Friends of Casco Bay
and
Casco Bay Estuary Project

Six-Year Water Quality Data Analysis: 1993 – 1998

Final Report

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Six-Year Water Quality Data Analysis: 1993 –1998

Executive Summary

Friends of Casco Bay (FOCB) has conducted the Citizens Water Quality Monitoring (CWQM) program in Casco Bay since 1993. The program is supported by the Casco Bay Estuary Project and carried out with the aid of volunteers who sample at more than 80 shore-based stations and assist FOCB staff at another 10 profile stations located throughout Casco Bay (Figure 1). The parameters measured include the standard oceanographic suite of temperature, salinity, pH, Secchi depth, and dissolved oxygen. This report presents an evaluation of six years of CWQM program data collected from 1993 to 1998. The main objectives for this evaluation are to characterize the water quality conditions and identify areas of concern in Casco Bay.

Our assessment focuses on dissolved oxygen (DO), a key indicator and integrator of water quality in coastal waters. As a basic necessity for aquatic life, DO levels directly affect ecosystem health. Dissolved oxygen is required for respiration by all forms of marine life and at low levels plants and animals may become stressed or even be killed (e.g. the fish kills that happened periodically in Casco Bay waters). The amount of DO contained in marine waters is a function of physical, chemical, and biological conditions. Seawater contains substantially less DO than freshwater and warm waters are able to hold less DO than cold waters for a given salinity. This temperature dependency results in a natural seasonal pattern in DO concentrations with winter maxima and summer minima. For a given temperature and salinity, there is a specific DO concentration at saturation (DO % saturation = 100%). It is the deviations from this DO saturation level that is the interesting part of the story played out by biological factors, which both increase and decrease DO concentrations. Just as plants in terrestrial ecosystems, phytoplankton and algae are the primary producers of organic material in coastal waters and oxygen is a by-product of this production. Phytoplankton and algae, along with other marine life including microbes, also utilize DO during respiration. One of the major sinks for DO in coastal waters is the degradation of organic material by microbes both in the water and the sediments. Associated with these biological processes, there is also a well-known relationship between DO in coastal waters and nutrient supplies. Increased nutrient supplies often lead to increased photosynthetic production by phytoplankton and this increase in production often results in super-saturated DO levels. Highly productive waters may experience super-saturated conditions during the day and under-saturated conditions at night, especially just before sunrise as respiration has been occurring throughout the night. Another physical factor that affects DO concentration in estuarine and coastal waters is mixing (or lack thereof). During the summer, deeper waters are often shut off from surface waters due to differences in water density. This process is called stratification and when these vertical density differences exist bottom waters may become hypoxic as dissolved oxygen solubility is low (warm temperatures), mixing is virtually non-existent (stratified water column), and ample supplies of labile organic carbon are available to support microbial respiration and benthic respiration in the bottom waters.

The report details the various graphical and statistical analyses that were conducted and presents the data on various spatial and temporal scales. The data are evaluated for Casco Bay as a whole, by geographical areas within the bay, and on a site-by-site basis. Summary statistics for all Casco Bay surface data is presented in Table 1. The minimum and maximum values for each of the parameters provide a good representation of the variability between sites, across the bay, and over time. The shallowest water depth was measured in Anthoine Creek and the deepest depth was consistently measured at Halfway Rock. The coolest temperatures were measured at the sites that are sampled year-round, while the warmest single water temperature was found at the Cousins River site in front of the Muddy Rudder Restaurant during the summer of 1995. During the summer, warm waters were consistently observed at the Presumpscot River site, but for swimming Wolf Neck State Park offered some of the most inviting waters with an August mean temperature of almost 20°C. For a refreshing swim try Willard Beach, which had one of the lower August mean temperatures at 16°C. The lowest pH and salinity values were obtained at sites at the

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Table 1. Summary Statistics for All Estuarine Surface Data

	Water Depth (m)	Temp (°C)	Salinity (ppt)	DO (mg/l)	DO (% saturation)	pH	Secchi Depth (m)
Mean	7.41	13.15	28.88	9.07	102.37	7.94	2.94
SD	7.93	5.11	4.55	1.40	12.10	0.18	1.33
Range	52.9	32.0	33.5	12.3	143.6	2.7	12.5
Minimum	0.1	-2.0	0.0	2.6	33.9	6.0	0.2
Maximum	53.0	30.0	33.5	14.9	177.5	8.7	12.7
Count	4195	5025	4954	4922	4847	4673	2922

The State of Maine does not have a water quality standard for DO concentration. In this report, a benchmark for DO concentration of 5.5 mg/l was used as it might be expected that lower concentrations than 5.5 mg/l could elicit subtle detrimental biological effects. This benchmark has been used in comparative studies in Maine in the past. The State does, however, have standards for DO % saturation. These standards are broken down by saltwater classes. The standard for class SA waters (highest quality) is dissolved oxygen "as naturally occurs" and is not directly quantified. In Casco Bay, only the offshore waters near Halfway Rock are classified as SA. The DO % saturation standards for class SB and SC (lowest quality) waters are 85% and 70%, respectively. Class SC waters are primarily located in the vicinity of Portland Harbor. As a matter of record, FOCB data was instrumental in the State reclassification of waters off Peaks and Little Diamond Islands, Two Lights in Cape Elizabeth and Willard Beach from class SC to SB.

Overall, the FOCB data indicate that water quality is generally good in Casco Bay and that DO concentrations and DO % saturation levels are only rarely a matter for concern. The distribution of all estuarine surface measurements of DO concentration and DO % saturation is presented in Figure 2. About 85% of the DO measurements had concentrations of 7 to 11 mg/l (mean of 9 ± 2 mg/l), which is within the normal range of DO concentrations. Only 0.6% of the values were below the 5.5 mg/l benchmark and just 5% of the values were less than 7 mg/l. A similar story can be told from the DO % saturation data. About 55% of the measurements were super-saturated with respect to DO and 38% of the values were somewhat under saturated, though above the class SB standard of 85% saturation. In all, almost 95% of the measurements were above the 85% saturation standard and <1% of the values was below the class SC standard of 70% saturation.

To understand the spatial distribution of the lower DO values across the bay, we contoured the mean DO values for each of the sites. This was also done for the other parameters – temperature, salinity, pH, and Secchi depth for which the trends were primarily associated with water depth/distance from shore and proximity to sources of fresh water. The contour of mean DO concentrations is presented in Figure 3. Similar spatial patterns were seen for both mean DO and mean % saturation with groupings of sites within different geographic areas of the bay. DO concentration and % saturation were relatively low in Portland Harbor, the three river systems, and a number of basins in Eastern Casco Bay (Maquoit Bay, Quahog Bay, and New Meadows River).

Because of the apparent geographic trends in the data, the sites were grouped by location and statistical analyses were run on both individual sites and the water body groupings. A series of comparisons was run for water body data collected during the summer months (July-September) when DO concentrations are at their lowest. Portland Harbor had the lowest mean DO concentration for this time period (7.6 mg/l) and was significantly lower than all other water bodies except for four that also had mean DO concentrations of <8.0 mg/l – Presumpscot River, Harraseeket River, Royal River, and Quahog Bay. These five water bodies were also the only water bodies that were under saturated (DO % saturation <100%) for this time period. Presumpscot River and Portland Harbor mean % saturation values were significantly lower than all other water bodies except for Royal River. The site-by-site comparison indicated that the mean DO concentration at three sites – Custom House Wharf, Stroudwater Bridge, and New Meadows Marina – was significantly lower than nearly all of the other sites. These three sites all had a mean DO concentration for the July to September time period of <7 mg/l.

Based on the results of these statistical analyses, a closer evaluation of site data in Portland Harbor, Quahog Bay, and New Meadows River was conducted. Both Portland Harbor and Quahog Bay had mean DO concentrations for the summer of <8.0 mg/l and New Meadows River's mean was only slightly higher at 8.03 mg/l. The site-by-site patterns within these water bodies, however, were different because of site- and water body-specific factors. In New Meadows River and Portland Harbor, low mean DO values (<7.0 mg/l) were observed at a limited number of sites and higher concentrations (>7.5 mg/l) were observed at the remaining sites. Comparison tests indicated that DO concentrations at New Meadows Marina were significantly lower than the rest of New Meadows River sites and that concentrations at Custom House Wharf and Stroudwater Bridge were significantly lower than the other four sites in Portland Harbor. In Quahog Bay, mean DO concentrations were more homogeneous and ranged from 7.55 mg/l at Perry's Landing to 8.26 mg/l at Gun Point. The low value observed for mean water body DO in Quahog Bay is due to relatively low concentrations throughout the embayment. Conversely, the mean water body DO concentrations for New Meadows River and Portland Harbor were lower in comparison to other water bodies because of specific sites that exhibited problematic DO conditions. In New Meadows River, the upper reaches of the water body (New Meadows Marina and Indian Rest sites), which have limited communication with offshore waters, had lower mean DO concentrations. In Portland Harbor, the low DO concentrations at Custom House Wharf and Stroudwater Bridge are likely caused by different local factors – point source discharges including combined sewage overflows (CSO) for Custom House Wharf and nonpoint source/freshwater inputs for Stroudwater Bridge. There are also a number of CSO upstream from the Stroudwater Bridge site.

At the 10 profile stations, data are collected at multiple depths over the water column. This dataset provides an additional perspective on water quality in Casco Bay as we can evaluate DO levels in the bottom waters where low DO concentrations are often found during the summer stratified conditions. A majority of profile DO measurements had concentrations of 8 to 11 mg/l. None of the values were below the benchmark of 5.5 mg/l and only ~1% of the values were less than 7 mg/l. The DO concentrations at these 10 sites are unlikely to pose any harm to marine life. The low temperatures measured in the bottom waters, however, resulted in an unexpectedly high number of DO % saturation values that were below the class SB water standard of 85%. The majority of the <85% saturation values were observed in the bottom waters at Halfway Rock and Broad Sound, which are the two deepest sites (>30 meters). The low DO % saturation values observed in the bottom waters at these deep-water stations result from a combination of extended seasonal stratification and biological utilization of oxygen. An examination of interannual trends suggests that values of less than 85% saturation may be naturally occurring events.

The interannual trends observed for the Casco Bay profile data – lowest bottom water DO concentrations in 1994, increasing bottom water concentrations from 1994-1997, and lower concentrations again in 1998 – are exactly the same as trends observed in Massachusetts Bay over this same time period. The bottom water DO concentrations in Massachusetts Bay in 1994 were the lowest observed over an eight-year period from 1992 to present. The recognition that Casco Bay is part of broader regional trends is important not only for understanding past trends in the data, but for evaluating future trends as well. By working with other monitoring programs in the Gulf of Maine, deviations from the broad regional trends will be a clear indication of significant local effects. At the same time, the regional data comparison will provide an understanding as to what may be driving some of the signals observed. The low DO % saturation values in the bottom waters at the deep, offshore sites are not necessarily due to local problems or inputs, but rather part of a wide-scale event likely due to variations in temperature and circulation in the Gulf of Maine.

Overall, dissolved oxygen is usually well above State standards and not close to levels that would impair biological processes. Over the entire six-year period evaluated in this report, minimum DO levels of less than 5.5 mg/l have been observed at only ten of the FOCB sites (Figure 4). Along with the FOCB CWQM program site minimum DO values, this figure presents land use data from NOAA. The yellow to red areas on the land use map represent developed areas (i.e. the major cities and towns) and the green areas are primarily forested areas or pastures. Generally, developed areas with potentially heavy nutrient loading and organic material exhibited the lowest minimum DO concentrations. This includes areas of direct loading from point sources and combined sewer overflows in Portland Harbor and sites in the vicinity of freshwater inputs and potential nonpoint source loading (Royal River, Presumpscot River, and Harraseeket River). Low DO concentrations, however, were also observed in less developed areas in Eastern Casco Bay where restricted circulation may exacerbate anthropogenic impacts (New Meadows River and Quahog Bay). Septic systems in Maquoit Bay are known to have been a significant source of nutrients into that bay and the prevalence of overboard discharge systems still in use along the shores of Harpswell Sound, Quahog Bay, and New Meadows River suggests that they are a likely source of nutrients in these bays.

On the whole, the FOCB monitoring program provides data with which to adequately characterize Casco Bay and identify areas of concern with respect to the parameters measured. There are, however, features of the monitoring program that could be expanded and improved upon. It is recognized that there are constraints under which FOCB, as a nonprofit organization, must operate. The recommendations are made with the thought that they may help FOCB to prioritize modifications and improvements to their already successful volunteer monitoring program. The recommendations focus on – changes in sampling frequency, time of sampling, and parameters measured at a limited set of "Primary" sites; continuation and expansion of the special studies to understand low DO events, nutrient loading, and circulation in Casco Bay; and that FOCB seek out partnerships with other organizations both within and outside of the State with which to share data and perhaps receive additional support.

Measurement of ambient nutrient and chlorophyll concentrations should be added to the existing program at the Primary sites. This would provide a wealth of information for not only assessing the cause of low DO conditions (a secondary indicator of eutrophication), but for providing additional information of primary indicators of eutrophication (nutrients and phytoplankton biomass). Phytoplankton biomass can be estimated by chlorophyll measurements and direct phytoplankton counts. Phytoplankton analyses provide an additional set of data on the species composition of the phytoplankton community, which could be especially useful in Casco Bay for alerting the public, shell fishermen, and aquaculturists as to the presence of potentially toxic or nuisance phytoplankton species.

FOCB has already undertaken a variety of focused studies including hypoxia studies in 1997 to 2000 and synoptic sampling to provide a snapshot of conditions across the bay. Nutrient loading and flushing rates for individual water bodies will have to be the focus of special studies, perhaps in conjunction with other organizations in the area. The Gulf of Maine Ocean Observing System (GoMOOS), for instance, is deploying 13 instrument moorings in the Gulf of Maine – two of which are tentatively slated for placement in Casco Bay. In conjunction with the ongoing FOCB Citizens Water Quality Monitoring program, the data from these moorings and new studies focused on nutrient loading and flushing rates will provide a growing body of data with which to better characterize and understand the Casco Bay system.

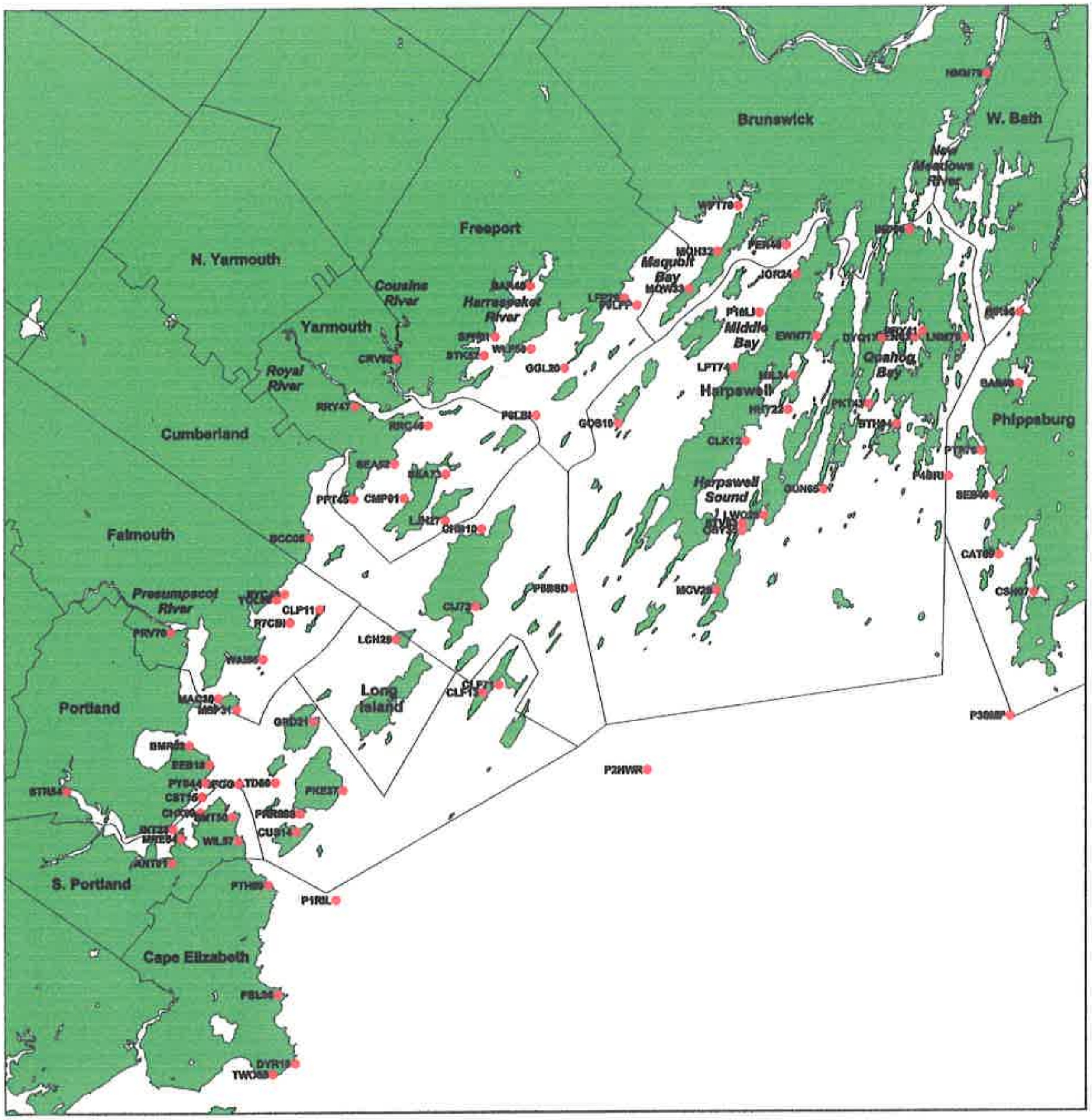


Figure 1. FOCB Citizens Water Quality Monitoring Program Site Locations.

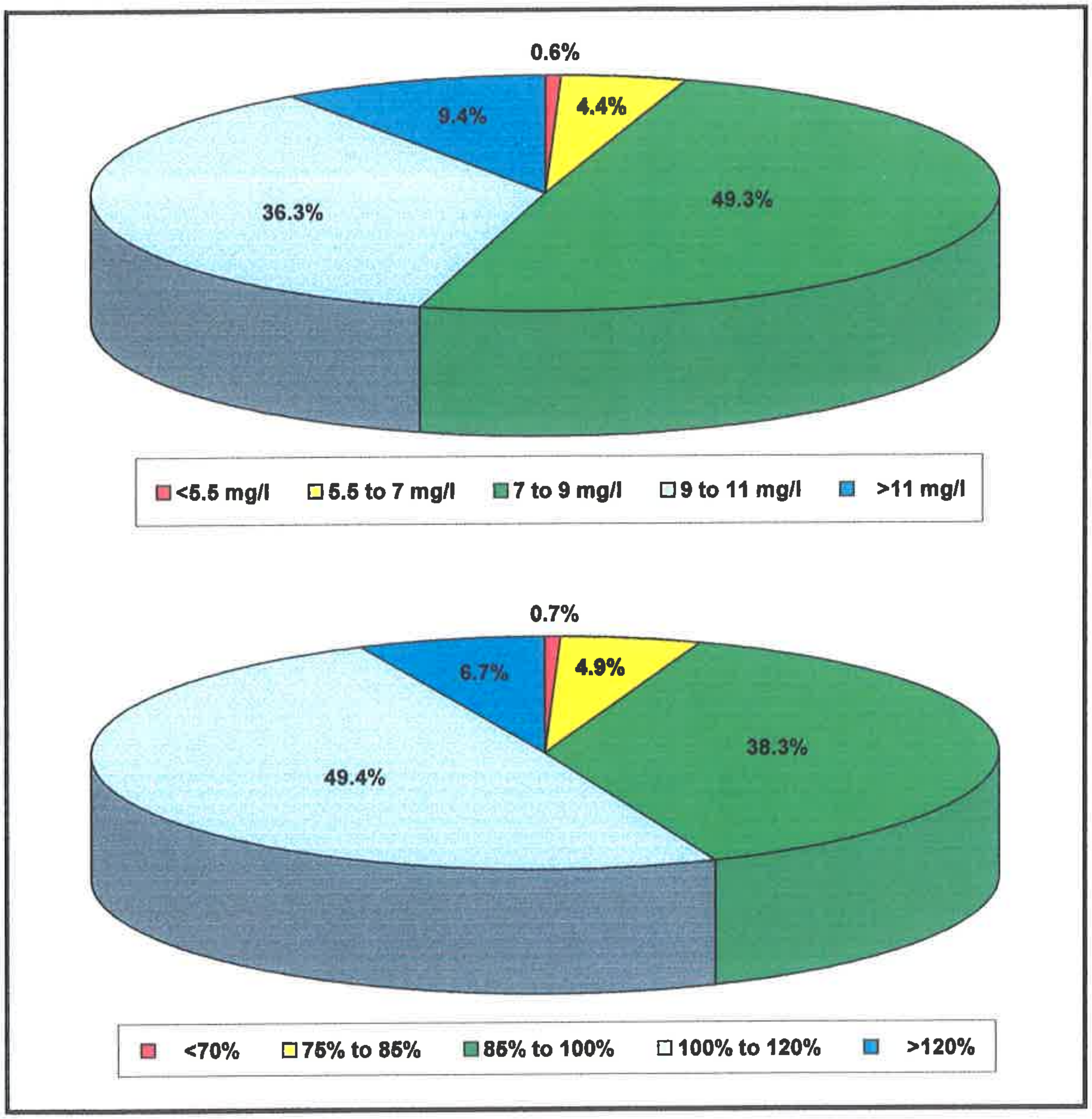
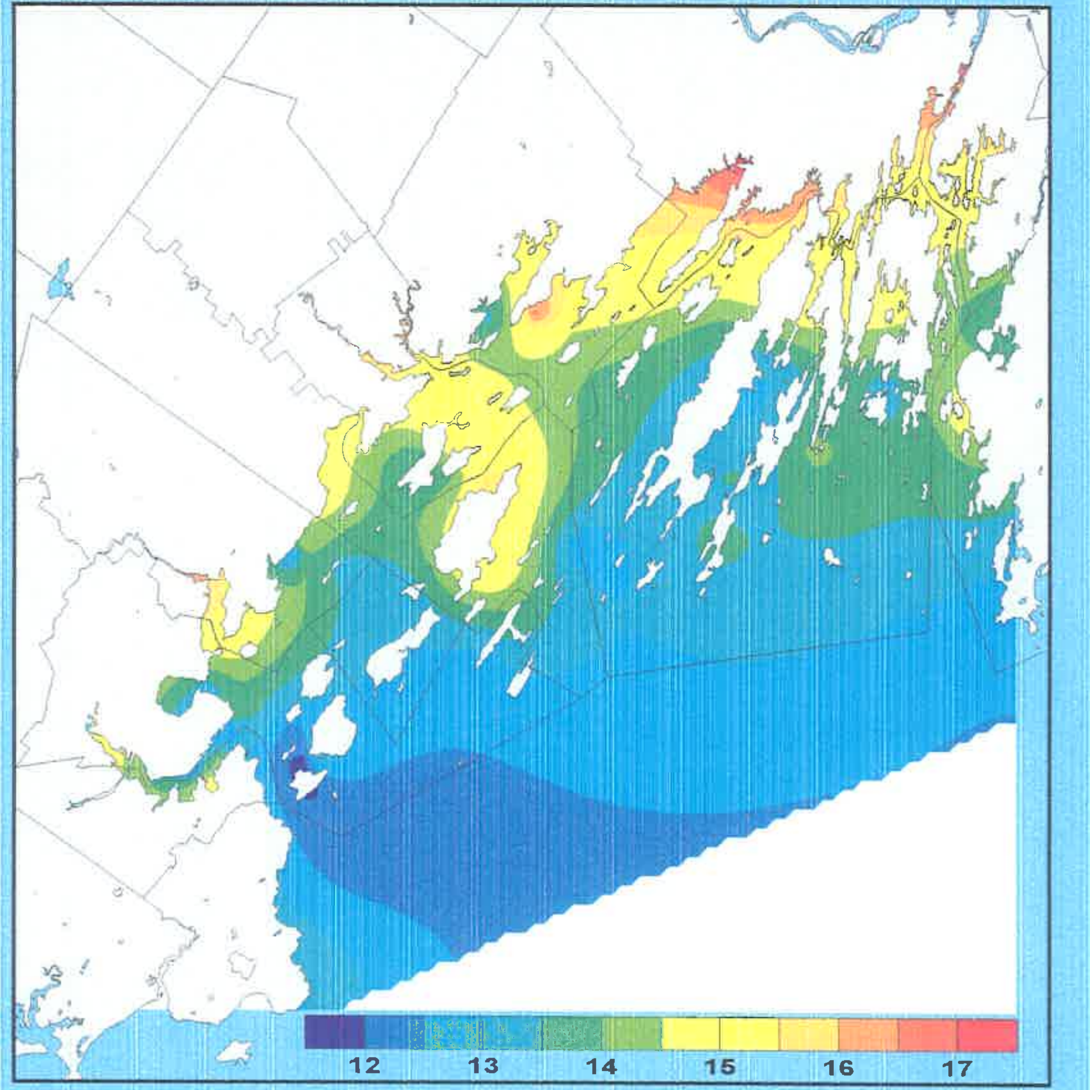


Figure 2. Breakdown of DO Concentration and DO % Saturation for all data.

Spatial Trends – Mean Temperature (April to Oct)



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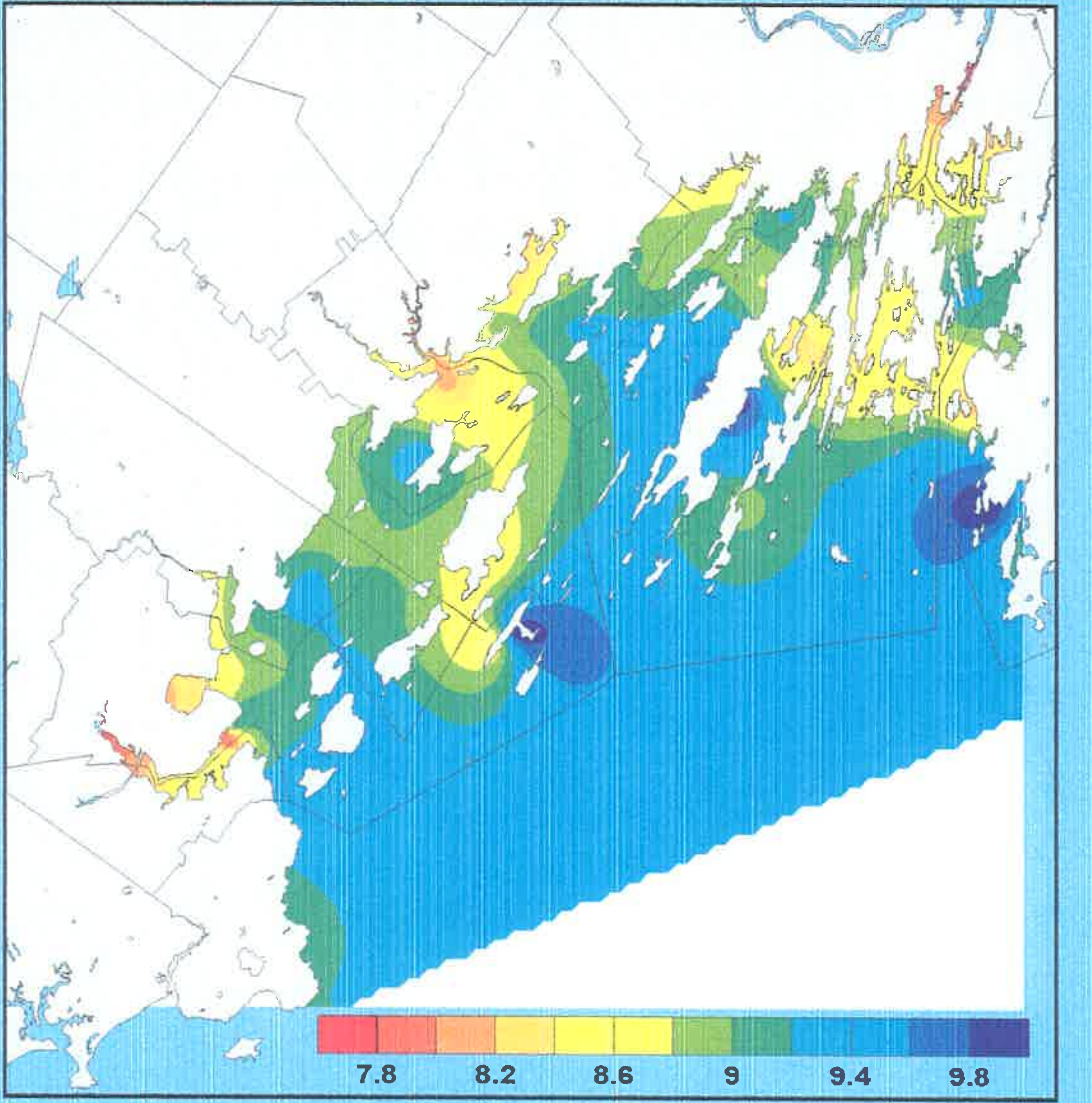

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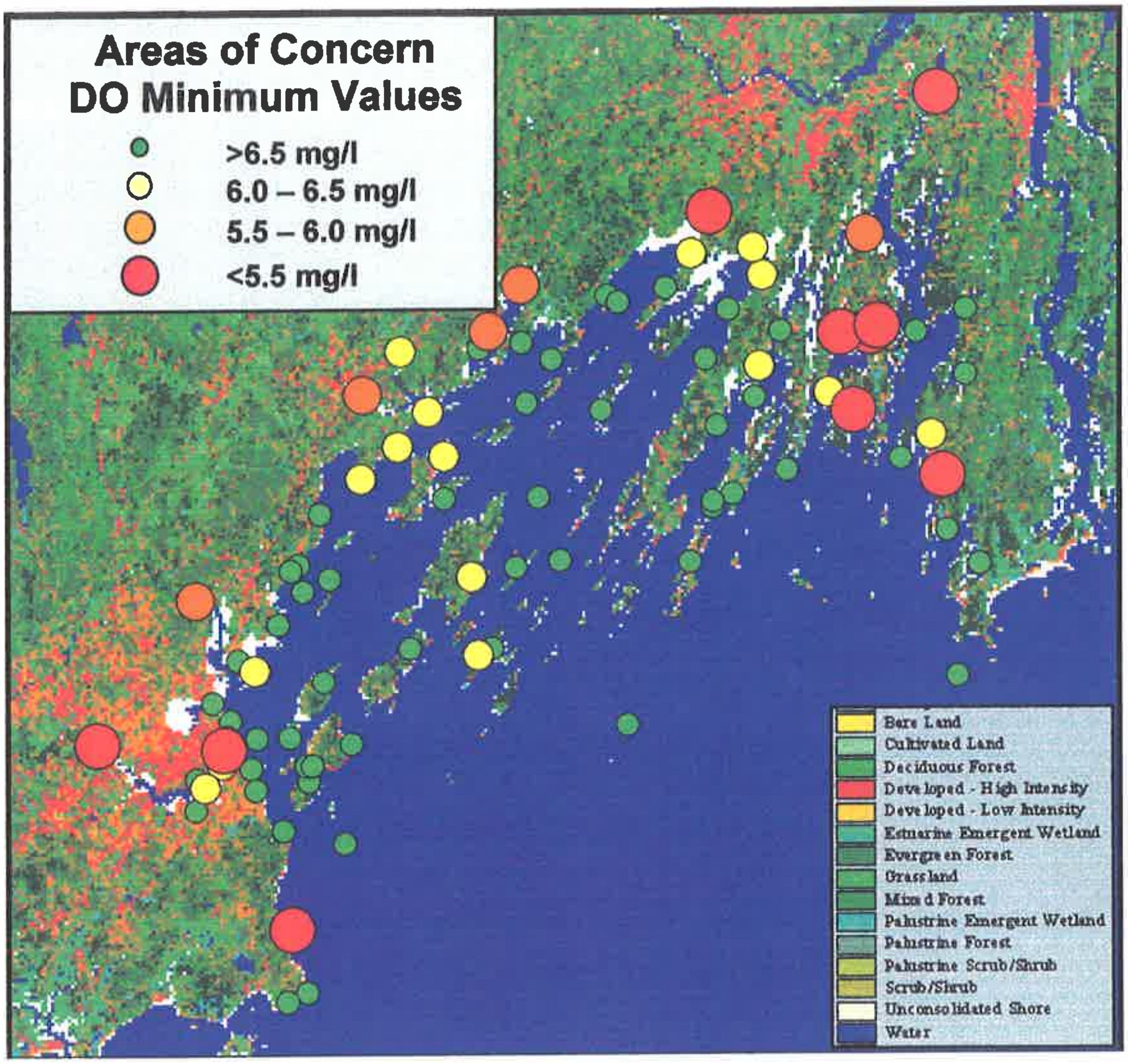

Figure 4. Areas of concern in Casco Bay based on minimum DO concentrations observed over entire 93-98 period (land use information obtained form NOAA).

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1.0 Introduction

Friends of Casco Bay (FOCB) has conducted the Citizens Water Quality Monitoring (CWQM) program in Casco Bay since 1993. The program has been supported by the Casco Bay Estuary Project and carried out with the aid of volunteers who sample at more than 80 shore-based stations and assist FOCB staff at 10 profile stations located throughout Casco Bay. The parameters measured include the standard oceanographic parameters of temperature, salinity, pH, Secchi depth, and dissolved oxygen plus ancillary air and water measurements. The parameters measured are in strict accordance with FOCB's Quality Assurance Project Plan (QAPP) approved by EPA Region 1 (FOCB, 1997a). The FOCB QAPP indicates that the CWQM program data will be used to aid environmental managers in:

- Establishing baseline water quality conditions.
- Determining long-term water quality trends.
- Documenting effects of water quality improvement programs.
- Screening for sources of pollution by identifying current problems.
- Making decisions on shoreline planning and zoning.

This report presents an evaluation of the six years of water quality data collected from 1993 to 1998 by the CWQM program. In line with the data uses highlighted in the QAPP, the main objectives for this evaluation are to characterize the water quality conditions and identify areas of concern in Casco Bay. This information will be used to evaluate the monitoring approach, provide input for optimization of the monitoring program, and provide a basis for future environmental management decisions.

