CHARLOTTE HARBOR NATIONAL ESTUARY PROGRAM

NUMERIC NUTRIENT CRITERIA

Task 10 Dissolved Oxygen

Letter Memorandum

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FOREWORD

This report was prepared by Janicki Environmental, Inc. for the Charlotte Harbor National Estuary Program in fulfillment of Task 10 of the Water Quality Target Refinement Project.

ACKNOWLEDGMENTS

Financial support for this project was provided by the Charlotte Harbor National Estuary Program, the Southwest Florida Water Management District, and the South Florida Water Management District. We wish to thank the many participants of the Technical Advisory Committee and Water Quality Quantifiable Objectives sub-committee meetings that led to the development of this process. We are grateful for the data collection efforts of the Coastal Charlotte Harbor Monitoring Network, the Charlotte Harbor Volunteer Monitoring Network, Lee County, Charlotte Harbor Aquatic Preserves, Cape Coral, Florida International University, The Peace River Manasota Water Supply Authority, Sarasota County, and Mote Marine Laboratory. We sincerely appreciate the contributions of Keith Kibbey, Peter Doering, Craig Hankins, Rob Johnson, Renee Duffy, Mindy Brown, Ray Leary, Ralph Montgomery, Sam Stone, and Kellie Dixon for allowing access to their data. Finally, we thank Lizanne Garcia and Kris Kaufman of the Southwest Florida Water Management District, Kevin Carter and Peter Doering of the South Florida Water Management District, and Lisa Beever, Liz Donley, and Judy Ott of the Charlotte Harbor National Estuary Program for supporting this work.

EXECUTIVE SUMMARY

The objective of this task was to characterize the dissolved oxygen levels in the segments of the Charlotte Harbor National Estuary Program area, assess principal drivers of DO exceedances, and evaluate the relevance of the empirical distribution of dissolved oxygen concentrations to the Florida Department of Environmental Protection's Impaired Water Rule standard for dissolved oxygen with respect to the development of recently proposed numeric nutrient criteria for the Charlotte Harbor National Estuary Program area (Janicki Environmental, 2011). This report is not intended to be used to assess DO for either state or federal Water Quality standards or for identification of impairment. This assessment included a descriptive characterization of the spatial and temporal attributes of observed dissolved oxygen concentrations.

The following conclusions can be drawn from the analyses and results from this task:

- The empirical evidence presented above suggests that the majority of CHNEP segments are meeting full aquatic life uses with respect to current state DO standards. Six segments (Dona and Roberts Bays, Lower Lemon Bay, Charlotte Harbor Proper, Pine Island Sound, San Carlos Bay, and Estero Bay) had no annual DO exceedences based on the current state DO standards. Of the five segments that had exceedences, Tidal Myakka and Tidal Caloosahatchee had a single exceedence while Upper Lemon Bay, Tidal Peace, and Matlacha Pass had three exceedences each. Examination of spatial distribution revealed no strong tendencies for DO less than 4 mg/l. However, the probability of DO values less than 2 mg/l was highest in the Tidal Peace and the upper portion of Charlotte Harbor Proper. Previous work by Camp, Dresser & McKee (1998) revealed that stratification was more prevalent when low DO concentrations occurred in the Tidal Peace and Charlotte Harbor. Logistic regression models developed for this report confirm that stratification is one of the principle drivers of DO exceedences in the Tidal Peace and Charlotte Harbor.

- The principal factor affecting DO in the segments of the CHNEP is temperature. This fact is evident in both the descriptive time-series plots and the results of ordinary least-squares regression.

- Additional models were developed to identify the explanatory variables that contribute to the probability of DO exceedences at the segment level. In all segments, temperature is the primary factor that is positively associated with a DO exceedence (a DO concentration < 4 mg/l). Though chlorophyll is included in the models of three segments (Tidal Myakka, Pine Island Sound, and Tidal Caloosahatchee), in Tidal Myakka and Tidal Caloosahatchee an increase in chlorophyll leads to a decrease in the probability of a DO exceedence. This contradicts the conceptual model proposed by FDEP that excess nutrients from anthropogenic assaults result in algal blooms which result in increased organic deposition and decomposition which in turn lead to reduced DO concentrations.

- There was evidence of a lack of fit in the models developed for several of the segments, therefore additional models were developed for these segments. These models estimate the probability of a bottom DO less than 4 mg/l as a function of several explanatory variables, including salinity stratification. There was no evidence of a lack of fit in the additional models. Temperature and stratification were the main drivers of DO exceedences in Tidal Peace and Charlotte Harbor Proper. Chlorophyll was not a significant predictor of bottom DO exceedences in either of the segments.

- Based on the weight-of-evidence presented here, it is reasonable to conclude that the proposed numeric nutrient criteria are protective of full aquatic life uses with respect to DO based on the current state DO standard.

