EXAMINATION OF THE SPATIAL AND TEMPORAL NATURE OF HYPOXIA IN TAMPA BAY, FLORIDA

Prepared for:

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FOREWORD

This report was prepared by Janicki Environmental, Inc. under the direction of Mr. Dick Eckenrod and Ms. Holly Greening of the Tampa Bay Estuary Program. This work was performed under Contract No. T-98-06 for the Tampa Bay Estuary Program.

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INTRODUCTION

Depletion of dissolved oxygen (DO) in some portions of Tampa Bay has been a matter of concern for those involved with restoring the ecological health of the bay. Within the past several years, concerns have been expressed regarding the possibility of an increase in the area of the bay subjected to low DO concentrations during portions of the year. To understand why these concerns exist, a description of the mechanisms of DO supply and uptake in the water column is necessary.

Biological processes both supply and remove DO from the water column. Primary production typically results in elevated DO levels in surface waters during daylight hours. Respiration needs during dark periods result in decreased DO levels throughout the water column, with the lowest DO concentrations typically found near the end of the dark period, just prior to the resumption of daytime primary production.

The diel variability in DO concentrations in the water column is a function of the daily rate of DO supply and consumption. The rate of DO supply depends largely upon the rate of primary production. The rate of primary production is a function of the rate of nutrient supply to the euphotic zone. As the nutrient supply rate increases, primary production typically increases. Increases in primary production lead not only to daytime increases in the supply rate of DO to the euphotic zone, but also to increases in algal biomass (organic matter) in the water column. During dark periods, respiration by the primary producers and consumers occurs when the supply rate of oxygen is at its lowest. The organic matter resulting from primary production constitutes a food source for decomposers, which consume oxygen in the water column, the sediment, and at the sediment-water interface. As the rate of organic matter supply increases, respiration increases, and the rate of oxygen consumption increases.

Variations in DO concentrations also occur on a seasonal time scale. In the Tampa Bay region, nutrient supply rates are typically greatest during the summer months, when rainfall is greatest. Algal biomass and primary productivity are correspondingly greater during this period than during other times of the year. Associated with the higher primary productivity is increased elaboration of organic matter and increased oxygen demand for respiration. As expected, variations in DO levels are typically greatest during the summer.

Especially during the summer, other factors also play a role in the variations in DO levels in the bay. In addition to the increases in DO supply and consumption rates, physical factors also influence the variations in DO concentrations. The warmer waters of the bay during the summer hold less DO than do colder waters. Physical factors can also contribute to isolation of bottom waters from mixing with oxygenated near-surface waters. The likelihood of bottom water isolation increases when large freshwater loading events occur. The freshwater overlies the deeper more saline water, increasing the potential for the water column to stratify. Stratification serves to isolate bottom waters from mixing with oxygenated surface waters. Diffusion of DO through the water column is also impeded by the density gradient, so that the more saline bottom waters are not re-supplied with oxygen as rapidly as if no density gradient existed. The supply of oxygen in the bottom waters can become depleted.

The concerns directing this report are that anthropogenic influences on external nutrient and hydrologic loads may be great enough to result in more extreme DO conditions than expected from natural processes. Development of the Tampa Bay watershed has lead to increases in nutrient loading compared to historical conditions (Zarbock et al., 1994). The magnitudes of the hydrologic loads during the current and historical periods are similar, but the timing of the hydrologic loads has been modified by development (Zarbock et al., 1995). Similar rainfall events result in greater rates of freshwater supply over shorter time periods under developed conditions than under historical conditions.

The specific objective of this report is to provide an evaluation of the spatial and temporal nature of hypoxia in Tampa Bay. Hypoxic conditions are commonly defined as existing when DO concentrations fall below 2 mg/L (Ritter and Montagna, 1999), although hypoxia is sometimes defined as less than 2 mg/L or less than 3 mg/L (NOAA, 1998). For the purposes of this evaluation, hypoxia is defined as concentrations of DO <2 mg/L. In Tampa Bay, it has been found that the number of fish species and abundance of fishes in estuarine portions of tributaries to the bay tend to be reduced at DO levels below 4 mg/L (SWFWMD, 1999). Given this information, some analyses were also performed in relation to DO concentrations <4 mg/L.

To satisfy this objective, a series of specific questions are addressed that assess the temporal and spatial nature of hypoxia in Tampa bay. These questions are as follows:

- What monitoring programs measure bottom DO and how is bottom DO measured by each program?
- During what times of year are bottom DO concentrations typically lowest?
- Where does hypoxia typically occur, and what makes these areas different from other areas in the bay?
- What is the areal extent of hypoxia in Tampa Bay?
- Has the areal extent of hypoxia in Tampa Bay changed over time?

- What are the major factors that affect the variation in the areal extent of hypoxia in Tampa Bay?

- Is there a relationship between mid-day and minimum DO?

- Are mid-day data adequate to identify areas where hypoxic conditions occur during the rest of the day?

- How persistent are hypoxic conditions in Tampa Bay?

- Are there long-term trends in bottom DO concentrations in Tampa Bay?

Descriptions of hypoxia in estuarine waters and the biological consequences of hypoxia follow. The remaining sections of this report address each of the questions identified above.

HYPOXIA IN ESTUARINE WATERS

The spatial and temporal nature of hypoxia is determined by the interaction of the biological and physical processes described above with the physical characteristics of the estuary and the degree of anthropogenic influence on these processes and physical characteristics. The following describes how these interactions determine the spatial and temporal nature of hypoxia in estuarine waters.

Increases in DO concentrations in estuarine waters occur primarily as the result of two processes;

- primary production, and
- the transfer of oxygen across the air-water interface.

Primary production by estuarine algae releases DO into the water column while creating organic matter. The rate of primary production is dependent upon the algal biomass and the nutrient supply rate. As the rate of nutrient supply increases, primary production rate and algal biomass also increase, resulting in increased DO supply during the daylight period. As algal biomass increases, the euphotic zone becomes shallower, so that the oxygen generated by high primary productivity is released to the near-surface portion of the water column.

Oxygen is also supplied to surface waters from the atmosphere. The rate of supply is largely a function of wind speed and water temperature. Higher wind speeds provide more mixing of the water column, exposing a greater water volume to the air-water interface and mixing DO deeper into the water column. Colder water holds more DO than does warmer water, so that water temperature is an important factor in oxygenation. These physical processes typically supply oxygen to the near-surface portions of the water column.

Oxygen in surface waters, originating from both primary production and air-water exchange, is transferred to the remainder of the water column by diffusion and vertical mixing processes. Diffusion occurs from portions of the water column with relatively high DO concentrations to those with relatively low DO concentrations, and is a relatively slow process. Mixing results from wind events, tidal action, and water density instabilities, and can supply oxygenated waters to deeper portions of the water column relatively rapidly.

Oxygen is consumed primarily through respiration in the water column. Respiration by both primary producers and consumers occurs at all times. Respiration during dark periods, when oxygen generation is lowest, results in DO consumption rates greater than the supply rate. The organic matter supply resulting from primary production results in a demand for oxygen throughout the water column.

The transfer of oxygen through the water column can be impeded by stratification. Stratification occurs when a vertical density gradient forms, as typically occurs following large freshwater inflow events, with the less dense freshwater overlying the more dense saline water of the estuary. Diffusion of DO through the water column is impeded by the density gradient, so that the more saline bottom waters are not re-supplied with oxygen as rapidly as if no density gradient existed.

Bathymetry also affects the likelihood of occurrence of hypoxic conditions. Deeper portions of an estuary are often more susceptible to low DO conditions, especially those isolated from water exchange via normal tidal mixing and from exchange with the upper water column because of stratification effects. Stratification effects are not only a function of vertical salinity differences, but of vertical temperature differences as well. Even when vertical salinity differences are low, stratification of the water column may occur when bottom waters are cooler than surface waters. Deeper portions of an estuary are likely to show greater surface to bottom salinity and temperature differences, impeding the exchange of DO between the surface and bottom waters. Biological processes, described above, can remove DO from the bottom of the water column at a greater rate than that of DO re-supply, resulting in low DO conditions.

Both natural and anthropogenic factors contribute to the likelihood of hypoxia, either through increasing the likelihood of bottom water isolation or increasing the rate of respiration. Natural factors include bathymetry, the fetch and direction of winds, and the ratio of the area of the watershed of the receiving water body to the volume of the receiving water body. Anthropogenic factors include hydrologic changes in the watershed, modified bathymetry from dredging, and accelerated nutrient supplies from anthropogenic activities.

As discussed above, deeper waters have a greater chance of being stratified, in general, than do shallower waters. The interaction of the bathymetry with the fetch and wind speed determines the effective mixing depth of the water column. As wind speed and fetch increase, the mixing depth increases, so that stronger winds over longer fetches result in deeper mixing of oxygenated surface waters.

The size of the watershed in relation to the volume of the receiving water body, and the magnitude of the freshwater inflows from the watershed to the water body, also affects the likelihood of low DO conditions. When relatively large volumes of freshwater, and the associated nutrient loads, from a large watershed drain to a relatively small receiving water body, the chances of low DO conditions occurring are increased due to the increased likelihood of stratification effects and increased production of organic matter. The stratification resulting from a freshwater lens overlying the more saline bottom water can lead to low bottom DO conditions by effectively isolating the bottom waters from oxygenation. Concurrently, the high productivity in response to the nutrient loads generates organic matter that sinks to the bottom waters, where decomposition consumes the DO. This combination of isolation of bottom waters from oxygenation and consumption of DO in the bottom waters can lead directly to hypoxia.

Anthropogenic factors are those that affect the likelihood of the establishment of stratified conditions that isolate bottom waters, and those that affect the rate of consumption of DO in the bottom waters. Hydrologic changes in the watershed leading to increased freshwater supply rates to the receiving water body are often associated with development. Also associated with development are bathymetric alterations, such as channel dredging and dredge-and-fill canal systems. Deeper waters in dredged channels are less likely to be exposed to surface oxygenation through wind-induced mixing. Similarly, bottom waters in dredge-and-fill canal systems may be less prone to wind-induced mixing, given the narrowness and depth of the canals. Locally, areas affected by dredging activities may also have increased residence times and associated decreased flushing rates, as deeper waters may be isolated from tidal flushing effects and resupply of oxygenated waters.

Of primary concern in most estuaries, however, are the effects of anthropogenically-derived nutrient over-enrichment due to accelerated nutrient supply (NRC, 2000; Turner and Rabalais, 1994). Increased rates of nutrient supply often result from land use changes associated with development, increased atmospheric deposition of nutrients associated with anthropogenic activities, and point source discharges, such as those from waste water treatment facilities. Increased nutrient supply rates can result in increased formation of organic matter, increased oxygen demand for decomposition of the organic matter throughout the water column, and low DO levels in bottom waters, where oxygen supply rates are slowest. In concert with the increased likelihood of stratification associated with the formation of a freshwater lens, increased nutrient supply from hydrologic events can lead to low bottom DO levels which persist because of the stratification.

BIOLOGICAL CONSEQUENCES OF HYPOXIA IN ESTUARINE WATERS

Estuarine communities that experience periodic hypoxic conditions of relatively short duration exhibit little change during or shortly after hypoxic events, being preconditioned to the stresses of hypoxia, and can be highly diverse. Communities experiencing greater persistence of hypoxic conditions, on the other hand, often contain only early successional stage communities, with less diversity, abundance, and biomass.

Dissolved oxygen concentrations are important determinants of the abundance, composition, and distribution of biota, especially in the benthic community. Reduced DO conditions can result in the modification of migratory patterns of benthic and demersal species, influence growth and recruitment, and result in death of estuarine organisms.

The severity of the biological responses to reduced DO conditions increases as DO levels decline. When DO concentrations reach certain levels, typically around 2 mg/L, motile fauna leave the area of reduced oxygen. Other less motile fauna experience differing levels of stress, dependent upon the oxygen requirements of the organisms. As DO concentrations decline further, larger non-swimming organisms experience increased stress levels, with mortality found below 1.5 mg/L along the western Gulf continental shelf (Harper and Rabalais, 2000). When DO levels reach about 1.0 mg/L along the western Gulf shelf, smaller benthic invertebrates have been observed displaying pronounced stress behavior. Gastropods on the sediment surface extend their siphons upward, bivalves migrate to the sediment surface, and crabs and other motile organisms climb onto elevated surfaces (Harper and Rabalais, 2000). As DO levels decline to near anoxic conditions (0.0 mg/L), benthic invertebrates leave their burrows and lie on the sediment surface. Death occurs when the minimum oxygen requirements of an organism in the low DO area are no longer met.

The intensity and duration of hypoxic events can affect population dynamics, with less temporally severe hypoxia acting as a mechanism for regulating benthic population dynamics (Breitburg, 1992; Dauer et al., 1992; Llanso, 1992). Benthic species show differing sensitivity to reduced DO conditions, with responses varying in relation to the frequency and duration of low DO events. Longer periods of hypoxia typically result in more severe behavioral responses than are found in response to short duration events. The benthic community may experience a shift from long-lived species to shorter-lived species where higher frequency or longer duration events occur (Pearson and Rosenberg, 1978).

The areal extent of hypoxic events also plays a role in the severity of response of benthic species. For those events with relatively small areal extent, motile organisms can more easily find refugia in nearby areas not affected by hypoxia. Recolonization of small areas affected by hypoxia can thus be more rapid than for larger areas.

Reductions in DO concentrations may also result in changes in predator-prey relationships in the water column. Some larval forms of opportunistic species may utilize hypoxic areas as refugia, and may not be affected by shorter duration events (Llanso, 1991). Zooplankton with diurnal vertical migration patterns may be forced to remain near the surface if low DO conditions exist near the bottom, so that increased predation may occur, as documented in Chesapeake Bay (Roman et al., 1993). Decreased grazing pressure on phytoplankton may then result in greater algal productivity, leading to increasing supply rates of organic matter to the lower water column, and even greater reductions in near-bottom DO concentrations. Motile species may remain in or return to hypoxic areas for feeding, if their oxygen requirements are met. Benthic infauna have been observed to move to the sediment surface during hypoxic events (Lllanso, 1992), creating an easily accessible food source for predators able to feed under hypoxic conditions. During extended reduced DO conditions, macrobenthic and burrowing benthic organism populations may decline. The loss of burrowing organisms, and their sediment mixing activities, may alter cycling of nutrients between the sediments and the overlying water column (NRC, 2000).

Recovery from hypoxic events may be rapid. In shallow waters, colonization of habitats following hypoxic events is typically dominated by opportunistic species. In Hillsborough Bay, it has been observed that the timing of the stress-response was stable from one year to the next, with only the magnitude of the recruitment varying from year to year (Santos and Bloom, 1980). Benthic recruitment may be aided by the availability of energy, in the form of organic matter from organisms killed during the hypoxic event, when the duration of hypoxic conditions is short enough to prevent remineralization of the organic matter by microbial processes.

QUESTION 1

What monitoring programs measure bottom DO and how is bottom DO measured by each program?

Bottom DO data are collected by the water quality monitoring programs of four local government agencies as described below.

- **Environmental Protection Commission of Hillsborough County**

The EPCHC has conducted monthly monitoring of ambient water quality in Tampa Bay since 1972, with complete records for most stations since 1974. Monitoring is currently performed at 52 fixed stations in Old Tampa Bay, Hillsborough Bay, Middle Tampa Bay, and Lower Tampa Bay (Figure 1-1). Bottom DO measurements are taken with a Hydrolab, sampling times are typically between 0900 and 1400. The Hydrolab is lowered to the bottom, then raised approximately 0.5 m. The bottom DO measurement is taken after waiting for the Hydrolab readings to stabilize (T. Cardinale, 2000).

Bottom DO data are collected as part of the TBEP Benthic Monitoring Program. Bottom DO data have been collected at benthic monitoring sites in Old Tampa Bay, Hillsborough Bay, Middle Tampa Bay, Lower Tampa Bay, Terra Ceia Bay, and Manatee River since 1993, and in Boca Ciega Bay since 1995. Sampling occurs in September and October, coinciding with the benthic program's sampling for benthos. This late summer period was selected as indicative of benthic conditions during the most stressful period of the year for the benthic community. The locations of the monitoring sites during each year are shown in Figures 1-2 through 1-7. Bottom DO data are collected by lowering the Hydrolab to the bottom, raising the Hydrolab approximately 0.2 m, allowing the readings to stabilize, then recording the measurements (S. Grabe, 2000). Continuous monitoring (fifteen-minute interval) of bottom DO concentrations are made at selected sites in each bay segment in each year.

- **Bay Study Group, City of Tampa Department of Sanitary Sewers**

The Bay Study Group, City of Tampa Department of Sanitary Sewers, performs water quality monitoring as described in the Baywide Environmental Monitoring Report 1993-1999 (TBEP, 1999). Monitoring is performed one to three times per month at 14 fixed stations (Figure 1-8), between morning and mid-afternoon. Monitoring began in 1978. Nine monitoring sites are in the Hillsborough Bay segment. Old Tampa Bay and Lower Tampa Bay contain one monitoring site each, and three monitoring sites are in Middle Tampa Bay. Bottom DO measurements are made using a Hydrolab. The Hydrolab is lowered to the bottom, then raised approximately 0.1 m above bottom, with the bottom DO measurements taken after the reading has stabilized (W. Avery, 2000).

- **Pinellas County Department of Environmental Management**

The PCDEM began monthly water quality monitoring in 1990 at fixed sites, and has monitored 202 sites in the county. Not all sites have been monitored since 1991. Monitoring sites include both freshwater and estuarine sites, with 11 fixed monitoring sites in Boca Ciega Bay, as shown in Figure 1-9. The PCDEM also began sampling in Boca Ciega Bay in 1997 using a probabilistic sampling design for monthly water quality monitoring. In 1997, 13 sites were monitored and in 1998, ten sites were monitored. These sites are shown in Figure 1-10. For both the fixed and probabilistic sampling sites, Hydrolab measurements are made at the surface, mid-depth, and bottom, between morning and mid-afternoon. Bottom DO measurements are taken by lowering the Hydrolab to the bottom, raising the Hydrolab approximately 0.2 m, waiting for the Hydrolab readings to stabilize, then obtaining the measurement (A. Squires, 2000).

- **Manatee County Environmental Management Department**

The MCEMD conducted monthly water quality monitoring (Ambient Water Quality Program - AWP) at a series of fixed stations in Tampa Bay from 1988 through 1994. The AWP monitoring included four sites in Lower Tampa Bay and three sites each in the Manatee River and Terra Ceia Bay (Figure 1-11). All water quality data collected by the AWP were obtained from surface samples. In 1995, the MCEMD discontinued AWP and initiated a monthly water quality monitoring based on a probabilistic sampling design as part of the Regional Ambient Monitoring Program (RAMP). Included in this monitoring effort are four sites in Terra Ceia Bay and five sites in the Manatee River (Figure 1-12). The DO measurements made in this sampling program include measurements made over an entire diel cycle at two stations in each segment in each month (R. Brown, 2000). The bottom DO measurements were made at 0.5 m above the bottom using a Hydrolab continuous recorder (fifteen-minute intervals).

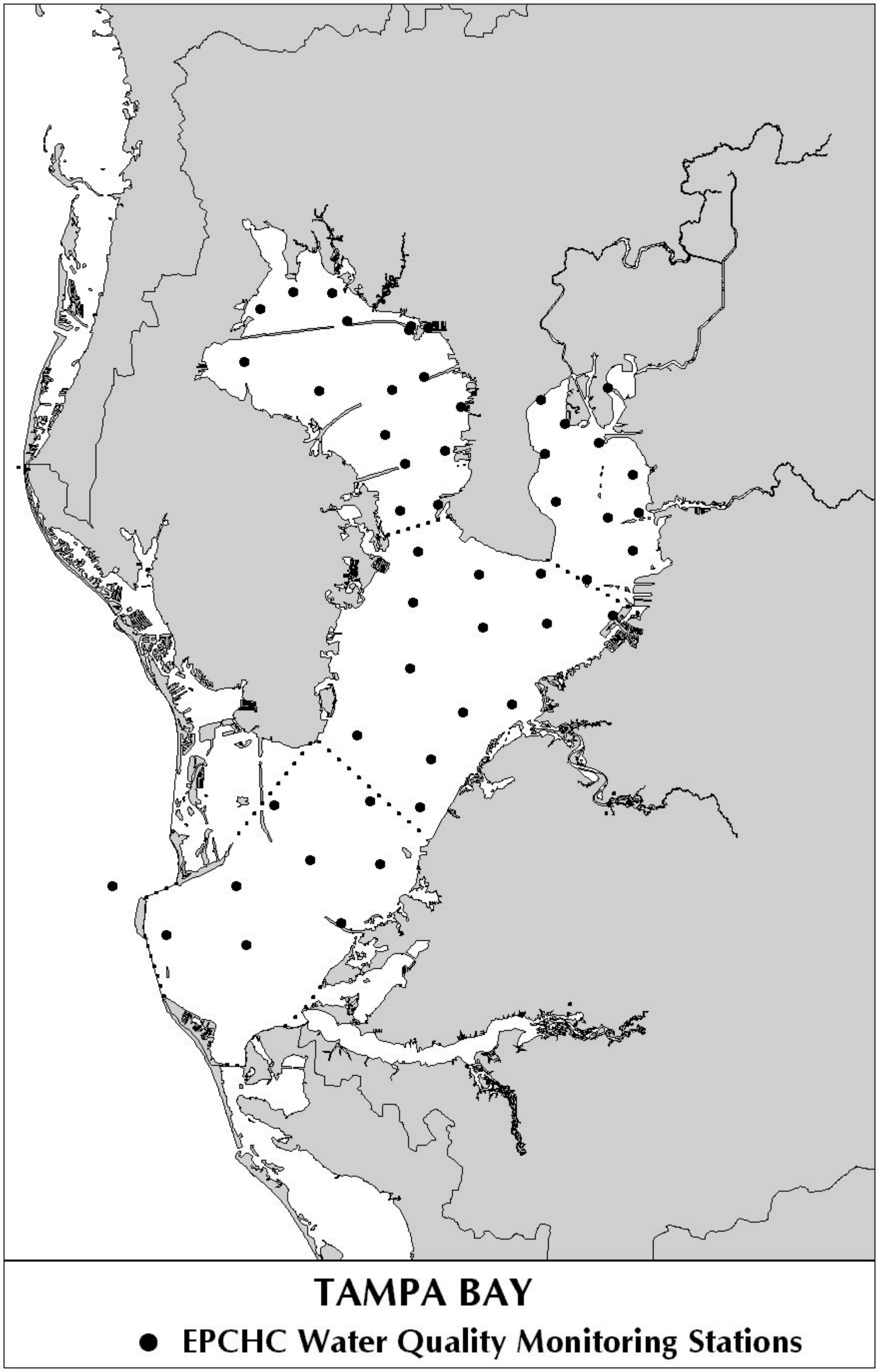

Figure 1-1. EPCHC Ambient Water Quality Monitoring stations – 1974-1998.

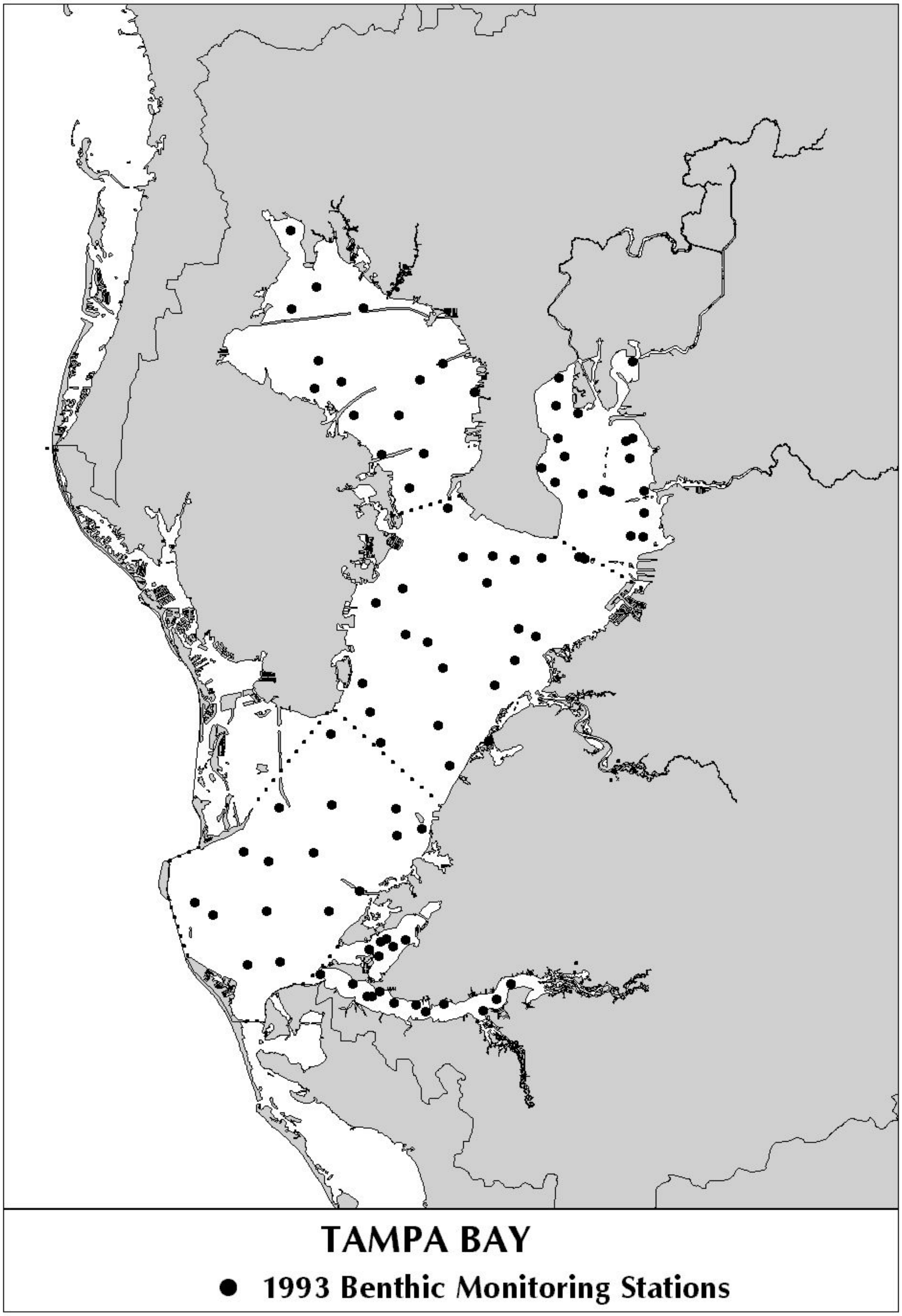

Figure 1-2. Tampa Bay Benthic Monitoring Program stations – 1993.

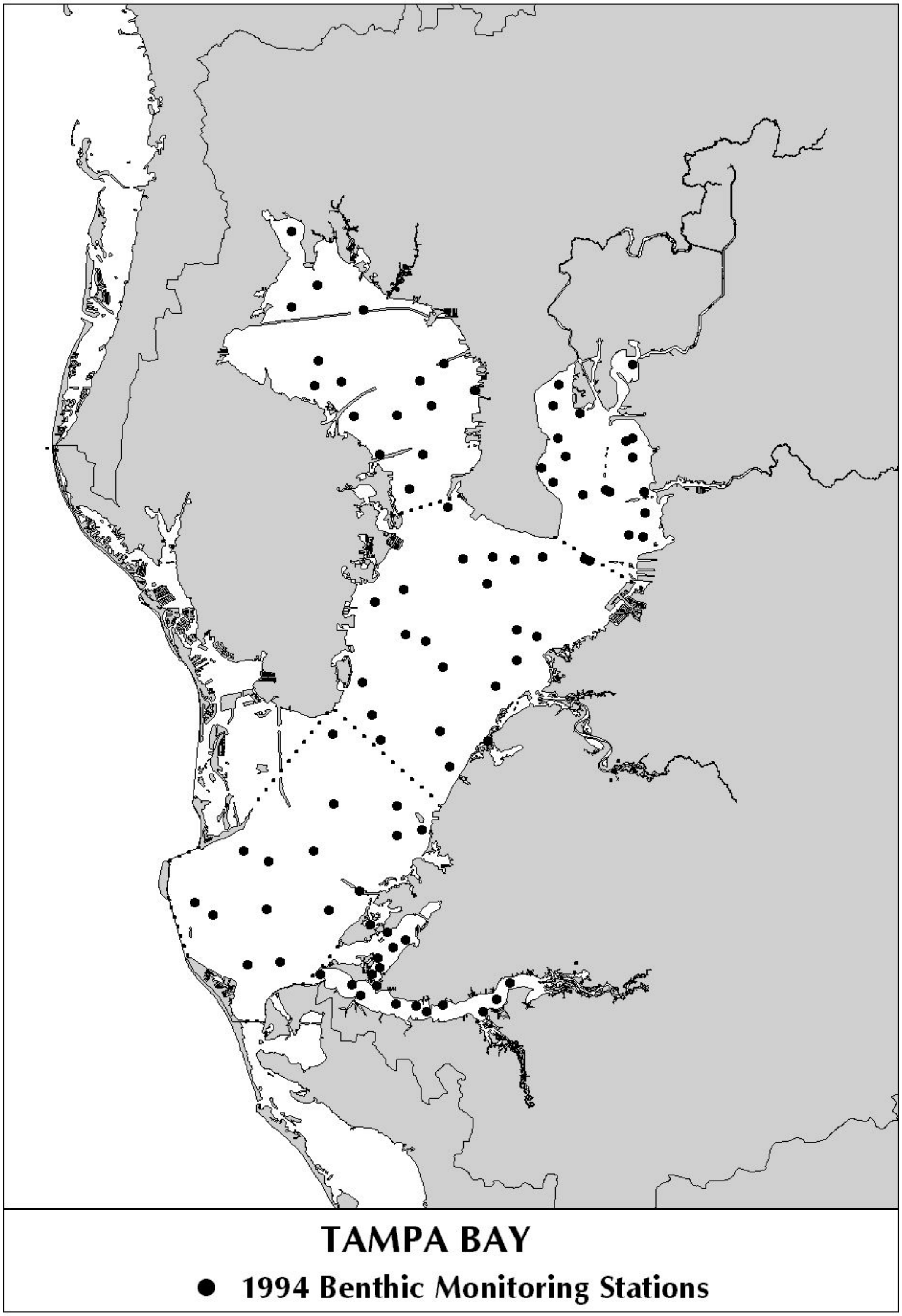

Figure 1-3. Tampa Bay Benthic Monitoring Program stations – 1994.

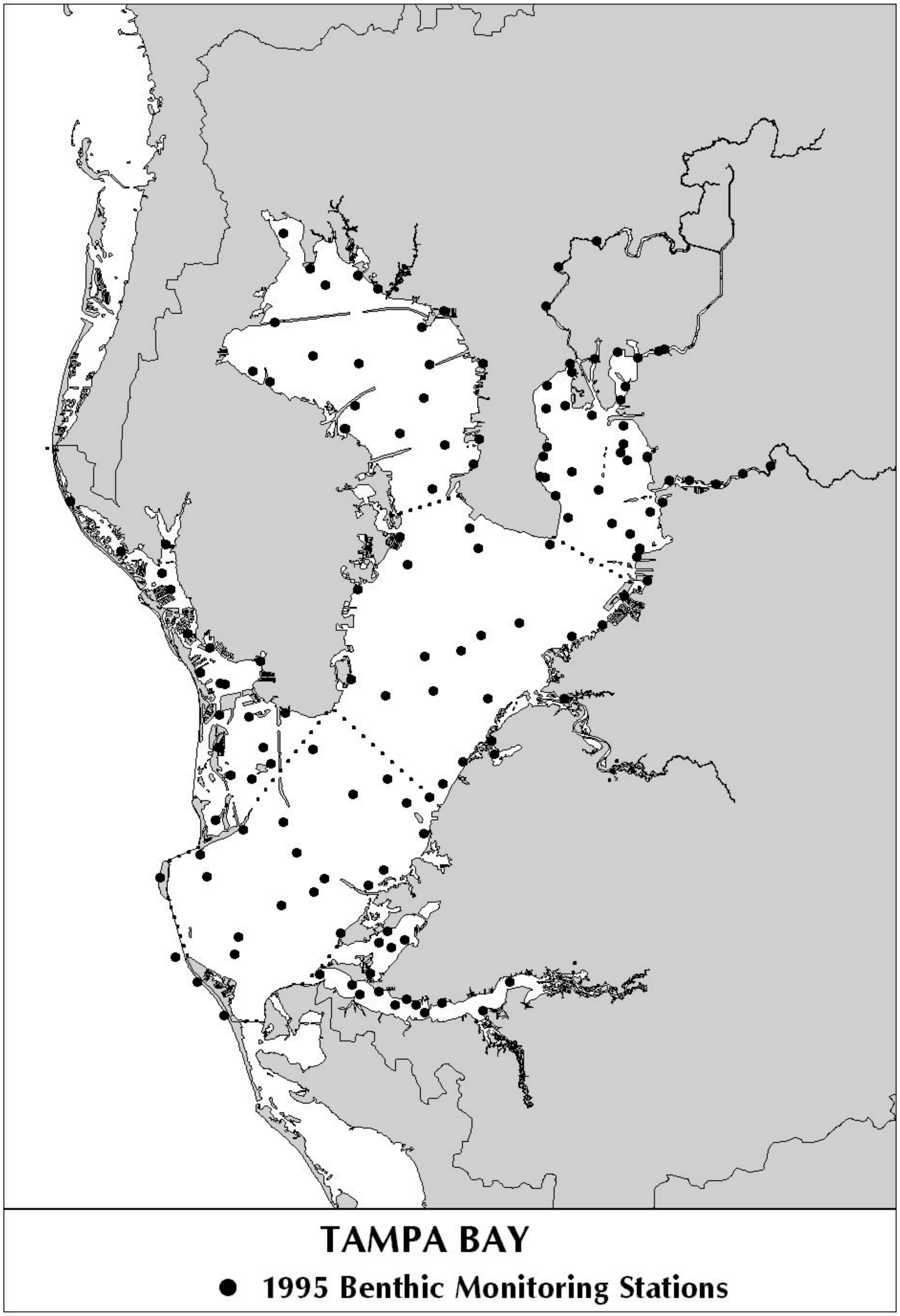

Figure 1-4. Tampa Bay Benthic Monitoring Program stations – 1995.

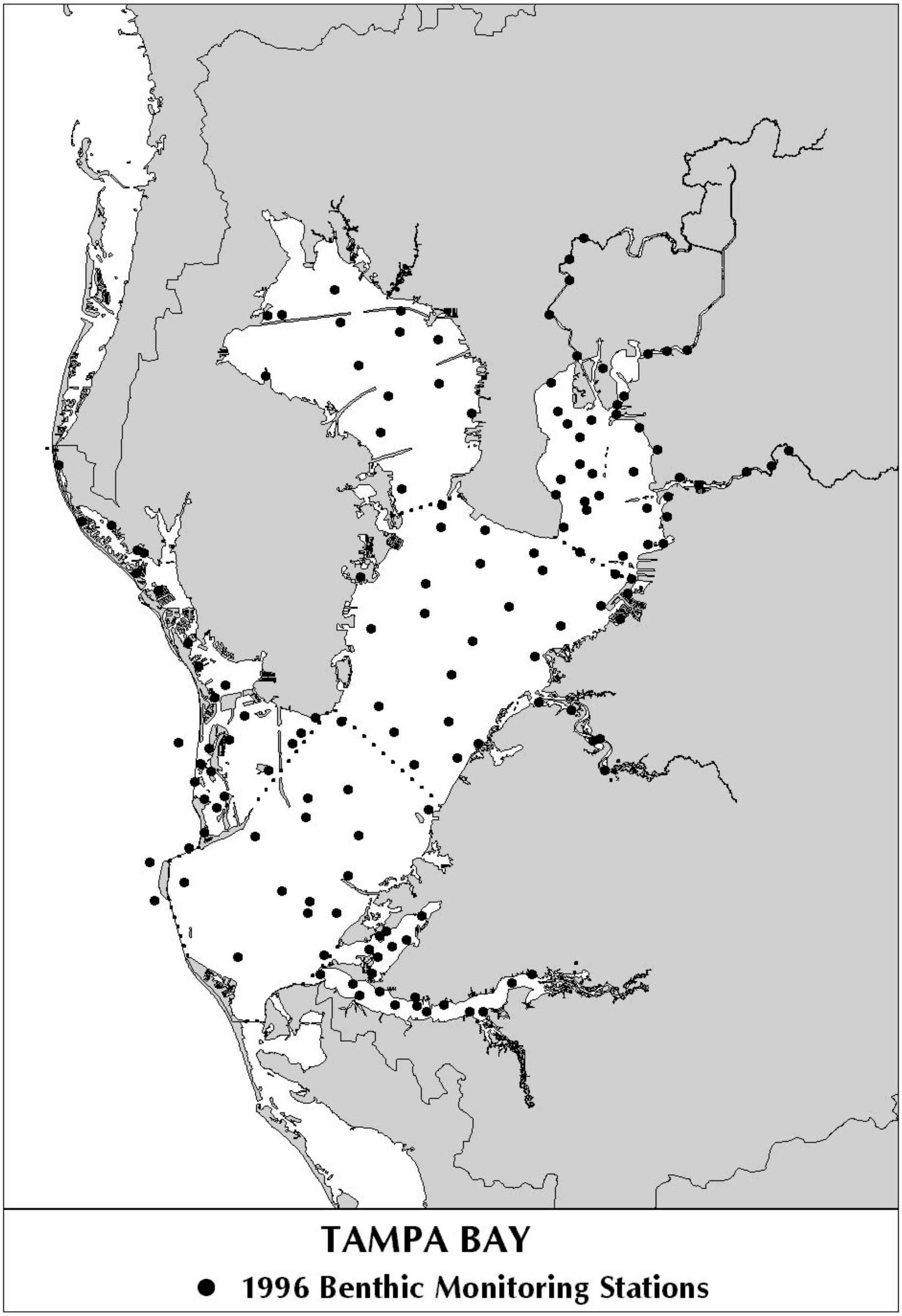

Figure 1-5. Tampa Bay Benthic Monitoring Program stations – 1996.

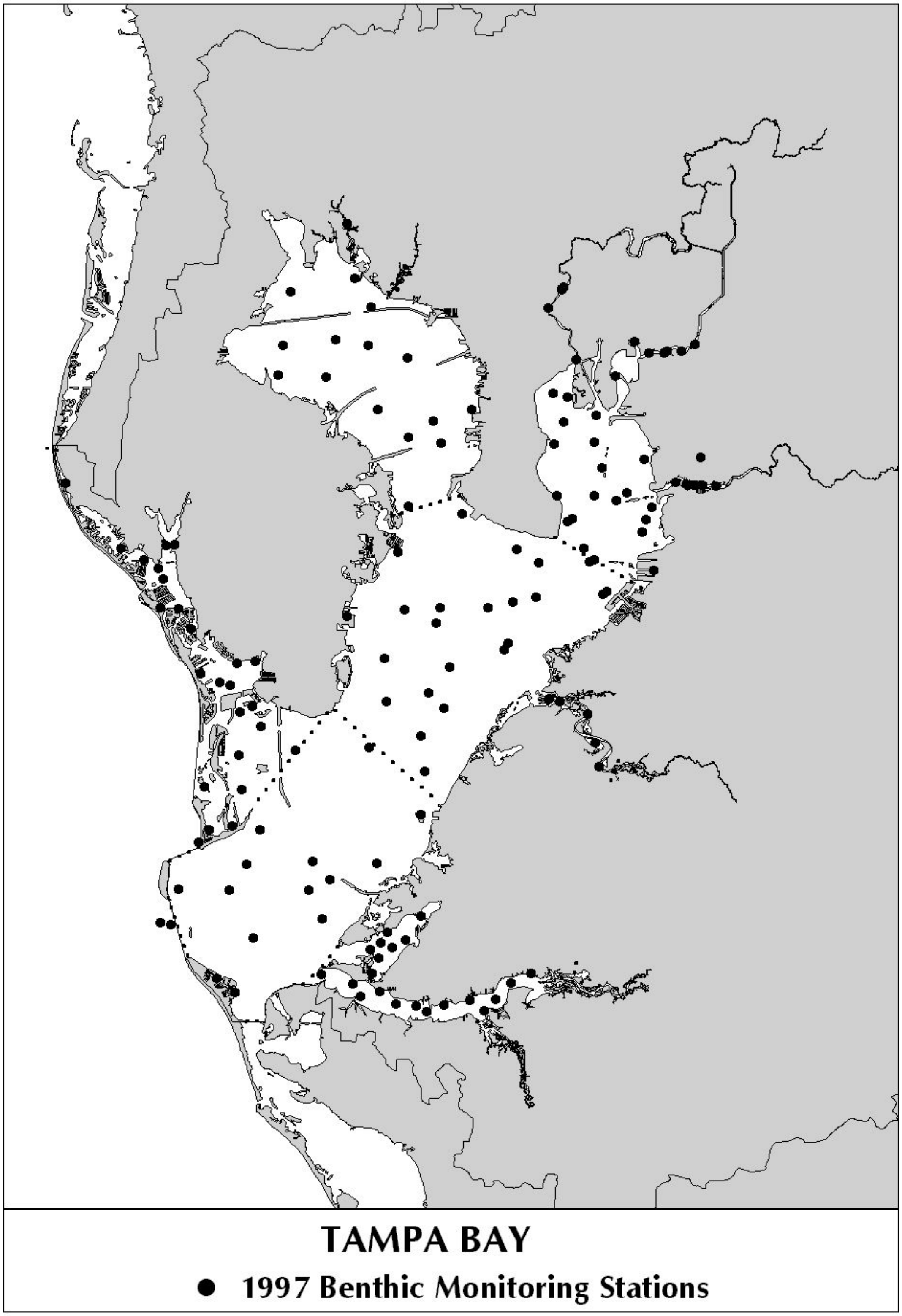

Figure 1-6. Tampa Bay Benthic Monitoring Program stations – 1997.

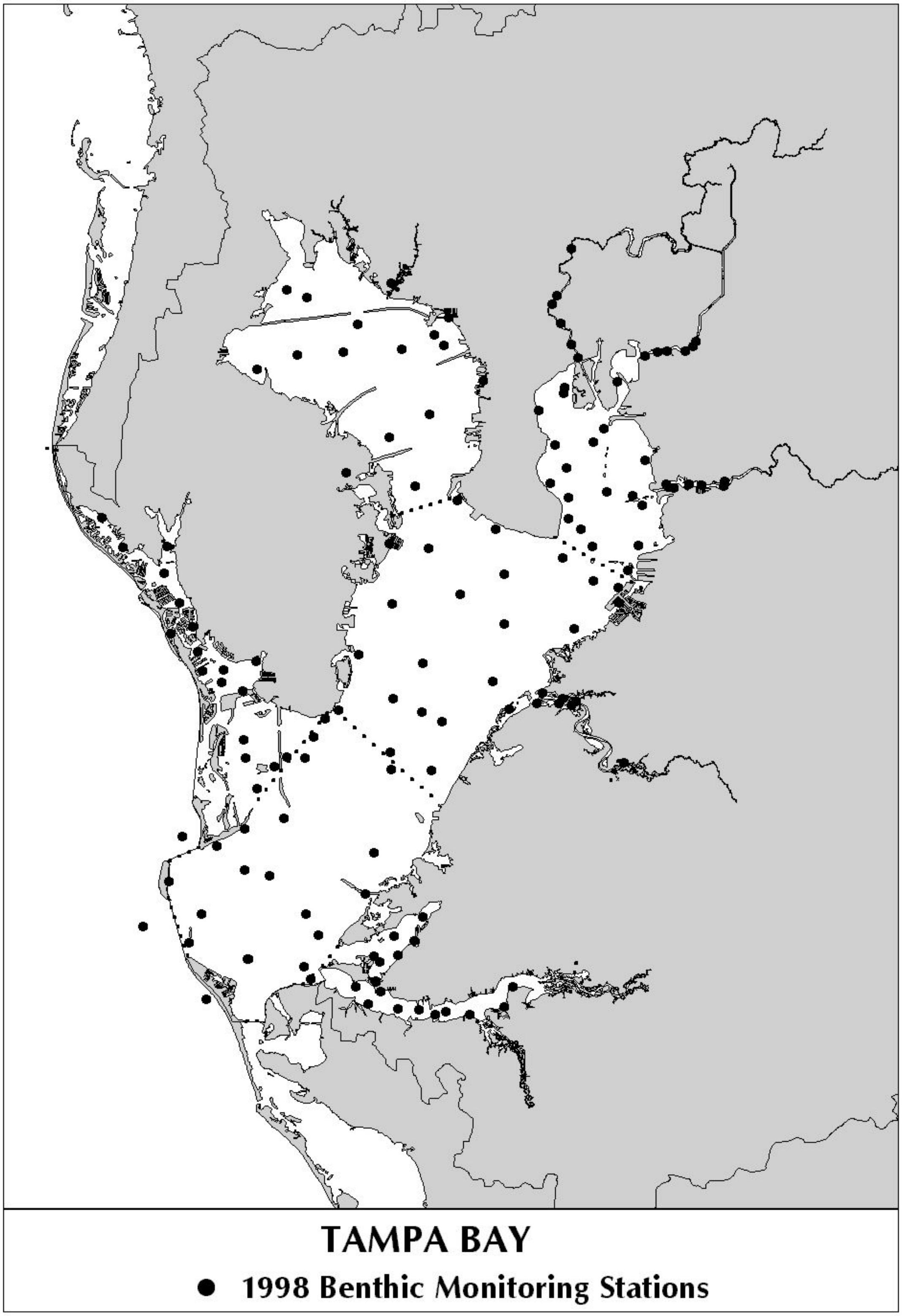

Figure 1-7. Tampa Bay Benthic Monitoring Program stations – 1998.

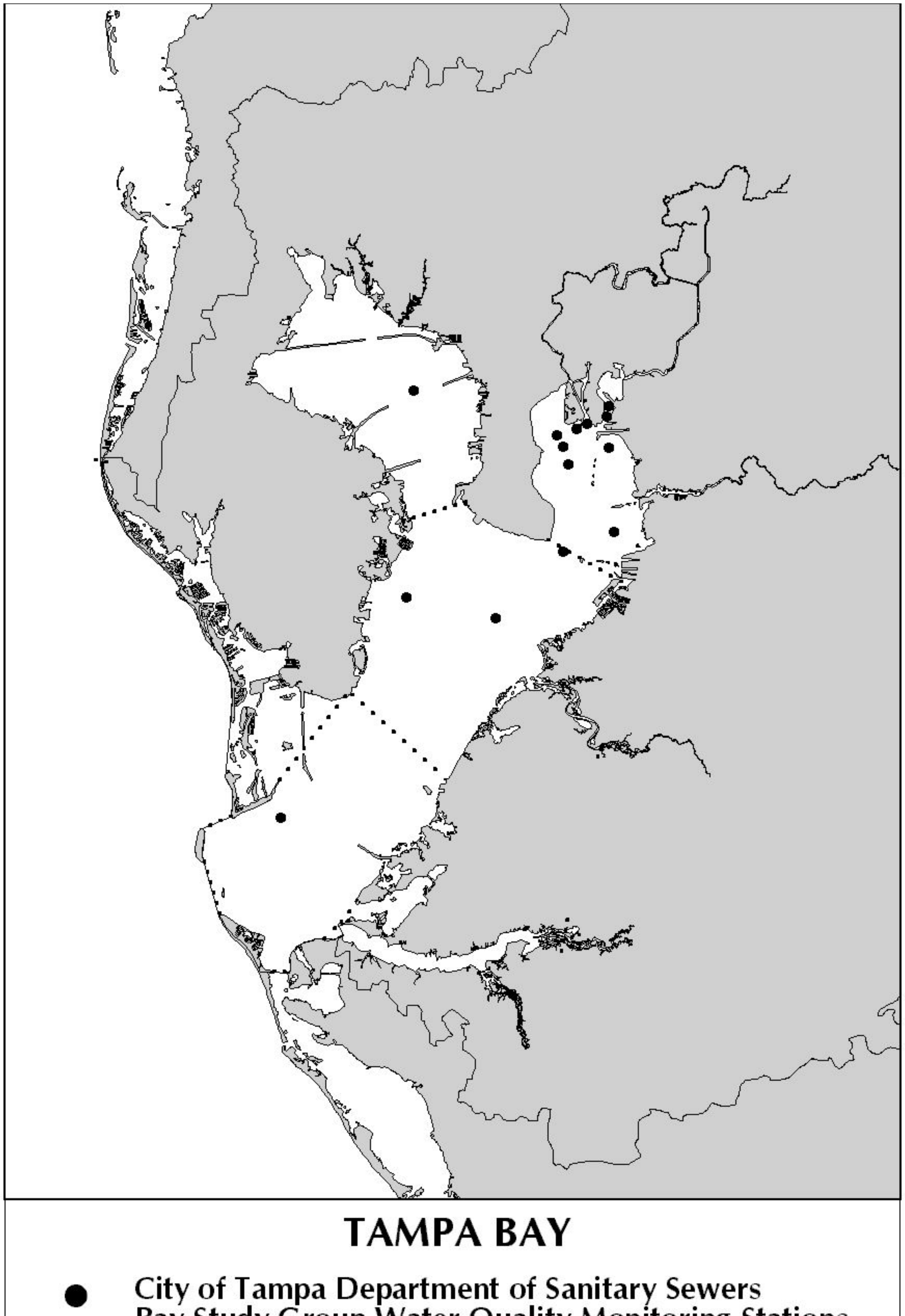

Figure 1-8. City of Tampa Bay Study Group Water Quality Monitoring stations.

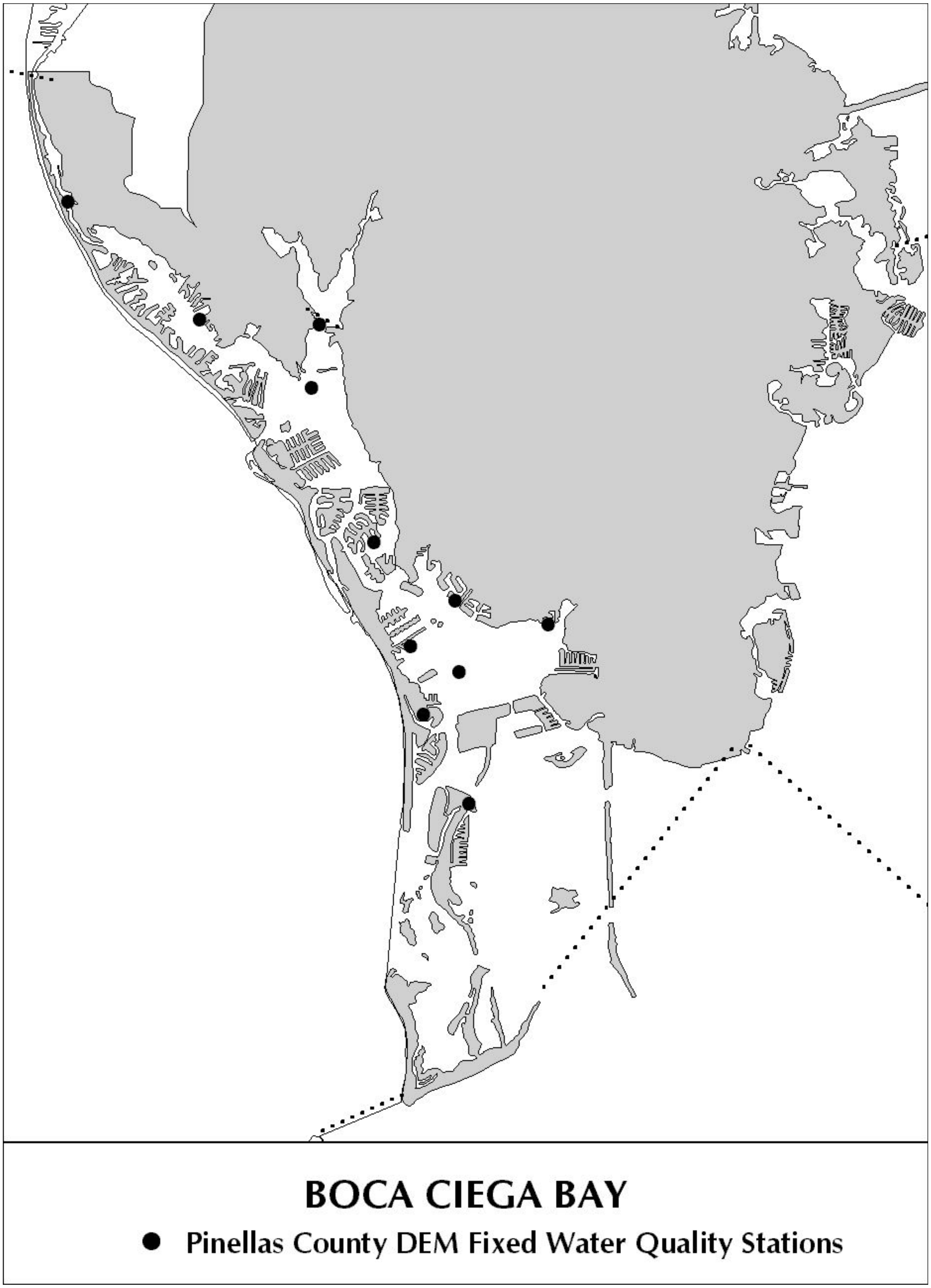

Figure 1-9. Pinellas County DEM Ambient Water Quality Monitoring fixed stations – 1991-1998.

