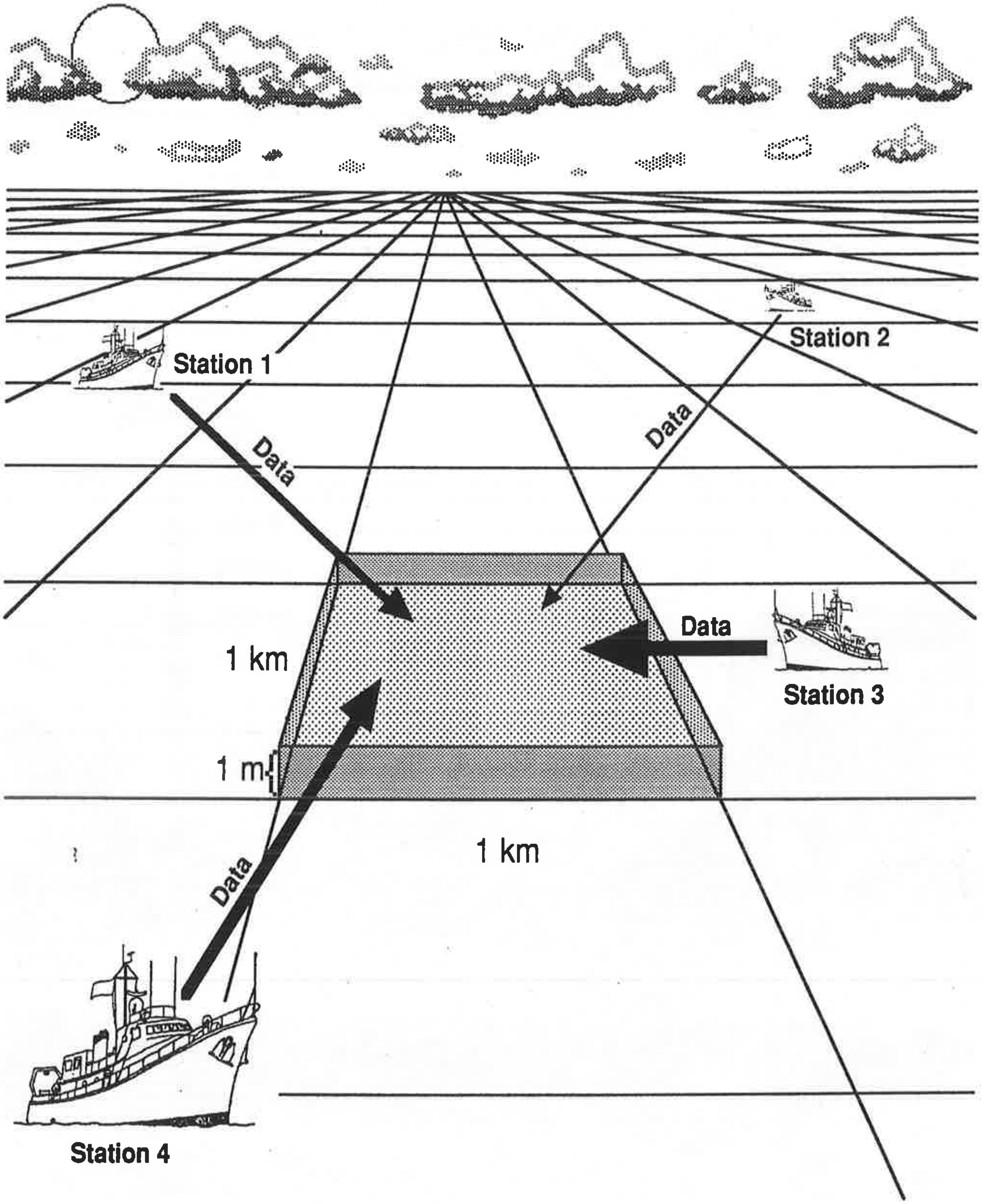


Figure 3. Inverse–Distance–Squared Estimation Method.

Using the interpolator, the concentration of dissolved oxygen was estimated for each cell in the grid. Volume and mass were computed by summing the volume or mass of all the cells. Monthly means were obtained by calculating the average dissolved oxygen concentration, mass, or volume for each sampling date, then averaging all dates for each month. Oxygen deficit was calculated for each date, then summed within the water year. Cubic meter days were also summed within each water year.

The usefulness of the estimates generated by the interpolator were evaluated by a technique called jackknifing (Clark, 1980). In this approach, measurements at monitored stations were compared to estimates for that location. To do this, observed data for the station in question were eliminated and values were estimated for the station using interpolated values from the closest cells. The correlation of estimated with observed values was calculated separately for shallow (less than 10 meters) and deep locations. The correlation coefficient for shallow locations was 0.93 (N=42494); the correlation coefficient for deep locations was 0.96 (N=24184). The high correlation coefficients provide confidence in the interpolator estimates for dissolved oxygen.

Results of the Analysis

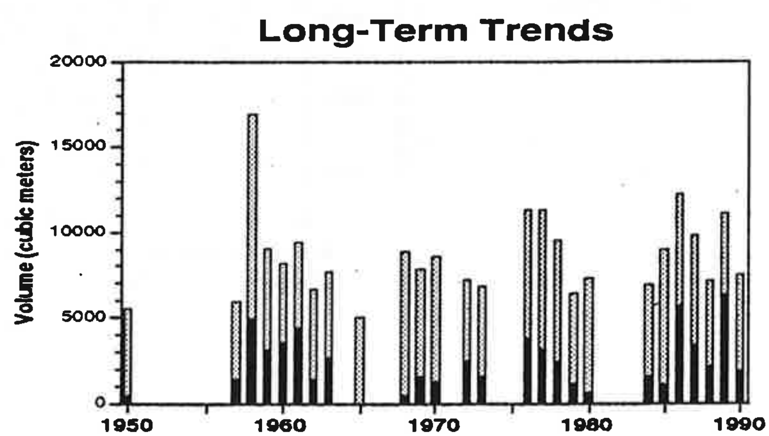
Long-Term Trends in Dissolved Oxygen (1950-1990)

Long-term (1950-1990) trends in dissolved oxygen were determined by examining changes in the volume of water containing under 5 mg/l and under 1 mg/l dissolved oxygen in the Maryland portion of Chesapeake Bay. The amount of water with dissolved oxygen concentrations less than 5 mg/l was relatively small in 1950 and 1957 (Figure 4) and increased dramatically in 1958. Note that in Figure 4, the years for which adequate data did not exist are not shown. The smallest volume of water under 5 mg/l was in 1965. Highs in the mid-1970's were about two thirds of the 1958 maximum. Peak volumes after the beginning of the Monitoring Program (in 1986, 1989) were also about this magnitude.

Figure 4. Volume of low dissolved oxygen in Maryland Chesapeake Bay from July.

Volume < 5 mg/l

Volume < 1 mg/l



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Variation in the volume of water with dissolved oxygen less than 1 mg/l showed a similar pattern through time (Figure 4) with some differences in magnitude. In 1958, the volume of water containing less than 1 mg/l was large, however, it constituted a smaller proportion of the water volume under 5 mg/l than in subsequent "bad" years. The volumes less than 1 mg/l in 1986 and 1989 were larger than any previous year for which there were data.

As freshwater flows into the Bay from the tributaries, it affects the depth and degree of water column stratification. This stratification, in turn, controls the amount of oxygen deprivation below the pycnocline. In some parts of the watershed, rainfall and snowmelt carry nutrients from the land to the streams, tributaries, and ultimately to the Bay. The amount of freshwater inflow at a given time may then indicate the quantity of water-borne nutrients. To provide the hydrologic background for trends in dissolved oxygen, the Susquehanna River was used since it is the largest source of freshwater to the Bay.

Figure 5 depicts the annual flow in the Susquehanna from 1950-1990 (averaged from July of one year through June of the next) compared to the 90-year (1900-1990) mean flow. Flow during the 1950s varied about the 90-year mean. From 1961 to 1969, the freshwater flow was considerably reduced; from 1971 to 1979, the flow was well above the mean. Another period of reduced flow followed in 1979 and continued until 1982. Since 1984 (when the CBP Monitoring Program began), flow has been variable but generally below the 90-year mean. Flow decreased from 1984 through 1988 and increased in 1989 and 1990. The highest flow of the decade occurred in the June 1983-July 1984 period, just preceding the start of the Monitoring Program.

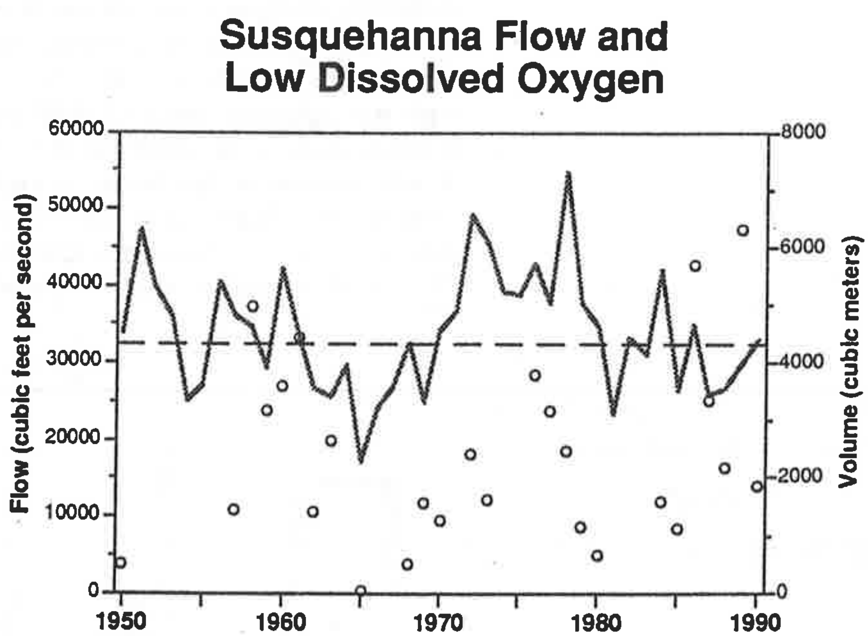

Figure 5. Low dissolved oxygen in Maryland Bay compared to annual Susquehanna flow.

- o Volume of D.O. < 1 mg/l
- ▬ Susquehanna Flow
- — — 90-Year Mean

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Dissolved oxygen in the Maryland Chesapeake Bay appears to be generally related to the Susquehanna's flow (Figure 5). The volume of hypoxic water decreased during the drought years of the 1960s, then increased with the higher flows of the early 1970s. It decreased again in the latter half of the decade, although flow was high. Since 1984, the volume of hypoxic/anoxic water has fluctuated widely. The very high volumes in July 1986 and July 1989 are particularly notable. These volumes of low dissolved oxygen are much higher than expected compared to equivalent flows in previous years.