Our assessment focuses on dissolved oxygen (DO), a key indicator and integrator of water quality in coastal waters. As a basic necessity for aquatic life, DO levels directly affect ecosystem health. Diaz and Rosenberg (1995) state that there is no other environmental variable of such ecological importance to coastal marine ecosystems that has changed so drastically in such a short period of time as dissolved oxygen. These authors argue that while hypoxic environments have existed through geological time, their occurrence in shallow coastal and estuarine areas appears to be increasing and the cause seems most likely to be accelerated by human activities (Nixon, 1995; Bricker et al., 1999).

The amount of DO contained in marine waters at saturation is a function of physical, chemical, and biological conditions. Cold waters hold more DO than warm waters at a given salinity. Seawater at equilibrium at a given temperature contains substantially less DO than freshwater. Thus, DO concentrations naturally follow a seasonal pattern of winter maxima and summer minima that is directly related to temperature, but influenced by biological processes. Biological production and utilization of DO in coastal waters has a well-known theoretical relationship to nutrient supplies. Increased nutrient supplies often lead to increased photosynthetic production of organic matter by phytoplankton or other algae. This increase in production often results in super-saturated DO levels in the upper water column. While a dominance of heterotrophic activity, especially microbial respiration, can lead to greatly under-saturated conditions. Highly productive waters may experience super-saturated conditions during the day and under-saturated conditions at night, especially just before sunrise as respiration has been occurring for maximal duration. Another factor that affects DO concentration in estuarine and coastal waters is mixing (or lack thereof). Deeper waters where vertical density differences exist, especially sub-pycnocline waters, may become hypoxic during the summer when DO solubility is lowest and ample supplies of labile organic carbon are available (due to sinking of senescent phytoplankton) to support microbial respiration and benthic respiration in the bottom waters. Dissolved oxygen utilization in deeper stratified waters may outpace DO replenishment through transport of atmospheric DO and mixing and any potential net gains of DO from photosynthesis. Dissolved oxygen concentration in coastal waters is a dynamic property that varies spatially and temporally depending on physical, seasonal, biotic, and anthropogenic influences.

The first step we took in the data evaluation was to establish a set of issues to address. Keeping the two project objectives in mind, characterization of water quality conditions and identification of areas of concern, the following questions were asked to determine the best approach for screening and evaluating the data:

- Are there spatial scales and temporal responses that are generally similar or different across the bay?
- Do the temperature vs. salinity diagrams suggest geographically distinct areas or do the areas show continuity in mixing of waters?
- Are there specific salinity regimes that might enable the commonality or coherence in the data to be identified?
- Are there geographic areas that have a level of commonality and thus allow the data to be grouped?
- How does hydrography or depth influence the DO concentrations?

Once areas of commonality were delineated, the data were used to characterize the bay and evaluate:

- Variations in parameters, specifically DO, at sites and basins across the bay.
- Potential causes for differences between sites and basins – e.g. closed basins vs. open or less restricted areas of the system, fresh water vs. tidally dominated, and high vs. low nutrient loading on a relative scale.
- Procedures for the monitoring program. Do the sampling protocols influence data variability and affect data interpretations? Can improvements be made to better represent water quality in Casco Bay?

These questions are addressed by the data evaluation presented in this report. The report provides an overall characterization of water quality in Casco Bay and highlights areas of concern.

2.0 Methods

2.1 FOCB Sampling and Analytical Procedures

The FOCB water quality data consists of data collected from 1993 to 1998 at 80 shore-based stations by citizen volunteers and 10 profile stations sampled by FOCB staff (Figure 1). Two of the shore-based stations were located in freshwater impoundments (Capisic Pond and Stroudwater Dam) and have not been included in this data analysis, which is focused on estuarine and coastal waters. At the shore-based CWQM stations, data were collected within the upper six inches of water. The profile stations were sampled within the upper six inches of water for surface samples, at 1 meter, and then at 2-meter intervals over the entire water column. Surface and profile stations were sampled twice per month in 1993-1995 and once per month in 1996-1998. The majority of the CWQM stations were sampled from April to October. The profile stations and a select few CWQM stations were sampled year round. A variety of air, water, and site data were recorded for each site-sampling event.

All regular sampling in the CWQM program involved ambient measurements collected and processed in the field. All measurements were made on-site, with the possible exception of DO, which could be fixed on-site, then titrated within eight hours after collection. A few of the CWQM stations were sampled from volunteers' boats, but most were sampled from bridges, piers, bulkheads, floats, jetties, docks, etc. where there is at least ten feet of water at low tide. This minimum water depth requirement allowed for a Secchi disk reading to be taken at almost any tide stage. Unfortunately, requiring a strict minimum depth was not feasible. Because of the limited number of ideal spots and because consistency is related to convenience, a number of stations are sampled by wading-in from shore. All CWQM stations were visited by FOCB staff or volunteer regional coordinators to measure latitude and longitude using a GPS unit, to take a reference photo, and to establish a point at the station from which sampling could be done both safely and consistently. All surface water samples were collected by 5-gallon bucket. The sampling period was designated as a Saturday plus or minus two days (i.e. Thursday through Monday). The recommended time frame was 9:00 AM to 3:00 PM and was not tide dependent (tide stage was recorded).

In addition to the stations sampled by citizen monitors, approximately ten stations were sampled from the BayKeeper boat by FOCB staff. These ten stations are located in either deep water, mid-channel, off a submerged discharge, or some other area only accessible by boat. At these stations, water column profiles are taken for DO, temperature, and salinity. The pH of the surface water and Secchi depth were also measured.

Different, yet comparable, methods were used for analysis and measurement of parameters at the shore-based and profile stations. All of the analytical methods are detailed in the FOCB Quality Assurance Project Plan (FOCB 1997a). At the CWQM shore-based stations, parameters were measured using a variety of tried and true field methods, though procedures for measuring pH, salinity, and water clarity are not EPA-approved. The pH was measured using a colorimetric method using a pH octet comparator. A gravimetric procedure using a hydrometer was used to measure salinity. For both pH and salinity, the non-electrometric methods are more appropriate for the CWQM program. A Secchi disk was used to measure water clarity at both the CWQM and profile stations. These methods have been approved for use by citizen programs in other EPA regions, i.e. Region 3, Chesapeake Bay Citizen Monitoring Program and Region 6, Galveston Bay Foundation TEST Program. EPA-approved methods were used to measure DO and water temperature. Dissolved oxygen is measured using the azide-modified Winkler Titration method and temperature is measured using an alcohol-filled thermometer.

At the profile stations, water temperature, salinity, DO, and pH were measured electrometrically. Although electrometric methods of measuring temperature are not EPA-approved, the procedure is included here because it is part of the salinity and DO measurements. Water temperature and DO are measured electrometrically using a YSI Model 58 Dissolved Oxygen meter with a digital display. Salinity is measured electrometrically using a YSI Model 33 Salinity-Conductivity-Temperature meter with an analog display. The pH is measured electrometrically using an Oakton Waterproof pHTestr 2 meter with automatic temperature compensation.

All data are reviewed by the Program Coordinator to ensure they meet program data quality objectives (Appendix A). The data quality objectives and validation procedures for this program have been designed to identify and correct problems in data collection and reporting. Should the results of data validation measures or quality assurance reviews indicate that the integrity of data are questionable and data quality objectives are not being met, the data set (or that portion which is deficient) are flagged as unacceptable for inclusion in the CWQM Data File. None of the suspect data was included in the data analysis presented.

After review, the data are entered into the MURPHY database program, a computer program developed by FOCB under contract to the Casco Bay Estuary Project. Another series of data checks and calculations is undertaken within the database. Raw data is used to calculate corrected pH, corrected salinity, and DO % saturation. The data are further evaluated graphically by mean, minimum, and maximum values for each parameter with site and time series plots of data every three months to ensure comparability between stations and across time.

2.2 Database Development

The data evaluation focuses on the key water quality parameters collected – temperature, salinity, pH, Secchi depth, and dissolved oxygen (concentrations and % saturation) with major emphasis on dissolved oxygen. The data received from FOCB for 1993-1998 were loaded into an Access database and working tables were developed for the profile data (FOCB_p93p98) and all surface data (FOCB_report). FOCB_report included data from both the profile and shore-based stations. The profile data were received from FOCB as seven separate files. One file included all surface data and ancillary information. The other six files included all *in situ* profile data for each monitoring year. The *in situ* profiles were compiled into FOCB_p93p98, which contains data for 10,192 sampling depths collected from 886 profiles. The profile surface data and all data collected at the shore-based sites were compiled into FOCB_report, which includes 5,150 site visits over the six-year period. A third table, FOCB_locations, was added to the database to provide location information for each of the sites. A series of queries was run to rectify discontinuities between the three tables (i.e. check for replicated data, cross-reference sites, etc.) and to update fields necessary for use with Battelle's ViewPoint data mapping software. After discussions with FOCB personnel, three sites were removed from the FOCB_locations table due to insufficient data – the Little John Island Bridge site (LJB73) was never sampled, the Royal River Yarmouth Water District site (RRY48) was only sampled once, and the Cousins Island Bridge site (CIB62) was sampled in 1994 but became the Seaborne Yarmouth site (SEA62) in 1995. The two freshwater sites, Capisic Pond and Stroudwater Dam, were also removed from the database table and not used in the data analysis. These five sites were removed from FOCB_report and a new database table (FOCB_report_estuarine) was produced for our statistical and graphical analyses. The 88 locations that remained for the evaluation are presented in Table 1. Upon completion of database population and prior to data analyses and interpretation, the Battelle Quality Assurance Unit audited the database for completeness. The final Access data tables were audited by comparison with the data files submitted by FOCB and no errors or omissions were found.

There have been a number of changes over the six years of the monitoring project. The number of sampling sites has increased from 30 shore-based stations and 8 profile stations in 1993 to the 80 shore-based and 8 profile stations listed in Table 1 in 1998. Following an initial review of the data, site data were grouped into basins or water bodies. The water body names and associated sites are listed in Table 1 and presented in Figure 2.

During 1993-1995, samples were collected every two weeks from April through October. From 1996-1998, sampling was conducted only once per month. For many of the graphical analyses, the data have been presented as monthly means to account for differences in sampling frequency. Another temporal factor that could have biased analyses, if not taken into account, was the fact that the profile sites and a few shore-based sites were sampled once per month over the winter during each of the years (Figure 3). Another database table (FOCB_report_EAO) was developed that was restricted to data collected in April through October. This data was used for a majority of the graphical and statistical analyses. The year-round data were grouped and saved in a separate database table for investigation of seasonal cycles over the whole year (FOCB_report_YR).

Intense sampling was conducted during a special study at the New Meadows Marina site in June-July 1997 and July 1998 to monitor water quality during a potential fish kill event. For the analyses presented, data collected during these periods were averaged to develop monthly mean values that were substituted for the high frequency sampling results in the working tables listed above. This was done so that the intense summer sampling during a low DO event did not bias the New Meadows Marina data. The raw data were presented in a report on the special New Meadows Marina study (FOCB, 1997b).

In addition to potential biases due to sampling locations and frequency, water depth at a station can cause significant biases on Secchi depth data. There are a number of stations where water depth and Secchi depth are equal (bottom is visible). Although the Secchi depth may be shallow at these stations, it does not necessarily mean water clarity is poor. To avoid biasing the Secchi data, a filtering procedure was developed to remove sites from a Secchi database (FOCB_report_EAO_secchi) that did not include a sufficient number of samples where Secchi depth was greater than the water depth. The filtering resulted in a database with 50 sites, all of which had a Secchi-depth to water-depth ratio of < 80% (Figure 4).

Once the database tables were finalized, a suite of queries was developed to group data spatially, temporally, or by parameter. The data from these queries and the database tables mentioned above were used for the data analyses that are presented in the following section.

Table 1. Site Locations for FOCB Water Quality Monitoring

Site Name	Site Code	Water Body Name	Water Body Code	Town	Water Class
Anthoine Creek	ANT01	Portland Harbor	PH	South Portland	SC
B&M Railroad Trestle	BMR02	Portland Coast	PC	Portland	SC
Bartol Island Causeway	BAR48	Harraseeket River	HR	Freeport	SB
The Basin	BAS68	New Meadows River	NMR	Phippsburg	SB
Bear Island[1]	P4BRI	Eastern Coast	EC	Phippsburg	SB
Ben Island	BEN03	Quahog Bay	QB	Harpswell	SB
Bethel Point	BTH04	Quahog Bay	QB	Harpswell	SB
Birch Point	BIR05	New Meadows River	NMR	West Bath	SB
Broad Cove	BCC06	Foresides	FS	Cumberland	SB
Broad Sound[1]	P5BSD	Mid Bay	EB	Cumberland	SB
Cape Small Harbor	CSH07	Eastern Coast	EC	Phippsburg	SB
Cat Cove West Point	CAT69	Eastern Coast	EC	Phippsburg	SB
Channel Crossing	CHX09	Portland Harbor	PH	South Portland	SC
Chebeague Island	CHB10	Western Bay	WB	Cumberland	SB
Chebeague Island Johnson Cove	CIJ72	Western Bay	WB	Cumberland	SB
Clapboard Island	CLP11	Western Bay	WB	Falmouth	SB
Clapboard Island[1]	P7CBI	Western Bay	WB	Falmouth	SB
Clark Cove	CLK12	Harpswell Sound	HS	Harpswell	SB
Cliff Island Boat Cove	CLF71	Western Bay	WB	Portland	SB
Cliff Island Public Landing	CLF13	Western Bay	WB	Portland	SB
CMP Dock	CMP61	Western Bay	WB	Yarmouth	SB
Cousins River Muddy Rudder	CRV63	Royal River	RR	Yarmouth	SB
Cushing Island	CUS14	Western Bay	WB	Portland	SB
Custom House Wharf	CST15	Portland Harbor	PH	Portland	SC
Dyer Cove, Cape Elizabeth	DYR16	Cape Elizabeth	CE	Cape Elizabeth	SB
Dyers Cove, Quahog Bay	DYQ17	Quahog Bay	QB	Harpswell	SB
East End Beach	EEB18	Portland Coast	PC	Portland	SC
Ewin Narrows	EWN77	Harpswell Sound	HS	Harpswell	SB
Fort Gorges[1]	P6FGG	Portland Coast	PC	Portland	SC
Googins Ledge	GGL20	Mid Bay	EB	Freeport	SB
Goslings	GOS19	Mid Bay	EB	Harpswell	SB
Great Diamond, Diamond Cove	GRD21	Western Bay	WB	Portland	SB
Gun Point	GUN65	Quahog Bay	QB	Harpswell	SB
Halfway Rock[1]	P2HWR	Offshore	OFF	US Government	SA
High Head Yacht Club	HHY22	Harpswell Sound	HS	Harpswell	SB
Indian Rest	IND66	New Meadows River	NMR	Harpswell	SB
International Ferry Terminal	INT23	Portland Harbor	PH	Portland	SC
Jordan Point	JOR24	Middle Bay	MB	Harpswell	SB
Little Bustins Island[1]	P8LBI	Mid Bay	EB	Freeport	SB

Site Name	Site Code	Water Body Name	Water Body Code	Town	Water Class
Little Chebeague	LCH25	Western Bay	WB	Long Island	SB
Little Diamond Island	LTD60	Western Bay	WB	Portland	SB[2]
Little Flying Point	LFP26	Maquoit Bay	MQ	Freeport	SB
Little Flying Point[1]	P9LFP	Maquoit Bay	MQ	Freeport	SB
Little Iron Island[1]	P10LI	Middle Bay	MB	Harpswell	SB
Littlejohn Island	LJN27	Western Bay	WB	Yarmouth	SB
Long Island, New Meadows	LNM75	New Meadows River	NMR	Harpswell	SB
Lookout Point	LPT74	Middle Bay	MB	Harpswell	SB
Lowells Cove, Orrs Island	LWC28	Harpswell Sound	HS	Harpswell	SB
Mackerel Cove, Bailey Island	MCV29	Harpswell Sound	HS	Harpswell	SB
Mackworth Causeway	MAC30	Foresides	FS	Falmouth	SC
Mackworth Stone Pier	MSP31	Foresides	FS	Falmouth	SB
Maquoit Bay, Haible	MQH32	Maquoit Bay	MQ	Brunswick	SB
Maquoit Bay, Wallace	MQW33	Maquoit Bay	MQ	Brunswick	SB
Marine East	MRE64	Portland Harbor	PH	South Portland	SC
Mill Cove	MIL34	Harpswell Sound	HS	Harpswell	SB
New Meadows Marina	NMM79	New Meadows River	NMR	Brunswick	SB
Orrs Yacht Club	OBY35	Harpswell Sound	HS	Harpswell	SB
Peabbles Cove	PBL36	Cape Elizabeth	CE	Cape Elizabeth	SB
Peaks Island Public Landing	PKP38	Western Bay	WB	Portland	SB[2]
Peaks Island, East	PKE37	Western Bay	WB	Portland	SB
Peaks Island, South	PKS39	Western Bay	WB	Portland	SB[2]
Pennellville Middle Bay	PEN40	Middle Bay	MB	Brunswick	SB
Perry's Landing	PRY41	Quahog Bay	QB	Harpswell	SB
Phippsburg Town Pier	PTP76	Eastern Coast	EC	Phippsburg	SB
Pinkham Point	PKT42	Quahog Bay	QB	Harpswell	SB
Portland Headlight	PTH59	Cape Elizabeth	CE	Cape Elizabeth	SB[2]
Portland Yacht Club	PYC43	Foresides	FS	Falmouth	SB
Portland Yacht Services	PYS44	Portland Harbor	PH	Portland	SC
Princes Point	PPT45	Foresides	FS	Yarmouth	SB
Ram Island Ledge[1]	P1RIL	Offshore	OFF	Portland	SB
Royal River Buoy C5	RRC46	Royal River	RR	Yarmouth	SB
Royal Yankee Marina	RRY47	Royal River	RR	Yarmouth	SB
RT9 Presumpscot Bridge	PRV70	Presumpscot River	PR	Falmouth	SC
Seaborne Yarmouth	SEA62	Foresides	FS	Yarmouth	SB
Seameadows	SEA73	Western Bay	WB	Yarmouth	SB
Sebasco Estates	SEB49	Eastern Coast	EC	Phippsburg	SB
Small Point[1]	P3SMP	Offshore	OFF	Phippsburg	SB
SMTC Pier	SMT50	Portland Coast	PC	South Portland	SC
South Freeport Town Landing	SFP51	Harraseeket River	HR	Freeport	SB
Stockbridge Point	STK52	Harraseeket River	HR	Freeport	SB
Stovers Point	STV53	Harpswell Sound	HS	Harpswell	SB
Stroudwater Bridge	STR54	Portland Harbor	PH	Portland	SC
Two Lights	TWO55	Cape Elizabeth	CE	Cape Elizabeth	SB
Waites Landing	WAI56	Foresides	FS	Falmouth	SB
Whartons Point	WPT78	Maquoit Bay	MQ	Brunswick	SB
Willard Beach	WIL57	Portland Coast	PC	South Portland	SB[2]
Wolf Neck State Park	WLF58	Mid Bay	EB	Freeport	SB
York Landing	YOL66	Foresides	FS	Falmouth	SB

[1] The ten profile sites. [2] These five sites were reclassified from SC to SB waters based on FOCB data.

2.3 Data Analysis

Preliminary analysis entailed developing summary statistics and graphical presentations of the data from all stations. The summary statistics included overall mean, minimum and maximum values, and other univariate statistics for each parameter of interest (temperature, salinity, pH, Secchi depth, and DO concentration and % saturation). Correlations and frequency plots were produced to describe the overall data distribution, and parameter vs. parameter scatter plots were used to evaluate potential linkages in the system. GIS maps and contour plots were also produced to depict the spatial distribution of monthly, seasonal, and annual mean values of selected parameters.

Sites were grouped following a review of mean surface data across Casco Bay. The review highlighted inshore to offshore and other geographic trends in the data. It was determined that groupings based on geographic basins would provide the best prospect for identifying areas of concern and understanding the potential causes of problematic conditions. Each of the basins, or water bodies, was evaluated by the same set of statistical tools used for the complete data set. Relationships between parameters and water bodies were examined utilizing Pearson correlation tests, parametric (ANOVA) comparison of difference tests, and associated planned comparison tests (Tukey's Studentized Range; Sokal and Rohlf, 1981). Log and natural log transformations of the data were evaluated, but did not provide any improvement of the variance associated with the raw data. Therefore, untransformed data were used for the planned comparison tests on DO and % saturation data by both site and water body. Differences between groups were evaluated at the 95% significance level. Results of the parametric comparison tests are useful for ranking a comparative evaluation of the FOCB CWQM sites and water bodies in Casco Bay.

To characterize temporal trends in the data, time series plots were produced to evaluate how parameters varied over the entire six-year period and seasonally (using monthly means). The time series plots were developed for a range of geographic scales – sites, water bodies, and baywide. At the profile stations, time series plots focused on variations in bottom and surface waters over time. Once water bodies and sites of concern were determined, a closer inspection of spatial and temporal variability was conducted by applying the same set of tools to a more defined set of data.

3.0 Results and Discussion

The data fall into two general categories based on sampling. The first includes all surface data (shore-based and profile stations). The other includes only the profile station data (all depths). The two sets were evaluated separately to account for the effect of sampling depth in the profile data.

3.1 Overview of Estuarine Surface Data

The summary statistics for all estuarine surface data are presented in Table 2. The minimum and maximum values for each of the parameters provide a good representation of the variability between stations, across the bay, and over time. The shallowest water depth was measured in Anthoine Creek and the deepest depth was consistently measured at Halfway Rock. The coolest temperatures were measured at the 14 sites that are sampled year-round, while the warmest single water temperature was found at the Cousins River site in front of the Muddy Rudder Restaurant during the summer of 1995. Warm waters were consistently observed at the Presumpscot River site, but for swimming Wolf Neck State Park (WLF58) offered an August mean water temperature of almost 20°C. Willard Beach (WIL57) had one of the lower August mean water temperatures at 16°C. The lowest pH and salinity values were obtained at sites at the mouths of both the Royal and Presumpscot Rivers, while the highest pH and salinity were found at Two Lights in Cape Elizabeth and Willard Beach in South Portland, respectively. The lowest DO and % saturation were found at Peabbles Cove where low DO and % saturation have been found to be associated with the decomposition of seaweed that naturally accumulates in that location due to ocean currents (FOCB, 1996a). The maximum values for DO and % saturation were found at Peaks Island Public Landing and Maquoit Bay (Haible), respectively, and are indicative of very high primary production. Peaks Island Public Landing is located within 400 m of a sewage treatment plant and may periodically experience elevated nutrient loading. The higher nutrient concentrations, in turn, may lead to higher primary production rates and higher DO concentrations. Secchi depths were at a minimum at a number of inshore sites including Mackworth Causeway, Maquoit Bay (Haible), Stroudwater Bridge, Royal River Yankee Marina, and Royal River C5. The maximum Secchi depth was found at Halfway Rock, in fact, all Secchi depths ≥ 10 m were observed at this offshore site.

Correlation analysis of the six parameters plus water depth for the surface estuarine data showed relatively minor relationships between most of the parameters (Table 3). Due to the large sample size (n~5000) used in this analysis, almost all of the correlations were significant at the 95% level. For a sample size an order of magnitude lower, n = 500, an r value of ≥ 0.088 suggests a significant relationship at the 95% confidence level. As a rule of thumb, statisticians recognize correlation coefficients of >0.80 as strong and 0.50-0.80 as indicative of moderate relationships. Due to the large sample sizes, the statisticians' rule of thumb will be used in this report when discussing the relationships between parameters in correlation analyses. The two most significant correlations for the estuarine surface data were between Secchi depth and water depth, and DO and temperature. The link between Secchi and water depth was discussed in Section 2.1 as one of the reasons the Secchi data might be biased in a comparison across the bay. Even with suspect data removed from the analysis, a positive correlation was observed between these parameters (r = 0.57). Lower Secchi depth values were observed in the inshore, shallow waters, while higher Secchi depths were observed further offshore in the deeper waters. The most significant correlation was found between DO and temperature (r = -0.66). DO concentrations are directly affected by changes in temperature – increasing temperatures result in lower DO. The negative correlation between these two parameters is illustrated in Figure 5.

Table 2. Summary Statistics for All Estuarine Surface Data

	Water Depth (m)	Temp (°C)	Salinity (ppt)	DO (mg/l)	DO (% saturation)	pH	Secchi Depth* (m)
Mean	7.41	13.15	28.88	9.07	102.37	7.94	2.94
SD	7.93	5.11	4.55	1.40	12.10	0.18	1.33
Range	52.9	32.0	33.5	12.3	143.6	2.7	12.5
Minimum	0.1	-2.0	0.0	2.6	33.9	6.0	0.2
Maximum	53.0	30.0	33.5	14.9	177.5	8.7	12.7
Count	4195	5025	4954	4922	4847	4673	2922

*Secchi depth summary statistics calculated from 50 selected sites.

Table 3. Correlation Coefficients between Parameters for Estuarine Surface Data

	Secchi Depth*	Water Depth	Temp	pH	Salinity	DO	% Saturation
Secchi Depth	1						
Water Depth	0.5832	1					
Temp	-0.2823	-0.2398	1				
PH	0.2132	0.1017	0.0087	1			
Salinity	0.3235	0.0747	0.0711	0.4184	1		
DO	0.2363	0.1905	-0.6607	0.2533	-0.1208	1	
% Saturation	0.1469	0.0478	0.1079	0.4381	0.1456	0.6436	1

*Secchi depth summary statistics calculated from 50 selected sites.

The frequency distribution of all estuarine surface measurements of DO concentration (n = 4922) is presented in Figure 6. Almost 75% of the DO measurements had concentrations of 7.5 to 10.5 mg/l (mean of 9 ± 1.5 mg/l). Only ~0.5% of the values were below 5.5 mg/l and <5% of the values were less than 7 mg/l. The DO concentration of 5.5 mg/l is an arbitrary benchmark that might be expected to elicit subtle detrimental biological effects and has been used in comparative studies in Maine in the past (Kelly, 1997). The State of Maine does not have a water quality standard for DO concentration. For reference, Massachusetts' state standard is 6 mg/l and the EPA is currently considering establishment of a standard of 4.8 mg/l for the waters from Cape Cod, MA to Cape Hatteras, NC (USEPA, 2000).

The frequency distribution for % saturation observations was similar to that of DO (Figure 7). A majority of the measurements ranged from 90 to 110% of saturation values. The State of Maine standards for class SB and SC waters are 85% and 70%, respectively. The standard for class SA waters is dissolved oxygen "as naturally occurs" and is not directly quantified. In Figure 7, almost 6% of the values were below 85% saturation and <1% were below 70% saturation. Upon closer inspection by water class, there was one surface % saturation value <85% for SA waters, 169 values <85% for SB waters (4.3% of total number of SB measurements), and 16 values <70% for SC waters (1.5% of total SC measurements). For class SC waters, all exceedences of the SC standards were found at sites in Portland Harbor, with the exception of one exceedence at the Presumpscot River site (PRV70). For class SB waters, sixteen of the exceedences of SB standards (out of 169) were actually below the 70% SC level. Multiple observations below 70% saturation for SB waters were observed at the Peabbles Cove, New Meadows Marina, Sebasco Estates, and a number of Quahog Bay sites [Ben Island, Bethel Point, and Dyers Cove]. Five of the six measurements below 70% at the Quahog Bay sites, however, were noted as being suspect due to possible analytical errors (FOCB, 1995).

3.2 Spatial Trends

A review of parameter means by site for estuarine data collected from April through October provided an integrated comparison across sites (see Appendix B for values). The coolest mean water temperature was observed at the Cushing Island site (CUS14) and the warmest at Whartons Point (WPT78) in Maquoit Bay (Figure 8). Warmer mean temperatures were generally observed at the sites in basins in Eastern Casco Bay and at sites with substantial freshwater input, low salinity, and low pH – Presumpscot, Royal and Cousins River sites, and the Stroudwater Bridge and Mackworth Causeway sites, which are near freshwater inputs (Figures 8 & 9). The highest mean salinities (>31.8 ppt) were found at the Chebeague Island Johnson Cove and Cliff Island Boat Cove sites in Western Casco Bay. The highest mean pH values (8.12) were from two Cape Elizabeth sites (Dyer Cove and Portland Headlight) and a site in Phippsburg (Cat Cove West Point).

High mean DO concentrations (>10 mg/l) and % saturation values (~115%) were found at Cat Cove West Point (CAT69), Cliff Island Boat Cove (CLF71), and York Landing (YOL66; Figures 10 & 11). The low mean DO concentrations were generally observed at the warmer eastern basin sites and riverine sites (Figure 10). Mean DO concentrations of < 8 mg/l were observed at New Meadows Marina (NMM79), Stroudwater Bridge (STR54), and Cousins River (CRV63). Although DO was negatively correlated with temperature in a comparison of site parameter means (Table 4), the lowest mean DO, which was found at Custom House Wharf (CST15) in Portland Harbor, exhibited a relatively low mean temperature. This suggests different mechanisms may influence the decline of DO at this site compared to the New Meadows Marina, Stroudwater Bridge, and Cousins River sites. The lowest DO % saturation values (~90% and lower) were observed at the Custom House Wharf, New Meadows Marina, Stroudwater Bridge, and Presumpscot River sites (Figure 11).

Mean Secchi depth was lowest (1.1 m) inshore at Stroudwater Bridge and highest (5.7 m) offshore at Halfway Rock. Secchi depth was positively correlated with water depth (r = 0.73) and exhibited a moderate negative correlation with temperature (r = -0.63) due to the inshore to offshore decreases in temperature and coincident increases in Secchi and water depth. Secchi depth and DO were also positively correlated (r = 0.52), which is also due to an inshore to offshore trend in both parameters. A prevalence of low DO concentrations was found at inshore sites that have shallow Secchi depths and higher DO concentrations were measured at deeper offshore sites like Halfway Rock that have deeper Secchi depths. A confounding factor affecting this relationship is the increase in DO concentrations in highly productive waters that, due to increases in phytoplankton biomass, should result in shallower Secchi depths.

Salinity, pH and DO % saturation were all positively correlated with one another, which is indicative of the effect of freshwater inputs into Casco Bay's near-shore waters. Freshwater inputs lower salinity and pH and often have higher concentrations of organic material (allochthonous or locally produced due to nutrient loading) that lead to lower DO and % saturation (Figures 10 & 11). Depending upon the water quality of the freshwater source, the input could directly lower DO concentrations and the combination of lower concentrations and low salinity result in an even stronger effect on % saturation.

Table 4. Correlation Coefficients between Parameters for Mean Site Data

	Temp	pH	Salinity	DO	% Saturation	Secchi Depth*	Water Depth
Temperature	1						
pH	-0.1955	1					
Salinity	-0.3246	0.7400	1				
DO	-0.4422	0.4602	0.2299	1			
% Saturation	-0.1550	0.6480	0.4655	0.8953	1		
Secchi Depth	-0.6280	0.4192	0.3723	0.5170	0.3907	1	
Water Depth	-0.4754	0.2392	0.1051	0.4106	0.2529	0.7342	1

*Secchi depth summary statistics calculated from 50 selected sites.

The mean site data were also used to graphically evaluate spatial trends in the data across the bay. The data was contoured using Surfer software and presented with GIS layers obtained from the Maine Office of Geographic Information Systems and NOAA. Figure 12 illustrates the inshore to offshore decrease in mean surface water temperature in Casco Bay and also shows that the eastern half of the bay is generally warmer than the western half. The maps of mean salinity and pH were not very descriptive as only five stations had mean salinity <25 ppt and five a pH <7.8 (four of the five sites had both low salinity and pH) and only highlighted the Royal, Cousins, and Presumpscot River sites and Stroudwater Bridge and Custom House Wharf in Portland Harbor. The trend of deeper Secchi depths at the offshore sites is clearly illustrated by mapping the mean site data (Figure 13). The distribution of mean DO and mean % saturation showed groupings of generally similar sites within geographic basins or areas of the bay (Figures 14 & 15). Both were relatively low in Portland Harbor, in the three river systems, and in a number of basins in Eastern Casco Bay.

Generally, the distribution of DO and % saturation site means suggests that water quality with respect to DO is consistently good. To determine if there was a spatial pattern that might suggest potential problem areas that deserved closer attention, we evaluated DO and % saturation minima for the six years of data (Figures 16 & 17). The patterns in the site minima for both parameters reconfirm those observed for mean values and also highlight the areas of concern in Eastern Casco Bay. Sites in Maquoit Bay, Quahog Bay, and New Meadows River had DO minima of <5.5 mg/l and % saturation values of <70% (the class SC standard and these are all class SB waters). Percent saturation minima of <85% had been observed in the surface waters of most sites (68 of 88 sites) at one time or another from 1993 to 1998. This suggests that problematic conditions may occur across most of Casco Bay relative to Maine Water Quality Standards. The unexpected number of % saturation minima <85% found at offshore stations, however, suggests that these relatively low values are within the natural range for the area and not the result of anthropogenic impacts or they may be due to pressures external to the Casco Bay system, such as the Kennebec River plume (FOCB, 1996b).

3.3 Water Body Evaluations

Based on the results discussed above, the sites were grouped on a geographic basis. Spatial trends in the data supported this grouping and the geographic groupings allow for better understanding of the causative factors resulting in the trends observed and provide a simpler mechanism for management actions. The water body designations are listed in Table 1 and illustrated in Figure 2. Parameter means for the April to October estuarine data are provided in Appendix C (Table C1). Means were also calculated for all estuarine data during the July through September time period (see Appendix C – Table C2) because this is when low DO concentrations and % saturation values tended to occur in Casco Bay. This allows investigation of correlations and trends between parameters and water bodies on both an annual and seasonal basis.

In general, the trends in maximum and minimum water body means were the same for the April to October and July to September time periods (Appendix C). Offshore and Cape Elizabeth sites were the coolest and Presumpscot River was the warmest. Middle Bay, Maquoit Bay, and Royal River were also warmer than the other water bodies. The lowest pH and salinity were observed in the Presumpscot River while the highest pH and salinity were found in Cape Elizabeth. The highest DO concentration was at the offshore sites and the lowest in Portland Harbor.

The grouping of sites led to a stronger set of correlations between parameters. Moreover, restriction of data to summer months (July-September) strengthened the correlations between temperature and the other parameters (Table 5). There was a very strong correlation between pH and salinity for both temporal groupings of data, as well as a strong positive correlation between pH and % saturation. By removing the Presumpscot River water body grouping, the relationship between pH and salinity is considerably weaker, but pH and % saturation remain strongly correlated and the correlation between pH and DO concentration increased for both the April to October and summer temporal groupings (data not shown).