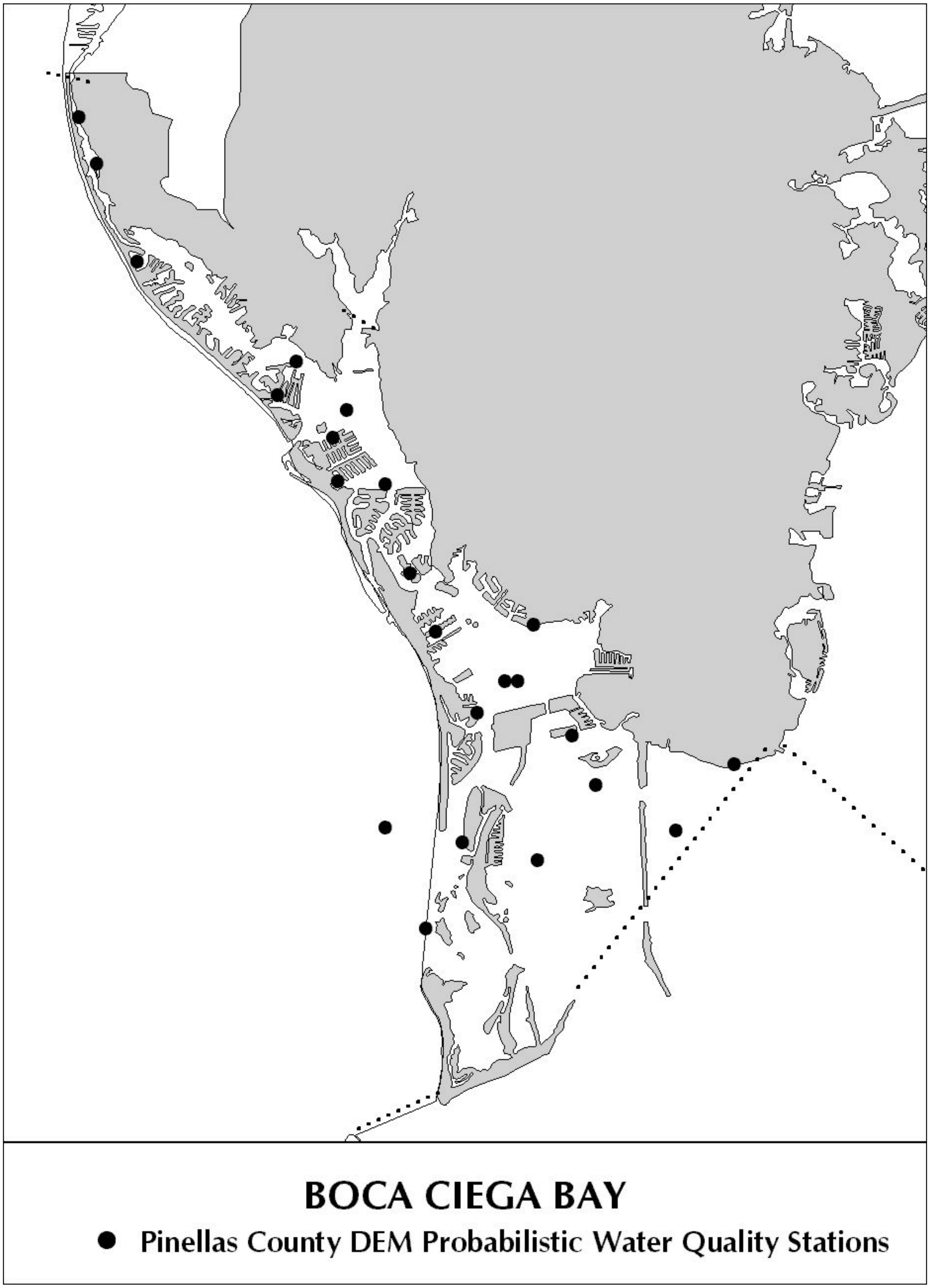

Figure 1-10. Pinellas County DEM Ambient Water Quality Monitoring probabilistic stations – 1997-1998.

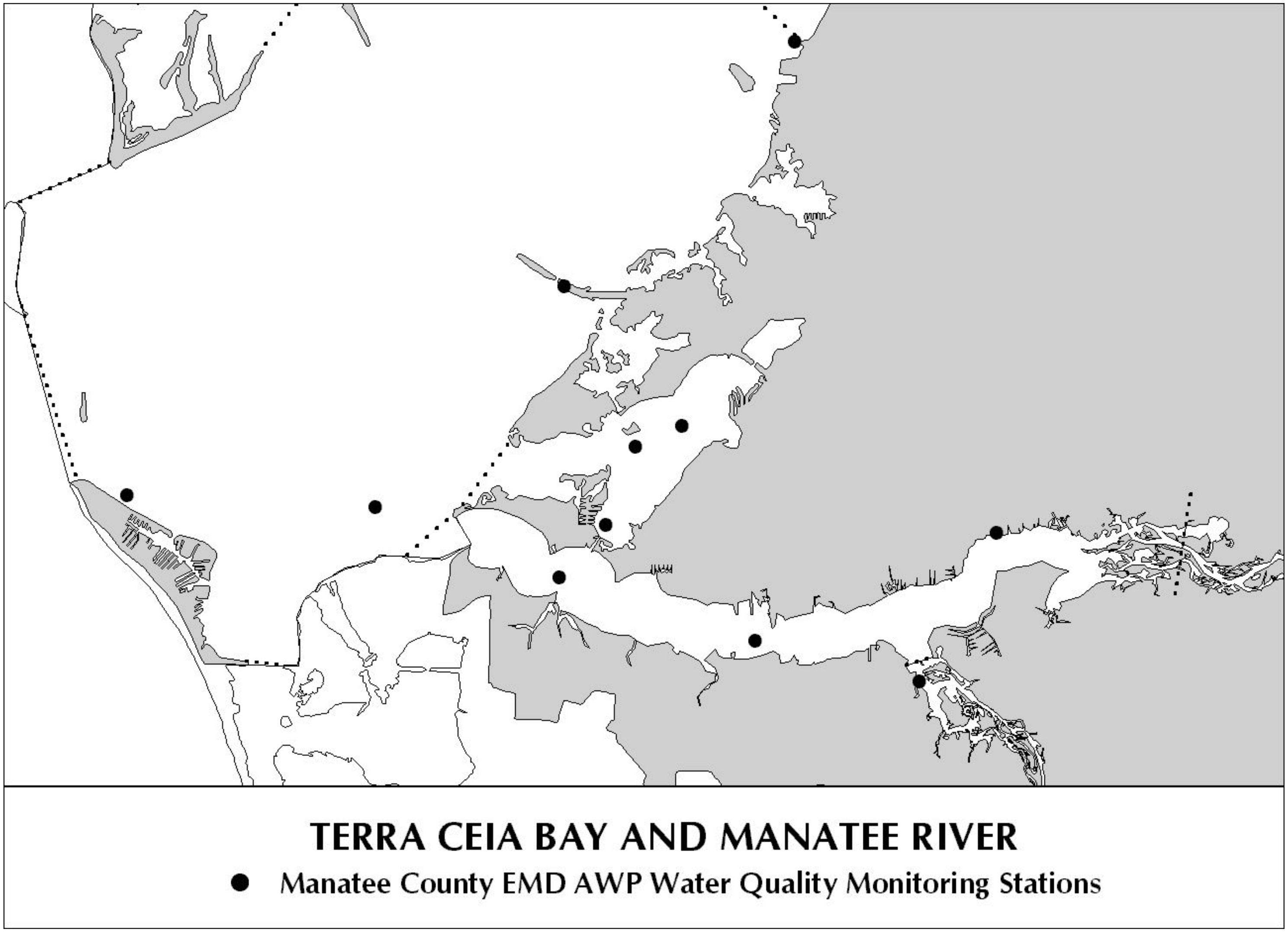

Figure 1-11. Manatee County EMD Ambient Water Quality Monitoring stations – 1988-1995.

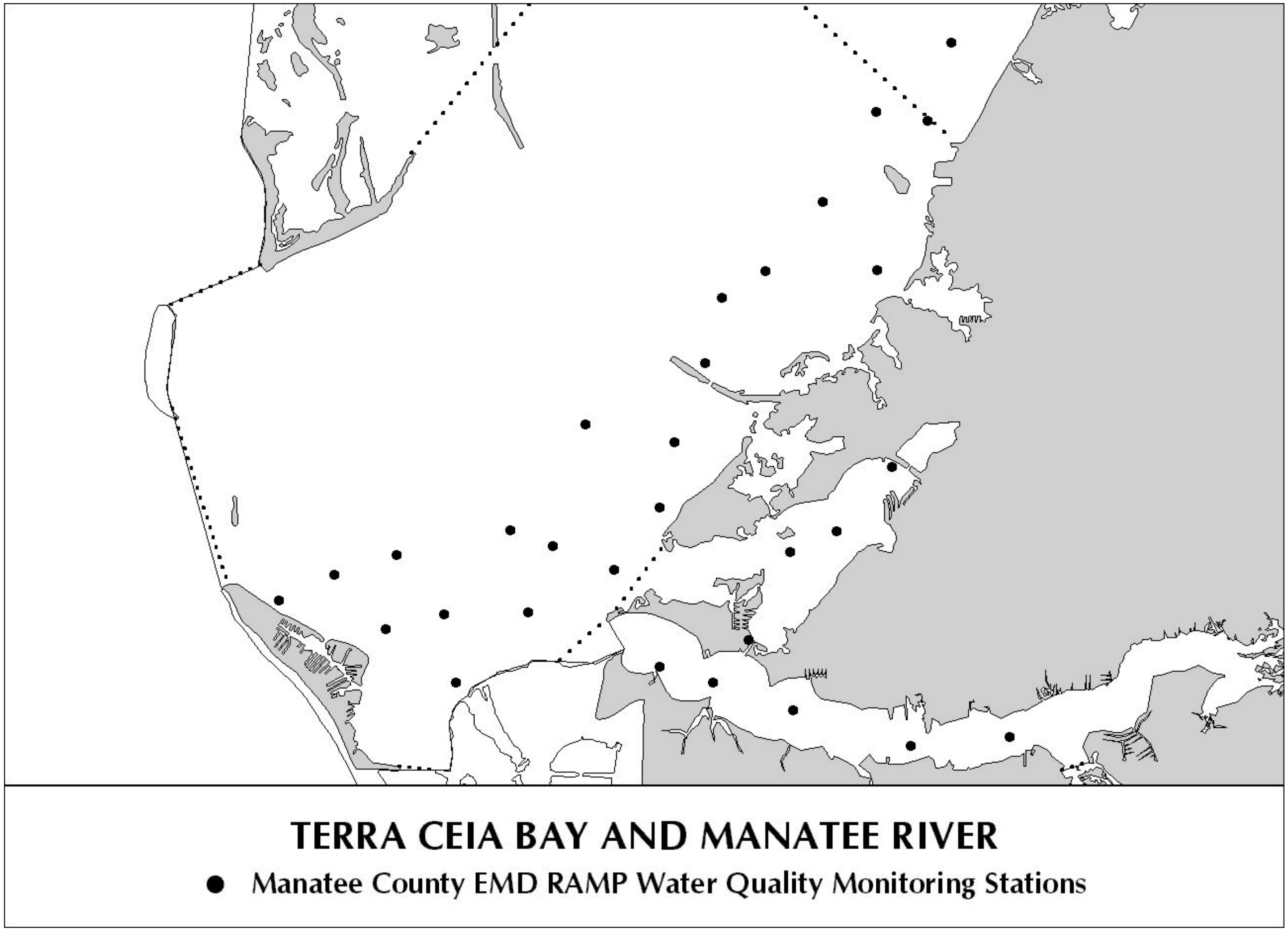

Figure 1-12. Manatee County EMD Ambient Water Quality Monitoring stations – 1995-1998.

QUESTION 2

During what times of year are bottom DO concentrations typically lowest?

The assessment of the seasonal variation of bottom DO concentrations provides focus for further data analyses, since the interest is in the times of year when bottom DO concentrations are typically lowest.

To address this question, bottom DO concentration data were plotted as box-and-whisker plots of monthly data by bay segment. The following figures present these plots:

- Figure 2-1 Hillsborough Bay – EPCHC Ambient Monitoring Program
- Figure 2-2 Old Tampa Bay - EPCHC Ambient Monitoring Program
- Figure 2-3 Middle Tampa Bay – EPCHC Ambient Monitoring Program
- Figure 2-4 Lower Tampa Bay – EPCHC Ambient Monitoring Program
- Figure 2-5 Boca Ciega Bay – Pinellas County DEM
- Figure 2-6 Terra Ceia Bay – Manatee County EMD
- Figure 2-7 Manatee River – Manatee County EMD

In these plots, the box is bounded by the 25th and 75th percentile values observed during a given month, with the median represented by the horizontal line in the box. The whiskers extend to the 10th and 90th percentile values, the 5th and 95th percentile values are represented by the dots nearest the ends of the whiskers, and the minimum and maximum values observed during that month are represented by the dots most distant from the whiskers.

The Terra Ceia Bay and Manatee River data are for surface DO measurements. Too few bottom DO measurements are available to characterize month-to-month variation effectively.

In all bay segments, the bottom DO concentrations were typically lowest in the late summer months, i.e., from July through September, with August nearly always at the minimum. These results are not surprising, given two factors. First, the solubility of oxygen in water is a function of water temperature, and water temperatures in all bay segments are highest during the July-September period. Secondly, primary production is typically high during this period, generating organic carbon that in turn becomes available for microbial processes that consume oxygen. Therefore, the greatest demand for oxygen to meet the demands of the microbial community, as well as the nighttime respiration demands of the primary producers, are also typically greatest during the summer months.

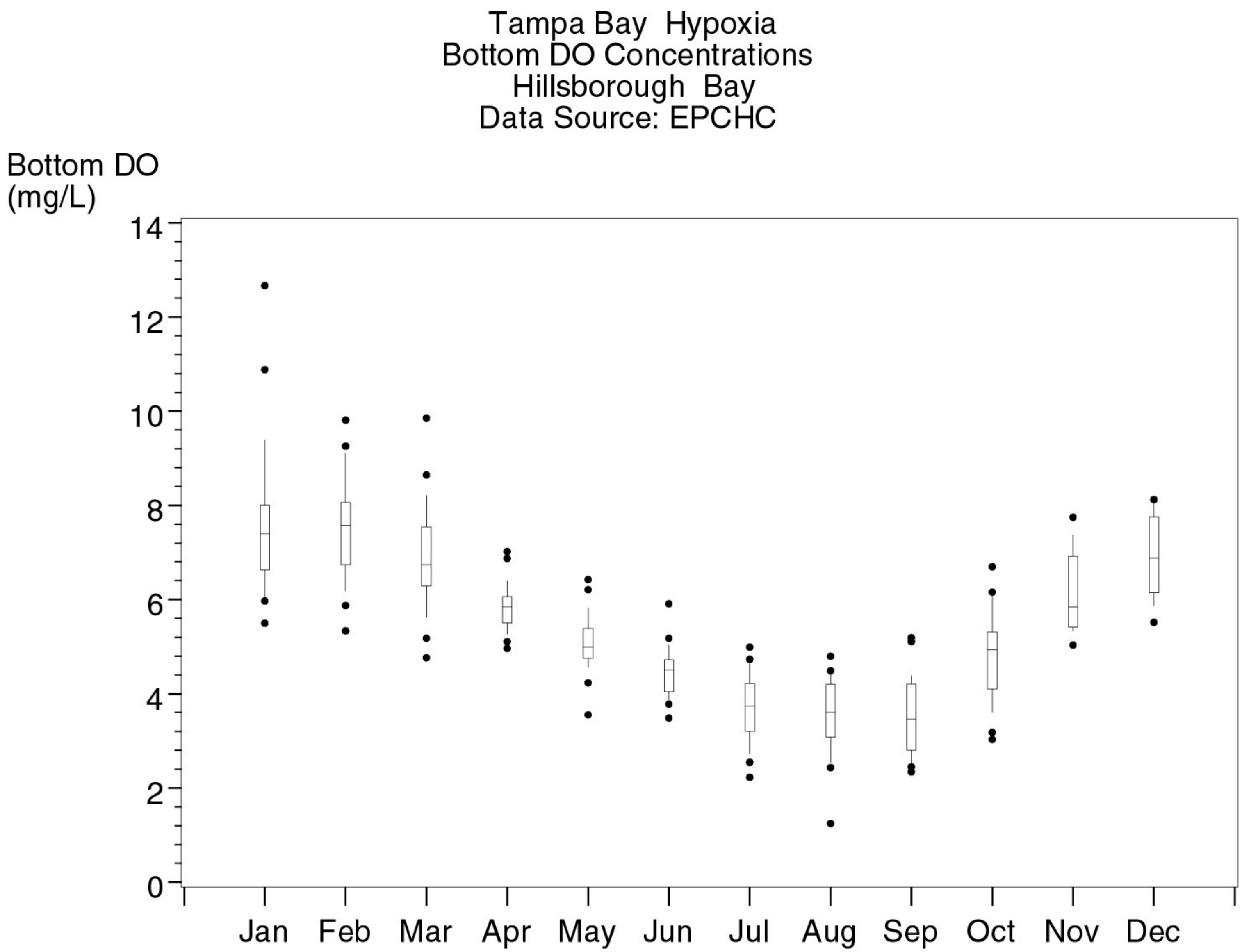

Figure 2-1. Monthly bottom DO data - Hillsborough Bay – EPCHC Ambient Monitoring Program – 1974-1998.

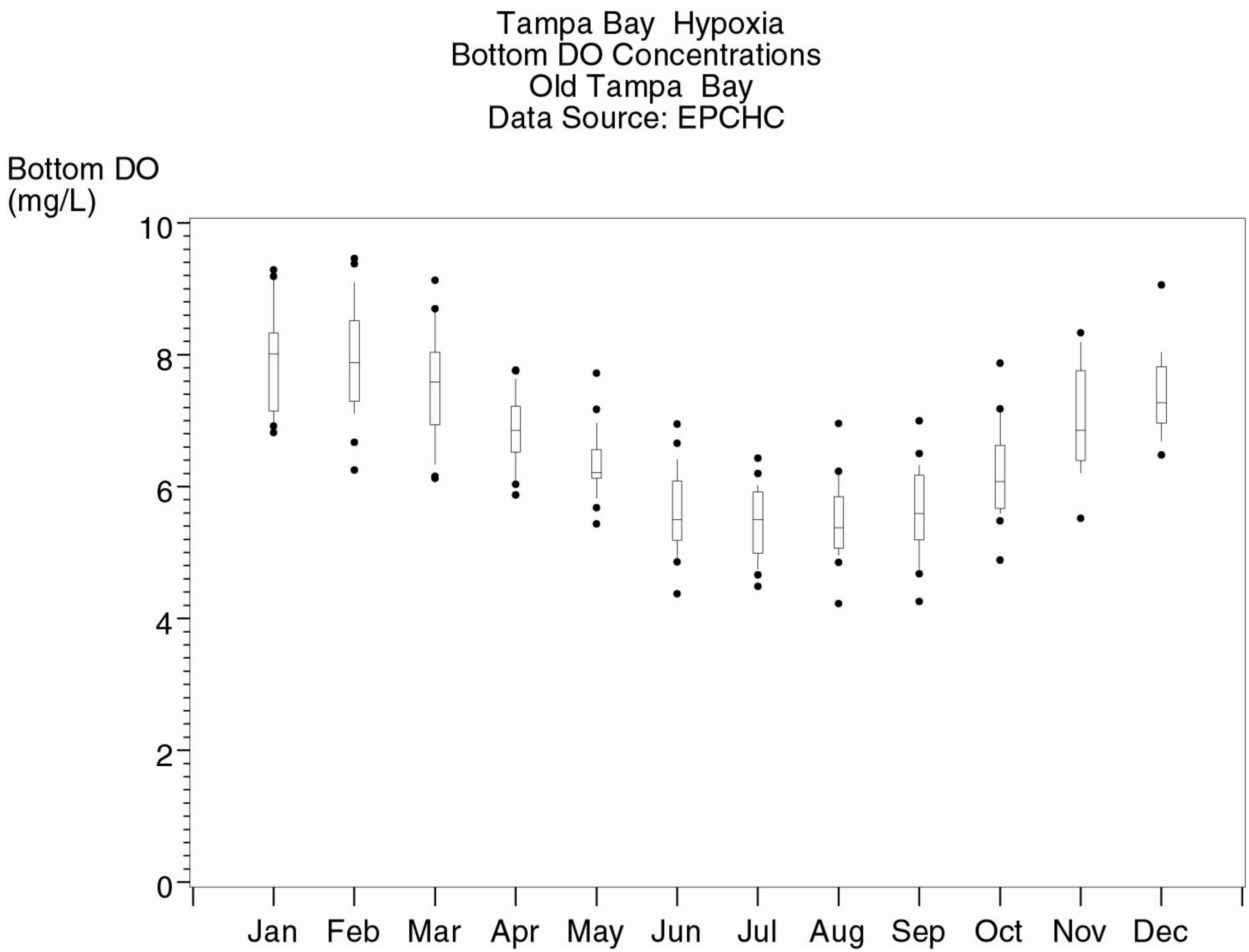

Figure 2-2. Monthly bottom DO data – Old Tampa Bay – EPCHC Ambient Monitoring Program – 1974-1998.

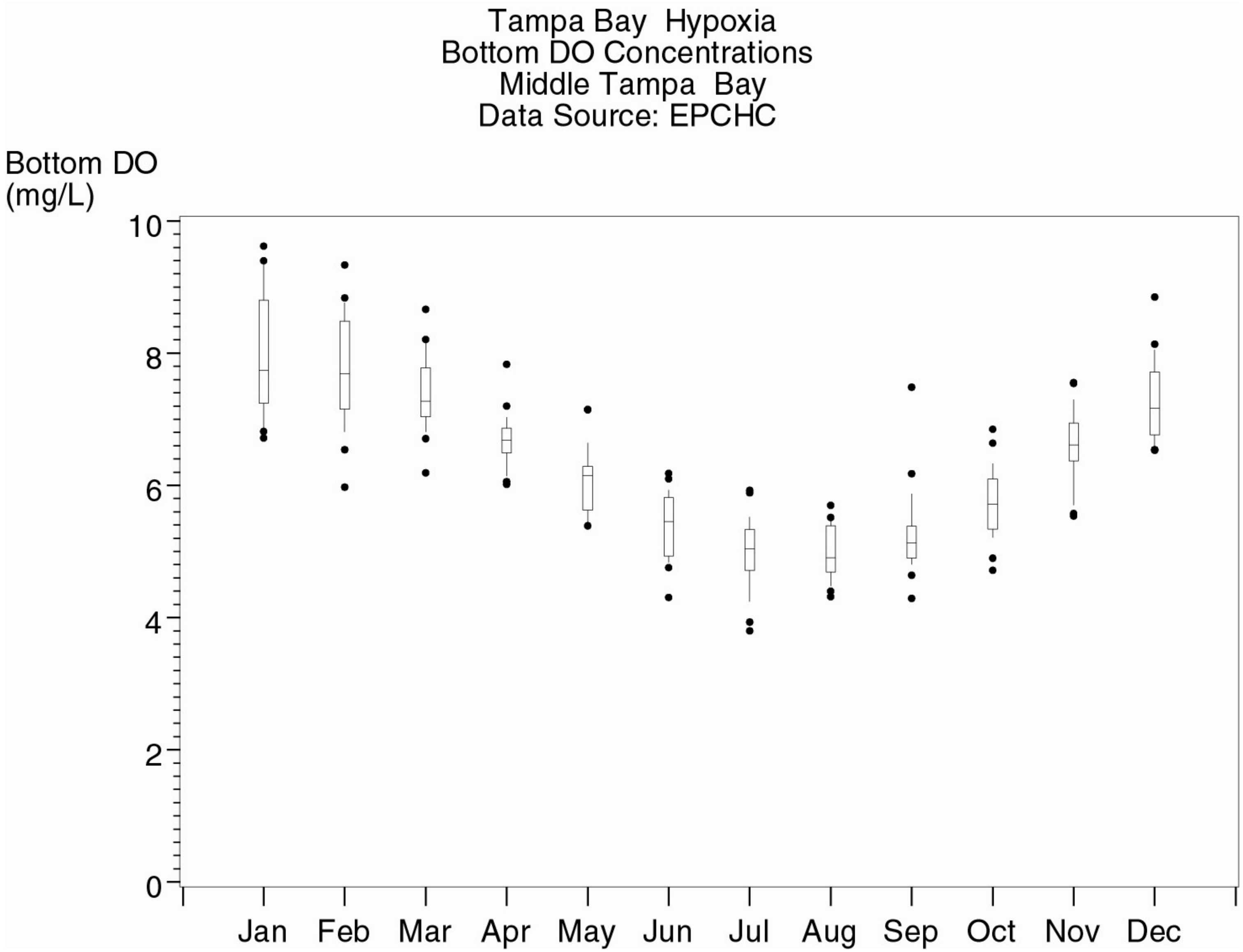

Figure 2-3. Monthly bottom DO data – Middle Tampa Bay – EPCHC Ambient Monitoring Program – 1974-1998.

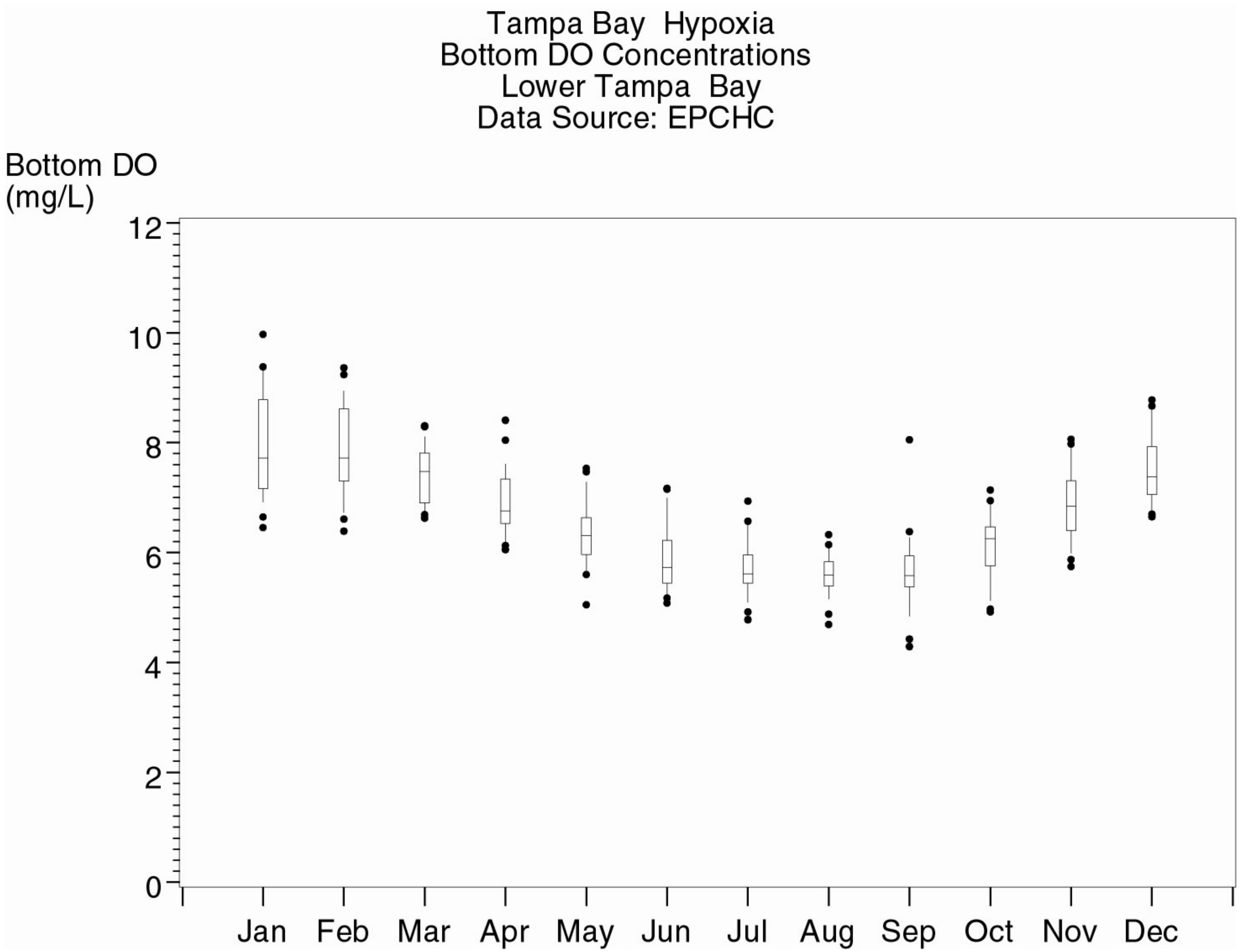

Figure 2-4. Monthly bottom DO data – Lower Tampa Bay – EPCHC Ambient Monitoring Program – 1974-1998.

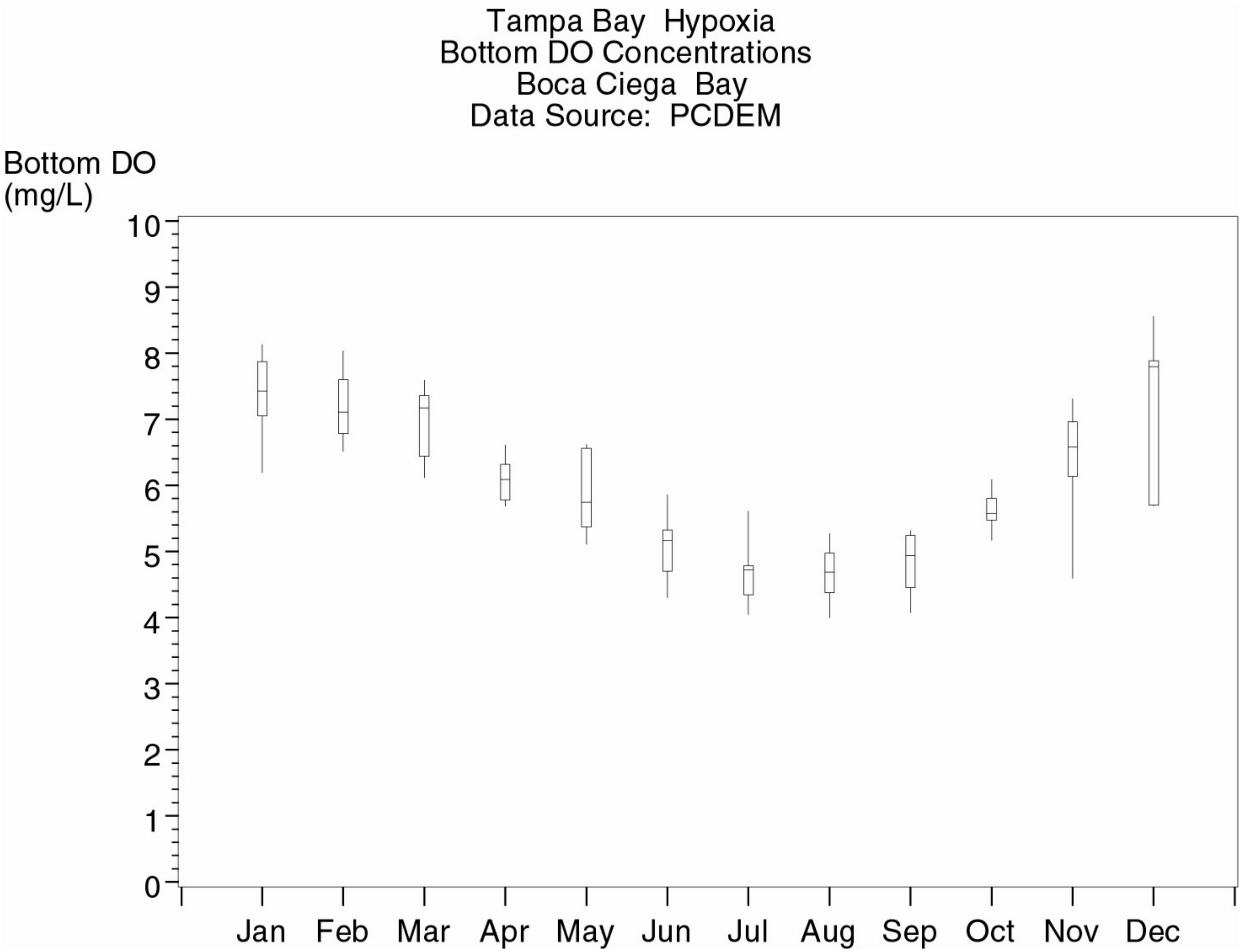

Figure 2-5. Monthly bottom DO data – Boca Ciega Bay – PCDEM Ambient Monitoring Program – 1991-1998.

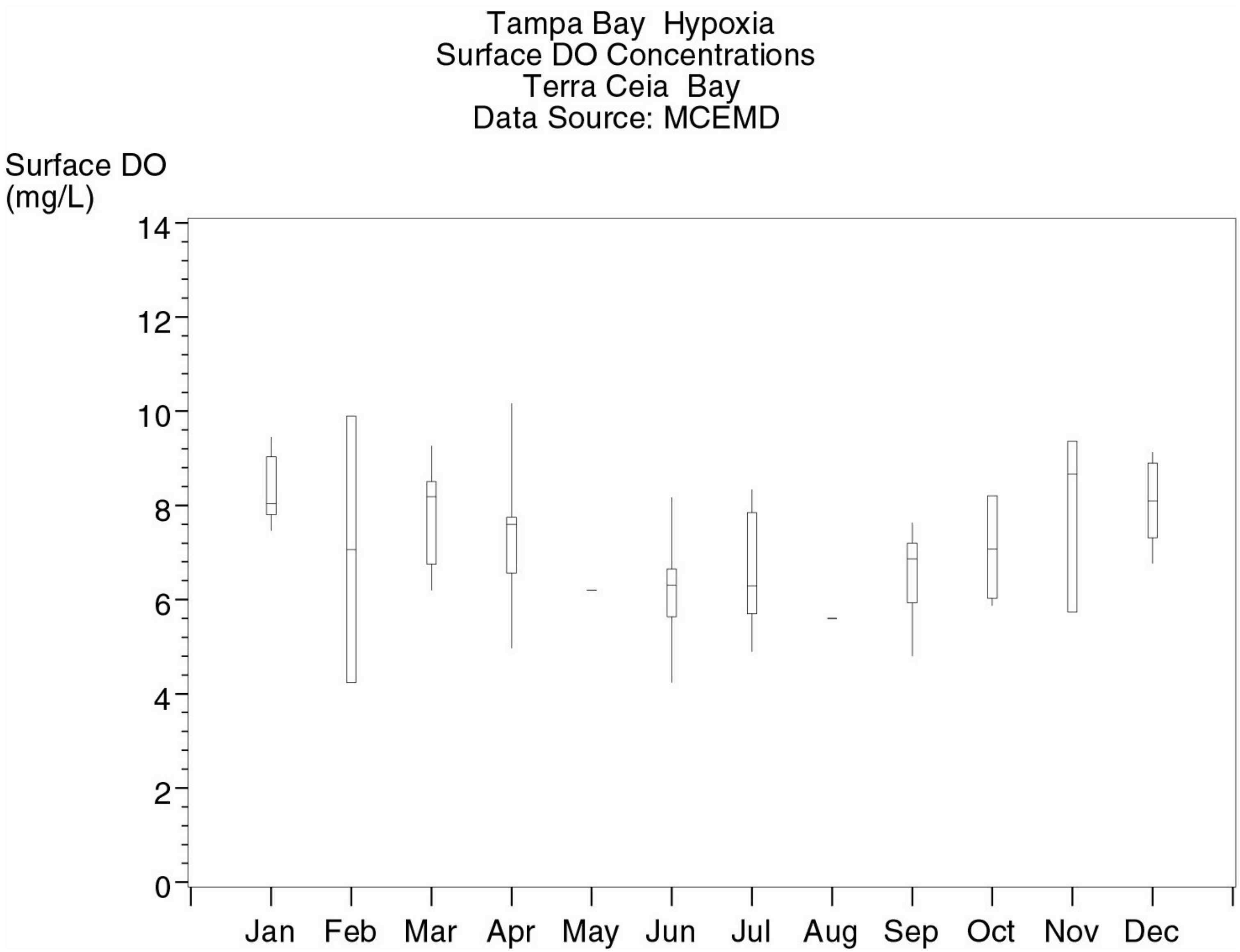

Figure 2-6. Monthly surface DO data – Terra Ceia Bay – MCEDM Ambient Monitoring Program – 1995-1998.

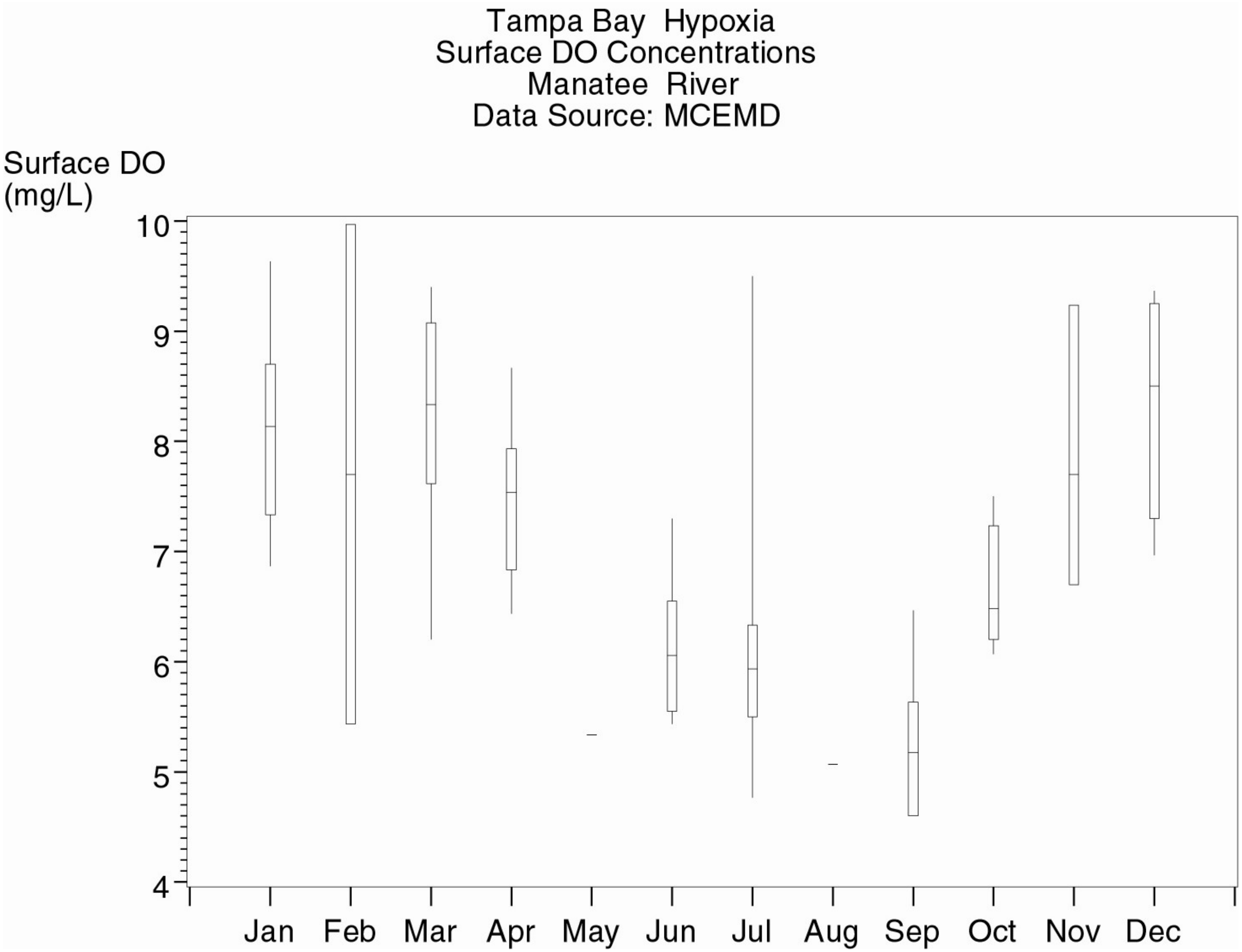

Figure 2-7. Monthly surface DO data – Manatee River – MCEDM Ambient Monitoring Program – 1995-1998.

QUESTION 3

Where does hypoxia typically occur, and what makes these areas different from other areas in the bay?

The occurrence of hypoxia is generally determined by a number of factors that relate to the degree of oxygen demand and the rate of re-oxygenation. These can include:

- Depth
- Sediment type - % silt-clay
- Degree of stratification
- Temperature
- Salinity
- Chlorophyll concentration
- BOD.

To address this question, the bottom DO concentration data for each station from the EPCHC and PCDEM monthly ambient monitoring programs were reviewed. This review focused on relatively recent data (1991-1998) to allow a valid comparison of these data.

Tables 3-1 through 3-4 present the following:

- the total number of observations (July-September, 1991-1998)
- the number of observations less than 4 mg/L
- the number of observations less than 2 mg/L
- the number of observations = 0 mg/L

for Hillsborough Bay, Old Tampa Bay, Middle Tampa Bay, and Boca Ciega Bay, respectively. Review of the data for Lower Tampa Bay revealed that during 1991-1998, there were only four observations of DO concentrations <4 mg/L, and none <2 mg/L, so that the data for this segment are not shown.

Several stations in Hillsborough Bay displayed relatively frequent hypoxic conditions (< 2 mg/L) – most notably stations 54 and 58, located in East Bay and McKay Bay, respectively. Only three stations in Old Tampa Bay exhibited hypoxic conditions, and only Station 61, located on the eastern end of the Courtney Campbell Causeway, displayed more than one such occurrence. Only two stations in Middle Tampa Bay displayed hypoxic occurrences. No hypoxic conditions were found in Boca Ciega Bay during this period.

The frequency of hypoxic conditions observed during the study period in each bay segment, as derived from monthly monitoring data, is as follows:

- Hillsborough Bay – 26%,
- Old Tampa Bay – 1%,
- Middle Tampa Bay – <1%,
- Lower Tampa Bay - < 1%, and
- Boca Ciega Bay - 0%.

In addition to these analyses to identify where hypoxia typically occurs, the bottom DO data from the Benthic Monitoring Program were plotted in the following figures:

- Figure 3-1 Hillsborough Bay
- Figure 3-2 Old Tampa Bay
- Figure 3-3 Middle Tampa Bay
- Figure 3-4 Lower Tampa Bay
- Figure 3-5 Boca Ciega Bay
- Figure 3-6 Terra Ceia Bay and Manatee River

In each figure, all sampling stations occupied during the 1993-1998 sampling periods were plotted and their relative bottom DO concentration identified:

- < 2 mg/L
- 2 – 4 mg/L
- > 4 mg/L

Most of the hypoxic conditions in Hillsborough Bay were found along Davis Islands at the mouth of the Hillsborough River, the McKay and East bay area, Ballast Point, and several near-shore sites along the eastern shore of the bay.

Fewer stations in Old Tampa Bay displayed hypoxic conditions, as compared to Hillsborough Bay. Several stations near the Courtney Campbell Causeway exhibited hypoxia, and several stations along the southeastern shoreline of Old Tampa Bay exhibited bottom DO concentrations in the 2-4 mg/L range.

Hypoxia was especially rare in Middle Tampa Bay and Lower Tampa Bay. In Middle Tampa Bay, stations located near Big Bend exhibited hypoxia during the 1993-1998 benthic sampling periods, while stations near Coffee Pot Bayou and near Picnic Island exhibited DO concentrations in the 2-4 mg/L range. Relative to Middle Tampa Bay, Lower Tampa Bay showed very little evidence of low DO concentrations, with DO concentrations in the 2-4 mg/L range only in the areas near Port Manatee and in areas adjacent to the southern end of the Sunshine Skyway Bridge.

No hypoxia was observed in Boca Ciega Bay during the 1995-1998 benthic sampling periods, with only five stations showing DO concentrations in the 2-4 mg/L range. In the Manatee River, four stations between the mouth of the Braden River and Snead Island showed relatively infrequent hypoxia. Only three stations in Terra Ceia Bay displayed DO concentrations in the 2-4 mg/L range during the study period.

Further analysis was performed to identify those factors that may discriminate the areas of Tampa Bay in which hypoxia occurs from those in which hypoxia is absent. The median values for the following factors were estimated for these two areas:

- Depth
- Sediment type - % silt-clay
- Degree of stratification
- Temperature
- Salinity
- Chlorophyll concentration
- BOD.

The median value for each of these factors was estimated from observations made when bottom DO was <2 mg/L and compared to the median estimated from those observations when bottom DO was >2 mg/L. Similar estimates were derived using 4 mg/L. Tables 3-5 through 3-7 present these estimates for Hillsborough Bay, Old Tampa Bay, and Middle Tampa Bay, respectively.

Generally, those stations where hypoxia has been observed are deeper, have finer sediments, have a higher degree of stratification, and have higher chlorophyll concentrations than those stations where hypoxia has been absent. Neither salinity, temperature, nor BOD concentrations discriminated those stations where hypoxia occurred from those where no hypoxia was observed.

The degree of stratification of the water column due to vertical density differences was derived based on the combined effects of salinity and temperature. The equation of state for density establishes the relationship between water density, temperature, and salinity, neglecting the relatively small effects of suspended solids, as follows:

$$\rho = \rho_T + \Delta\rho_S$$

where

ρ = density of seawater (kg/m^3),

ρ_T = density of pure water as a function of temperature, and

$\Delta\rho_S$ = change in density due to dissolved solids (salt).

The density of pure water as a function of temperature, ρ_T, is calculated as follows (Martin and McCutcheon, 1999):

$$\rho_T = 1000\left[1 - \frac{T + 288.9414}{508929.2(T + 68.12963)}\left(T - 3.9863)^2\right)\right]$$

where

T = water temperature (°C).

The change in density of water due to salinity, $\Delta\rho_S$, is calculated as follows (Martin and McCutcheon, 1999):

$$\begin{aligned}\Delta\rho_S &= \left(0.824493 - 4.0899x10^{-3}T + 7.6438x10^{-5}T^2 - 8.2467x10^{-7}T^3 + 5.3875x10^{-9}T^4\right)C_{SL} \\ &+ \left(-5.72466x10^{-3} + 1.0277x10^{-4}T - 1.6546x10^{-6}T^2\right)C_{SL}^{1.5} + 4.8314x10^{-4}C_{SL}^2\end{aligned}$$

where

T = water temperature (°C) and

C_{SL} = salinity concentration in parts per thousand (ppt).

The stratification parameter was estimated as the difference in surface and bottom density, divided by the depth separating the surface and bottom temperature and salinity measurements. Low values of the stratification parameter therefore signify smaller degrees of stratification than do high values.

Table 3-1. Hillsborough Bay – Number of observations of hypoxic conditions from EPCHC monitoring data, July-September 1991-1998.

EPC Station	Number of Bottom DO Measurements	Number < =4 mg/L	Number < =2 mg/L	Number =0 mg/L
6	24	14	4	0
7	24	16	8	0
8	19	4	0	0
44	22	10	1	0
52	24	16	3	0
54	24	24	22	0
55	24	20	7	0
58	24	24	18	0
70	23	14	7	0
71	24	11	4	0
73	24	2	0	0
80	24	3	0	0
Total	280	158	74	0

Table 3-2. Old Tampa Bay – Number of observations of hypoxic conditions from EPCHC monthly data, July-September 1991-1998.

EPC Station	Number of Bottom DO Measurements	Number < =4 mg/L	Number < =2 mg/L	Number =0 mg/L
36	24	0	0	0
38	24	0	0	0
40	24	0	0	0
41	24	0	0	0
46	23	3	0	0
47	24	0	0	0
50	24	1	0	0
51	24	0	0	0
60	16	0	0	0
61	24	13	3	0
62	23	10	0	0
63	24	3	0	0
64	15	2	1	0
65	24	4	1	0
66	24	1	0	0
67	24	0	0	0
68	24	0	0	0
Total	389	37	5	0

Table 3-3. Middle Tampa Bay – Number of observations of hypoxic conditions from EPCHC monthly data, July-September 1991-1998.

EPC Station	Number of Bottom DO Measurements	Number < =4 mg/L	Number < =2 mg/L	Number =0 mg/L
9	24	11	1	0
11	24	2	0	0
13	24	2	0	0
14	24	1	0	0
16	24	0	0	0
19	24	0	0	0
28	24	0	0	0
32	24	4	1	0
33	24	0	0	0
81	24	12	0	0
82	24	0	0	0
84	24	1	0	0
Total	288	33	2	0

Table 3-4. Boca Ciega Bay – Number of observations of hypoxic conditions from PCDEM monthly data, July-September 1991-1998.

PCDEM Station	Number of Bottom DO Measurements	Number < =4 mg/L	Number < =2 mg/L	Number =0 mg/L
48-3	4	3	0	0
56-1	24	12	0	0
57-1	23	1	0	0
58-1	26	11	0	0
58-2	17	0	0	0
59-1	24	1	0	0
59-2	14	5	0	0
59-3	12	4	0	0
60-1	25	6	0	0
60-2	16	1	0	0
60-3	12	4	0	0
60-4	24	1	0	0
Total	221	49	0	0

Table 3-5. Hillsborough Bay – Comparison of median condition for factors that potentially affect the occurrence of hypoxia. Data include EPCHC (1974-1998) and Tampa Bay Benthic Monitoring Program (1993-1998) data.

FACTOR	Bottom DO ≤ 2 mg/L	Bottom DO > 2 mg/L	Bottom DO ≤ 4 mg/L	Bottom DO > 4 mg/L
Depth (m)	4.0	2.7	3.7	2.4
Silt-clay (%)	46	6	37	4
Bottom Salinity (ppt)	23.6	23.3	23.6	23.0
Bottom Temperature (°C)	29.7	29.6	29.7	29.5
Degree of Stratification ($kg/m^3/m$)	0.84	0.36	0.57	0.35
Chlorophyll a (µg/L)	17.7	15.7	16.2	16.5
BOD (mg/L)	2.2	2.4	2.2	2.4

Table 3-6. Old Tampa Bay – Comparison of median condition for factors that potentially affect the occurrence of hypoxia. Data include EPCHC (1974-1998) and Tampa Bay Benthic Monitoring Program (1993-1998) data.

FACTOR	Bottom DO ≤ 2 mg/L	Bottom DO > 2 mg/L	Bottom DO ≤ 4 mg/L	Bottom DO > 4 mg/L
Depth (m)	4.0	3.0	2.7	3.1
Silt-clay (%)	24	4	9	3
Bottom Salinity (ppt)	22.3	23.6	22.3	23.8
Bottom Temperature (°C)	29.6	29.6	29.6	29.6
Degree of Stratification ($kg/m^3/m$)	0.77	0.07	0.21	0.06
Chlorophyll a (µg/L)	28.3	9.7	11.5	9.6
BOD (mg/L)	3.4	1.9	2.2	1.8

Table 3-7. Middle Tampa Bay – Comparison of median condition for factors that potentially affect the occurrence of hypoxia. Data include EPCHC (1974-1998) and Tampa Bay Benthic Monitoring Program (1993-1998) data.

FACTOR	Bottom DO ≤ 2 mg/L	Bottom DO > 2 mg/L	Bottom DO ≤ 4 mg/L	Bottom DO > 4 mg/L
Depth (m)	4.6	4.7	4.6	4.8
Silt-clay (%)	12	4	10	3
Bottom Salinity (ppt)	26.0	26.4	25.6	26.4
Bottom Temperature (°C)	30.9	29.5	30.0	29.5
Degree of Stratification ($kg/m^3/m$)	0.25	0.11	0.20	0.10
Chlorophyll a (µg/L)	12.3	9.4	12.1	9.2
BOD (mg/L)	1.8	1.4	1.6	1.4

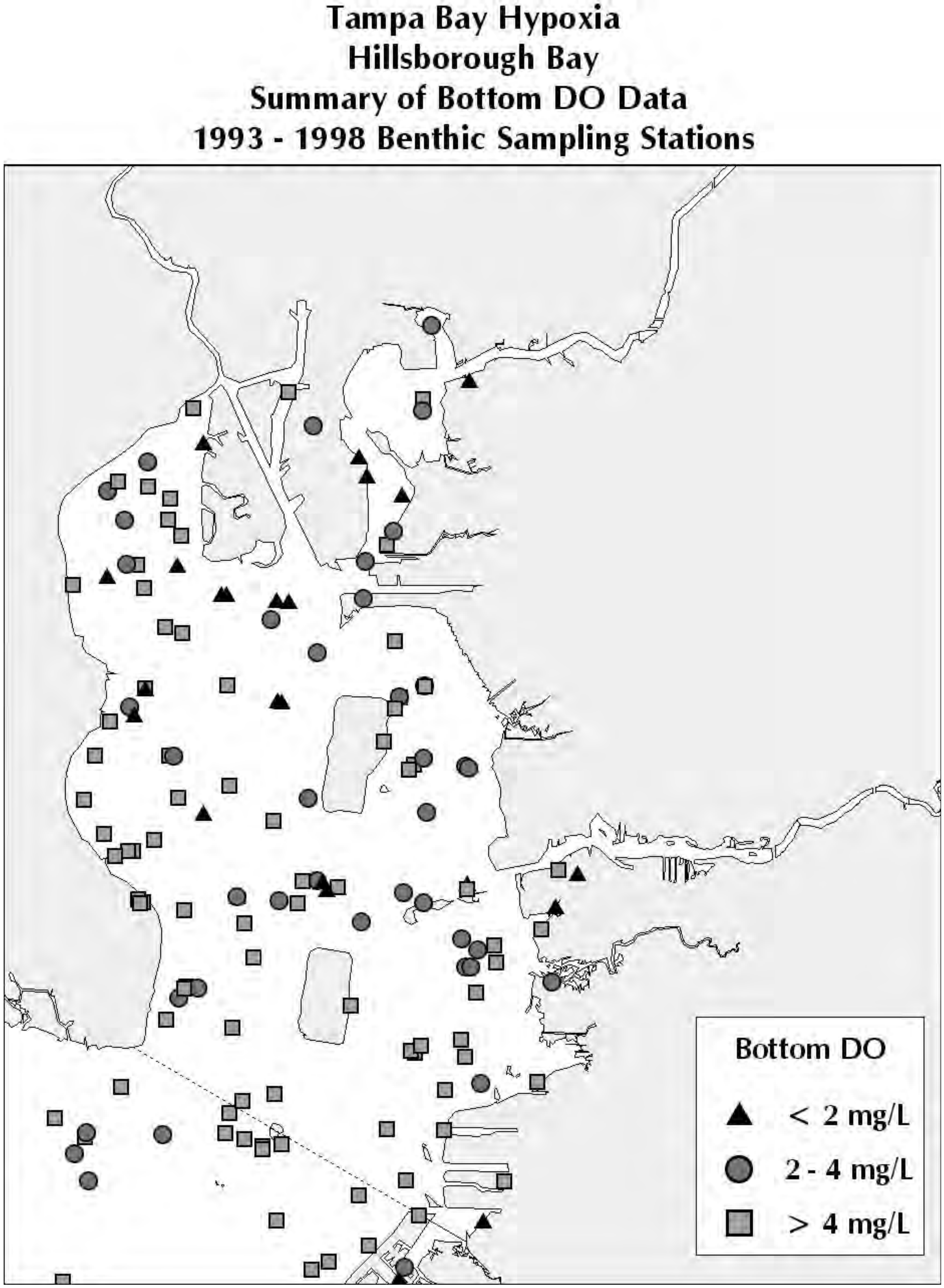

Figure 3-1. Classification of bottom DO data from Hillsborough Bay - Benthic Monitoring Program stations (1993-1998).