1.0 INTRODUCTION AND OBJECTIVES

The Charlotte Harbor National Estuary Program (CHNEP) has recommended numeric nutrient criteria to U.S. Environmental Protection Agency (EPA) for Dona and Roberts Bays, Upper Lemon Bay, Lower Lemon Bay, Tidal Myakka River, Tidal Peace River, Charlotte Harbor Proper, Pine Island Sound, Matlacha Pass, San Carlos Bay, Tidal Caloosahatchee River, and Estero Bay (Figure 1-1). The criteria, as proposed to EPA, are segment-specific and are expressed as annual total nitrogen (TN) and total phosphorus (TP) concentrations and loads (Janicki Environmental, 2011a; 2011b). An integral component of the establishment of numeric nutrient criteria involves the assessment of protecting full aquatic life support within the estuary. This investigation examines the characteristics of dissolved oxygen concentrations in CHNEP segments with respect to the Florida Department of Environmental Protection's (FDEP) dissolved oxygen standard of 4 mg/l as part of that process. The FDEP has established the state water quality standards (FAC 62.302) to protect the designated uses of Florida waterbodies. The standard established for DO in predominantly marine waters requires meeting the 4 mg/l standard no less than 90% of the time (i.e., a 10% exceedance). Dissolved oxygen is also used as an additional indicator of eutrophic conditions and can serve as an indicator of habitat suitability for a wide range of aquatic fauna (e.g., fishes and benthic invertebrates) (USEPA, 2001).

The conceptual model applied by FDEP in establishing the DO standard is that excess nutrients from anthropogenic assaults result in algal blooms which in turn result in increased organic deposition and decomposition which in turn lead to reduced DO concentrations. There are several case studies that support that excess nutrients from poorly treated municipal wastewater as well as non-point source runoff have contributed to eutrophic estuarine conditions. Symptoms of eutrophication include excess primary production, deposition and decomposition of phytodetritus and consequently increased biological oxygen demand which reduces the DO content of estuarine waters (Nixon, 1995). The objective of this effort was to assess the percentage of state standard exceedances in DO and assess drivers of DO exceedances in the segments of the CHNEP area with respect to the development of recently proposed numeric nutrient criteria for the CHNEP area (Janicki Environmental, 2011a; 2011b). This study also explores evidence that the FDEP conceptual model described above is currently relevant in the CHNEP segments. In particular, this assessment investigated the relationship between the percentage of DO exceedances in each of CHNEP segments and the threshold values for chlorophyll *a* established as part of an overall nutrient control strategy (Janicki Environmental, 2011a). Descriptive and quantitative analyses were used to evaluate the effects of known drivers of DO including temperature, color, stratification, and chlorophyll *a* concentrations.

Figure 1-1. CHNEP Bay Segments and Water Management District Boundaries.

2.0 BACKGROUND

Cultural eutrophication, which is nutrient excess leading to overproduction of microalgae and associate trophic imbalances, is common in estuaries near human population centers. Under conditions of eutrophication DO may exhibit extreme diel cycles. Photosynthesis via algae production elevates DO levels in the water during the day. However, at night when respiration is high, DO levels can drop dangerously low. Eutrophication can also lead to periodic or long term hypoxia (water column oxygen concentrations <2 mgl) and anoxia in estuarine ecosystems. Fishes, crabs and shrimp will attempt to move away from oxygen concentrations of less than 2 mgl and few marine animals survive in prolonged exposure to hypoxic conditions. DO levels are often quite variable in estuarine systems due to fluctuations in temperature, salinity, basin morphology, and overall productivity. At times, the Charlotte Harbor estuary has a significant hypoxic zone that approaches 90 km^2 in September (Camp, Dresser, and McKee, Inc. 1998). In the following paragraphs, three papers are reviewed which address DO in Charlotte Harbor, Florida.

The first report was written by Camp Dresser and McKee detailing a study initiated by the Surface Water Improvement & Management (SWIM) Department of the Southwest Florida Water Management District (SWFWMD) to determine the historic and present extent of hypoxia in upper Charlotte Harbor and to determine the potential future extent of hypoxia in the upper harbor. The project had five main goals:

1) Estimate the occurrence of hypoxia at a reference station using historical data;
2) Implement a monitoring program to define the relationships between the bottom water dissolved oxygen at the reference station and stations distributed through the upper harbor;
3) Characterize the onset and spread of a hypoxic event;
4) Evaluate the relationship between stratification and hypoxia; and,
5) Propose and evaluate conceptual models of the cause of oxygen depletion leading to hypoxia.

Sampling was coordinated by Mote Marine Laboratory and sampling was conducted in 1996 on 10 sampling dates from September 16 through November 12. Sampling was completed at 16 stations with vertical profiles of temperature, salinity, and dissolved oxygen collected at 0.5 m intervals. Samples were also collected for color and secchi depth readings were taken. One station in the upper harbor was designated as a “reference station” and was visited more frequently during each sampling day. The data set contained over 2,450 values for temperature, salinity and dissolved oxygen, with 324 separate station visits. Historical data was reported from the Environmental Quality Laboratory (EQL) of Port Charlotte with monthly DO data from 1975.

Analysis of historical data showed lower DO concentrations relative to location with 4.0

mg/l or less observed in the lower Myakka and Peace rivers and upper Charlotte Harbor. Lower Charlotte Harbor stations had DO concentrations of 4.0 mg/l or less for only 5% or less of total samples. Upper harbor and lower rivers also had hypoxic conditions during more months of the year as compared to those in the lower harbor. The duration and frequency were related to station location. June through October had the most frequent and widespread occurrences of DO concentrations less than 4.0 mg/l. September had the most widespread hypoxia with seven of the EQL stations at 2.0 mg/l or less. Comparison of annual data revealed no temporal trend in DO for the period 1975 through 1990.