Table 5. Correlation Coefficients between Parameters by Water Body Means

	Temp	pH	Salinity	DO	% Saturation
April-October					
Temp	1				
pH	-0.5870	1			
Salinity	-0.6221	0.9503	1		
DO	-0.4840	0.5357	0.3552	1	
% Saturation	-0.4355	0.8861	0.7863	0.7915	1
July-September					
Temp	1				
pH	-0.6901	1			
Salinity	-0.7120	0.9291	1		
DO	-0.6146	0.6251	0.4194	1	
% Saturation	-0.5342	0.8494	0.7048	0.8738	1

A graphical comparison of mean summer (July-September) temperature and DO concentrations by water body shows the expected decrease in DO with increasing temperature (Figure 18a). This relationship is represented by the line indicating DO concentrations at 100% saturation based on temperature at a salinity of 30 ppt (Weiss, 1970). Four water bodies had DO concentrations that fell below this line including areas of nutrient/organic loading (Portland Harbor), freshwater inputs and potential loading (Royal River and Harraseeket River), and limited flushing and high residence times (Quahog Bay). Kelly and Libby (1996) reported a flushing time of 27 hours for Quahog Bay. Another Eastern Casco Bay water body with limited flushing, New Meadows River (47 hours), had slightly higher mean DO values. The only other water body with a mean DO concentration of ≤8.0 mg/l was the Presumpscot River. Although the mean salinity for FOCB data in July to September was 30 ppt, the mean at in the Presumpscot River was <3 ppt and the "100% saturation line" does not hold true at lower salinity. The low DO % saturation for the Presumpscot River is evident in a comparison of temperature and % saturation for the same time period (Figure 18b), five water bodies had summer mean % saturation of <100% and were undersaturated. The Presumpscot River area was the lowest and the only water body with a mean DO % saturation (87.4%) that approached the State standard for class SB waters of 85%.

Statistical tests were conducted to determine if the differences in DO concentration and % saturation between water bodies were significant. ANOVA tests for both parameters indicated that there were significant differences across the 16 water bodies (P<0.001). Comparison tests were run to test each water body against one another for both parameters and the results are presented in Figures 19 and 20. Although numerous comparisons were conducted, the results have been simplified for presentation by ranking the water bodies by mean values and then connecting groups of water bodies that were not significantly different from one another (in respect to the parameter considered) under the different comparisons. Due to the relatively small range of differences in the means, the results of the planned comparisons indicate a great deal of overlap between water bodies.

The DO mean for the Offshore sites was significantly higher than all other water bodies except for the Eastern Coast (Figure 19). The Portland Harbor DO mean concentration was significantly lower than all water bodies with a mean concentration of >8.0 mg/l. The five water bodies with mean DO concentrations of <8.0 mg/l were not significantly different from one another, but were significantly lower than the upper half of water body means (Portland Coast to Offshore, see Figure 19). The only exception was the Presumpscot River, which was only significantly different from Western Bay, Eastern Coast, and Offshore. The reason for this exception is the limited number of samplings for Presumpscot River (n=14) in comparison to the other water bodies (n= 58 to 327). For the other 10 water bodies, there were overlapping groupings of water bodies that were and were not significantly different from one another. For instance, Harpswell Sound was not significantly different from Presumpscot River, Royal River, New Meadows River, Maquoit Bay, Portland Coast, Foresides, Middle Bay, Mid Bay, or Cape Elizabeth but was significantly higher than Portland Harbor, Harraseeket River, and Quahog Bay and lower than Western Bay, Eastern Coast, and Offshore.

This analysis was also conducted on a site-by-site comparison, but the results are far too complex to interpret and present in a meaningful way. This is because of the large number of sites, relatively low number of measurements, and the small difference along the continuum of site means. The analysis did, however, indicate that the mean DO concentration at three sites – Custom House Wharf (CST15), New Meadows Marina (NMM79), and Stroudwater Bridge (STR54) – was significantly lower than nearly all of the other sites. These three sites all had a mean DO concentration for the July to September time period of <7 mg/l (see Appendix B).

The ranking and comparison groupings of water bodies for mean % saturation were similar to those observed for DO concentration, but there was more overlap in the groupings (Figure 20). Presumpscot River and Portland Harbor were significantly lower than all other water bodies except Royal River. Royal River, Harraseeket River, and Quahog Bay were not significantly different from each other, but were significantly lower than a number of the other water bodies. All five of these water bodies were undersaturated in respect to DO. The other 11 water bodies had mean % saturation of >100% and fell into overlapping groups.

Based on the comparison results and a review of DO and % saturation minimum values for each water body, Portland Harbor, Quahog Bay and New Meadows River were examined in closer detail to evaluate trends in DO data and differences among sites within these water bodies. The mean DO concentrations for each site within the three water bodies are presented in Figure 21. Two patterns are evident in the distribution of mean DO within each water body. In New Meadows River and Portland Harbor, low mean DO values (<7.0 mg/l) were observed at a limited number of sites and higher concentrations (>7.5 mg/l) were observed at the remaining sites. Comparison tests indicated that DO concentrations at the Custom House Wharf (CST15) and Stroudwater Bridge (STR54) sites were significantly lower than the other four sites in Portland Harbor and that New Meadows Marina (NMM79) was significantly lower than the rest of New Meadows River sites ($P<0.001$ for all three sets of comparisons).

In Quahog Bay, mean DO concentrations were more homogeneous and ranged from 7.55 mg/l at Perry's Landing (PRY41) to 8.26 mg/l at Gun Point (GUN65). In the step-wise comparison analysis, the sites separated into two overlapping groups. One included all five of the sites with mean DO concentrations of <8 mg/l and the other included Bethel Point (BTH04), Dyers Cove (DYQ17), and Gun Point (GUN65). In general, there is little difference in DO concentrations among sites in Quahog Bay. The low value observed for mean water body DO in Quahog Bay (see Figure 18a) is due to relatively low concentrations throughout the embayment. Conversely, the mean water body DO concentrations for New Meadows River and Portland Harbor were lower in comparison to other water bodies because of specific sites that exhibited problematic DO conditions. In New Meadows River, the upper reaches of the water body (New Meadows Marina and Indian Rest sites), which have limited communication with offshore waters, had lower mean DO concentrations. In Portland Harbor, the low DO concentrations at Custom House Wharf and Stroudwater Bridge are likely caused by different local factors – point source discharges including combined sewage overflows (CSO) for Custom House Wharf and nonpoint source/freshwater inputs for Stroudwater Bridge. There are also a number of CSO upstream from the Stroudwater Bridge site. The New Meadows Marina and Custom House Wharf sites are examined in more detail later in this section.

3.4 Temporal Trends

A time series of monthly mean temperature and DO from the 14 sites sampled year-round clearly shows the seasonality of these parameters, as well as their inverse trends (Figure 22). Though there are small year-to-year variations in range, the cycle is relatively consistent. An examination of data for individual year-round sites shows similar patterns, but also gives an indication of the variability of the cycle in different locations in Casco Bay. The Mill Cove site in Harpswell Sound, for instance, is consistently warmer in the summer and cooler in the winter than the year-round station mean (Figure 23). Surface water temperatures at the three sites in Eastern Casco Bay water bodies (Mill Cove, Little Flying Point, and Little Iron Island) were approximately 2-3°C warmer in the summer than the year-round station mean (Figure 23). In 1998, the summer temperatures at these three stations were substantially higher reaching a maximum of 27°C at Mill Cove in July. The peak in temperature for the six years at Mill Cove was coincident with the minimum DO concentration of ~6 mg/l (Figure 24). For the sites examined in Figure 24, the Mill Cove site had the lowest yearly DO minimum for each of the six years. Interestingly, the DO minima for each of the sites tended to increase from the summer of 1994 through the summer of 1997. Due to the geographic coverage of Casco Bay that these stations represent, this increase in DO minima values may correspond to a regional Gulf of Maine effect. The trend did not continue at these sites into 1998 as the DO minima declined in association with higher temperatures.

An examination of DO % saturation at these year-round sites showed less defined seasonal and interannual trends (Figure 25). Generally, higher % saturation was observed in the spring and summer and lower % saturation in the fall and winter, but there is considerable variability both within and between years and sites. The trend and variability in % saturation is due to the combination of factors that affect this parameter in these surface waters – temperature, salinity, and biological utilization and production of dissolved oxygen. As shown in Figure 22, temperature and DO concentration vary inversely to one another over the seasonal cycle. This tends to dampen seasonal variations in % saturation in the surface waters – higher temperatures result in lower concentrations of dissolved oxygen necessary for 100% saturation and thus, even though DO concentrations are decreasing, % saturation values may actually increase. DO % saturation is also directly affected by variations in salinity – lower salinity waters have a higher DO concentration at 100% saturation compared to higher salinity waters. The Mill Cove site tended to have the lowest % saturation for the sites presented in Figure 25. The year-round mean data and most of the individual sites appear to show an increase in both annual minima and maxima % saturation from early 1993 to the spring of 1997. This is different from the interannual trend observed for DO concentrations, which appeared to increase from the summer of 1994 to the winter of 1998 (Figure 24).

An examination of the interannual cycles from all of the estuarine sites suggests that annual minimum and maximum DO concentrations have varied without any clear trends from 1993 to 1998 (see "All" data line in Figure 26). Interannual trends of increasing DO minima were, however, observed for Portland Harbor, Quahog Bay, and Maquoit Bay from 1993 to 1996 until decreasing in the summer of 1997 (Figure 26). In fact, Portland Harbor and Maquoit Bay exhibited the lowest monthly mean DO concentrations during the summer of 1997 for the six-year period evaluated. It will be interesting to see if 1997 was a short deviation from an overall long-term trend of increasing DO minima in Casco Bay.

To examine seasonal rather than annual variations in parameters, we plotted the mean monthly values for all six years from select water bodies. Plots of temperature echoed previous results indicating that the water bodies of Eastern Casco Bay were consistently warmer than the baywide average during the summer. The offshore area and other areas directly influenced by offshore waters (Portland Coast, Western Bay, and Cape Elizabeth) were consistently cooler. Trends in DO concentrations also reiterated themes from previous data evaluations with lower summer DO surface water minima in Portland Harbor (~0.8 mg/l lower than mean) and water bodies in the eastern portion of the bay (Quahog Bay and New Meadows River ~0.5 mg/l lower than mean; Figure 27). DO concentrations for Middle and Maquoit Bay were generally at or above the mean for all data (Figure 27). DO % saturation in Middle and Maquoit Bay were higher than the mean for all data during each of the twelve months and was often >5% higher (Figure 28). Monthly mean % saturation in New Meadows River was not substantially different from the overall mean values, while the monthly mean values in Portland Harbor and Quahog Bay were lower than the overall mean for each of the twelve months. DO % saturation in Portland Harbor was 5 to 10% lower than the overall mean from May through October and undersaturated with respect to DO during all months except March and April (Figure 28).

There was a disconnect between monthly trends in DO concentration and % saturation. DO maximum concentrations occurred during the winter months (January-March) coincident with minimum temperatures, while % saturation tended to reach maximum levels later in the spring and early summer. This trend was noted previously during the examination of interannual trends for select year-round sites (see Figures 24 & 25). Surface waters examined were undersaturated with respect to DO in January due to cold temperatures. Colder waters are able to maintain higher DO concentrations at 100% saturation and even limited utilization of DO during the winter leads to % saturation of less than 100%. In the spring, DO concentration decreases with increasing temperature. This can obfuscate the biological effect of increased primary production and production of DO. This biological production, above the physical decrease in the amount of DO at saturation, results in an increase in % saturation and the persistent supersaturated conditions through early summer in many of the water bodies within Casco Bay. In the fall and early winter, the opposite is the case. The increase in DO concentration is not on par with the decrease in temperatures because of the continued utilization of DO for respiration and degradation of organic material.

Trends in Secchi depth over the year were not as clear, although the data suggest that Secchi depth is shallower from April to October compared to the winter months (Figure 30). This trend is to be expected, as production and phytoplankton biomass are normally higher during these months in comparison to the winter months. Another contributing factor to the trend is the limited sampling during the winter and the preponderance of sampling at deeper, offshore sights in the winter. An inspection of monthly mean trends in Secchi depth at selected sites shows relatively little change in the parameter from April to October except at the offshore site at Halfway Rock (P2HWR), which exhibits as much variation within this time period as over the entire year (Figure 30).

The monthly trends for the six years of data in DO concentrations and % saturation highlight the potential problem sites in Portland Harbor and eastern basins with lower DO and % saturation than the mean for the system (Figures 30 & 31). Monthly mean DO concentrations were 6 to 7 mg/l at the Custom House Wharf (CST15) and New Meadows Marina (NMM79) sites from June to September (through October for CST15), which are 1.5-2.0 mg/l lower than the mean surface water concentrations for Casco Bay (Figure 30). Monthly mean % saturation remained <100% for each of the months that data were obtained for these two sites (Figure 31). In late summer and early fall, the mean % saturation at Custom House Wharf was ≤80% over the six-year period. Sites in Quahog Bay and Harpswell Sound (Pinkham Point and Mill Cove, respectively) were also undersaturated with respect to DO for nearly all of the months that data were collected.

A comparison of correlations between parameters at the Custom House Wharf and New Meadows Marina sites was conducted to examine the processes that may be contributing to the low DO problems observed on a year-to-year basis at these sites. Correlation coefficients for all the data collected at the two sites over the six-year period are presented in Table 6. Strong correlations between DO concentration and both temperature and pH (r = -0.86 and 0.84, respectively) are evident at New Meadows Marina. Although a moderate correlation was observed between these parameters at Custom House Wharf, the relationship is not as strong. Plots of these parameters show the increased scatter observed in the Custom House Wharf data in comparison to the New Meadows Marina data and suggest that other factors may have a significant effect on the variability observed in these parameters at the Custom House Wharf site (Figure 32). In both cases, however, the decrease in DO and pH was not linked to freshwater inputs as these parameters were negatively (and poorly) correlated with salinity. This suggests that the relationship between DO and pH is driven by the decomposition of organic matter at these two sites, especially at New Meadows Marina. The organic matter may be allochthonous or locally produced by phytoplankton and other algae. Although nutrient data are limited with which to verify loading or ambient nutrient levels, evidence suggests that these sites are in areas of elevated nutrient loading (Kelly and Libby, 1996). The FOCB data suggest that the upper reaches of New Meadows River have potentially problematic low DO conditions that result from a combination of elevated levels of organic material (most likely due to high production locally) and limited flushing. Biological degradation of locally produced organic matter is certainly a factor in the low DO concentrations observed at the Custom House Wharf site, but the relationship may be influenced by additional factors including direct input of organic material (with high biological oxygen demand).

Table 6. Correlation Coefficients between Parameters at the Custom House Wharf and New Meadows Marina Sites

	DO	% Saturation	Temp	pH	Salinity
			Custom House Wharf		
DO	1				
% Saturation	0.8811	1			
Temp	-0.6283	-0.2246	1		
pH	0.5128	0.6212	-0.1993	1	
Salinity	-0.4265	-0.2308	0.3732	-0.1474	1
			New Meadows Marina		
DO	1				
% Saturation	0.8896	1			
Temp	-0.8573	-0.5356	1		
pH	0.8492	0.7784	-0.7256	1	
Salinity	-0.4042	-0.3207	0.3653	-0.2283	1

Two confounding factors that have not been addressed thus far are time of day and tidal stage of sample collection. This data is recorded for all sampling events, but it was impossible to remove this factor from the analyses conducted in the previous sections. To evaluate and account for these factors, sampling frequency must be higher such that there is replication on a shorter temporal scale than years or months. A special study was conducted at the New Meadows Marina site (NMM79) in June and July of 1997 in response to a volunteer monitor's observations of low DO concentrations and the presence of numerous fish. The site was sampled twenty-one times from June 25 to July 6. On nine of the twelve days, the site was sampled in the morning and the evening and samples were collected over most of the tidal range. Dissolved oxygen concentration and % saturation were very strongly correlated ($r = 0.98$), therefore, only the DO concentration data are presented. The time that samples were collected exhibited no significant ($r^2 = 0.02$) relationship with DO concentrations for the New Meadows Marina study (Figure 33a). This was unexpected as time of day during the summer often shows a strong positive correlation with DO from daily minima in the morning to maxima in the afternoon due to production of DO by algae.

A comparison of DO concentrations with tide stage, however, suggested a relatively strong relationship with lower DO being observed closer to high tide and higher concentrations closer to low tide (Figure 33b). For the FOCB program, tide stage was determined based on the time interval from last low tide. This is defined as follows: low as 0 ± 0.5 hr, low flood as 0.5 to 1.5 hr, flood as 1.5 to 4.5 hr, high flood as 4.5 to 5.5 hr, high as 5.5 to 6.5 hr, high ebb as 6.5 to 7.5 hr, ebb as 7.5 to 10.5 hr, and low ebb as 10.5 to 11.5 hr after low tide. One of the reasons for DO being more closely associated with tide stage rather than time of day may have been that the biological pressure on DO concentration at this site was not dominated by primary producers, but rather by the extremely high number of fish arriving with the incoming tide. Instead of having phytoplankton production leading to increases in DO concentrations during the day and respiration lowering concentrations at night, the respiration and utilization of oxygen by the fish, which were primarily present during the incoming tides during this special study (FOCB, personal communication), may have led to the low DO situations. Fortunately, however, it did not lead to extremely low DO concentrations or result in a fish kill during the summer of 1997 (FOCB, 1997b).

Unlike the New Meadows Marina study, an inspection of all surface data collected for estuarine waters from April to October shows that there was a strong relationship between time of day and DO concentrations (Figure 34a) across Casco Bay. This is the usual trend observed in coastal waters. Figure 34a also points out that FOCB sampling is generally conducted from 10AM to 3PM and only a limited number of samples were collected earlier in the day (0.5% before 8AM and only 5.5% by 9AM).

A review of tide stage of sample collection for the April to October data shows a trend similar to that observed for the New Meadows Marina special study with lower DO concentrations being found around high tide compared to low tide (Figure 34b). A step-wise comparison test was run for this set of data that revealed that there are two distinct groups. DO concentrations at high flood, high, high ebb and ebb are significantly lower than those observed at the other four tide stages ($P < 0.05$ for all comparisons between tide stages except ebb and low had $P = 0.053$). It is unclear as to why DO concentrations were lower during the higher tide stages. Biological factors, such as the fish run theory discussed above, may play a role, but it is difficult to ascribe the trend to any particular factor or factors at this time. The physical circulation in Casco Bay may also be a factor. The combination of a relatively large tidal range (~3 m), shallow bays, and narrow channels leads to complex circulation patterns and mixing in the shallow waters that may influence DO dynamics (CBEP, 1996a).

The trends presented in Figure 34 bring up two issues for sample collection – the present sampling protocol does not sample consistently in the morning when DO minima usually occur, but it does seem to capture DO minima as related to tide stage. The effect of time of day on DO concentrations is known (although the signal or relationship may become overwhelmed at times due to extraordinary events) and can be accounted for by changing the sampling protocol or simply understanding that the daily minimum DO concentrations may be missed. The reason for the prevalence of sample collections occurring at high or near high tide is difficult to determine. Sample collection is limited by tide stage at only 6 of the 88 site locations and cannot be the reason for 60% of the samples being collected at high flood, high, high ebb and ebb tide stage (almost 85% if flood tide is included; Figure 34b). Although most of the sites can be sampled at any tide stage, it is likely that many of the sites are more accessible and sampling is easier during the higher stages.

3.5 Profile Station Data

At the profile stations, the correlations between the physical parameters are consistent with oceanographic depth trends – cooler, more saline, and denser water with increasing depth (Table 7). A very weak negative correlation of DO and depth suggests that low DO in bottom waters may not be a significant problem at these 10 Casco Bay stations. In Massachusetts Bay, for instance, there is a stronger negative correlation between DO and depth and lower DO conditions are primarily observed in the bottom waters. The surface and mid-depth waters generally have higher DO concentrations due to a combination of diffusion across the air/water interface and biological production of oxygen by primary producers. During the summer, a subsurface DO maxima is often observed that is associated with oxygen production in a subsurface chlorophyll maximum layer. During the summer, the water column in coastal areas of the Gulf of Maine, including Massachusetts Bay and Casco Bay, becomes stratified and the bottom waters are essentially cut off from the surface waters and sources of DO. Biological utilization of oxygen occurs over the entire water column; but, during the summer stratified period, it is essentially unchecked by diffusion or production process in the bottom waters. Subsequently, the bottom waters (shutoff from sources of oxygen) usually exhibit a steady decline in DO concentrations and % saturation over the summer because of continued water column and benthic respiration.

Table 7. Correlation Coefficients between Parameters at Profile Sites

	Depth	Temp	Salinity	Density	DO	% Saturation
Depth	1					
Temp	-0.2149	1				
Salinity	0.3998	-0.0551	1			
Density	0.4851	-0.5523	0.8565	1		
DO	-0.0874	-0.7321	-0.2412	0.1452	1	
% Saturation	-0.3153	-0.0595	-0.3492	-0.2844	0.7160	1

The frequency distribution of all measurements of DO concentration at profile sites (n~10,000) is presented in Figure 35. A majority of profile DO measurements had concentrations of 8 to 11 mg/l (mean of 9.5±1.5 mg/l). None of the values were below the benchmark of 5.5 mg/l and only ~1% of the values were less than 7 mg/l. The frequency distribution for % saturation observations was similar to that of DO (Figure 36). Approximately 70% of the measurements ranged from 90 to 110% of saturation values. All of the % saturation values less than the State standards for class SC waters (70%) were observed at the Halfway Rock site, which is the only site designated as class SA. These measurements were all collected on October 5, 1998 at depths of 14 to 33 meters. The majority of the <85% values were observed in the bottom waters at Halfway Rock (P2HWR) and Broad Sound (P5BSD), which are the two deepest stations with average water depths of >30 meters. The low DO % saturation values observed in the bottom waters at these deep-water stations result from a combination of extended seasonal stratification and biological utilization of oxygen. These processes are discussed in more detail below.

To examine trends in bottom waters, DO concentration was plotted as monthly means for five selected profile stations for the six-year period (Figure 37). DO minima were consistently observed in the bottom waters during August at the inshore sites of Little Flying Point (P9LFP) and Little Iron Island (P10LI) in Maquoit and Middle Bays, respectively, and in September to October at the deeper, more offshore sites of Bear Island (P4BRI) and Halfway Rock (P2HWR). The Fort Gorges site (P6FGG) tended to follow the trend of the offshore sites, but the DO minima were not as low. The inshore to offshore progression in annual bottom water DO minima is often observed in other regional waters (Libby et al., 1999). This is due to a combination of temperature and the timing of the breakdown of seasonal stratification. The shallower inshore waters are generally warmer and, accordingly, respiration rates are higher leading to a quicker decrease in bottom water DO concentrations in comparison to deeper offshore waters. Seasonal stratification breaks down earlier in the late summer or fall in the shallow inshore waters, as surface winds and waves are able to penetrate to the bottom waters more quickly. This is illustrated in Figure 38 showing the interannual trends in bottom water temperature. Annual bottom water temperature maxima are higher (>15°C each year) and reached earlier in the year at the two inshore sites in comparison to the two deeper sites. The Fort Gorges site tends to fall somewhere in between the range of temperatures and the seasonal progression of the shallow and deeper sites.

The density gradient between surface and bottom waters is a good indicator of the strength of stratification and the isolation of bottom waters from sources of dissolved oxygen. A density gradient of 1 kg/m^3 has been used as a gross indicator of moderate stratification (Libby et al., 1999). A review of density gradients at these five sites indicates that the inshore sites (Little Flying Point and Little Iron Island) were rarely even moderately stratified (density gradient usually < 1). The deeper Halfway Rock and Bear Island sites, however, were strongly stratified each summer (Figure 39). At Fort Gorges, the density gradient was similar to the other two deep-water sites, but the signal was more erratic with some very high gradients resulting from freshwater plumes from nearby sources (i.e. Presumpscot River) following storm events (data not shown as it obscured the patterns for the other four sites).

The lowest bottom water DO values for each of the sites was observed during the summer/fall of 1994 (Figure 37). Evidence from other Gulf of Maine coastal waters indicates that this was a regional trend in low DO (Kelly and Turner, 1995). DO concentrations did not, however, approach the 5.5 mg/l benchmark. The trend observed for surface water, increasing DO minima from 1994 to 1997 (see Figure 24), is also suggested by the bottom water at the five sites shown in Figure 37. The low bottom water DO values observed in 1994 and the trends of increasing DO minima concentrations from 1994 to 1997 are likely related to regional Gulf of Maine trends, rather than the consequence of local conditions.

DO % saturation in the bottom waters exhibited a more variable signal, but there are some interesting trends in the data (Figure 40). The State standard for class SB waters is consistently exceeded each year. At Halfway Rock (SA) and Bear Island (SB), % saturation minima were <85% during each of the six years examined and in October of 1998 values at Halfway Rock were <70%. In 1994, the year when low DO concentrations were observed at each of the five sites, the annual % saturation minima for each station was <85%. This was the only year in which % saturation was below 85% at the inshore sites (Little Flying Point and Little Iron Island) and the Portland Harbor site (Fort Gorges), which is the only site examined that is in class SC waters. The interannual trends in % saturation suggest that exceedences of 85% saturation may be naturally occurring events.

4.0 Conclusions and Recommendations

Overall, the FOCB data indicate that water quality is generally good in Casco Bay though there may be cause for concern in some areas. The temperature and salinity data illustrate the dynamic nature of Casco Bay spatially and temporally with changing seasons. DO concentrations, an important indicator and integrator of coastal water quality, naturally follow a seasonal pattern that is directly related to temperature and influenced by biological processes and local freshwater inputs. As a basic necessity for aquatic life, DO levels directly affect ecosystem health. Anthropogenic impacts such as nutrient and organic loading have the potential to intensify problems associated with naturally low summer DO concentrations.

Dissolved oxygen is usually well above State standards and not close to levels that would impair biological processes. Over the entire six-year period evaluated in this report, minimum DO levels of less than the 5.5 mg/l benchmark have been observed at ten of the FOCB sites and levels close to the benchmark (5.5 – 6.0 mg/l) have been measured at an additional five sites (Figure 41). Generally, developed areas with potentially heavy nutrient loading and organic material exhibited the lowest minimum DO concentrations. This includes areas of direct loading from point sources and combined sewer overflows in Portland Harbor (CBEP, 1996b) and sites in the vicinity of freshwater inputs and potential nonpoint source loading (Royal River, Presumpscot River, and Harraseeket River). Estuarine waters with lower salinity (mean salinity for Royal River and Presumpscot River were <25 ppt) generally have higher nutrient concentrations (Kelly, 1997). Low DO concentrations, however, were also observed in less developed areas in Eastern Casco Bay where restricted circulation may exacerbate anthropogenic impacts (New Meadows River and Quahog Bay). Septic systems in Maquoit Bay have been cited as a significant source of nutrients into that bay (Horsley and Witten, 1996) and the prevalence of overboard discharge systems still in use along the shores of Harpswell Sound, Quahog Bay and New Meadows River (CBEP, 1996b) suggests that they are a likely source of nutrients in these bays.

The results of the FOCB data evaluation were similar to those found for Casco Bay water bodies during studies conducted by the Wells National Estuarine Research Reserve (NERR) and Maine Department of Environmental Protection (MEDEP) in 1995 and 1996 (Kelly and Libby, 1996; Kelly, 1997). Most important is the consistent finding from each of these studies that Casco Bay DO levels are generally high and not problematic, though there are areas of concern that may be more susceptible to low DO in the future. The 1996 Wells NERR and MEDEP study measured additional parameters including chlorophyll and various nitrogenous nutrients, which also indicated that conditions in Casco Bay were relatively good in comparison to eutrophic coastal waters. Chlorophyll concentrations in Casco Bay (as well as the rest of the locations along the coast of Maine) were consistently low (means < 2.5 µg/l) and variability in chlorophyll concentrations did not appear to be a major factor in DO variability (Kelly, 1997). A cursory review of data from Quahog Bay, however, does suggest that the low August 1996 DO concentrations in bottom waters were coincident with high concentrations of POC, PON and chlorophyll (Dionne, 1997). This suggests that organic material was readily available in these bottom waters and the heterotrophic degradation of this material was likely a factor in the concomitant low DO concentrations. Dissolved inorganic nitrogen (DIN) concentrations, like chlorophyll, were not indicative of eutrophic conditions, but DIN at the Harraseeket and Cousins River sites was higher than most of the other water bodies examined during the 1996 study. The measurement of additional nutrient parameters during the 1996 Wells NERR/MEDEP study indicated that there were correlations in the trends of DO and nutrient concentrations. Two reasons for this correlation were cited. Overall, nutrient concentrations increased with decreasing DO and this was attributed to nutrient loading from freshwater sources, but on a site-specific basis there appeared to be a covariance between decreasing DO and increasing nitrogen end products of in situ metabolism of organic material (primarily NH4 and DON; Kelly, 1997). These trends need to be evaluated in more detail and over a longer time period. To this end, the addition of chlorophyll and nutrient measurements to the FOCB CWQM program would be of great benefit for understanding existing conditions and provide a basis with which to better assess future effects due to local changes (i.e. development, zoning, and point and nonpoint source discharge regulations)

The evaluation of the six-year data set identified specific areas of concern, but it also highlighted the relative consistency of seasonal and annual cycles across the bay and called attention to the fact that Casco Bay is part of a larger system and often exhibits a broader regional signal. This was especially evident in the examination of bottom water DO concentrations over the six-year period (see Figure 37). The trends observed for the Casco Bay data – lowest bottom water DO concentrations in 1994, increasing bottom water concentrations from 1994-1997, and lower concentrations again in 1998 – are exactly the same as trends observed in Massachusetts Bay over this same time period (Libby et al., 1999). The bottom water DO concentrations in Massachusetts Bay in 1994 were the lowest observed over an eight-year period from 1992 to present. The recognition that Casco Bay is part of broader regional trends is important not only for understanding past trends in the data, but for evaluating future trends as well. By working with other monitoring programs in the Gulf of Maine, deviations from the broad regional trends will be a clear indication of significant local effects. At the same time, it will provide an understanding as to what is driving some of the signals observed. The exceedences of State water quality standards in the bottom waters examined in this report (see Figure 40) are not necessarily due to local problems or inputs, but rather part of a wide-scale event likely due to variations in temperature and circulation.

The other end of the spectrum was also evaluated by assessing short-term and local or site-specific variability. For the New Meadows Marina special study in 1997, we examined the effect of time of day and tide stage on sampling. For the New Meadows Marina site (NMM79), it was determined that time of day was not as important as tide stage in relation to changes in DO concentration. This was different from the correlation between DO and time of day for the data set as a whole, where DO concentration for the entire estuarine data set was closely related to time of sampling. The DO vs. tide stage relationship was evident and significant for both the New Meadows Marina and the estuarine data set as a whole. The lack of a relationship between time of day and DO concentrations at New Meadows Marina was apparently due to the effect of numerous fish on the incoming tides and increasing biological utilization of DO at the higher tide stages. For the data set as a whole, it is unclear as to why DO concentrations were lower during the higher tide stages. The expectation of lower DO concentrations at low tide is generally attributed to DO concentrations in the bottom water and may not necessarily be applicable to the surface waters (Kelly and Libby, 1996). Biological factors, such as fish runs and benthic respiration, or physical circulation dynamics may play a role in the prevalence of lower DO concentrations at higher tide stages in Casco Bay, but at this time and with the data available, it is difficult to ascribe the tidal trend to any particular factor or factors. The effect of time of sampling on variations in DO concentrations that was seen for the entire data set, however, could be removed by conducting sampling in the early morning hours. This is inherently difficult to implement for a volunteer monitoring program, but it has been done for other volunteer programs and met with much success (e.g., Buzzards Bay Monitoring Program).

On the whole, the FOCB monitoring program provides data with which to adequately characterize Casco Bay and identify areas of concern with respect to the parameters measured. There are, however, features of the monitoring program that could be expanded and improved upon. It is recognized that there are constraints under which FOCB, as a nonprofit organization, must operate. The recommendations listed below are made with the thought that they may help FOCB to prioritize modifications and improvements to their already successful volunteer monitoring program. The recommendations focus on changes in sampling frequency, time of sampling, and parameters measured for what we will call Primary stations. It is also recommended that FOCB seek out partnerships with other organizations both within and outside of the State with which to share data and perhaps receive additional support.

No specific recommendations have been made on reducing or increasing the spatial scale of sites within Casco Bay nor are any included that suggest the frequency of sampling should change for the majority of the sites. The nature of a citizens monitoring program leads to potential for attrition in volunteer numbers and fluctuations in available funding. If there is a need to scale back the spatial and temporal scope of the FOCB CWQM program, the data summaries and evaluations provided in this report should serve as a basis for determining which sites or sampling times may be dropped. In areas where site density is relatively high and data indicate that water quality is uniform and comparatively good, such as Foresides, Portland Coast, Mid Bay, or Harpswell Sound for example, the loss of a site should not impact the integrity of the dataset. The data indicate that the most important time period of the year to sample is the summer months from July to September, so scaling back sampling in the winter or from April to June (at some or many sites) will not affect the ability of the program to capture low DO events. If, however, additional parameters are measured – chlorophyll and nutrients – spring sampling should be conducted to lay the groundwork for understanding the low summer DO events.

We recommend the adoption of a "Primary Station" approach that keys in on the areas of concern discussed in this evaluation. This entails the following:

- Collect samples early in the morning – 6 to 9 AM
- Increase sampling during months of concern – June to September
- Add nutrient and biomass measurements to quantify loading and ambient conditions – suite of nitrogen parameters and chlorophyll concentration

Other general recommendations include:

- Develop a strategy for characterizing low DO events
- Development of better estimates of flushing times for Eastern Casco Bay water bodies
- Continuation of special studies that provide information at a site or water body specific level such as:
  - → Quantification and characterization of nutrient loading
  - → Additional spatial coverage in Portland Harbor – specifically near Custom House Wharf
  - → Quantify water quality impacts of New Meadows Lake on New Meadows River system
  - → Evaluation of high tide vs. low tide sampling during intensive annual hypoxia study or a series of synoptic sampling events (early morning in August)
- Increased communication with other Gulf of Maine monitoring programs and research initiatives

As a starting point for discussion, we recommend that the list of core sites include four of the profile sites (Little Bustins Island, Clapboard Island, Halfway Rock, and Little Iron Island), year-round shore-based sites (International Ferry Terminal and Mill Cove), sites of concern (Custom House Wharf, Presumpscot River, and New Meadows Marina), and sites in areas of concern including, but not limited to, Whartons Point and Perry's Landing (Figure 42). Additional sites would be advantageous, but this set of eleven Primary sites should be sufficient to assess DO minimum conditions, relative effects of nutrient loading, and differences across the bay.