As mentioned above, the selected July data from 1950 to 1983 are marginal, sporadic, and limited to the upper half of the Bay. Conditions at a single point in time do not adequately represent an entire season or year, and dissolved oxygen may have been much higher or lower in other months and years for which data were not available.

Dissolved Oxygen Trends (1984-1990)

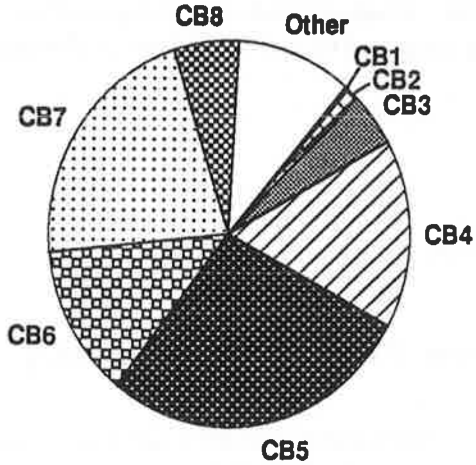
Since oxygen is crucial to the Bay's aquatic life, the onset, spatial extent, and duration of oxygen deficiency is particularly important to their well-being. Dissolved oxygen goals recently drafted by CBP to protect and restore Chesapeake Bay's living resources identify 1, 3, and 5 mg/l as key threshold levels for assessing the health of Bay waters (CBP, 1991c). Another critical concentration is around 0.2 mg/l, below which anaerobic chemical reactions occur that release nutrients and toxic sulfides from the sediments. The Monitoring Program data provide an opportunity to examine both seasonal and annual trends as well as identify differences among Bay segments.

A gradual downward trend in the average concentration of dissolved oxygen was observed in the Bay from 1984 to 1990 (see total Bay, Figure 6), with minima occurring in July 1986 and July 1989. This trend was not evident in all mainbay segments. Segment CB1 showed a slight upward trend in concentration, while segment CB2 showed no trend (Figure 6). Segments CB3 through CB8 exhibited downward trends of varying degree (Figure 6).

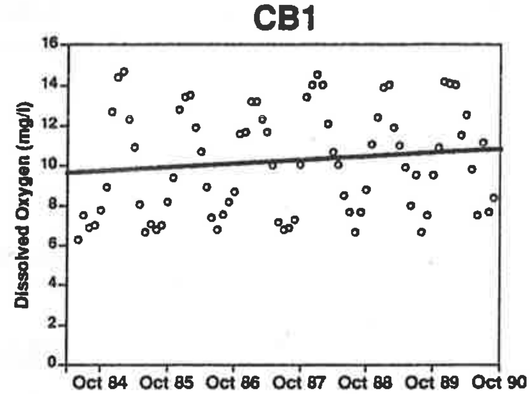
Not only is the concentration of dissolved oxygen important to the Bay's aquatic life, but also the extent and duration of low dissolved oxygen. Figure 7 shows each segment's volume of dissolved oxygen at 5, 3, 1, and 0.2 mg/l for each sampling date. (Note that plots for CB1, CB2, CB3, and CB8 are not shown since the volume of low dissolved oxygen was negligible in these segments). The time when oxygen levels dropped most rapidly was between April and May or May and June. Hypoxic/anoxic conditions occurred quickly thereafter. In segment CB4, for example, water with less than 0.2 mg/l had appeared by May in 1985, 1988, and 1990 (Figure 7). In 1988, these anoxic waters remained through the summer and into October.

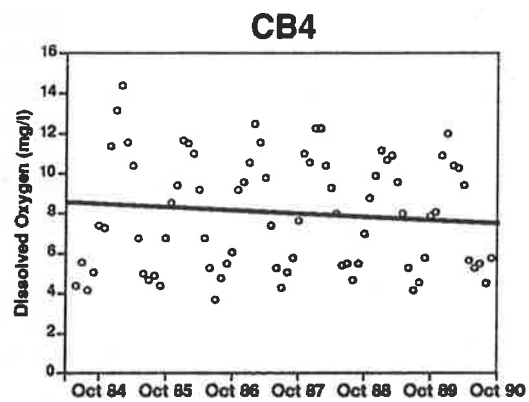
Station CB4.1C in segment CB4 is a typical station in the Chesapeake Bay deep trench (Figure 8). The dissolved oxygen profiles at this station show chronic severe oxygen depletion in this part of the Bay. Notice that anoxic or near anoxic water extended over 75 percent of the water column. In 1984 and 1989, for example, anoxia extended from the bottom of the Bay (at 35 meters deep) up to 7 meters below the surface.