The authors attempted to estimate the spatial extent of hypoxia from historical data based on DO relationships between the reference station and other locations in the harbor, but the model was limited by sample size. The authors noted that during the 1996 sampling only 27 of 2,093 samples were hypoxic, limiting all observations to a single sampling day. As a result, an alternate approach of comparing the relationship of hypoxic conditions at the reference site to the other physical and chemical conditions was completed. Linear regression techniques were employed to determine the flow metric which best explained variation in DO saturation at the reference site. The model included cumulative flows of the Myakka and Peace Rivers for the current day and seven previous days and had an r^2 of 0.55. Possible additional covariates including color, nitrate, ammonia, total phosphorus and long term wind data were evaluated. Wind and nitrate were significantly correlated with flow so were included in further analyses. Nitrate did not improve the model fit, but cumulative wind for the three previous days did. The final model for the reference site included cumulative flows from the Myakka and Peace Rivers for the current day and seven previous days, cumulative wind for the three previous days, and monthly intercepts. This model explained 56% of the variation in bottom DO saturation.

Using the model that was developed for the reference site as a starting point, the authors developed models for the Peace River upstream of the reference station. In the first model the authors used a single variable to explain variation in DO saturation. Highest correlation was found when Peace River flows for current day and 7 previous days were used. Using Peace River flows resulted in an r^2 of 0.50. Using other variables including ammonia, nitrate, and chlorophyll caused the r^2 values to drop substantially. In the second model, Peace River flow and a covariate were used. R^2 improved only slightly, to between 0.52 and 0.54, for all other variables. These included current month nitrate, previous month TP, current month ammonia, and current and previous month chlorophyll.

Additional models were used to investigate the relationship between hypoxic conditions and three stations within close proximity to the reference station. Two stations were below the reference station in the harbor and the other was in the Peace River. The relationship between hypoxia as defined by DO saturation and flow predicted between 54-67% of the variation within the three stations. After the flow model was developed, other parameters including color, ammonia, nitrate + nitrite, total phosphorus and long term wind data were tested for correlation with stream flow at each station. Color and

NH_3 significantly correlated to flows at all sites and were discarded. Same day TP and NO_2+NO_3 did not improve the model's fit and were not used. The combination of flow and wind data significantly improved the models. The new models with independent monthly intercepts predicted between 54-64% of the variation in the bottom DO saturation at the three stations.

A comparison of hypoxia with salinity stratification showed hypoxic conditions were accompanied by strong salinity and oxygen stratification on some sampling dates but were absent from others. Time series of delta salinity and delta percent saturation showed a strong seasonal agreement. Regressions were developed for both the delta salinity versus bottom percent DO saturation and for surface minus bottom percent saturation. Correlations ranged from 0.36-0.54 for linear, log, power and exponential trial fit. While the relationship was significant, the delta salinity only explained 55% of the variation.

Potential oxygen sinks were investigated as they relate to residence time, sediment oxygen demand (SOD) and biological oxygen demand (BOD) using total system volume and flow rates. Flushing rates of around 38 days for summer months were calculated for Charlotte Harbor proper. These values agreed with those found by Miller and McPherson (1991). The EPA conducted calculations of SOD during the 1980s. The range of SOD values in Upper Charlotte Harbor were 1.06-1.49 g $O_2/m^2/d$. In the absence of external oxygen inputs and a starting water column of 6.0 mg/l of O_2, in 6.7 days the resulting O_2 concentrations were calculated to be 2.0 mg/l O_2. BOD was monitored during limited sampling and averaged 2.1 mg/l. The authors calculated that the depletion of O_2 from 6 mg/l to 2mg/l would take about 7 days on average, which agreed with SOD calculations. Oxidation of algal biomass was also compared using date from the WASP model and modeling literature values. The authors assumed an algal bloom producing 50 g/l of chlorophyll. Using kinetic rates included in the WASP model, daily oxidation consumption would require approximately 19 days for the water column to go from 6.0 mg/l O_2 to 2 mg/l O_2. The lack of SOD and BOD correlation was noted with personal communication from A. Janicki, citing attempts to model algal cycles in Charlotte Harbor as disappointing.

Due to the lack of hypoxia, SWFWMD extended the monitoring component of the project into 1997 with the goal to monitor and understand the spread of hypoxia. On July 24, 1997, a Hydrolab Datasonde 7 was deployed and set at 15 minute intervals. Transects were conducted on July 31, August 4, and August 14 to characterize the spatial extent of hypoxia. Analysis of the data revealed that during large shifts in dissolved oxygen there was an inverse relationship between oxygen saturation and salinity. Shifts in dissolved oxygen occurred rapidly, with over 30% change in the course of several hours. Unfortunately, during the July 24 sampling several areas of super-saturation were recorded but there was no hypoxia observed.

In conclusion, the occurrence of hypoxia in Charlotte Harbor was significantly related to flow and wind speed, explaining 50% of the variation bottom water oxygen concentration. Salinity stratification was also prevalent during times of low oxygen which inhibited gas exchange and resulted in persistence of hypoxia through the late summer, peaking in September with a hypoxic zone of 34 mi^2.

Tomasko et al. (2006) investigated dissolved oxygen dynamics in Charlotte Harbor in response to Hurricanes Charley, Frances, and Jeanne. The unpredictability of storm occurrence, track and strength made directed studies of the impacts of hurricanes inherently difficult. Some research projects had studies underway when a hurricane impacted their study area, allowing them to measure direct responses from the storm. Following Hurricane Andrew, massive fish kills occurred in Everglades National Park, possibly from depleted oxygen levels (Tilmant et al., 1994). Hurricane Fran in 1996 caused severe dissolved oxygen deficits and high contaminant loading near Cape Fear, North Carolina, resulting in massive fish kills (Burkholder, 2004) and declines in total benthic abundance (Mallin et al., 1999; 2002). In 1999, three sequential hurricanes (Dennis, Floyd, and Irene) impacted Pamlico Sound, North Carolina, resulting in strong vertical stratification of the water column, bottom water hypoxia and a sustained increase in algal biomass (Paerl et al., 2001).