For a volunteer monitoring program, it would be difficult for FOCB to implement early morning sample collection across all of the sites due to other commitments and demands on the time of volunteers. Although this would be the best-case scenario, we recommend implementation of early morning sampling at the Primary sites. This would maximize the likelihood that measurements are made during the daily DO minimum and provide a basis for comparison across sites without time of day being a confounding factor. It is also recommended that sampling at the Primary sites be conducted at a higher frequency during the summer months. Biweekly or weekly measurements would help ensure that low DO conditions would be detected. A predetermined strategy for assessing low DO events should also be developed so that when DO data and ancillary information collected at the regular sampling intervals suggest that problematic situations exist, sampling efforts are intensified. The sampling effort would be similar to that undertaken by FOCB in New Meadows River during the summer of 1997, but a trigger for implementation and a sampling plan would be predefined to ensure that the event is adequately characterized.

Nutrient loading and flushing rates have been discussed in this report as important factors influencing lower DO conditions in Casco Bay. The concentrations and rates used, however, are based on limited sampling, qualitative estimates, or best scientific judgement. Measurements of ambient nutrient and biomass concentrations, quantitative estimates of nutrient loading, and measurement-based calculations of flushing rates are needed to extend and solidify the interpretation. Measurement of ambient nutrient and chlorophyll concentrations could be added to the existing program at the Primary sites. This would provide a wealth of information for not only assessing the cause of low DO conditions (a secondary indicator of eutrophication), but for providing additional information of primary indicators of eutrophication (nutrients and phytoplankton biomass). As nitrogen is generally the limiting nutrient in Gulf of Maine coastal waters (Kelly, 1997), nutrient measurements should, at a minimum, include the full suite of nitrogen forms – ammonium, nitrate, nitrite, dissolved organic nitrogen, and particulate organic nitrogen. Phytoplankton biomass can be estimated by chlorophyll measurements and direct phytoplankton counts. Phytoplankton analyses provide an additional set of data on the species composition of the phytoplankton community, which could be especially useful in Casco Bay for alerting the public, shell fishermen, and aquaculturists as to the presence of potentially toxic or nuisance phytoplankton species.

FOCB has already undertaken a variety of focused studies including hypoxia studies in 1997 to 2000, high frequency sampling studies such as the New Meadows Marina study discussed in this report, and synoptic sampling to provide a snapshot of conditions across the bay. Nutrient loading and flushing rates for individual water bodies will have to be the focus of special studies, perhaps in conjunction with other organizations in the area. The Gulf of Maine Ocean Observing System (GoMOOS), for instance, is deploying 13 instrument moorings in the Gulf of Maine. Preliminary plans indicate that one of the GoMOOS coastal moorings will be positioned near the Portland shipping channel and another movable mooring has been tentatively assigned for deployment in Maquoit Bay. The instruments that will be deployed on each of these moorings have not been finalized, but potential measurements may include currents, wind, wave height, temperature, salinity, DO, and chlorophyll. In conjunction with the FOCB Citizens Water Quality Monitoring program, the data from these moorings and new studies focused on nutrient loading and flushing rates will provide a growing body of data with which to better characterize and understand the Casco Bay system.

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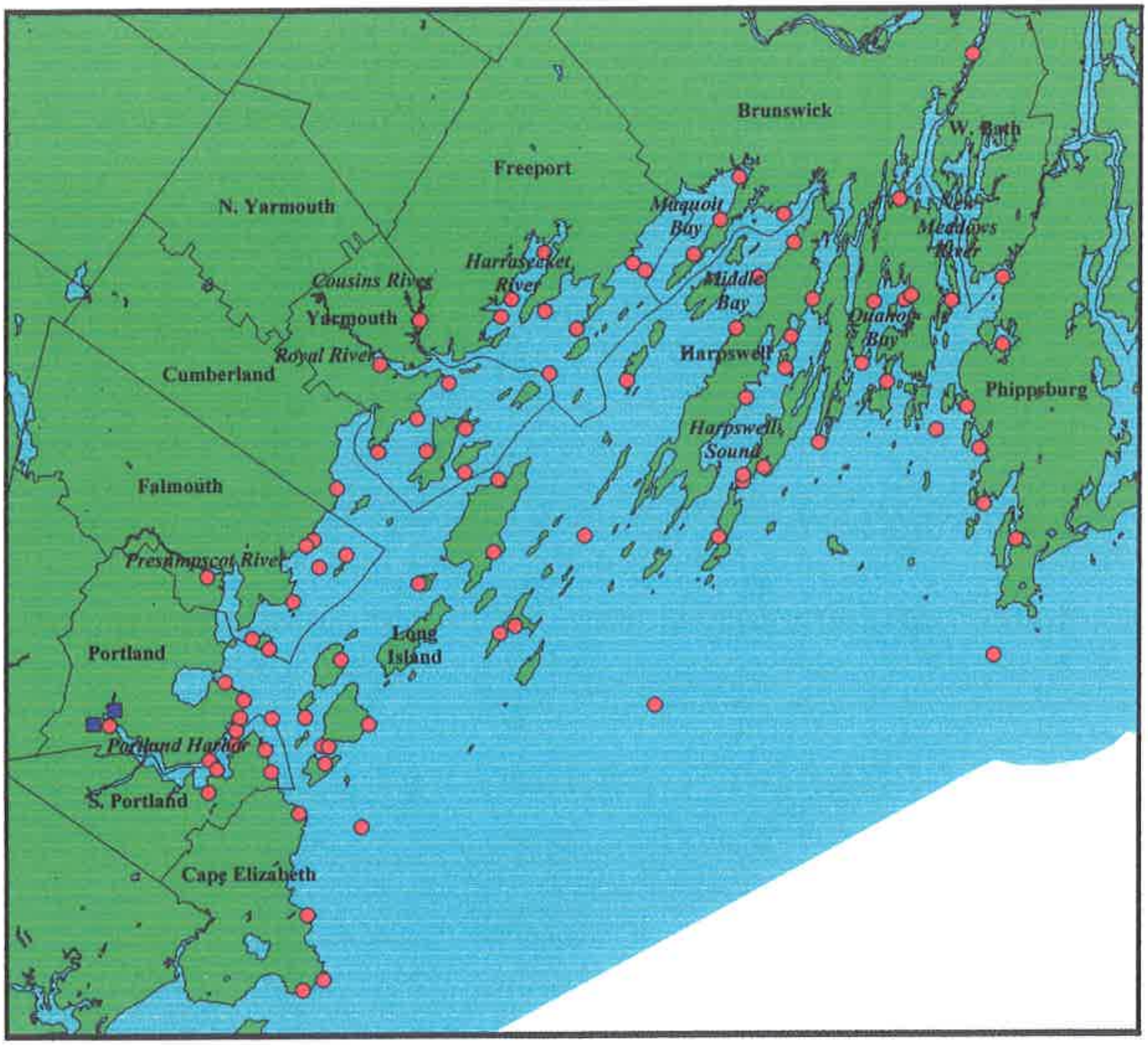


Figure 1. FOCB Water Quality Monitoring Sites 1993-1998 (freshwater sites in blue)

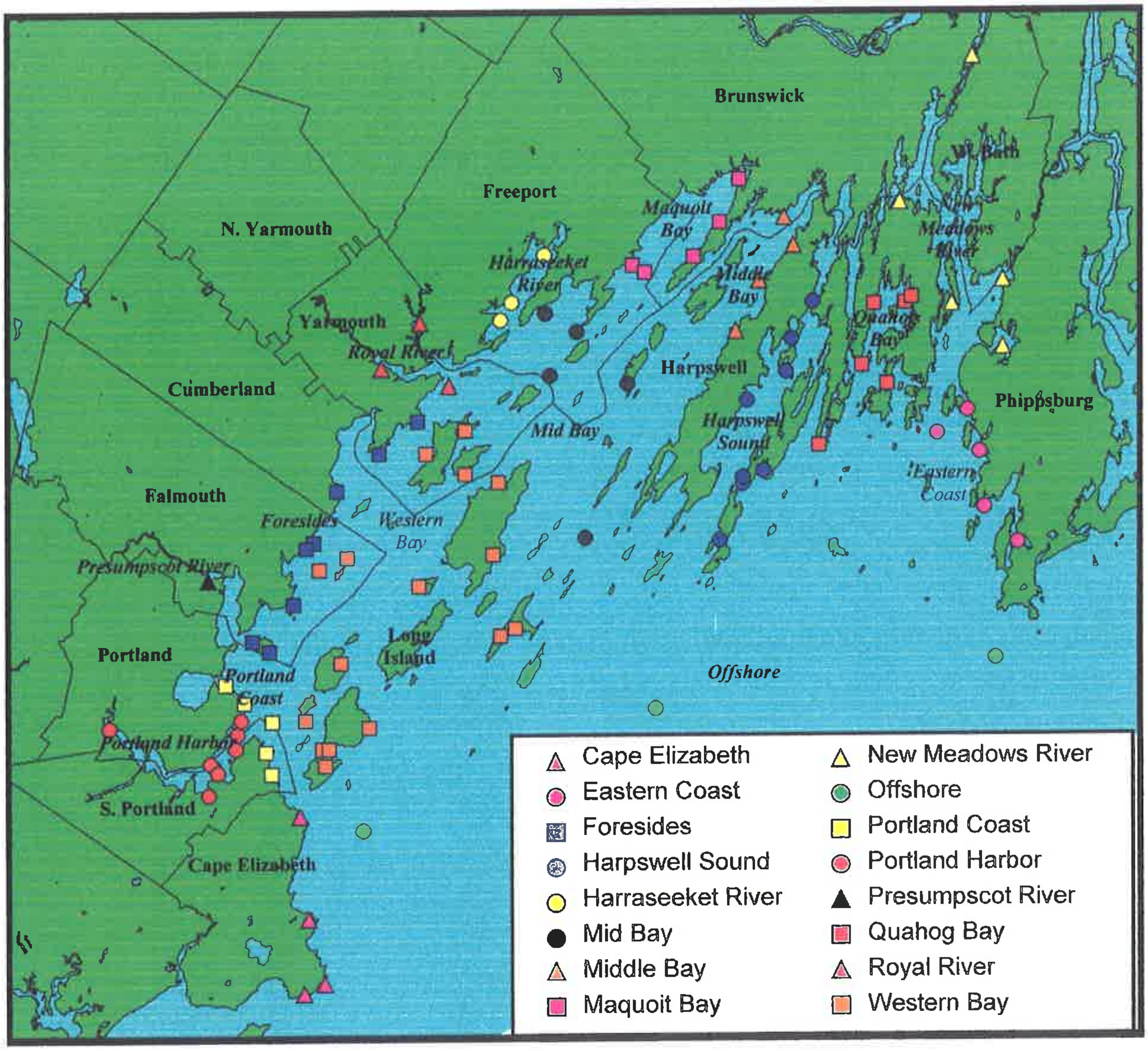


Figure 2. FOCB Water Quality Monitoring Sites Color-Coded by Water Body.

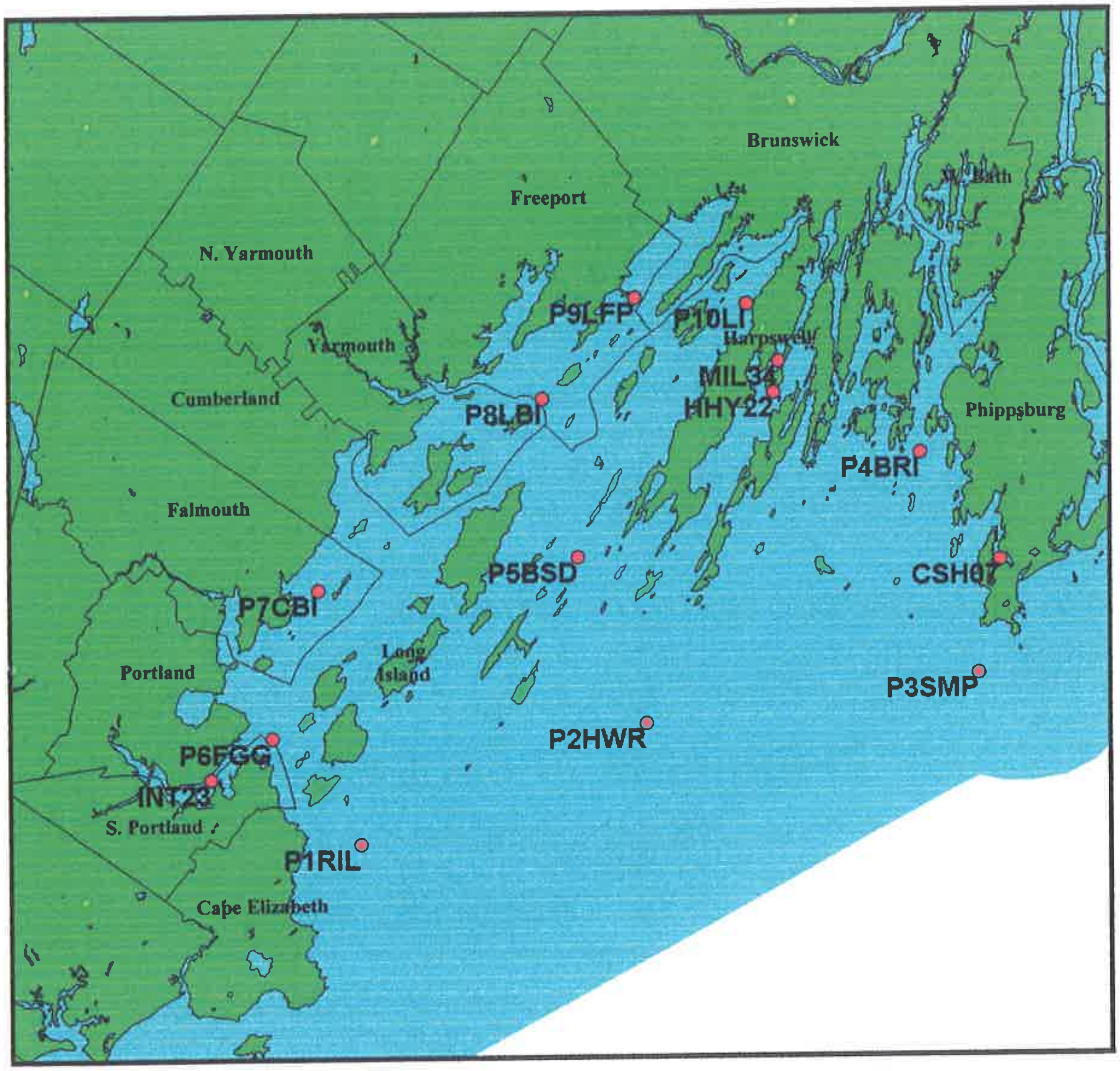


Figure 3. FOCB Water Quality Monitoring Year-round Sites.

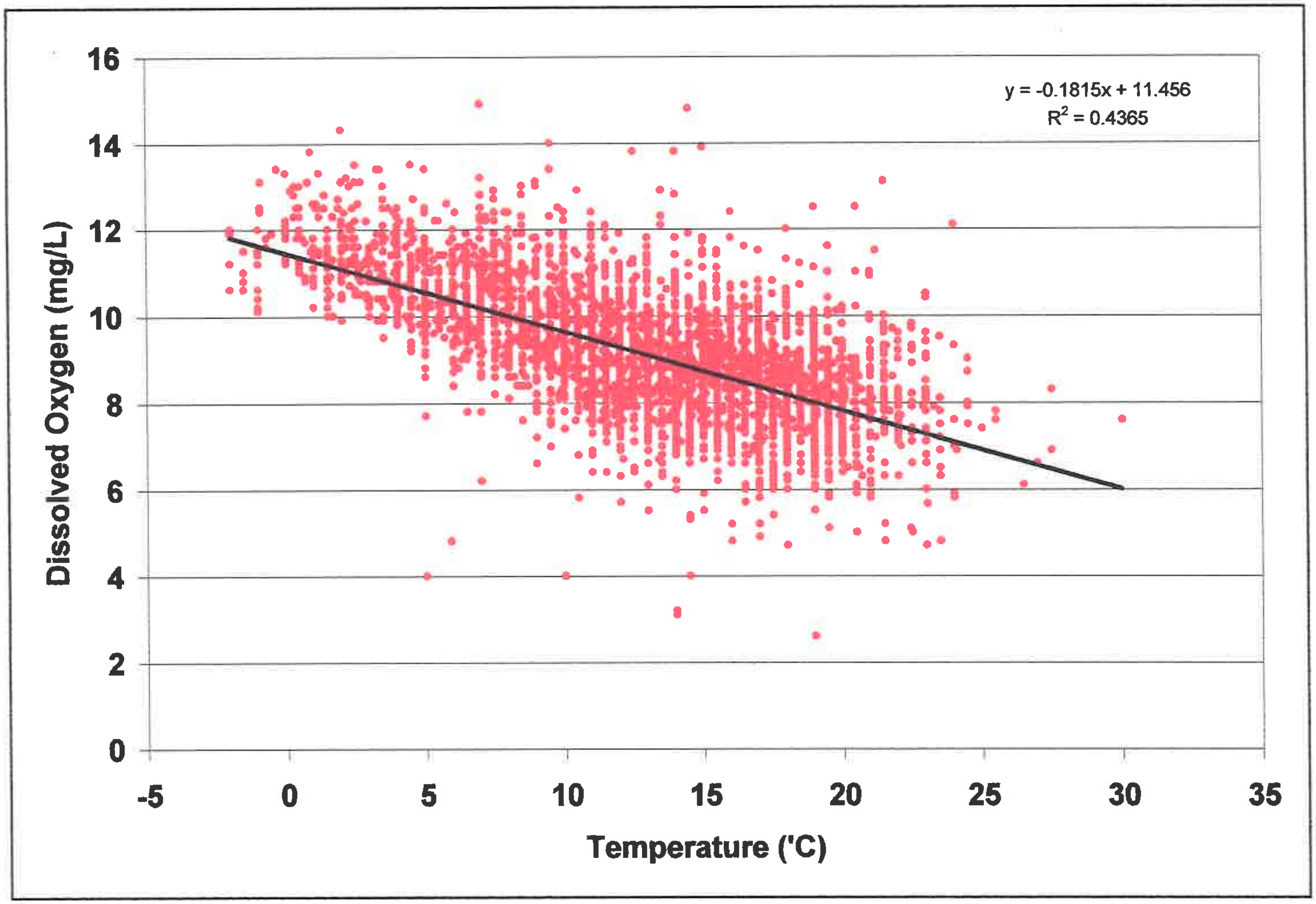


Figure 5. Scatter Plot of Temperature vs. DO for All Estuarine Surface Data.
Trend line and equation represent linear regression of data.

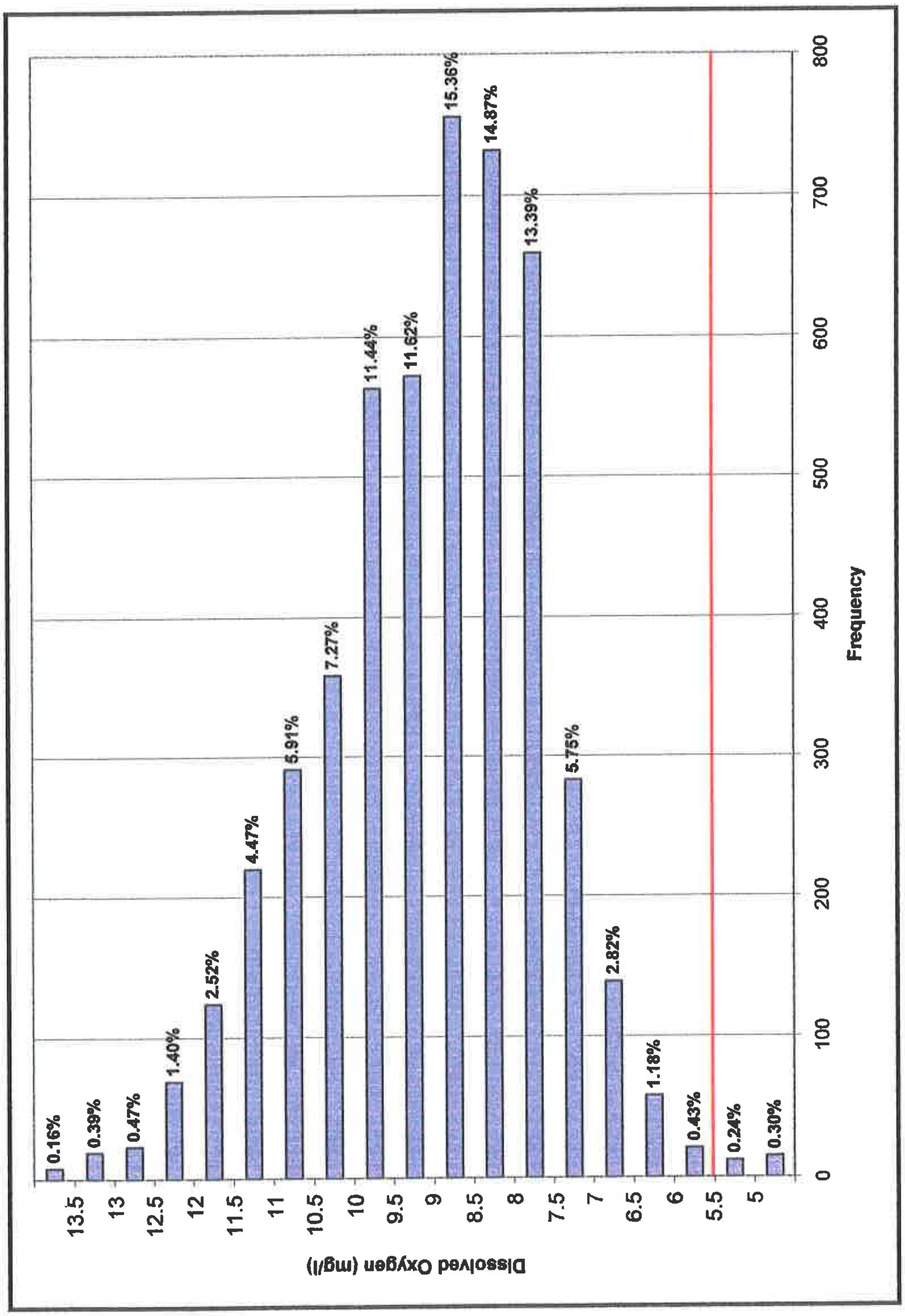


Figure 6. Frequency distribution of all DO data (mg/l) for surface estuarine samples. (Benchmark of ≥5.5 mg/l highlighted)

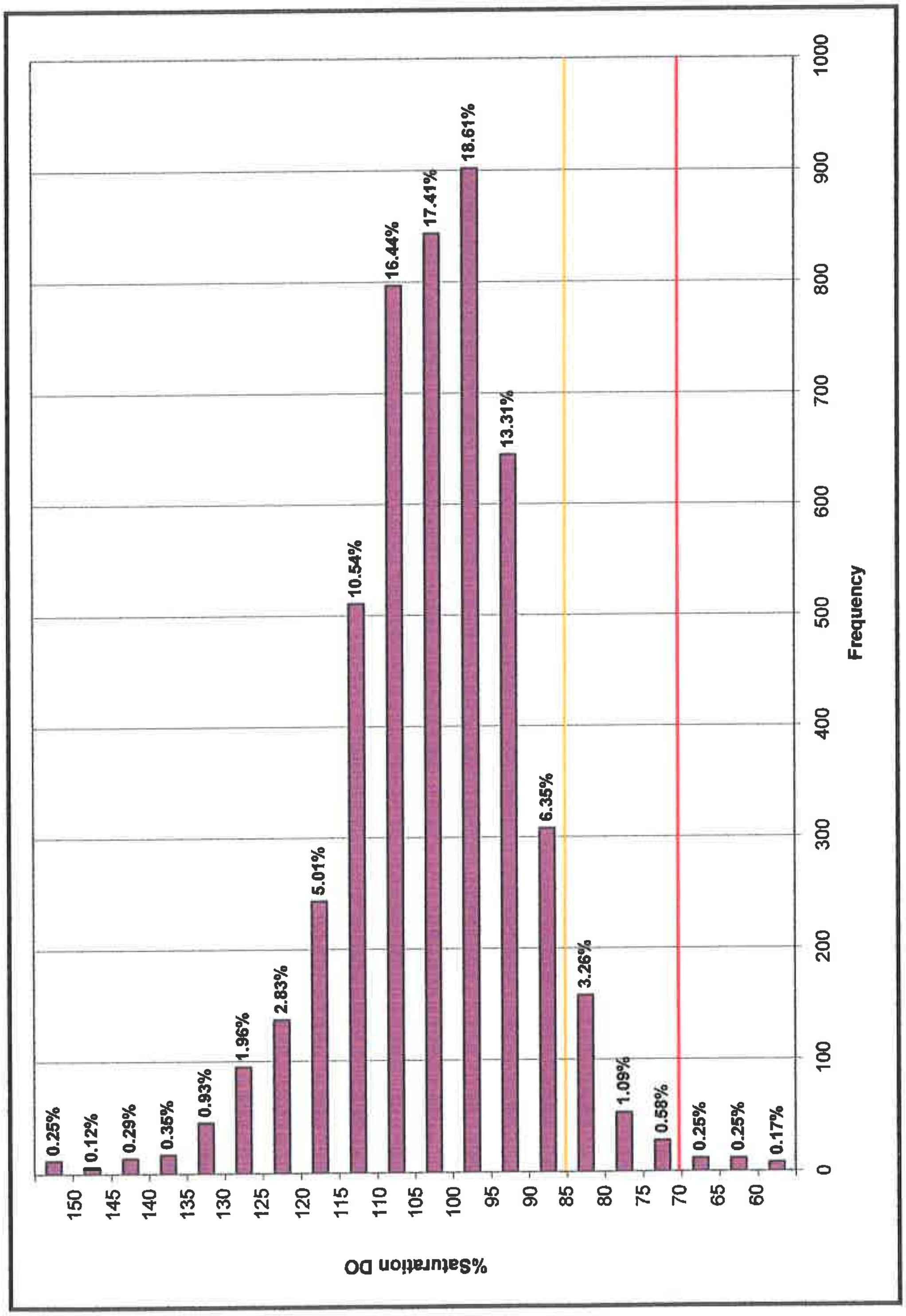


Figure 7. Frequency distribution of all %saturation data for surface estuarine samples. [State standards for class SB (≥85%) and SC (≥70%) noted on graph]

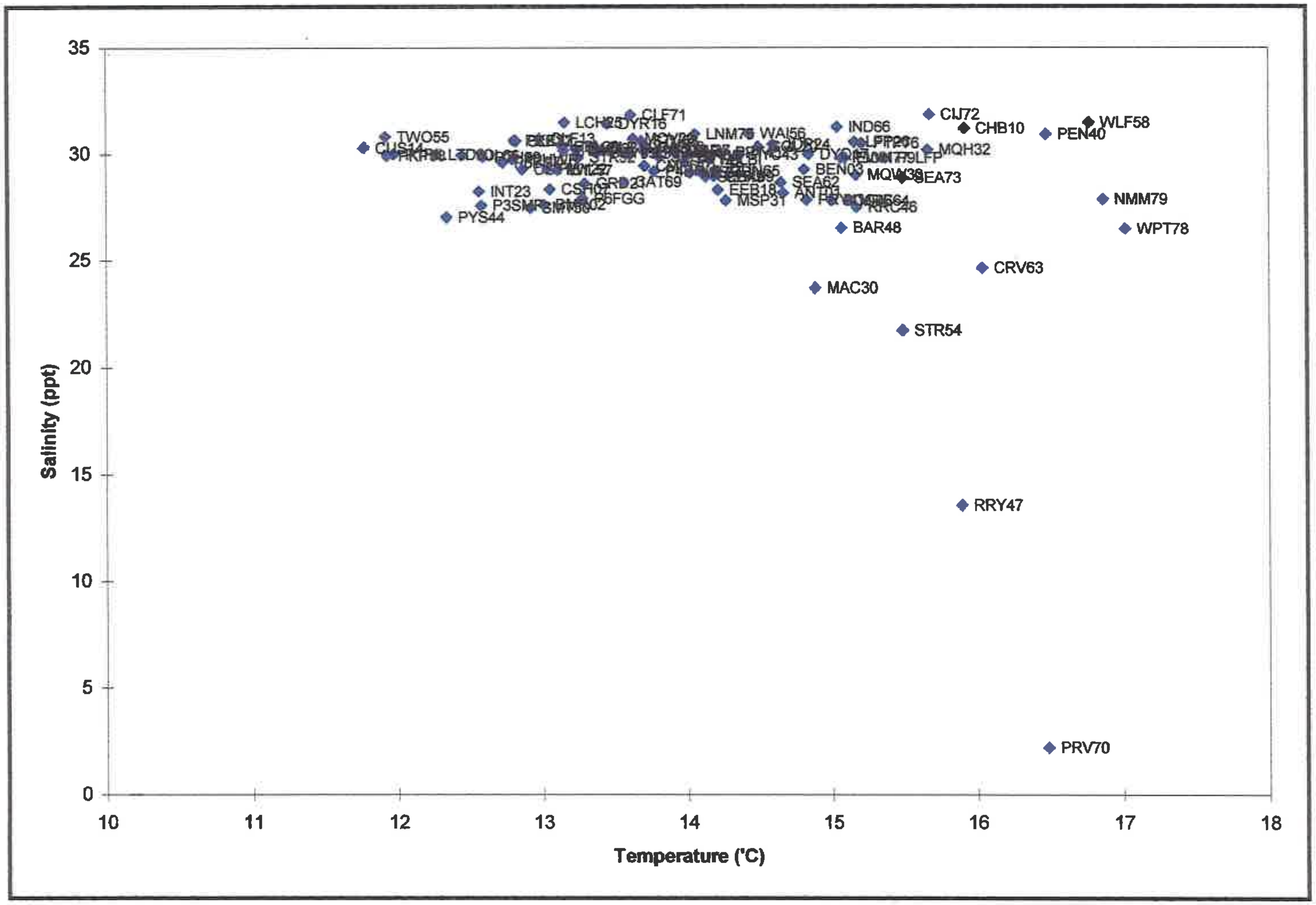


Figure 8. Scatter plot of Site Mean Temperature vs. Salinity for Estuarine Data Collected April-October.

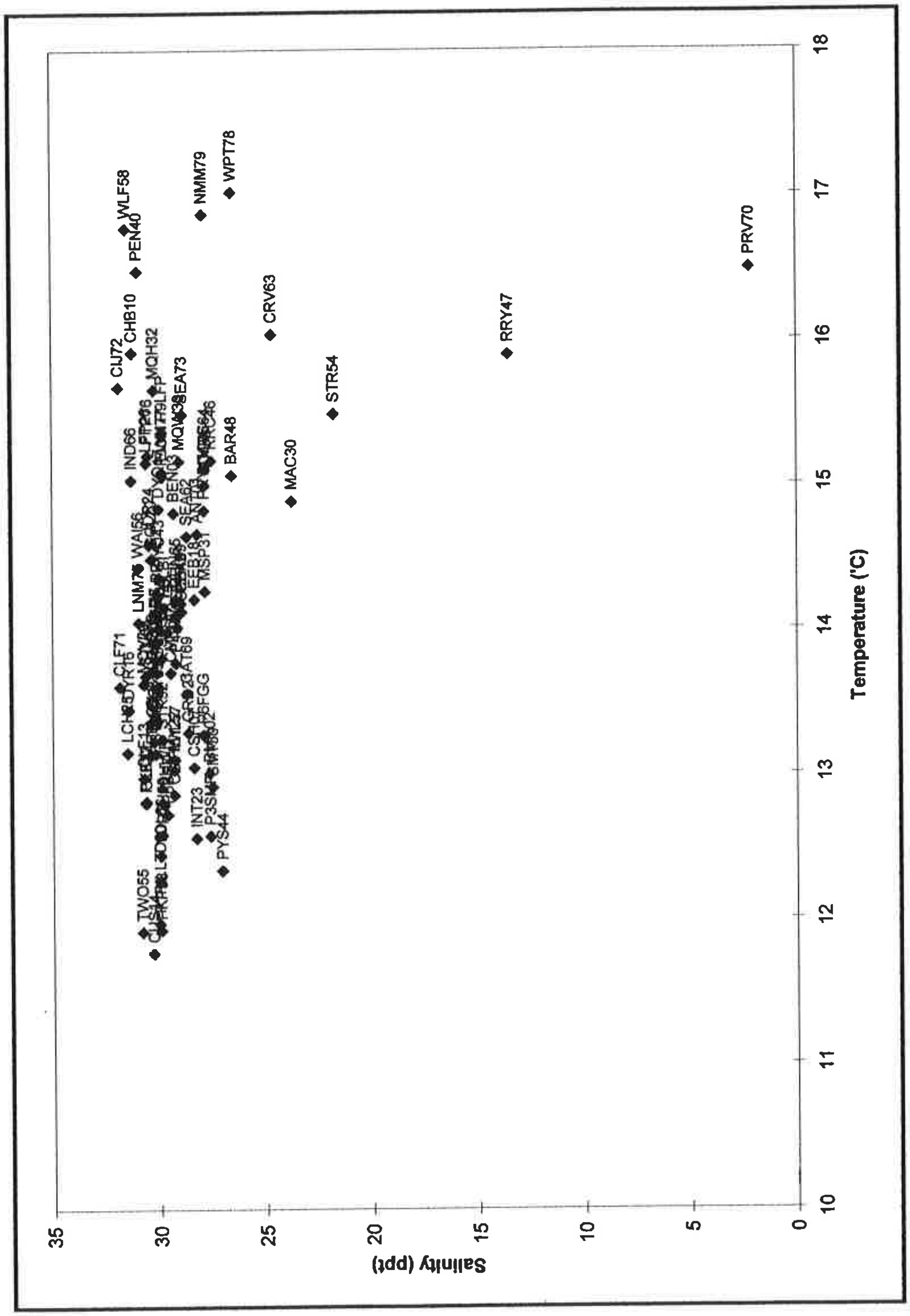


Figure 8. Scatter plot of Site Mean Temperature vs. Salinity for Estuarine Data Collected April-October.