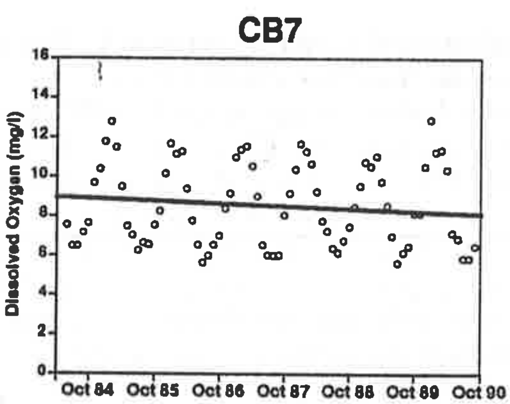
Dissolved Oxyger

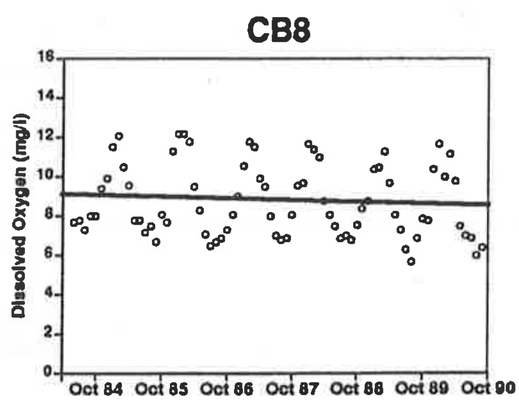


Relative Volume of Water in Bay Segments

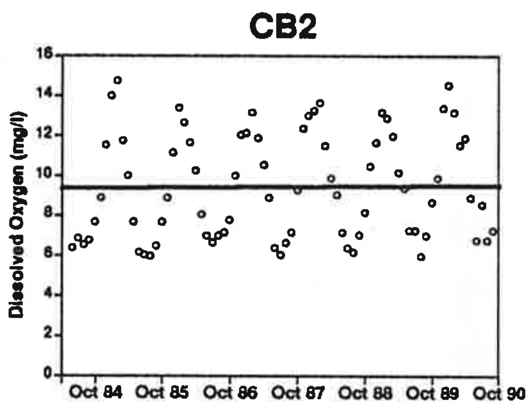


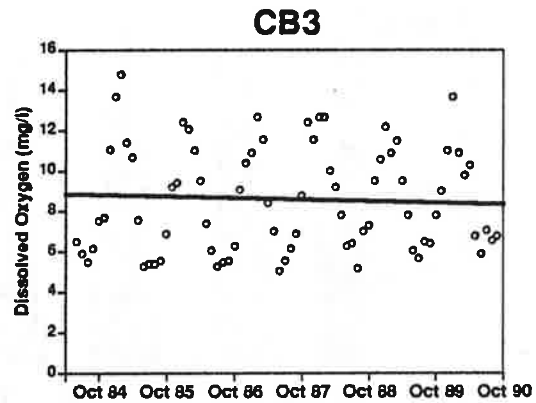


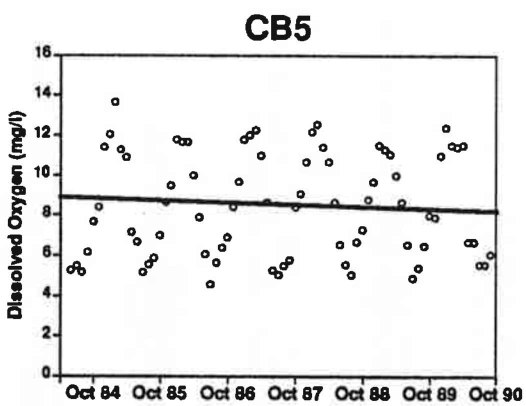


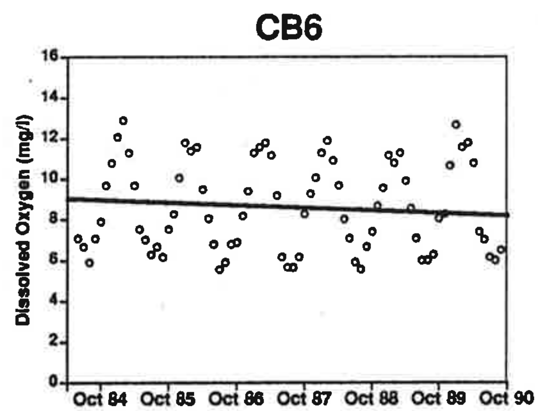


Concentration









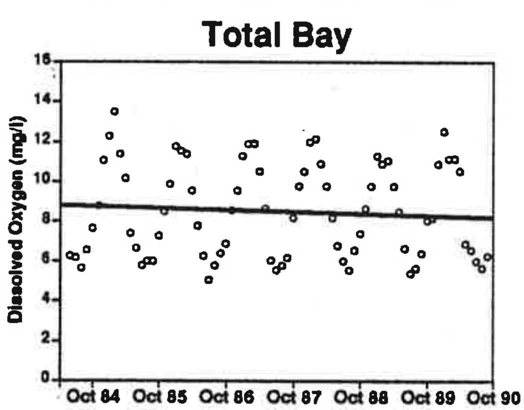
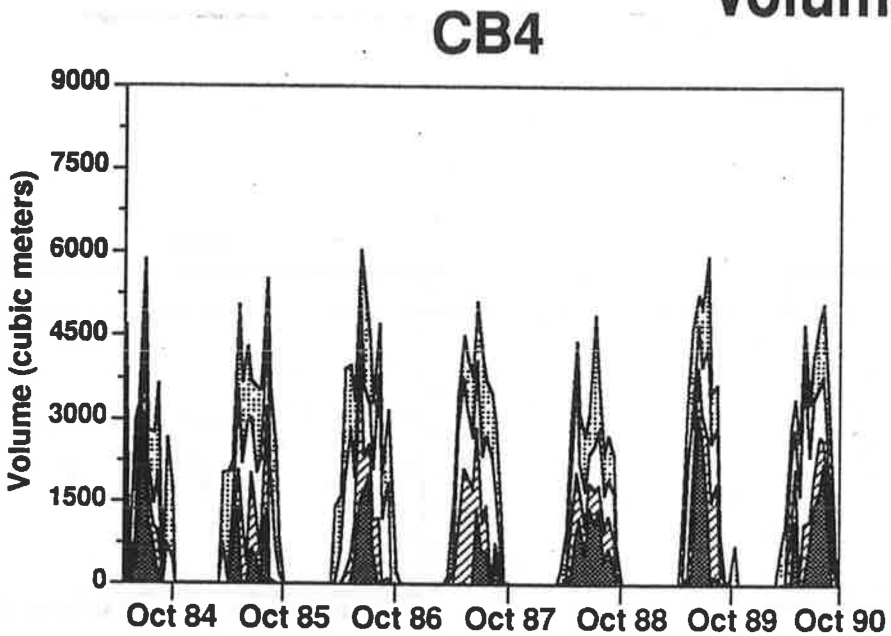
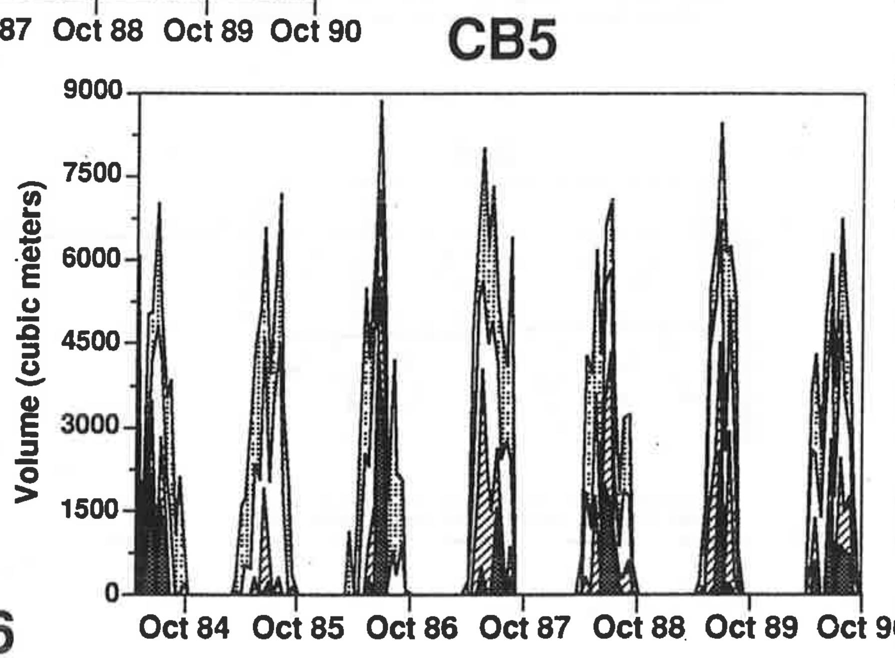
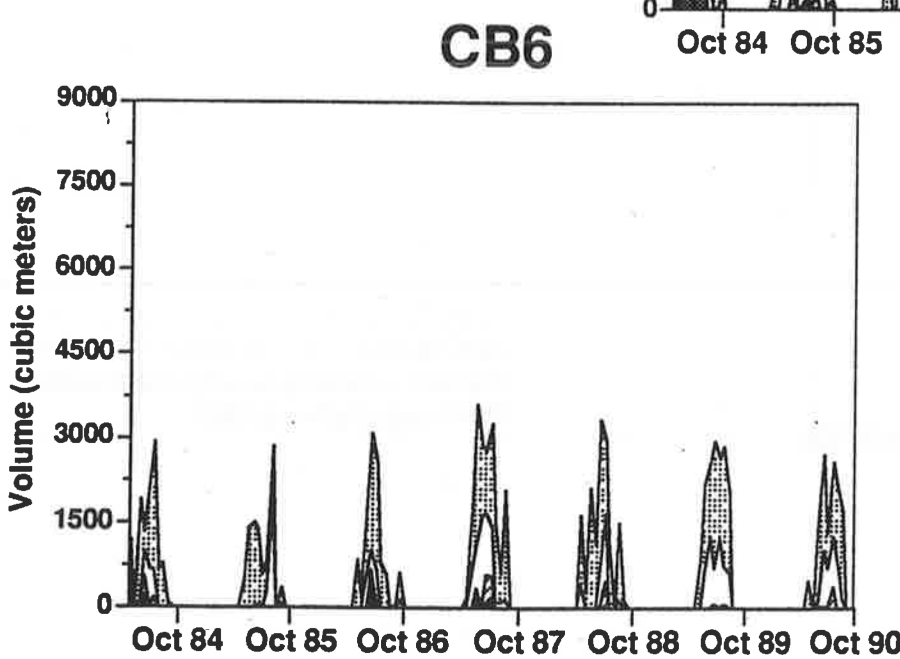


Figure 6. Average monthly concentration of dissolved oxygen in Chesapeake Bay Segments (Trend lines were computed using data from October 1984 through September 1990).

Volume of Low Dissolved







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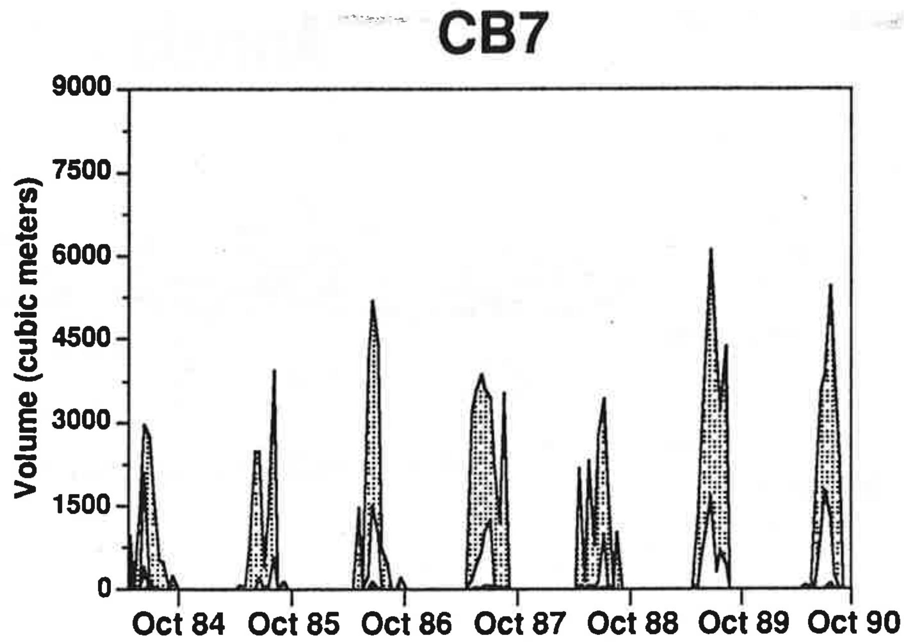
Oxygen Over Time



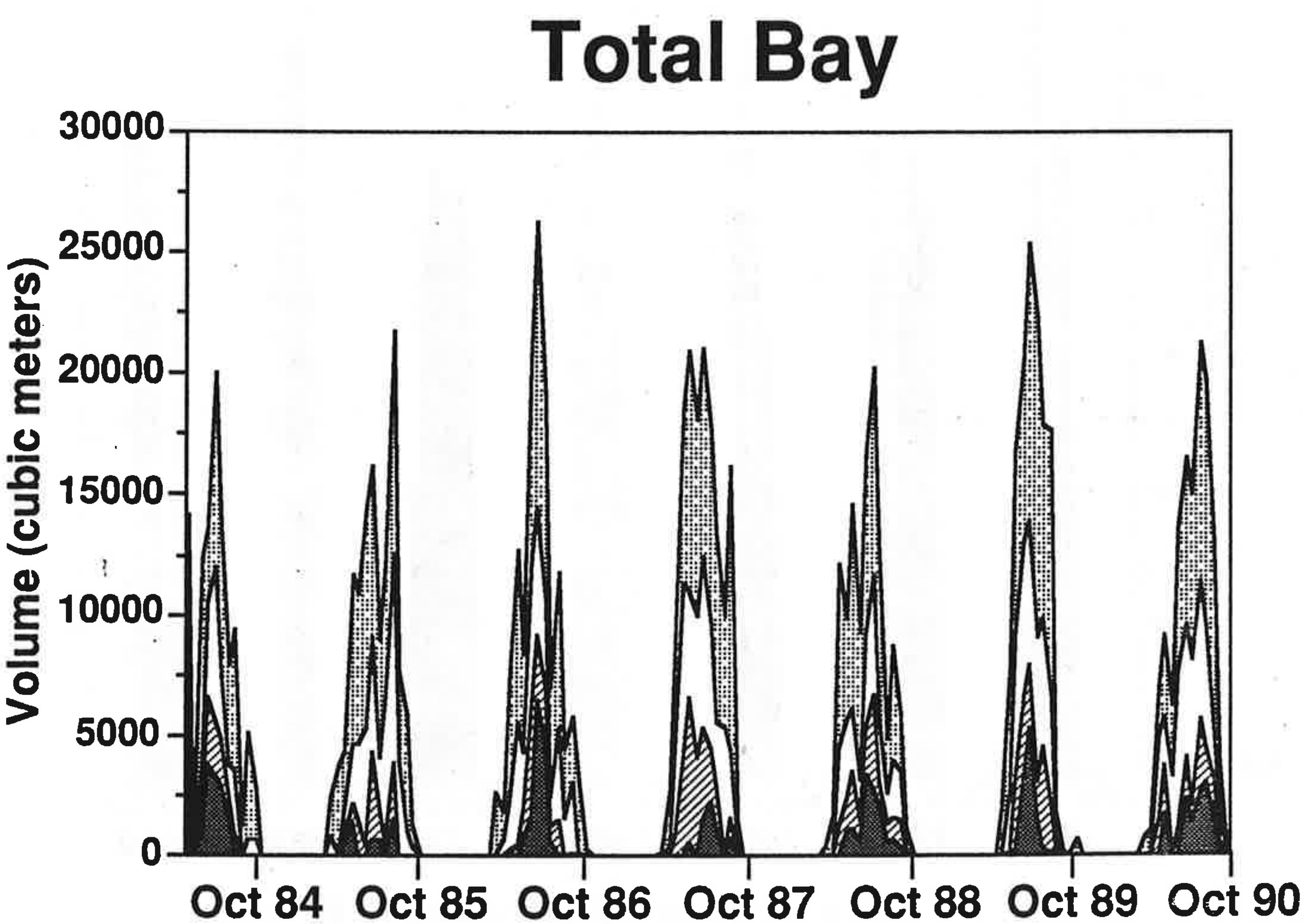


Figure 7. Volume of water with low dissolved oxygen concentrations.