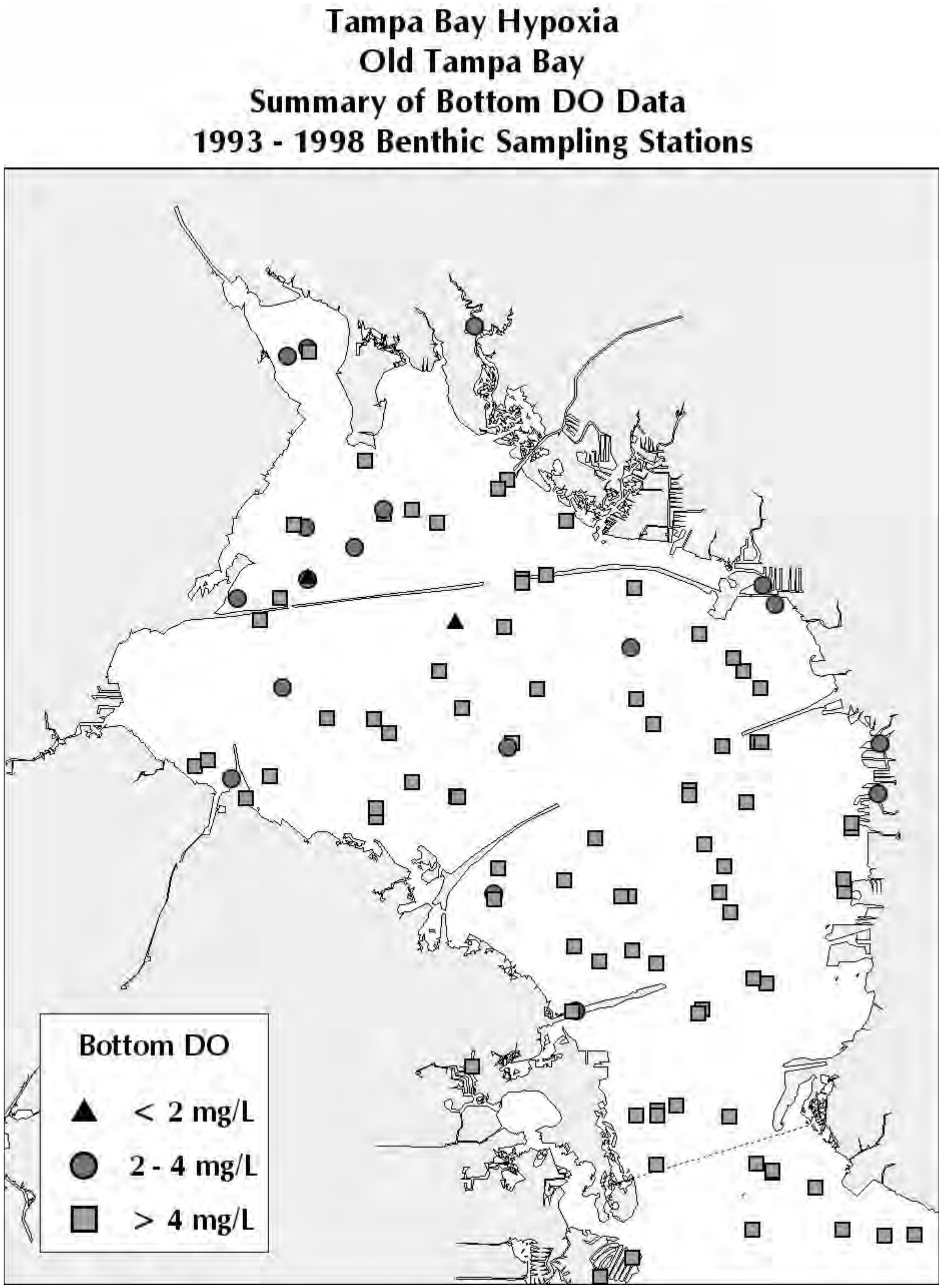

Figure 3-2. Classification of bottom DO data from Old Tampa Bay - Benthic Monitoring Program stations (1993-1998).

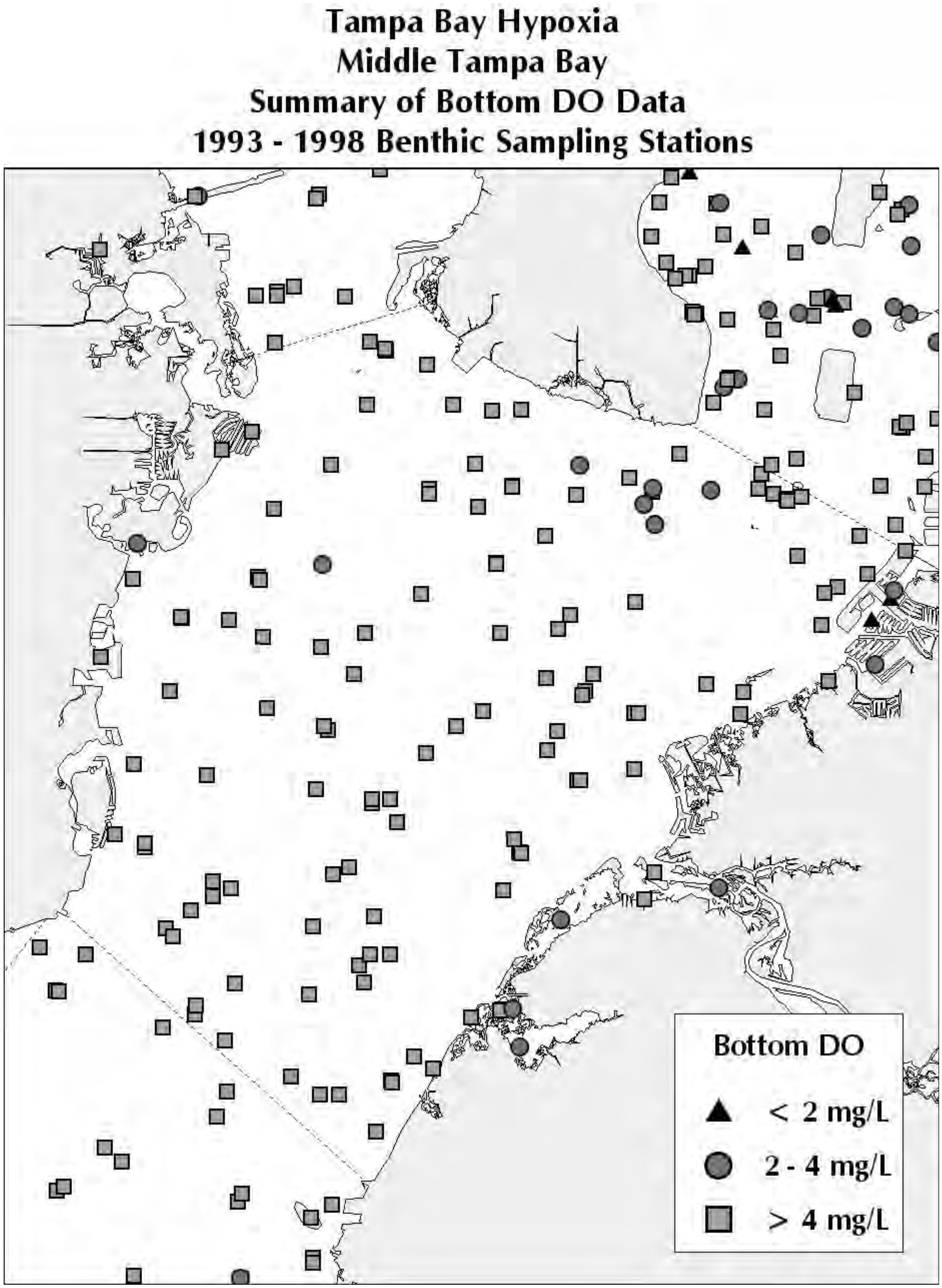

Figure 3-3. Classification of bottom DO data from Middle Tampa Bay - Benthic Monitoring Program stations (1993-1998).

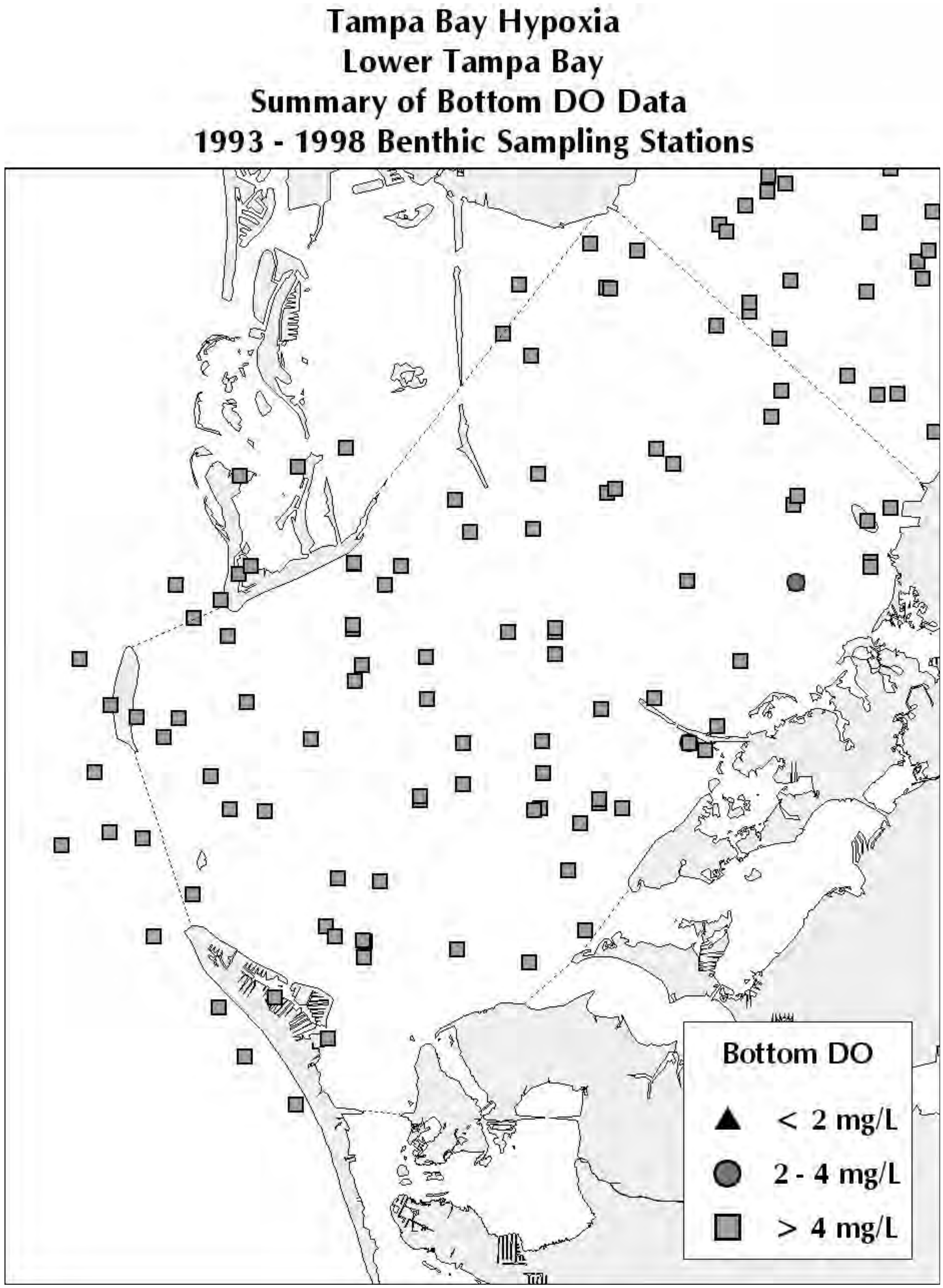

Figure 3-4. Classification of bottom DO data from Lower Tampa Bay - Benthic Monitoring Program stations (1993-1998).

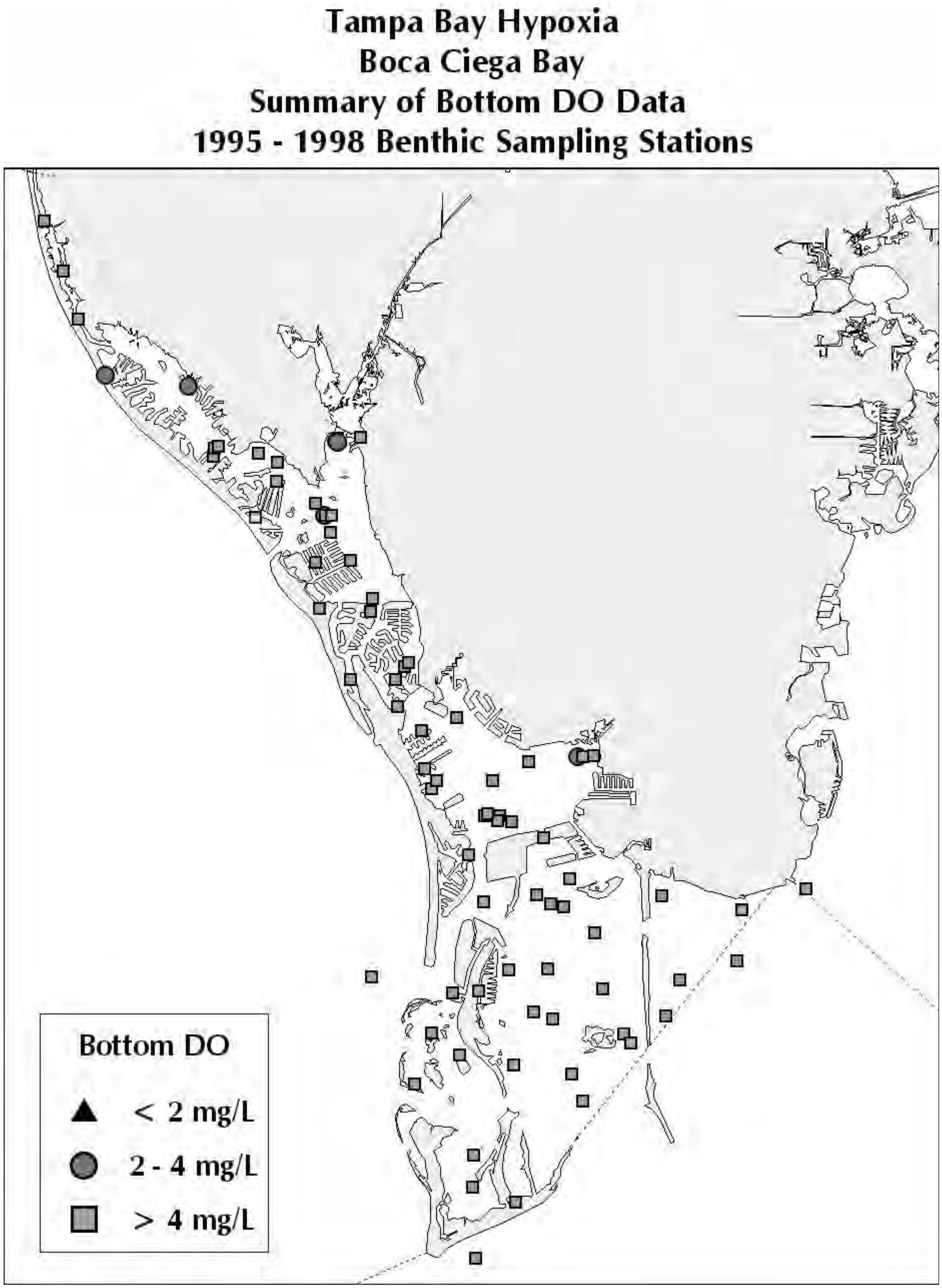

Figure 3-5. Classification of bottom DO data from Boca Ciega Bay - Benthic Monitoring Program stations (1993-1998).

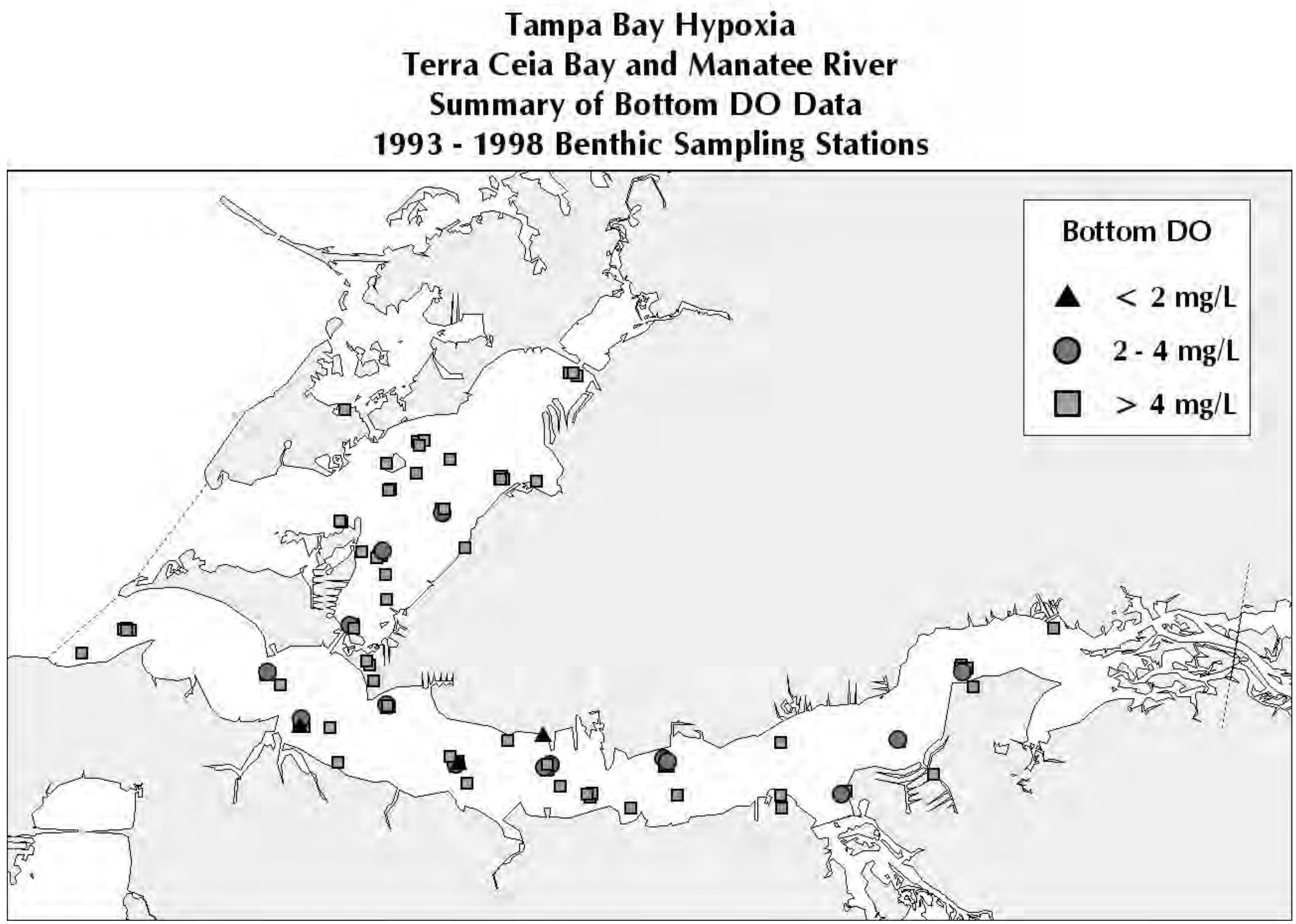

Figure 3-6. Classification of bottom DO data from Terra Ceia Bay and Manatee River - Benthic Monitoring Program stations (1993-1998).

QUESTION 4

What is the areal extent of hypoxia in Tampa Bay?

One measure of the potential risk faced by the Tampa Bay estuary by the occurrence of hypoxic conditions is its areal extent. To provide a ***relative*** measurement of the areal extent of hypoxic and low DO conditions (<2 mg/L and <4 mg/L, respectively), the bottom DO data were applied to an interpolation procedure to develop contour maps for the bay. The interpolation procedure chosen was an inverse distance squared method as provided by the Surfer software package. This procedure does extend the data beyond the range of observed values, but can create concentric contours around data points. A simplified shoreline of the bay was used to estimate the areal extent of DO conditions less than 2 mg/L and less than 4 mg/L.

Figures 4-1 and 4-2 present the bottom DO contour maps created from the EPCHC ambient monitoring data collected in August and September 1998, respectively. Hypoxic conditions (<2 mg/L) were found in Hillsborough Bay in both months. Hypoxia was found in Old Tampa Bay in September and in Middle Tampa Bay in August.

The estimates of the areal extent of low DO conditions in the mainstem portion of Tampa Bay are as follows:

	Area <2 mg/L	Area <4 mg/L
August 1998	13 km^2	95 km^2
September 1998	19 km^2	149 km^2

The estimates of the areal extent of low DO conditions in Hillsborough Bay, for September only, are as follows:

	Area <2 mg/L	Area <4 mg/L
September 1998	8 km^2	64 km^2

Figure 4-3 presents the bottom DO contour map created from the benthic monitoring data collected in September and October 1998. Hypoxic conditions (<2 mg/L) were found only in Hillsborough Bay. The estimates of the areal extent of low DO conditions in the mainstem portion of Tampa Bay are as follows:

	Area <2 mg/L	Area <4 mg/L
Late Summer 1998	7 km^2	67 km^2

To put these estimates into perspective, the total area extended by the interpolation procedure is approximately 2,430 km^2. Therefore, it is clear that the areas of hypoxia in Tampa Bay are relatively small.

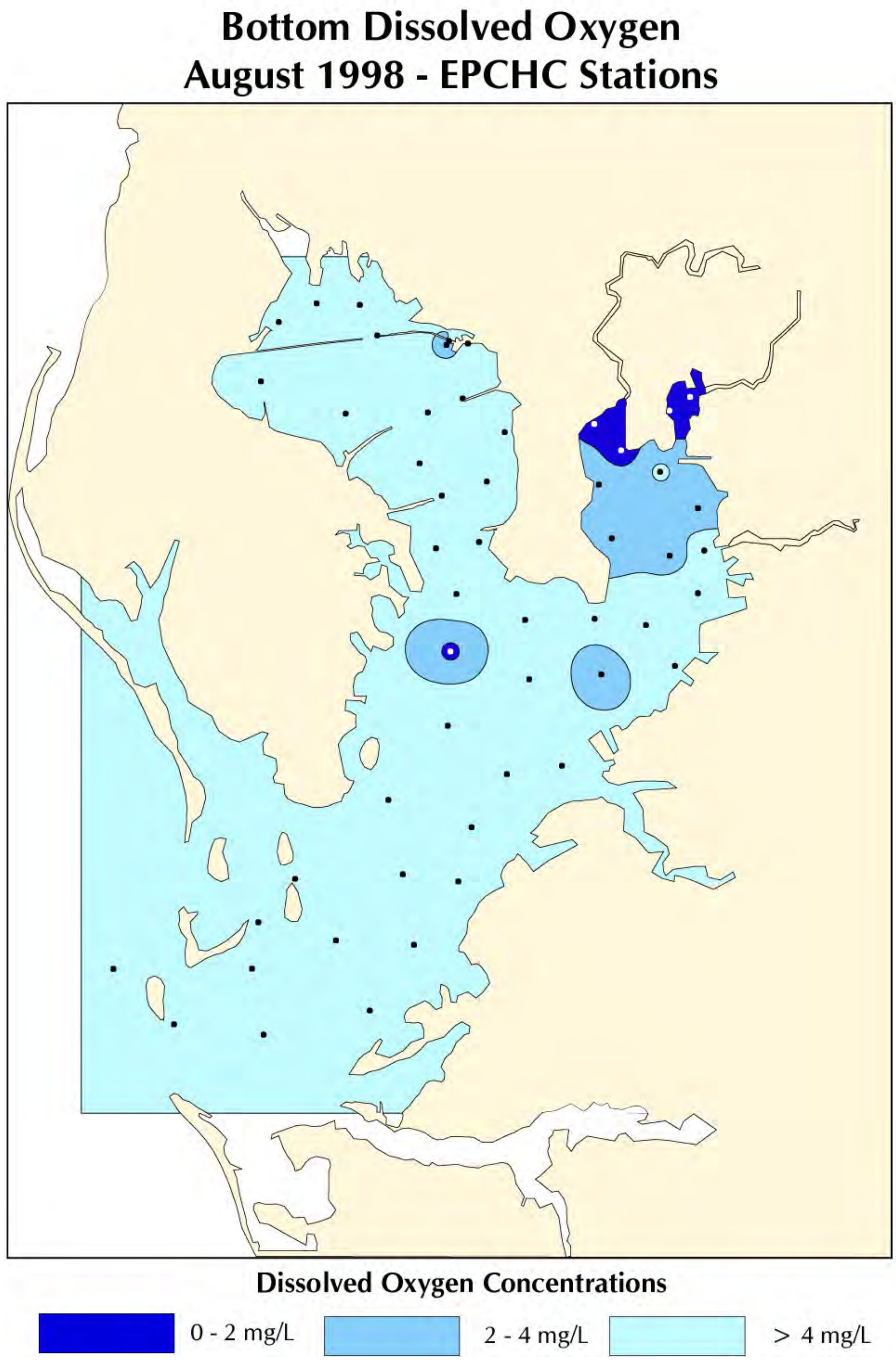

Figure 4-1. Bottom DO contour map developed from August 1998 data collected at EPCHC Ambient Water Quality Monitoring stations.

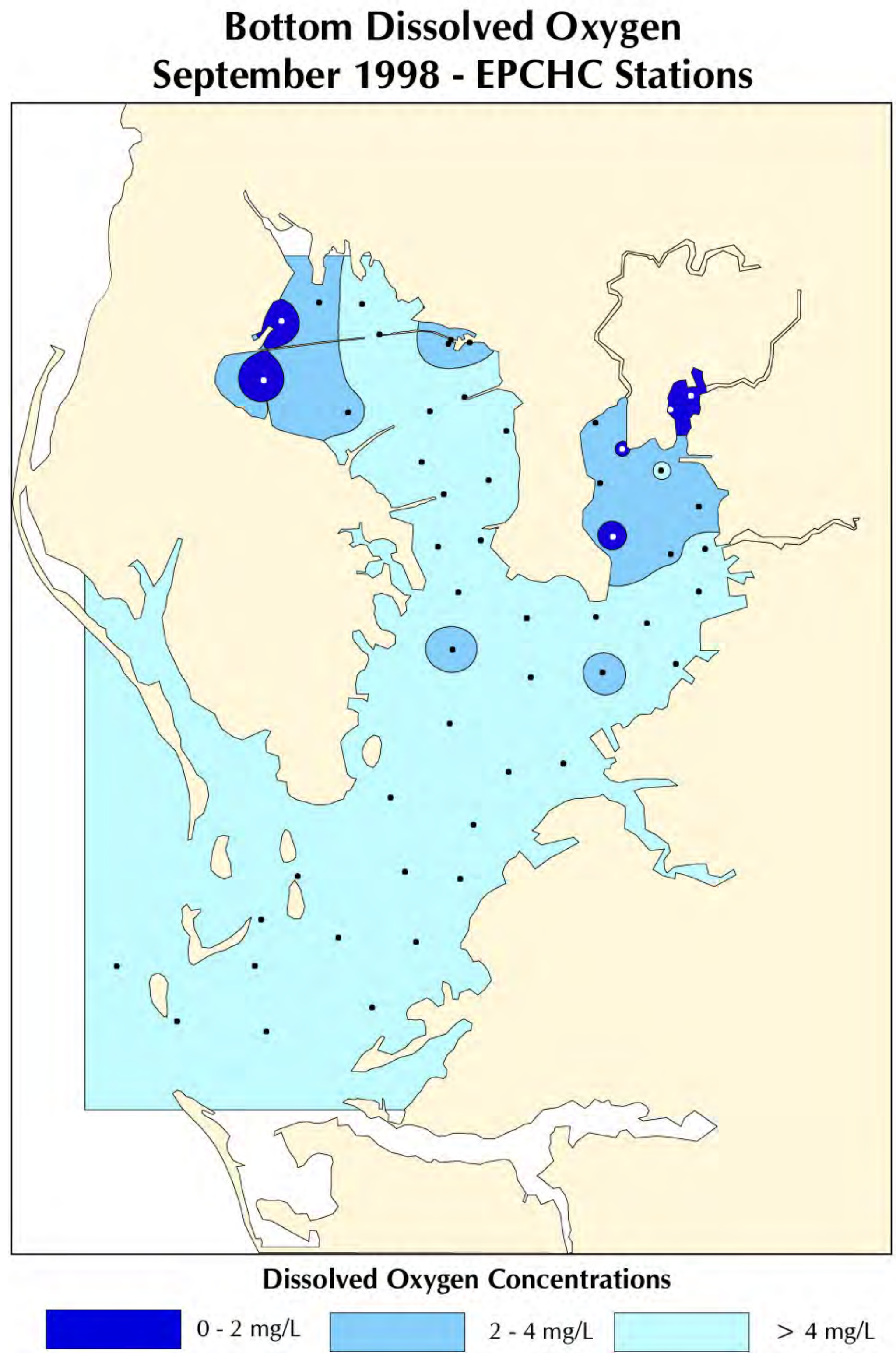

Figure 4-2. Bottom DO contour map developed from September 1998 data collected at EPCHC Ambient Water Quality Monitoring stations.

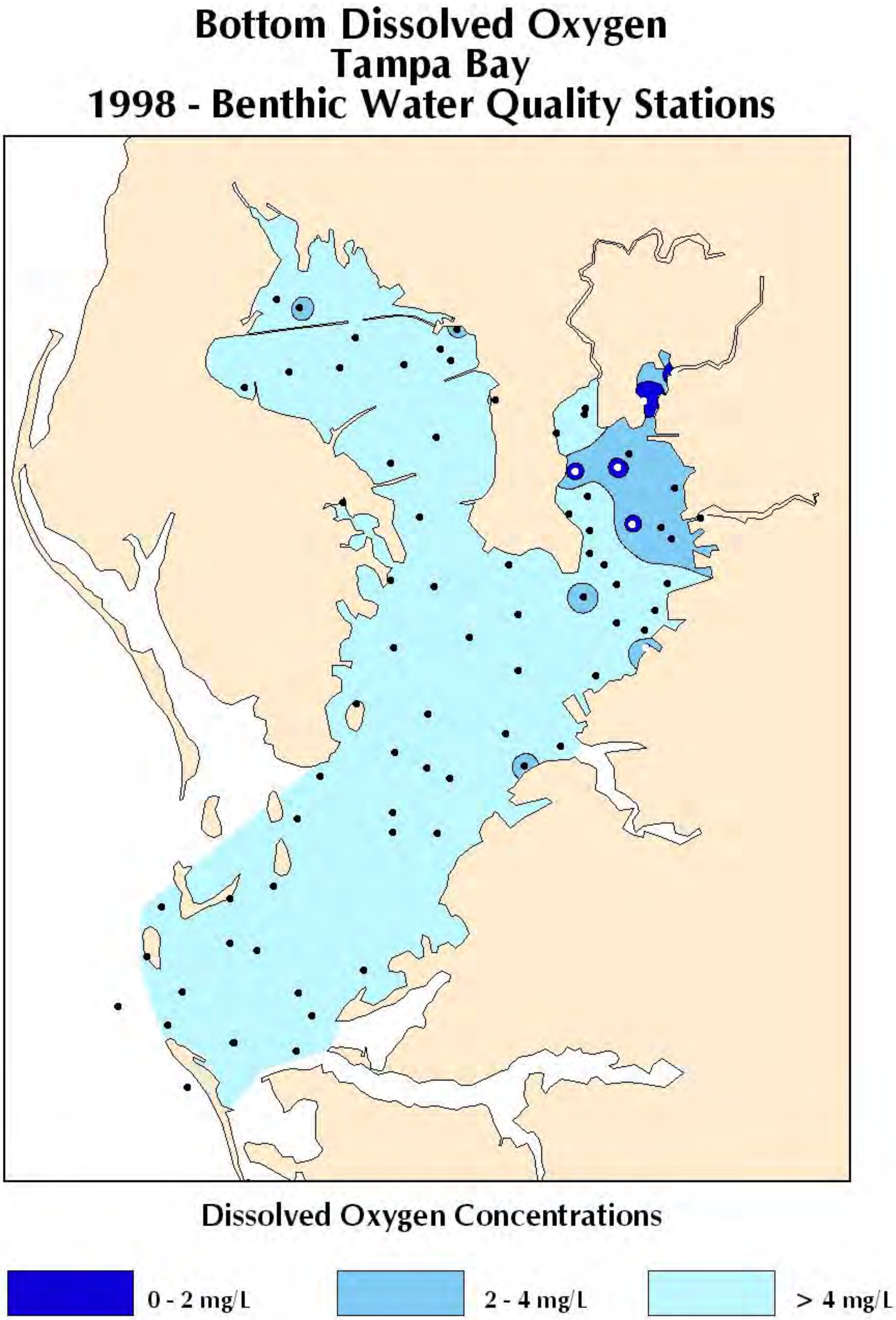

Figure 4-3. Bottom DO contour map developed from data collected at Tampa Bay Benthic Monitoring Program stations during the 1998 sampling period.

QUESTION 5

Has the areal extent of hypoxia in Tampa Bay changed over time?

Clearly, concern regarding the effects of hypoxia in Tampa Bay would be expressed if the areal extent of these conditions displayed an increasing trend over time. To address this question, the areal extents of hypoxic and low DO conditions (<2 mg/L and <4 mg/L, respectively) were estimated for the months of August and September for the 1975 through 1998 EPCHC Ambient Monitoring Program sampling period. The same methods employed to estimate the current areal extent were applied, using a simplified shoreline of the bay. Maps displaying the extent of low DO conditions for August and September of each year are found in the Appendix.

Figures 5-1 and 5-2 present the time series of areal estimates of bottom DO concentrations less than 2 mg/L and less than 4 mg/L observed in August from 1975 through 1998 in the mainstem portion of the bay. Figures 5-3 and 5-4 present similar estimates for September from 1975 through 1998, for both the mainstem portion of the bay and for Hillsborough Bay. Table 5-1 presents the mainstem Tampa Bay estimates for August and September. Recall that the total area extended by the interpolation procedure for the entire bay is approximately 2,430 km^2, so that the estimated areas of low bottom DO conditions shown in Table 5-1 are relatively small. Table 5-2 presents the Hillsborough Bay estimates for September, in tabular form. The total area of Hillsborough Bay is approximately 108 km^2, so that the estimated areas of <4 mg/L bottom DO conditions in this segment are sometimes a large proportion of the segment. Hypoxic (<2 mg/L) conditions are generally found in only a small proportion of Hillsborough Bay, however.

There are no apparent temporal trends in the areal extent of hypoxia in either August or September for mainstem Tampa Bay, or in September for Hillsborough Bay. There is a great deal of year-to-year variation in the estimates. Recently, relatively high estimates were found in 1995, 1997, and 1998, the last three years in which relatively high rainfall amounts were observed.

Table 5-1. Areal extents of low bottom DO conditions, km^2, in August and September in mainstem Tampa Bay, from EPCHC ambient monitoring data.

	August		September	
Year	Area # 4 mg/L (km^2)	Area # 2 mg/L (km^2)	Area # 4 mg/L (km^2)	Area # 2 mg/L (km^2)
1975	145	77	46	1
1976	Insufficient Data	Insufficient Data	43	0
1977	15	0	85	27
1978	61	1	8	1
1979	92	9	74	17
1980	15	0.5	Insufficient Data	Insufficient Data
1981	26	5	61	13
1982	121	17	12	4
1983	Insufficient Data	Insufficient Data	75	17
1984	28	6	Insufficient Data	Insufficient Data
1985	71	7	Insufficient Data	Insufficient Data
1986	Insufficient Data	Insufficient Data	58	6
1987	76	4	45	1
1988	228	15	145	6
1989	68	0	98	5
1990	51	5	26	5
1991	45	6	20	2
1992	20	5	69	27
1993	44	3	84	21
1994	39	6	19	5
1995	72	14	58	18
1996	28	0	58	5
1997	118	19	34	0
1998	95	13	149	19

Table 5-2. Areal extents of low bottom DO conditions, km^2, in September in Hillsborough Bay, from EPCHC ambient monitoring data.

	Area # 4 mg/L (km^2)	Area # 2 mg/L (km^2)
1975	36	1
1976	43	0
1977	71	23
1978	5	1
1979	73	17
1980	Insufficient Data	Insufficient Data
1981	60	13
1982	9	4
1983	58	17
1984	Insufficient Data	Insufficient Data
1985	80	4
1986	42	6
1987	25	1
1988	27	5
1989	69	5
1990	22	5
1991	18	2
1992	68	27
1993	72	21
1994	19	5
1995	56	18
1996	47	5
1997	6	0
1998	64	8

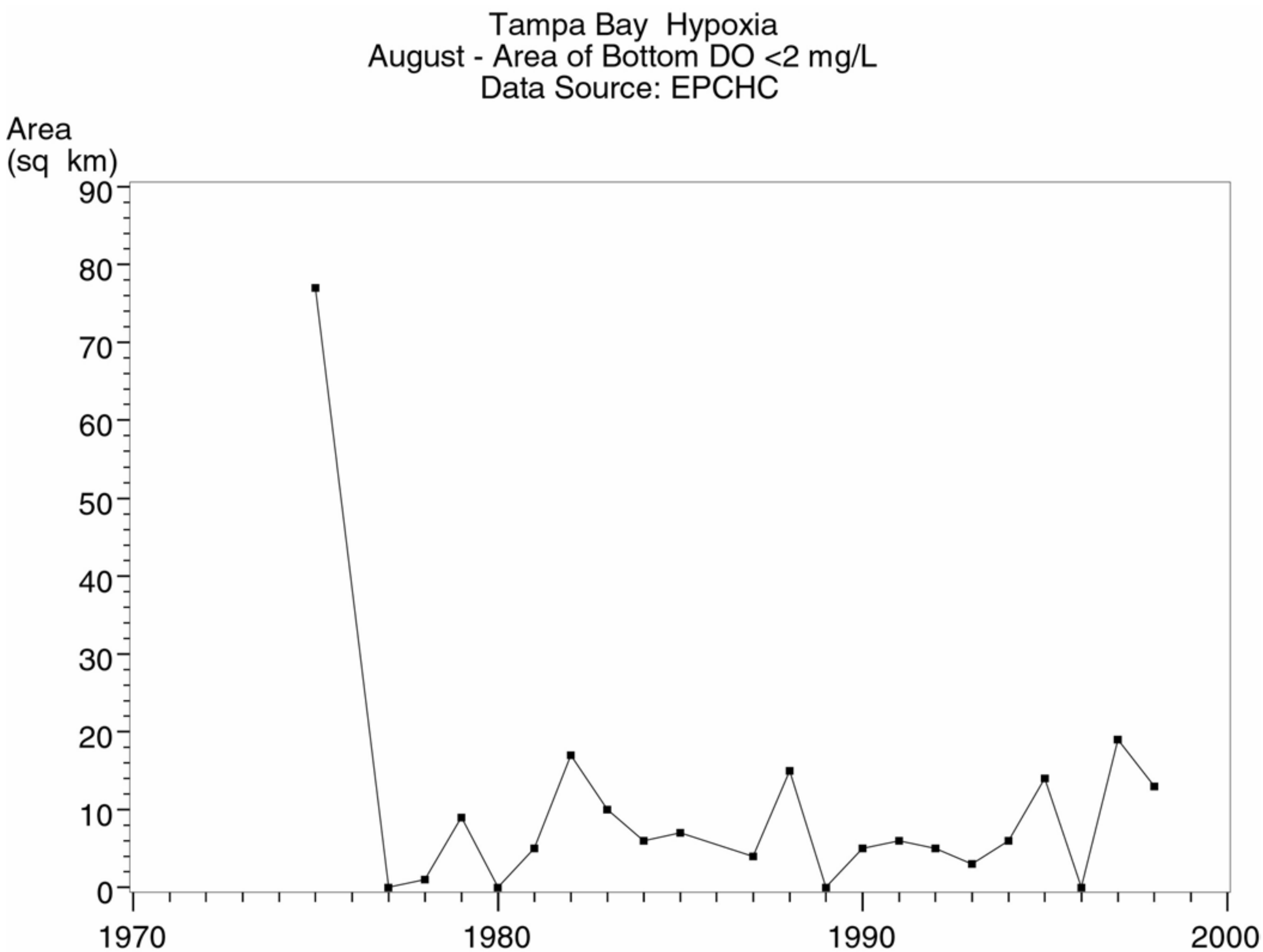

Figure 5-1. Time series of areal estimates of bottom DO conditions less than 2 mg/L in August, mainstem Tampa Bay, from 1975 through 1988 using data collected at EPCHC Ambient Water Quality Monitoring stations.

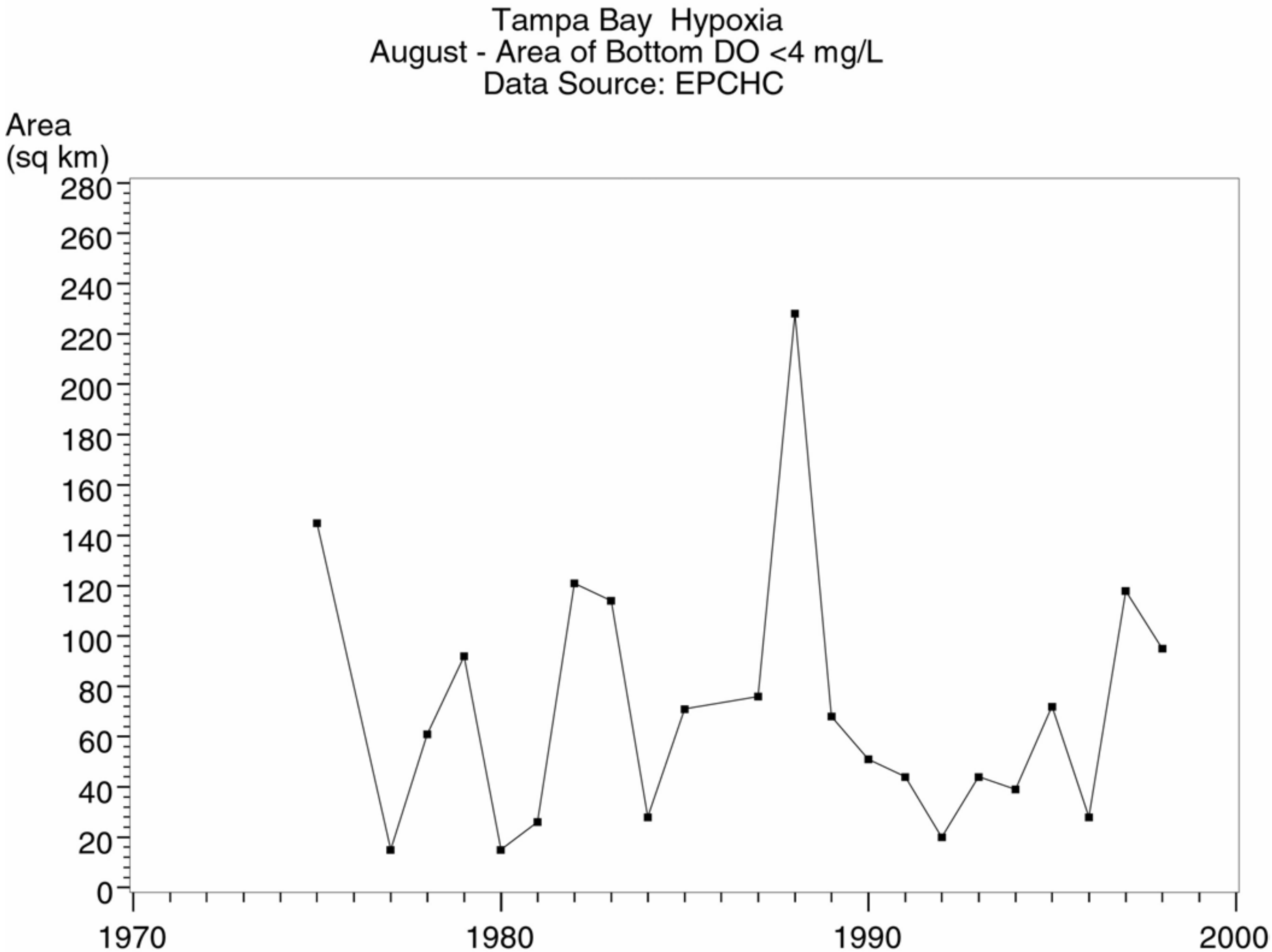

Figure 5-2. Time series of areal estimates of bottom DO conditions less than 4 mg/L in August, mainstem Tampa Bay, from 1975 through 1988 using data collected at EPCHC Ambient Water Quality Monitoring stations.

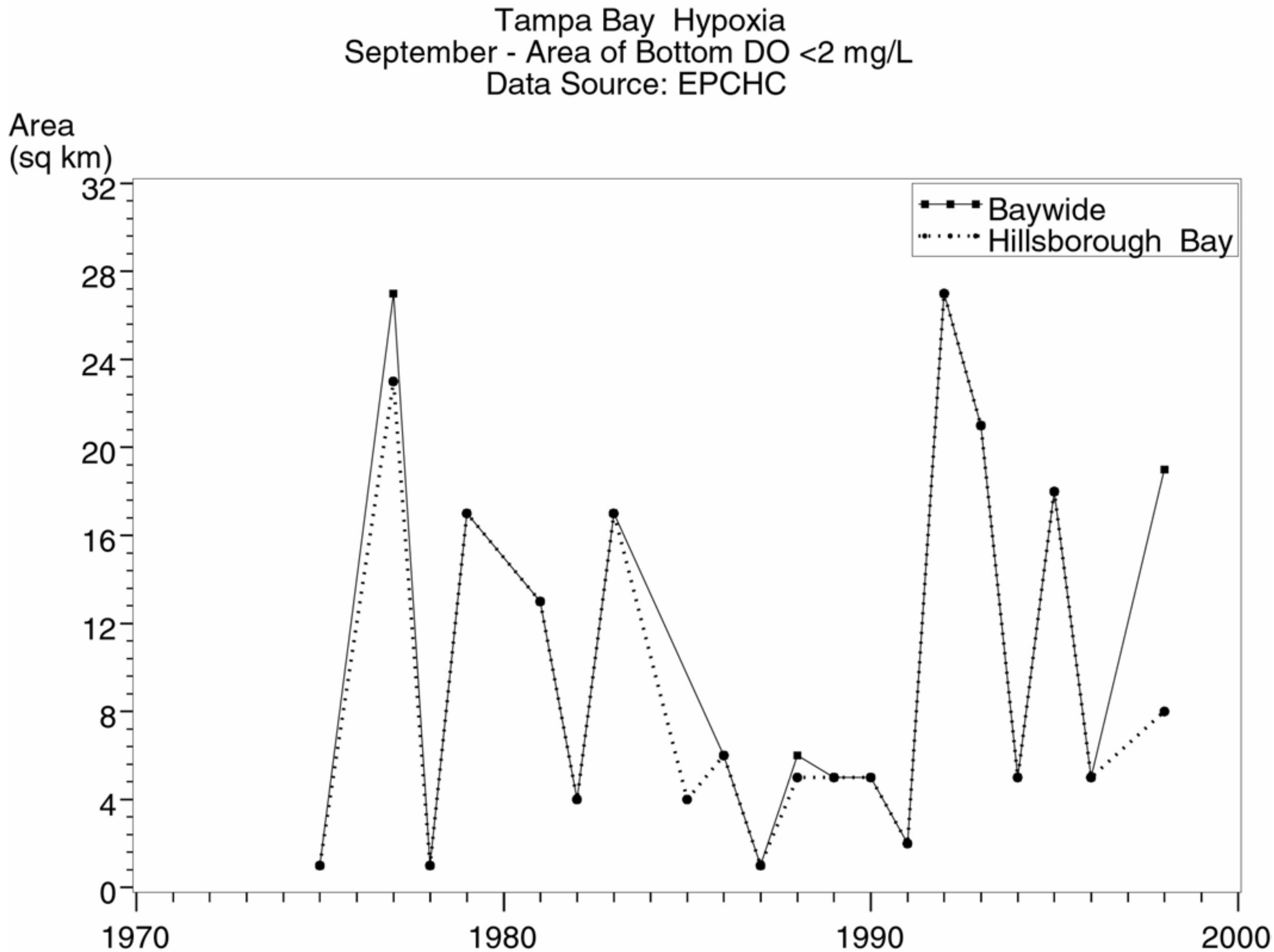

Figure 5-3. Time series of areal estimates of bottom DO conditions less than 2 mg/L in September, mainstem Tampa Bay and Hillsborough Bay, from 1975 through 1988 using data collected at EPCHC Ambient Water Quality Monitoring stations.

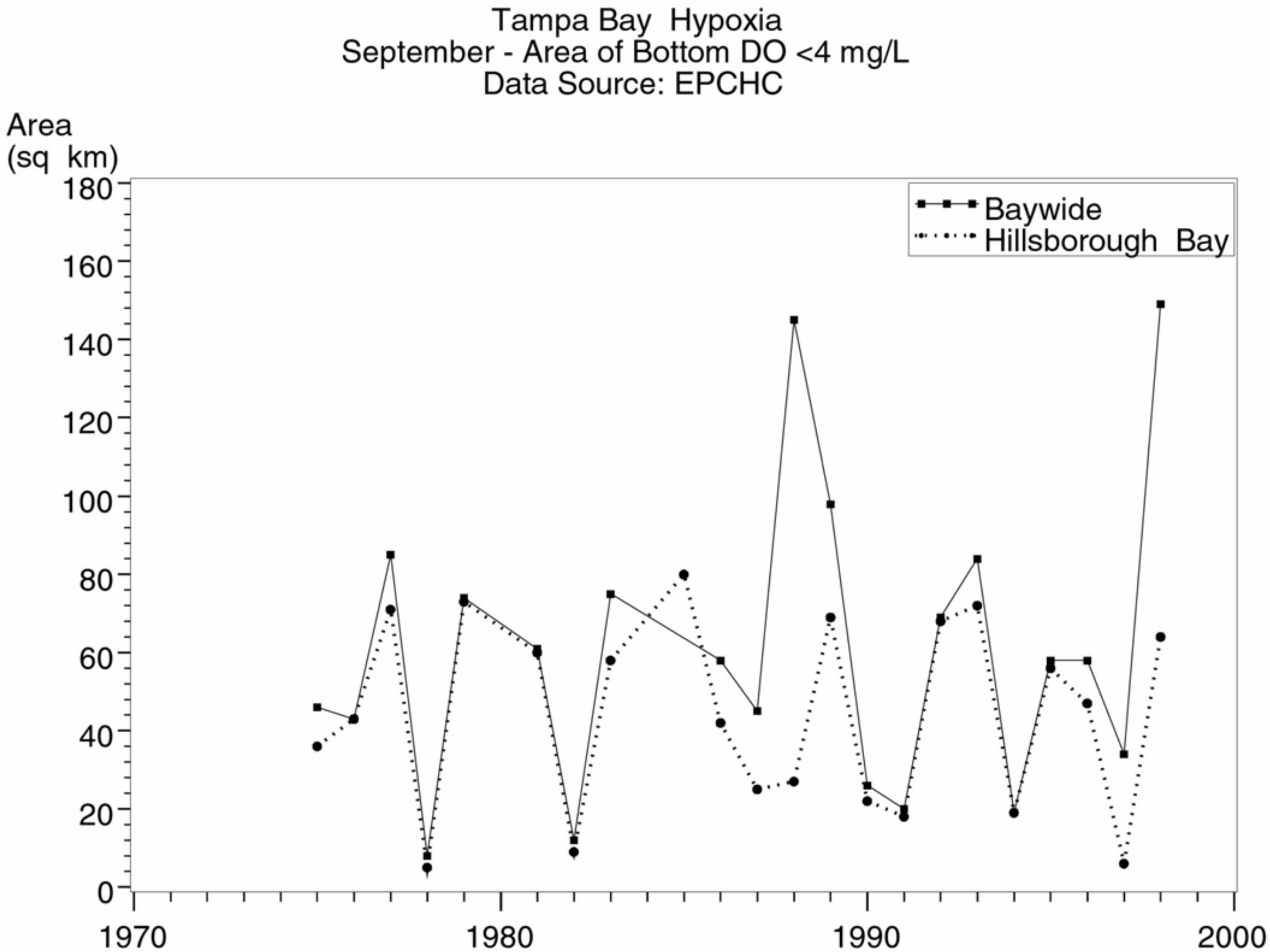

Figure 5-4. Time series of areal estimates of bottom DO conditions less than 4 mg/L in September, mainstem Tampa Bay and Hillsborough Bay, from 1975 through 1988 using data collected at EPCHC Ambient Water Quality Monitoring stations.

QUESTION 6

What are the major factors that affect the variation in the areal extent of hypoxia in Tampa Bay?

There are a number of factors that can contribute to the year-to-year variation in the areal extent of hypoxia. These are typically factors that either affect the supply of organic material available for microbial decomposition and respiration, the residence time, or the degree of stratification.

The following factors have been examined for their potential role in determining the inter-annual variation in the areal extent of hypoxia in Tampa Bay:

- Rainfall
- River flow
- BOD
- Chlorophyll concentrations
- Salinity
- Temperature
- Degree of Stratification
- Nitrogen Loading.

To assess the relative influence these factors have on the inter-annual variability in the areal extent of hypoxia, Spearman rank correlations were calculated, which quantify the degree of relationship between two variables. Table 6-1 presents the results of the correlations.

Significant positive relationships were found between the areal extent of hypoxia in Tampa Bay in August and spring rainfall, summer flow in the Hillsborough River, and the degree of stratification in the summer months (July-August). Thus, the areal extent of hypoxia is expected to increase under high rainfall and flow conditions that likely contribute to the degree of stratification due to salinity differences. No significant relationship was found between external nitrogen loads and the areal extent of hypoxia.

Table 6-1. Results of correlation analyses relating the areal extent of hypoxia in August from 1975 through 1998 with a series of factors that may affect the inter-annual variation in the extent of hypoxia. * significant at p=0.05.

FACTOR	Spearman r
Rainfall - July-August	0.39
Rainfall - April-July	0.57 *
Hillsborough River Flow - July-August	0.49 *
Hillsborough River Flow - April-July	0.15
BOD - July-August	0.05
Chlorophyll - July-August	0.07
Degree of Stratification – July-August	0.71 *
Bottom Water Temperature	-0.08
Bottom Salinity – July-August	-0.09
TN Load – July-August	0.40
TN Load – April-July	-0.17

QUESTION 7

Is there a relationship between mid-day and minimum DO?

Are mid-day data adequate to identify areas where hypoxic conditions occur during the rest of the day?

Most of the DO data collected in Tampa Bay represent midday conditions. It has long been known that in many water bodies, especially relatively productive waters, significant diel variation in DO concentrations is common. During daylight hours the rate of production of oxygen via photosynthesis exceeds the rate of respiration. Following dusk, the primary producers become oxygen consumers and, in concert with the organisms at higher trophic levels, can significantly deplete the oxygen store established in the daylight hours. In many cases, DO concentrations near daybreak are at their minima.

Since the biota respond to the entire DO regime to which they are exposed, including the DO minima, uncertainty remains as to the ability of the midday DO measurements to identify DO conditions that may be stressful to the more sensitive biota. To this end, the relationship between the midday DO concentrations and the DO minima observed during the studies of diel DO variation conducted as part of the Benthic Monitoring Program has been examined. Specifically, the midday DO (mean DO observed during the 0900 and 1400 period) was compared to both the minimum daily DO and the 5th percentile of the daily DO measurements. More than 90% of the EPCHC Ambient Monitoring Program data are collected during the 0900 to 1400 period.

Figures 7-1 through 7-6 present the results of these comparisons. In all comparisons there is a generally linear relationship between the midday DO and either the minimum or 5th percentile DO values. The relationships are not particularly strong, however.

The second closely related question deals with the ability to identify areas where hypoxia exists during some part of the day other than the midday period in which DO measurements are typically made. To address this question the results shown in Figures 7-1 through 7-6 are revisited. Each of these plots has two lines that delineate the data domain into four quadrants:

- The upper left quadrant where the midday DO is > 2 mg/L but either the minimum DO or 5th percentile value is < 2 mg/L; this represents a case where the midday DO fails to identify hypoxia when it occurs in some other portion of the day.

- The lower left quadrant where both the midday DO and either the minimum DO or 5th percentile value is < 2 mg/L; this represents a case where the midday DO successfully identifies hypoxia when it occurs in some other portion of the day.
- The upper right quadrant where both the midday DO and either the minimum DO or 5th percentile value is > 2 mg/L; this represents a case where the midday DO successfully identifies an area where hypoxia is lacking.
- The lower right quadrant where the midday DO is < 2 mg/L and neither the minimum DO nor 5th percentile value is < 2 mg/L; this represents an unusual case where the midday DO successfully identifies hypoxia when it occurs only during the midday period.

The following matrices summarize these analyses.