During August and September 2004, three hurricanes impacted the Charlotte Harbor watershed. The first hurricane, Hurricane Charley, was a category 4 storm with surface winds of 130 knots at landfall. Within the next six weeks, Hurricanes Frances and Jeanne struck the east coast of Florida, bringing high rainfall to the Charlotte Harbor watershed. In response to water quality concerns, water quality sampling was increased from monthly to weekly. Water quality station locations included Bartow (24 km), Fort Meade (11km), Wauchula (0 km), Zolfo Springs (4km), Charlie Creek near Gardner (6km), Arcadia (0km), Joshua Creek at Nocatee (2km), Peace River WSA Intake (0km), Horse Creek near Mayakka Head (26 km), Horse Creek near Arcadia (13 km), and Charlotte Harbor. The values in parentheses represent the distance from the eyewall of Hurricane Charley. Field sampling parameters included temperature, DO, and pH. Additional laboratory parameters included turbidity, total suspended solids (TSS), color, and biological oxygen demand.

Results showed that close proximity to the eyewall of Hurricane Charley impacted the presence of hypoxia. At Fort Meade, Charlie Creek, and Joshua Creek, DO concentrations were hypoxic. In Horse Creek, hypoxia was not found at Myakka Head, but it was found at Aracadia with closer proximity to the eyewall. In the upper and middle portion of the Peace River, oxygen levels took three months to recover to pre-Charley levels. All stations had elevated TSS (above the median but below the threshold for top 10%), color (all sites had values in excess of 200 PCU), and BOD (five of six sites had anoxia values higher than the threshold value for the highest 10% of values), indicating high amounts of dissolved organic matter.

Two reasons have been identified for increased hypoxia within Charlotte Harbor; stratification (Camp, Dresser & McKee, 1998), and increased organic loads (Turner et al., 2006). The authors stated that while hypoxia was a common occurrence throughout the watershed during the wet season (which coincides with warmer temperatures), the combined effects of Hurricanes Charley, Frances, and Jeanne resulted in widespread hypoxia specifically with close proximity to the eyewall of Hurricane Charley. Increased organic material caused increased BOD which lead to hypoxic conditions. Increased freshwater flow resulted in salinity stratification which increased the duration of hypoxic conditions. Hypoxic conditions in the harbor were resolved within 1 month due to shorter residence times as compared to 3 months of hypoxic conditions in the Peace River.

Turner et al. (2006) investigated water quality changes from 1800 to 2000 in Charlotte Harbor using sediment analysis from cores collected from the midsummer hypoxic zone. Four sediment cores 10 cm in diameter by 50 cm long were collected by divers at <2m depth from two locations. Biological and geochemical proxies were used to investigate the occurrence of low oxygen conditions and to hypothesize what caused the significant hypoxic zone which approaches 34 mi^2 in late summer in Charlotte Harbor Estuary. Paleo-indicators included biologically bound silica (BSi), which measures remnant diatom frustules, a direct measure of productivity. Phytoplankton pigments including chlorophyll *a* were used to examine the phytoplankton community and changes within this community. As eutrophication in coastal ecosystems increases biological species composition can change from more desired (diatoms) to less desired species (cyanobacteria). Carbon sources were evaluated to determine if they were terrestrial or in-situ in origin. Total Carbon and nitrogen and percentage organic carbon are often expressed as C:N ratios. The quality of organic matter also controls the balance between N mineralization or ammonification (the release of NH_4-N from decomposed organic matter) and incorporation of NH_4-N into bacterial biomass (Schlesinger 1997). At high C:N ratios, N is sequestered in biomass, whereas at lower ratios NH_4-N is released. Grain size determines how much organic matter is found within the sediments and may be a good proxy of overall ecosystem organic matter. Elemental analysis for trace metals were analyzed and included Al, Rn, Pb, Ba, Ca, Cd, Cu, Fe, Mn, P, S, Si, and V.

Results of the analyses showed oxygen concentrations in the estuary varied from greater than 100% saturation in surface waters to 0% saturation in bottom waters. Oxygen concentrations declined from 1975 to 1995 but returned to pre-1975 values by 1998. The authors found that long-term declines in river flow affected the oxygen dynamics by raising salinity which increased stratification. Linear regression analysis showed a 3.36% decline in oxygen saturation for a one μg/L increase in chlorophyll *a*. A linear regression between chlorophyll *a* and total nitrogen yielded an r^2 of 0.24. In summary, phytoplankton production was related to nitrogen loading and increased N loading led to increased oxygen consumption.

Total carbon and sediment density increased in all cores sampled. Percent organic C increased around 1950 which implied greater loading via phytoplankton. Calculations of estimated carbon loading demonstrated a carbon accumulation rate of 59 mg C m^{-3} h^{-1} for a 2.4 m water column (McPherson et al. 1990). The authors believe this high carbon accumulation was from primary production by phytoplankton, although alternate explanations could be from allochthonous inputs from terrestrial sources.
Results from elemental analysis showed increases in S isotopic composition with time, which was consistent with increased organic loading and reducing conditions with lower

oxygen concentrations. The concentration of biogenic silica BSi increased from 1900 onward, which is indicative of pelagic rather than terrestrial sources of organic carbon. As BSi increased, δ^{14} S values became heavier, which may indicate a link between algal production and higher sulfate reduction.