■ < .2; ▨ < 1.0 ; □ < 3.0; ▩ < 5.0

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Anoxia

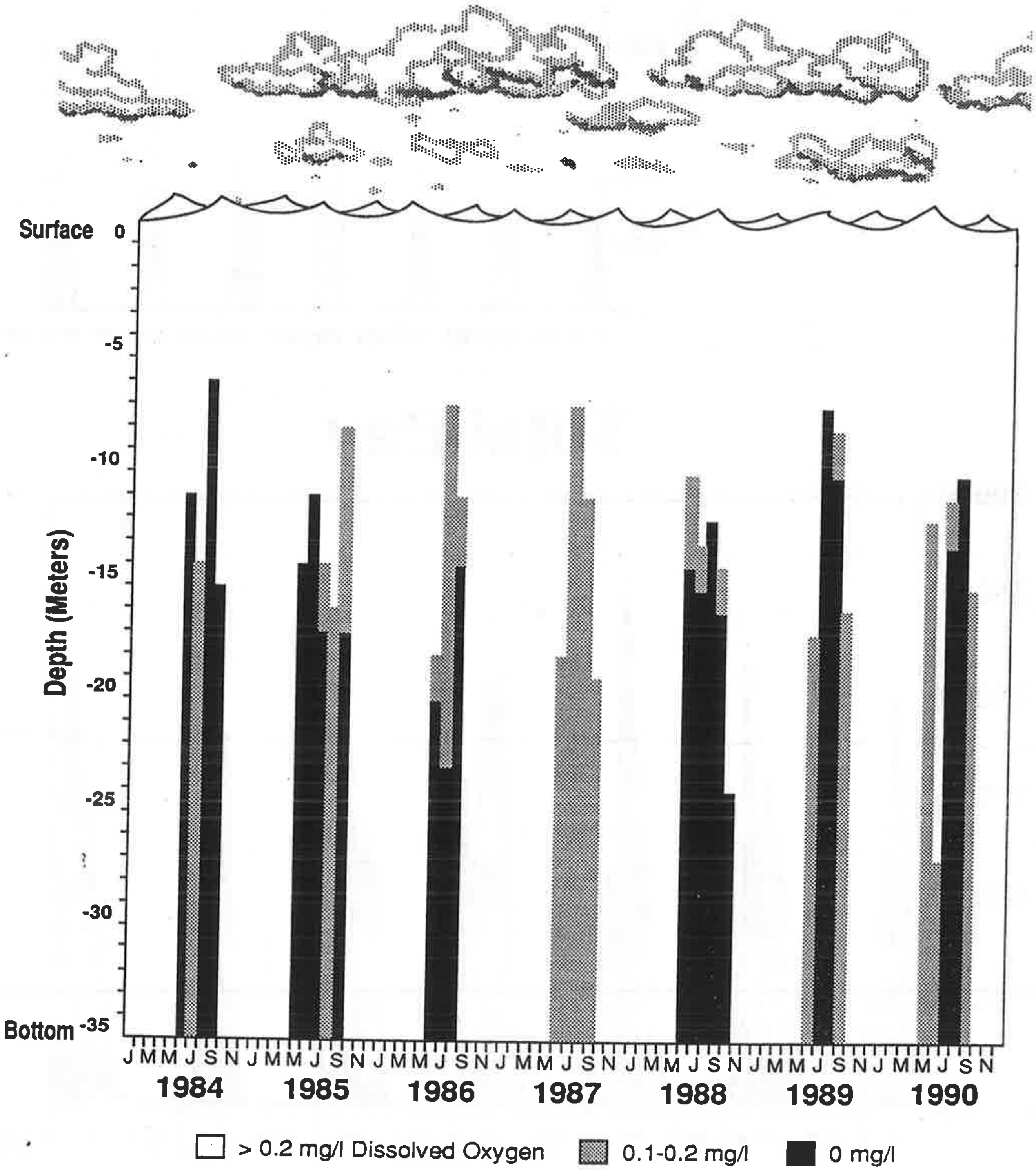

Figure 8. Anoxic conditions at Station CB4.1C.

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The extent and duration of low dissolved oxygen are more easily characterized and visualized in terms of the number of "cubic meter days" at particular concentrations (Figure 9). The lowest oxygen concentrations generally occur in the deepest parts of the Bay. These graphs show that appreciable water masses, with concentrations under 1 and 0.2 mg/l, occurred in segments CB3 through CB5. The volume of water in each of these two concentration categories has generally increased over time in segment CB4 and varied without distinct trend in segments CB3 and CB5. Water volumes with less than 3 mg/l occurred in CB2 through CB7; these volumes generally increased in segments CB5 through CB7. Water volume with concentrations under 5 mg/l tended to decrease in the upper Bay segments down through segment CB5 and increase in the lower Bay segments. The Bay as a whole showed no distinct trend in any of the concentration categories (Figure 9).

The plots of dissolved oxygen deficit for the total Bay showed no definitive trend through time (Figure 10). In the upper Bay, oxygen deficit decreased in segments CB1 and CB2. In segment CB8, oxygen deficit increased, while in segments CB3 through CB7, oxygen deficit was variable without distinct trends (Figure 10).

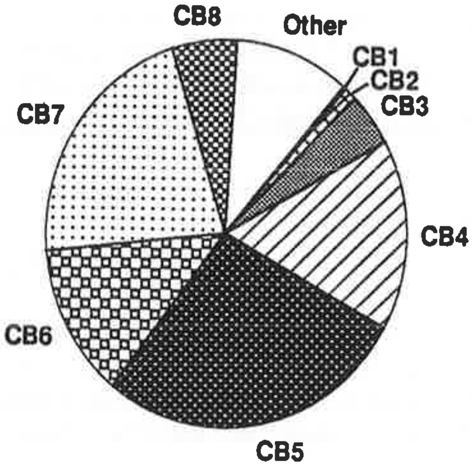
Dissolved Oxygen Trends and Other Water Quality Parameters

The causes of the apparent trends are not clear. Because dissolved oxygen levels depend on so many factors, relating dissolved oxygen to nutrient loadings, freshwater flow, or any individual factor is likely to be unsuccessful. Nevertheless, it is helpful to consider concurrent trends in some of the possible contributing factors.

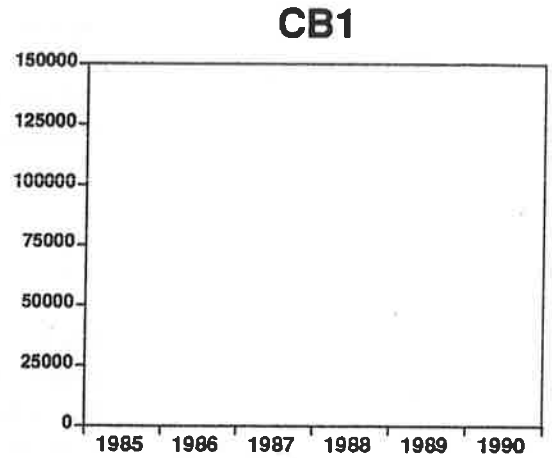
Average water temperature calculated with the interpolator, showed a general increase since the beginning of the Monitoring Program (Figure 11). The increase was primarily attributable to warmer winter temperatures, although summer temperatures have increased slightly as well. Average salinity showed freshening trends of varying degree in most segments (e.g., segments CB4 and the total Bay, Figures 12 and 13, respectively). This finding is surprising, considering the general decrease in freshwater Susquehanna River flow over the period (Figures 5 and 14). Decreases occurred in all but the winter seasons and do not seem to be correlated with changes in seasonal freshwater inflow. Spring rains and melting snow typically raise Susquehanna flow in March and April. The spring pulses have decreased in volume over the years since 1984 (Figure 14) and they have occurred somewhat later in the season in recent years. The flow regime in the Susquehanna, however, may not reflect flows of the major lower Bay tributaries.

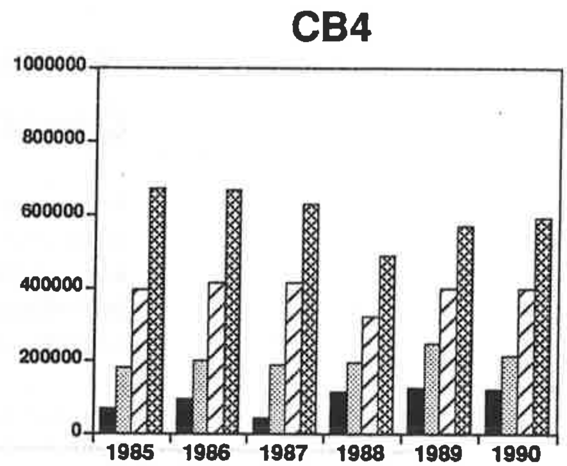
The depth of the pycnocline is affected by flow and salinity. In segment CB4, for example, within the summer season of an individual year, the depth of the pycnocline varied inversely with salinity; that is, the pycnocline was found deeper in the water column as salinity increased (Figure 15). However, between years, the average depth of the pycnocline tended to vary directly

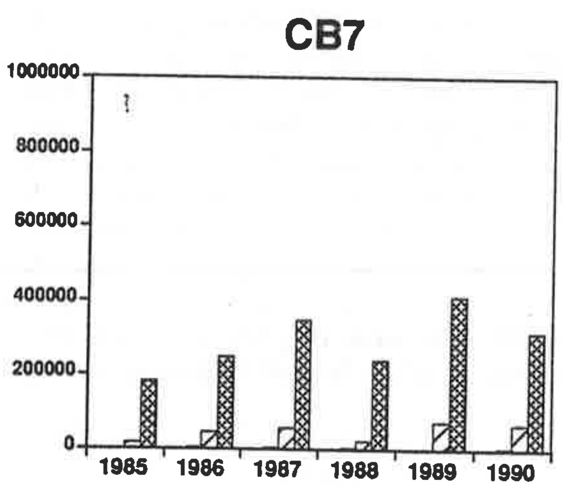
Cubic Meter Days o.