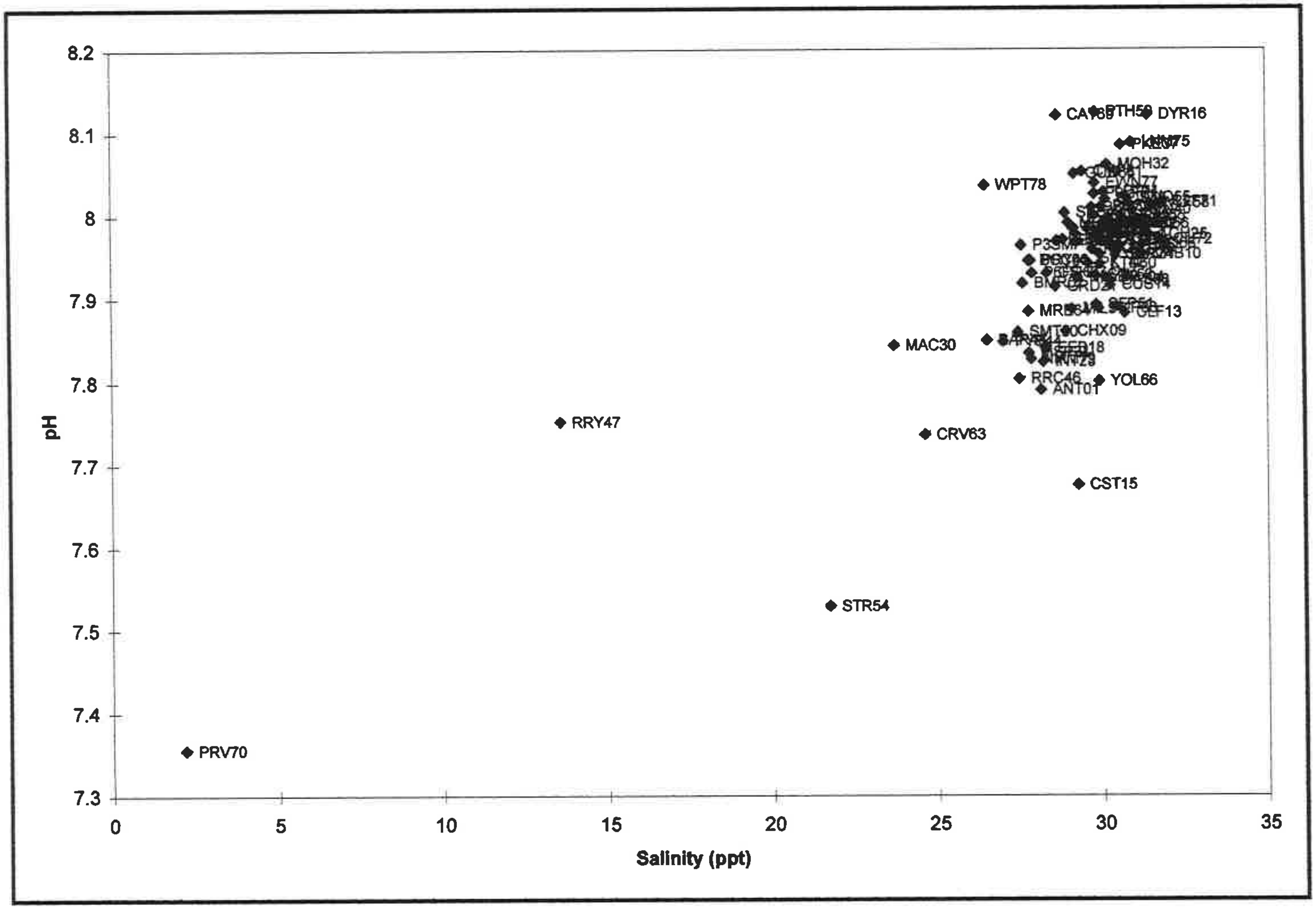


Figure 9. Scatter plot of Site Mean Salinity vs. pH for Estuarine Data Collected April-October.

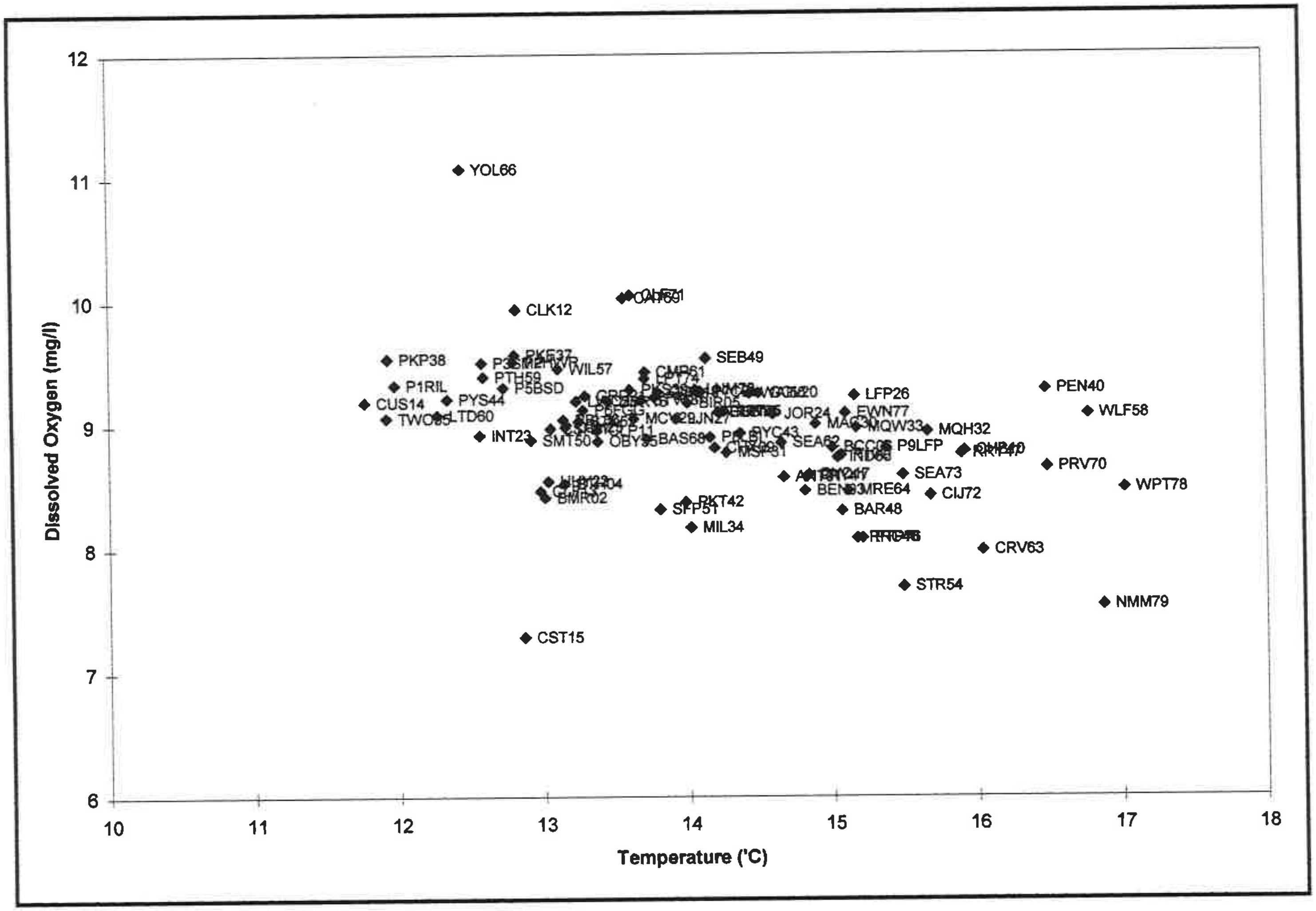


Figure 10. Scatter plot of Site Mean Temperature vs. Dissolved Oxygen for Estuarine Data Collected April-October.

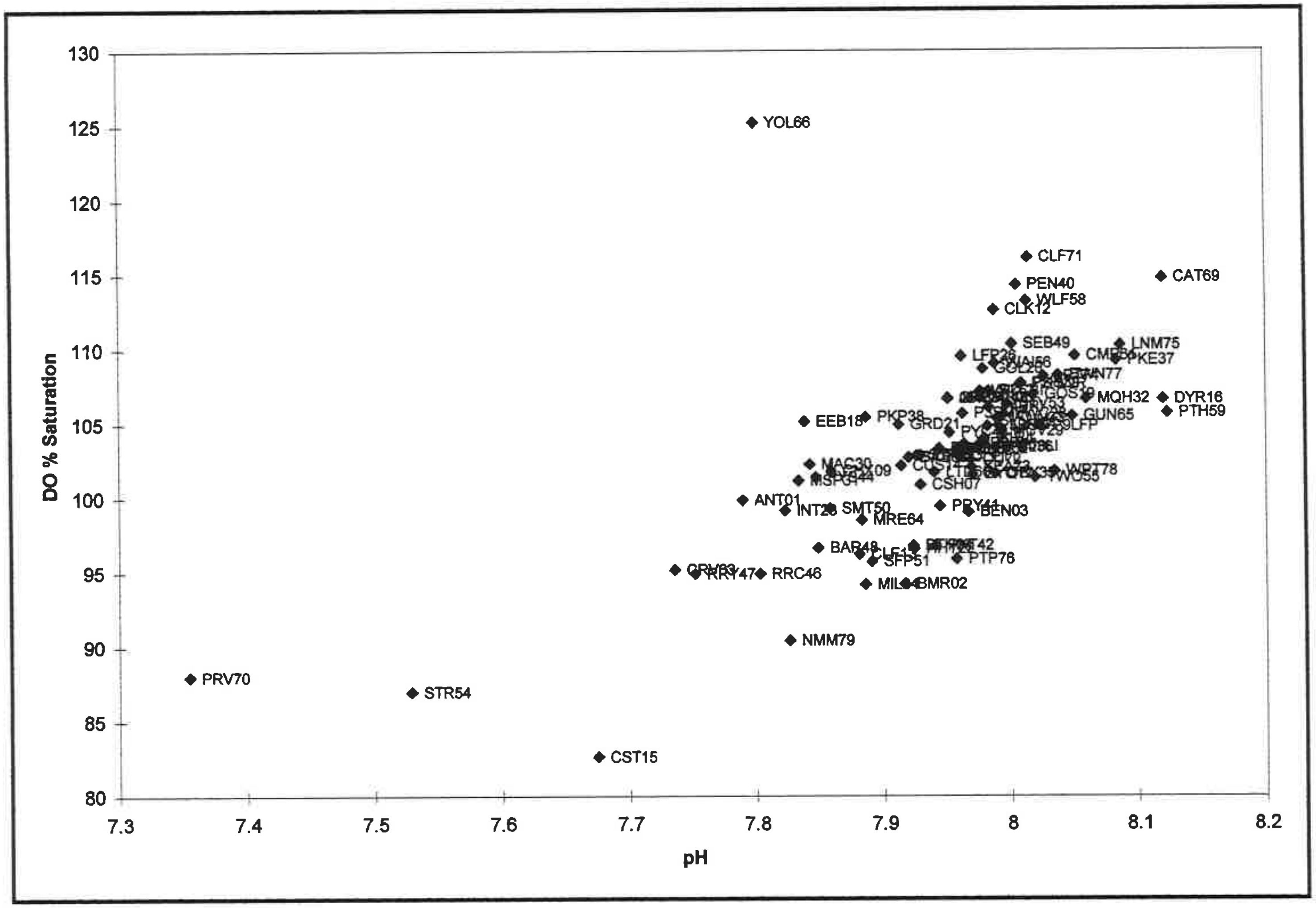


Figure 11. Scatter plot of Site Mean pH vs. DO % Saturation for Estuarine Data Collected April-October.

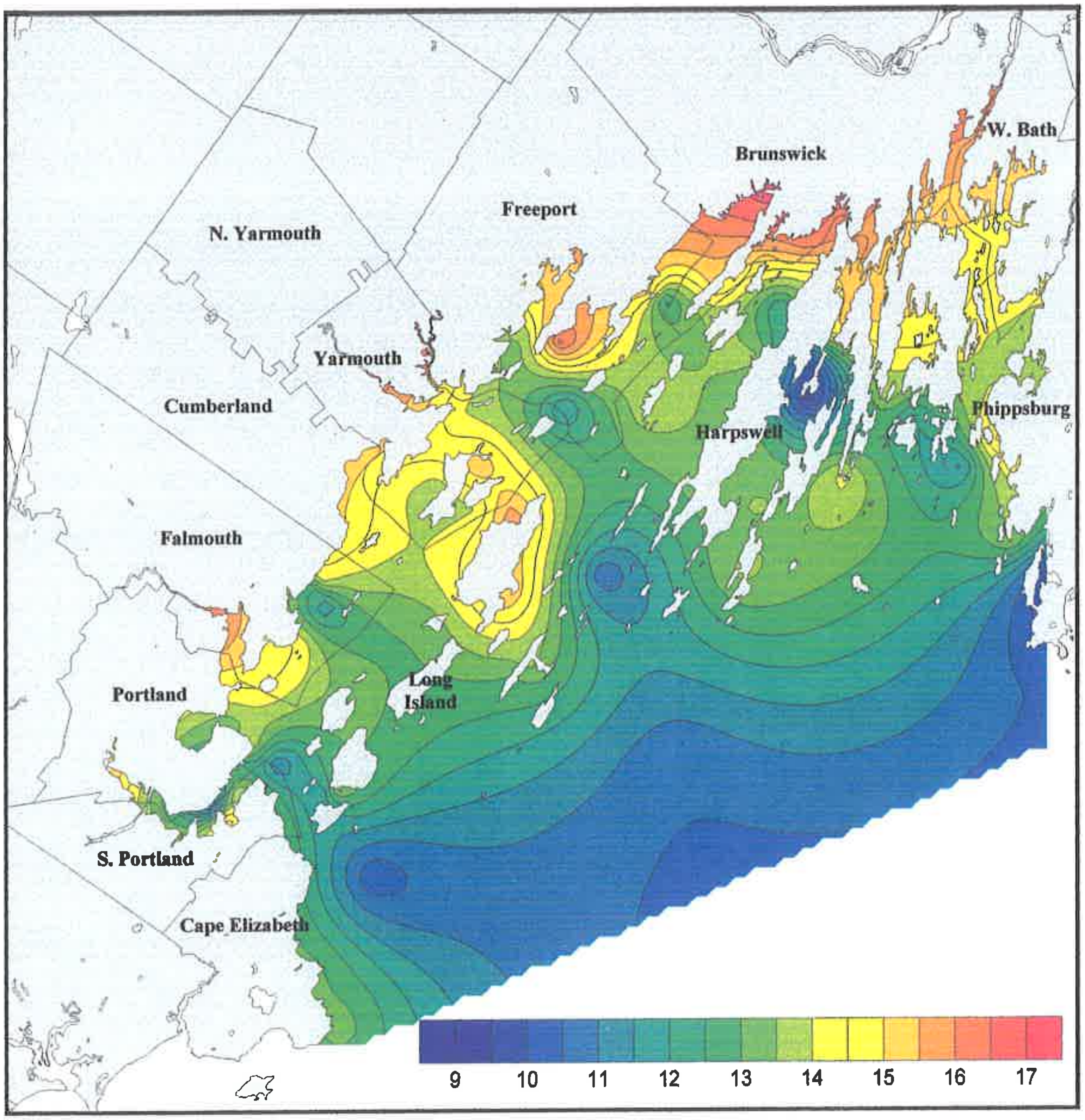


Figure 12. Geographic distribution of mean surface temperature (°C) for 1993-1998 April to October data.

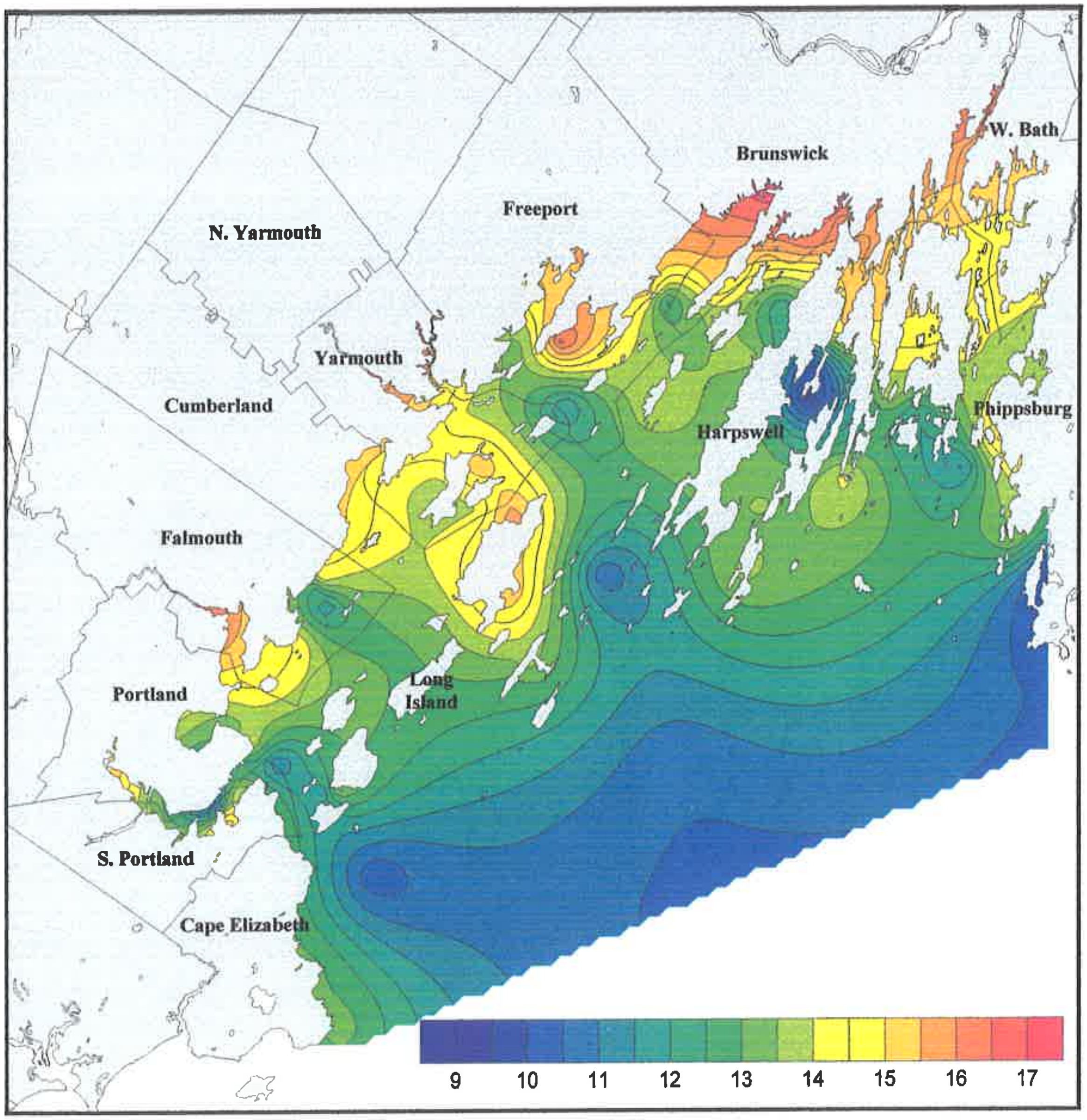


Figure 12. Geographic distribution of mean surface temperature (°C) for 1993-1998 April to October data.

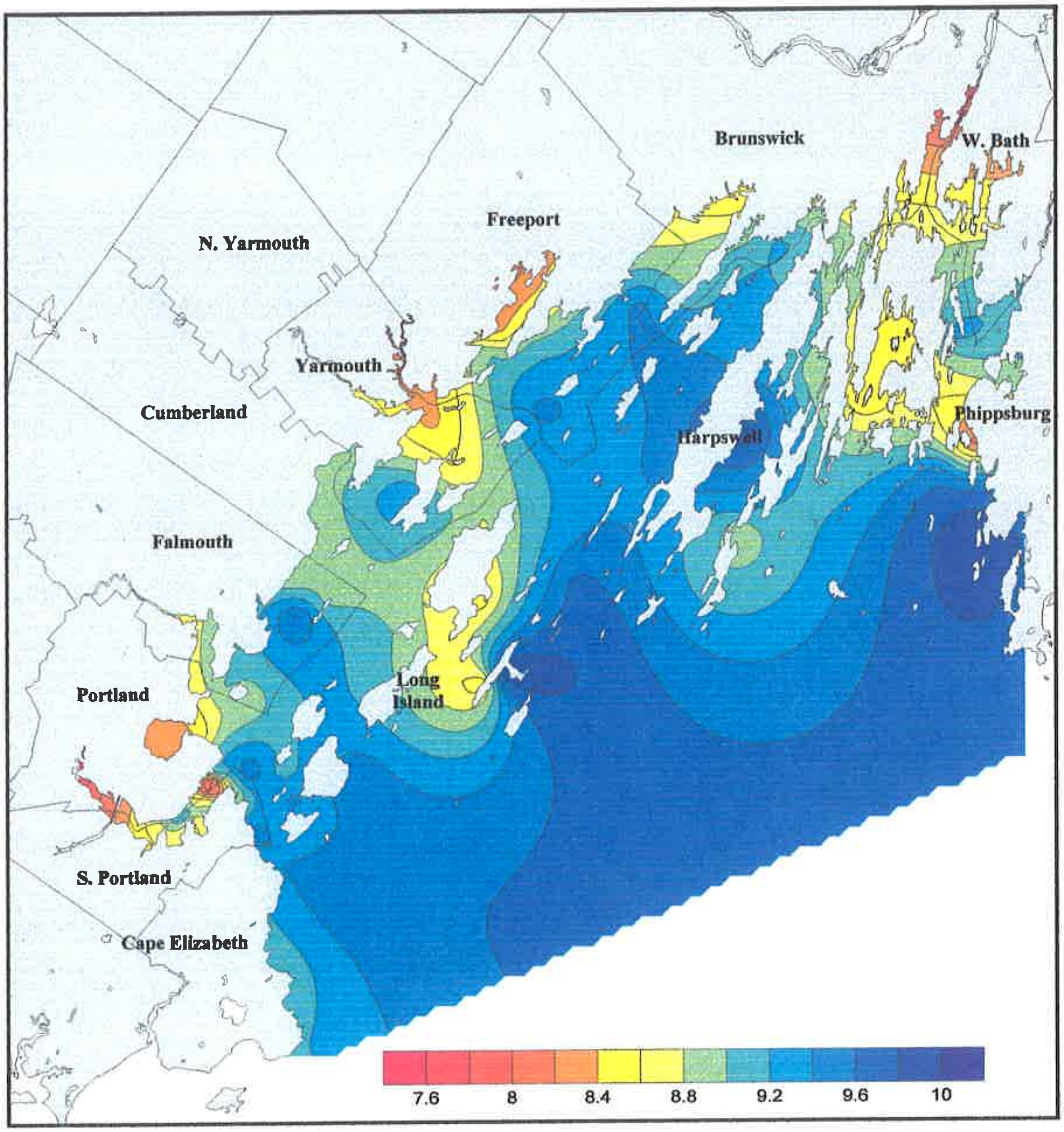


Figure 14. Geographic distribution of mean DO concentration (mg/l) for 1993-1998 April to October data.

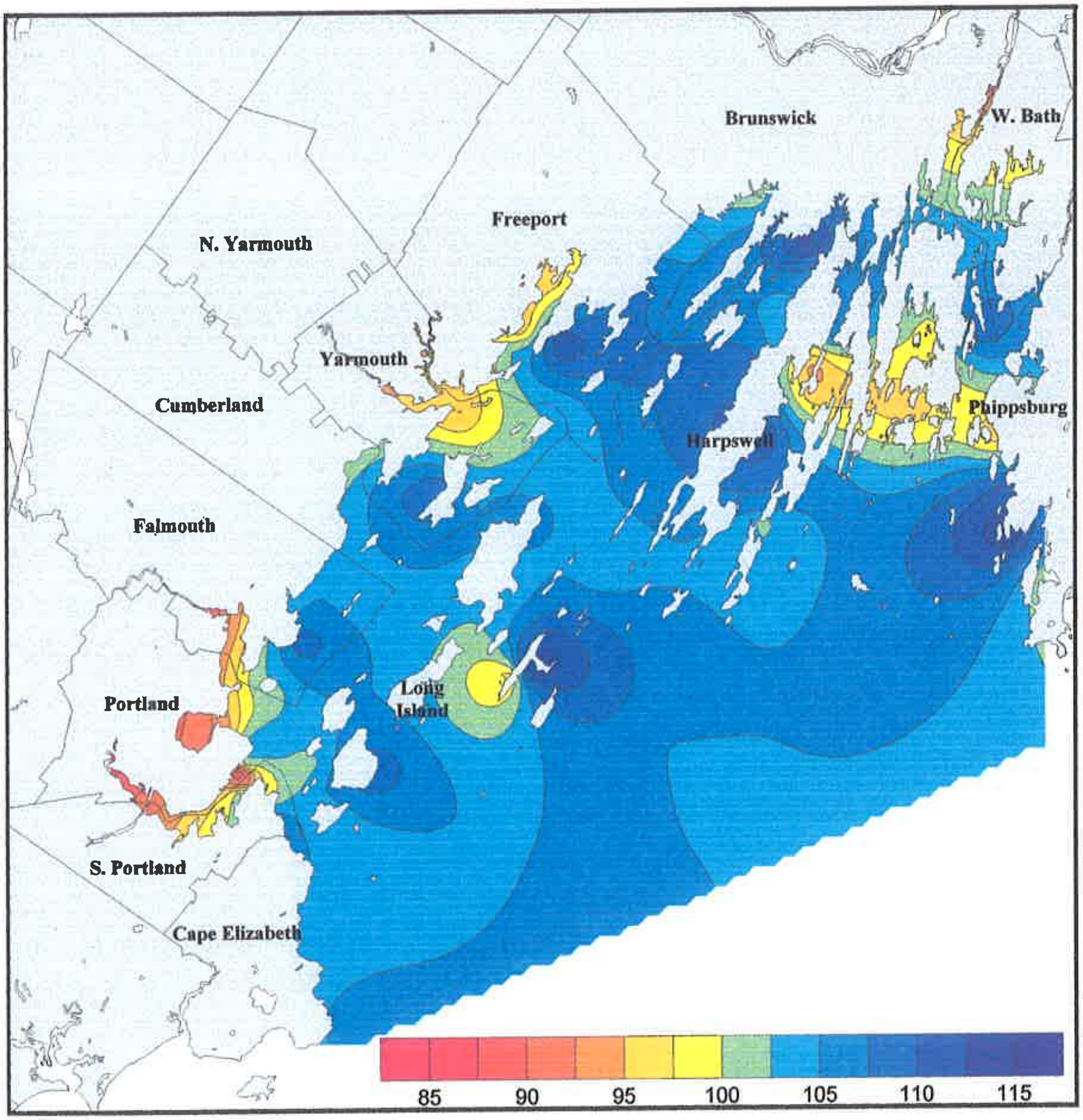


Figure 15. Geographic distribution of mean DO % saturation for 1993-1998 April to October data.

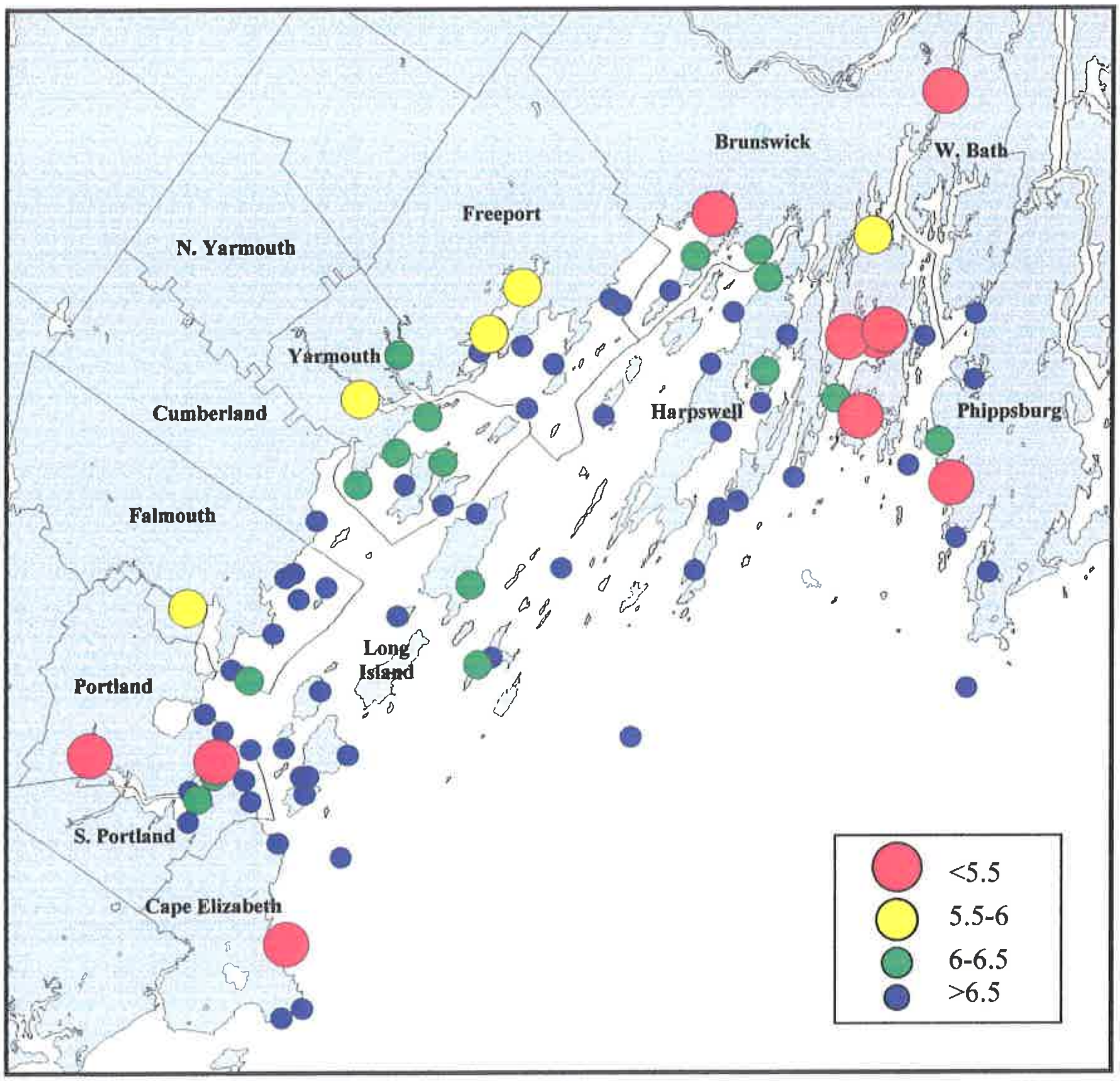


Figure 16. Minimum DO concentration (mg/l) observed at sites over entire 93-98 period.

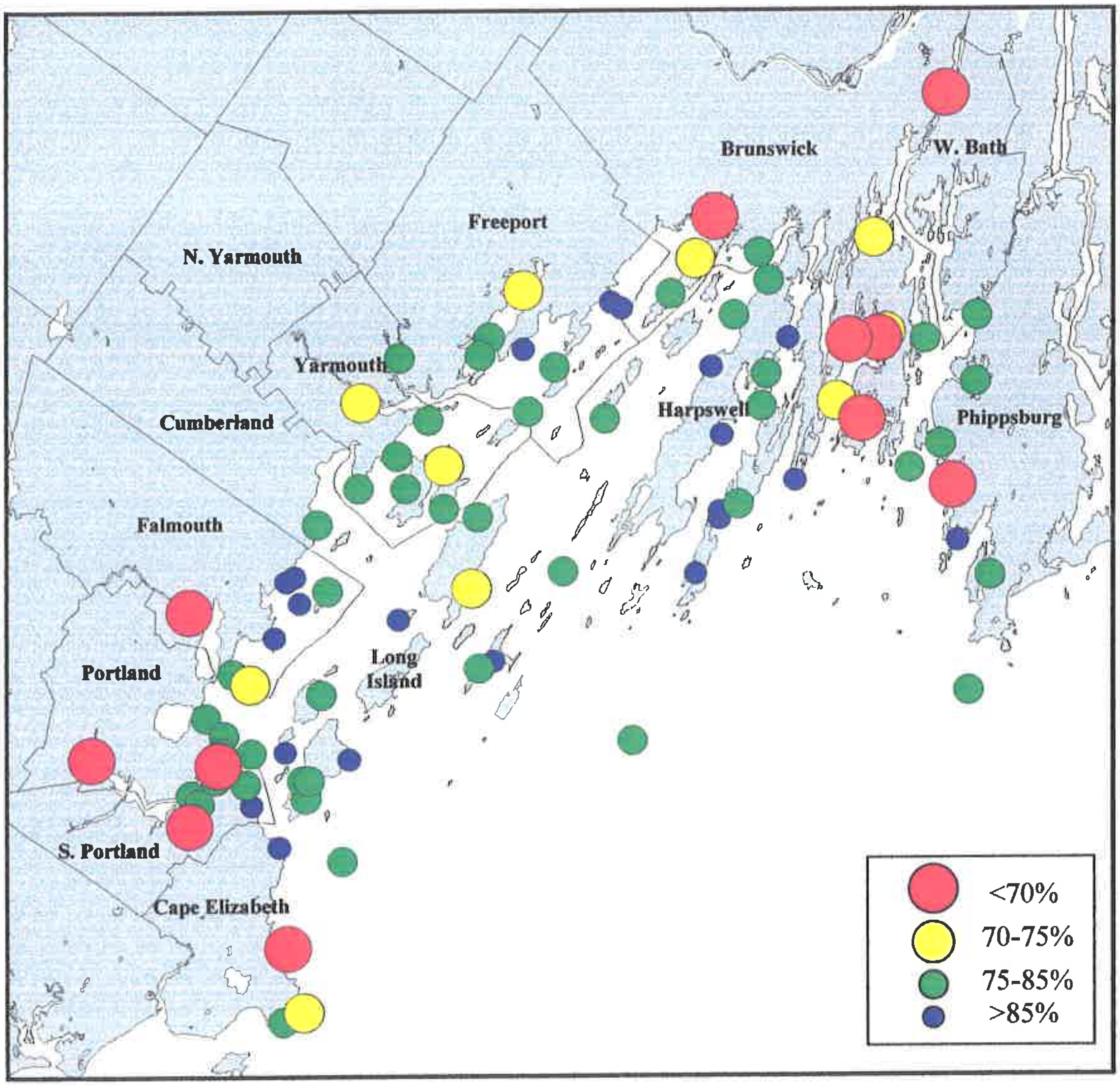


Figure 17. Minimum DO %saturation observed at sites over entire 93-98 period.