Phytoplankton pigment results showed higher concentrations of flucoxanthin, an indicator of diatoms. Zeaxanthin, an indicator of cyanobacteria, were higher in the upper sections of the sediments. No cyanobacteria traces were found in Charlotte Harbor sediments from 1800-1925, indicating that cyanobacteria were not present in Charlotte Harbor during this time.

Overall, the authors provided two hypotheses for the rise in organic matter in sediments since the 1950s. The first was the "eutrophication" hypothesis which concluded that production and deposition occurred from within the water column. The second hypothesis was the "watershed" hypothesis which assumed materials washed in from allochthonous sources. C:N ratios and δ^{13}C were more consistent with the eutrophication hypothesis because of sources of more local origin. The authors used an inverse graphing technique and a mixing model, both of which demonstrated increases in organic C resulted from algal inputs and not terrestrial origin. In conclusion, the authors believe the data showed that phytoplankton in Charlotte Harbor estuary were nitrogen limited and nitrogen loading increased. This increase resulted in in-situ organic loading which expanded hypoxic water formation during the summer months.

3.0 DATA SOURCES

Ambient water quality data were obtained from the following agencies and programs:

- City of Cape Coral (CCC),
- Coastal Charlotte Harbor Monitoring Network (CCHMN),
- Florida Fish and Wildlife Conservation Commission Fisheries Independent Monitoring Program (FFWCC),
- Florida International University (FIU),
- Lee County (LeeCo),
- Peace River Manasota Regional Water Supply Authority (PRMRWSA),
- Sarasota County (SarCo), and
- South Florida Water Management District (SFWMD).

In addition to the above water quality data, data were available from the Charlotte Harbor Estuaries Volunteer Water Quality Monitoring Network. However, DO data from the volunteer network were not included in our analyses as the sampling protocol calls for samples to be collected at sunrise, often in shallow near shore waters. As noted by Duffey et al. (2007), "Because of this sampling design, the results represent the lowest daily DO values found following night-time absence of photosynthesis combined with community respiration. In addition, shallow, near shore DO results may exhibit low values as a result of consumption of oxygen via decomposition of organic materials from shoreline vegetation."

In total, 48,192 DO observations were analyzed from 19,777 sampling stations in the segments of the CHNEP. It should be noted that there is a bias toward daytime sampling in the available data. Several sampling programs use a fixed station sampling design (FIU, PRMRWSA, SarCo, and SFWMD) while others use a random sampling design (CCC, FFWCC, and CCHMN). Lee County (LeeCo) uses a combination of random and fixed station sampling. The Sarasota County water quality sampling station locations are presented in Figure 3-1. The fixed station sampling locations from PRMRWSA, SFWMD, and FIU are presented in Figure 3-2. The sampling station locations for CCHMN, City of Cape Coral, and Lee County are presented in Figure 3-3. Lastly, the water quality sampling locations from the Fisheries Independent Monitoring of the FFWCC are presented in Figure 3-4. The total number of DO observations in each year from 1996 through 2009 is provided for each segment in Figure 3-5 through 3-15. For convenience, all data in this report are presented from north to south.