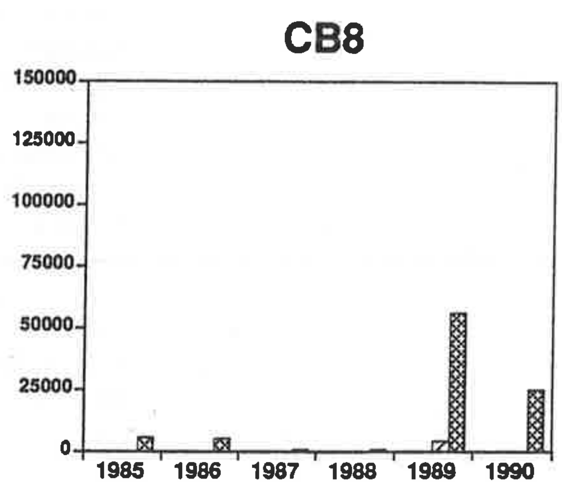


Relative Volume of Water in Bay Segments

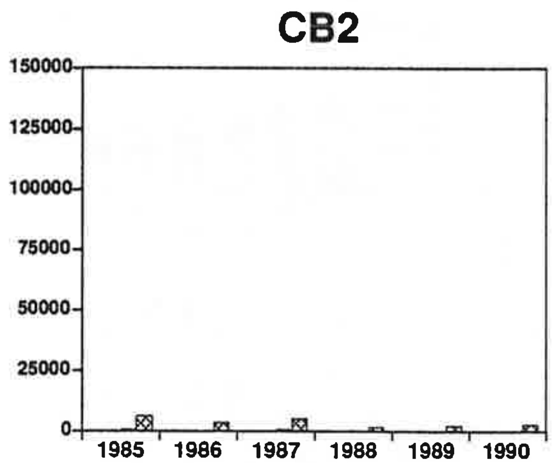


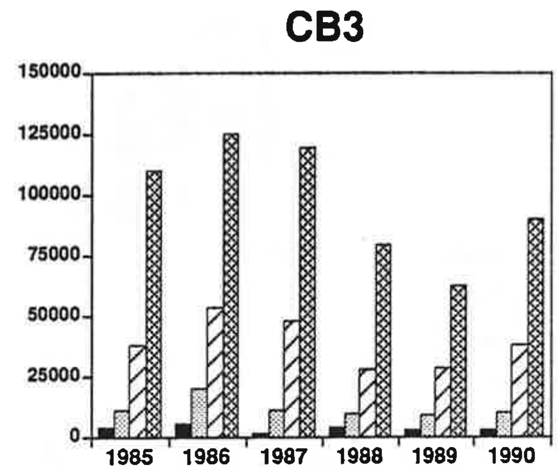


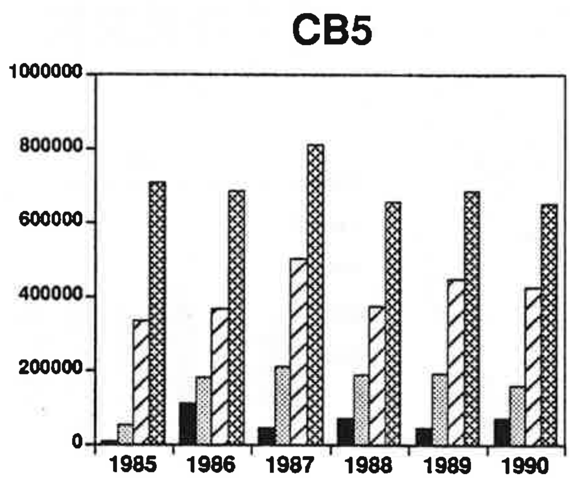


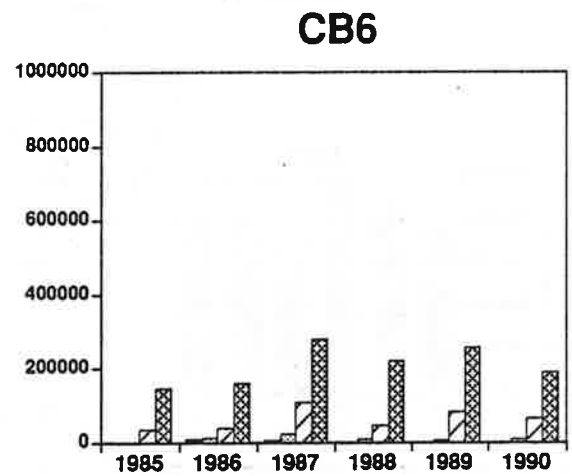


Low Dissolved Oxygen









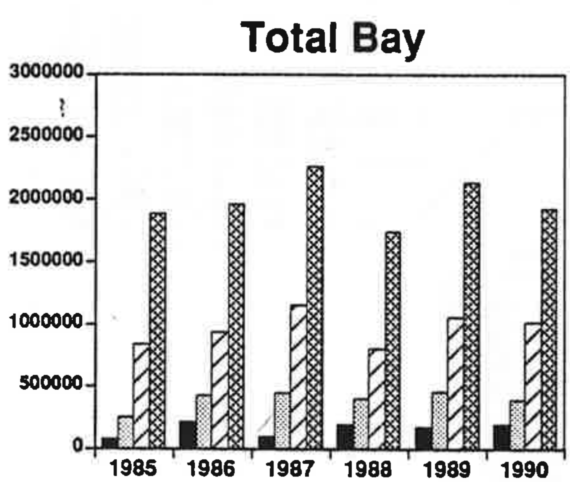


Figure 9. Cubic meter days of low dissolved oxygen.

- Below .2
- Below 1
- Below 3
- Below 5

Dissolved Oxygen Deficit

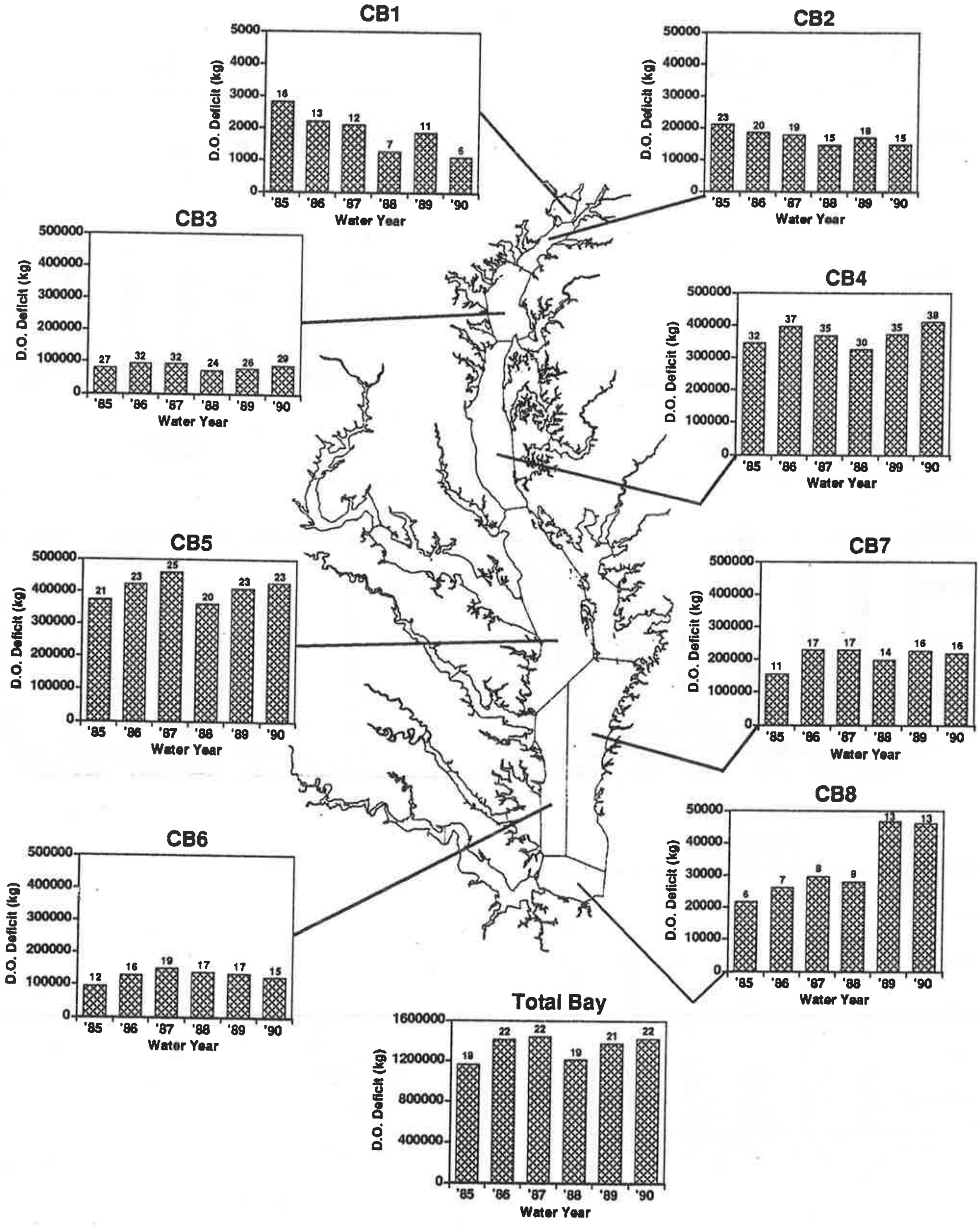


Figure 10. Total oxygen deficit mass summed over each water year. The numbers above the bars indicate the deficit as a percentage of potential dissolved oxygen mass at saturation.

Figure 11. Average temperature in Chesapeake Bay from June 1984 through September 1990.