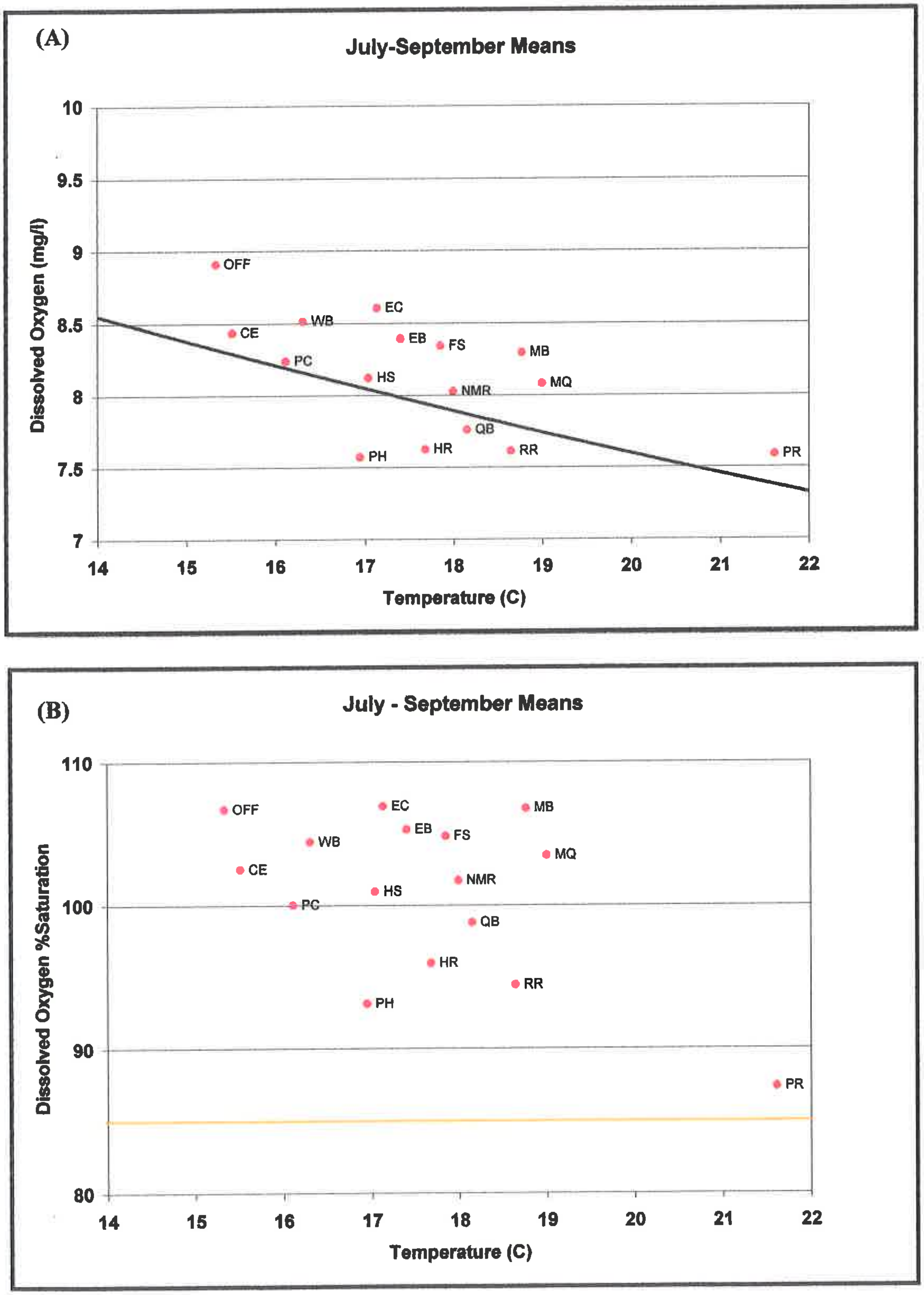
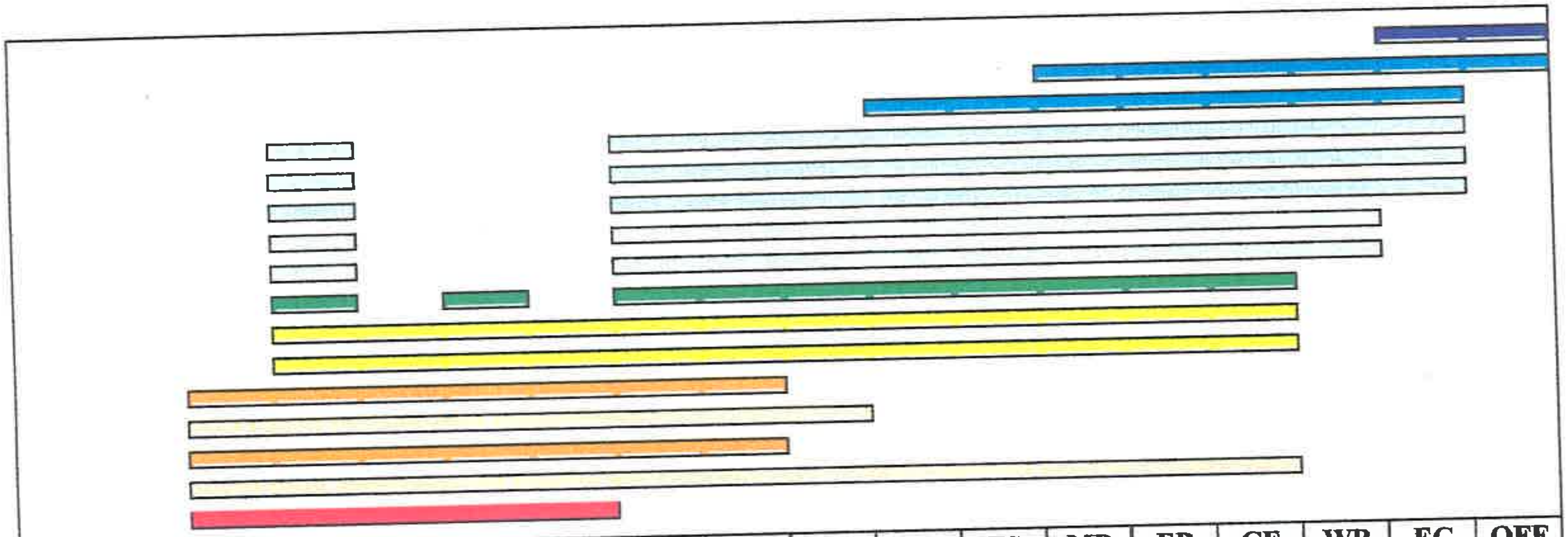
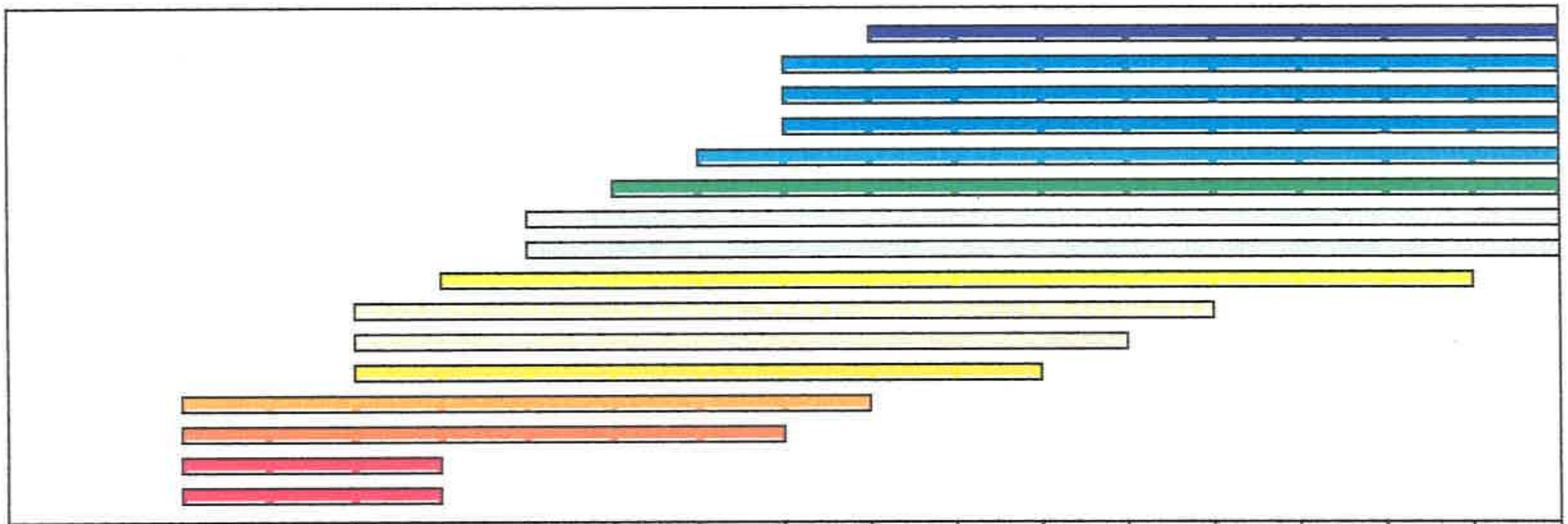


Figure 18. Scatter plots of water body means for estuarine July-September data. The line in 18A represents the relationship between DO concentration and temperature at 100% saturation for salinity = 30ppt (Weiss, 1970).



Water Body	PH	PR	HR	RR	QB	NMR	MQ	HS	PC	FS	MB	EB	CE	WB	EC	OFF
Mean	7.57	7.59	7.62	7.66	7.76	8.03	8.06	8.10	8.24	8.29	8.30	8.39	8.44	8.51	8.68	8.91
Standard Deviation	1.06	0.86	0.89	0.56	0.70	1.03	1.12	0.81	0.66	0.58	0.90	0.65	1.29	0.82	1.28	0.51
Minimum	4.9	5.8	5.8	6.2	4.8	4.8	4.7	6.1	6.7	6.1	6.1	7	2.6	6.2	4.8	7.6
Maximum	10.7	8.7	11.4	9.2	9.3	10.3	12.1	10.8	10.8	10.9	10.6	10.4	12.5	12.4	12.5	10.1
Count	174	14	65	58	177	90	83	177	135	172	97	139	94	327	99	91

Figure 19. Summary statistics for DO concentration by water body and results of comparison test for data collected July-September (includes all sites sampled 3 or more years). Each line represents the planned comparison of one water body with the other 15 and connects systems that are not significantly different from one another.



Water Body	PR	PH	RR	HR	QB	PC	HS	NMR	CE	MQ	FS	WB	EB	OFF	MB	EC
Mean	87.35	93.14	94.82	95.96	98.78	100.02	100.66	101.73	102.51	103.41	104.24	104.40	105.28	106.70	106.74	107.93
Standard Deviation	9.02	13.44	6.01	11.32	9.81	8.49	10.76	12.95	16.88	15.26	10.89	11.30	8.74	7.71	12.66	15.45
Minimum	70.5	60.7	77.5	74.4	59.2	81.8	77.5	67.2	33.9	65.2	79.5	73.1	84.1	88.8	82.6	65.3
Maximum	98.4	130.3	105.2	138.3	128.8	127	136	135.5	161.8	172.1	142.3	152.7	132.2	122.7	147.6	166.7
Count	14	174	56	64	174	134	175	86	90	82	173	315	136	91	95	98

Figure 20. Summary statistics for DO %saturation by water body and results of comparison test for data collected July-September (includes all sites sampled 3 or more years). Each line represents the planned comparison of one water body with the other 15 and connects systems that are not significantly different from one another.

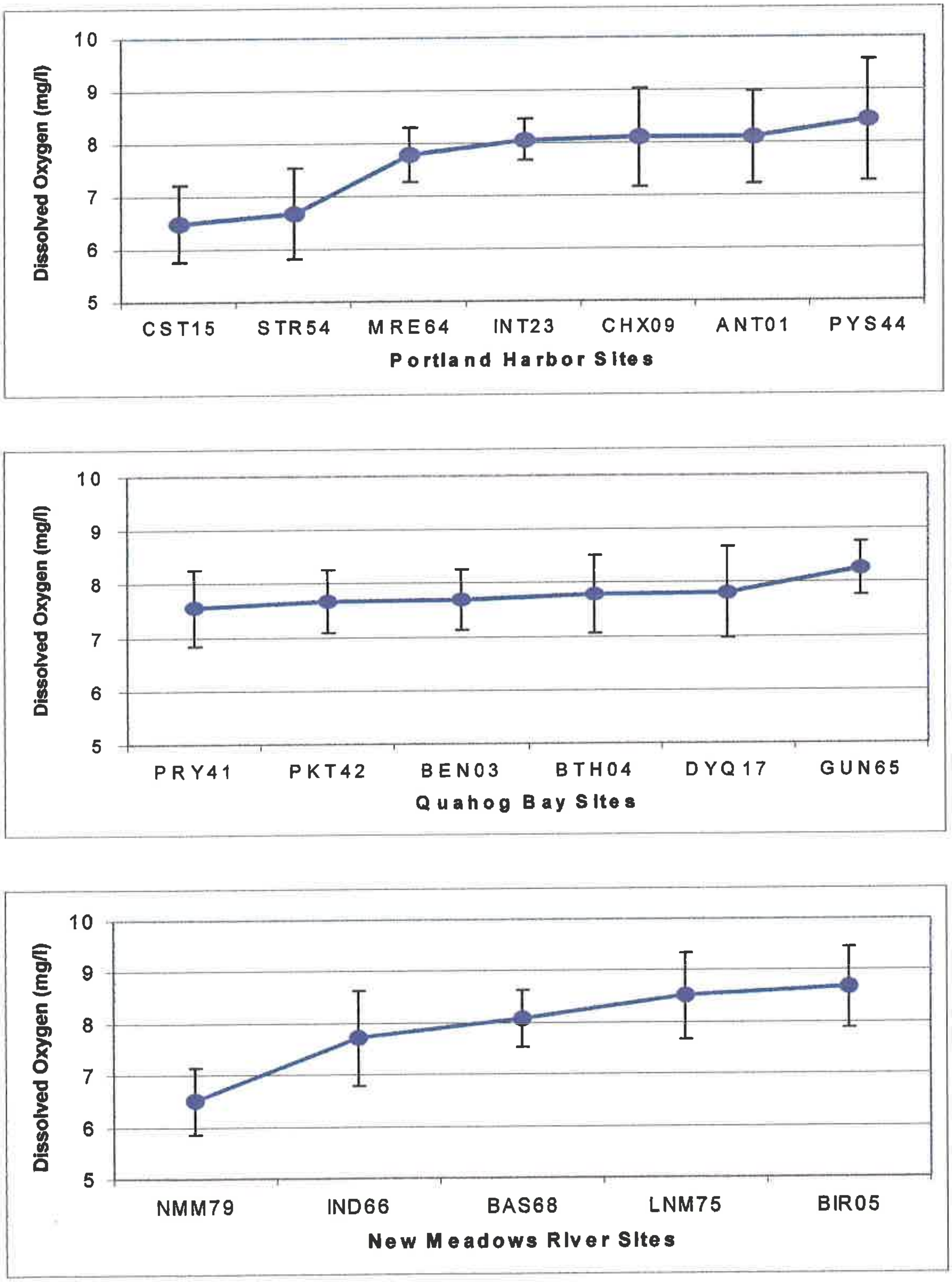


Figure 21. Site mean DO concentrations for selected water bodies – July-September data. (Error bars represent ± one standard deviation)

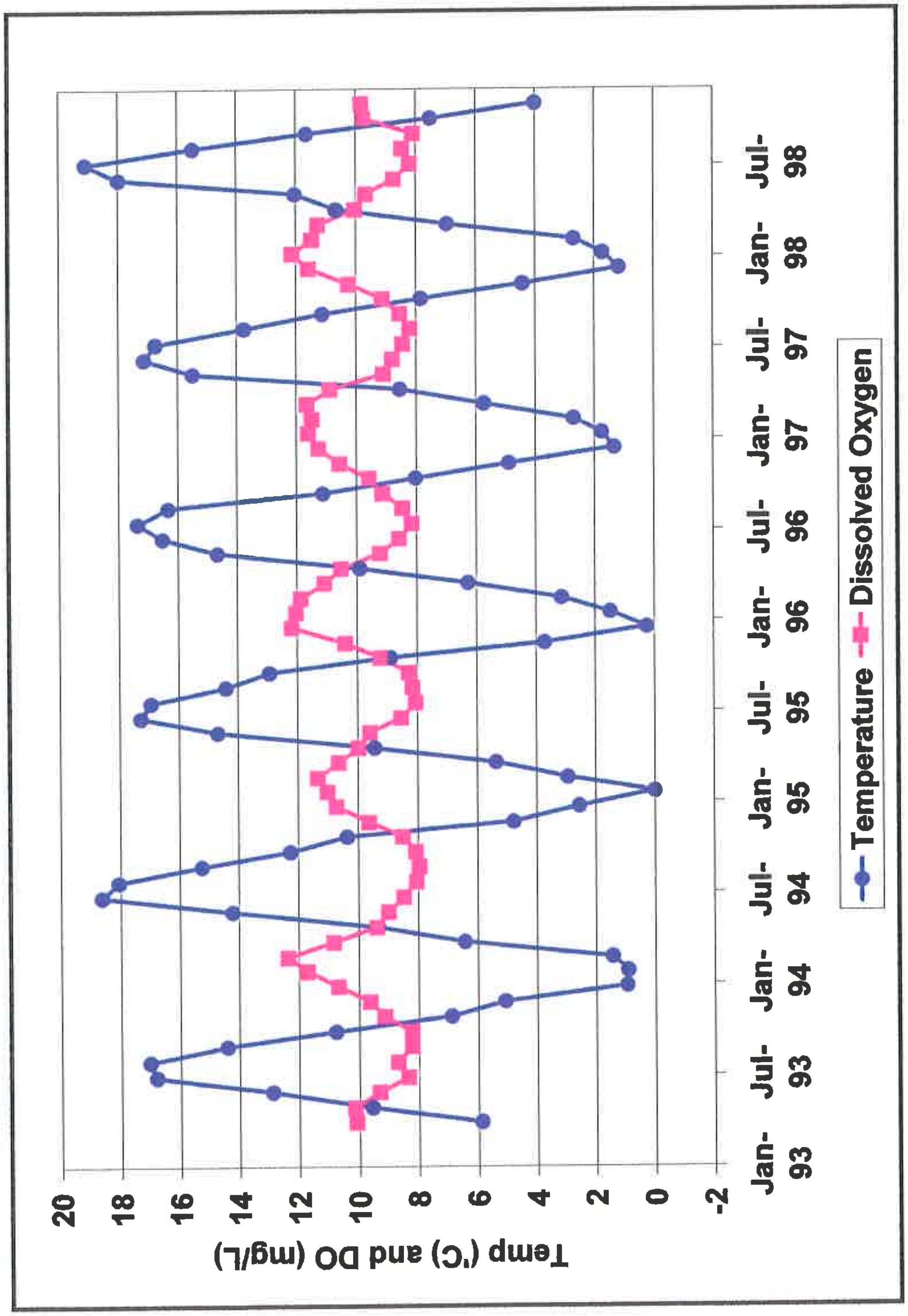


Figure 22. Time series of monthly mean temperature and DO data from all year-round sites.

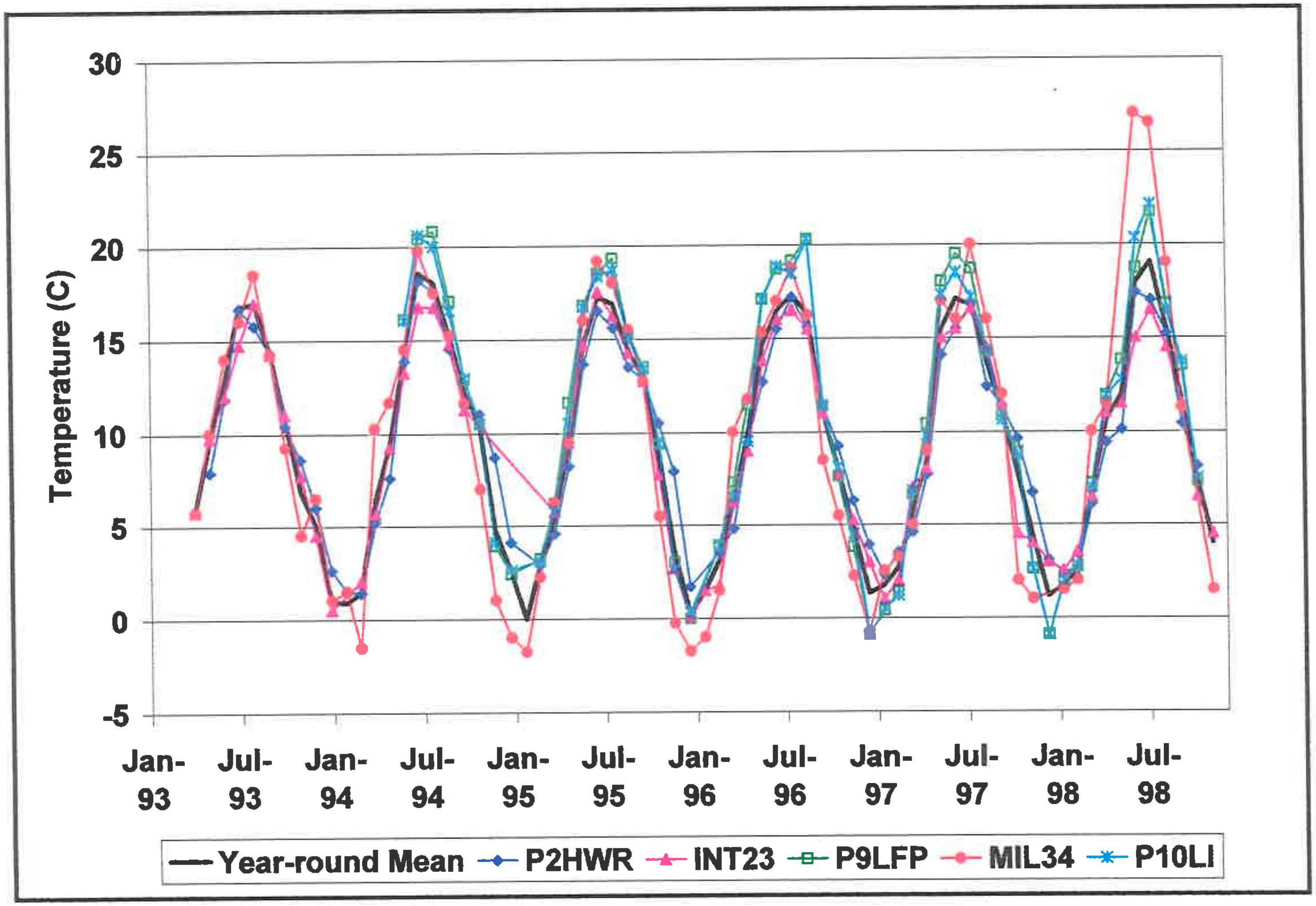


Figure 23. Time series of monthly mean temperature at selected year-round sites.

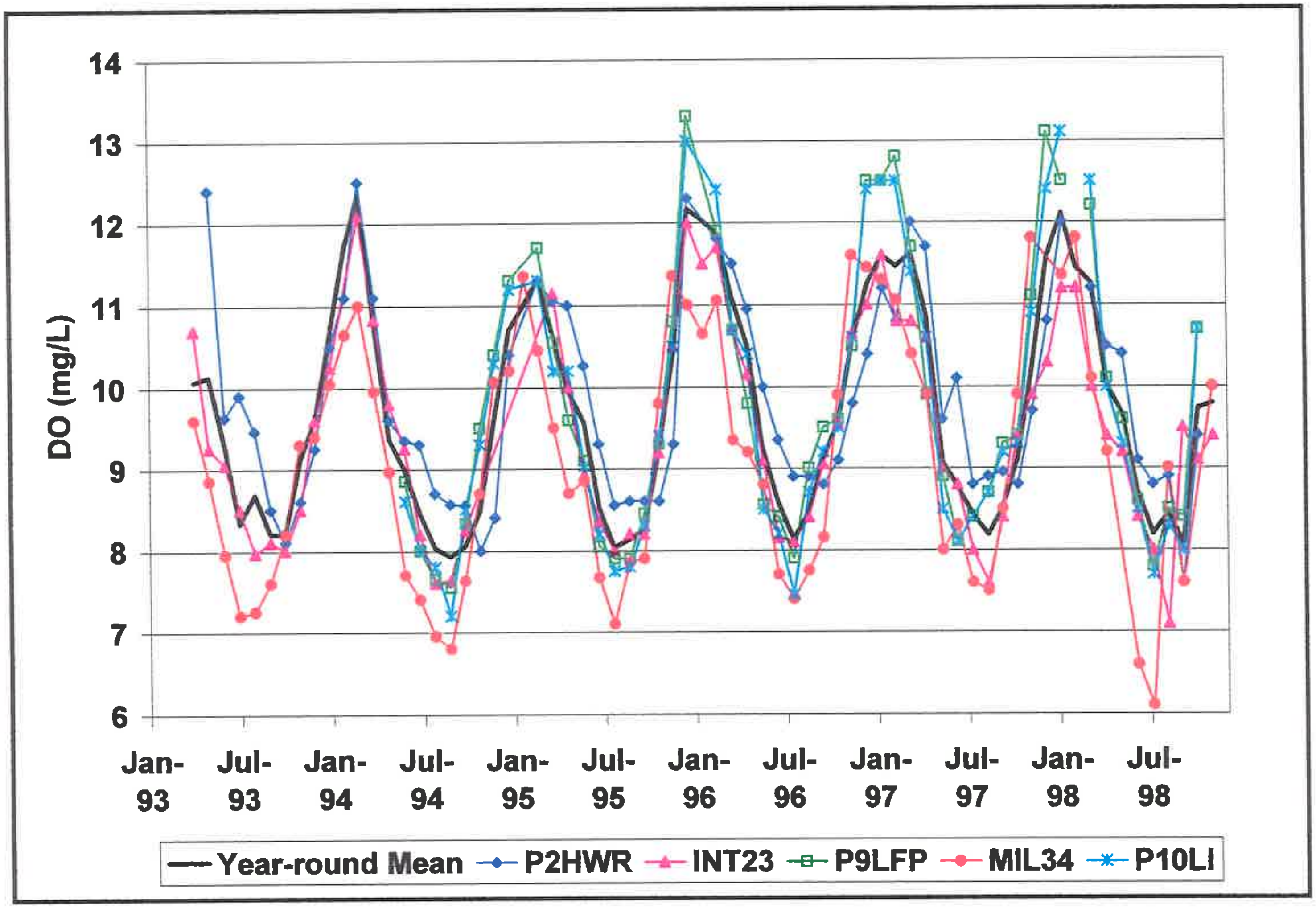


Figure 24. Time series of monthly mean DO concentration at selected year-round sites.

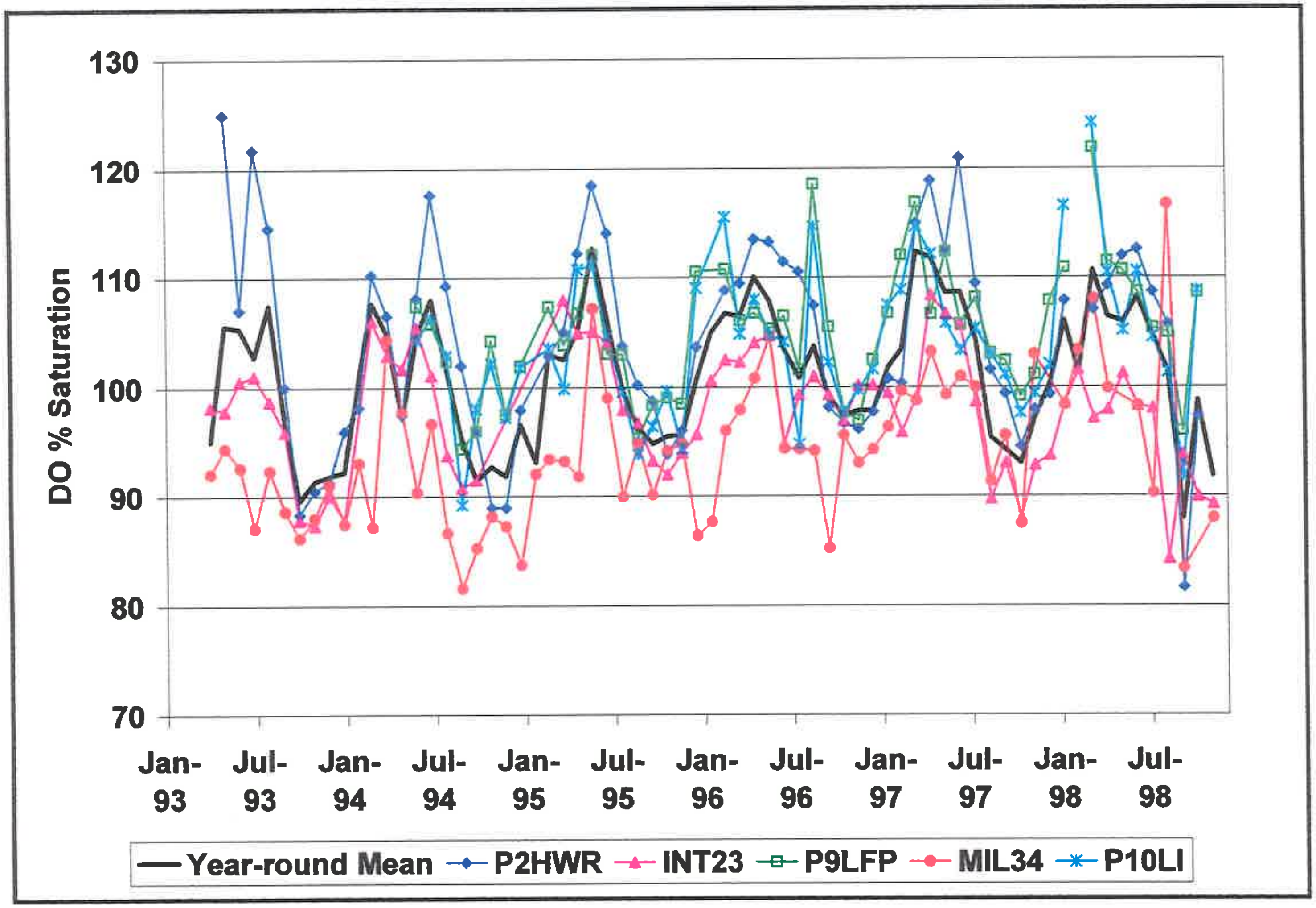


Figure 25. Time series of monthly mean DO % saturation at selected year-round sites.

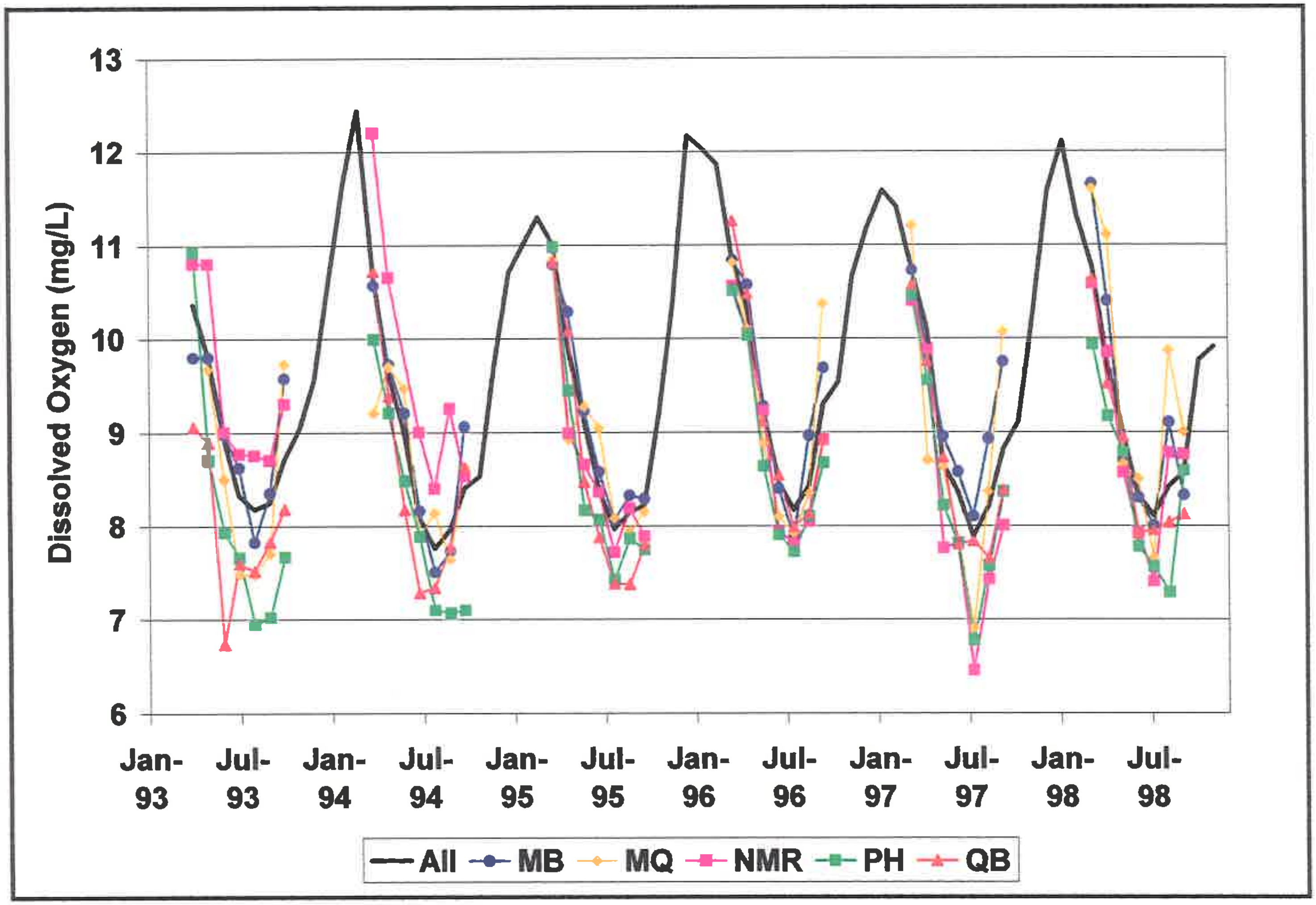


Figure 26. Time series of monthly mean DO concentration for selected water bodies (April to October data only).