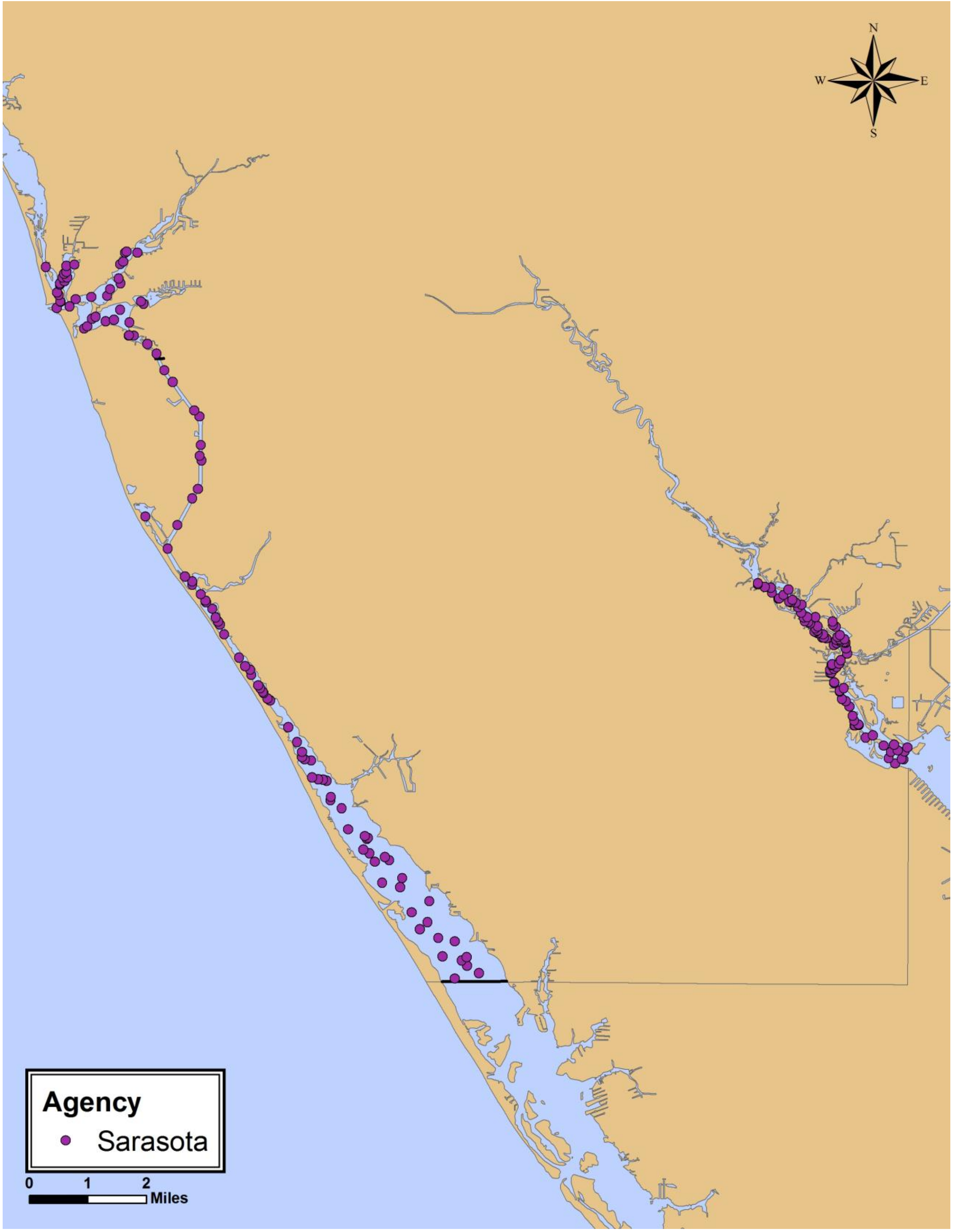

Figure 3-1. Sarasota County ambient water quality sampling station locations.

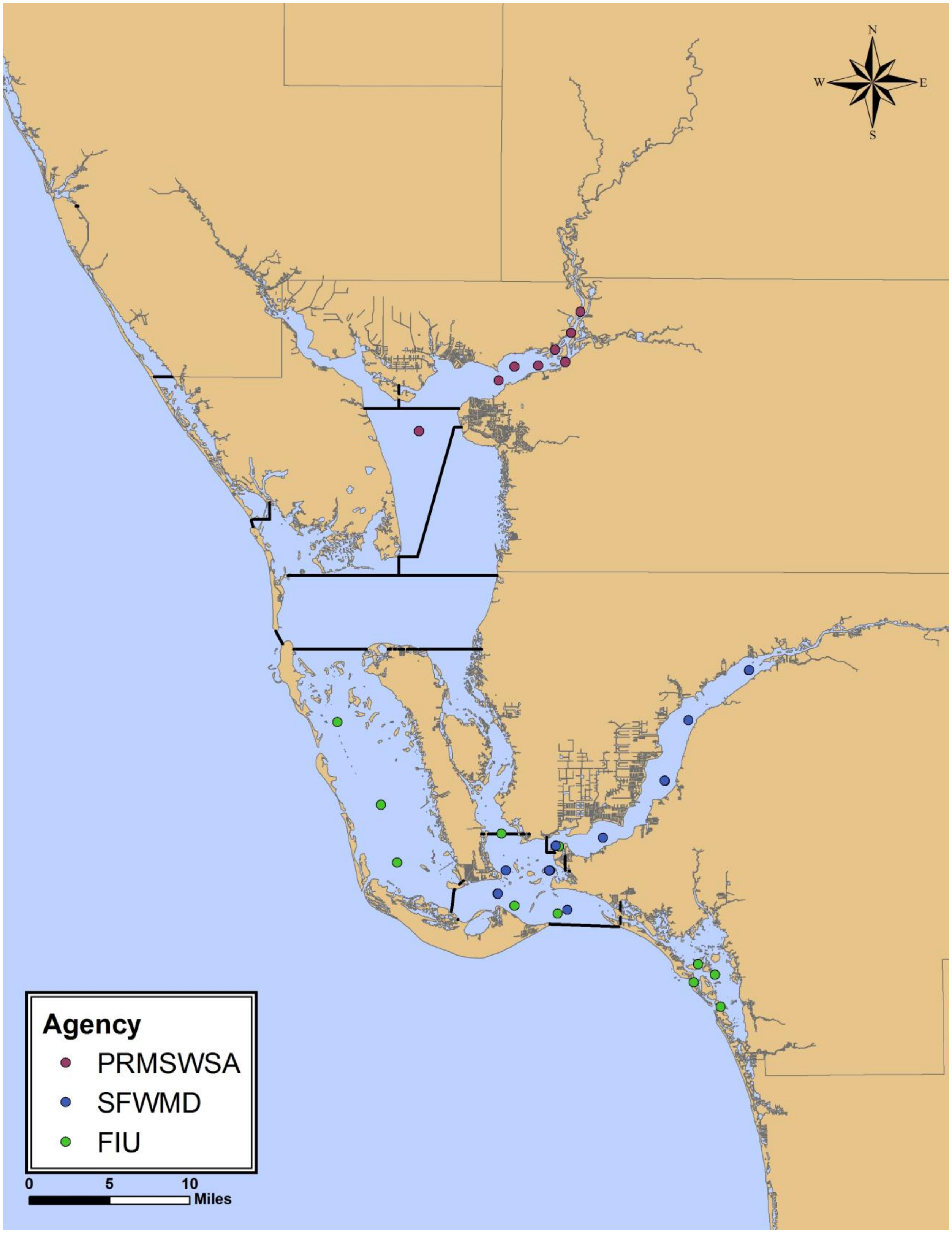

Figure 3-2. PRMRWSA, SFWMD, and FIU ambient water quality sampling station locations (black lines represent estuarine segment boundaries).