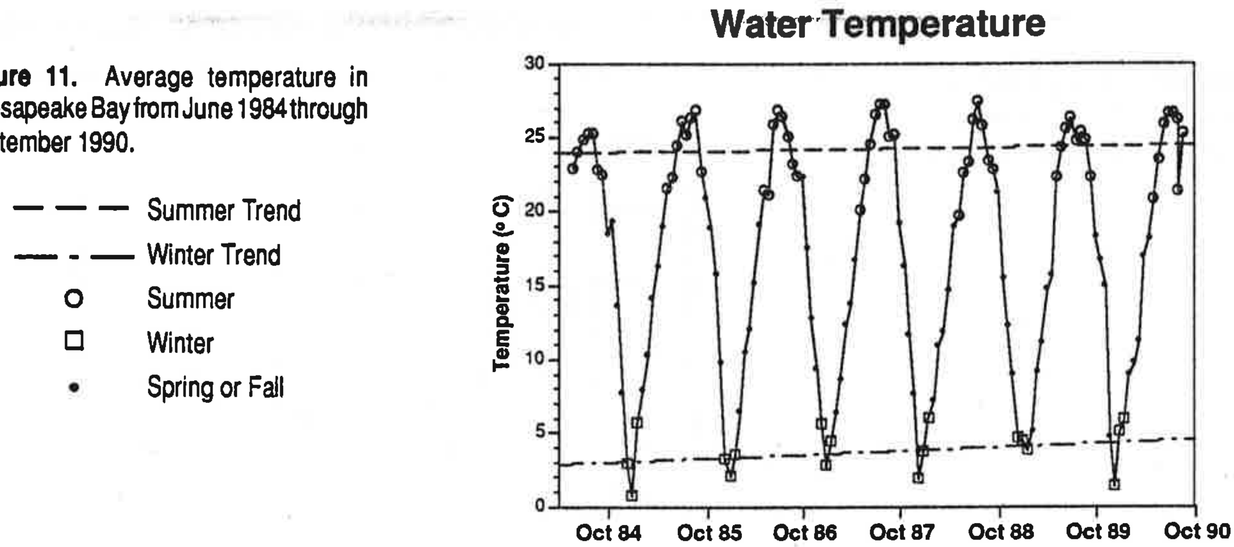


Figure 12. Summer salinity in Segment CB4.

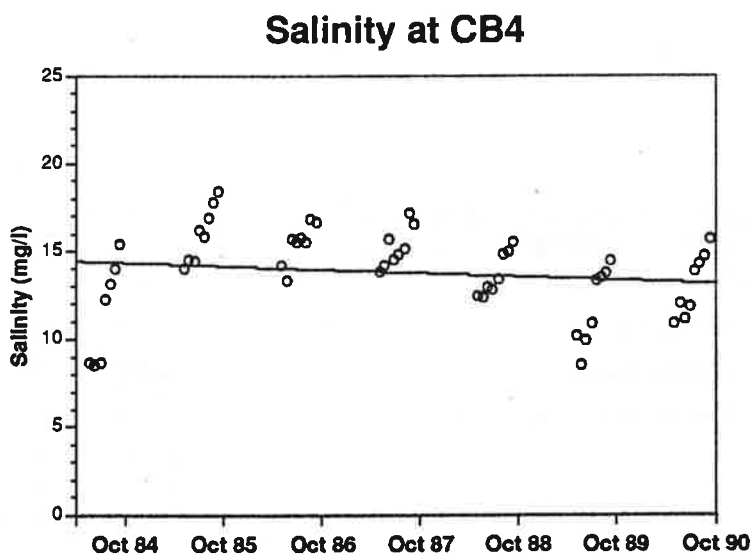
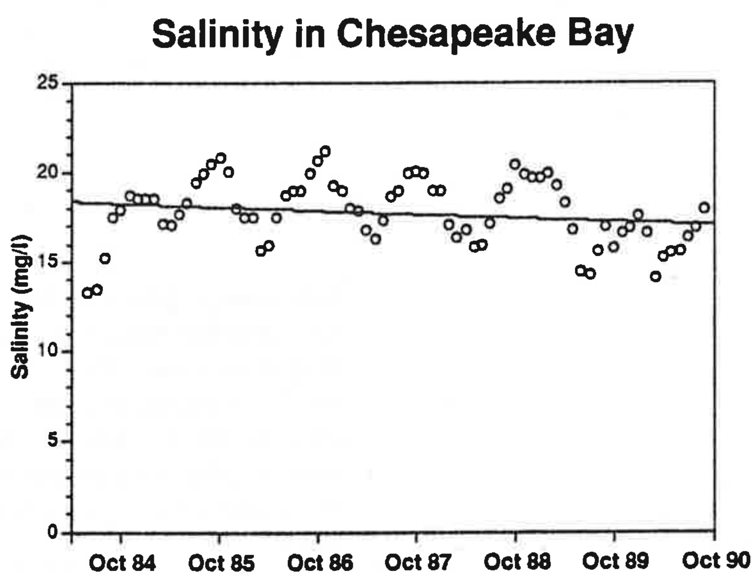


Figure 13. Average monthly salinity in Chesapeake Bay (Trend line computed using data from October through September 1990).



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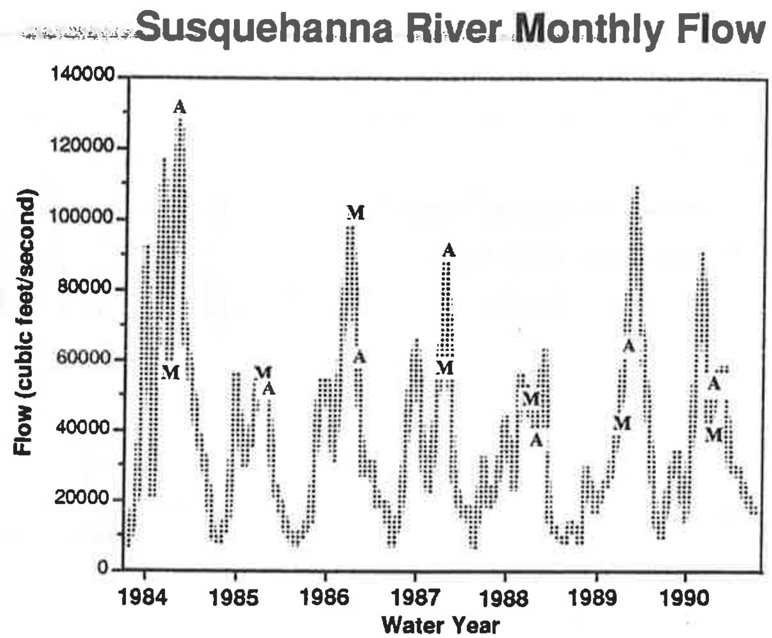

Figure 14. Average monthly Susquehanna River flow from January 1984 through September 1990.

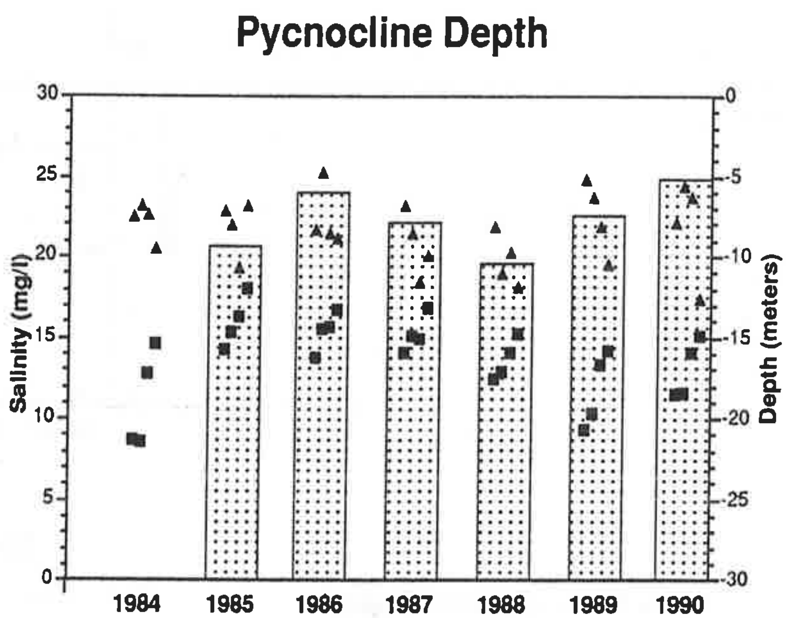

Figure 15. An example of the change in depth of the pycnocline with changes in salinty.

▲ Pycnocline Depth

■ Summer Salinity

▩ Oxygen Deficit Mass

with salinity. Lowering the depth of the pycnocline reduces the volume of subpycnocline water, theoretically lessening the volume of water subject to oxygen depletion. Since oxygen deficit is the measure which accounts for the effect of temperature and salinity on oxygen saturation, it possibly could show the effect of differences in pycnocline depth alone. Oxygen deficit in segment CB4 does appear to parallel yearly changes in pycnocline depth; the oxygen deficit is higher when the pycnocline is shallower and vice versa (Figure 15).

Production of new organic material (primary production) in the Bay, as indicated by chlorophyll *a*, was highest in the spring and early summer most years (Figure 16). Spring "blooms" were observed in at least a few segments every year except in 1989. (Either there was no spring bloom that year or it was missed by the Monitoring Program). Interestingly, 1989 was among the worst years for dissolved oxygen since the Program's beginning, as gauged by most measures used in this analysis. A relationship between primary production and trends in dissolved oxygen is otherwise difficult to establish in these data. Additionally, because chlorophyll *a* is highly variable in both time and space, the error associated with interpolator estimates is likely to be higher than for other parameters.

What The Results Mean

This volumetric analysis shows that the amount of hypoxic and anoxic water varies with hydrologic condition. Under the conditions existing since the Monitoring Program began, anoxic waters have appeared each summer.

The volume of hypoxic and anoxic waters in the Bay is vitally important, as is the concentration of dissolved oxygen. However, oxygen deficit is a better measure of trends in dissolved oxygen, since it compensates for the direct effects of upbay-downbay gradients in temperature and salinity as well as seasonal and annual differences. The apparent opposite trends in oxygen deficit in upper and lower Bay segments are particularly interesting. However, the affected segments (CB1 and CB2 in the upper Bay and CB8 in the lower Bay) are small relative to the others (Figure 1) and the magnitude of change in oxygen deficit is also relatively small.

One question central to the trend analysis is whether the sampling frequency of the Monitoring Program is sufficient to capture the spatial extent and duration of hypoxia and anoxia in Chesapeake Bay. This topic is discussed in more detail in Appendix A and only briefly here.

Experimental data from remote sensing buoys positioned near the Bay bottom suggest that individual subpycnocline locations can experience large variations in dissolved oxygen over short periods. This is due largely to horizontal movement of water masses of different oxygen content, vertical movement of the pycnocline, or irregular re-aeration events, such as storms. Nevertheless, comparisons of such continuous data with Monitoring Program data from the same region yield similar measures of average conditions (Figure 2, Appendix A). The extent of the Monitoring Program's geographic coverage can apparently compensate, in large part, for a lesser sampling frequency by adequately assessing dissolved oxygen in the spatially variable but temporally stable water masses of a region. Short-lived changes which might be caused by storms destratifying a region of the Bay, however, are likely to be missed by Monitoring Program sampling. Such events have important, immediate ecological effects, but their effect on trends is likely negligible. The findings encourage confidence in the use of Monitoring Program data to estimate long-term trends.