	Minimum DO < 2 mg/L	**Minimum DO** > 2 mg/L
Midday DO > 2 mg/L	26%	63%
MiddayDO < 2 mg/L	11%	0%

	5th Percentile DO < 2 mg/L	**5th Percentile DO** > 2 mg/L
Midday DO > 2 mg/L	22%	67%
MiddayDO < 2 mg/L	11%	0%

Clearly, approximately 25% of the observations were misclassified as lacking hypoxia by the midday DO data when hypoxic conditions did occur in some other portion of the day. However, mid-day data correctly reflect the occurrence of hypoxia approximately 75% of the time. There also appears to be a relationship between mid-day and minimum DO; however, more data will allow improvement in the quantification of this relationship.

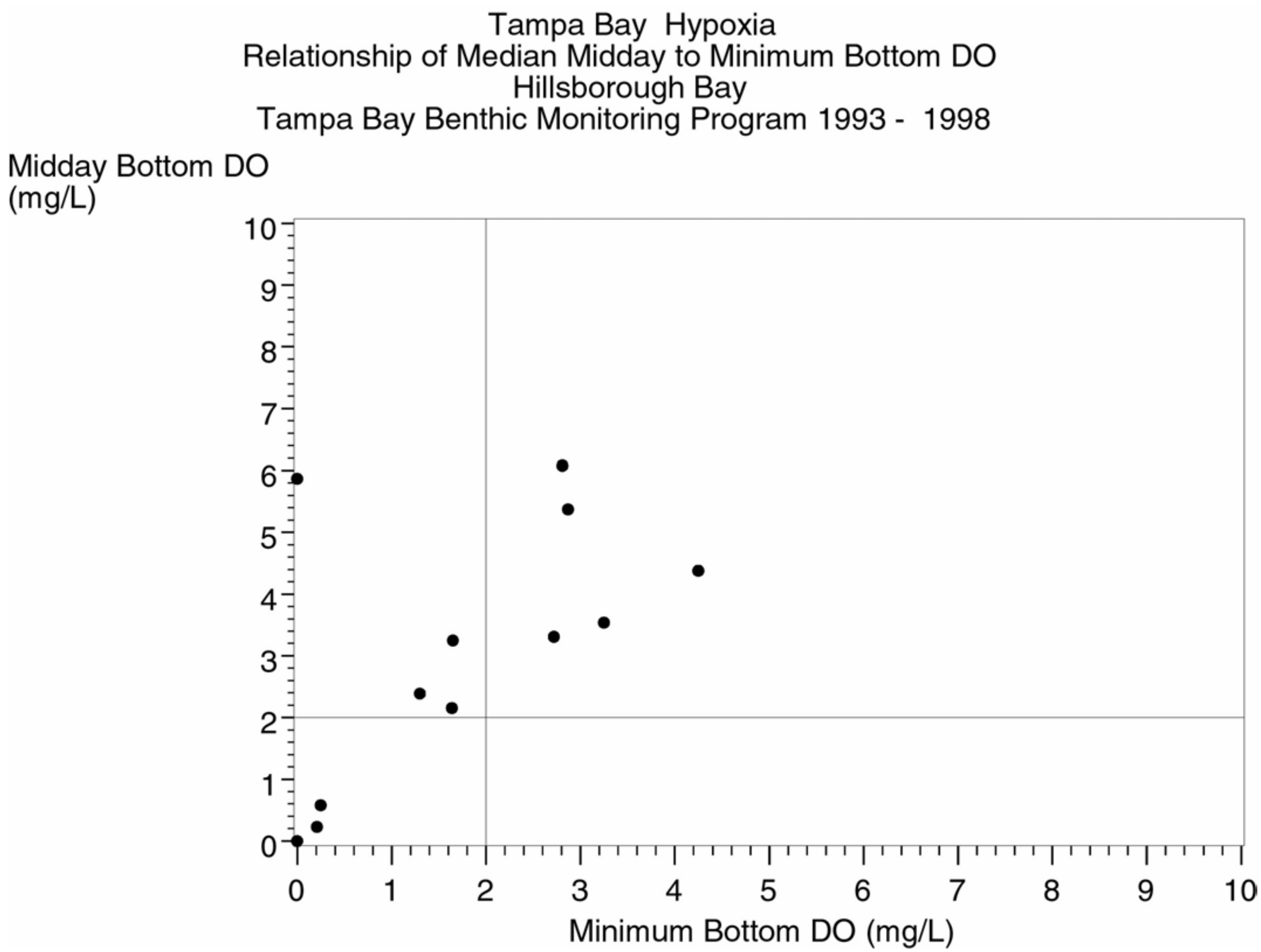

Figure 7-1. Relationship between midday and minimum bottom DO using data collected in Hillsborough Bay by the Tampa Bay Benthic Monitoring Program diel DO data - 1993-1998.

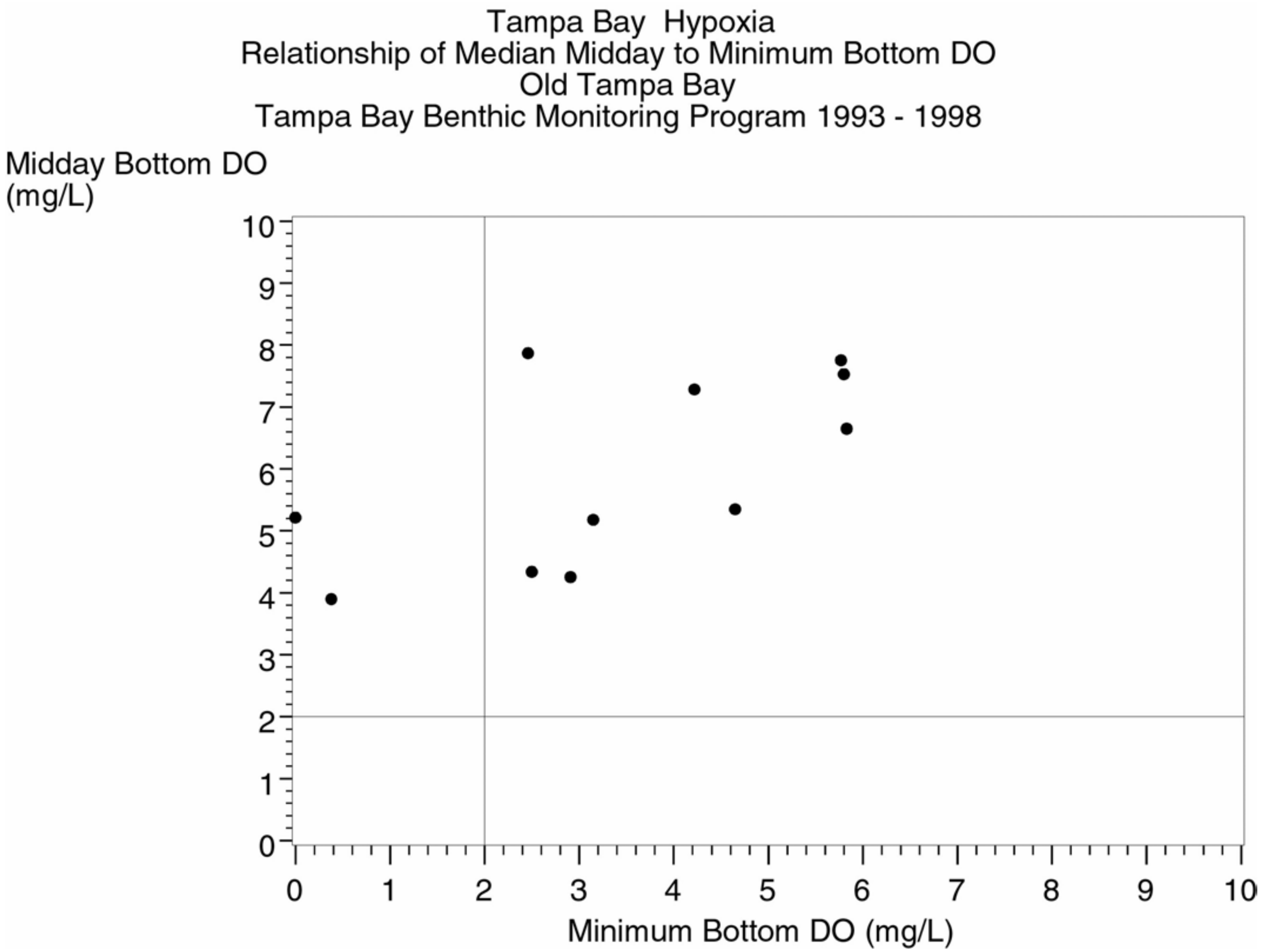

Figure 7-2. Relationship between midday and minimum bottom DO using data collected in Old Tampa Bay by the Tampa Bay Benthic Monitoring Program diel DO data - 1993-1998.

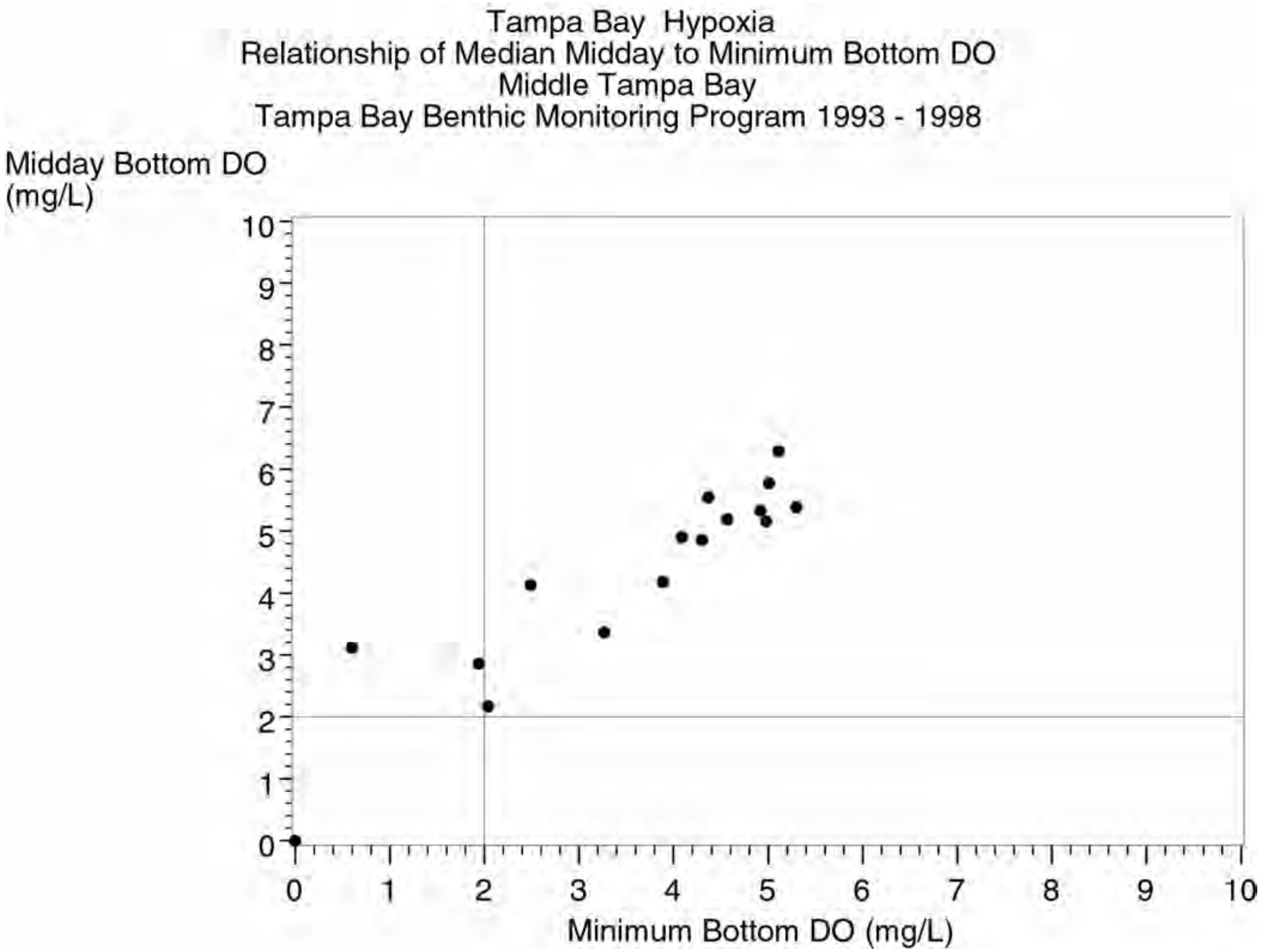

Figure 7-3. Relationship between midday and minimum bottom DO using data collected in Middle Tampa Bay by the Tampa Bay Benthic Monitoring Program diel DO data - 1993-1998.

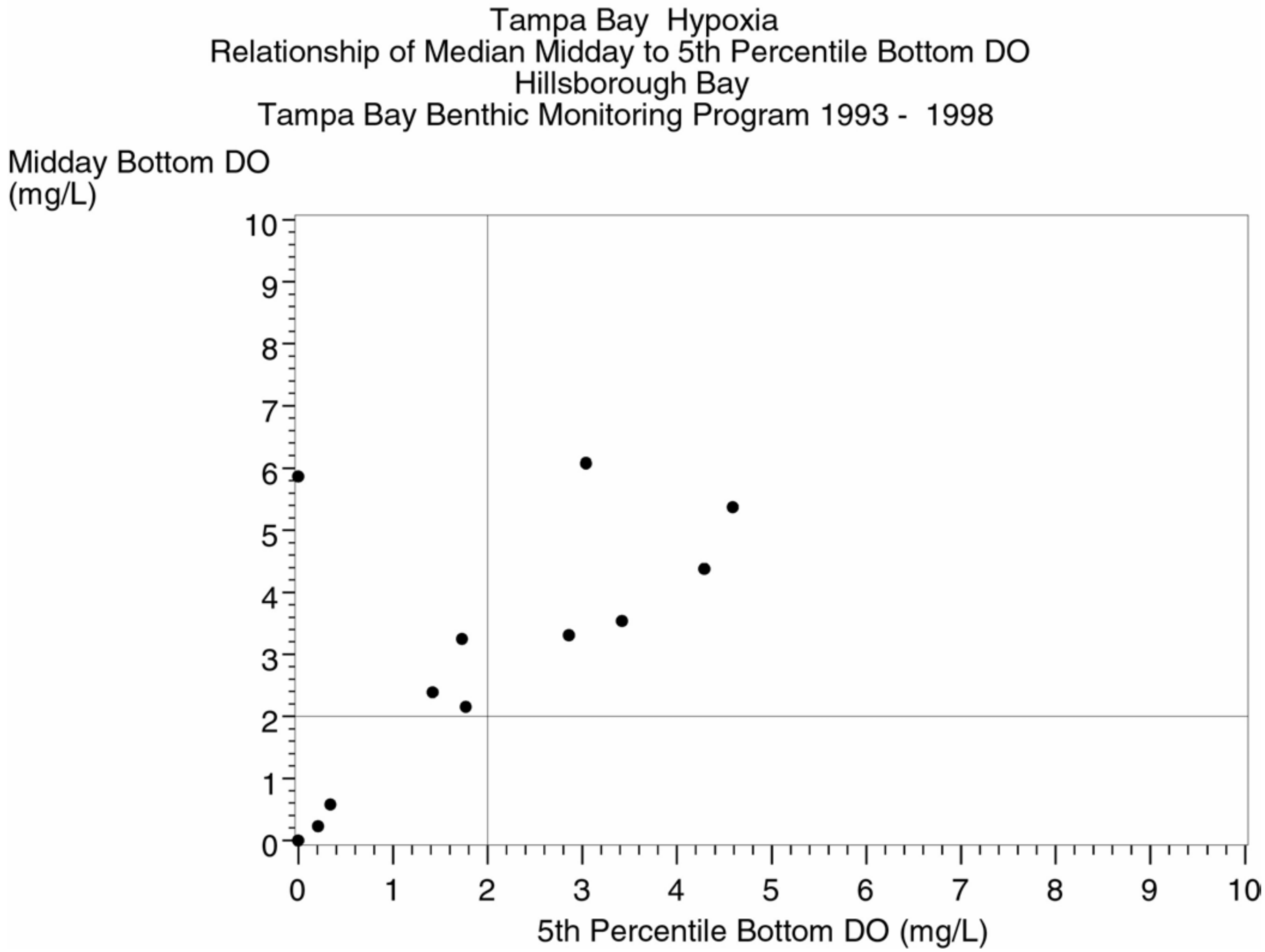

Figure 7-4. Relationship between midday and 5th percentile bottom DO using data collected in Hillsborough Bay by the Tampa Bay Benthic Monitoring Program diel DO data - 1993-1998.

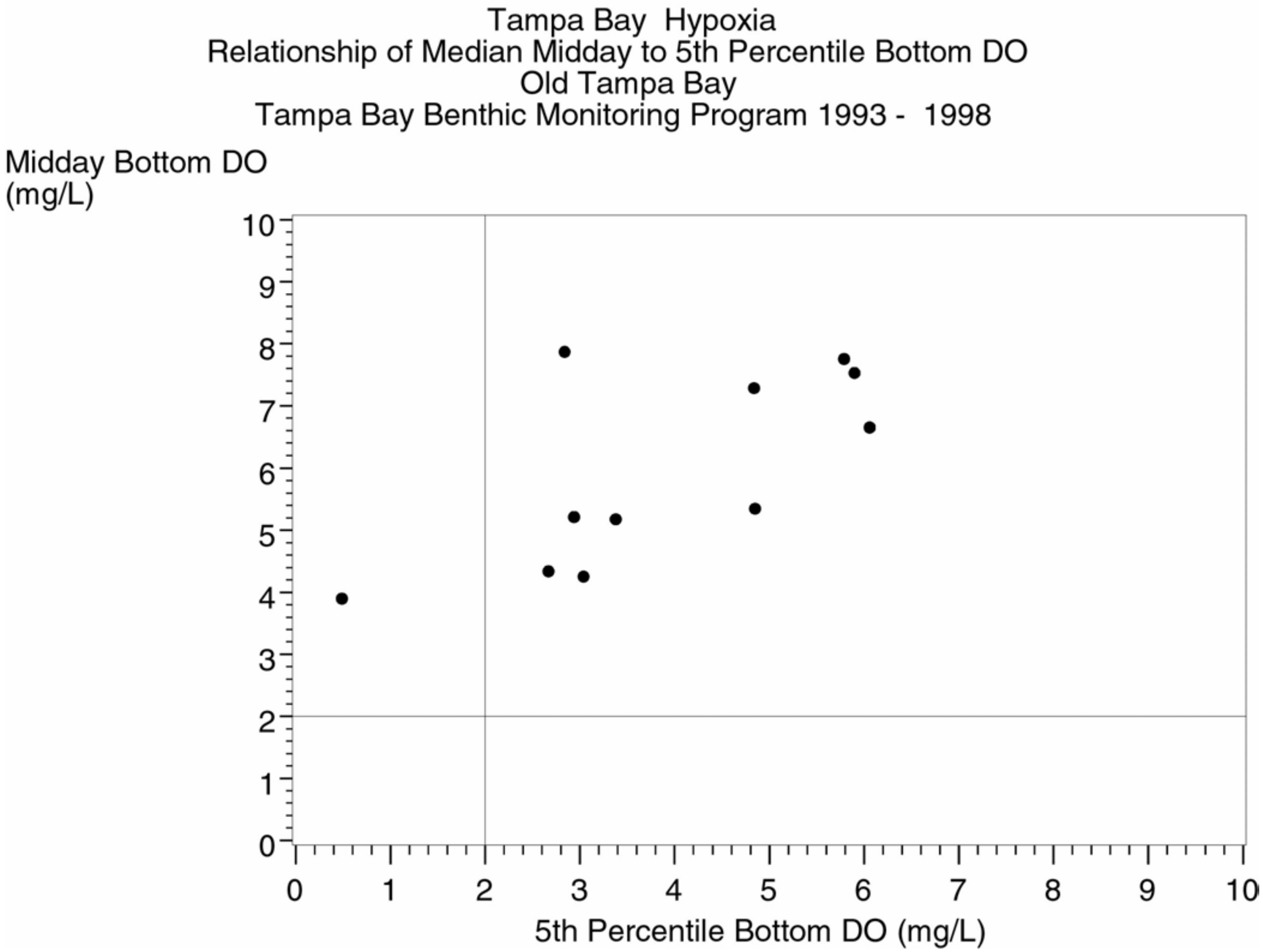

Figure 7-5. Relationship between midday and 5th percentile bottom DO using data collected in Old Tampa Bay by the Tampa Bay Benthic Monitoring Program diel DO data - 1993-1998.

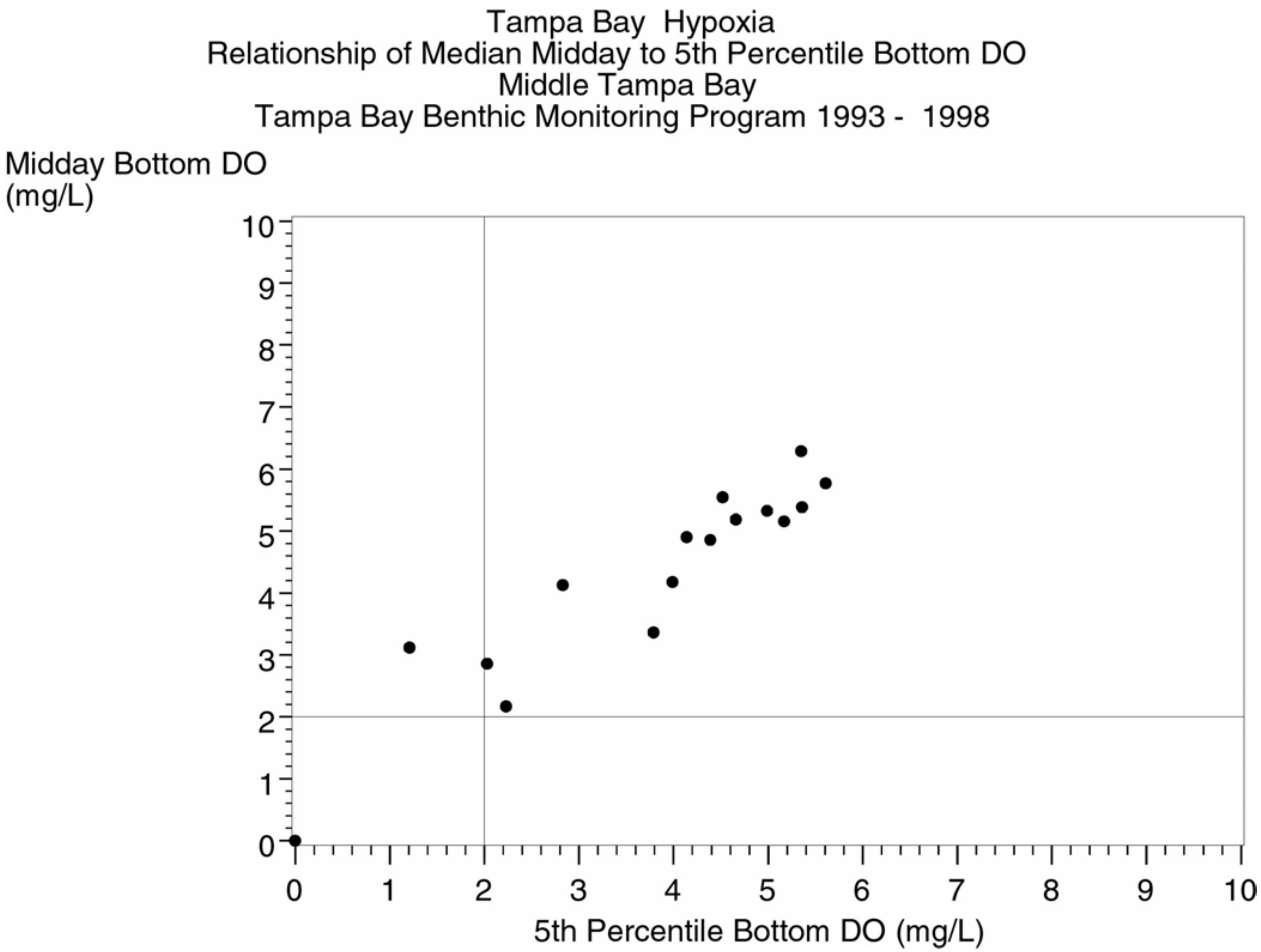

Figure 7-6. Relationship between midday and 5th percentile bottom DO using data collected in Middle Tampa Bay by the Tampa Bay Benthic Monitoring Program diel DO data - 1993-1998.

QUESTION 8

How persistent are hypoxic conditions in Tampa Bay?

The temporal persistence of hypoxic conditions is also of concern to resource managers since more prolonged exposure to low DO can be more stressful to organisms that are sensitive to hypoxia, as discussed previously. To address this question two temporal scales were examined. In the first case, the EPCHC Ambient Monitoring Program data were analyzed to determine if the mean duration of hypoxic conditions has increased over time. Secondly, the diel DO data were analyzed to determine if the persistence of hypoxia during a single day has increased over time.

Table 8-1 presents the mean number and duration of hypoxic events in Hillsborough Bay from1975 through 1998, as derived from the EPC ambient monitoring data. The number of hypoxic events is the sum of the number of events at each monitoring station in Hillsborough Bay. The number of hypoxic events has varied appreciably over time. In recent years there appears to be tendency towards a larger number of events than observed in the early 1990s.

There has also been appreciable interannual variation in the mean monthly duration of hypoxic events in Hillsborough Bay (Table 8-1). During the 1980s the duration of hypoxia varied greatest. There is no apparent temporal trend in the duration of hypoxic events in recent years. The mean duration is typically two months or less.

The mean durations of hypoxic events at an hourly temporal scale were estimated based on the diel data sets collected by the benthic monitoring program in the mid to late 1990s. Mean durations are relatively short, ranging from 6.4 hours in Hillsborough Bay to 5.5 hours in Old Tampa Bay and 4.5 hours in Middle Tampa Bays.

Table 8-1. Number and mean duration of hypoxic events in Hillsborough Bay - EPCHC Ambient Monitoring Program.

Year	Number of Hypoxic Events	Mean Duration of Hypoxic Events (months)
1975	8	1.5
1976	9	1
1977	10	1.1
1978	6	1
1979	7	1.4
1980	2	1.5
1981	5	1.8
1982	8	1.5
1982	5	3
1984	3	1.7
1985	6	1.5
1986	8	1.9
1987	4	2
1988	4	1.5
1989	9	1.8
1990	2	3.5
1991	6	1.8
1992	7	2
1993	7	2
1994	11	1.5
1995	10	1.8
1996	10	1
1997	10	1.4
1998	6	2.8

QUESTION 9

Are there long-term trends in bottom DO concentrations in Tampa Bay?

Again, concern regarding the effects of hypoxia in Tampa Bay would be expressed if DO concentrations displayed a decreasing trend over time. Such trends could well be indicative of worsening conditions where respiration rates exceed the rates of oxygen production and re-oxygenation. To address this question, the long-term trends in bottom DO concentrations were estimated using methods recently employed by Janicki et al. (2001) to assess trends in water quality of Tampa Bay. These methods include both nonparametric and parametric tests.

Three series of trends tests were performed. The first entailed an assessment of the long-term trends in the mean bottom DO concentrations by bay segment. Figures 9-1 through 9-4 present time series plots of the mean monthly bottom DO concentrations in Hillsborough Bay, Old Tampa Bay, Middle Tampa Bay, and Lower Tampa Bay. The data analyzed were collected by the EPCHC Ambient Monitoring Program. Table 9-1 summarizes the results of these long-term trend analyses.

Table 9-1. Long-term trend test results examining mean monthly bottom DO concentration by bay segment. EPCHC Ambient Monitoring Program

Bay Segment	Seasonal Kendall τ Test	Parametric Test
Old Tampa Bay	Negative	Negative
Hillsborough Bay	No Trend	No Trend
Middle Tampa Bay	Negative	Negative
Lower Tampa Bay	Negative	Negative

No significant trend in bottom DO concentrations in Hillsborough Bay were detected. All other bay segments displayed significant decreasing trends in mean bottom DO concentrations. Inspection of the test results shows that the slope of these trends is relatively small; thus, the rate of change is small. The time series plots show that the decreasing trend is due to a reduction in the higher range of bottom DO concentrations. Thus, the DO maxima are decreasing which may well be due to the reductions in chlorophyll concentrations, especially those resulting from large algal blooms that may have led to high DO concentrations during the midday conditions monitored by the EPCHC. Clearly, there does not appear to be an increase in the preponderance of low DO values over time.

The second series of trend tests examined the long-term trends in only August and September bottom DO values in the four mainstem bay segments, using data collected by the EPCHC Ambient Monitoring Program. Nonparametric trend tests were performed for August, September, and mean August-September bottom DO. Only in Old Tampa Bay in September was a significant trend in bottom DO found, with a rate of decrease of 0.042 mg/L per year. No significant trends were found in any other bay segment in August or September.

The third series of tests examined the bottom DO concentrations from those stations where hypoxic conditions are frequently found. These stations included EPCHC 54, 55, and 58 in Hillsborough Bay, and 61 and 62 in Old Tampa Bay. Additionally, the long-term trends in bottom DO concentrations at three stations (4, 12, and 13) visited by the City of Tampa Bay Study Group were also analyzed. Table 9-2 presents the results of these trend tests. Figures 9-5 through 9-12 present time series plots of the monthly bottom DO concentrations at these stations.

Table 9-2. Long-term trend test results examining monthly bottom DO concentration at several selected stations from the EPCHC Ambient Monitoring Program and City of Tampa Bay Study Group.

Station	Seasonal Kendall τ Test	Parametric Test
Hillsborough Bay		
Station 54	Negative	Negative
Station 55	Negative	Negative
Station 58	No Trend	-
Old Tampa Bay		
Station 61	No Trend	Negative
Station 62	No Trend	-
BSG		
Station 4	Negative	-
Station 12	No Trend	-
Station 13	No Trend	Negative

Again mixed results were obtained, with either no significant trend or significant negative trends in bottom DO concentrations. As was observed in the mean bottom DO trend tests, the significant decreasing trends were due to lower DO values in the high range and not a decrease in the lower DO values over time. The rates of change for the significant trends were all less than 0.05 mg/L/year.

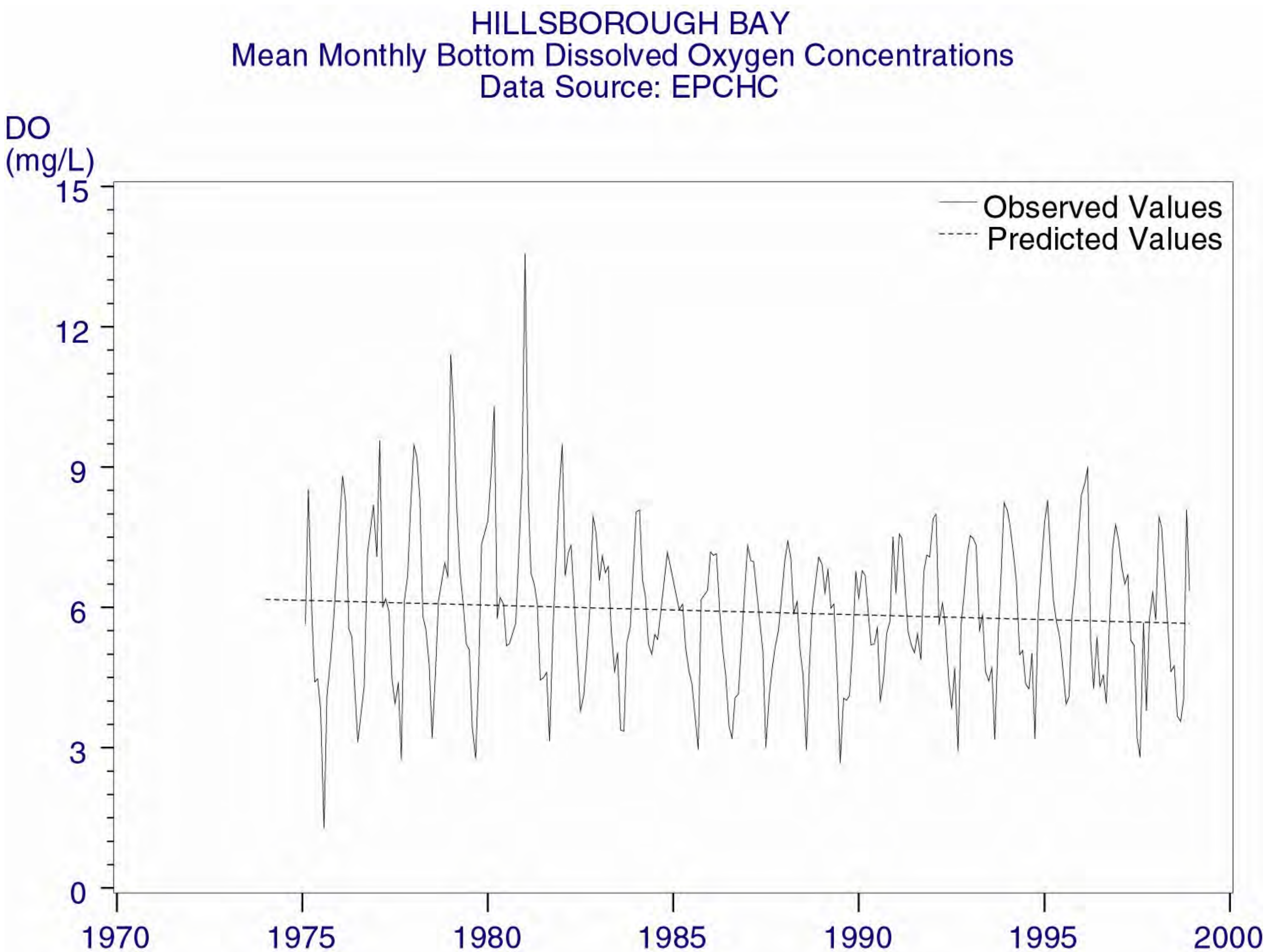

Figure 9-1. Time series of mean monthly bottom DO concentrations in Hillsborough Bay using data collected at EPCHC Ambient Water Quality Monitoring stations.

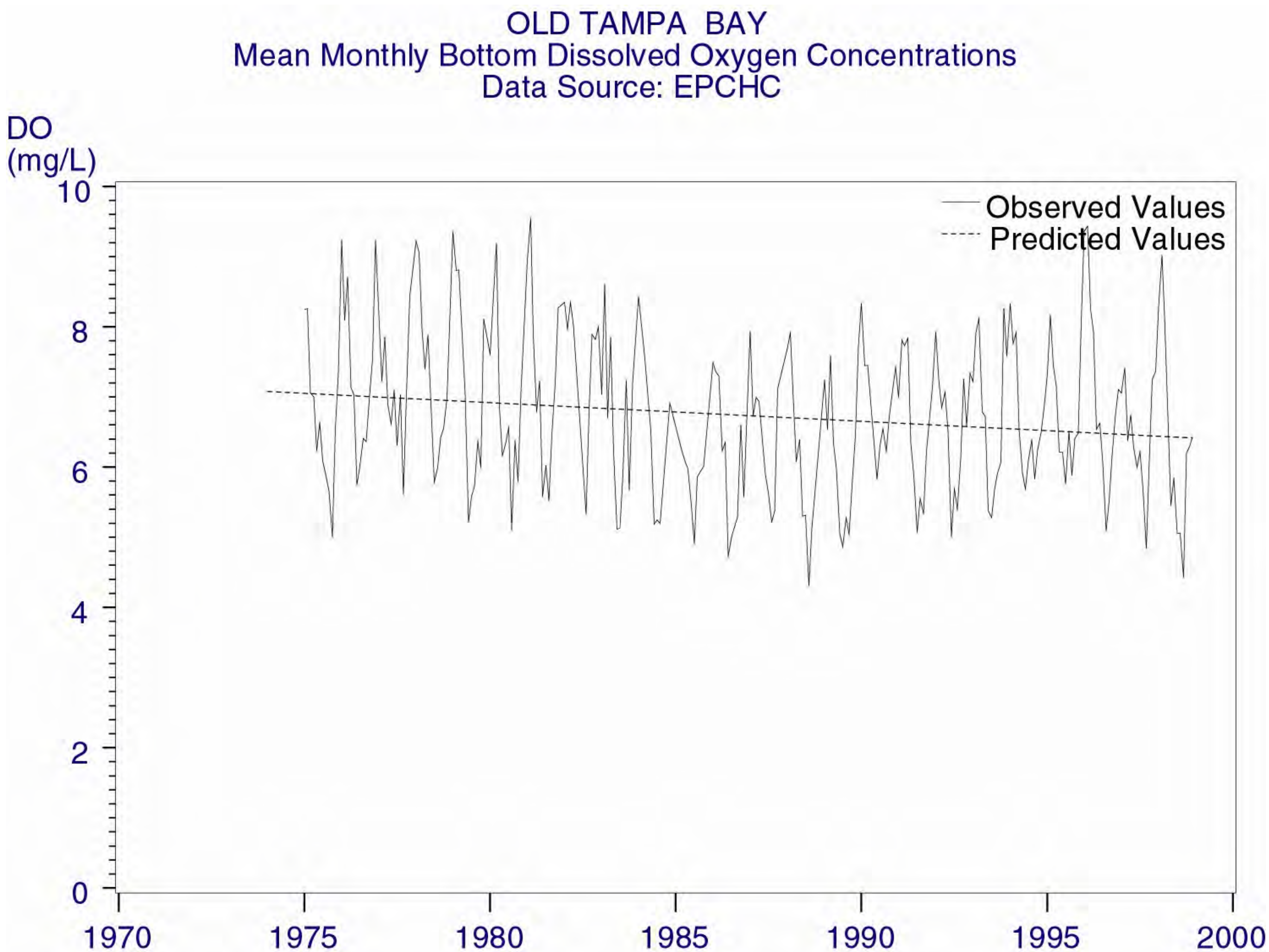

Figure 9-2. Time series of mean monthly bottom DO concentrations in Old Tampa Bay using data collected at EPCHC Ambient Water Quality Monitoring stations.

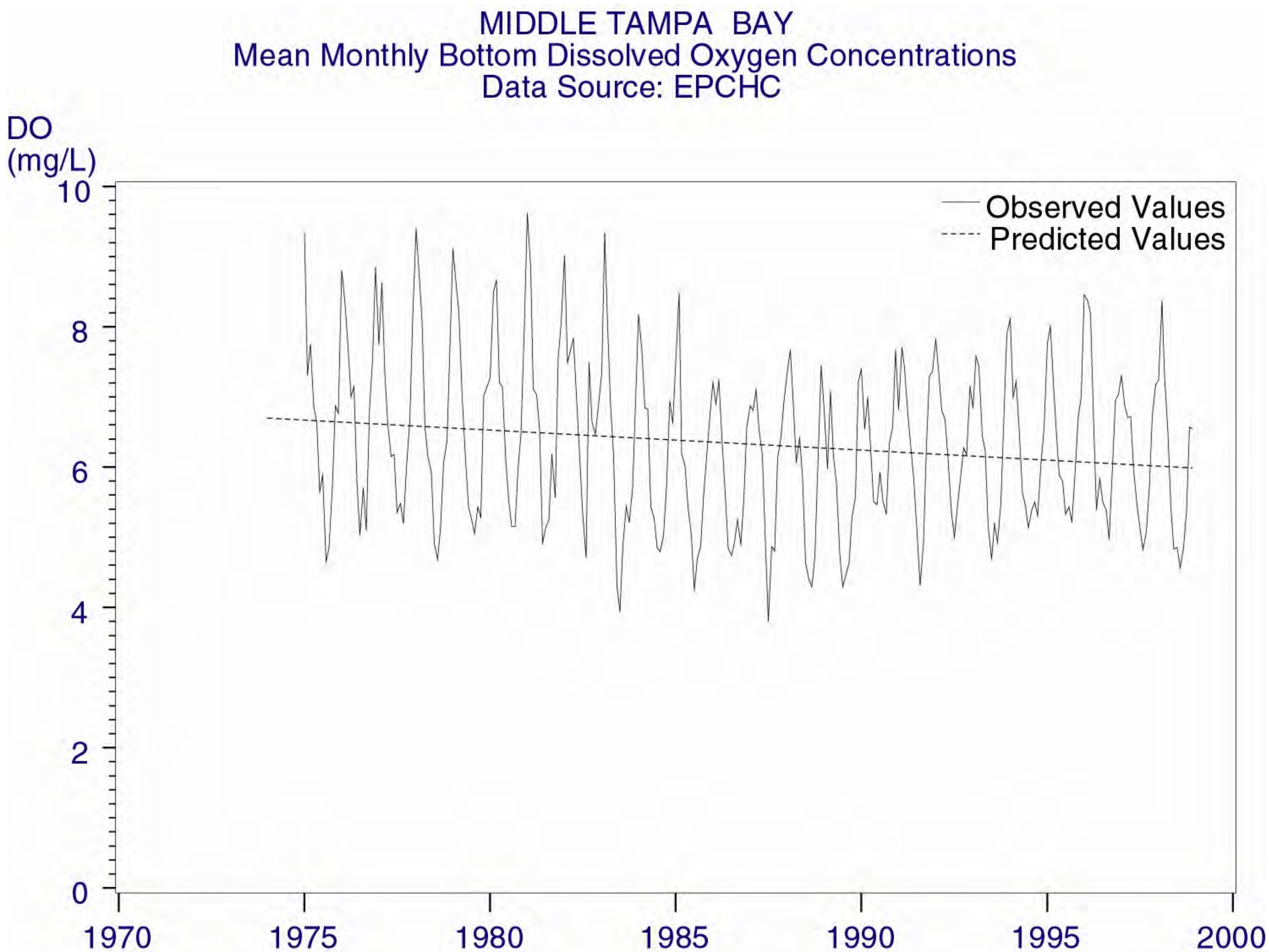

Figure 9-3. Time series of mean monthly bottom DO concentrations in Middle Tampa Bay using data collected at EPCHC Ambient Water Quality Monitoring stations.

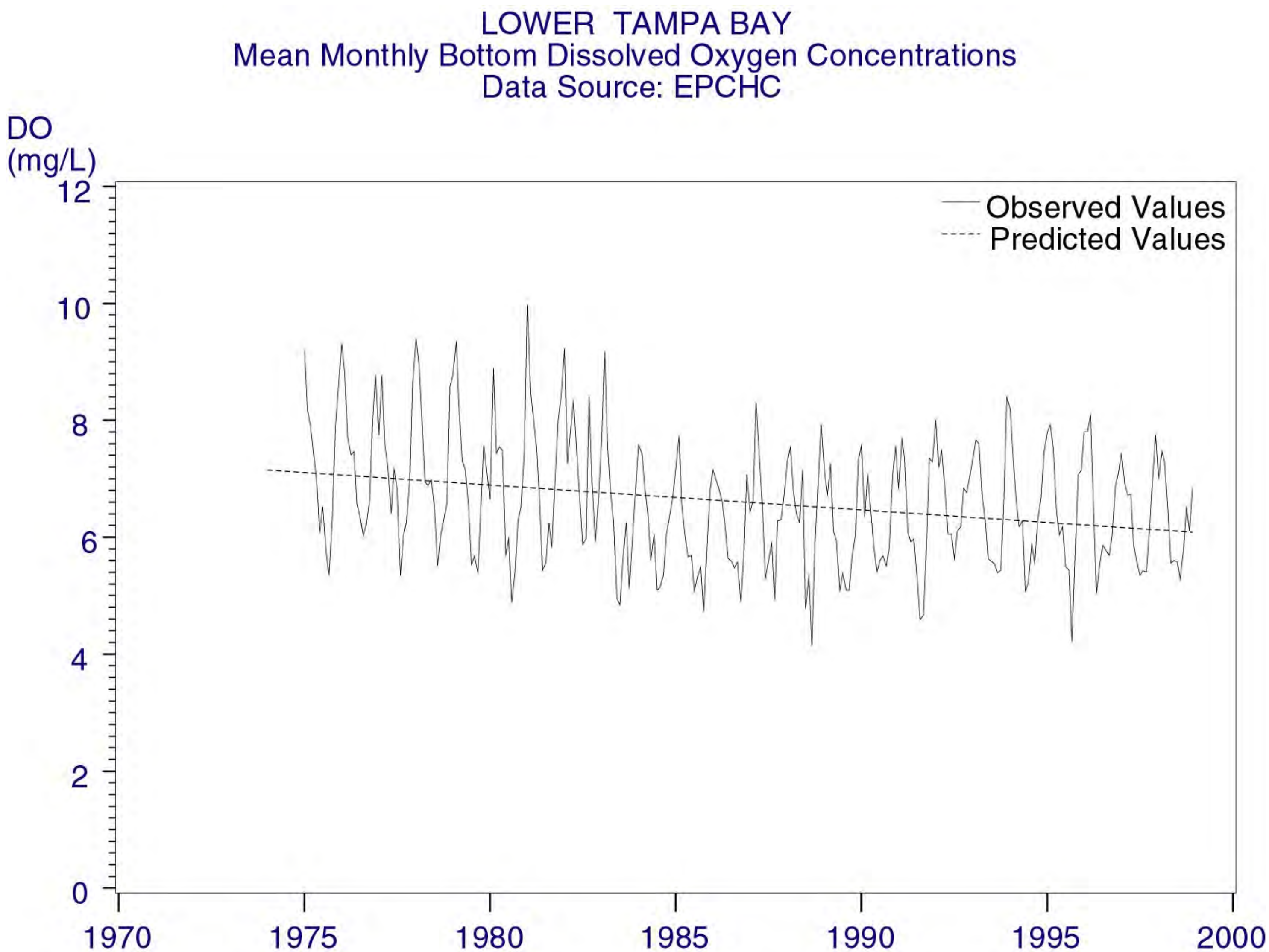

Figure 9-4. Time series of mean monthly bottom DO concentrations in Lower Tampa Bay using data collected at EPCHC Ambient Water Quality Monitoring stations.

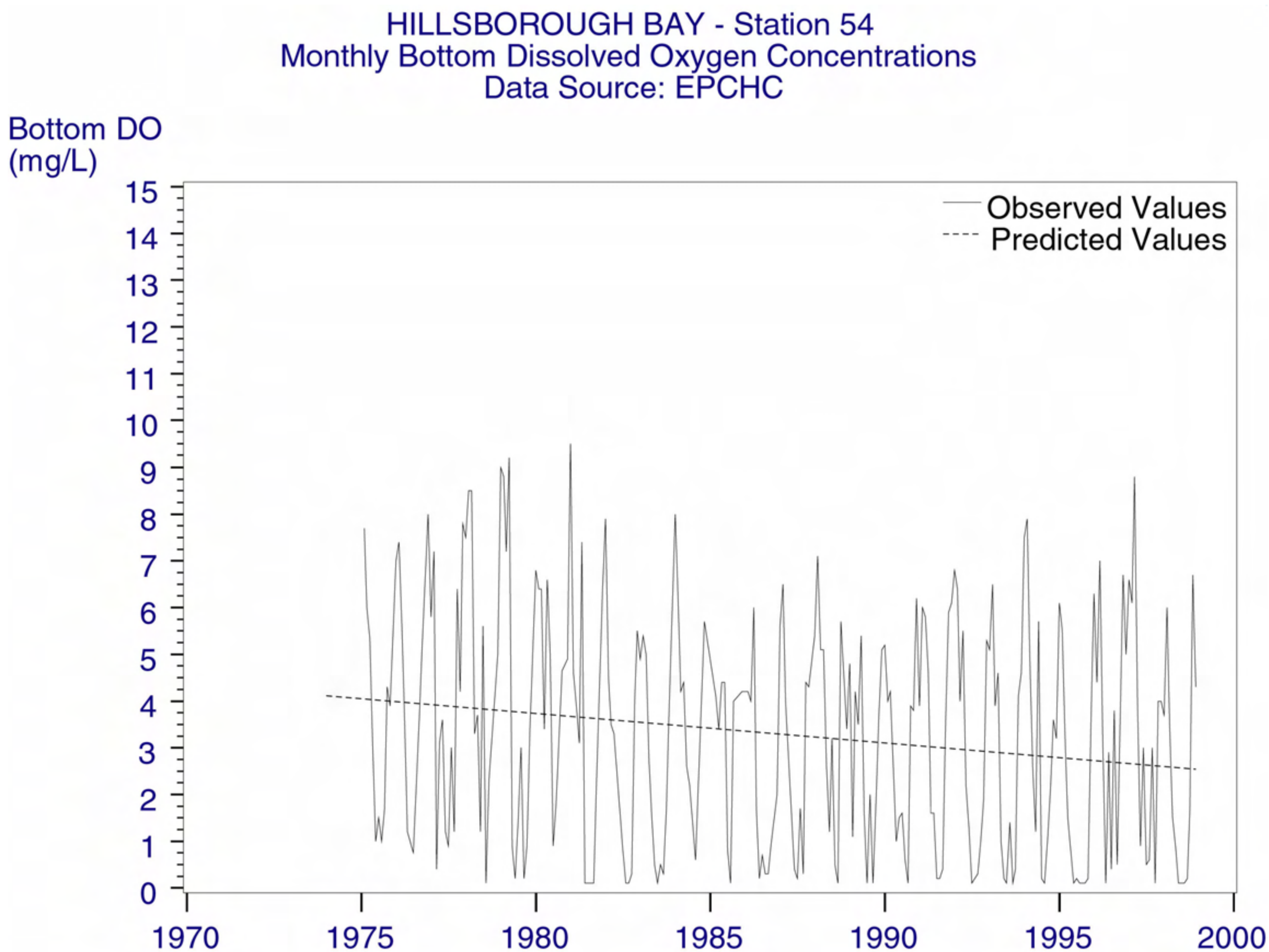

Figure 9-5. Time series of monthly bottom DO concentrations at Station 54 in Hillsborough Bay using data collected by EPCHC Ambient Water Quality Monitoring Program.

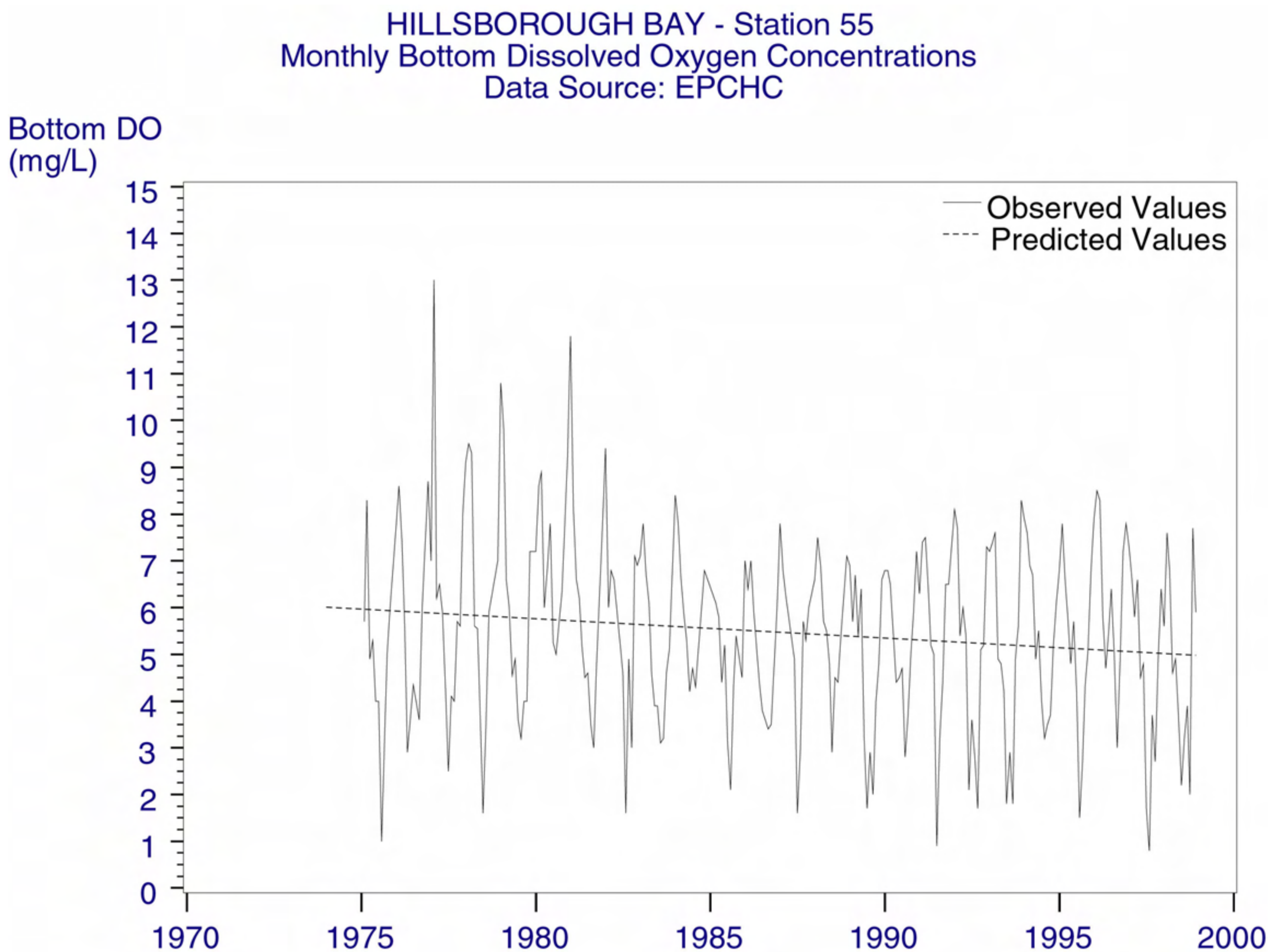

Figure 9-6. Time series of monthly bottom DO concentrations at Station 55 in Hillsborough Bay using data collected by EPCHC Ambient Water Quality Monitoring Program.