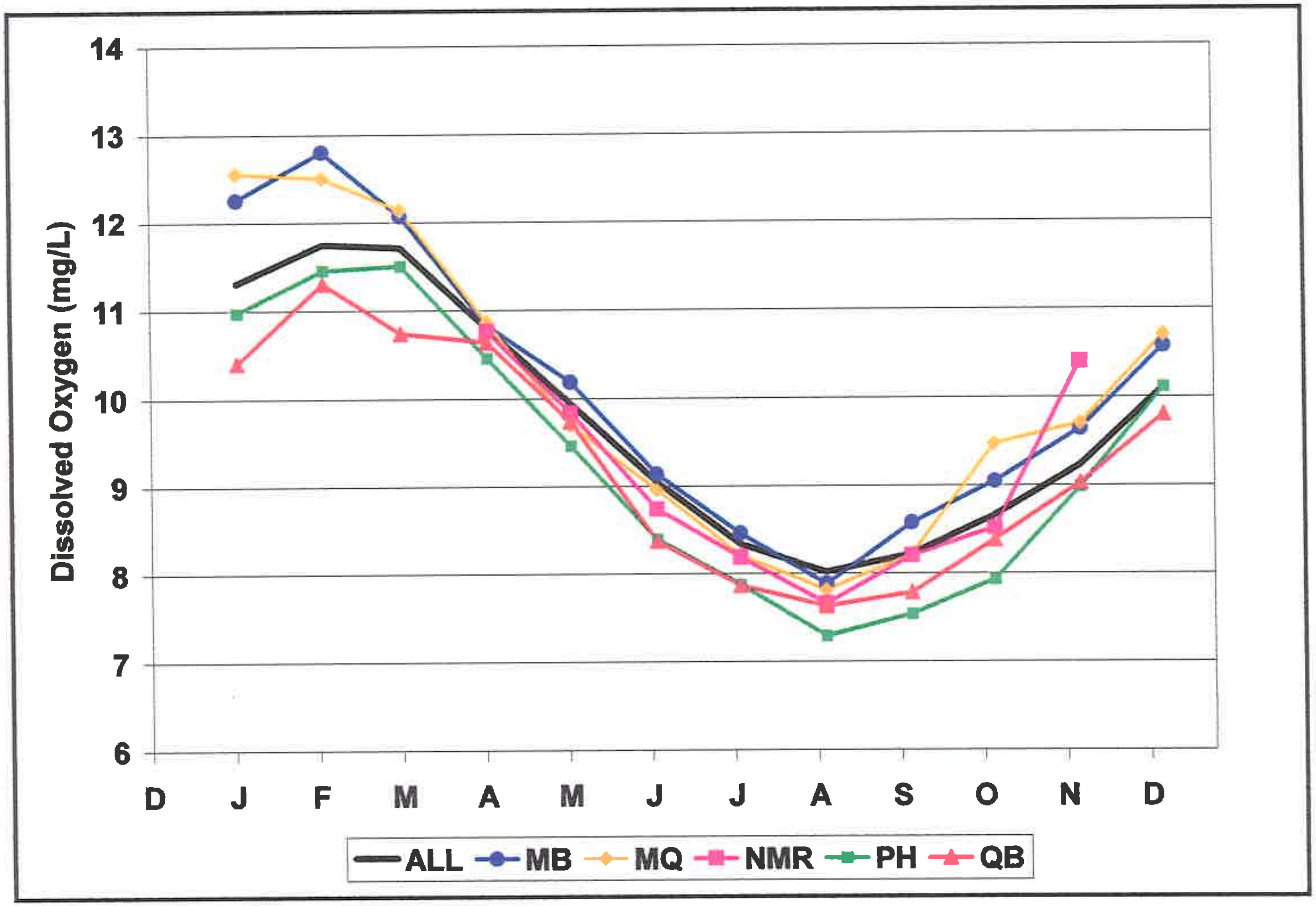


Figure 27. Seasonal cycle of DO concentration for selected water bodies. Monthly means for entire six-year period.

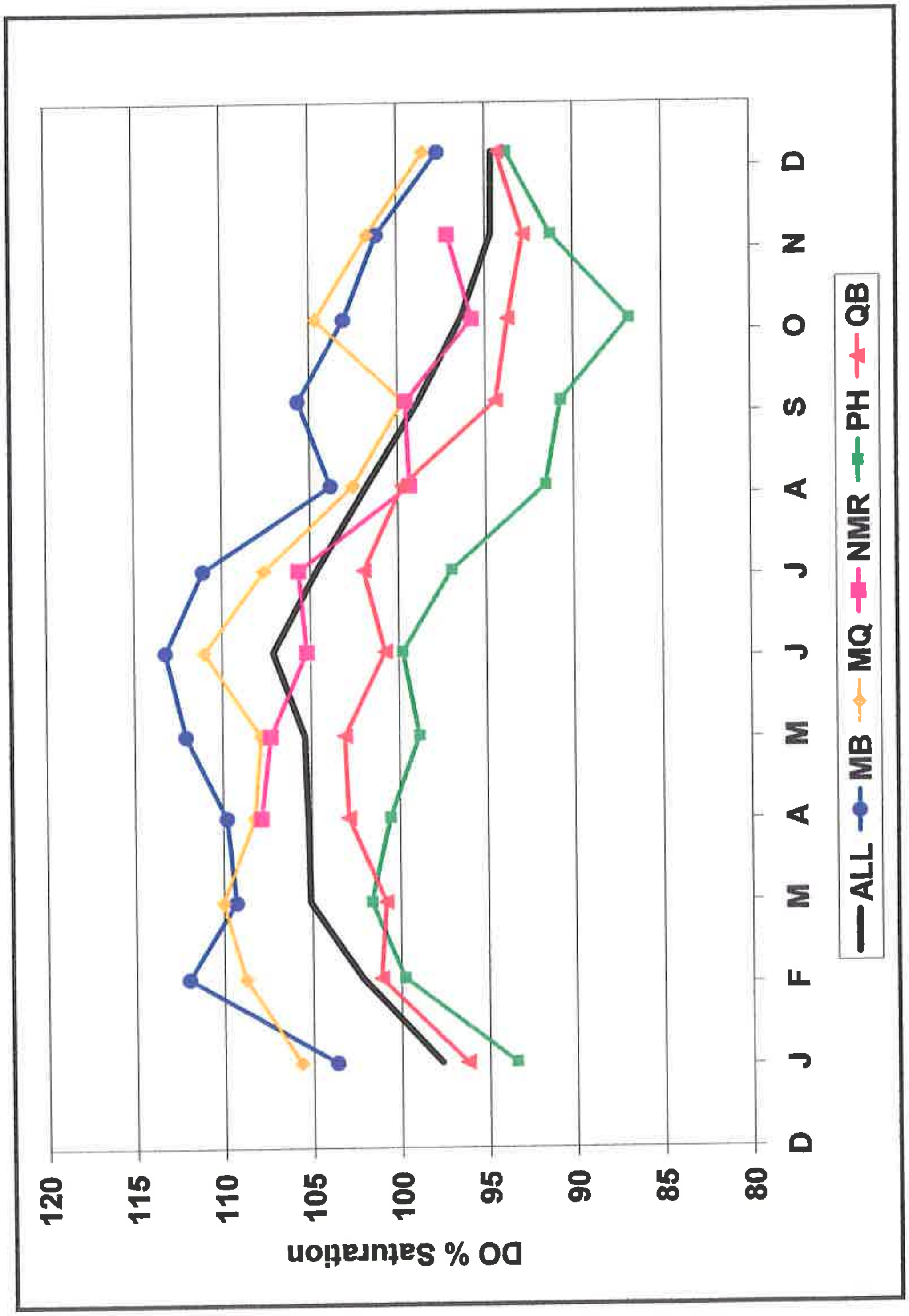


Figure 28. Seasonal cycle of DO % saturation for selected water bodies. Monthly means for entire six-year period.

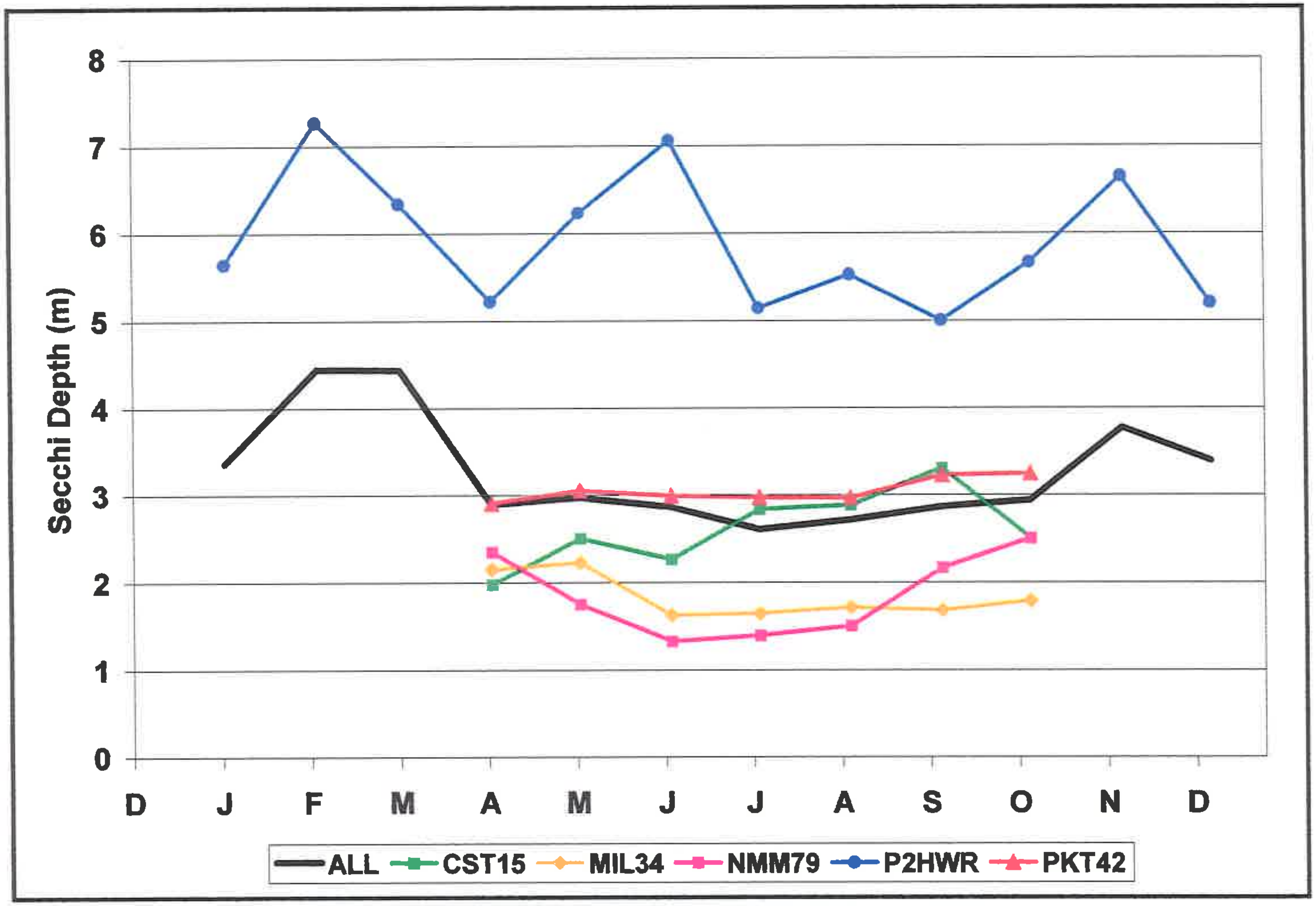


Figure 29. Seasonal cycle of Secchi depth at selected sites. Monthly means for entire six-year period.

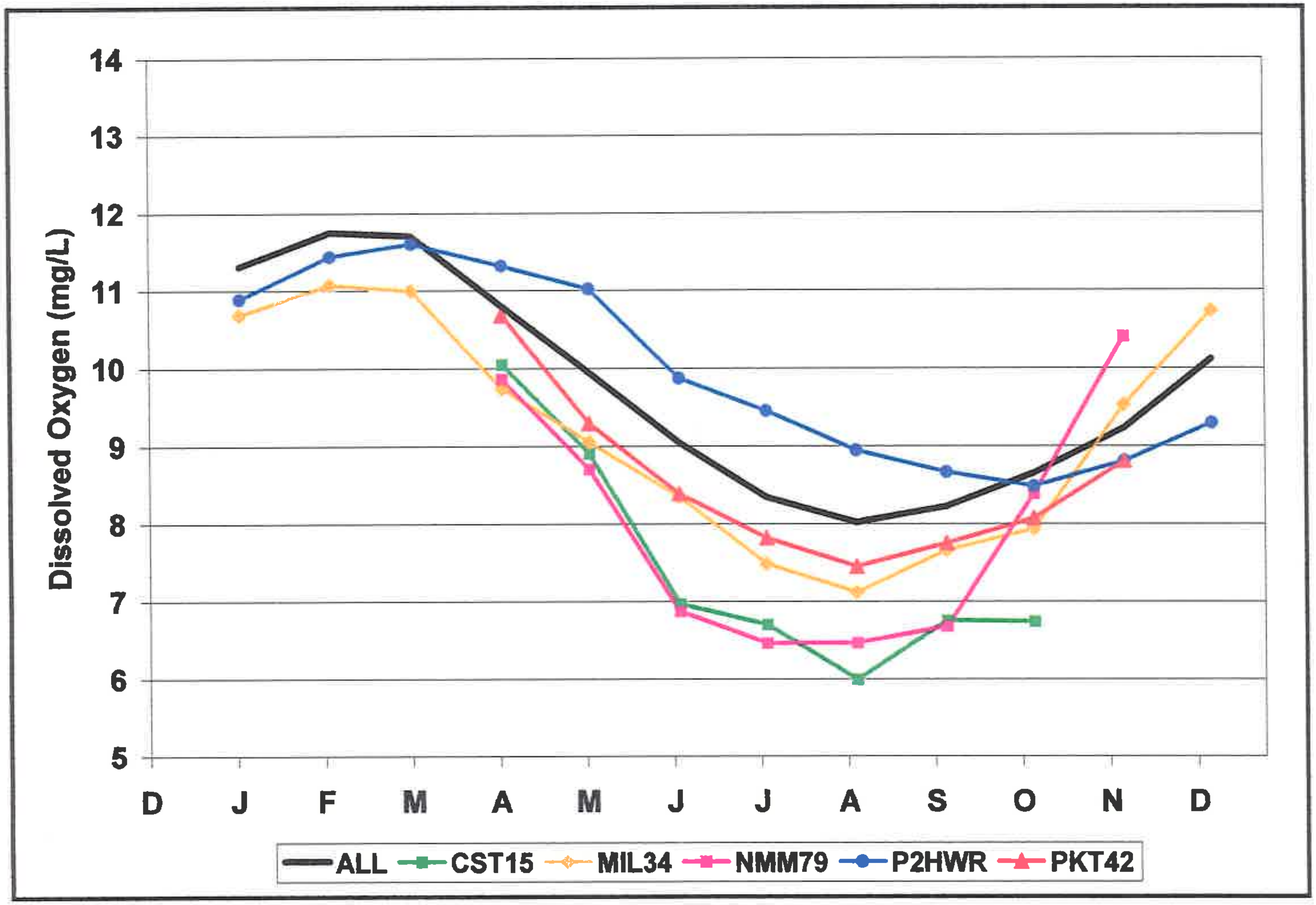


Figure 30. Seasonal cycle of DO concentration at selected sites. Monthly means for entire six-year period.

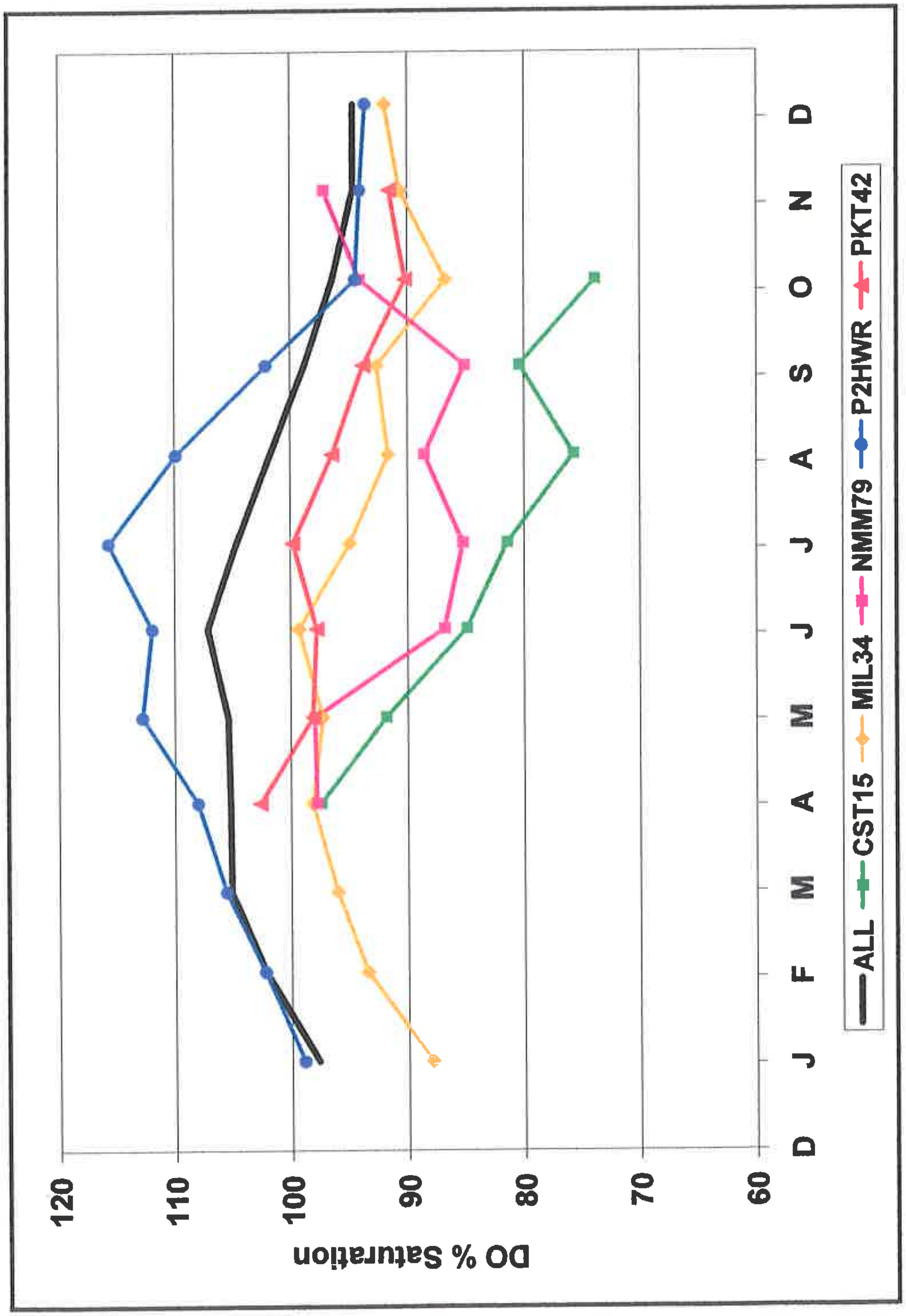


Figure 31. Seasonal cycle of DO % saturation at selected sites. Monthly means for entire six-year period.

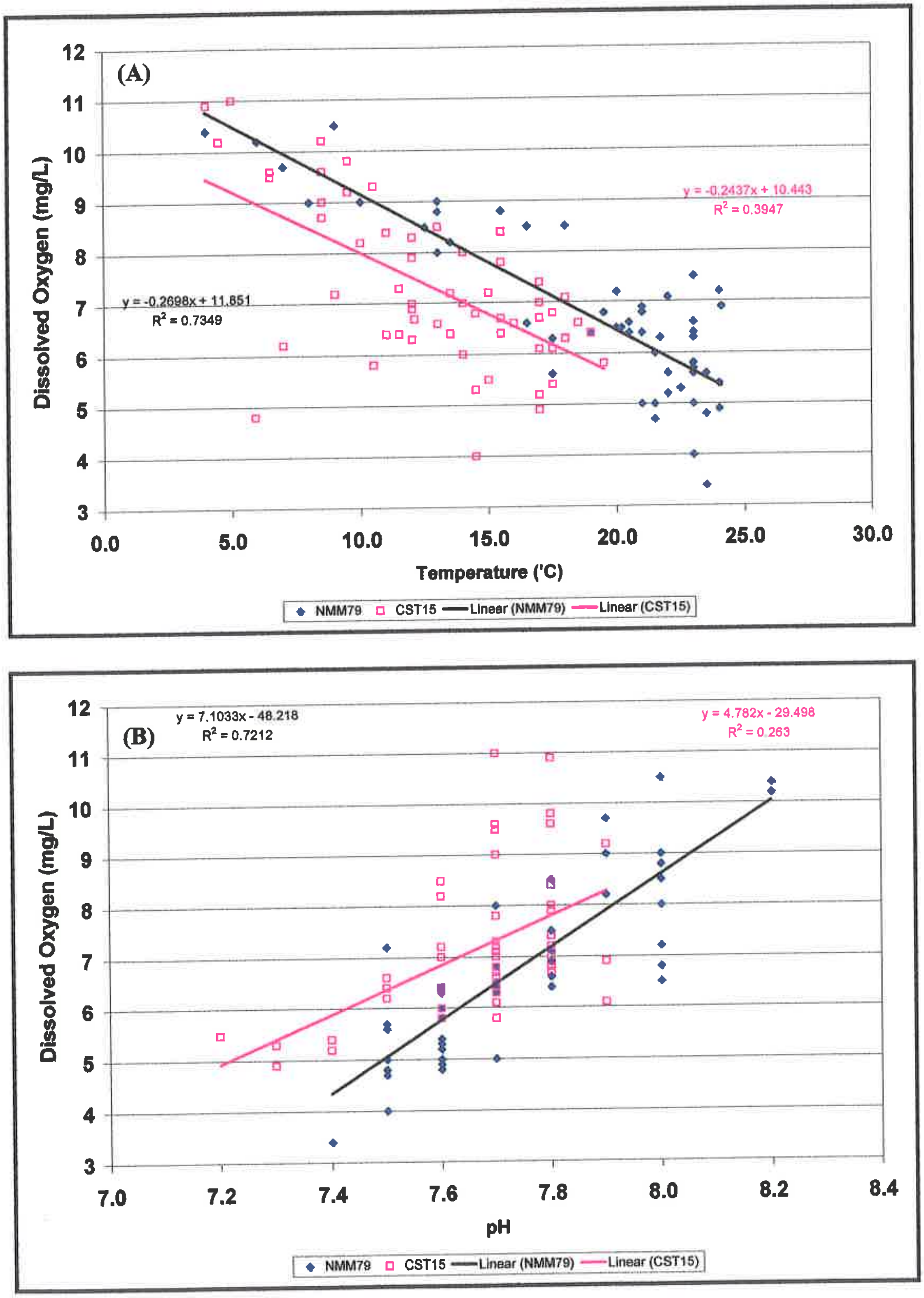


Figure 32. Scatter plots of data collected at Custom House Wharf and New Meadows Marina sites (all data).

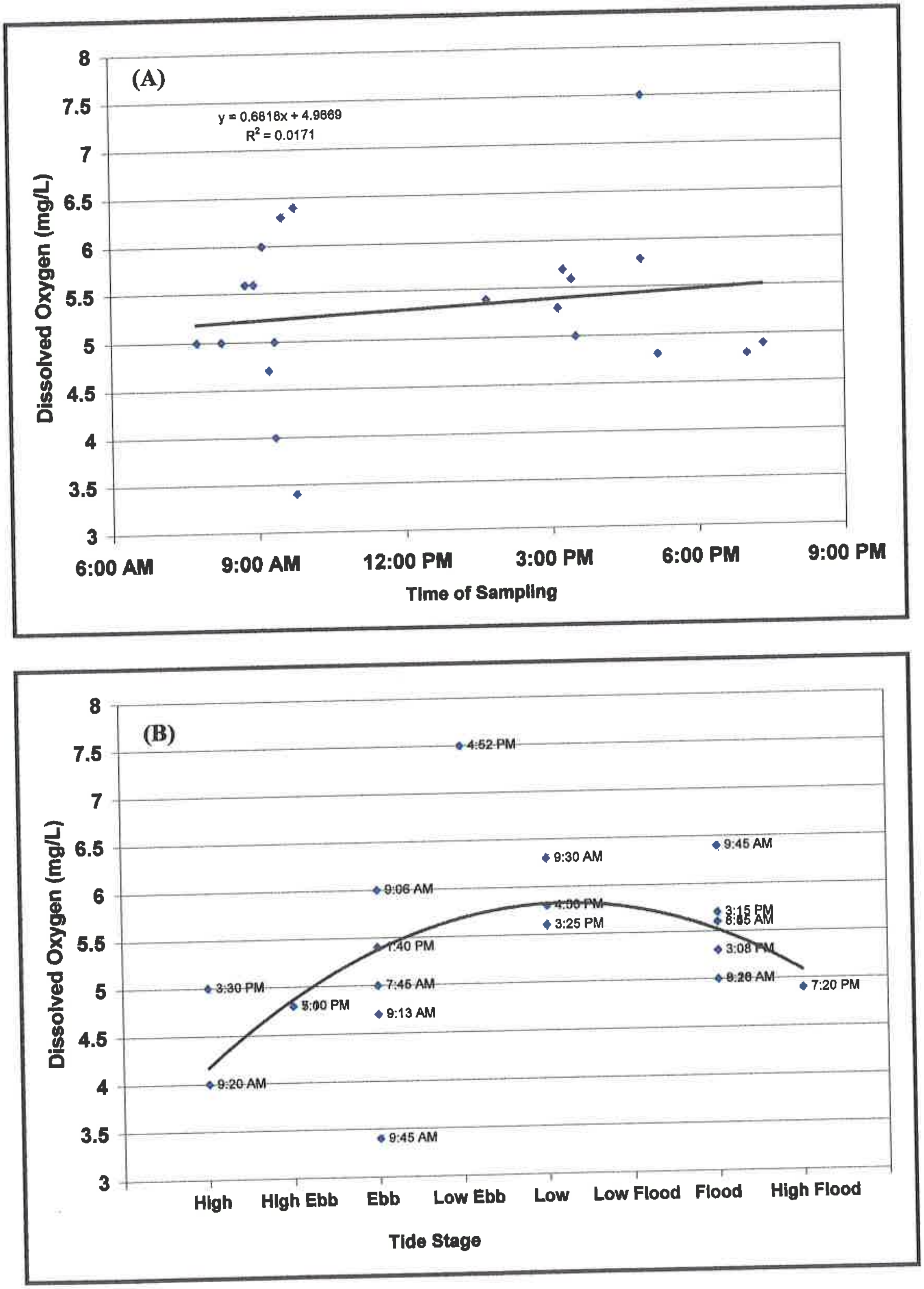
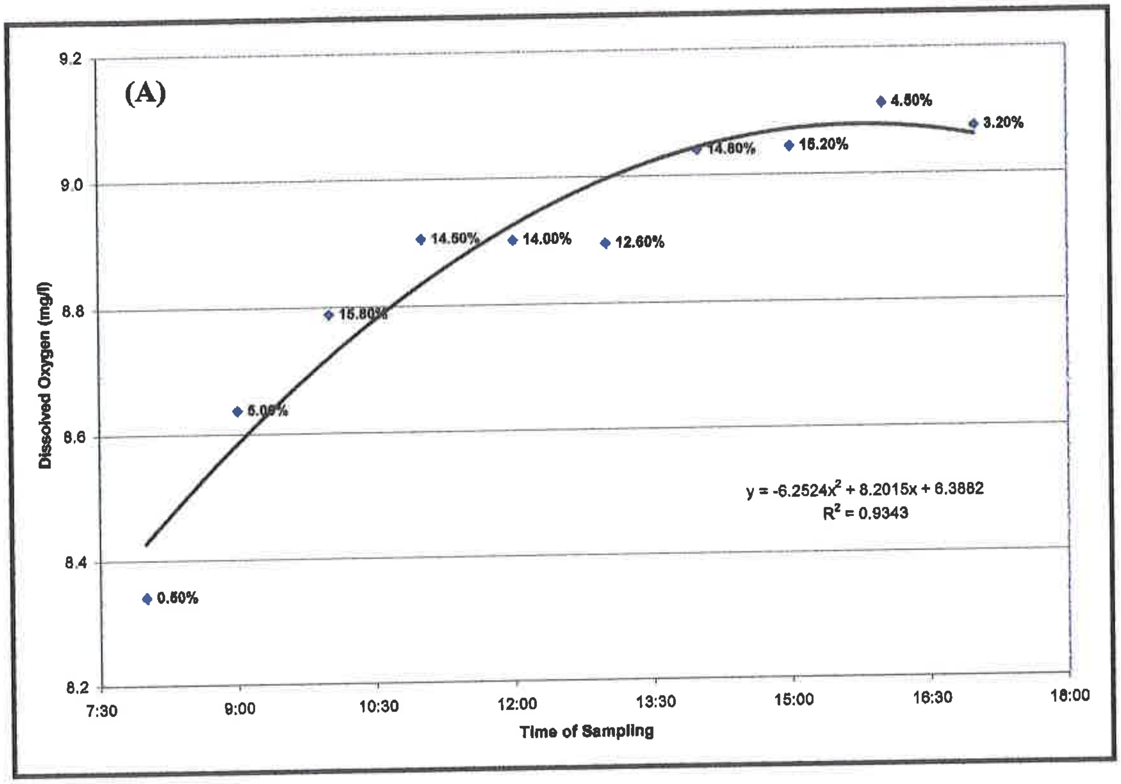


Figure 33. Evaluation of effect of (A) time of day and (B) tide stage on DO concentration. Data from 1997 special study at New Meadows Marina site. Trend line in A represents a linear regression of the data. Trend line in B is for presentation purposes only.



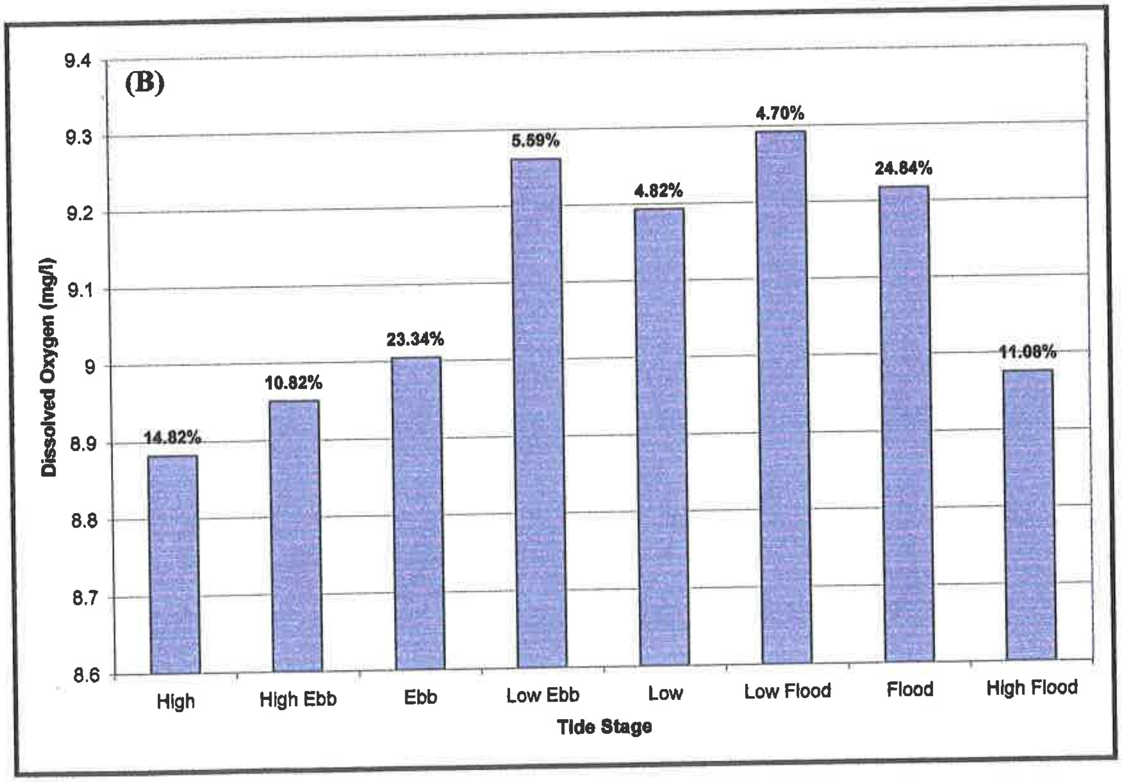


Figure 34. Evaluation of effect of (A) time of day and (B) tide stage on DO concentration (all estuarine data). Trend line in A for presentation purposes only. Labels for data points and above bars indicate the percentage data represented by data group.