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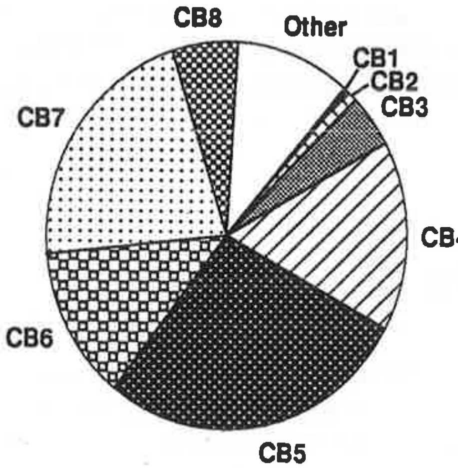
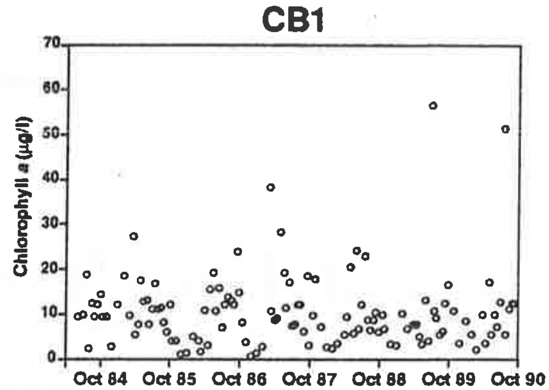
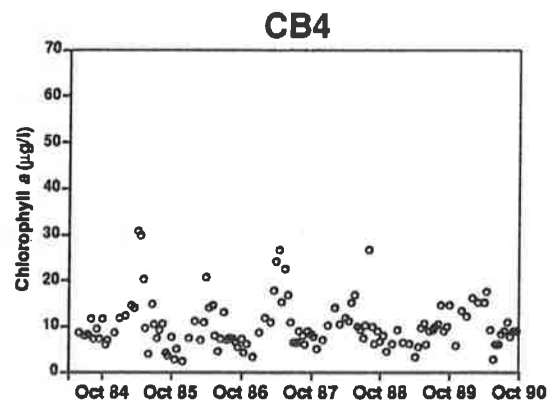
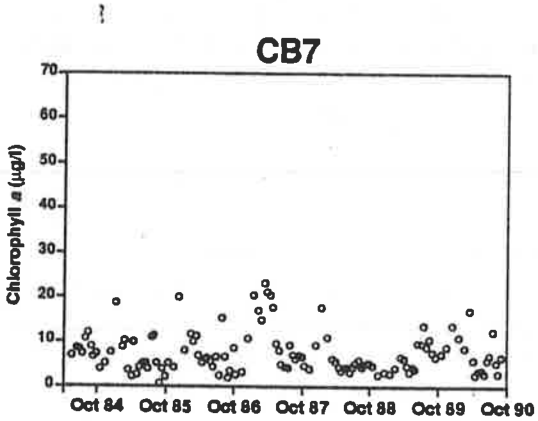
Chlorophyll *a*

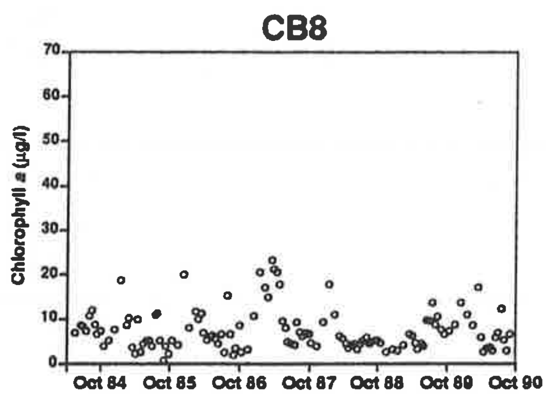


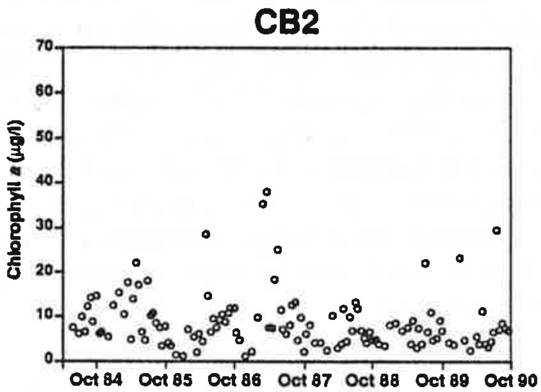
Relative Volume of Water in Bay Segments

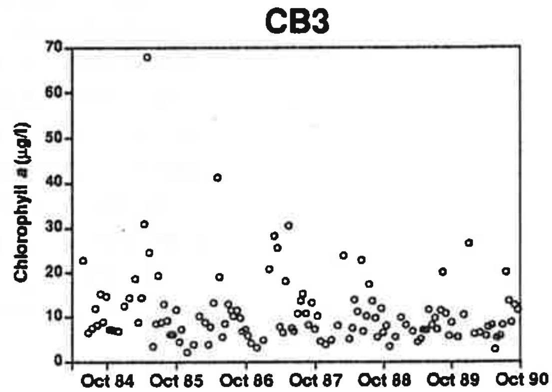


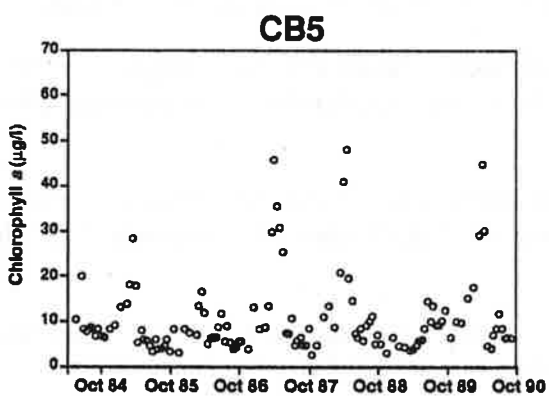


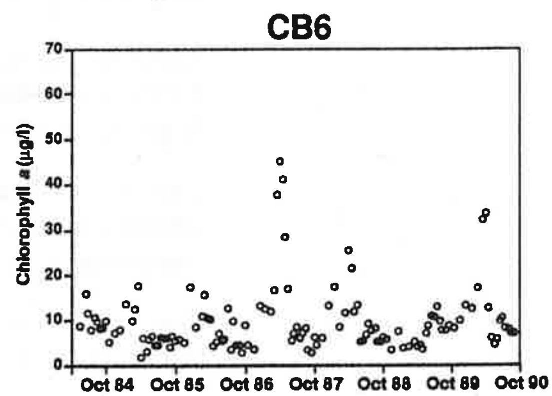












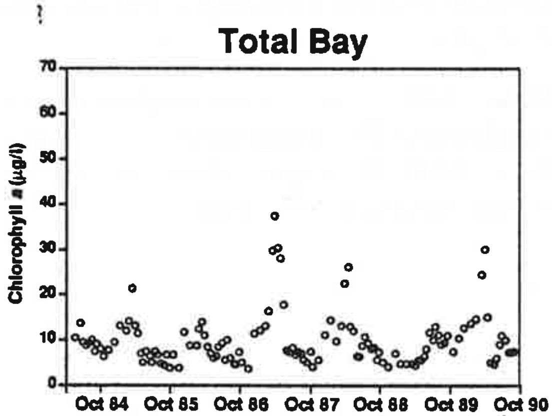


Figure 16. Chlorophyll *a* in Chesapeake Bay.

Conclusions

The trends in dissolved oxygen described by the different measures are consistent with one another, suggesting that the volume of water with low dissolved oxygen has increased from 1950 to 1990. Since 1984, the average dissolved oxygen concentration decreased slightly over most of the Bay, with some improvement in upper Bay segments. Oxygen deficit declined in upper segments, increased in the lower Bay, while the major portion of the segments exhibited considerable interannual variability with no discernible trend. The extent and duration of hypoxic and anoxic conditions in the deep regions of the middle Bay showed no trend. Although significant reductions in phosphorus levels have been achieved, corresponding improvements in dissolved oxygen have not yet been seen.

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Appendix A

Semi-Continuous Oxygen Records
and Dissolved Oxygen
Measured by the Chesapeake Bay
Water Quality Monitoring Program

Introduction

Low levels of dissolved oxygen are a major concern in Chesapeake Bay. The extent and duration of low dissolved oxygen directly affect the Bay's living resources, requiring that they be accurately assessed to monitor trends and progress in the restoration efforts.

Modern remote-sensing devices allow the collection of relatively long-term semi-continuous or close-interval oxygen data. These records have revealed unexpected scales of variation—large fluctuations in dissolved oxygen over days and even hours. Dissolved oxygen is measured routinely in the Chesapeake Bay Water Quality Monitoring Program; however, these measurements represent momentary conditions at a single point. During the summer, when sampling is most frequent, measurements are made twice monthly.

Dissolved oxygen data from semi-continuous datasets were compared to that collected under the Monitoring Program to evaluate the program's estimates.

Semi-Continuous Dissolved Oxygen Data

In recent years, several investigators have collected close-interval dissolved oxygen data in Chesapeake Bay (Mountford et al. 1989; Breitburg 1990; Sanford et al. 1990; Diaz et al. in press; R. Summers (Maryland Dept. of Environment); S. Weisberg (Versar)). The Sanford data were best suited for this comparison because they provided synoptic records at four locations in the vicinity of Monitoring Program stations (Figure 1). In addition, these locations were in the middle Bay where low dissolved oxygen is a chronic problem.

Buoys bearing the monitoring devices were deployed for 28 days—from August 12 to September 9, 1987. At each location (each differing in total depth), a sensor was fixed approximately 1 meter off the bottom. At the westernmost site, a second meter was fixed at approximately mid-depth. Sanford used Endeco (R) pulsed sensors to record dissolved oxygen, temperature, and salinity every 5 or 15 minutes, depending on the site. To standardize the datasets for this comparison, only data at 15-minute intervals were used. The depths thus monitored were two at 6 meters and one each at 9, 13, and 19 meters. The 6-meter data from the site inside the Choptank River were omitted so that there were an approximately equal number of observations at each depth. Figure 1 shows the time-series records from each site.