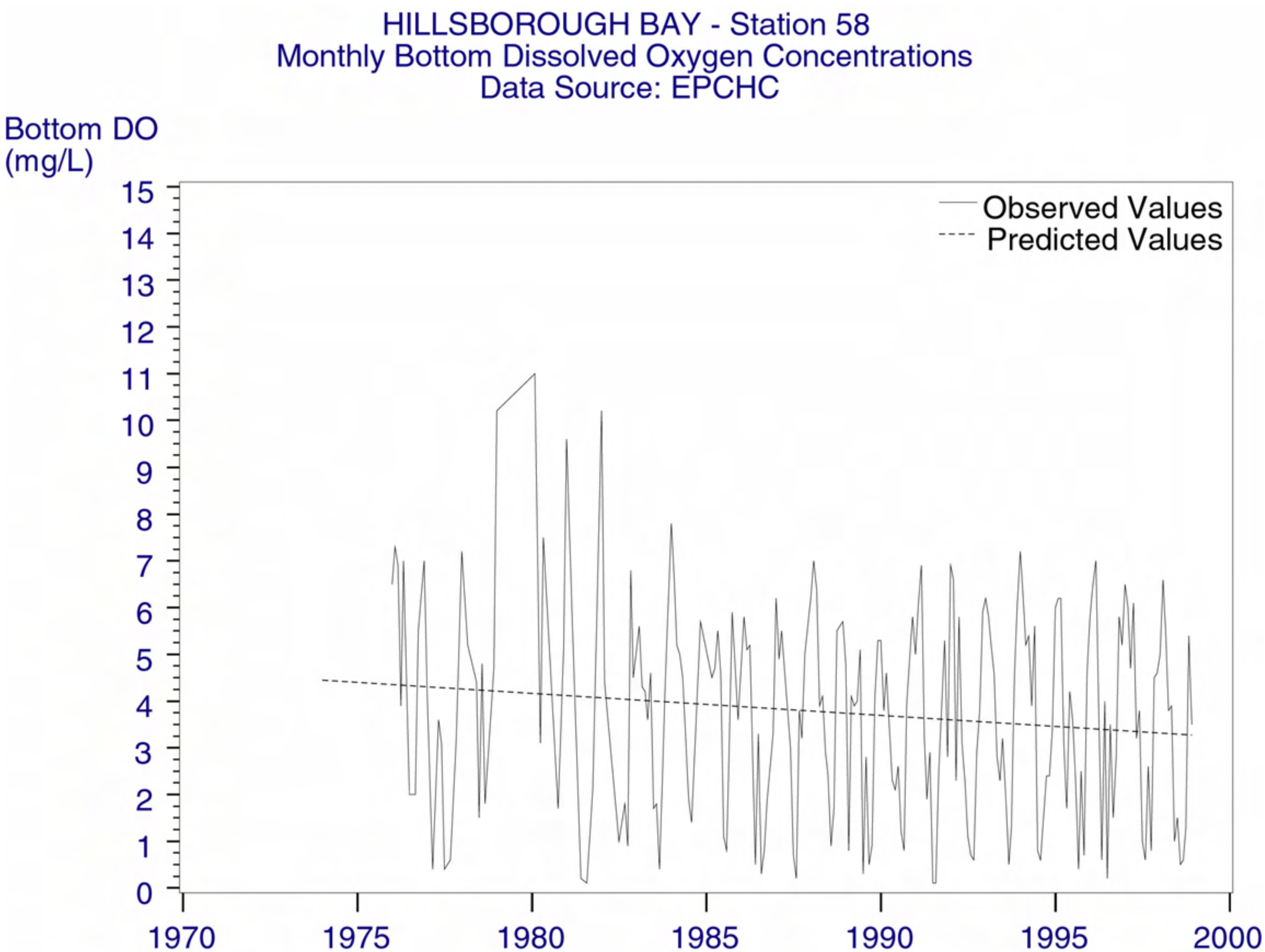

Figure 9-7. Time series of monthly bottom DO concentrations at Station 58 in Hillsborough Bay using data collected by EPCHC Ambient Water Quality Monitoring Program.

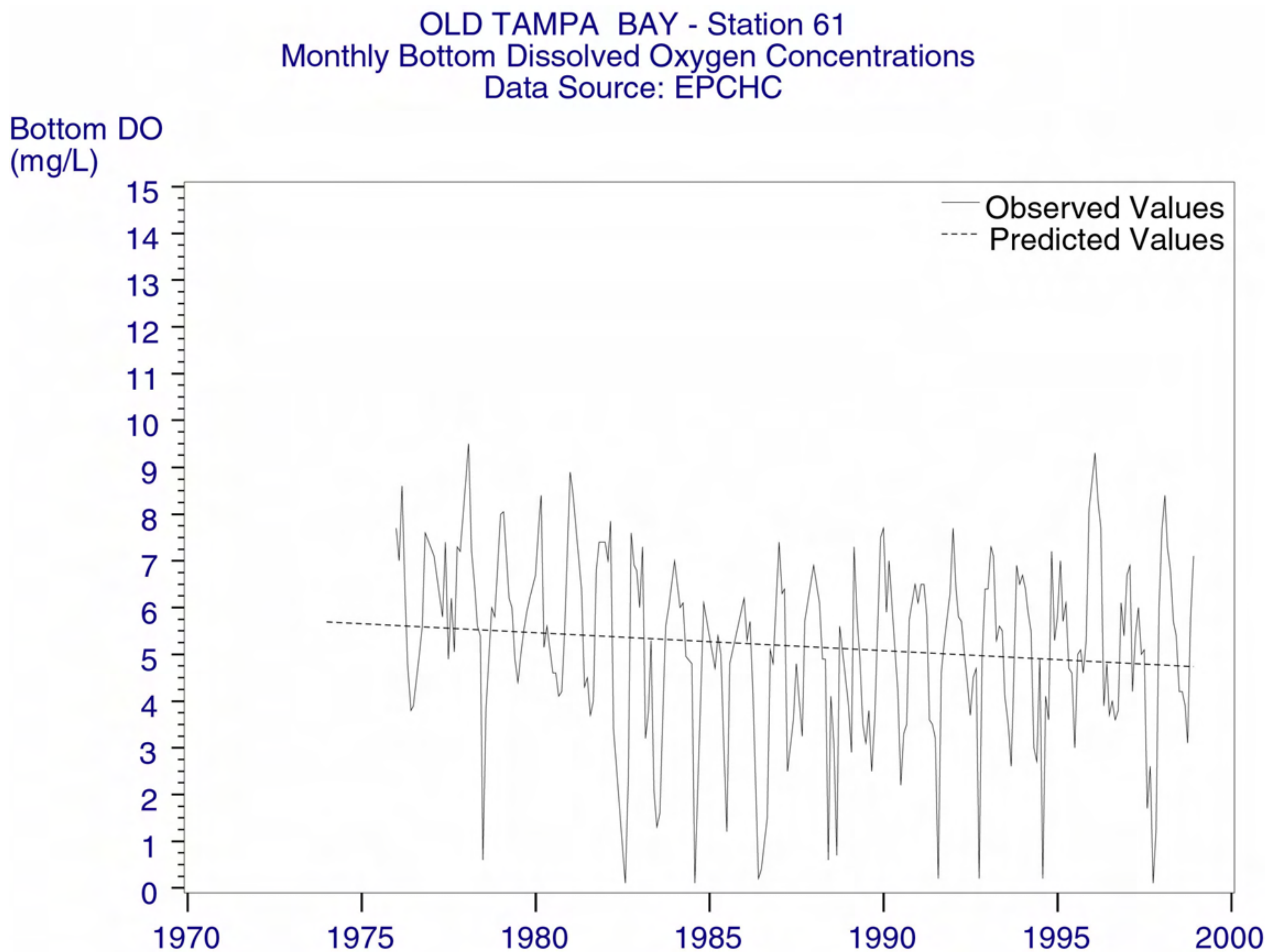

Figure 9-8. Time series of monthly bottom DO concentrations at Station 61 in Old Tampa Bay using data collected by EPCHC Ambient Water Quality Monitoring Program.

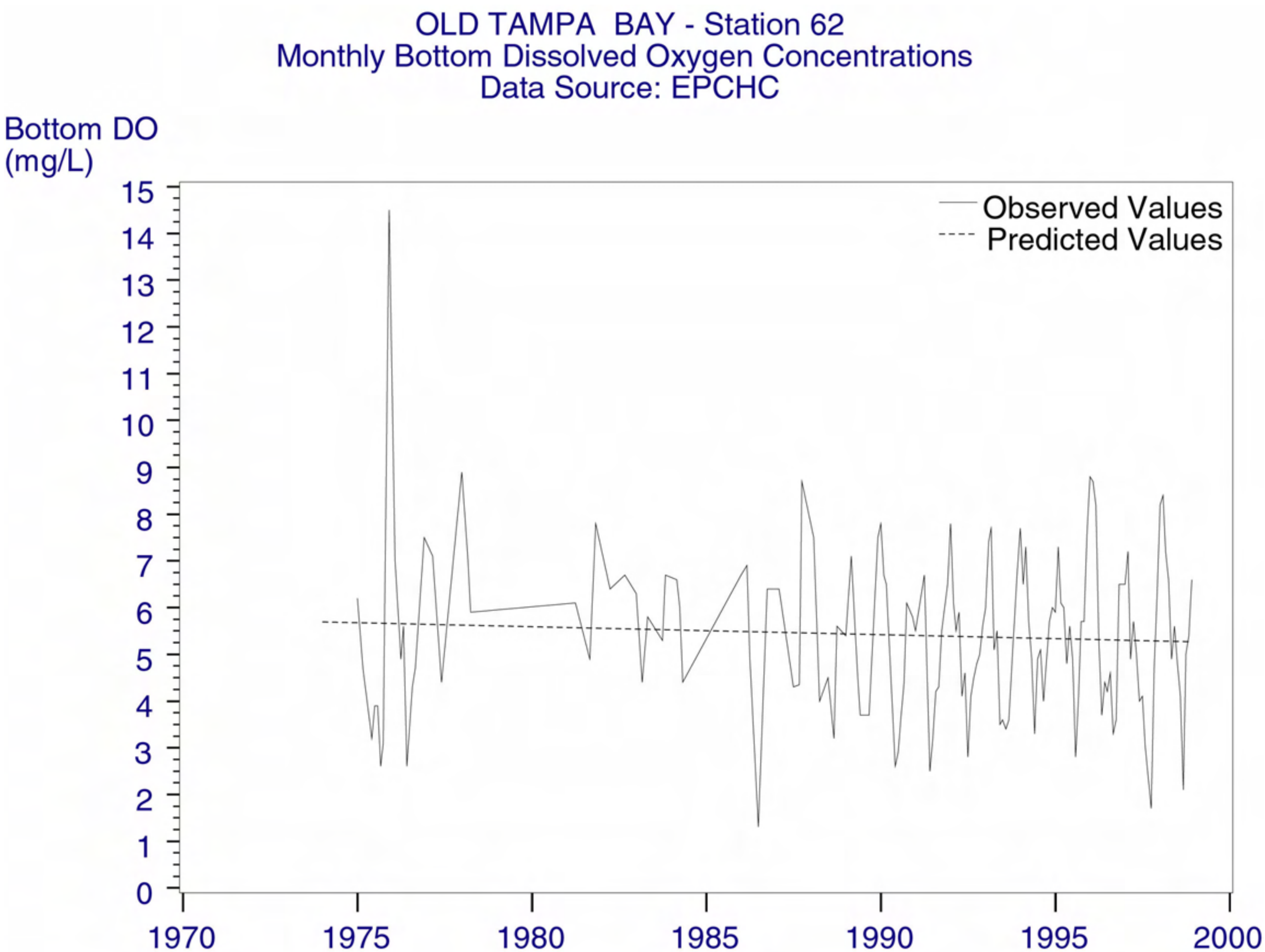

Figure 9-9. Time series of monthly bottom DO concentrations at Station 62 in Old Tampa Bay using data collected by EPCHC Ambient Water Quality Monitoring Program.

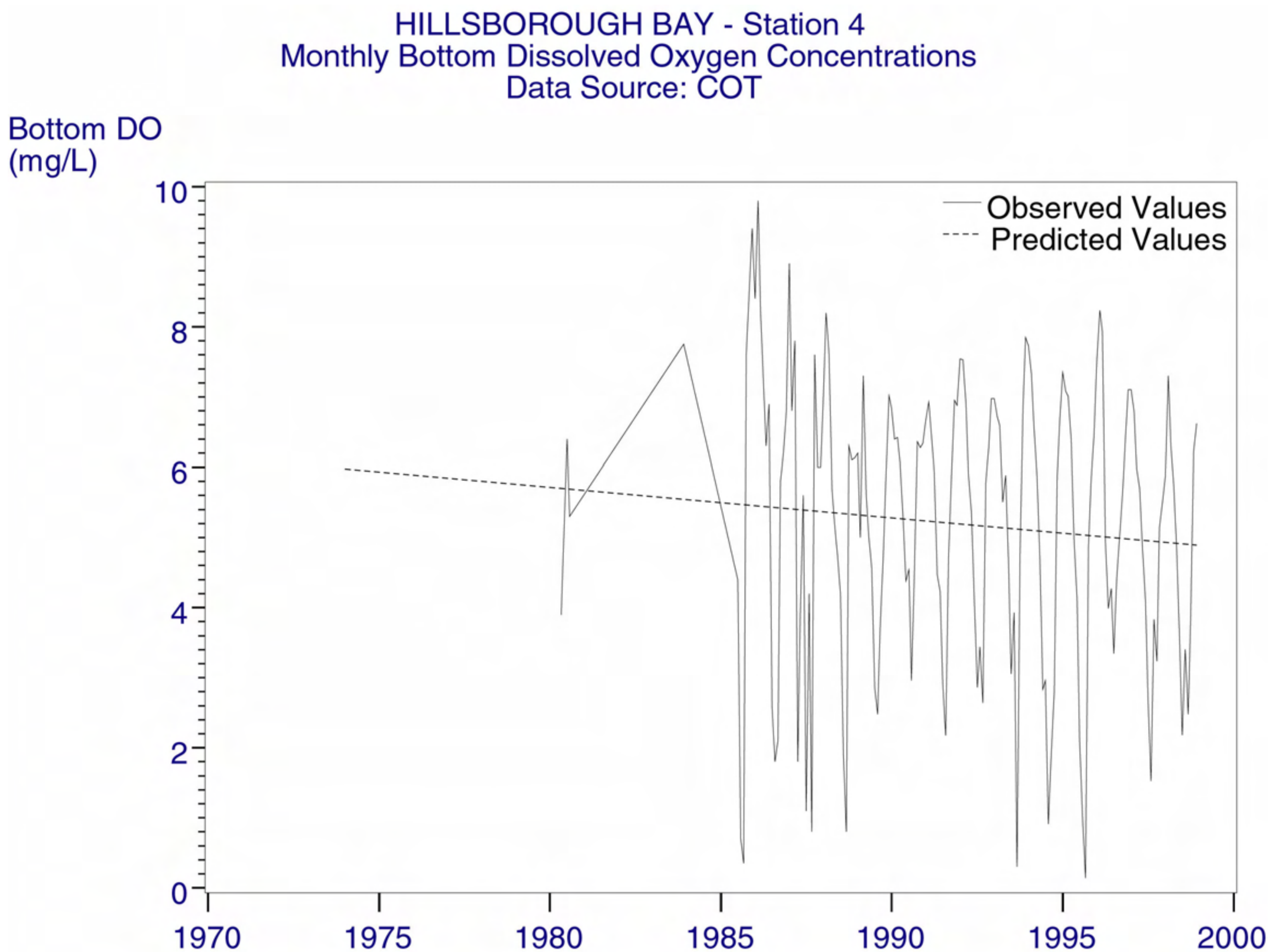

Figure 9-10. Time series of monthly bottom DO concentrations at Station 4 using data collected by the City of Tampa Bay Study Group.

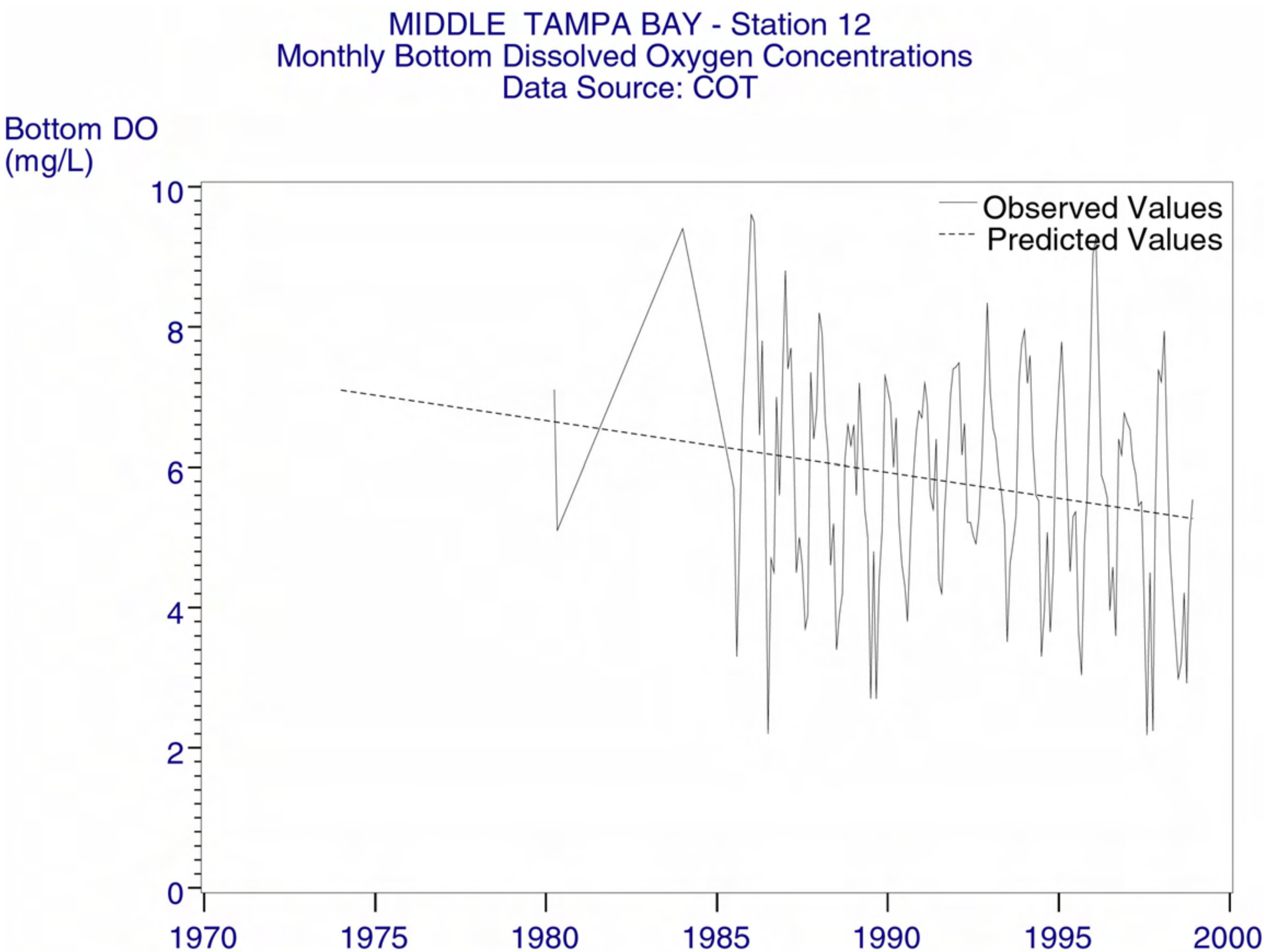

Figure 9-11. Time series of monthly bottom DO concentrations at Station 12 using data collected by the City of Tampa Bay Study Group.

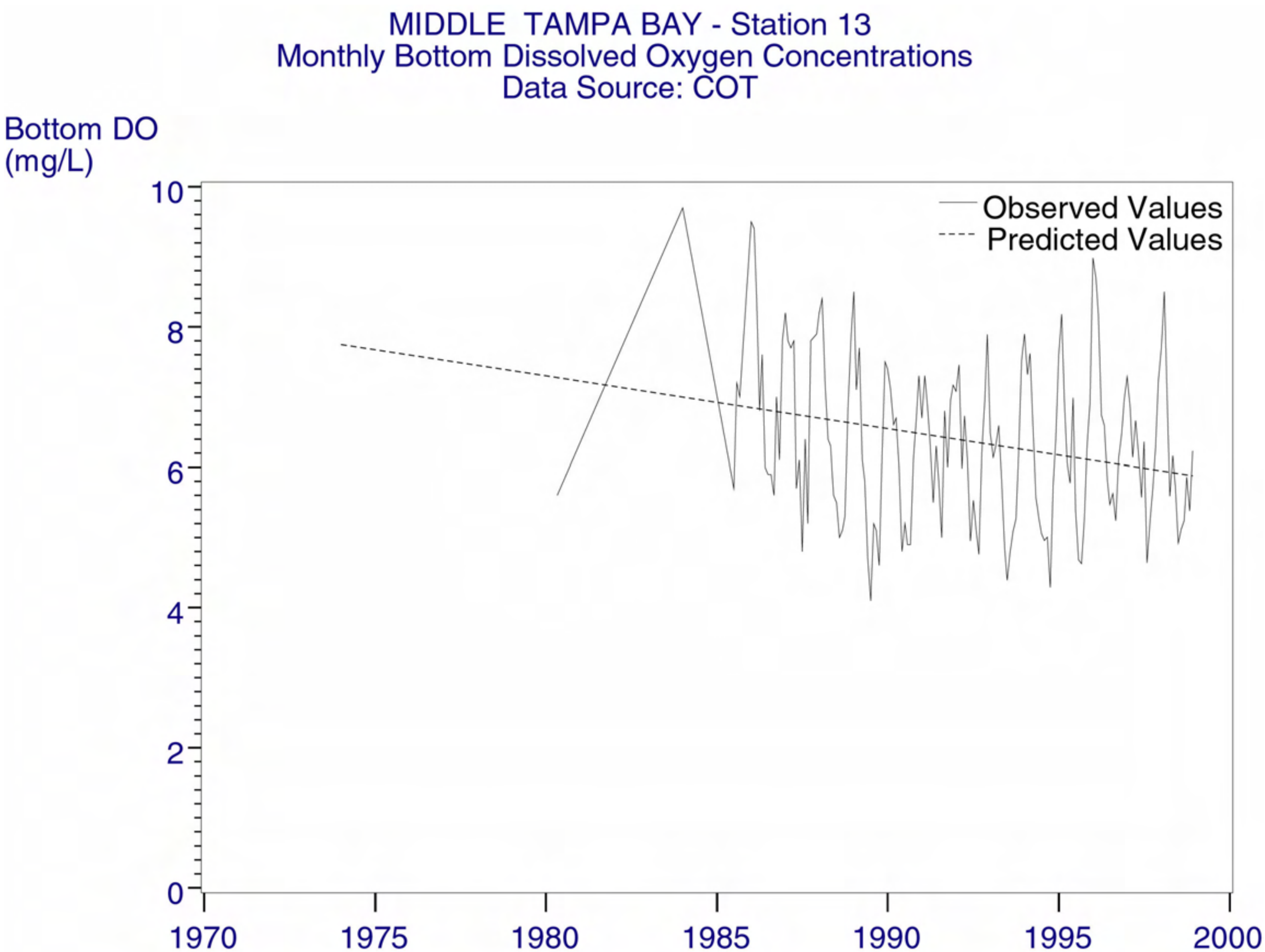

Figure 9-12. Time series of monthly bottom DO concentrations at Station 13 using data collected by the City of Tampa Bay Study Group.

CONCLUSIONS AND DISCUSSION

Within the past several years, concerns have been expressed regarding the possibility of an increase in the area of the bay subjected to low DO concentrations during portions of the year. This project was conducted to address these concerns, and examines the spatial and temporal nature of hypoxia in the bay. For the purposes of this evaluation, hypoxia is defined as concentrations of DO <2 mg/L.

Bottom DO measurements are collected by monthly water quality monitoring programs of four local government agencies: the Environmental Protection Commission of Hillsborough County; the Bay Study Group, City of Tampa Department of Sanitary Sewers; the Pinellas County Department of Environmental Management; and the Manatee County Environmental Management Department. In addition, the TBEP Benthic Monitoring Program collects bottom DO measurements at all benthic monitoring sites, and diel DO measurements at selected benthic sites.

Hypoxic conditions in Tampa Bay typically occur in the late summer months, from July through September. Minimum bottom DO concentrations nearly always occur in August. This result is not surprising, given the high water temperatures (low oxygen solubility) and the typically high primary production (increasing the demand for DO for respiration) of the period.

Hypoxic conditions are found primarily in Hillsborough Bay and less frequently in Old Tampa Bay. In September 1998, hypoxic conditions extended over approximately 19 km^2 in the bay, with about half of this area found in Hillsborough Bay and the remainder in Old Tampa Bay.

There are several factors that distinguish those sites at which hypoxia is typically found from those sites where hypoxia rarely occurs. Sites that frequently display hypoxic conditions have greater water column depth, finer sediments, a higher degree of stratification, and higher chlorophyll concentrations.

To assess if significant changes in areal extent of hypoxia in the bay have occurred over time, areal estimates of low DO conditions were developed for each August and September of the 1975-1998 period. No significant trends in areal extent across years were found for either the August or September extent of low DO conditions for the mainstem portion of the bay, or for the September extent of low DO conditions for Hillsborough Bay. A great deal of year-to-year variation was found in the estimates, with relatively high estimates found in 1995 and 1998, when relatively high rainfall was observed.

Several factors that affect the year-to-year variation in the areal extent of hypoxia were found. The year-to-year variation in the extent of hypoxia is significantly correlated with spring rainfall, summer river flow, and the degree of stratification.

Therefore, the areal extent of hypoxia is expected to increase under high rainfall and flow conditions that likely contribute to the degree of stratification due to salinity and temperature differences.

By far, mid-day DO collected by the monthly monitoring programs provide the primary data available to assess hypoxia in Tampa Bay. However, hypoxia is more likely to be found just prior to dawn, after the prolonged period of respiration during the night. To assess the adequacy of mid-day DO concentration data to identify occurrences of hypoxia, the relationships between mid-day and minimum DO data were examined. Comparison of these data indicates that the mid-day data correctly reflect the occurrence of hypoxia approximately 75% of the time. There is a significant relationship between mid-day and minimum DO; however, more data will allow improvement in the quantification of this relationship. Thus, in the future our ability to predict minimum DO from mid-day DO data will improve.

Both monthly monitoring data and diel monitoring data were evaluated to examine persistence at two different temporal scales. The monthly monitoring data reveal that the duration of hypoxia at this temporal scale is typically two months or less in Hillsborough Bay. From the diel monitoring data, the mean duration of hypoxic events at this temporal scale in Hillsborough Bay is typically six hours or less, and less than this in Old Tampa Bay and Middle Tampa Bay. From this evaluation, hypoxic events in the bay are relatively short duration events.

Significant long-term trends in bottom DO concentrations in Tampa Bay have been detected. Statistically significant declines were found in Hillsborough Bay and Old Tampa Bay from 1974 through 1998. However, the rate of decline was small, and appears largely due to the reduction in relatively high DO values between the late 1970s and early 1980s period and during the period since 1985. No change in the DO values in the lower portion of the observed range of DO concentrations was apparent during the early part of the record. Thus, while a statistically significant trend was detected, more stressful conditions have not necessarily resulted.

In addition to the questions addressed in the analyses described above, there are remaining questions that are broader in scope and directly related to bay management. These questions are discussed below.

Given the spatial and temporal extent of hypoxia in Tampa bay, to what degree do natural and anthropogenic factors influence hypoxia in the bay?

As discussed above, if hypoxic conditions are found in the bay, they are typically found in Hillsborough Bay. The important factors that appear to affect the current DO conditions in Hillsborough Bay are:

- the morphometry and hydrologic setting of Hillsborough Bay and ,
- the availability of organic carbon in the sediments.

Both of these factors have been affected by anthropogenic activities, as described below.

The most important influence on hypoxia in Hillsborough Bay is its morphometry. This portion of Tampa Bay has a relatively small volume in relation to the size of its watershed. Three major rivers, the Hillsborough, the Alafia, and the Palm, discharge to Hillsborough Bay. The relatively large size of the watershed results in relatively large freshwater inflows and associated nutrient loads from rainfall events, which influence Hillsborough Bay to a greater degree than a larger water body would be influenced. Despite the shallowness of Hillsborough Bay, high freshwater inflows can lead to a high degree of stratification, reducing oxygen exchange from the surface to the bottom waters.

Anthropogenic influences can potentially affect the rate of freshwater supply to, and the flushing rate of, Hillsborough Bay. Analyses of historical freshwater inflows reported in Zarbock et al. (1995) suggest that the timing of freshwater loading events has been modified as a result of development. Changes in the hydrology of the watershed can affect the rate of freshwater supply and the residence time of a water body. Historically, loading events occurred over longer duration pulses, with development resulting in a shortening of the pulse duration. Increases in the rate of freshwater loads during an event are expected to increase the area of Hillsborough Bay subjected to low DO conditions, given the results of the analyses suggesting that river flow and the degree of stratification are positively related to the observed year-to-year variation in the extent of low DO conditions.

Dredge and fill activities may also affect the flushing rate in constructed canals and dredged channels, as well as in larger portions of the bay. An increased possibility of isolation of deeper bottom waters exists in constructed canals, where tidal exchange and wind-induced mixing may not sufficiently mix deeper portions of the water column. Dredged channels may also increase the rate of flushing, however, as has occurred due to the shipping channel dredged into Hillsborough Bay. In a study of changes in circulation and flushing resulting from dredge and fill activities in Tampa Bay, Goodwin (1987) found that most of Tampa Bay is subject to greater tide-induced circulation and flushing than in the pre-development period.

Conversely, the occurrence of hypoxia in Old Tampa Bay is likely influenced by the construction of the causeways, which limit tidal exchange with the rest of the bay. The flushing rate north of the Howard Frankland Bridge, especially on the western shore, has likely been reduced due to reduced tidal exchange. An even more extreme alteration of historical flushing is likely north of the Courtney Campbell Causeway, with most of the tidal exchange between northern Old Tampa Bay and the remainder of the bay occurring through a very narrow open water portion near the center of the bridge. In comparison to pre-development conditions in Old Tampa Bay, modeled changes in water transport due to tidal action are greatest north of the Courtney Campbell Causeway (Goodwin, 1987).

Due to nutrient enrichment in the past and related organic material production with subsequent sedimentation, there are still appreciable amounts of organic matter in the sediments of Hillsborough Bay. The amount of organic matter in the sediment at a given site is correlated with the occurrence of low DO conditions at the site. The rate of nutrient supply has increased with increasing development (Zarbock et al., 1994), leading to increased rates of algal production, greater algal biomass, and subsequent increases in organic matter supply to the sediments. The high nutrient supplies also contribute to increased elaboration of organic matter, which in turn leads to higher respiration demands in the bottom waters, increasing the likelihood of low DO conditions occurring.

The relative degree of influence of natural and anthropogenic factors on the extent of hypoxia cannot be quantified. It is likely that both types of factors affect the year-to-year variation in spatial extent of hypoxia. However, analyses point to freshwater inflow and the degree of stratification as the primary determinants of the year-to-year variation in hypoxia in Tampa Bay. Freshwater inflow is a function of both natural and anthropogenic factors. Those portions of the freshwater loads attributable to anthropogenic influences are subject to management actions, as are dredge and fill activities affecting the residence and flushing times of Hillsborough Bay and other portions of the bay.

Are the hypoxic conditions observed in Tampa bay (specifically in Hillsborough Bay) adequately severe or persistent to affect the biota in the bay?

Killam et al. (1992) identified the life history requirements for a series of important and representative estuarine species. One component of this effort was identification of the tolerance to DO concentrations of developmental stages of various species. The results of this review are shown in Table 10-1. These are typical estuarine species having relatively wide tolerances to varying DO concentrations. Variations in DO tolerance levels are found from species to species, with non-motile species, such as the hard clam and the oyster, showing tolerances to DO concentrations of 1.0 mg/L and less for adults. Variations in tolerances also exist within different life stages of the same species, with larval northern hard clams tolerant of 0.5 mg/L DO concentrations, whereas adult tolerance is only to 1.0 mg/L. In general, the tolerance ranges of these organisms reflect their estuarine nature, with relatively high tolerances for hypoxic conditions found for many species. If any responses by the biota to hypoxic conditions exist, the responses are probably at the sub-lethal level, and are most likely behavioral.

Historically, severe responses to low DO conditions have been observed in Tampa Bay. Santos and Simon (1980) reported on the almost annual occurrence of anoxia (DO = 0 mg/L) at Ballast Point on the western side of Hillsborough Bay. Complete depauperization of the benthic community was found in this area as a result of anoxic conditions.

Data have become available to allow a more robust evaluation of the degree to which hypoxia affects the benthic community of Tampa Bay. The Tampa Bay Benthic Monitoring Program has collected benthic community and concurrent water quality data since 1993, and diel DO measurements have been collected at benthic monitoring sites since 1996. Analyses of the relationship of benthic community structure to DO concentrations can provide a more detailed examination of the effects of low DO on the benthos of the bay.

Table 10-1. Preferred, lower limit, and ranges of DO conditions for estuarine species (after Killam et al., 1992). Letters in parentheses represent life stage: E = egg; L = larval; J = juvenile; A = adult.				
Species	**Preferred**	**Lower Limit**	**Range**	**Reference**
Tarpon	Tolerant of very low DO waters, potentially anoxic (J)			Wade, 1962 Ellis, 1956
Bay Anchovy		3.0 (E,L)	1-15.2 (J,A)	FIMP Chesney & Houde, 1989
Striped killifish			1.4-11.1 (J,A)	FIMP
Snook	4-7 (J)	0.4 (J)	1.3-8.4 (J)	Haddad et al.,1992 Shafland & Koehl, 1979
Red drum		2 (J)		Neill, 1990
Silver perch			1.3-15.2 (J,A)	FIMP
Spot	>4 (J,A)	0.49 (J) 1 hr LC_{50} 0.70 (J) 96 hr LC_{50}	To <2 (J,A)	Thornton, 1975; Burton et al., 1980; Rothschild, 1990 Markle, 1976; Chao & Musick, 1977; Rothschild, 1990 Burton et al., 1980; Burton et al., 1980
Striped mullet		4 (L) <4.5 (E)		Sylvester et al., 1975
Blue crab	<0.5 (J,A)			Lowery & Tate, 1986
Oyster			To <1 (L,A)	Sparks et al., 1958; Widdows et al., 1989
Hard clam	>4.2 northern (L) >5 northern (A)	2.4 (L) To 0.5 (L) To 1.0 (A)	4-7.8 southern (A)	Morrison 1971 Savage, 1976 Godcharles & Jaap, 1973
Grass shrimp			2.8-4.4 (A) 6-11 (A)	Rozas & Hackney, 1984 Barrett et al., 1978

Is a management strategy that addresses the anthropogenic factors that affect hypoxia in Tampa Bay necessary?

The need for a management strategy can be driven by requirements in a regulatory framework to address hypoxia in Tampa Bay, or by the desire to manage the bay's resources potentially affected by hypoxia. Within the regulatory framework, the State of Florida has established standards for DO. Chapter 62-302 of the Florida Administrative Code describes the rule, which includes the DO standards:

- DO concentrations should not average less than 5.0 mg/L during a 24 hour period; and
- DO concentrations should never be less than 4.0 mg/L

Clearly, these standards are violated at times within various portions of Tampa Bay, being most likely in Hillsborough Bay.

Currently, two types of management actions are being taken that contribute to reducing the likelihood of hypoxia in Tampa Bay. First, the Nitrogen Management Consortium is addressing the rate of nitrogen supply to the bay. The paradigm of the Nitrogen Management Strategy is that by managing nitrogen loads, phytoplankton biomass as measured by chlorophyll a concentrations can be managed. As shown in the literature and from our analyses, the Nitrogen Management Strategy should reduce the probability of establishing hypoxia in Tampa Bay.

Second, establishment of minimum flows for rivers and actions to restore hydrologic regimes in the watershed of the bay are currently being performed. Both minimum flows to the estuary and stormwater management actions that temper the rate at which freshwater enters the estuary during hydrologic events are expected to mitigate the effects of increased development on the nature of the freshwater and nutrient loads to the bay.

Therefore, the current bay management actions have likely reduced and will continue to reduce the spatial and temporal extent of hypoxia in Tampa Bay. There are two lines of evidence to support this conclusion. The first is the long-term trends in bottom DO, which show no decline in minimum DO concentrations. The second is the anecdotal information from bay researchers, who have observed less severe symptoms of hypoxia, such as hydrogen sulfide presence and organically enriched sediments, in the recent period than previously (Johansson, 2001).

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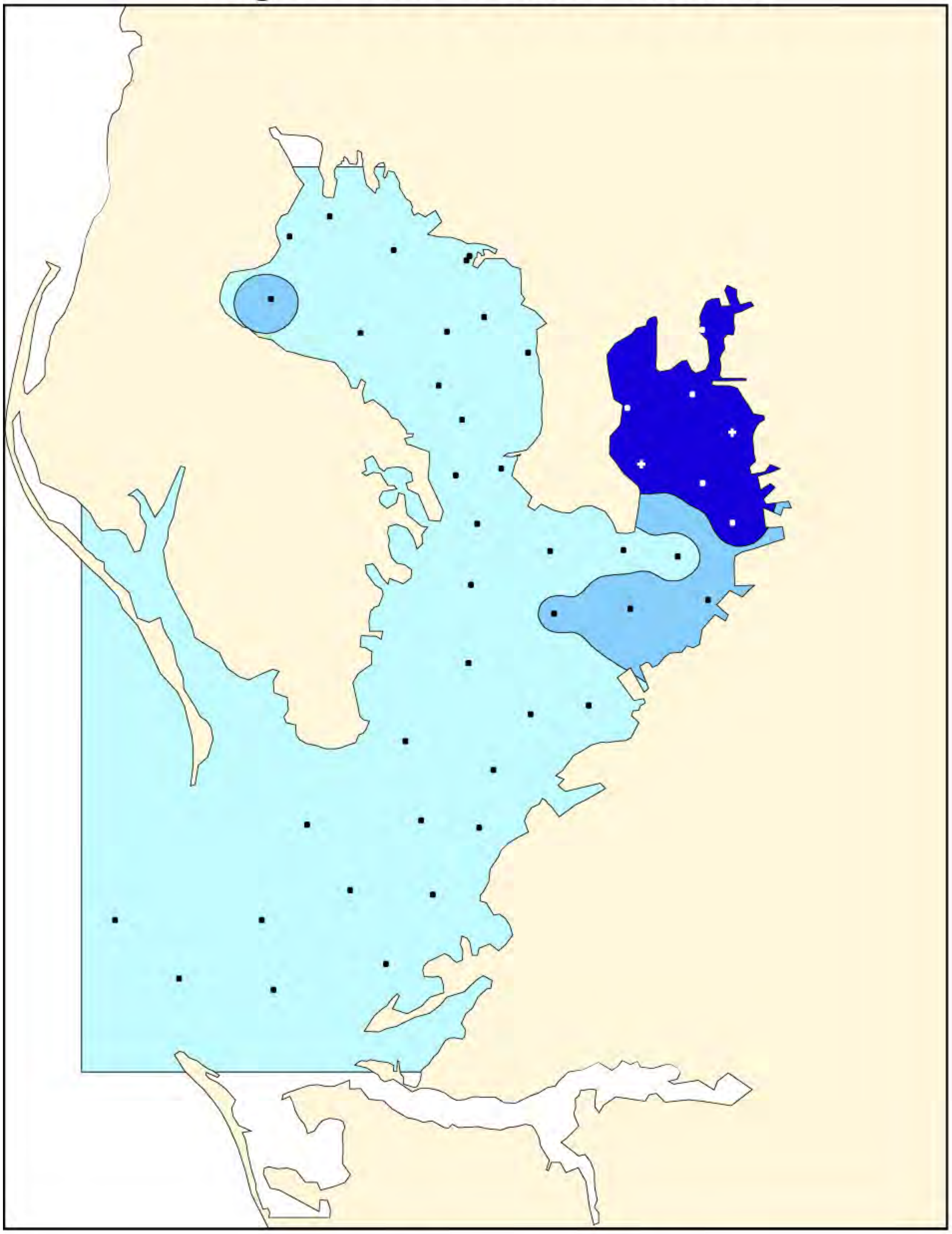
APPENDIX

August and September bottom DO contour maps, from EPCHC Ambient Water Quality Monitoring stations, 1975-1998.

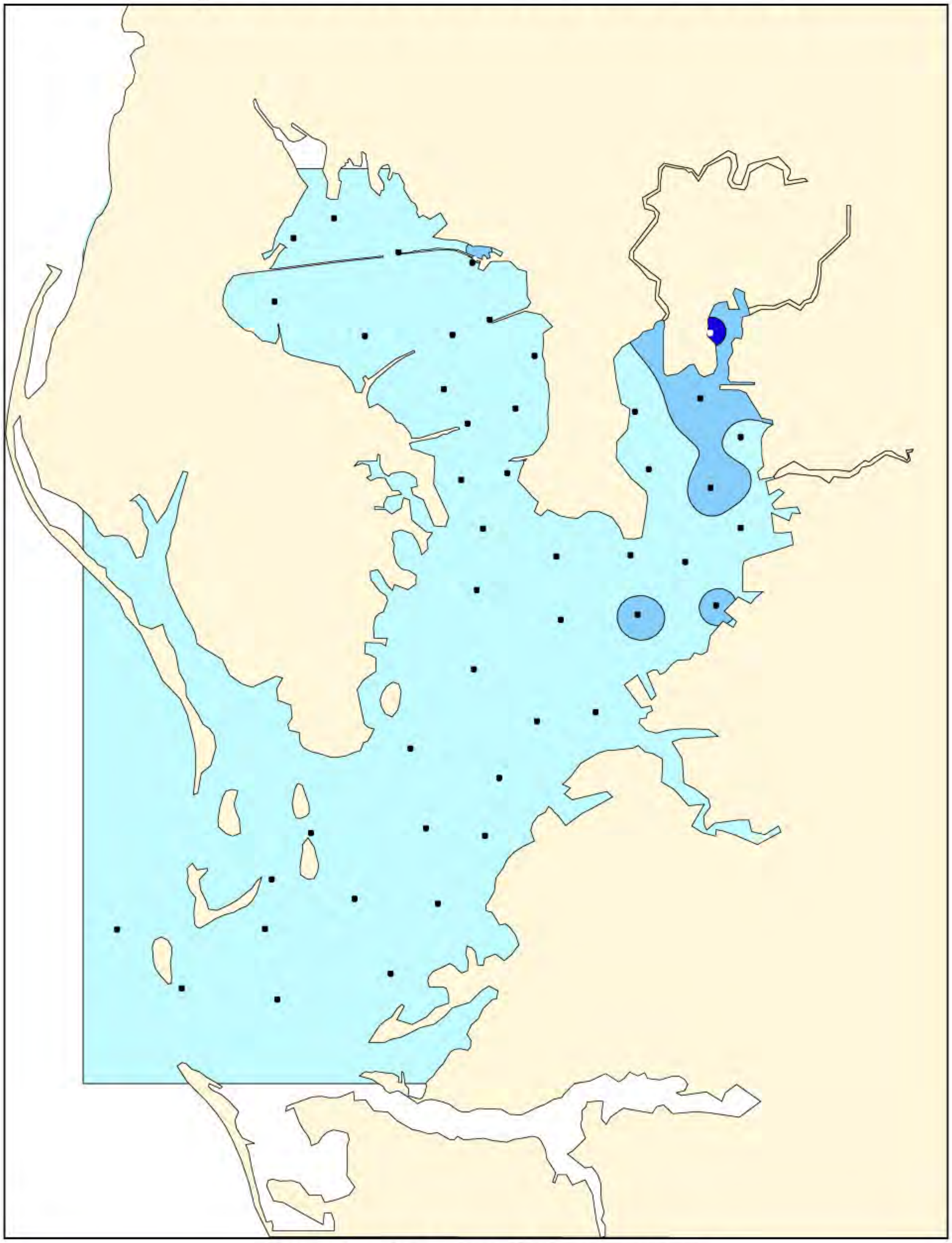
Bottom Dissolved Oxygen
August 1975 - EPCHC Stations



Dissolved Oxygen Concentrations

0 - 2 mg/L | 2 - 4 mg/L | > 4 mg/L

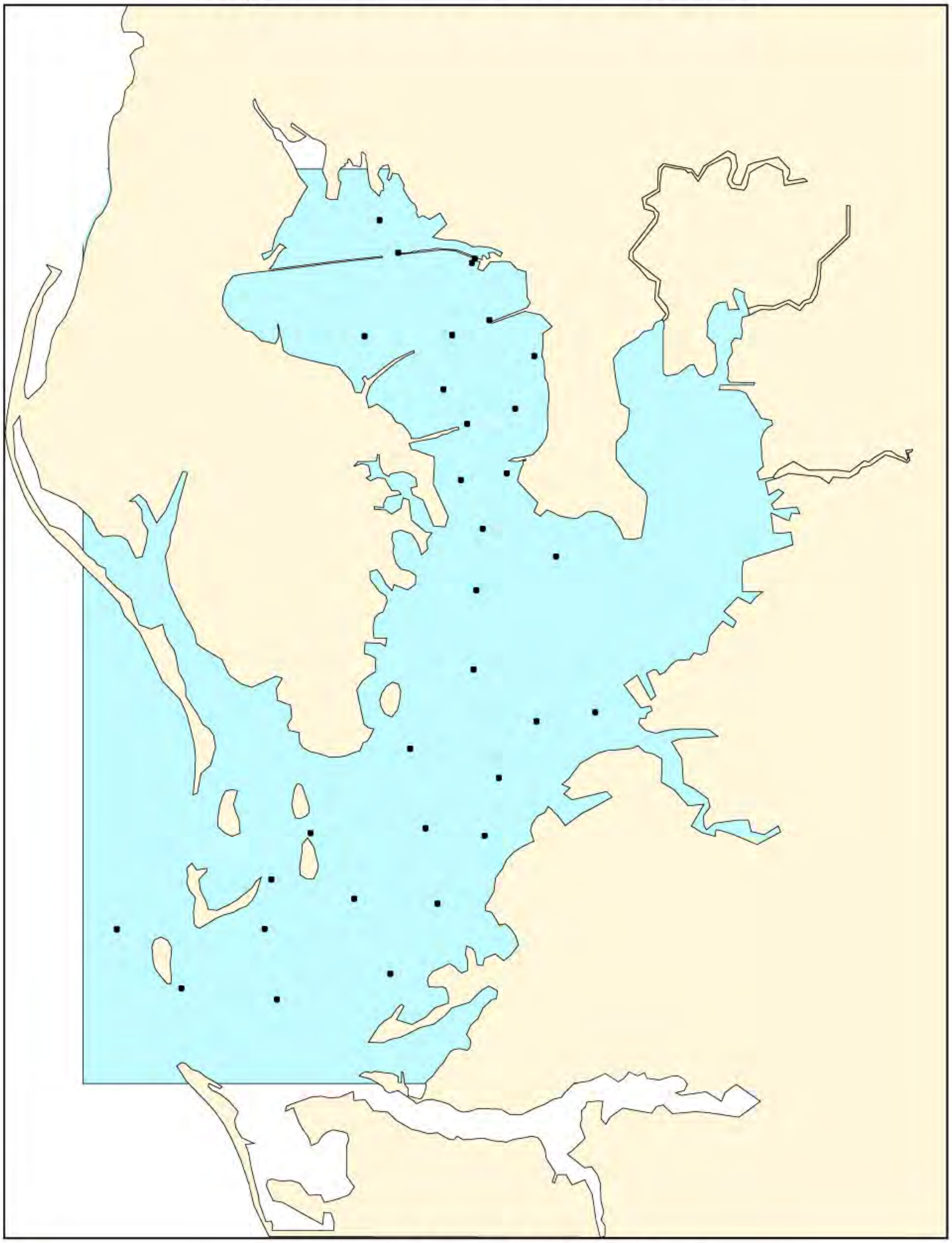
Bottom Dissolved Oxygen
September 1975 - EPCHC Stations



Dissolved Oxygen Concentrations

0 - 2 mg/L | 2 - 4 mg/L | > 4 mg/L

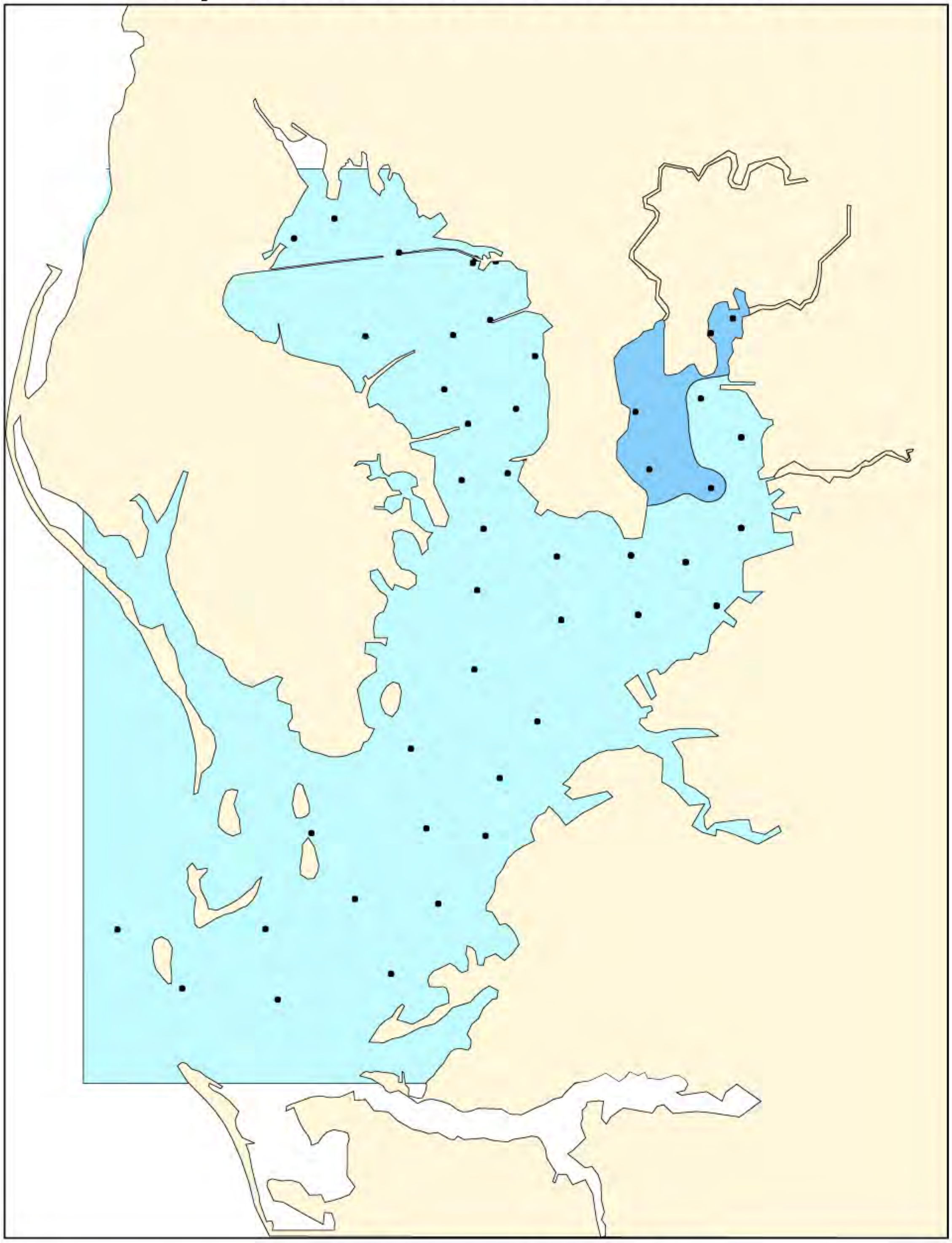
Bottom Dissolved Oxygen
August 1976 - EPCHC Stations