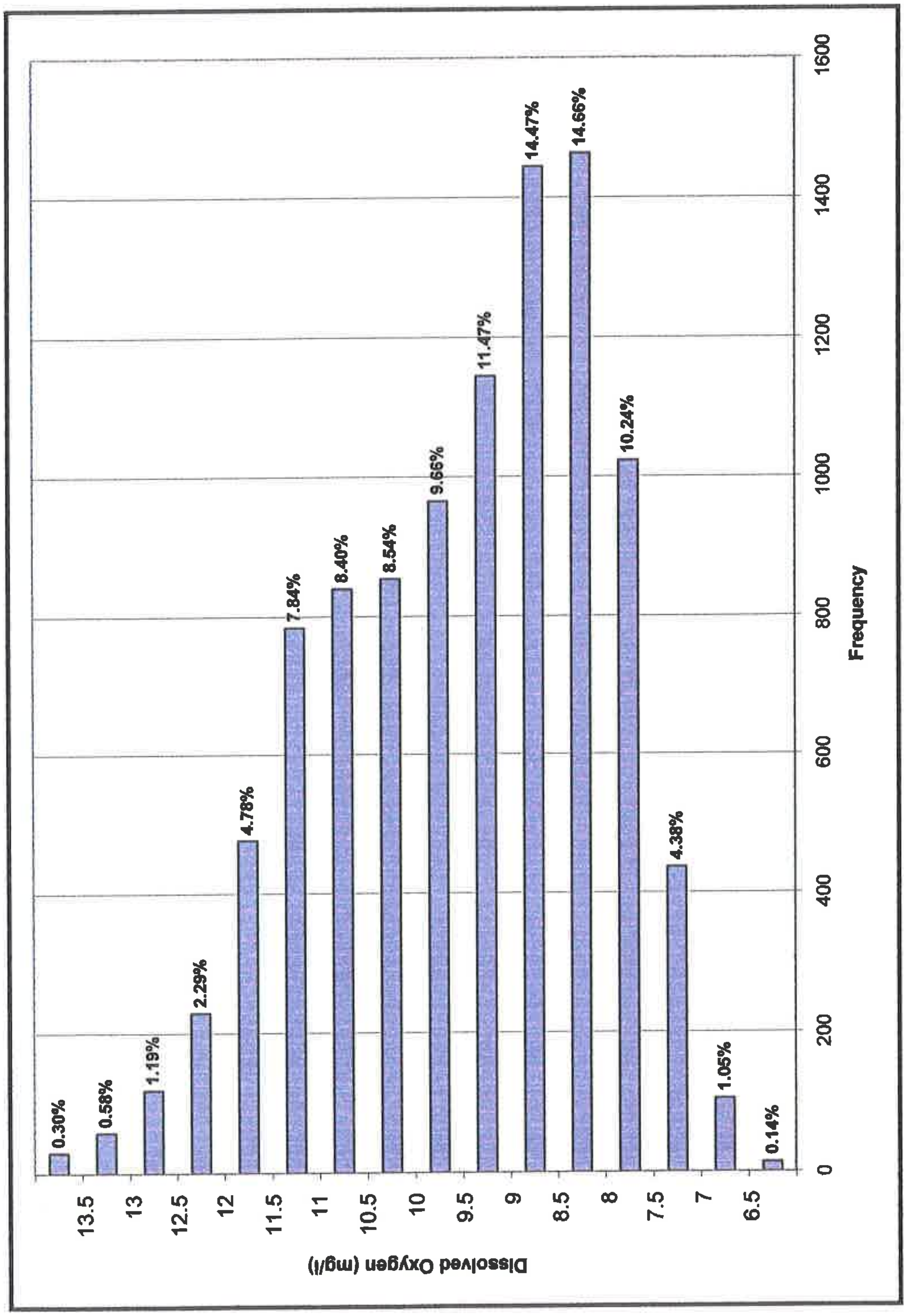


Figure 35. Frequency distribution of all DO concentration data (mg/l) for profile samples.

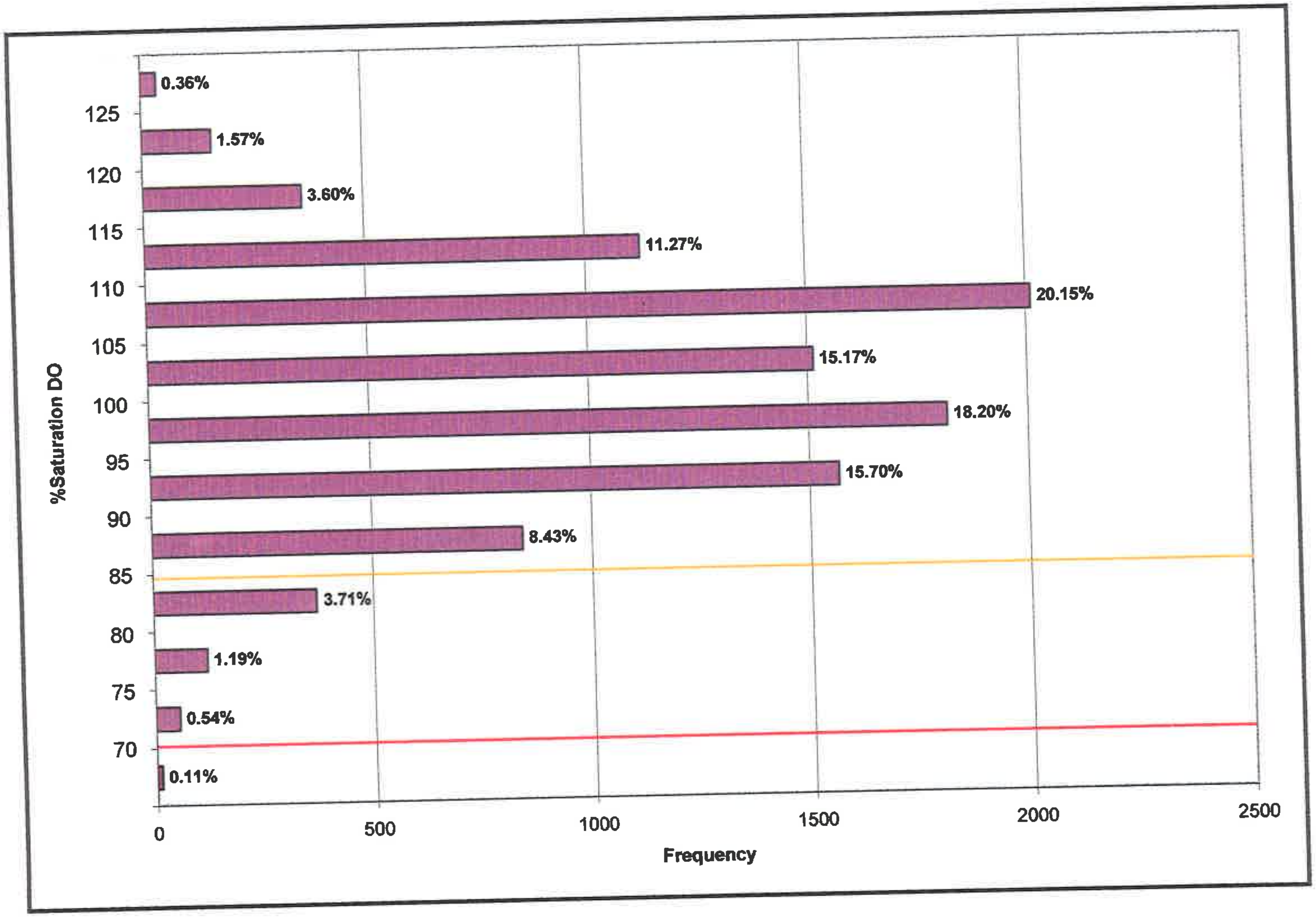


Figure 36. Frequency distribution of all DO % saturation data for profile samples. [State standards for class SB (≥85%) and SC (≥70%) noted on graph]

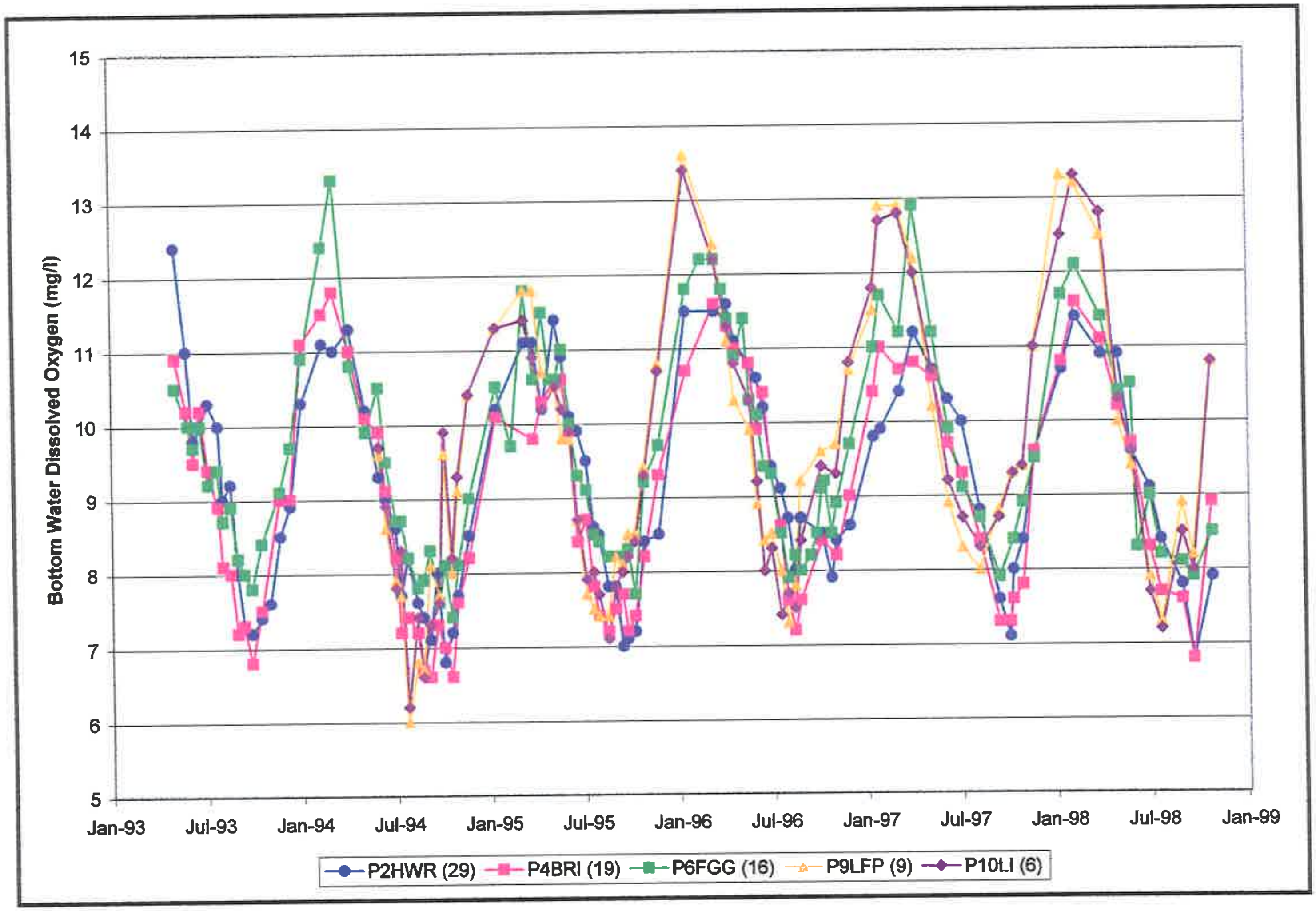


Figure 37. Time series of bottom water DO concentration at selected profile sites. Mean bottom water sample depth in parentheses.

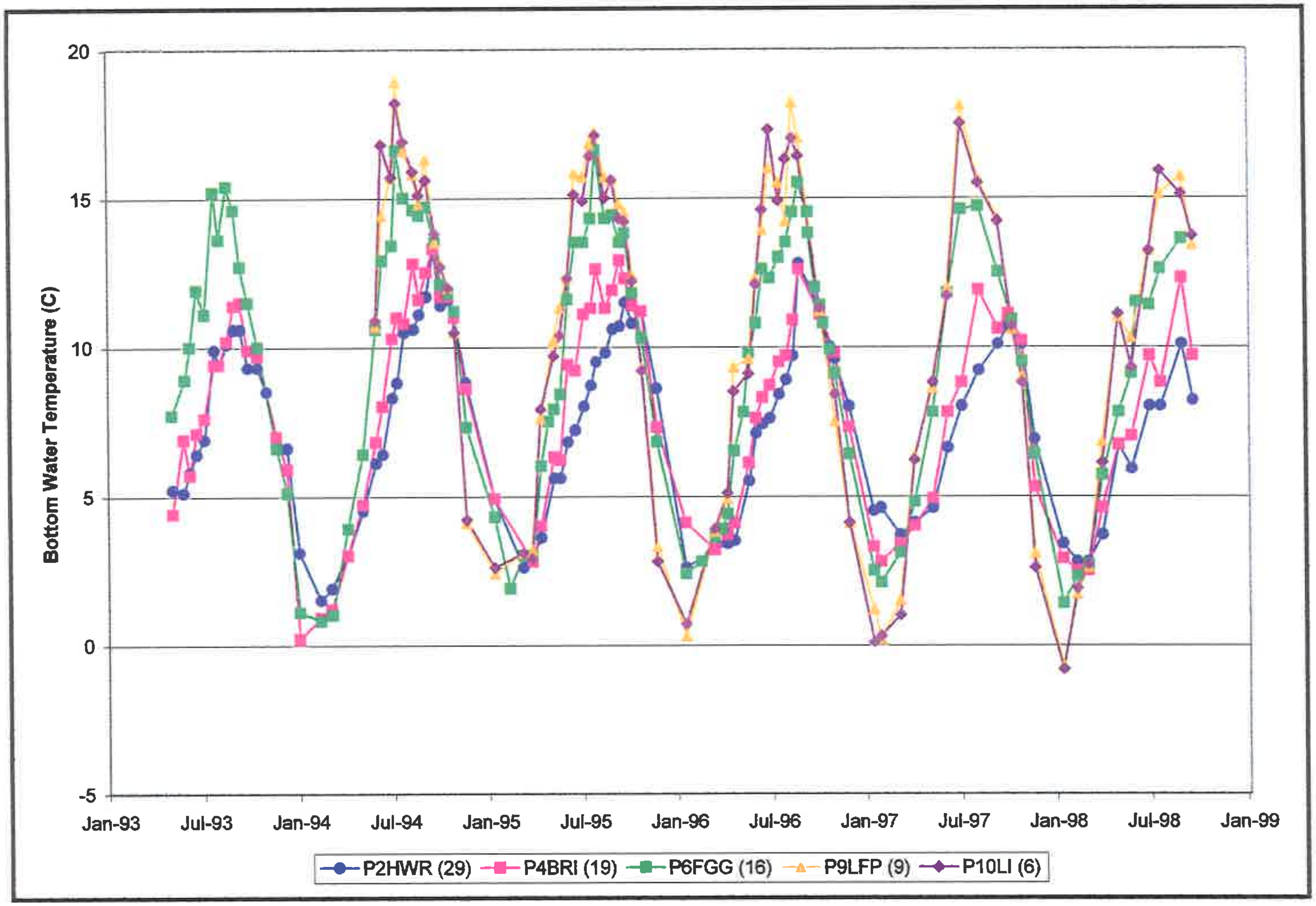


Figure 38. Time series of bottom water temperature at selected profile sites. Mean bottom water sample depth in parentheses.

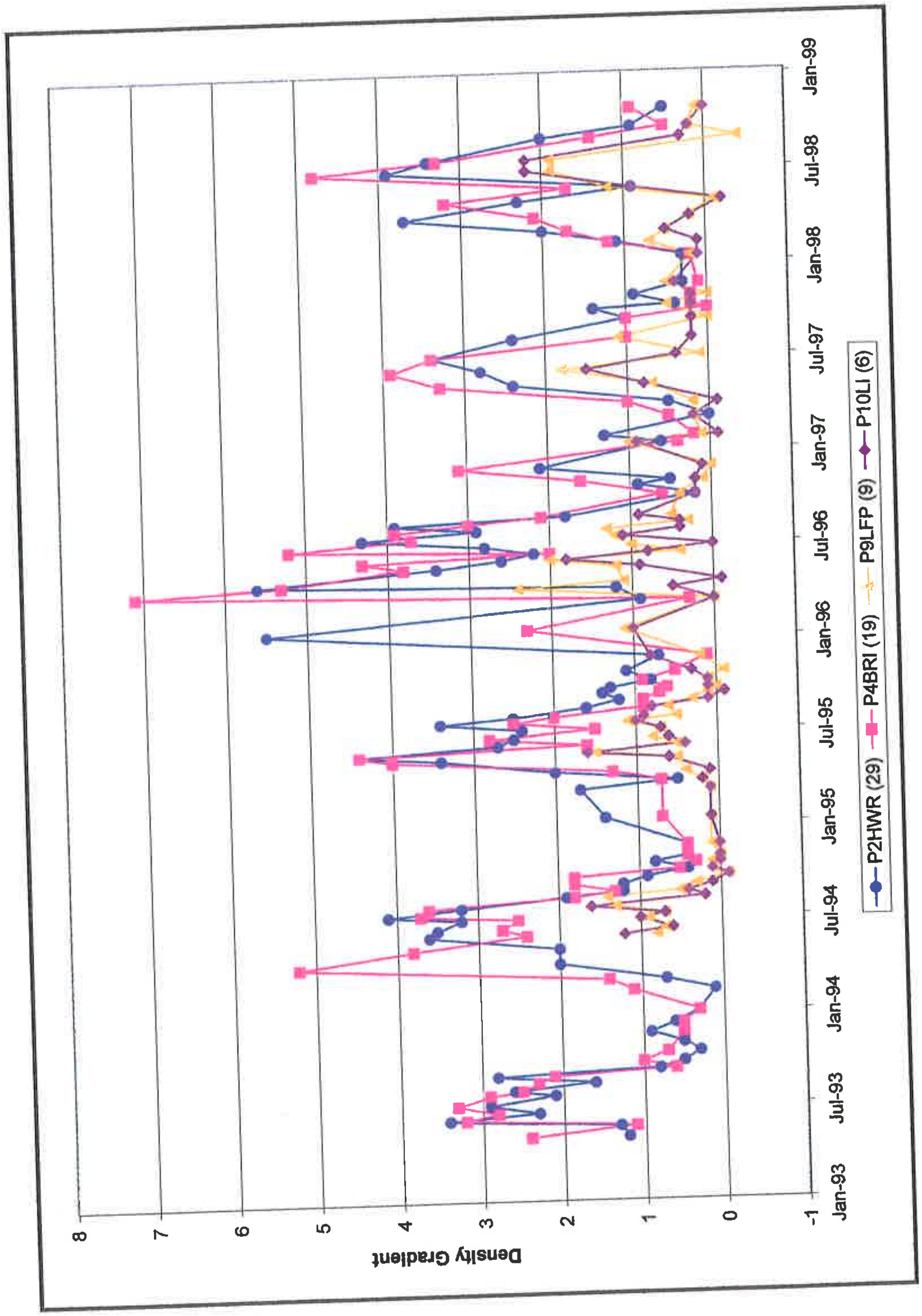


Figure 39. Time series of the density gradient between surface and bottom waters at selected profile sites. Mean bottom water sample depth in parentheses.

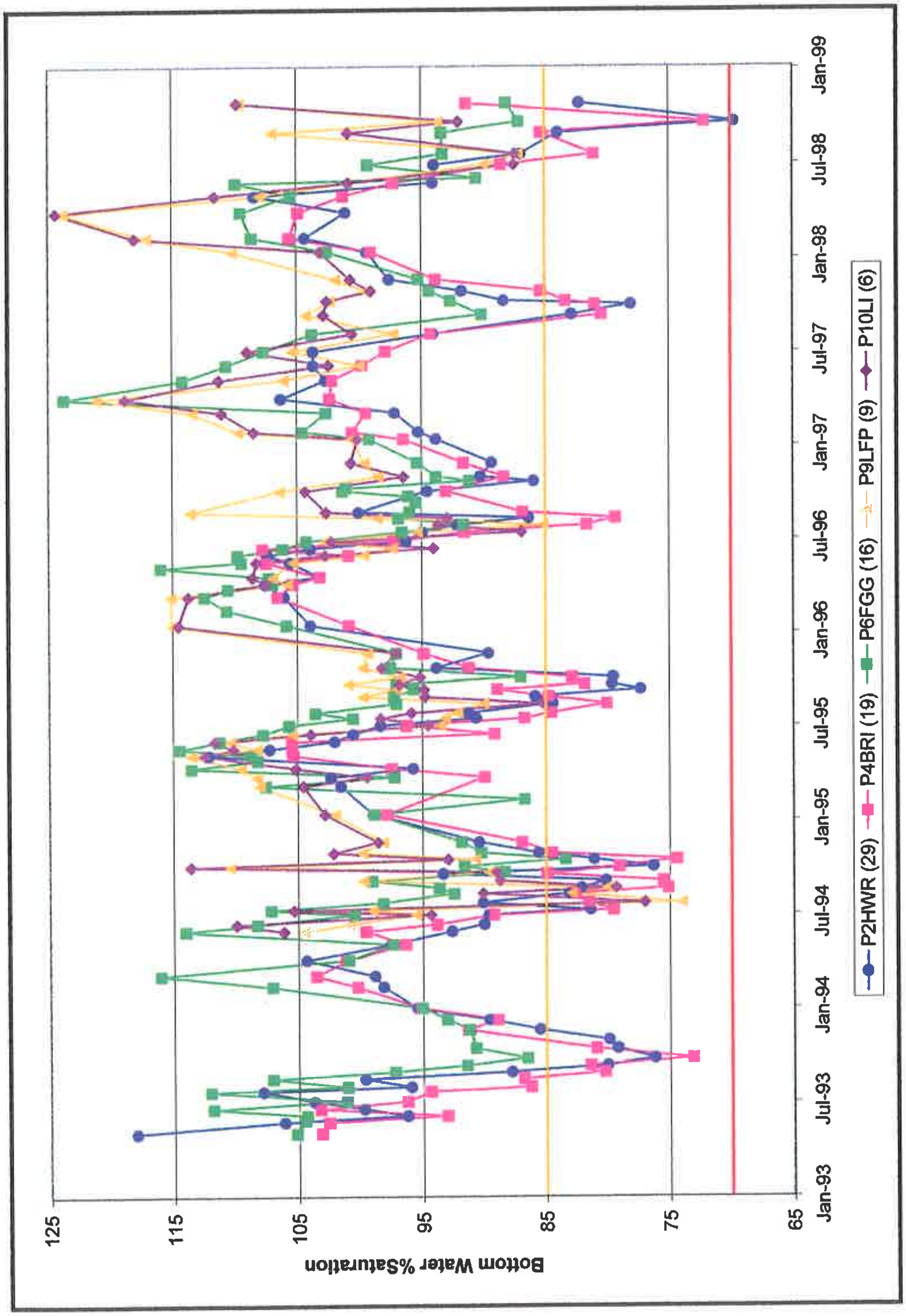


Figure 40. Time series of bottom water DO % saturation at selected profile sites.
[State standards for class SB (≥85%) and SC (≥70%) noted on graph]

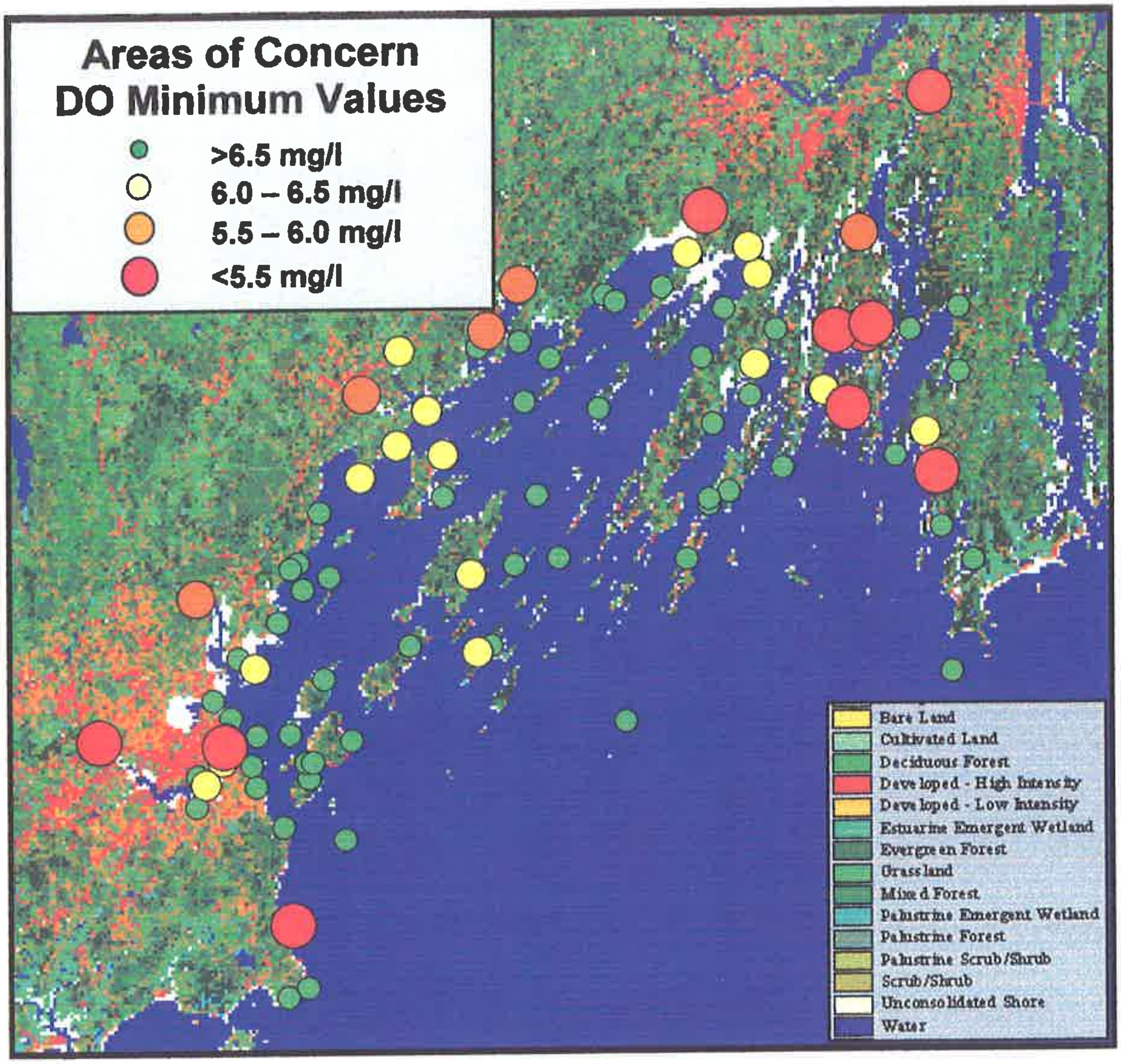


Figure 41. Areas of concern in Casco Bay based on minimum DO concentrations observed over entire 93-98 period (land use information obtained from NOAA).

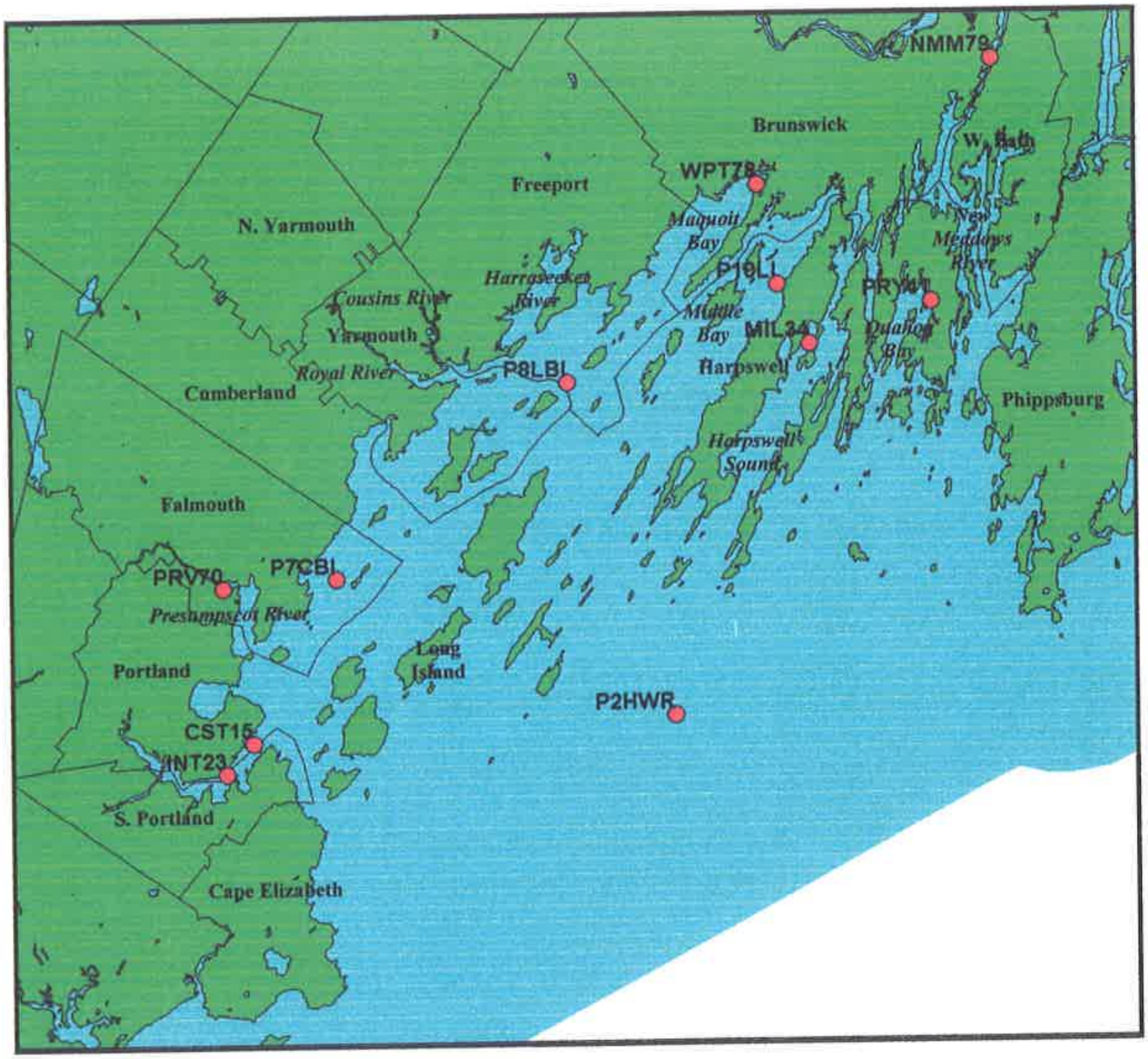


Figure 42. Proposed Primary Sites for expanded suite of analyses and AM sampling.

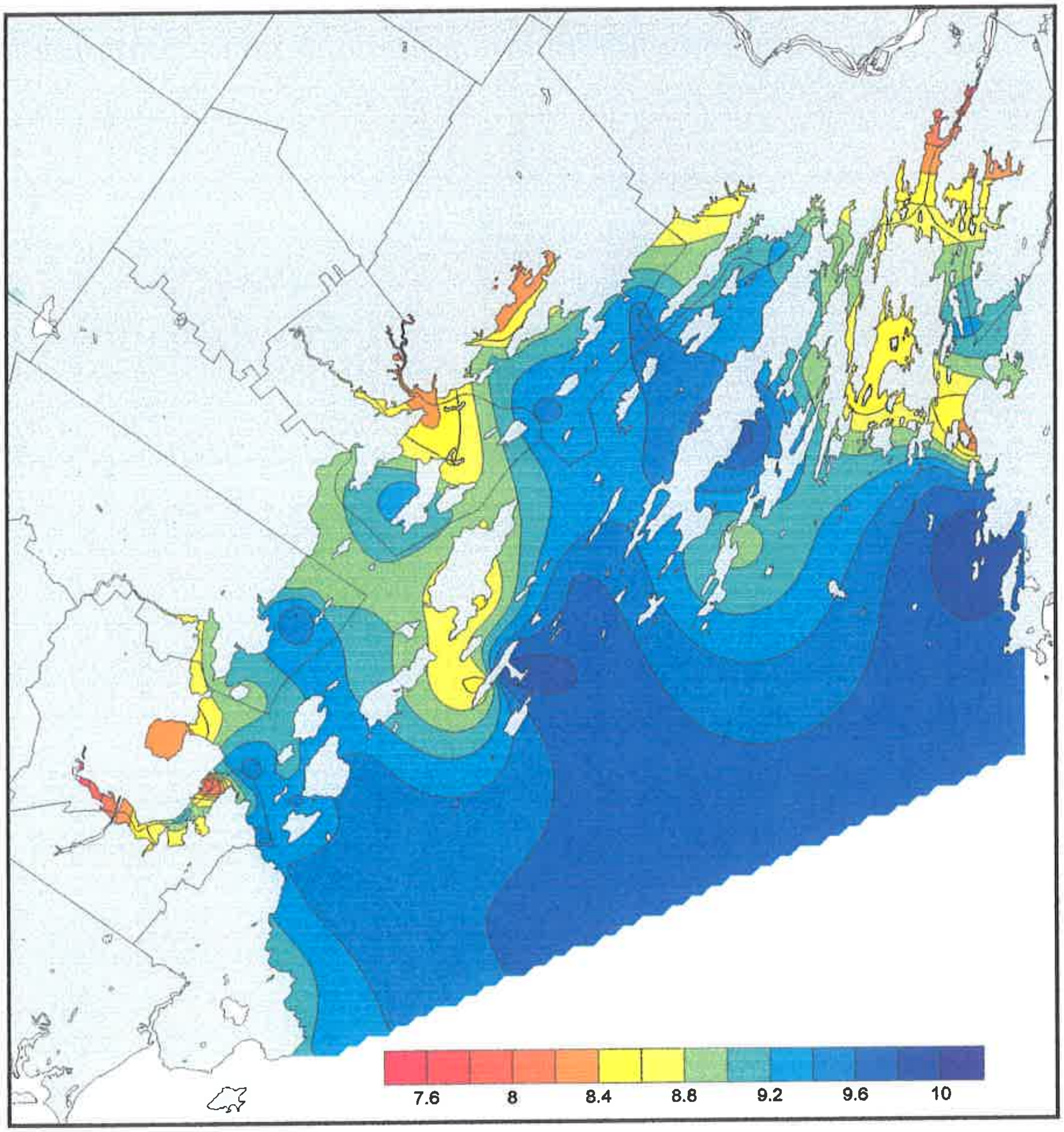


Figure 3. Contour plot of site mean DO concentration for April to October 93-98 data.