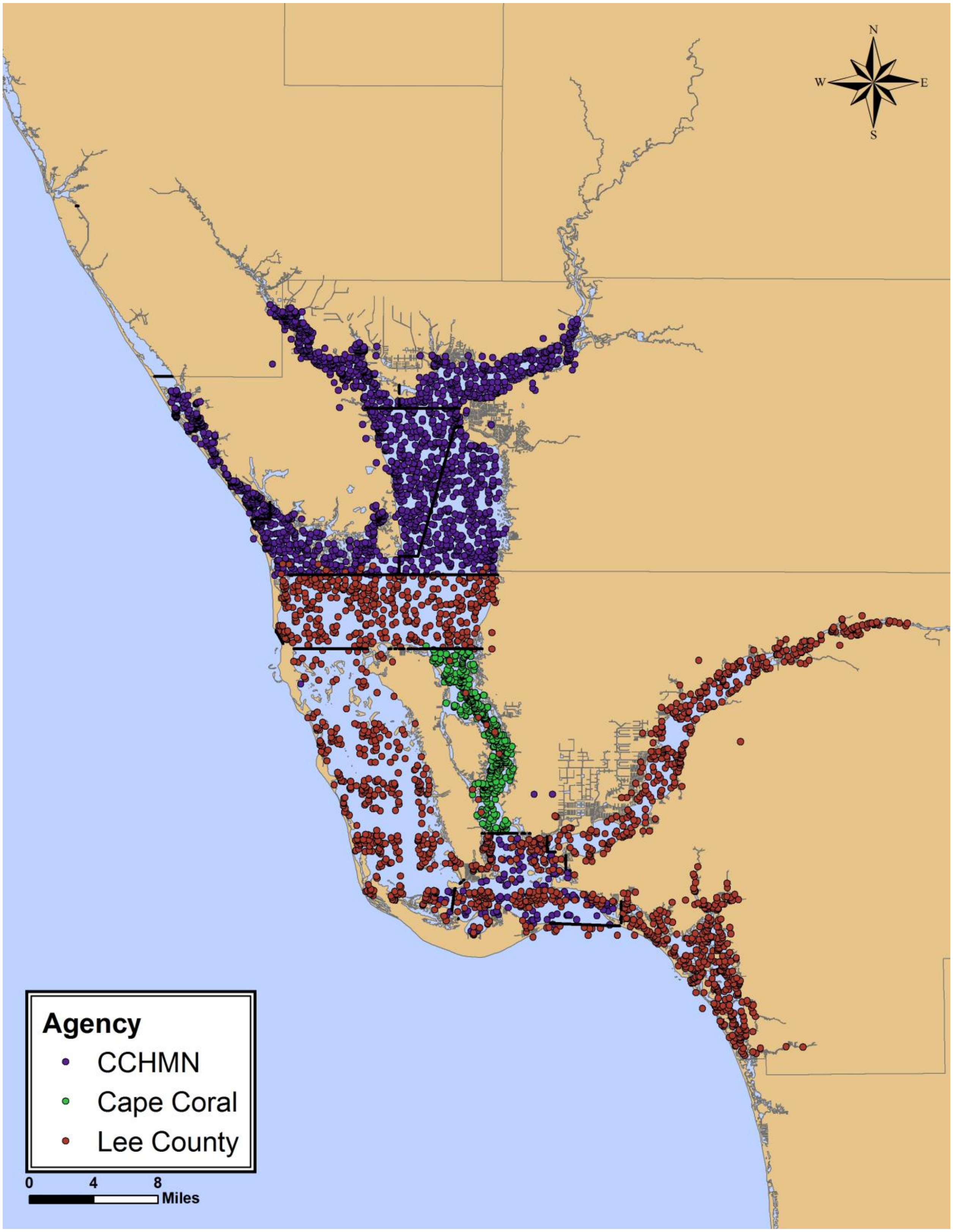

Figure 3-3. CCHMN, City of Cape Coral and Lee County ambient water quality sampling station locations (black lines represent estuarine segment boundaries).