Dissolved Oxygen Concentrations

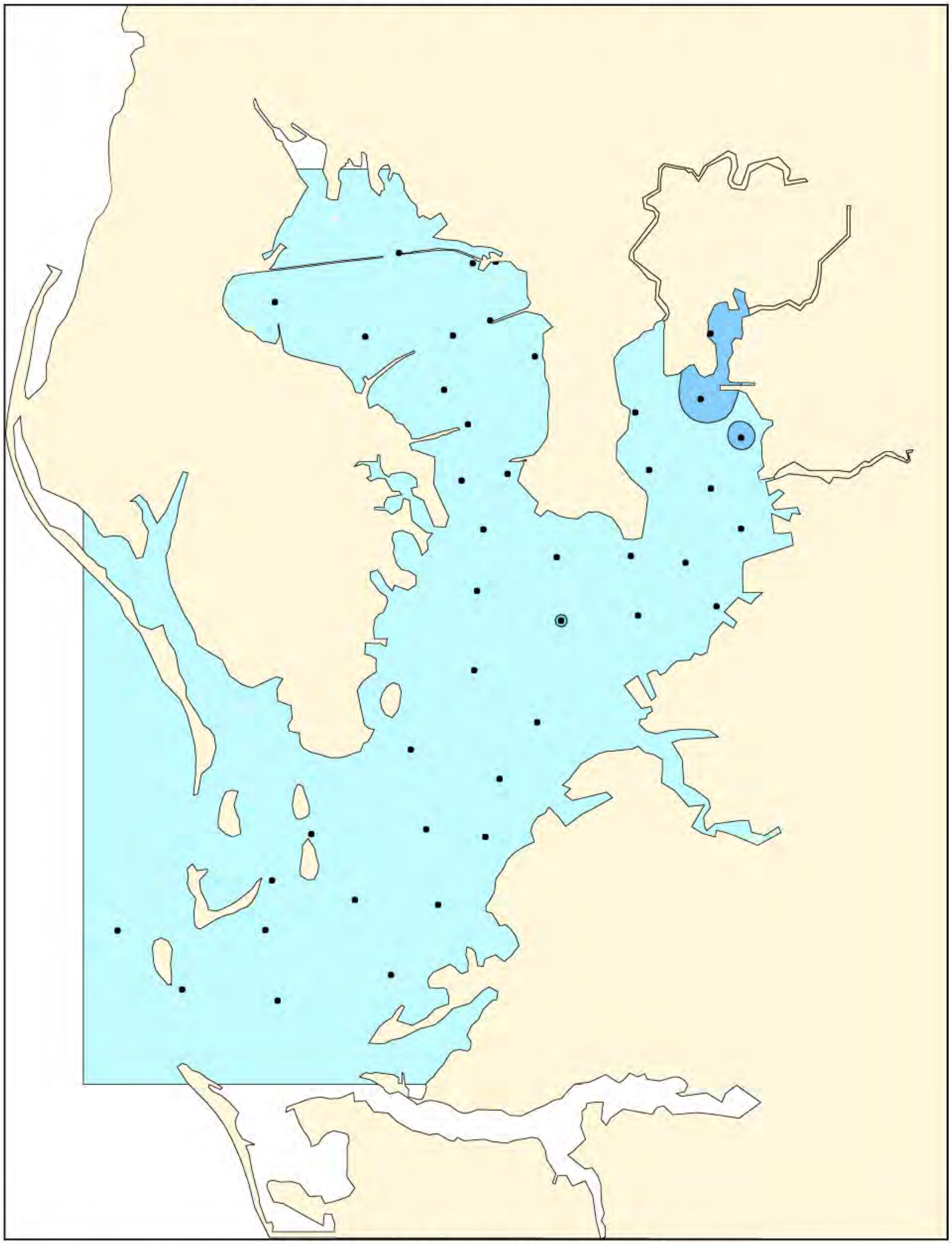
0 - 2 mg/L | 2 - 4 mg/L | > 4 mg/L

Bottom Dissolved Oxygen
September 1976 - EPCHC Stations



Dissolved Oxygen Concentrations

Bottom Dissolved Oxygen
August 1977 - EPCHC Stations



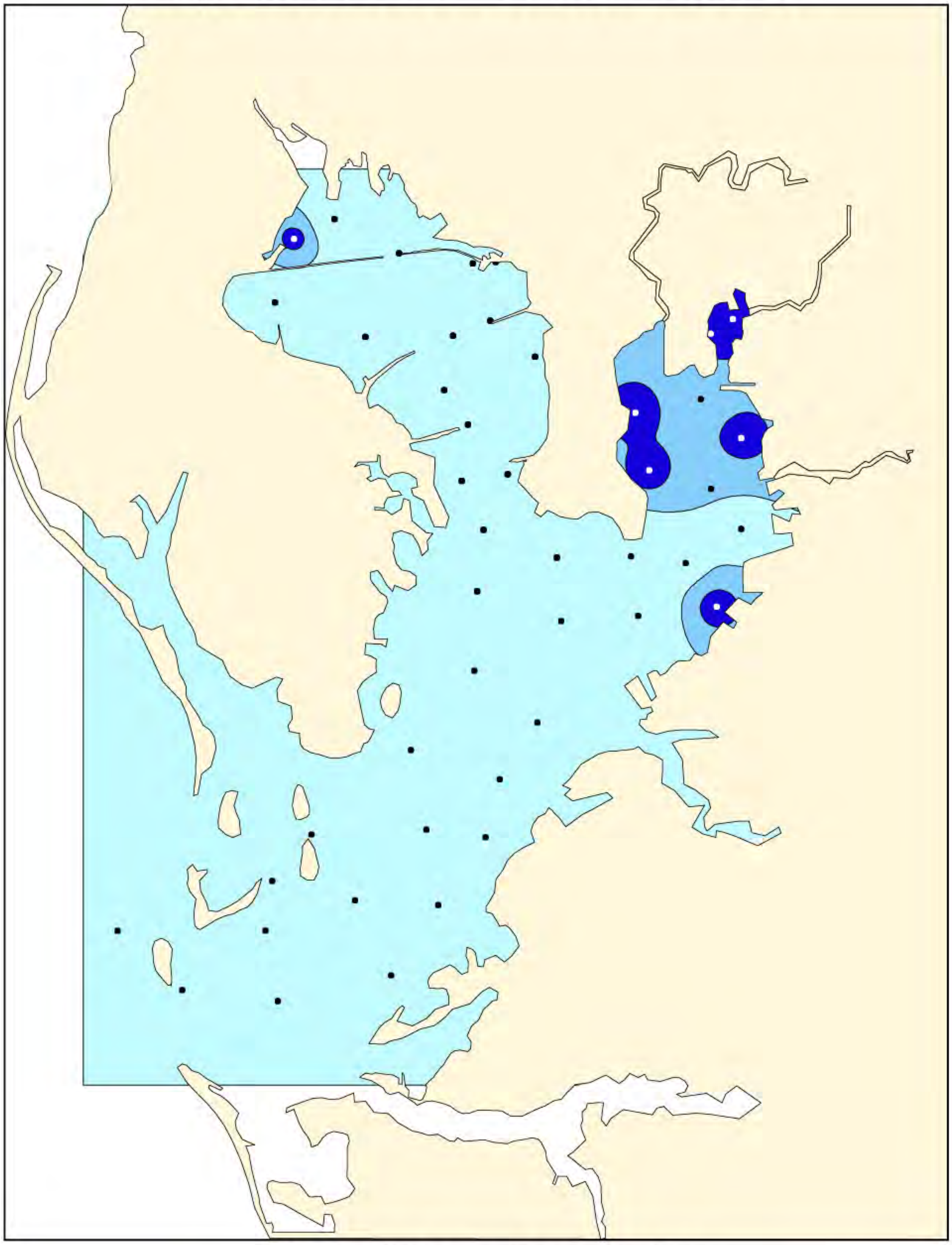
Dissolved Oxygen Concentrations

0 - 2 mg/L

2 - 4 mg/L

> 4 mg/L

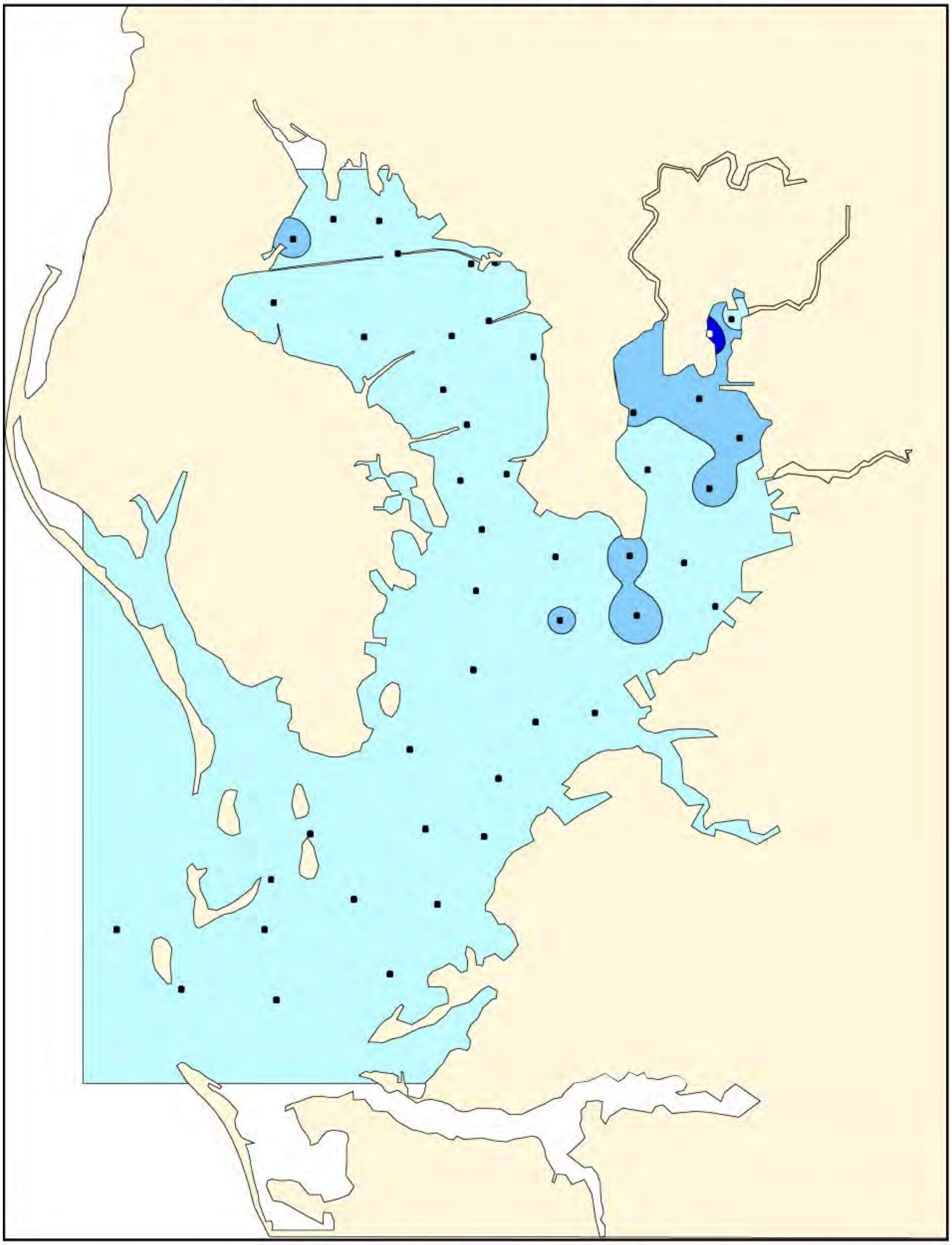
Bottom Dissolved Oxygen
September 1977 - EPCHC Stations



Dissolved Oxygen Concentrations

0 - 2 mg/L   2 - 4 mg/L   > 4 mg/L

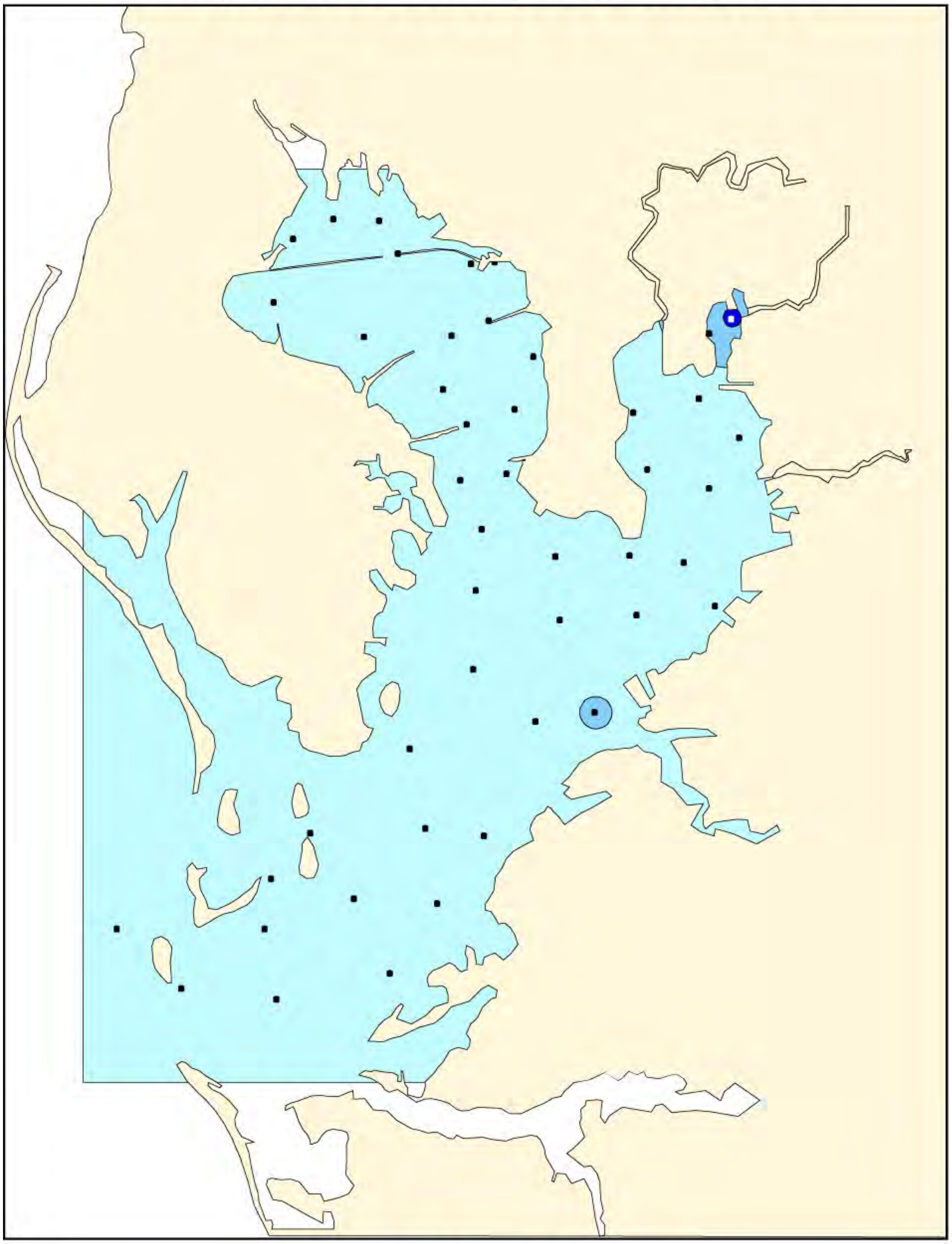
Bottom Dissolved Oxygen
August 1978 - EPCHC Stations



Dissolved Oxygen Concentrations

0 - 2 mg/L　2 - 4 mg/L　> 4 mg/L

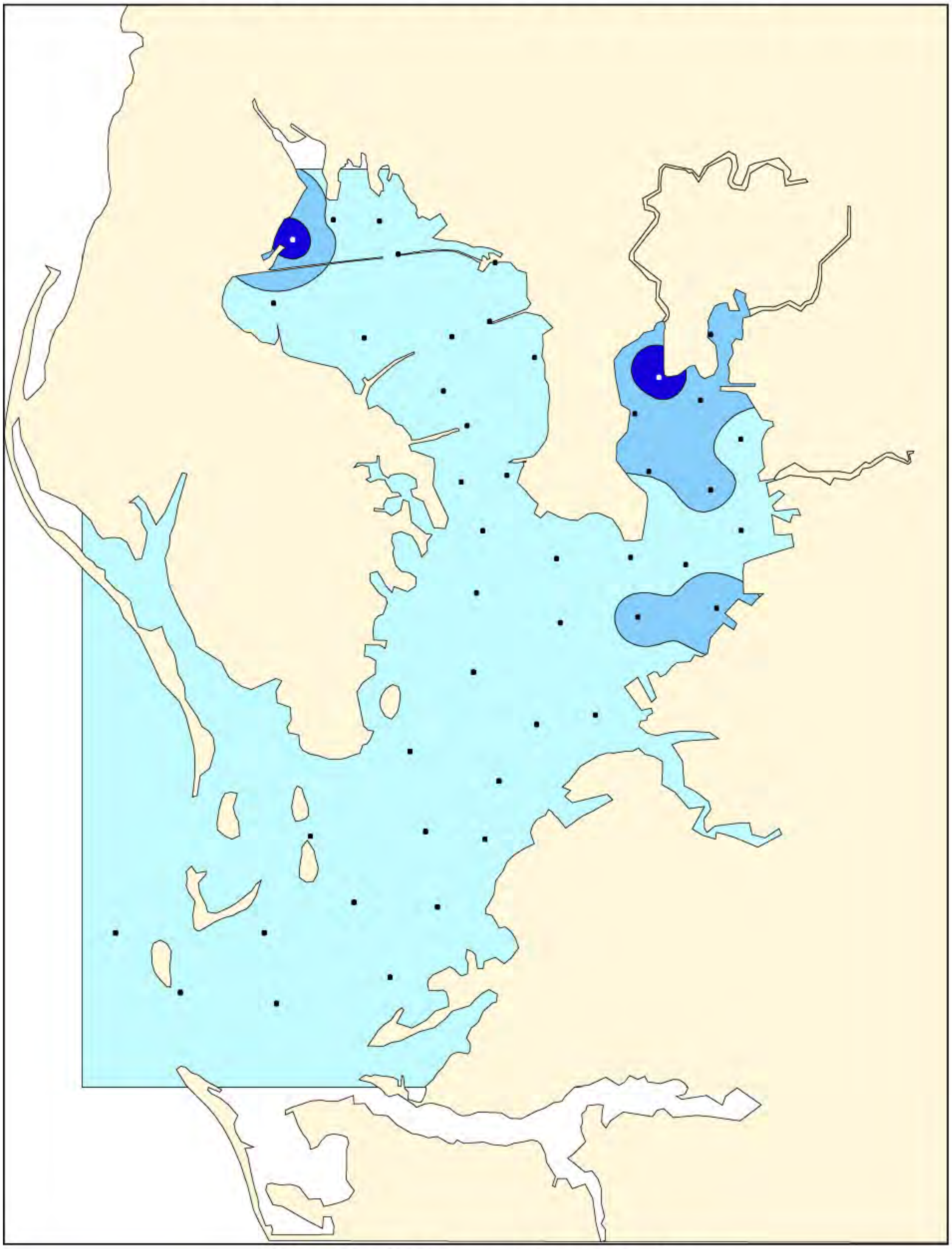
Bottom Dissolved Oxygen
September 1978 - EPCHC Stations



Dissolved Oxygen Concentrations

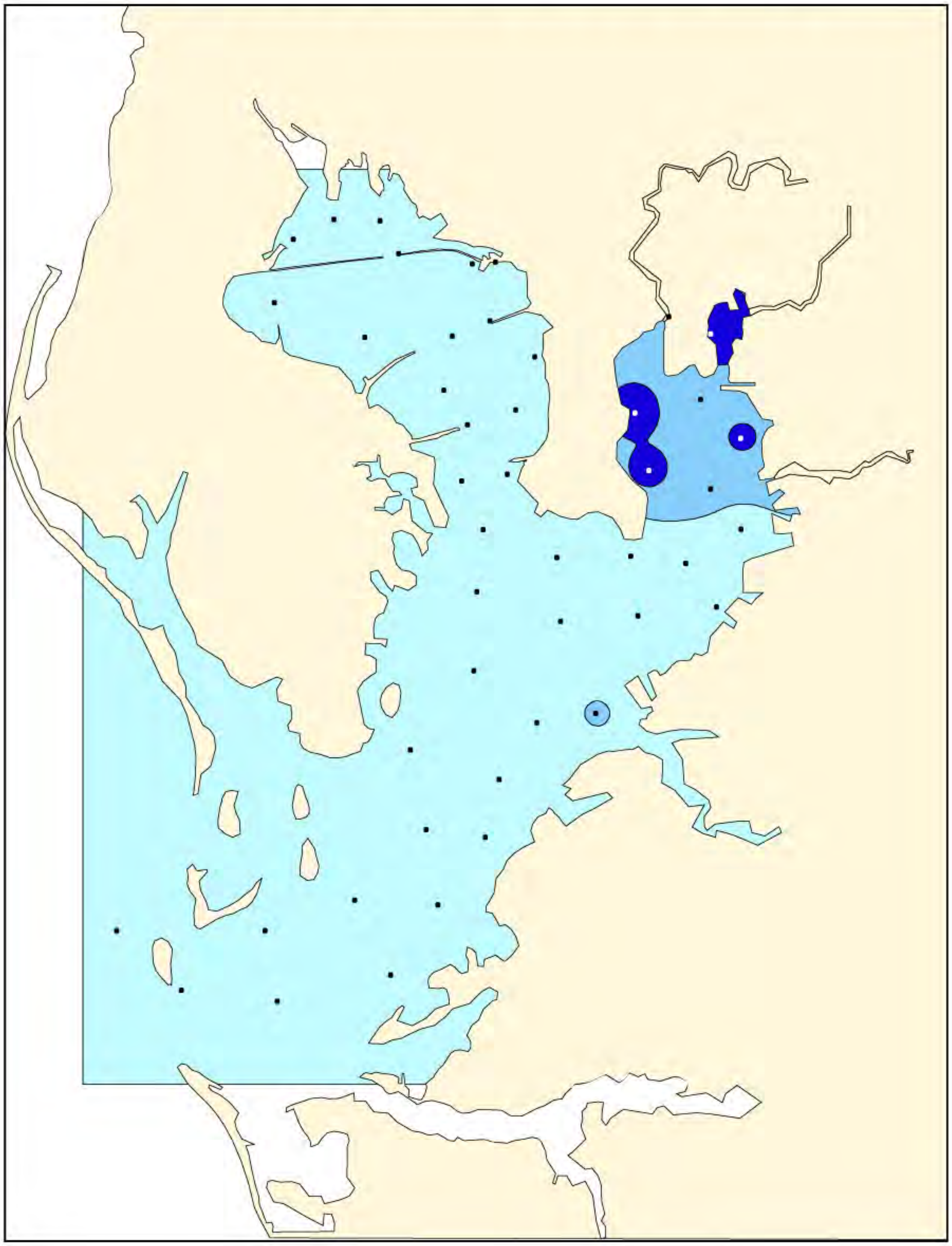
0 - 2 mg/L   2 - 4 mg/L   > 4 mg/L

Bottom Dissolved Oxygen
August 1979 - EPCHC Stations

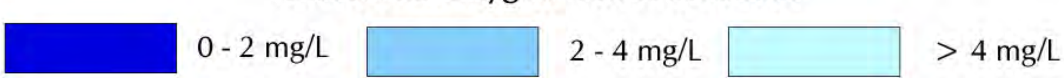


Dissolved Oxygen Concentrations

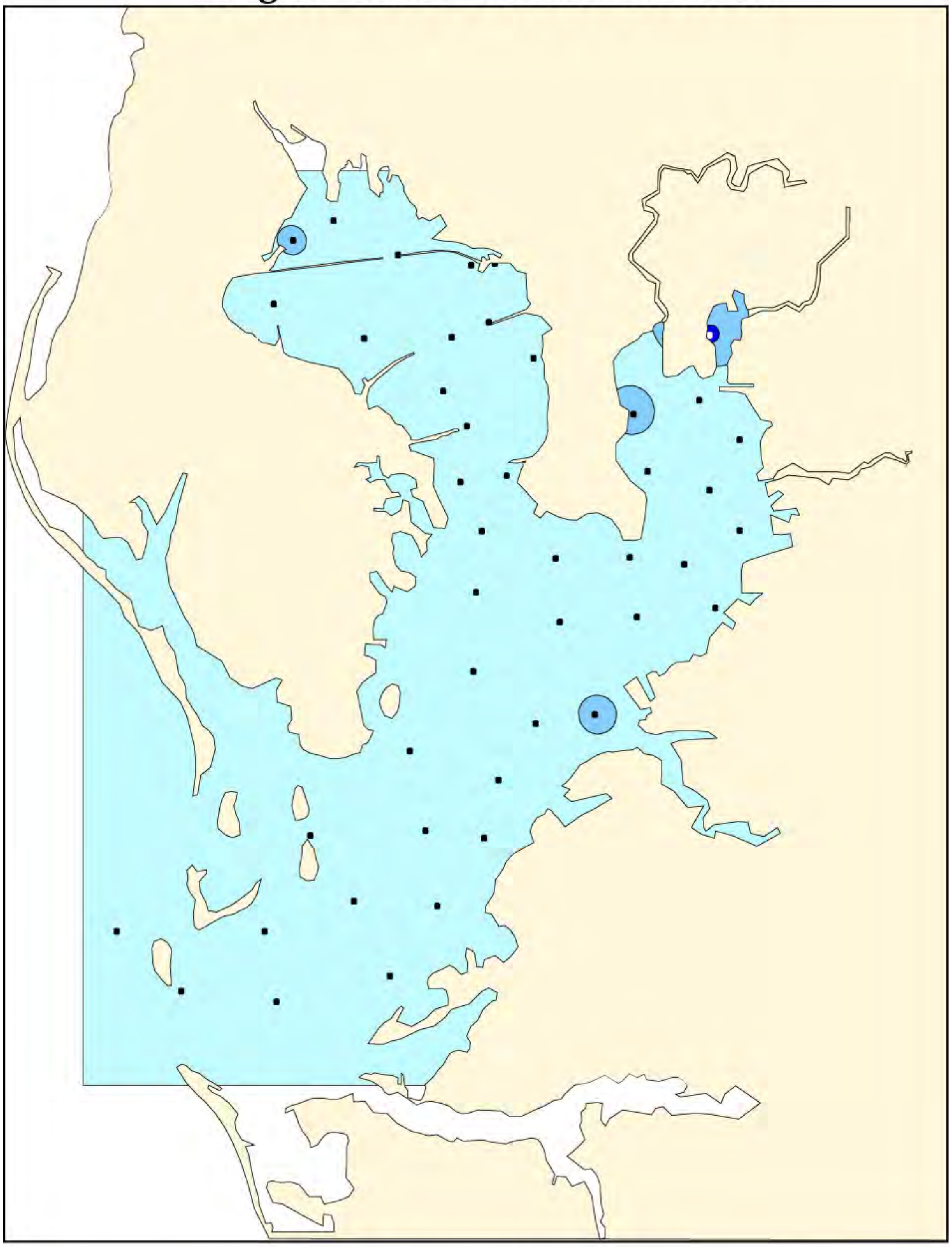
Bottom Dissolved Oxygen
September 1979 - EPCHC Stations



Dissolved Oxygen Concentrations



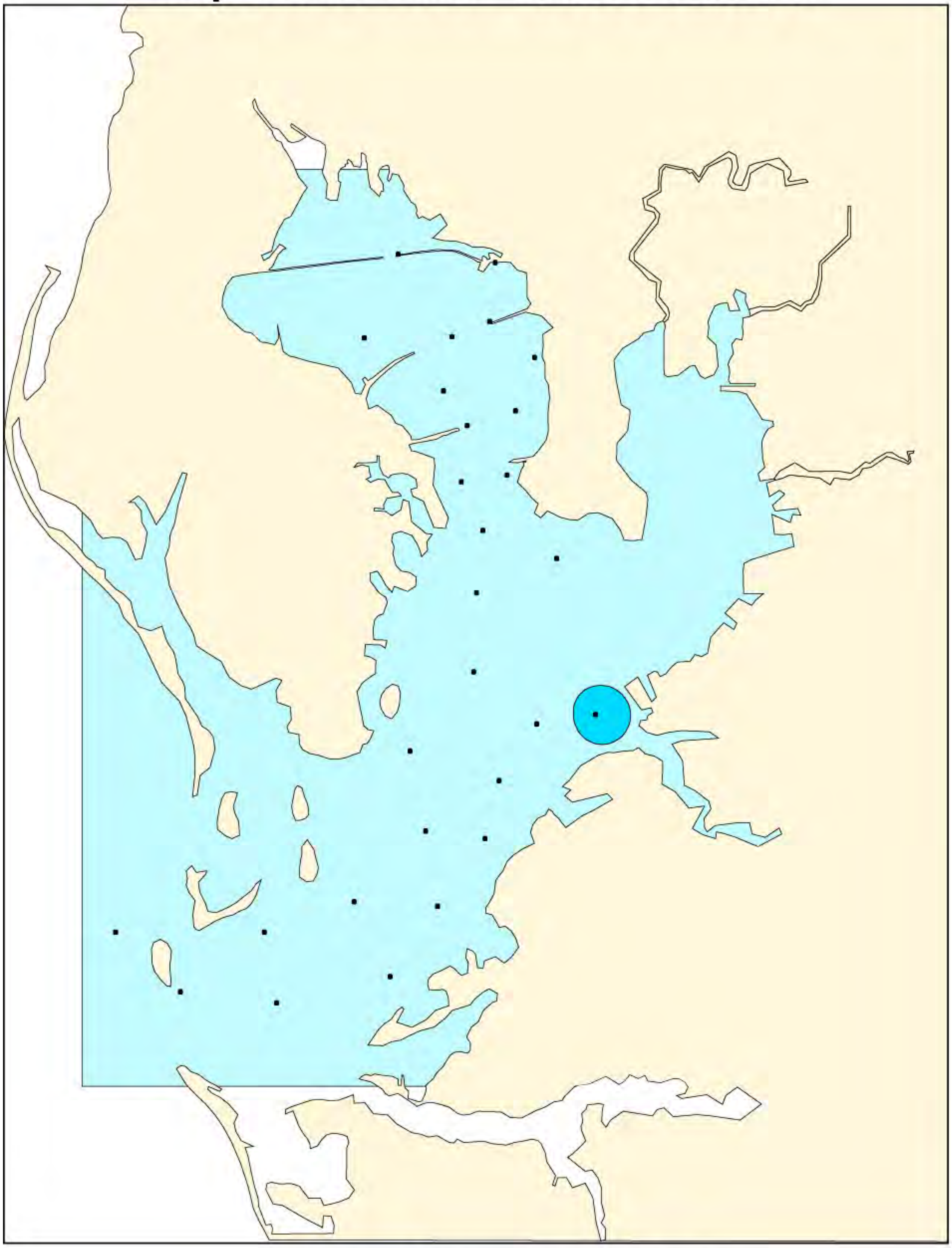
Bottom Dissolved Oxygen
August 1980 - EPCHC Stations



Dissolved Oxygen Concentrations

0 - 2 mg/L   2 - 4 mg/L   > 4 mg/L

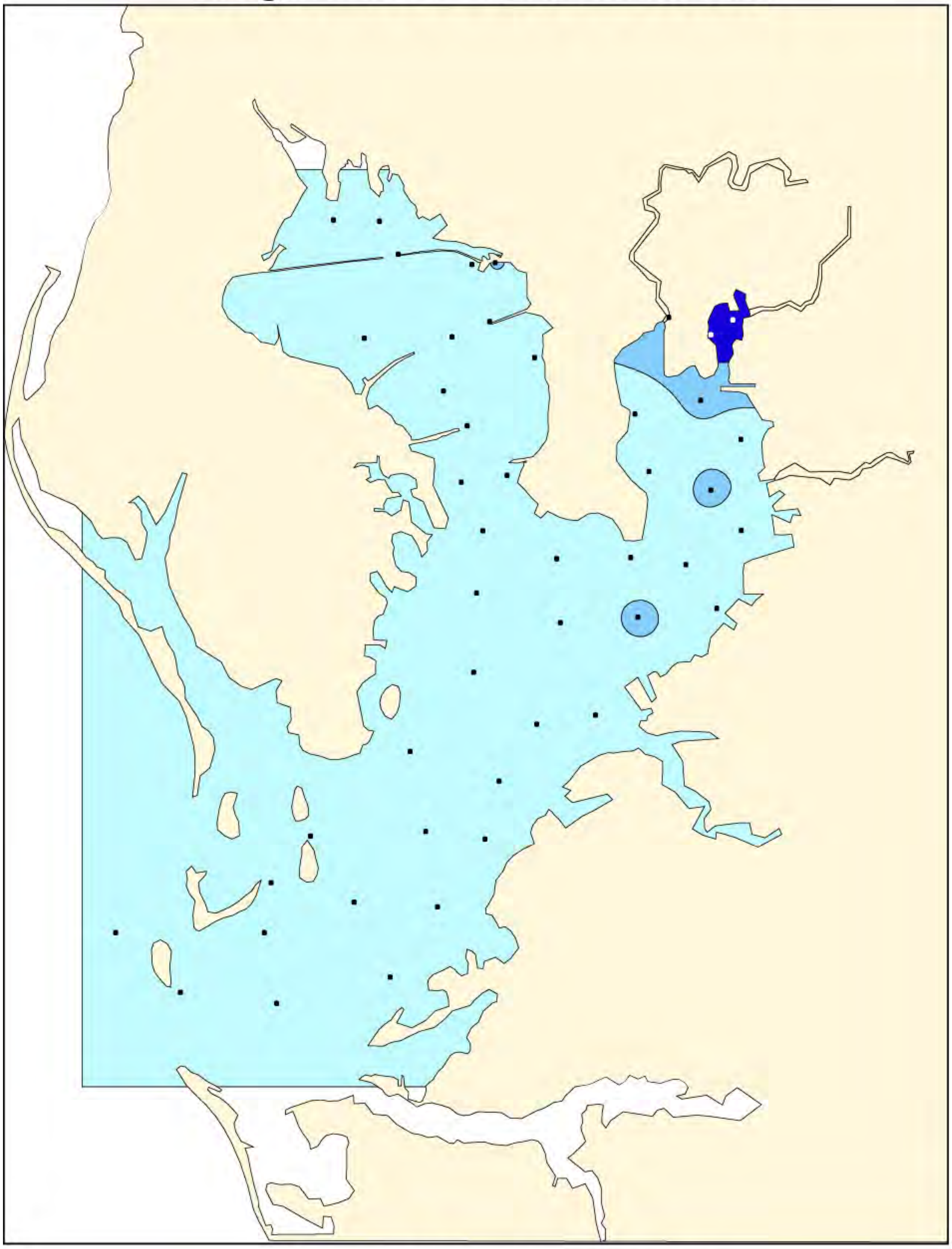
Bottom Dissolved Oxygen
September 1980 - EPCHC Stations



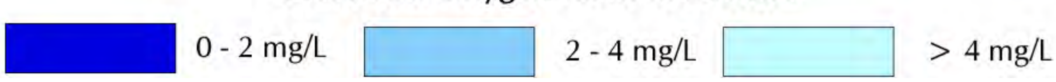
Dissolved Oxygen Concentrations

0 - 2 mg/L   2 - 4 mg/L   > 4 mg/L

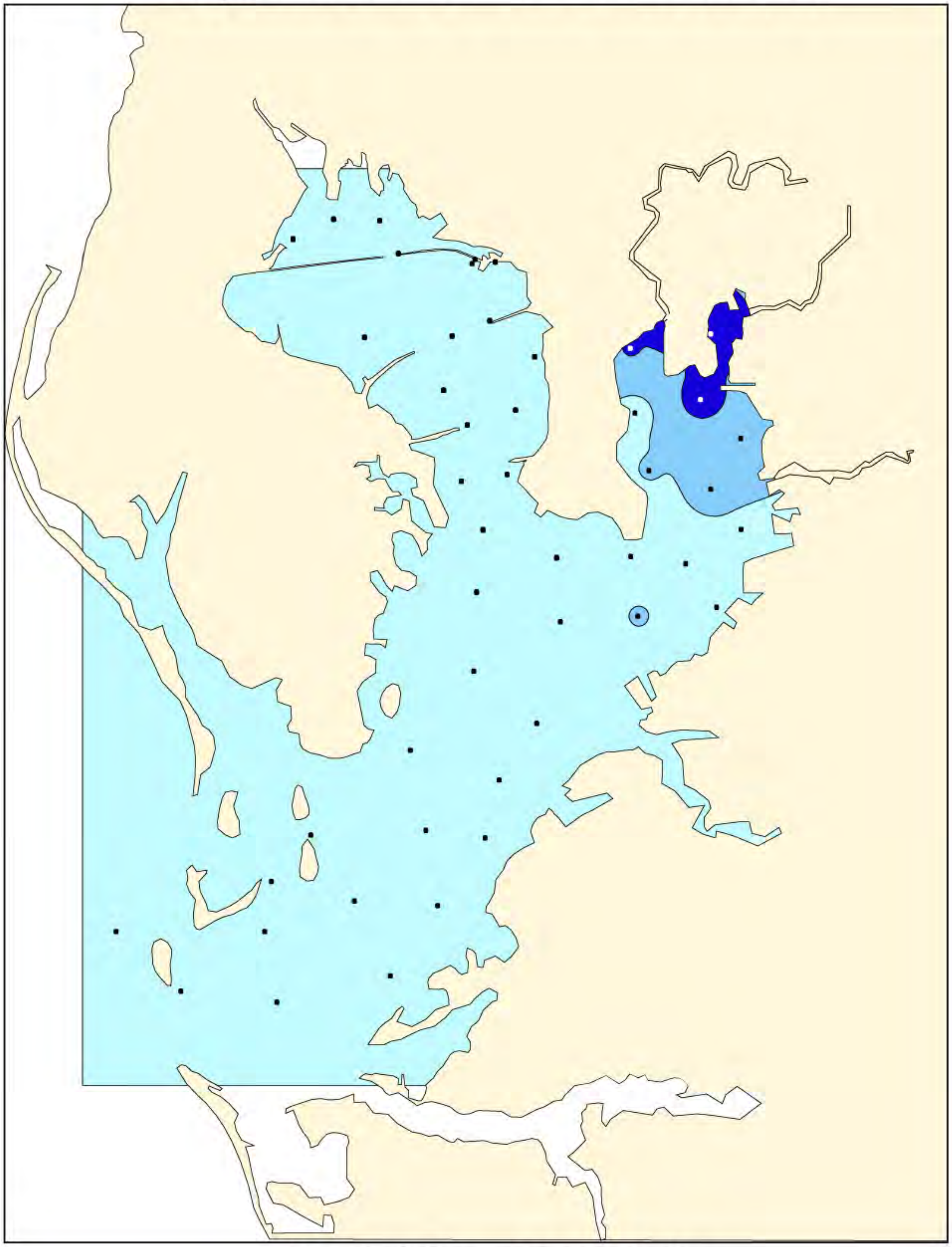
Bottom Dissolved Oxygen
August 1981 - EPCHC Stations



Dissolved Oxygen Concentrations



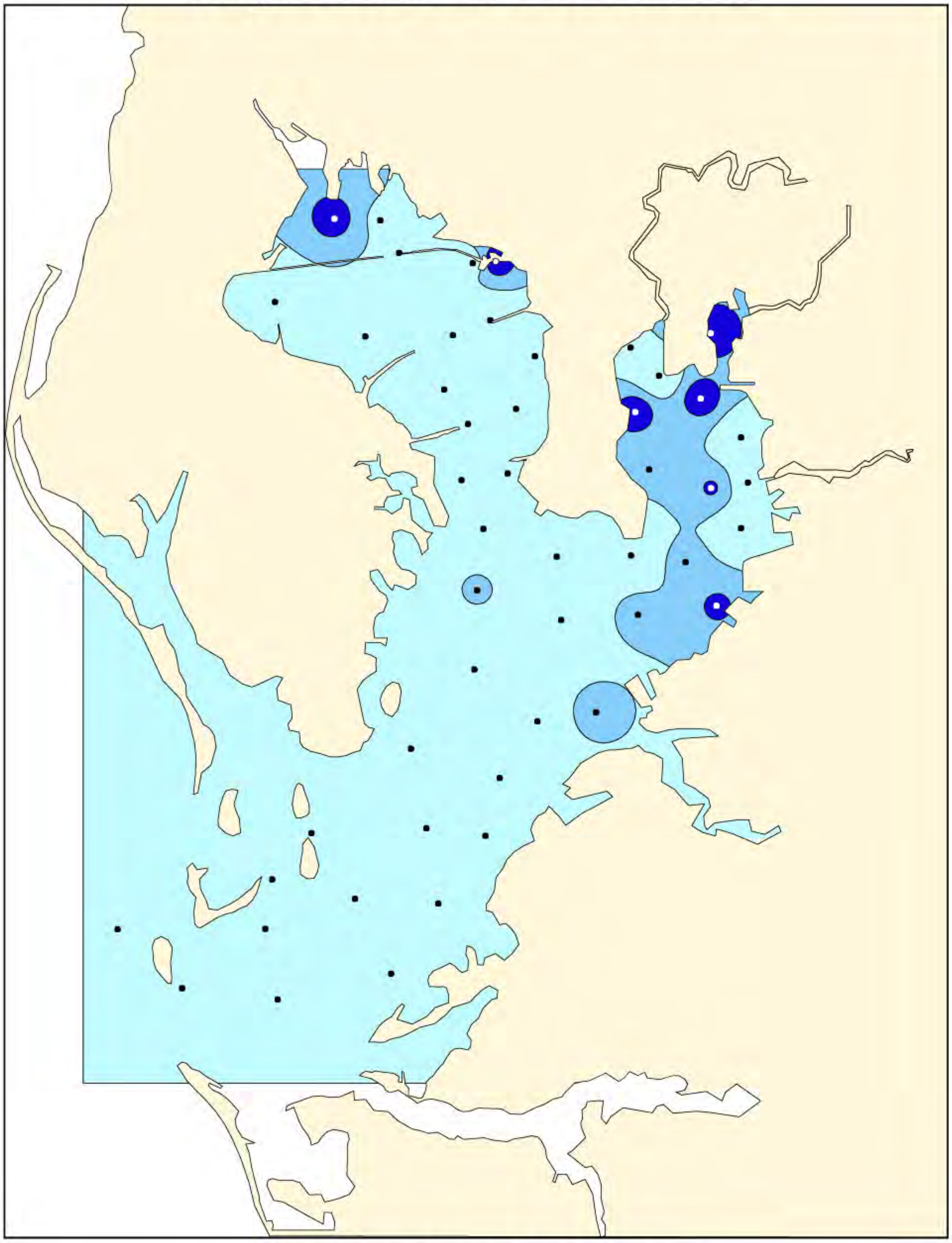
Bottom Dissolved Oxygen
September 1981 - EPCHC Stations



Dissolved Oxygen Concentrations

0 - 2 mg/L   2 - 4 mg/L   > 4 mg/L

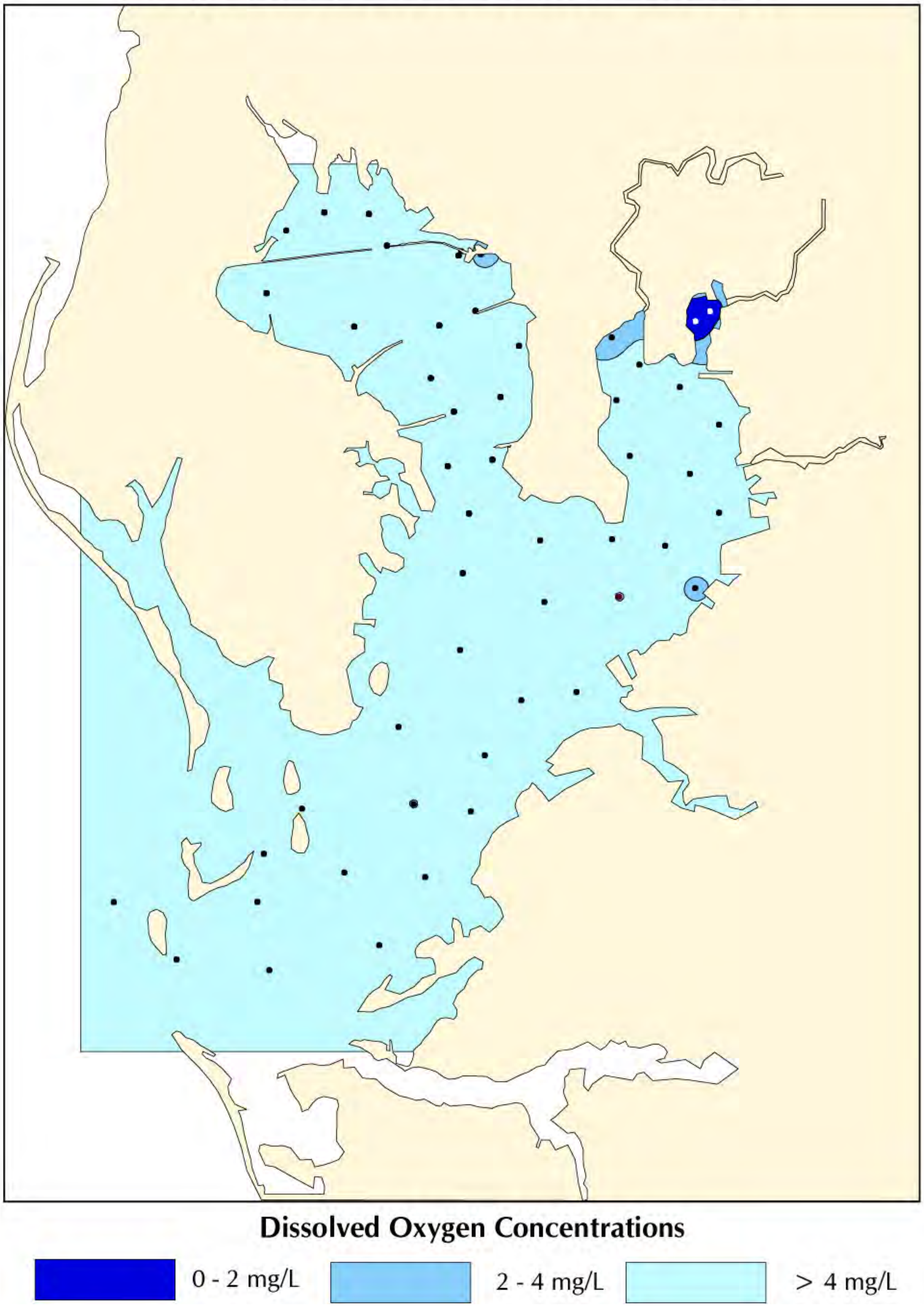
Bottom Dissolved Oxygen
August 1982 - EPCHC Stations



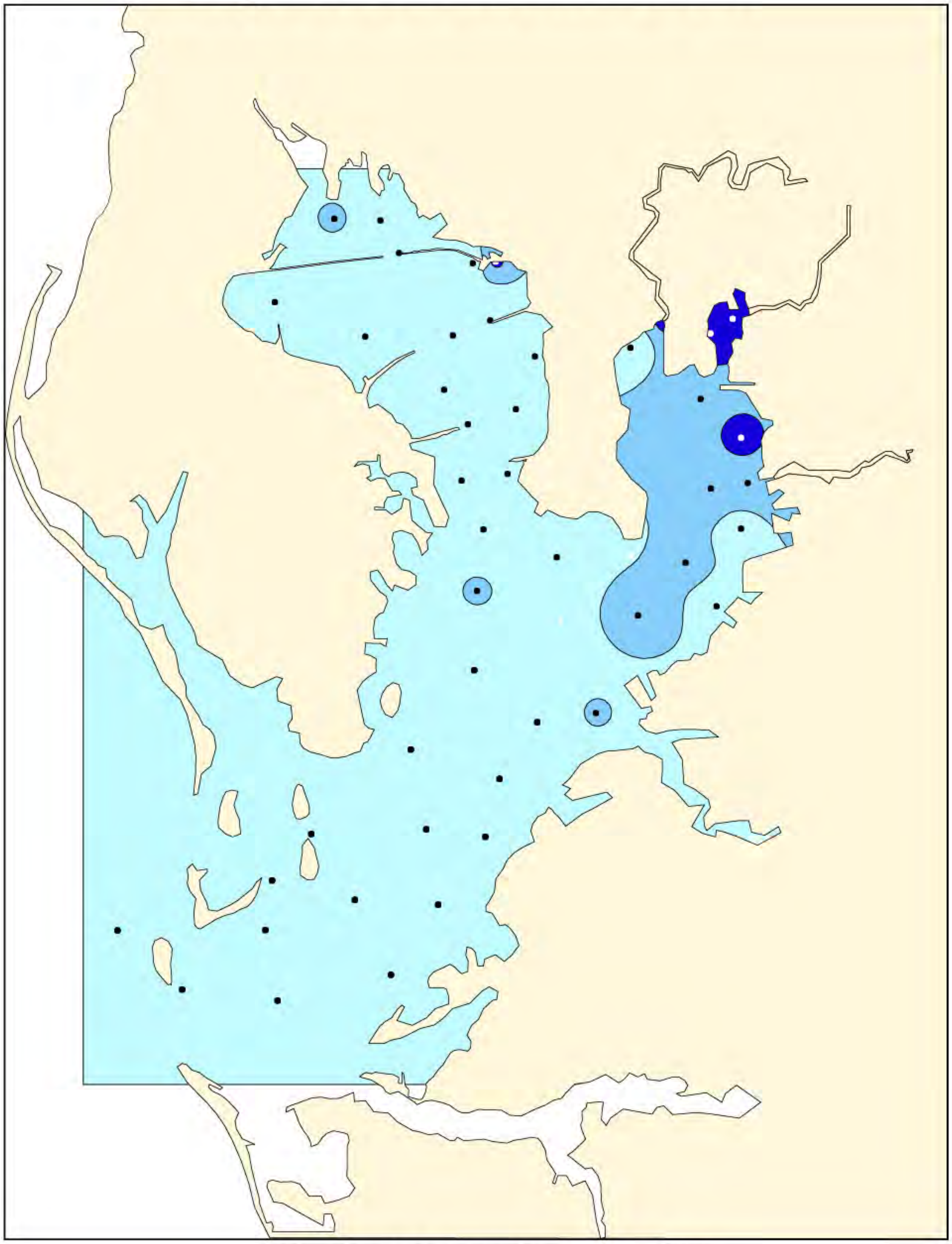
Dissolved Oxygen Concentrations

0 - 2 mg/L	2 - 4 mg/L	> 4 mg/L

Bottom Dissolved Oxygen
September 1982 - EPCHC Stations



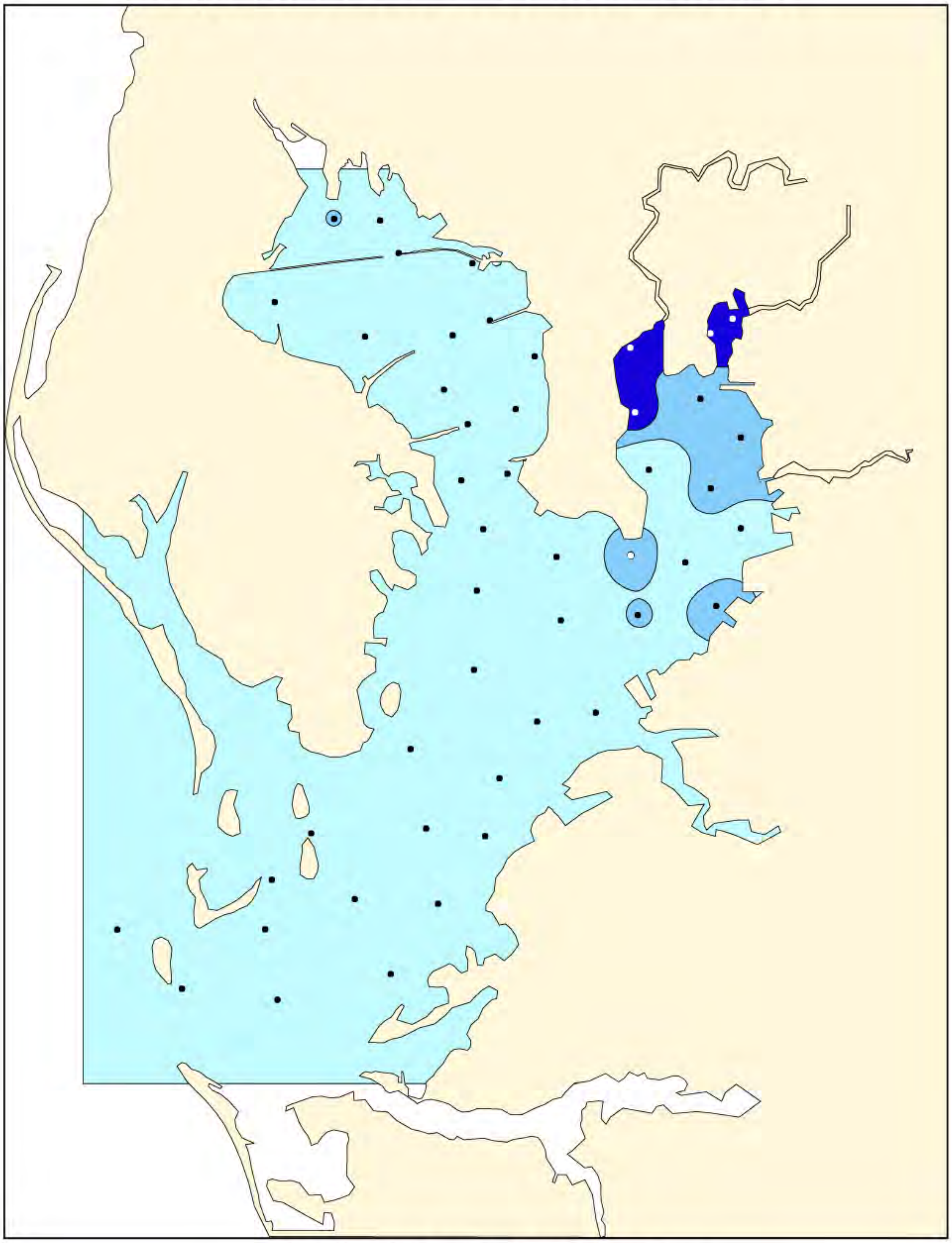
Bottom Dissolved Oxygen
August 1983 - EPCHC Stations



Dissolved Oxygen Concentrations

0 - 2 mg/L   2 - 4 mg/L   > 4 mg/L

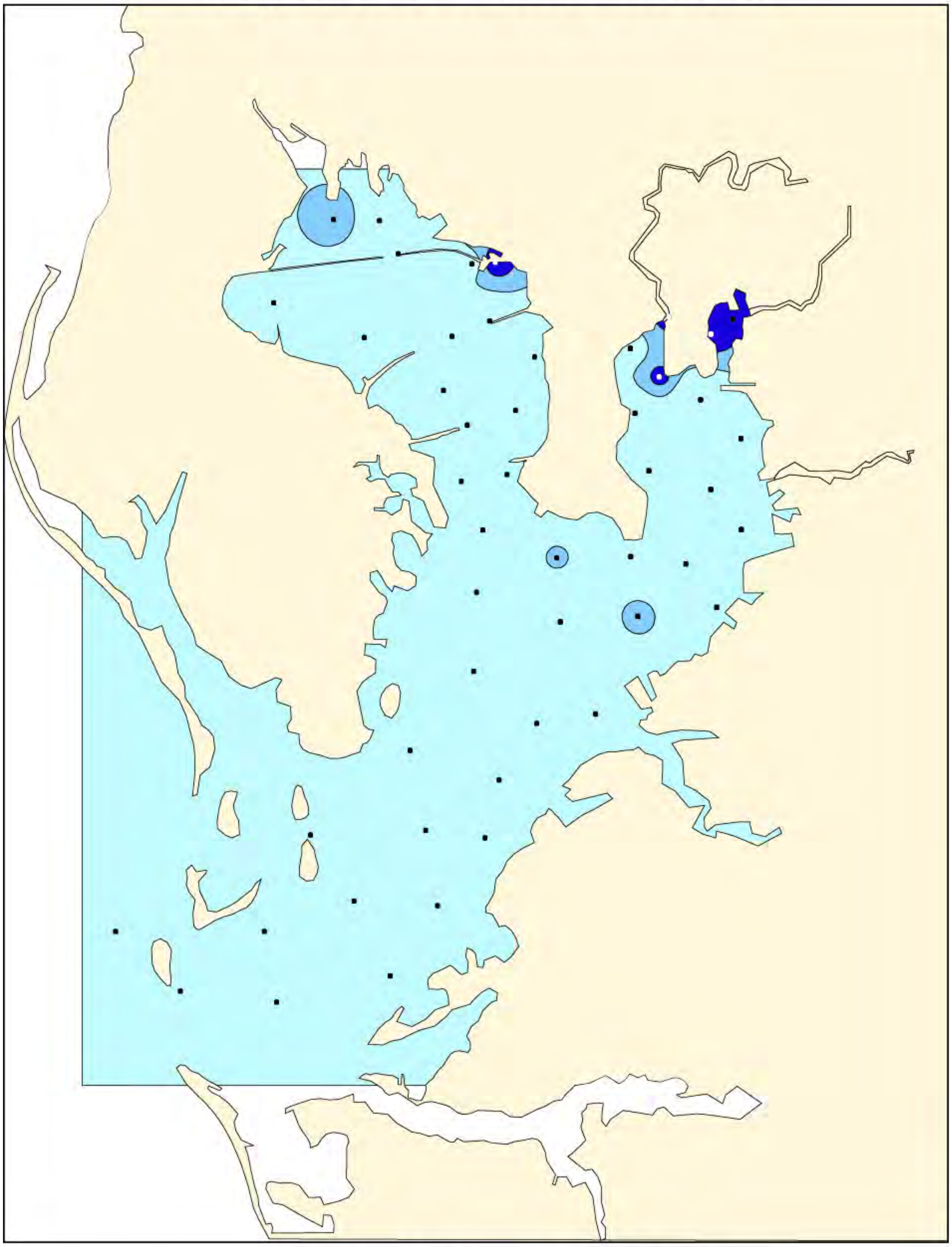
Bottom Dissolved Oxygen
September 1983 - EPCHC Stations