Remote-Sensing Locations and Monitoring Program Stations

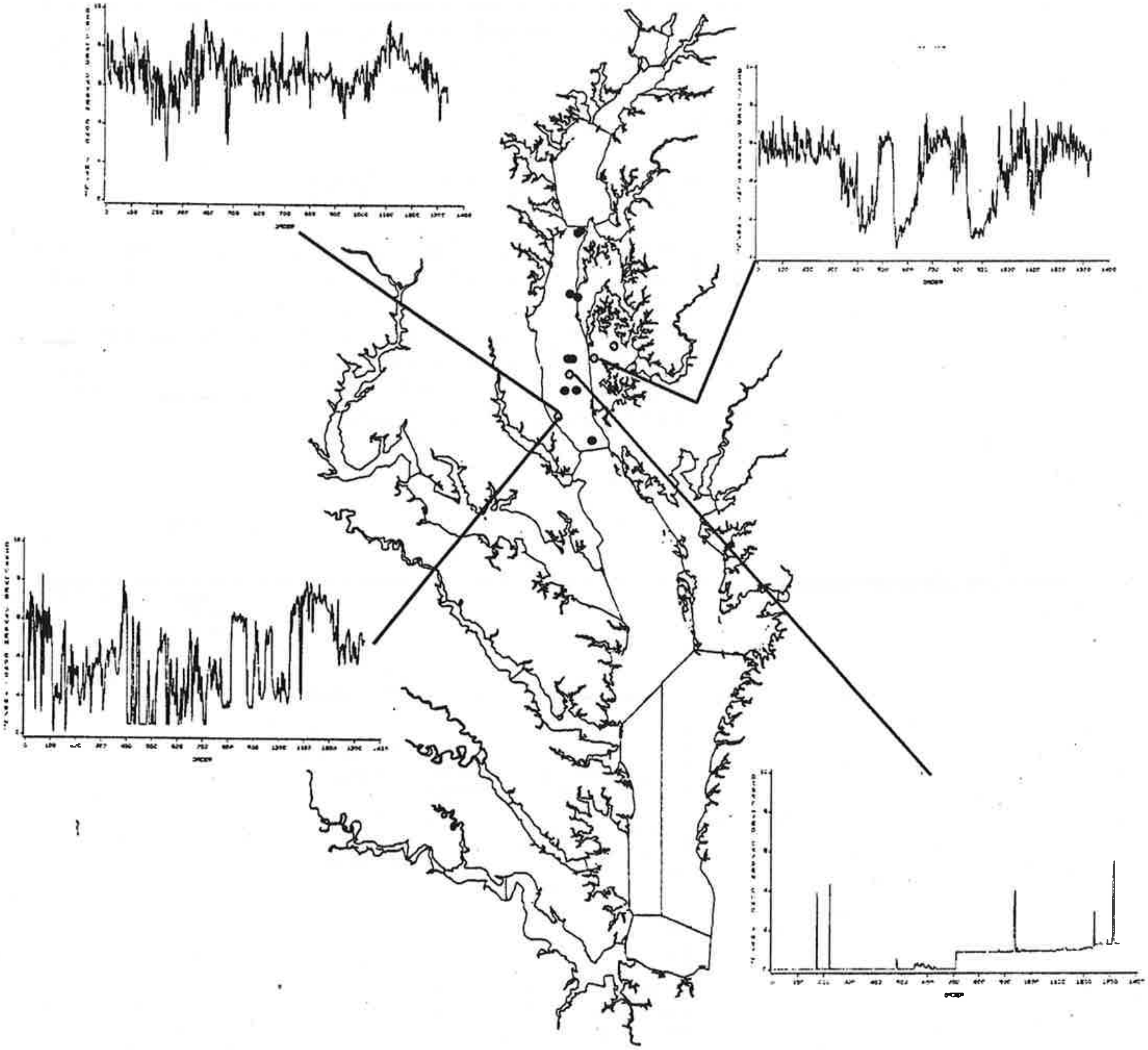

Figure 1.
Grey Dots = Remote-Sensing Sites
Black Dots = Monitoring Stations Used inthe Comparison

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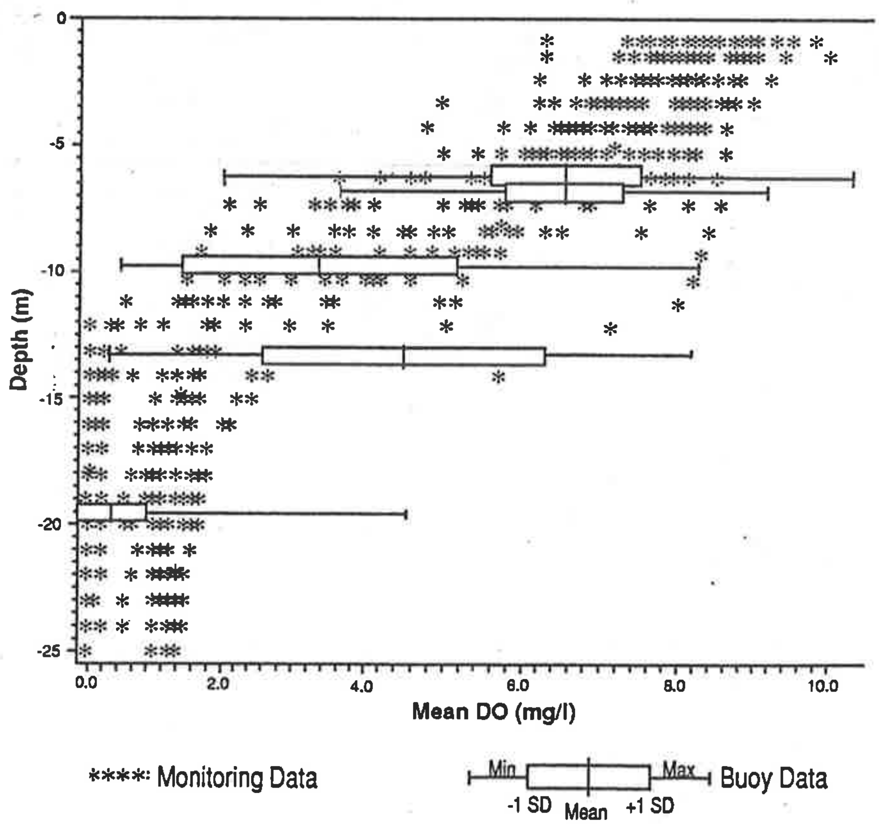
Dissolved Oxygen Data from the CBP Monitoring Program

Monitoring Program data used in the comparison consisted of measurements collected at stations deeper than 19 meters in segment CB4 (stations CB3.3C, CB4.1C, CB4.1E, CB4.2C, CB4.3C, CB4.3E, and CB4.4 shown in Figure 1) on routine monitoring cruises, August 16-17 and September 2-3, 1987. These cruises took place during the same time the Sanford buoys were deployed. In the Monitoring Program protocol, dissolved oxygen is typically measured at one- to two-meter intervals between the surface and bottom at each station.

Comparison of the Datasets

The dissolved oxygen profile data from the buoy records were averaged and the mean concentration, standard deviation, minimum and maximum concentrations at each depth were plotted (Figure 2). Means over seven Monitoring Program stations over the two cruises during the same time period were overlayed as asterisks for comparison. The buoy data occurred during the period of August 16 to September 3, 1987 and the monitoring cruises were August 17-18 and September 2-3, 1987.

Figure 2. Comparison of monitoring data and buoy data.



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The statistics for the semi-continuous data at 6, 9 and 19 meters closely matched those for comparable depths at the Monitoring Program stations. Minima and maxima of the semi-continuous data exceeded those of the Monitoring Program data. The standard deviations were also of approximately the same magnitude (Table 1).

Table 1. Comparison of continuous and Monitoring Program dissolved oxygen datasets.

Depth	Number of CON Observations	Number of MON Observations	Average D.O. CON	Average D.O. MON	Standard Deviation CON	Standard Deviation MON	Minimum D.O. CON	Minimum D.O. MON	Maximum D.O. CON	Maximum D.O. MON
6m	2672	42	6.7	6.5	1.0	1.4	1.9	2.0	9.7	8.6
9m	2672	42	3.8	4.5	2.0	1.7	0.0	1.4	8.1	8.4
13m	2659	42	4.7	1.7	1.7	1.5	0.4	0.1	8.1	7.1
19m	2671	41	0.6	0.8	0.6	0.6	0.0	0.1	5.5	1.7

CON = Continuous Monitoring Sample
MON = Monitoring Program Dissolved Oxygen Sample

The data from the sensor moored on the eastern side of the Bay at 13 meters did not have the same characteristics as the 13-meter data from the Monitoring Program. The bottom at the eastern location apparently experienced more aeration (i.e., the mean dissolved oxygen concentration of the continuous data was considerably higher than the mean from the Monitoring Program at that depth). The 13-meter depth is approximately the depth of the pycnocline in that region of the Bay and may alternately show characteristics of above or below pycnocline environment. The 13-meter data from the Monitoring Program are more like those from below the pycnocline; the data from the continuous monitor may be more like areas above the pycnocline.

Discussion

In the middle region of the Bay, where these data were collected, the average depth of the pycnocline is usually between 6 and 12 meters during the summer. Areas in the shallow littoral zone where the bottom deepens to 6 meters or greater are subject to the intrusion of higher salinity, subpycnocline waters from the deep channel. Waters below the pycnocline typically have little or no dissolved oxygen for much of the summer. Movement of these oxygen-depleted bottom waters into shallower areas occurs when wind-forcing of surface water causes the pycnocline to tilt. Such episodes may last from a few hours to several days. The sharp spikes and troughs in the semi-continuous records shown in Figure 1 are signs of these ephemeral intrusions.

Breitburg (1990) addressed the problem of dissolved oxygen variablity as it relates to the monitoring and assessment of nearshore benthic habitats. She found that measurements taken at the frequency of the Monitoring Program were unlikely to adequately assess low dissolved oxygen exposures at particular sites. However, the comparisons above suggest that the Monitoring Program data do provide an adequate assessment of bottom dissolved oxygen conditions on a regional basis. The spatial coverage of the Monitoring Program station network in this portion of the Bay can apparently compensate for a lesser sampling frequency. The various water masses of differing dissolved oxygen content—the source of deepwater variability at individual sites—are represented within the sampling station design. The extreme conditions within a region to which a particular site *may* be exposed are identified for the most part. However, the minima and maxima of the continuous data—the result of short-lived events—exceeded the minima and maxima of the Monitoring Program data.

Semi-continuous records from different locations in the Bay and different time periods have been acquired recently and further analysis is underway. In the meantime, the comparison with the semi-continuous data has encouraged confidence in using Monitoring Program data to look at status and trends in dissolved oxygen regionally and Baywide.

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