Dissolved Oxygen Concentrations

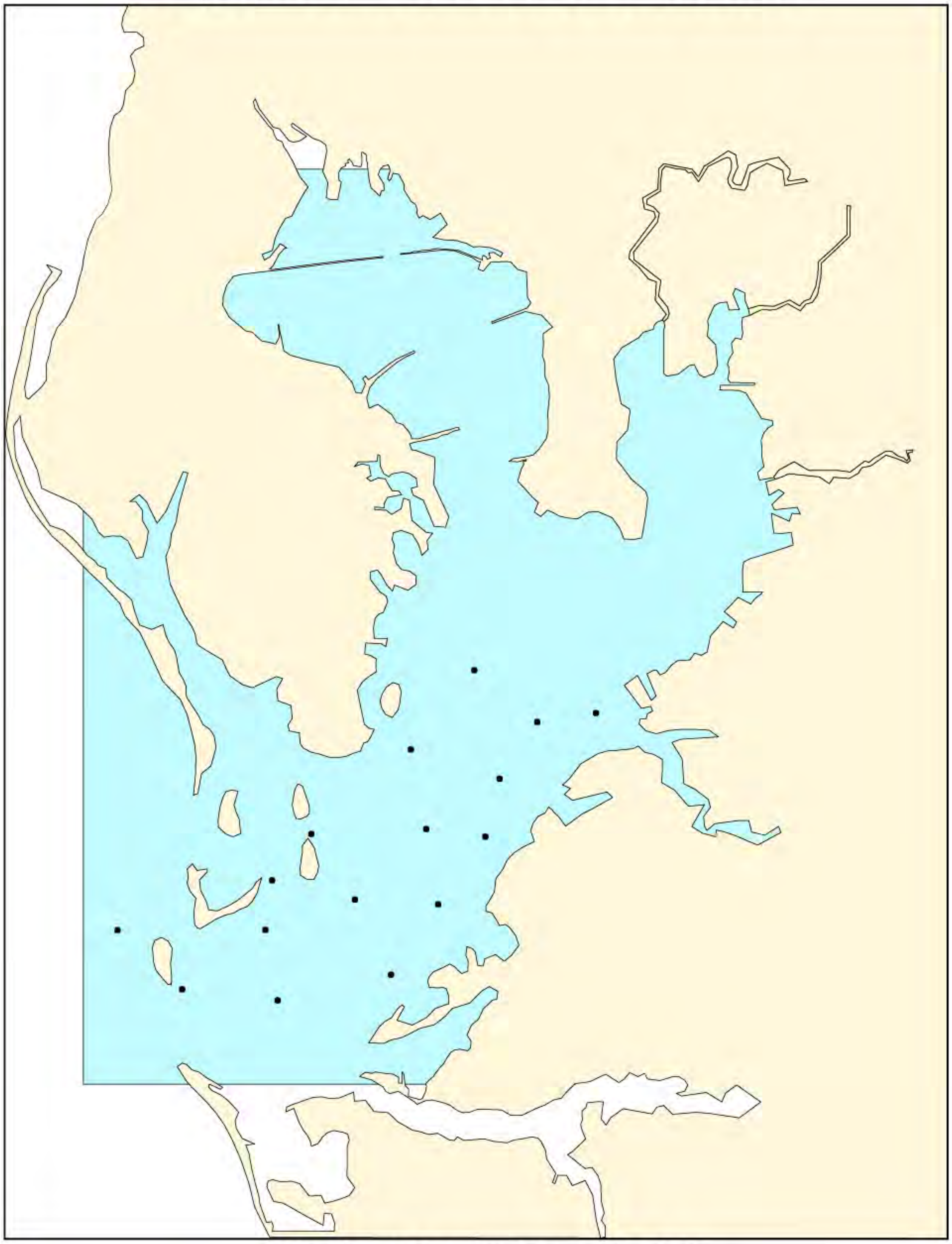
0 - 2 mg/L | 2 - 4 mg/L | > 4 mg/L

Bottom Dissolved Oxygen
August 1984 - EPCHC Stations



Dissolved Oxygen Concentrations

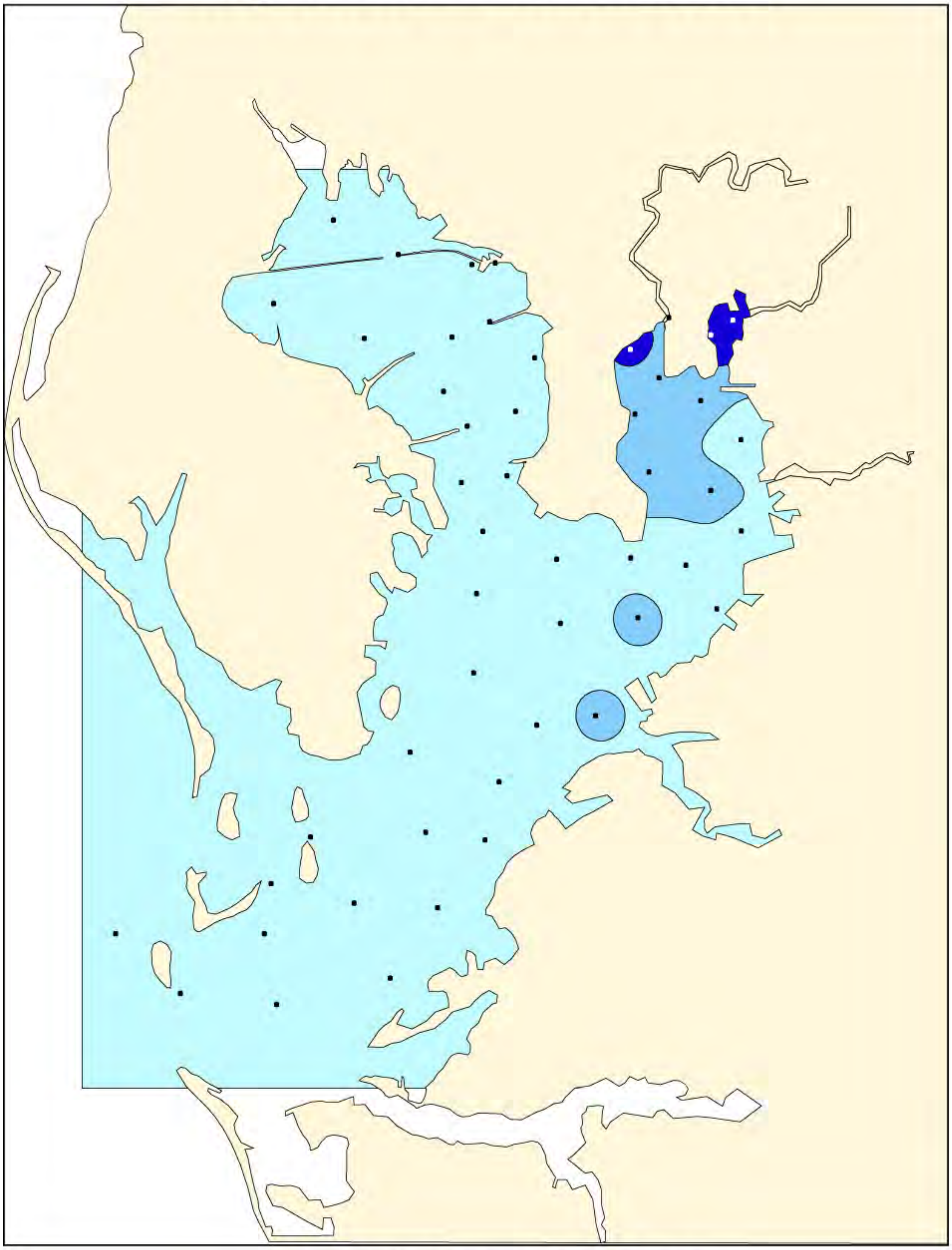
Bottom Dissolved Oxygen
September 1984 - EPCHC Stations



Dissolved Oxygen Concentrations

0 - 2 mg/L | 2 - 4 mg/L | > 4 mg/L

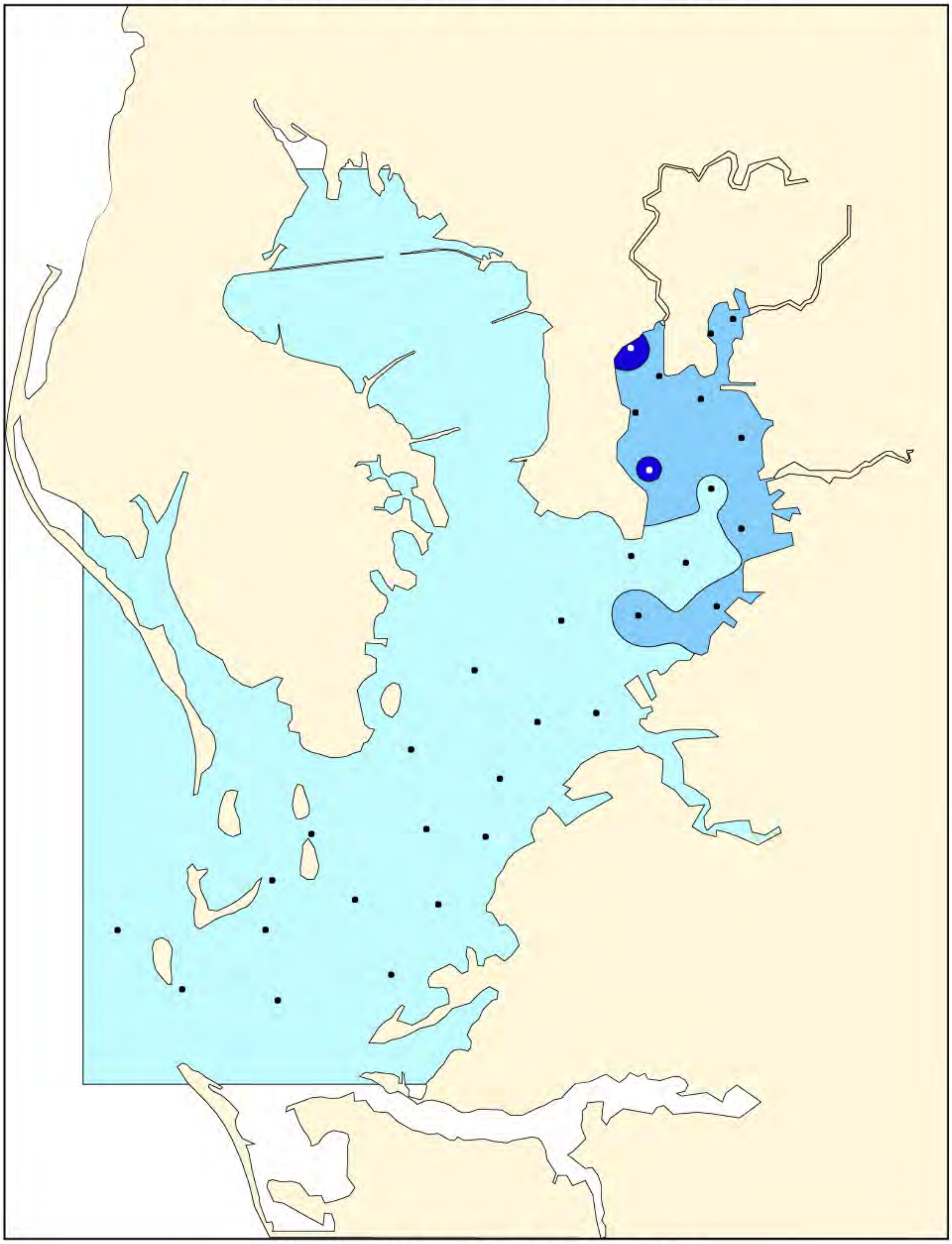
Bottom Dissolved Oxygen
August 1985 - EPCHC Stations



Dissolved Oxygen Concentrations

0 - 2 mg/L   2 - 4 mg/L   > 4 mg/L

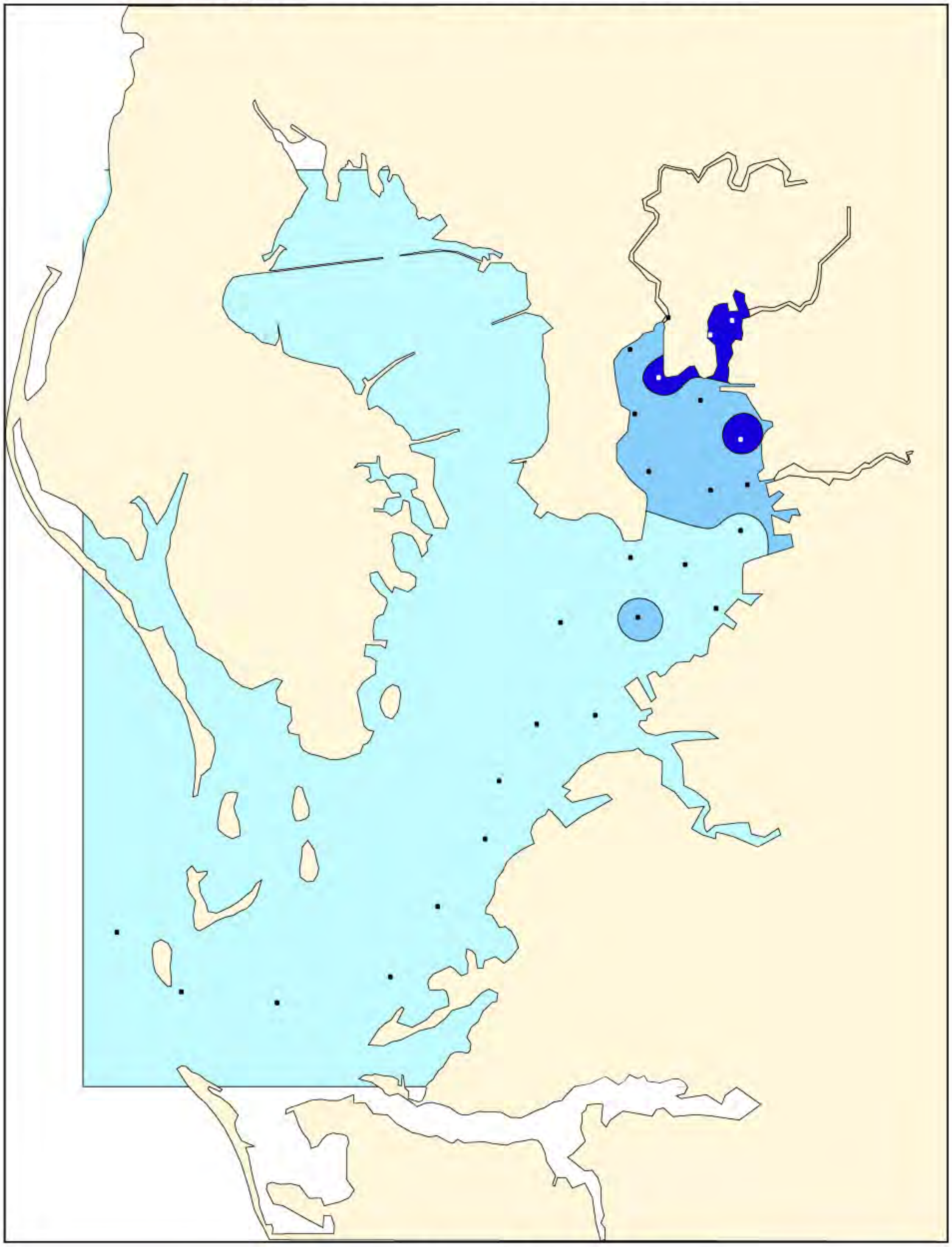
Bottom Dissolved Oxygen
September 1985 - EPCHC Stations



Dissolved Oxygen Concentrations

0 - 2 mg/L	2 - 4 mg/L	> 4 mg/L

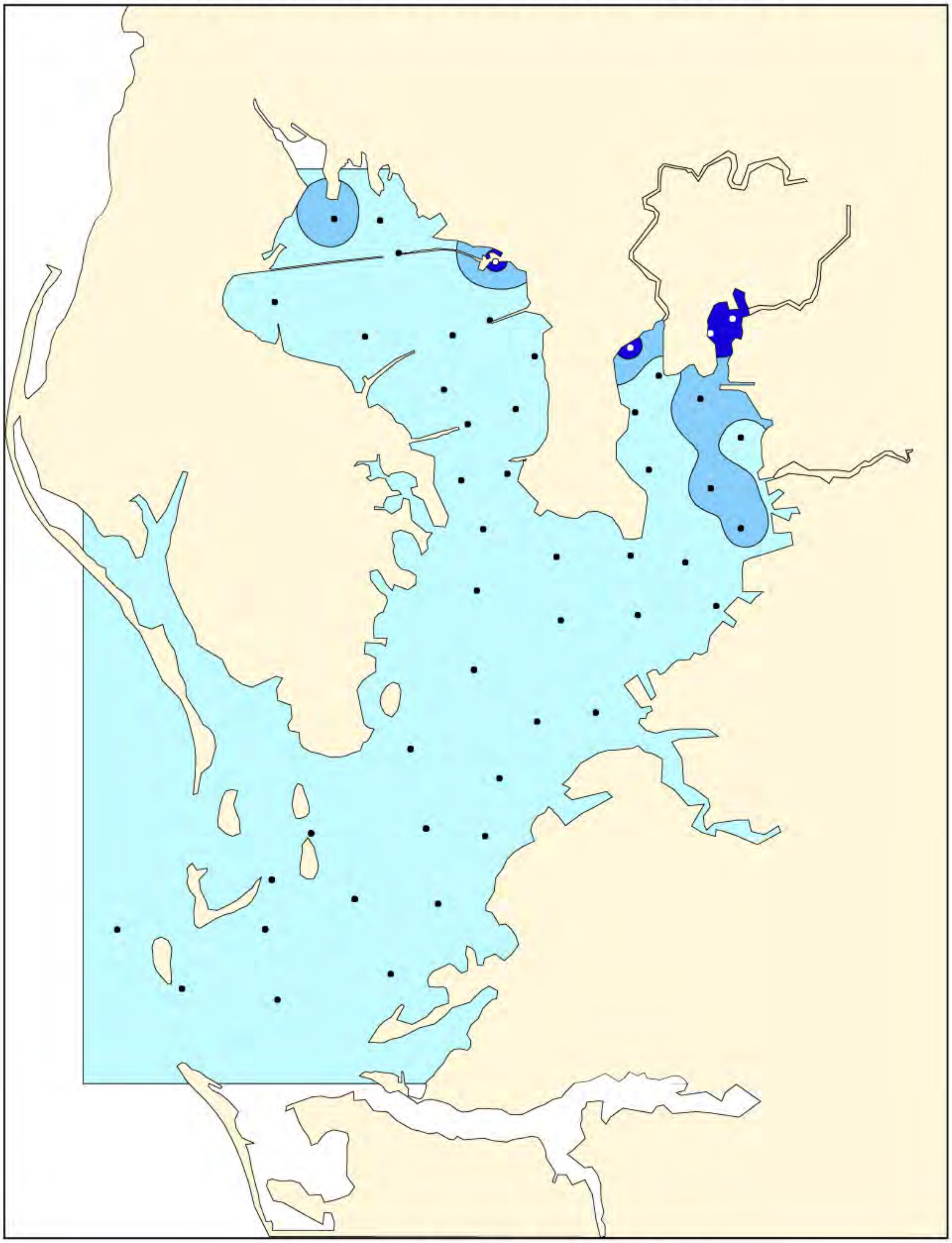
Bottom Dissolved Oxygen
August 1986 - EPCHC Stations



Dissolved Oxygen Concentrations

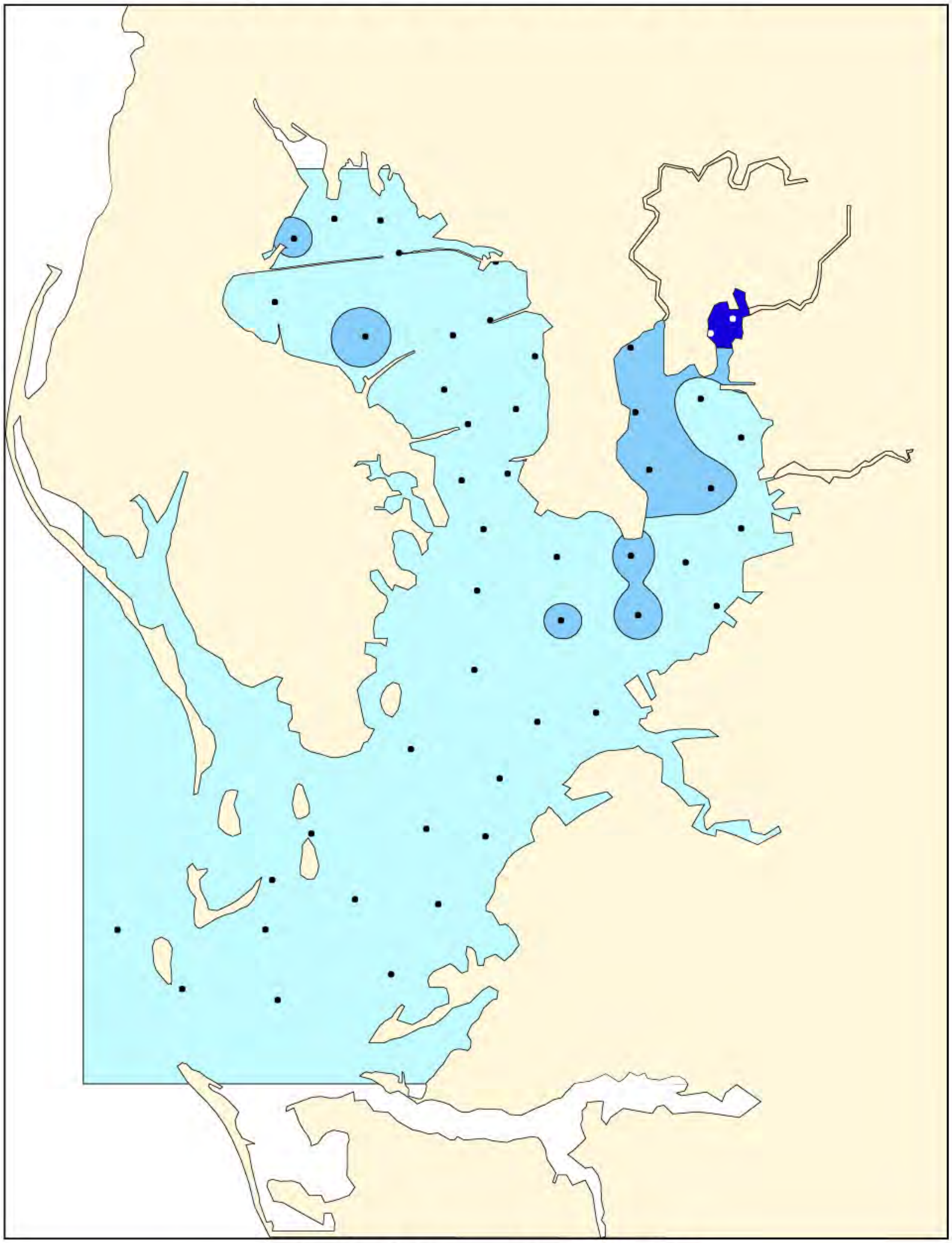
0 - 2 mg/L   2 - 4 mg/L   > 4 mg/L

Bottom Dissolved Oxygen
September 1986 - EPCHC Stations



Dissolved Oxygen Concentrations

Bottom Dissolved Oxygen
August 1987 - EPCHC Stations



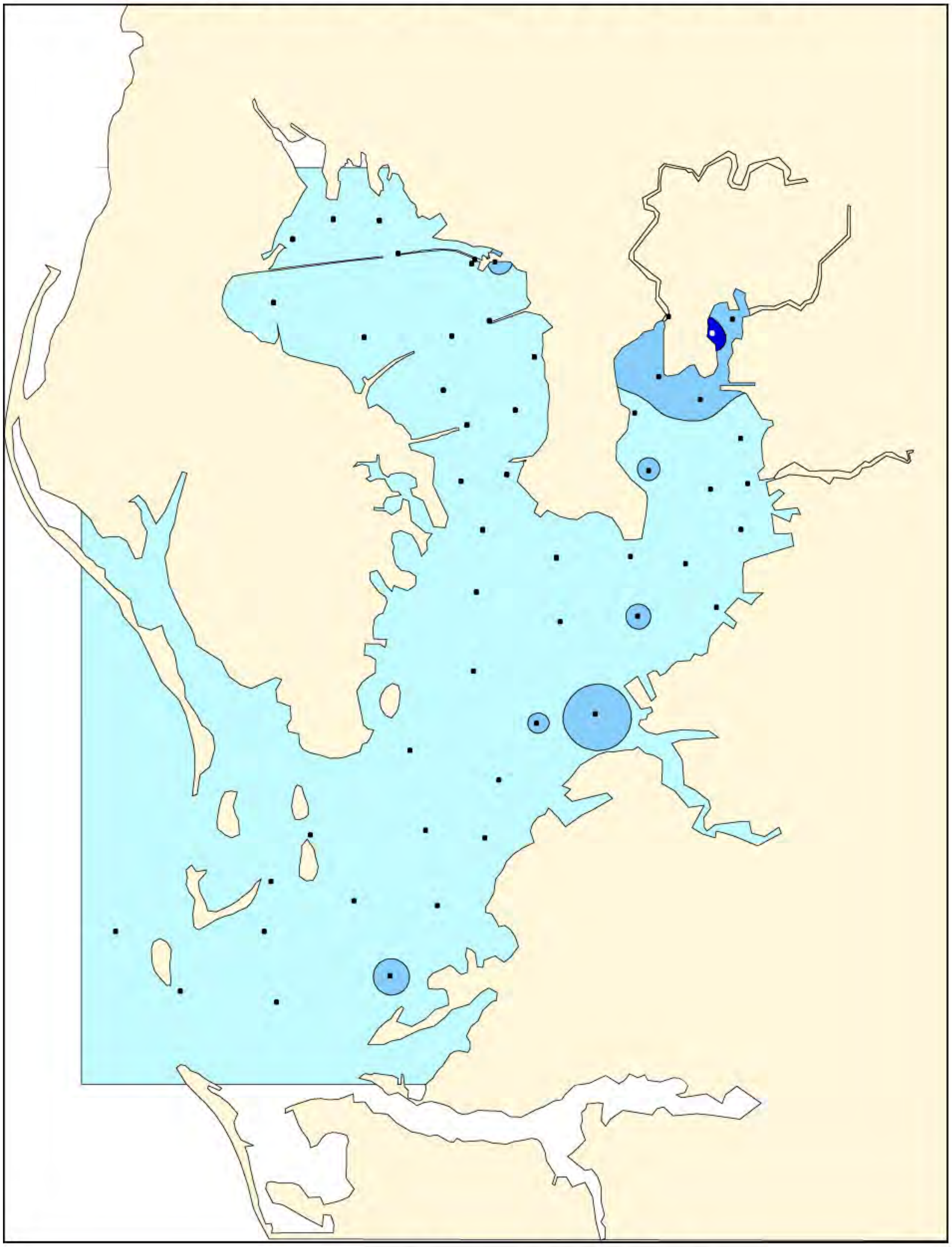
Dissolved Oxygen Concentrations

0 - 2 mg/L

2 - 4 mg/L

> 4 mg/L

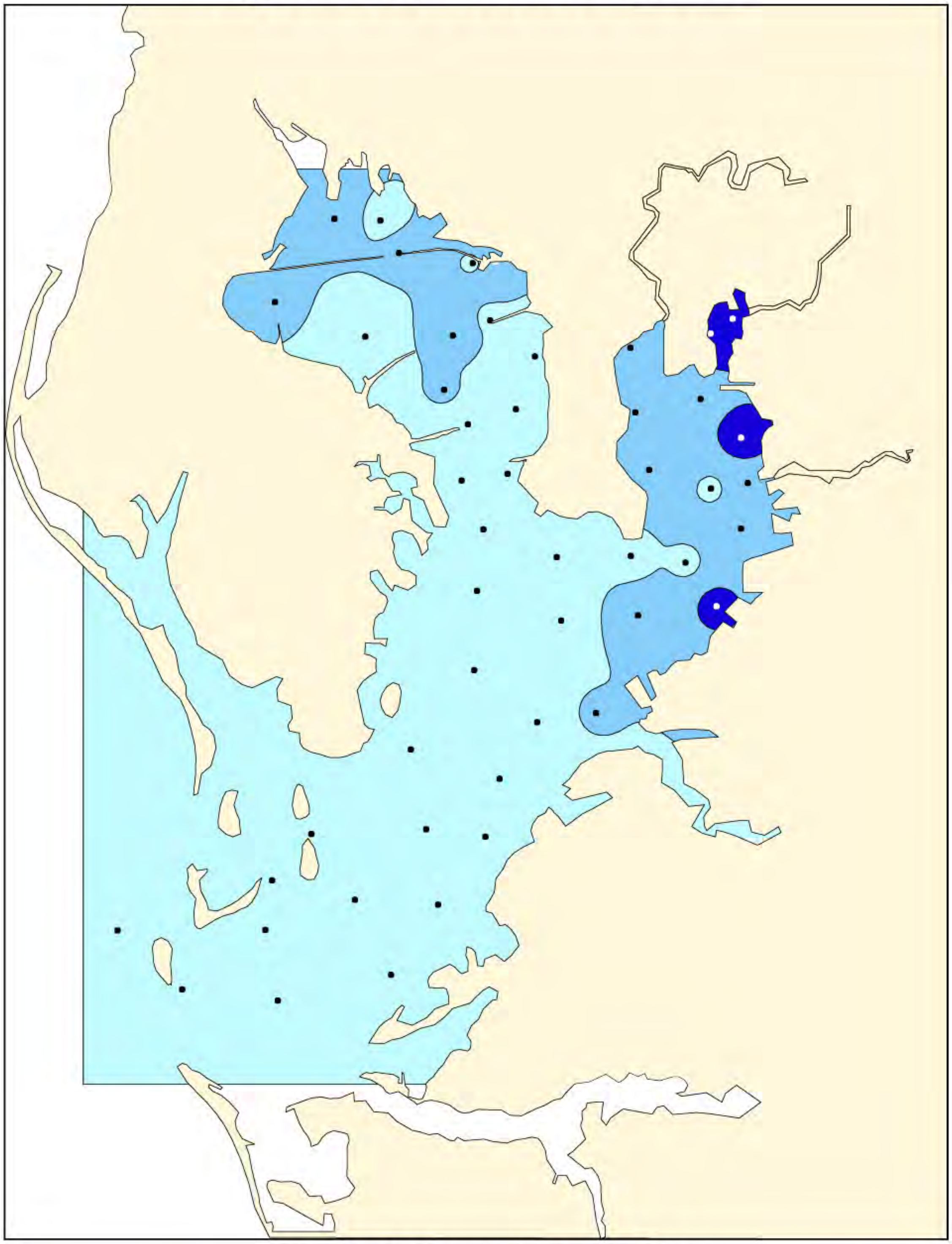
Bottom Dissolved Oxygen
September 1987 - EPCHC Stations



Dissolved Oxygen Concentrations

0 - 2 mg/L | 2 - 4 mg/L | > 4 mg/L

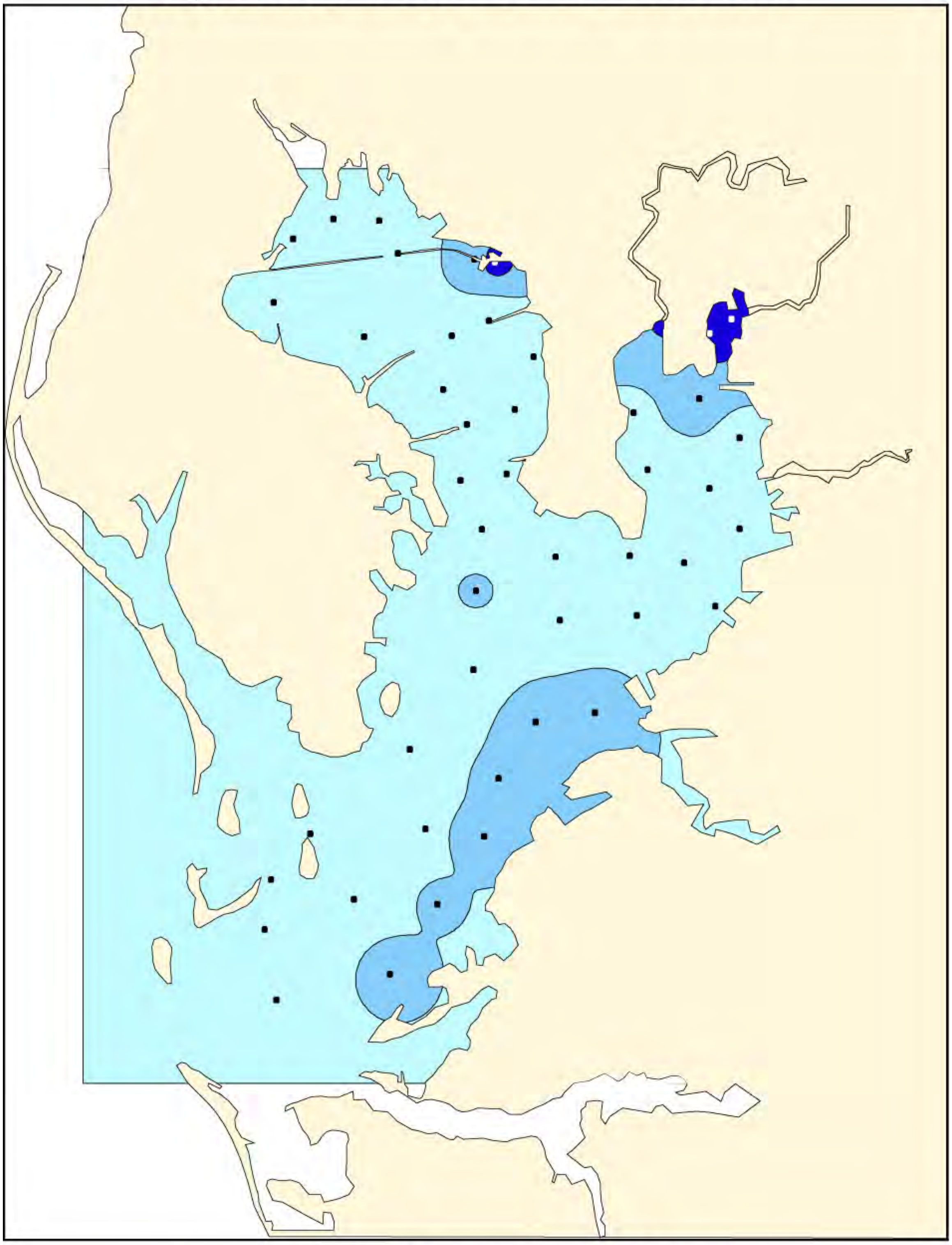
Bottom Dissolved Oxygen
August 1988 - EPCHC Stations



Dissolved Oxygen Concentrations

0 - 2 mg/L | 2 - 4 mg/L | > 4 mg/L

Bottom Dissolved Oxygen
September 1988 - EPCHC Stations



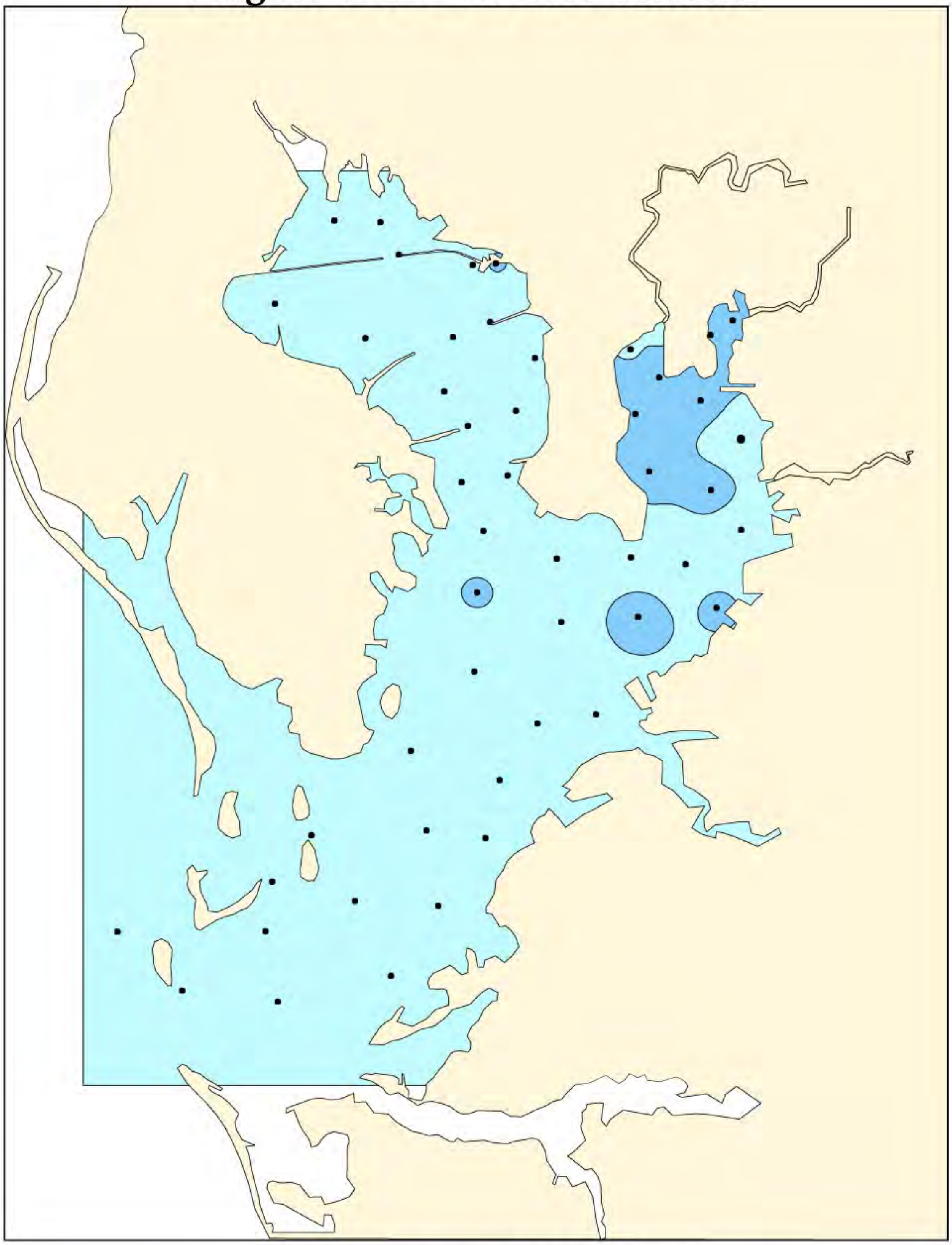
Dissolved Oxygen Concentrations

0 - 2 mg/L

2 - 4 mg/L

> 4 mg/L

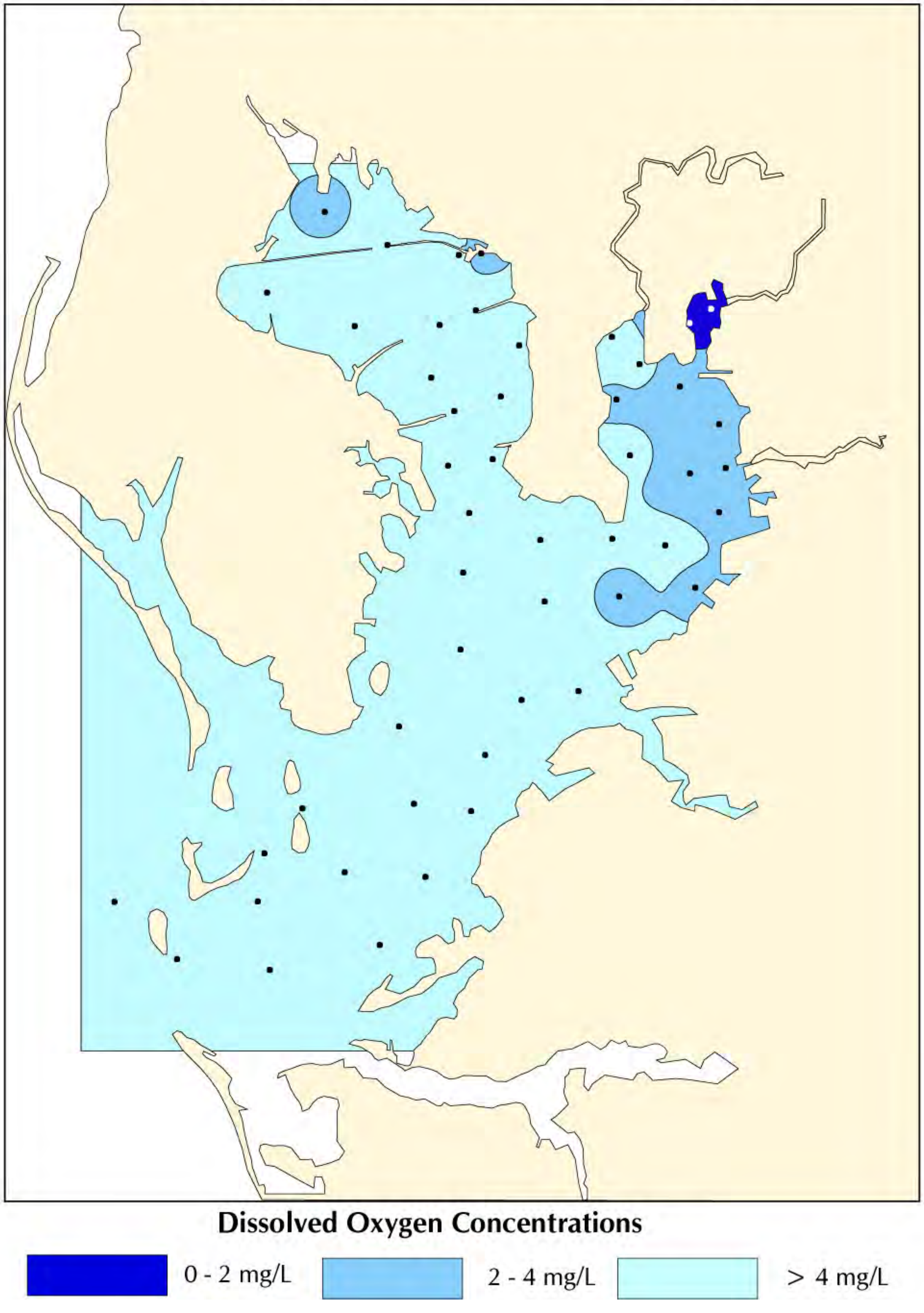
Bottom Dissolved Oxygen
August 1989 - EPCHC Stations



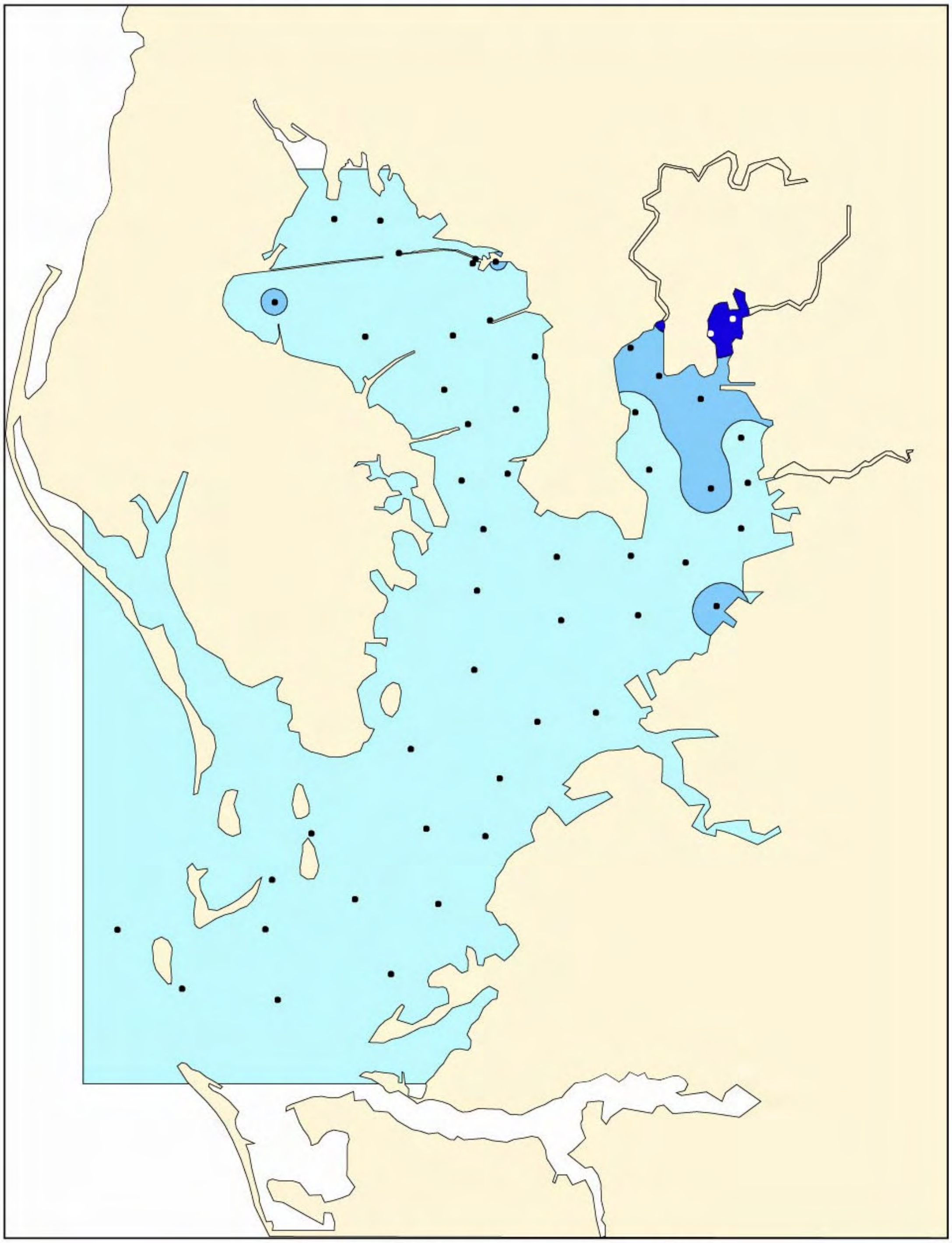
Dissolved Oxygen Concentrations

0 - 2 mg/L   2 - 4 mg/L   > 4 mg/L

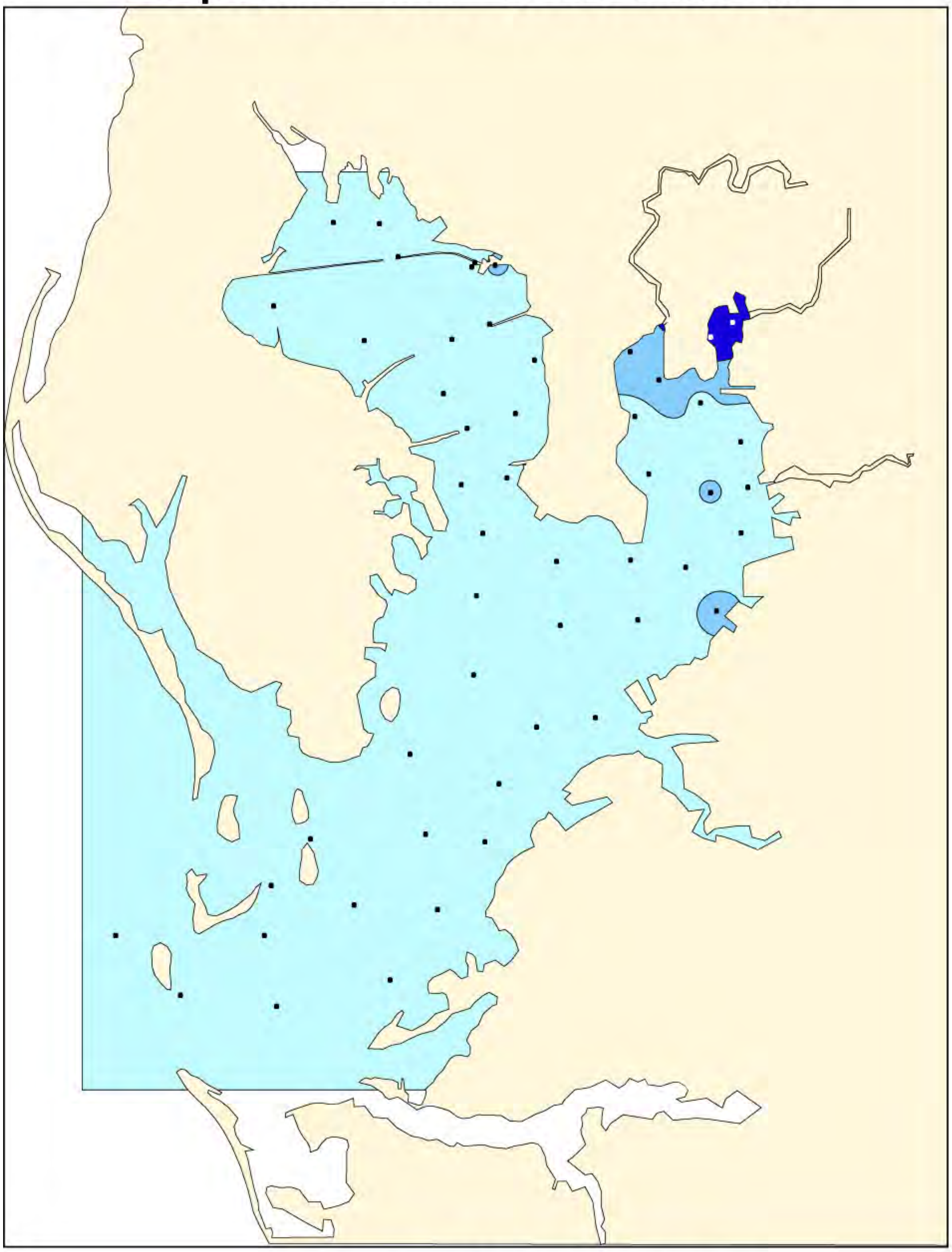
Bottom Dissolved Oxygen
September 1989 - EPCHC Stations



Bottom Dissolved Oxygen
August 1990 - EPCHC Stations



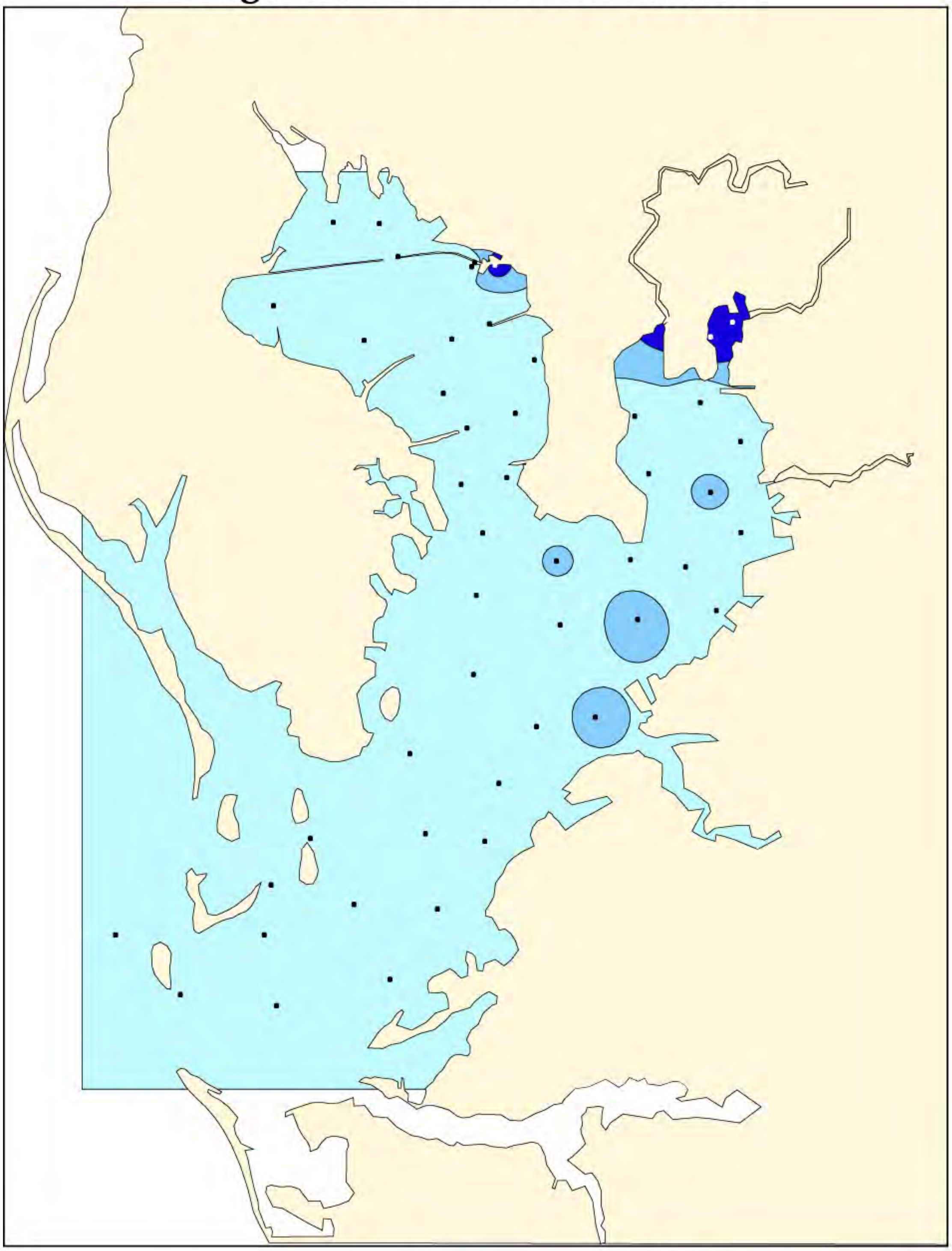
Bottom Dissolved Oxygen
September 1990 - EPCHC Stations



Dissolved Oxygen Concentrations

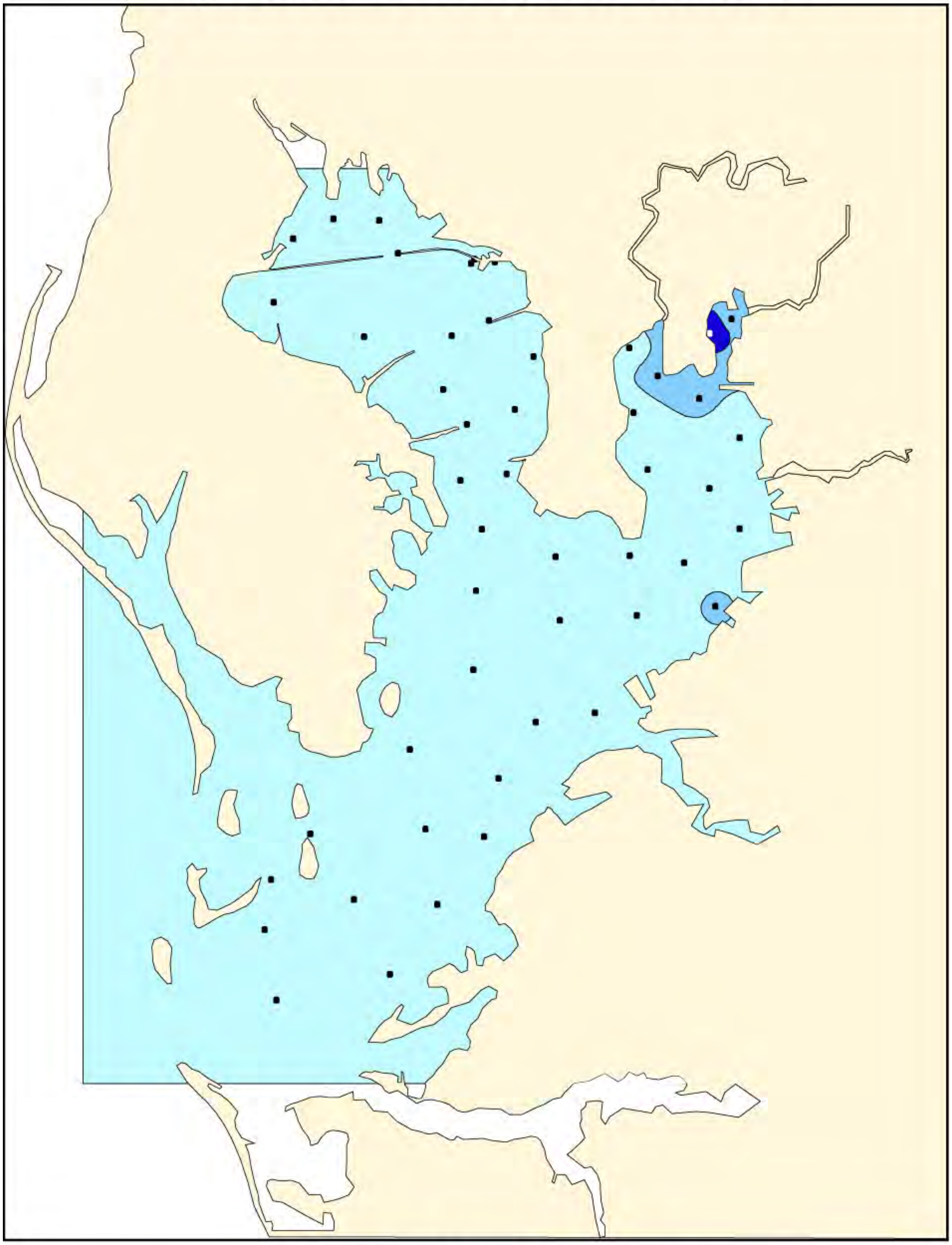
0 - 2 mg/L 2 - 4 mg/L > 4 mg/L

Bottom Dissolved Oxygen
August 1991 - EPCHC Stations



Dissolved Oxygen Concentrations

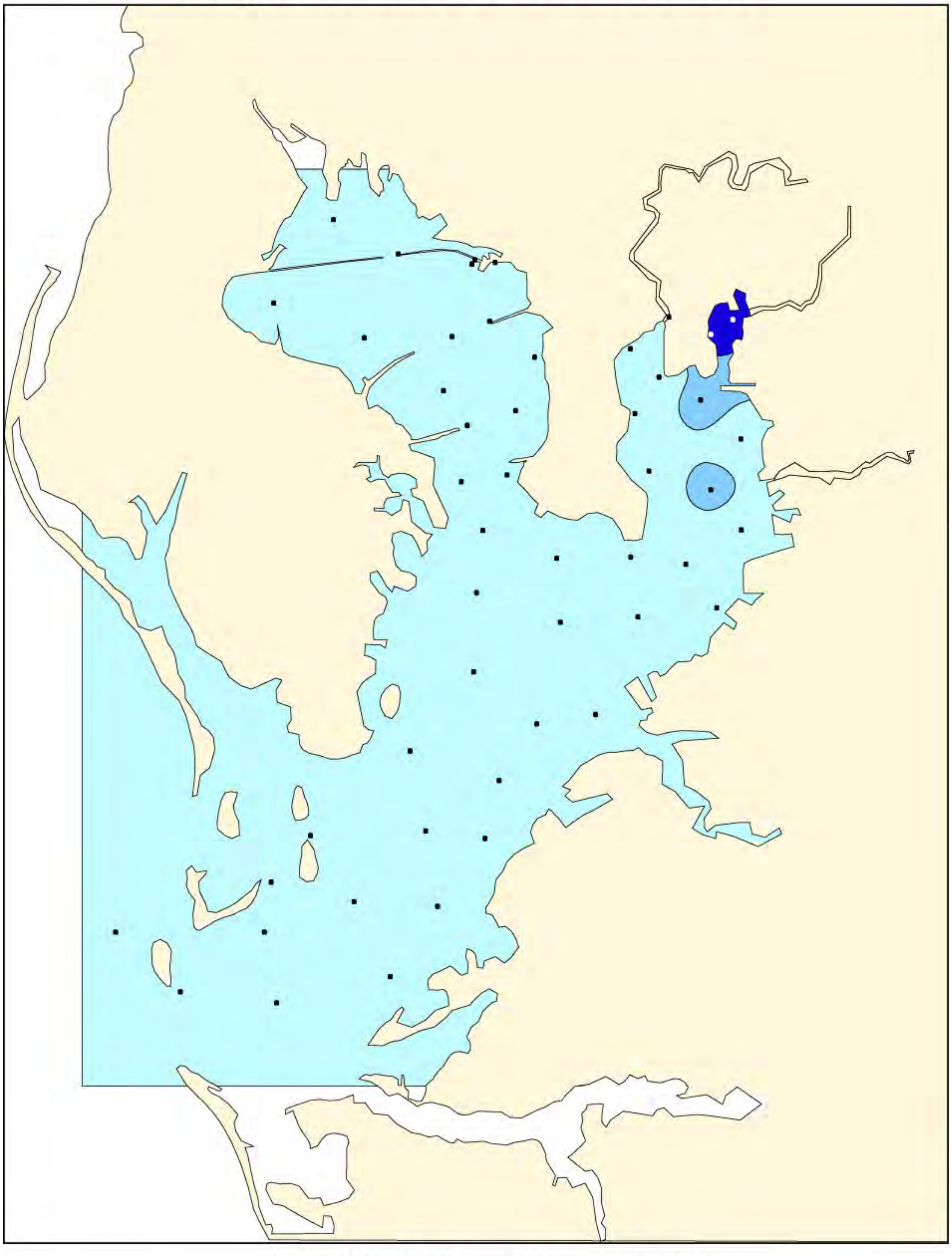
Bottom Dissolved Oxygen
September 1991 - EPCHC Stations



Dissolved Oxygen Concentrations

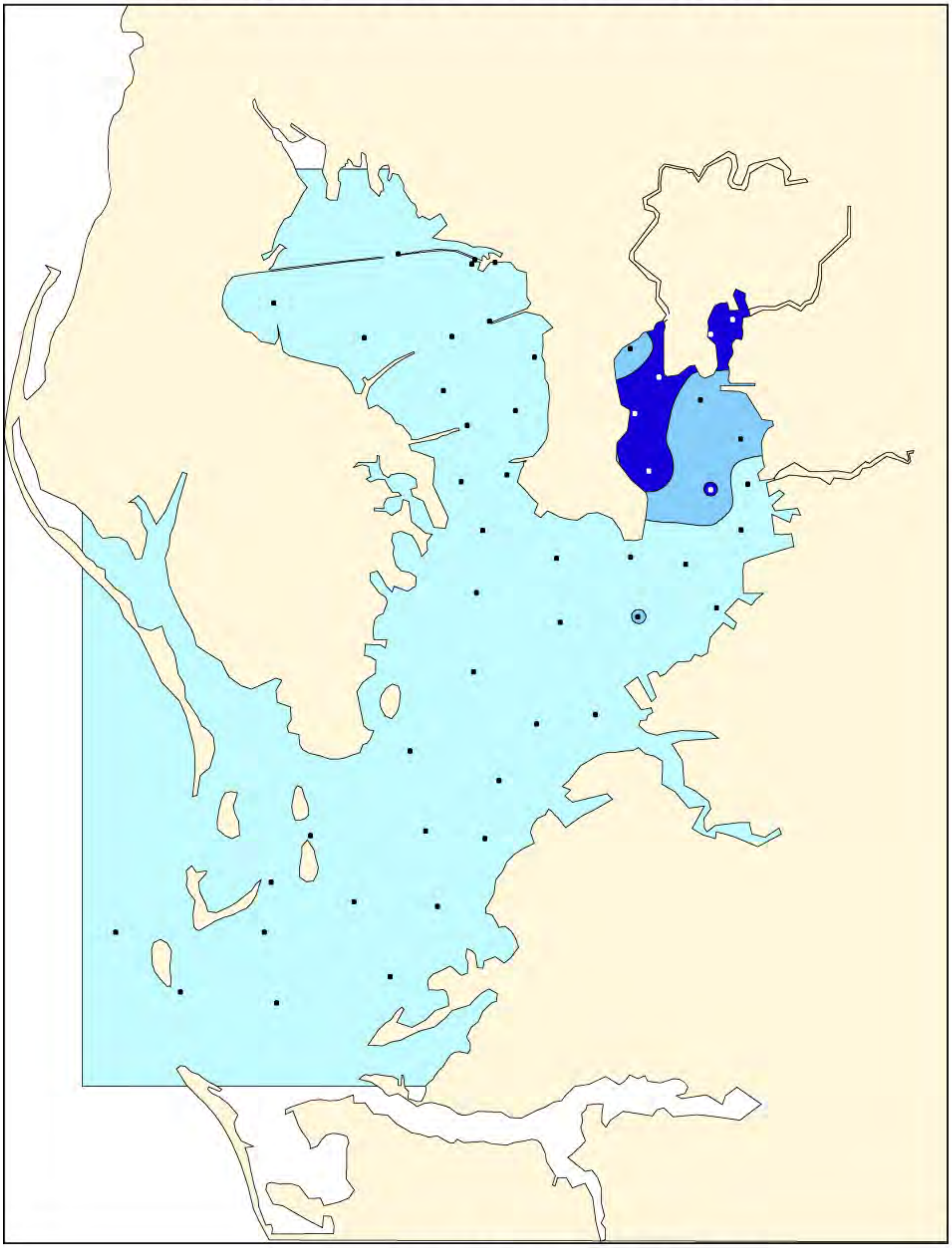
0 - 2 mg/L | 2 - 4 mg/L | > 4 mg/L

Bottom Dissolved Oxygen
August 1992 - EPCHC Stations



Dissolved Oxygen Concentrations

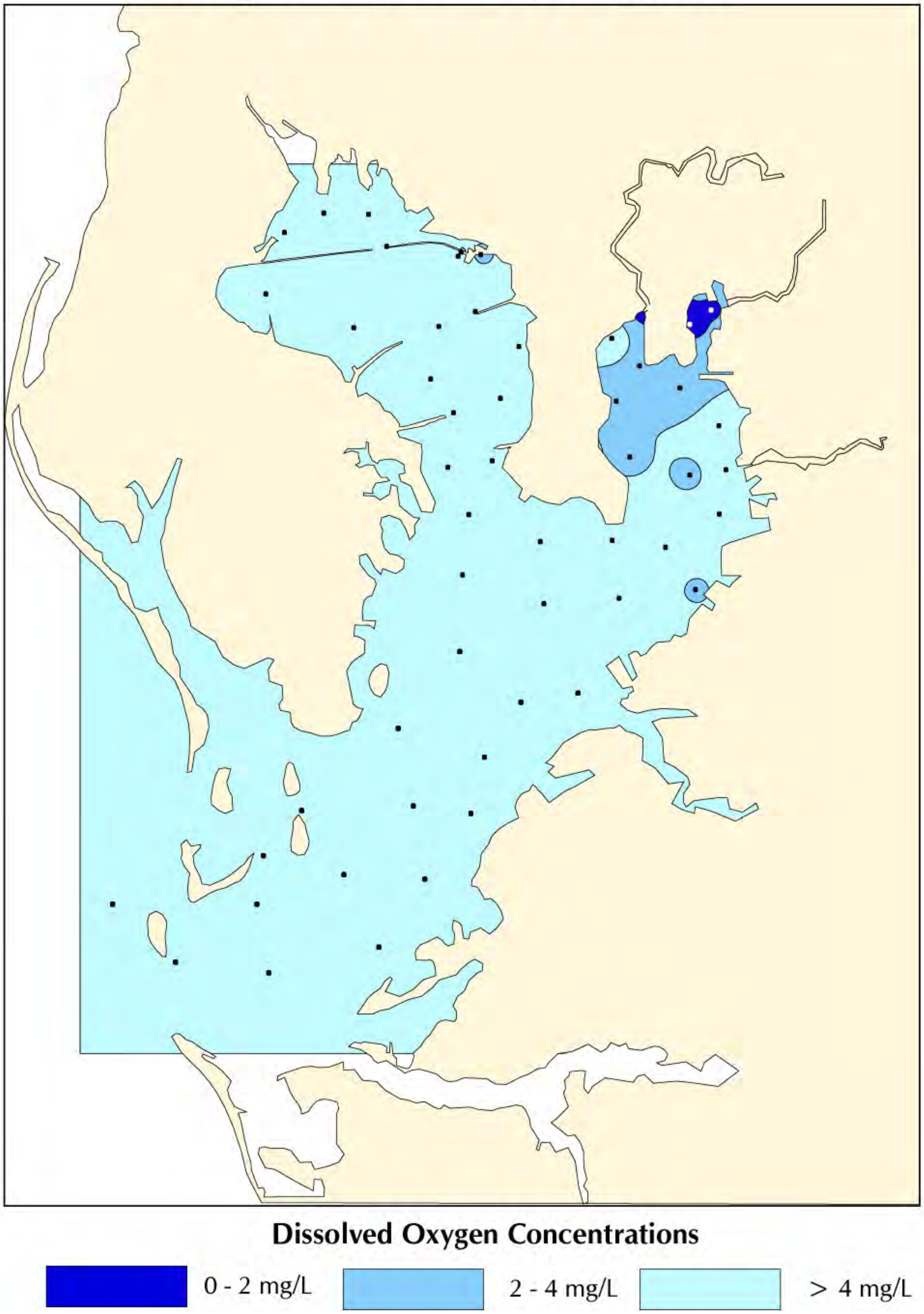
Bottom Dissolved Oxygen
September 1992 - EPCHC Stations



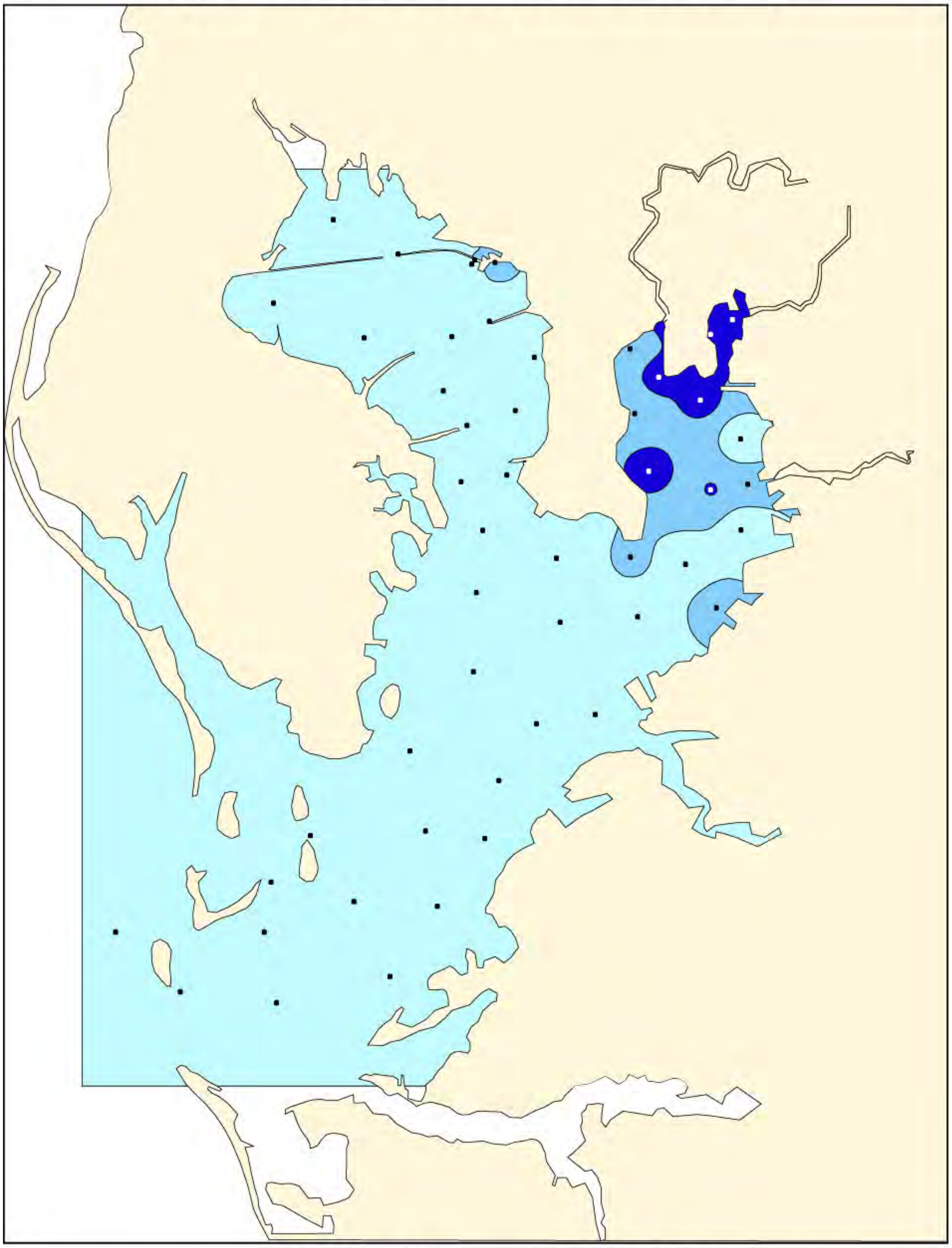
Dissolved Oxygen Concentrations

0 - 2 mg/L | 2 - 4 mg/L | > 4 mg/L

Bottom Dissolved Oxygen
August 1993 - EPCHC Stations



Bottom Dissolved Oxygen
September 1993 - EPCHC Stations



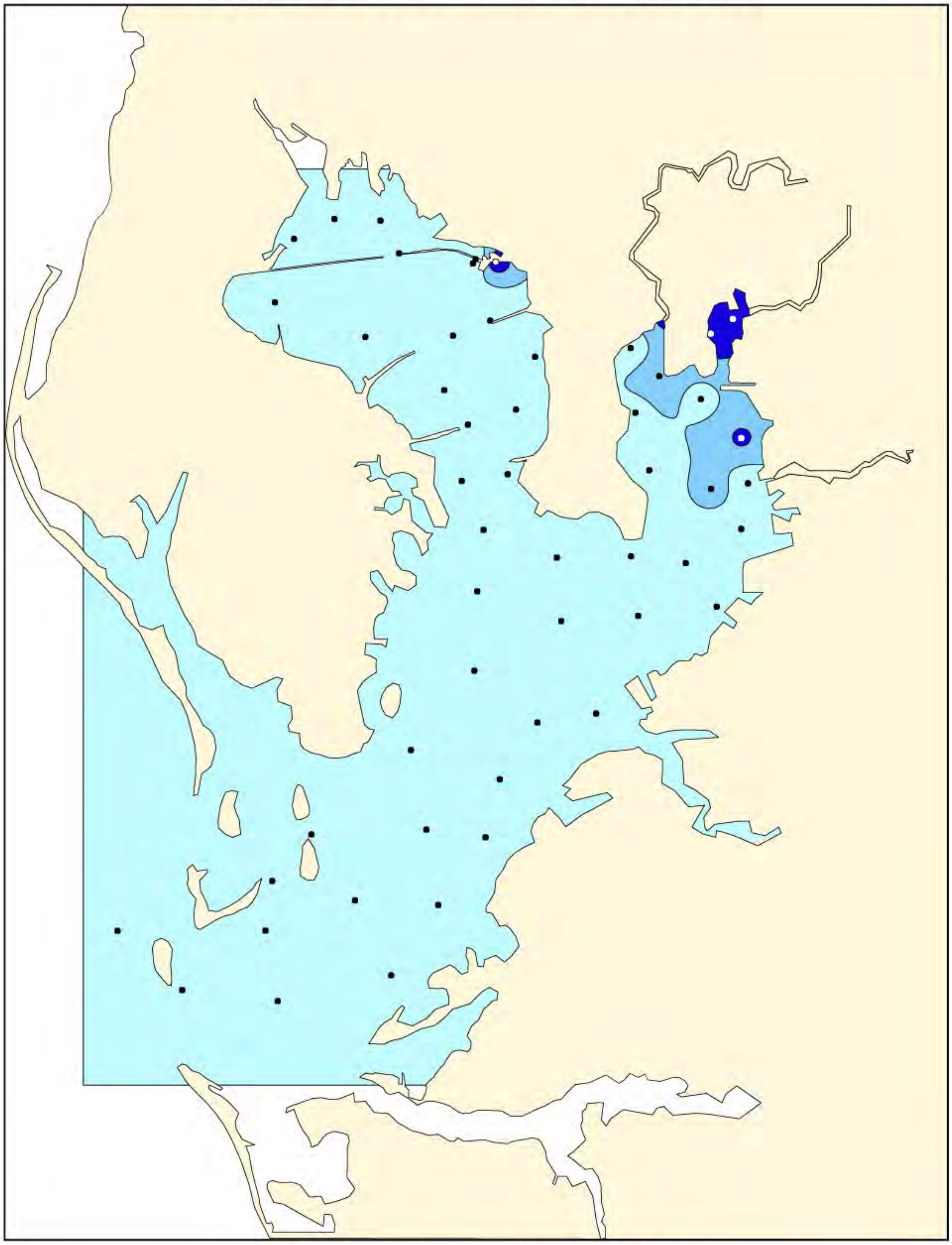
Dissolved Oxygen Concentrations

0 - 2 mg/L

2 - 4 mg/L

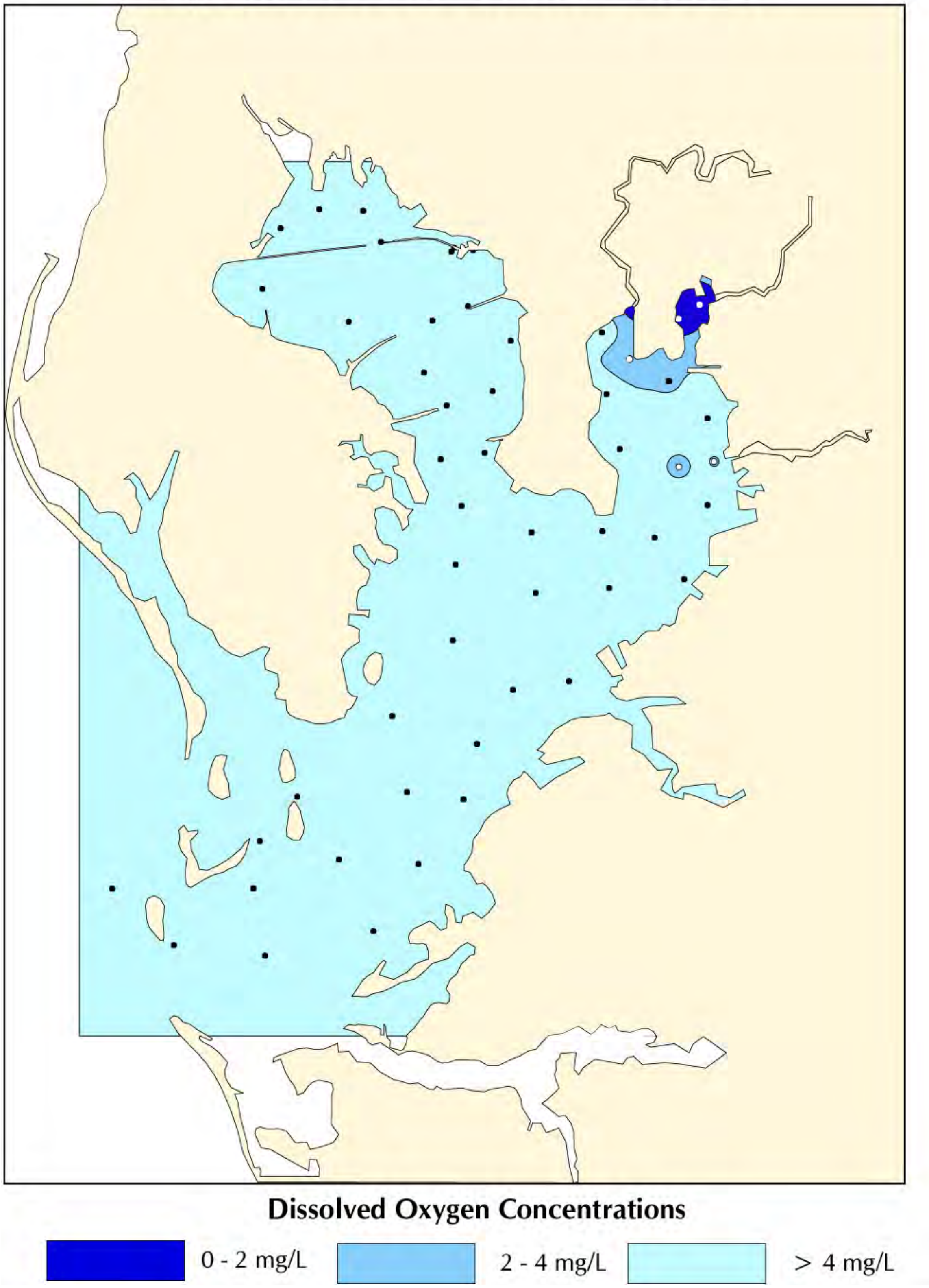
> 4 mg/L

Bottom Dissolved Oxygen
August 1994 - EPCHC Stations

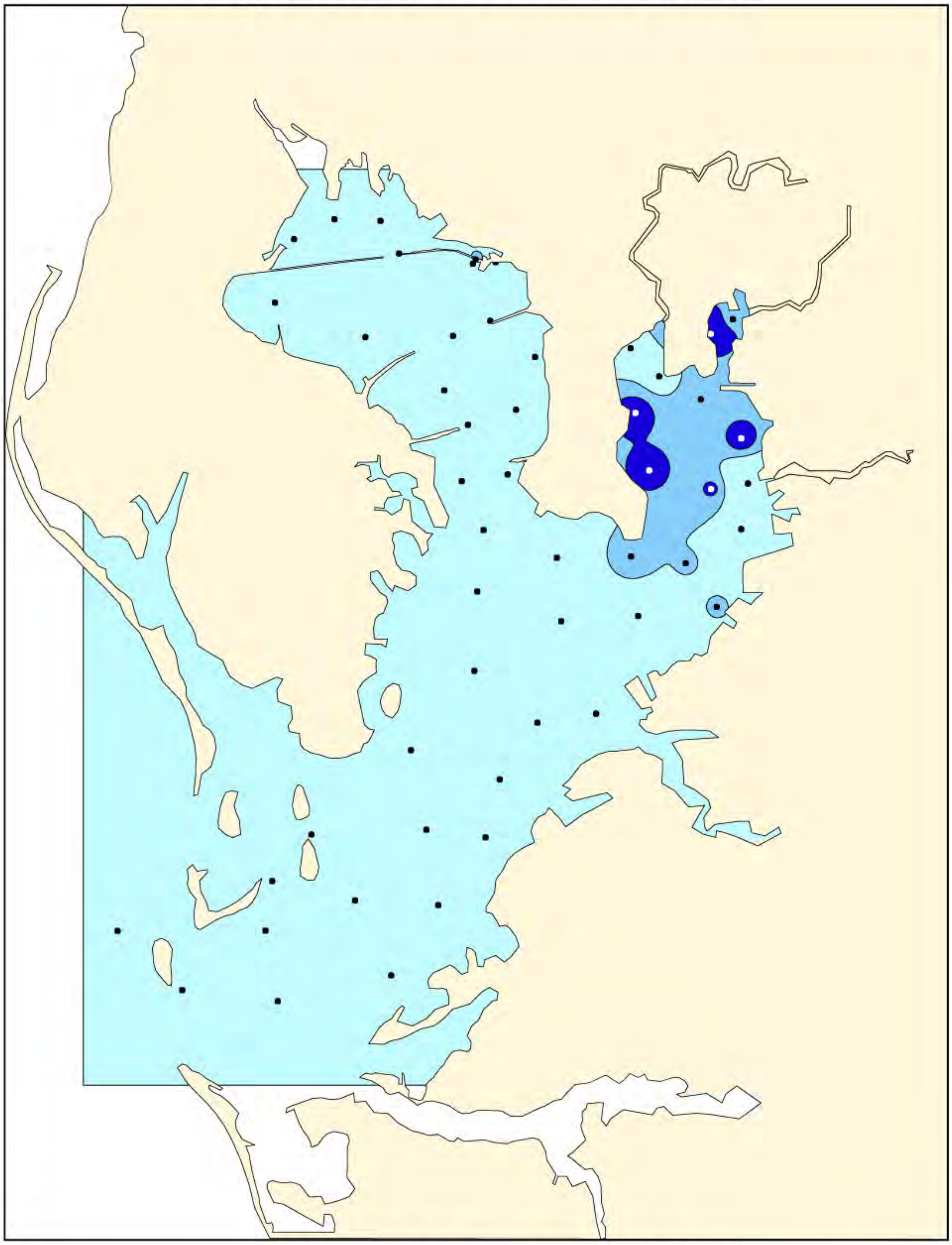


Dissolved Oxygen Concentrations

Bottom Dissolved Oxygen
September 1994 - EPCHC Stations



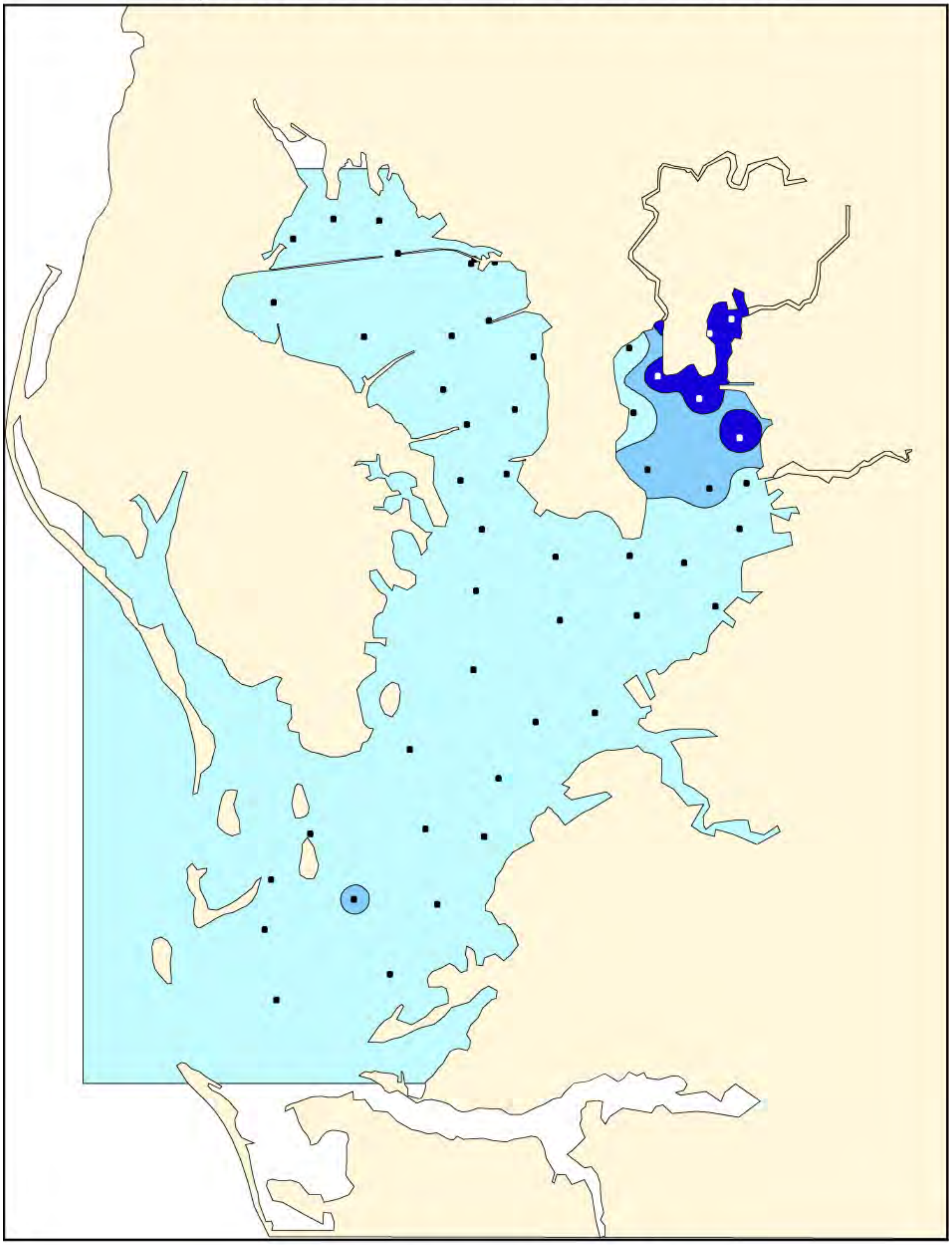
Bottom Dissolved Oxygen
August 1995 - EPCHC Stations



Dissolved Oxygen Concentrations

0 - 2 mg/L   2 - 4 mg/L   > 4 mg/L

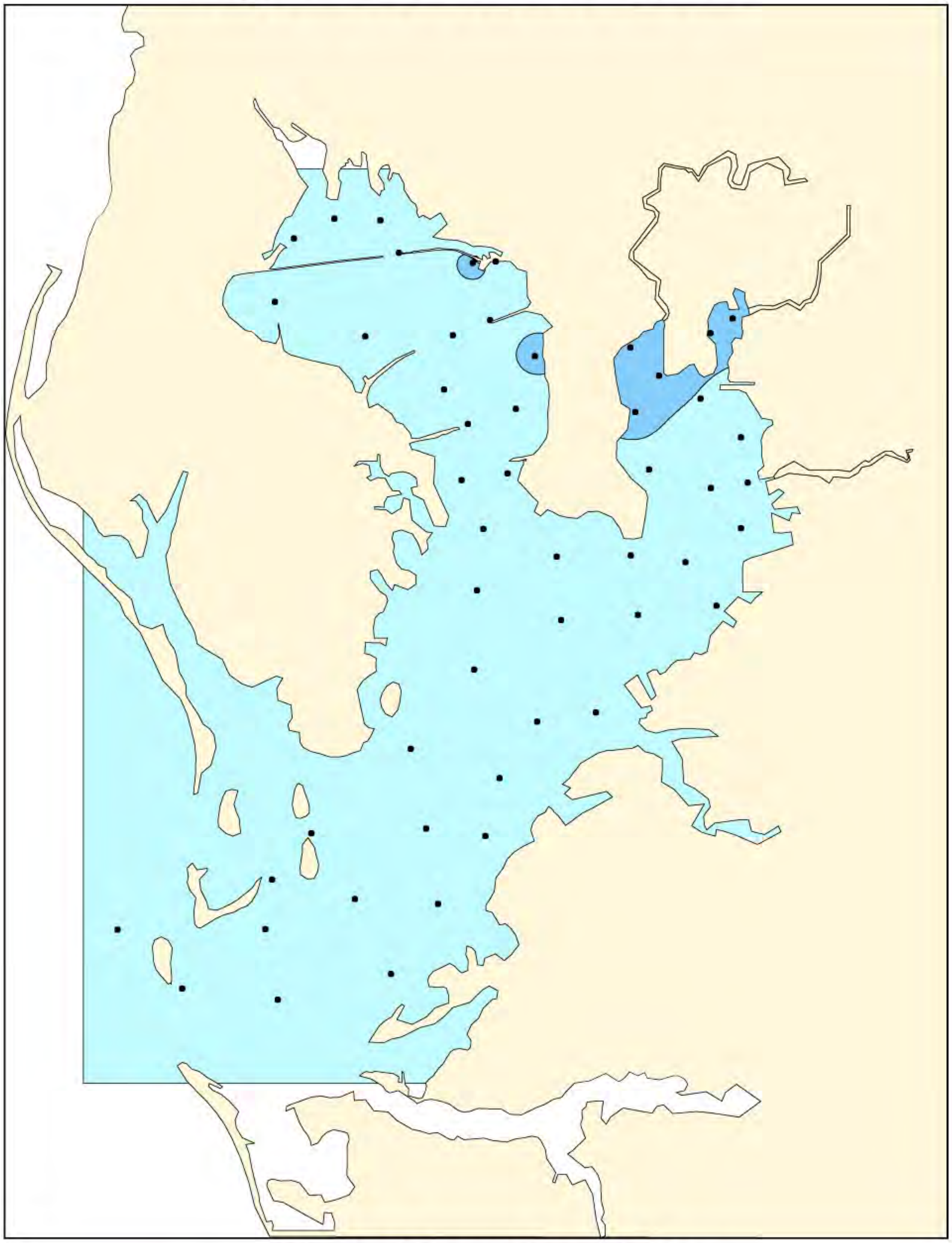
Bottom Dissolved Oxygen
September 1995 - EPCHC Stations



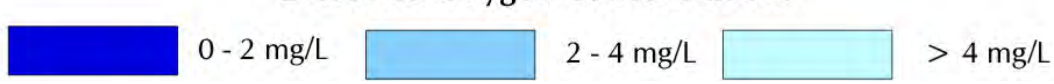
Dissolved Oxygen Concentrations

0 - 2 mg/L   2 - 4 mg/L   > 4 mg/L

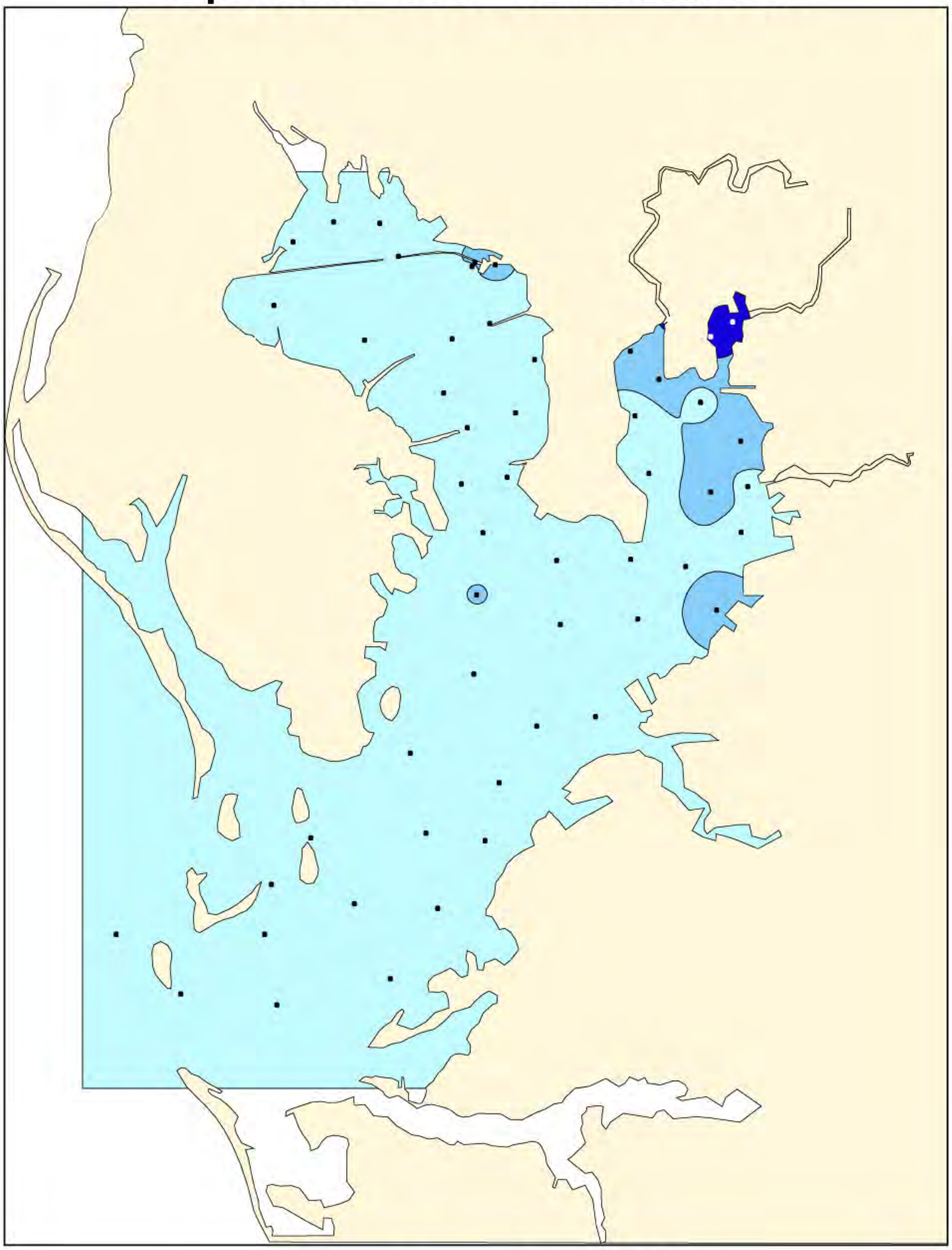
Bottom Dissolved Oxygen
August 1996 - EPCHC Stations



Dissolved Oxygen Concentrations



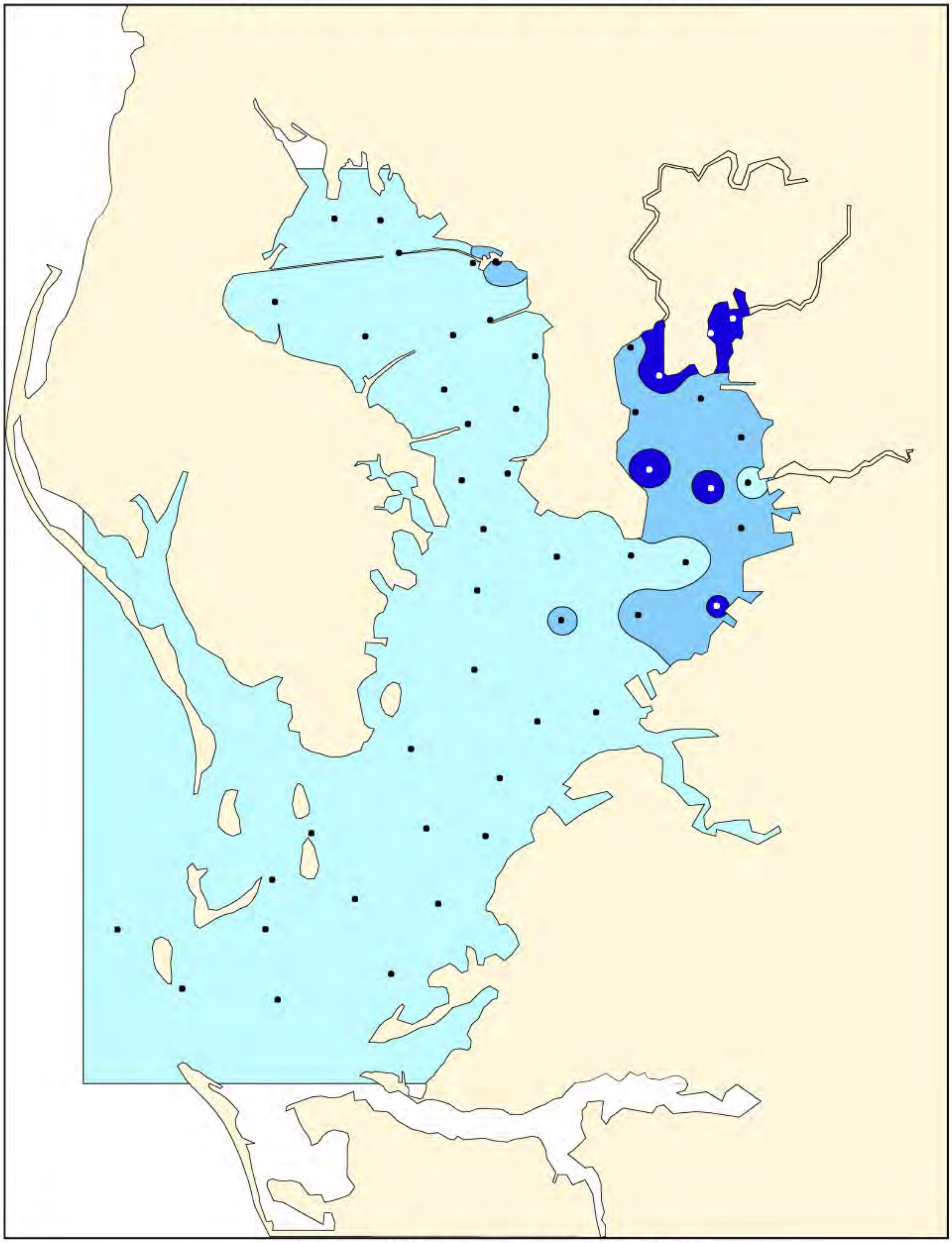
Bottom Dissolved Oxygen
September 1996 - EPCHC Stations



Dissolved Oxygen Concentrations

0 - 2 mg/L   2 - 4 mg/L   > 4 mg/L

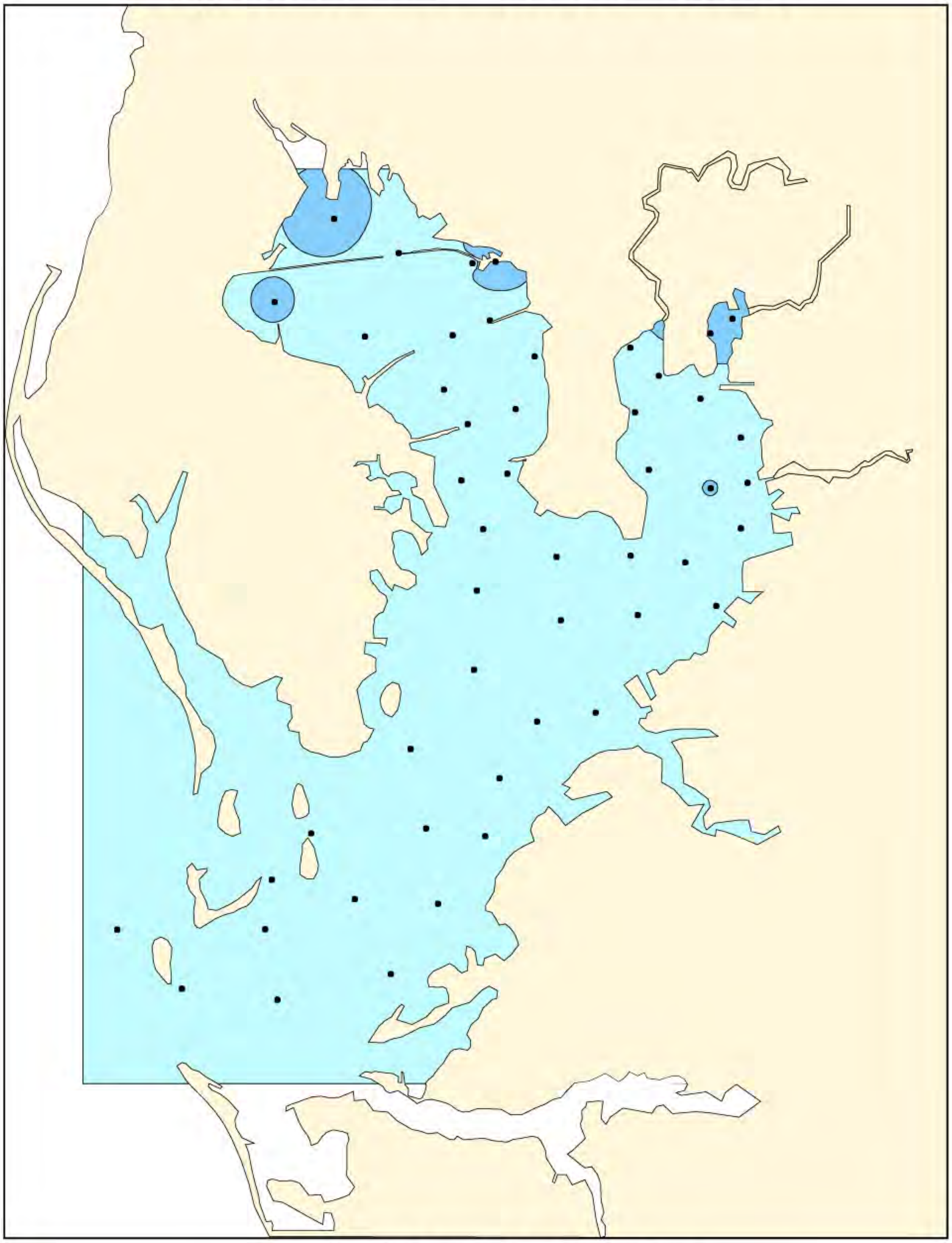
Bottom Dissolved Oxygen
August 1997 - EPCHC Stations



Dissolved Oxygen Concentrations

0 - 2 mg/L | 2 - 4 mg/L | > 4 mg/L

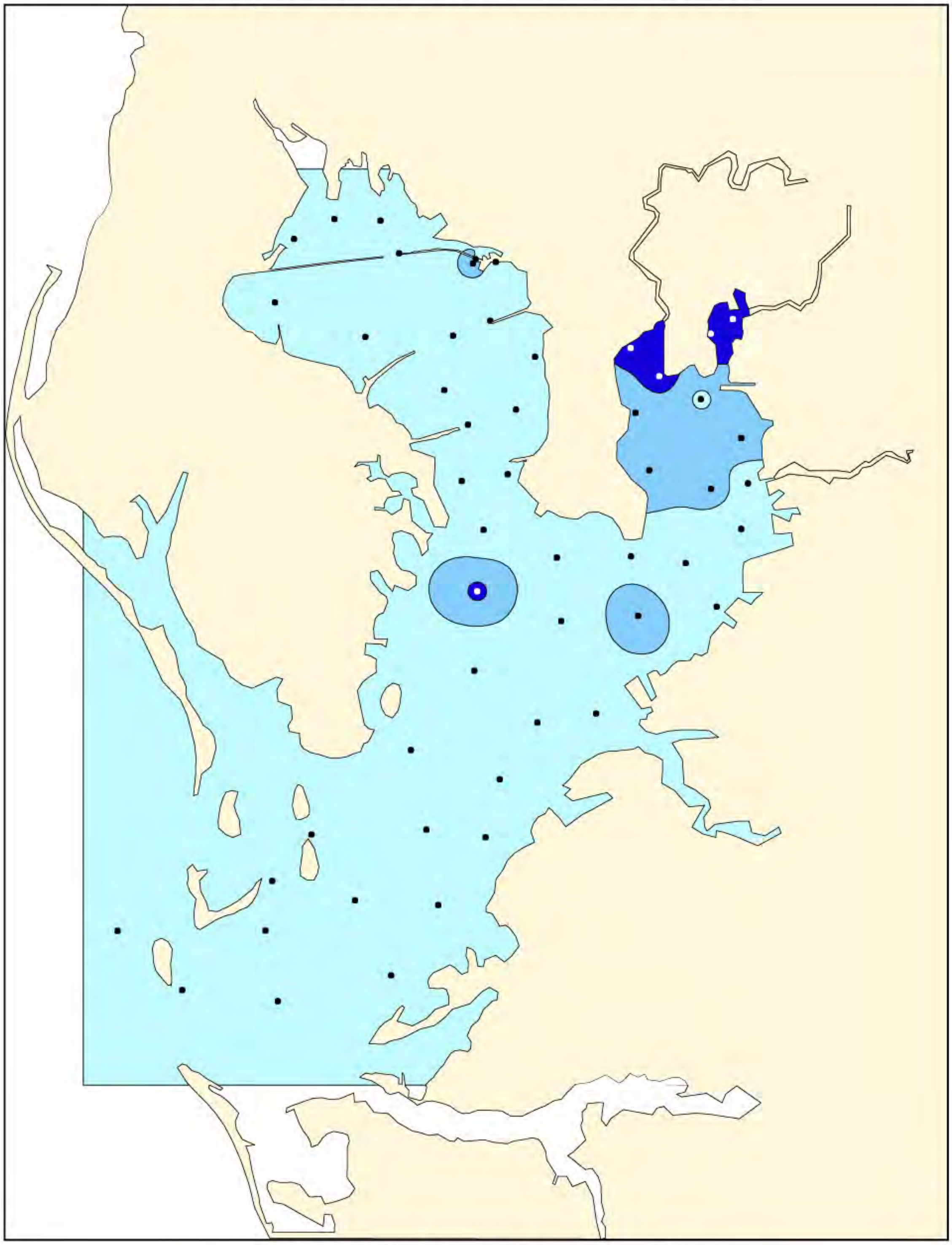
Bottom Dissolved Oxygen
September 1997 - EPCHC Stations



Dissolved Oxygen Concentrations

0 - 2 mg/L | 2 - 4 mg/L | > 4 mg/L

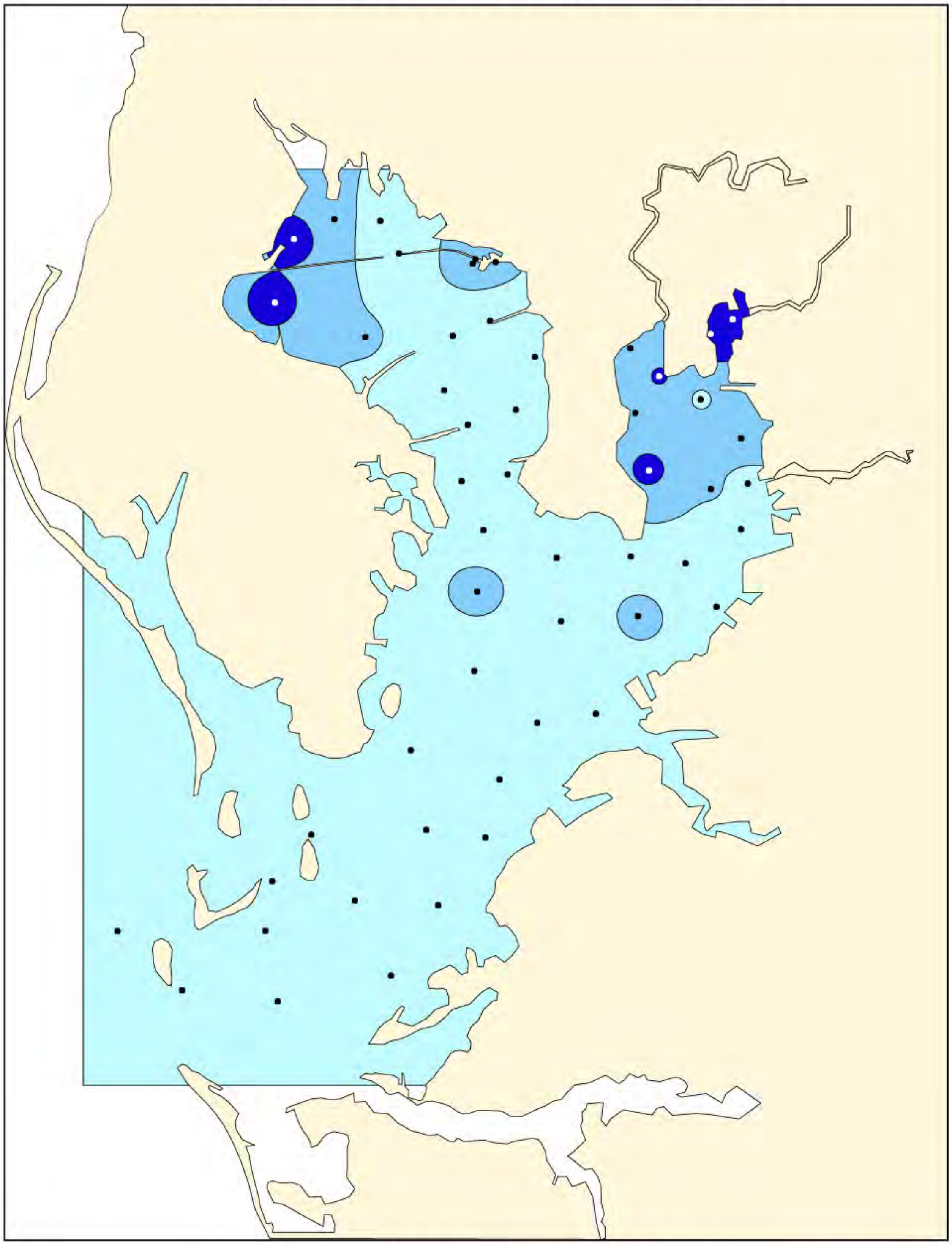
Bottom Dissolved Oxygen
August 1998 - EPCHC Stations



Dissolved Oxygen Concentrations

0 - 2 mg/L | 2 - 4 mg/L | > 4 mg/L

Bottom Dissolved Oxygen
September 1998 - EPCHC Stations



Dissolved Oxygen Concentrations

0 - 2 mg/L   2 - 4 mg/L   > 4 mg/L