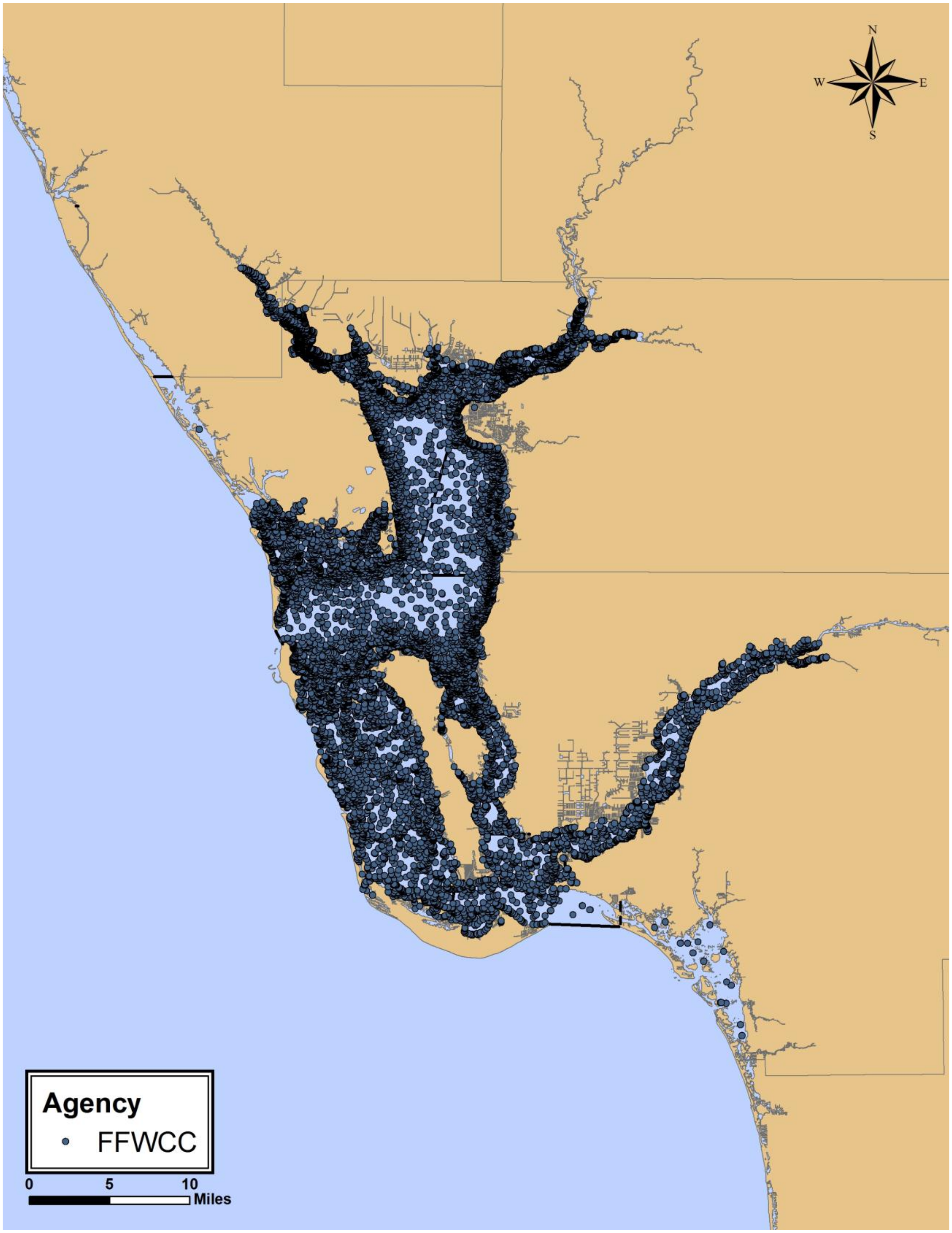

Figure 3-4. FFWCC water quality sampling station locations (black lines represent estuarine segment boundaries).

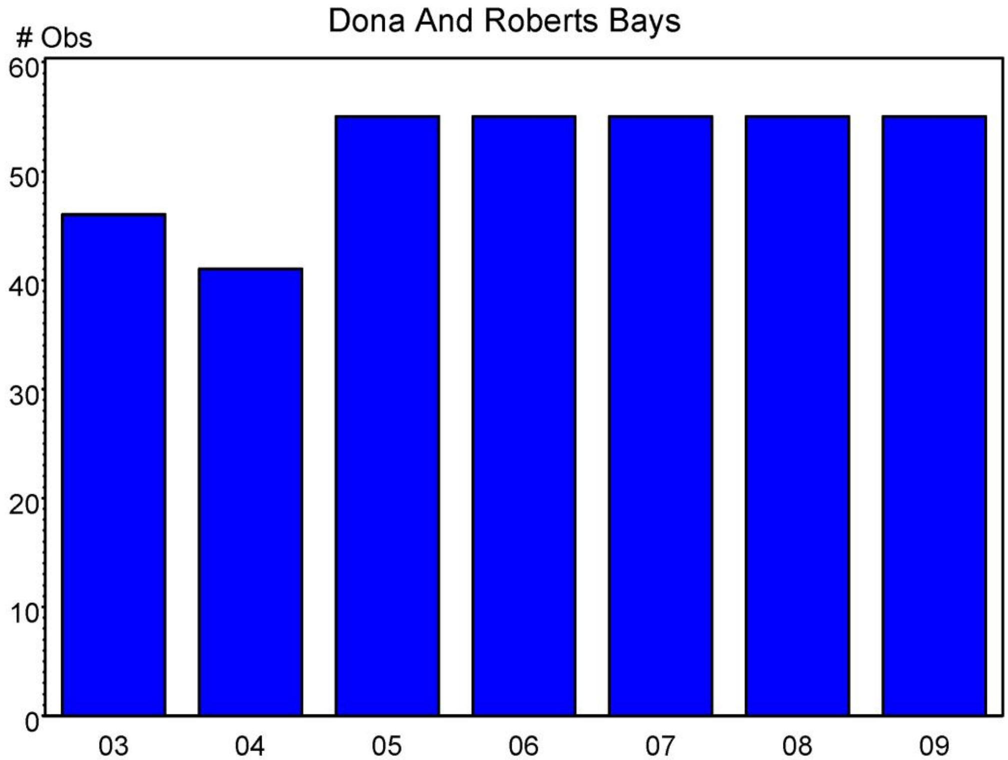

Figure 3-5. Number of total DO observations, Dona and Roberts Bays.

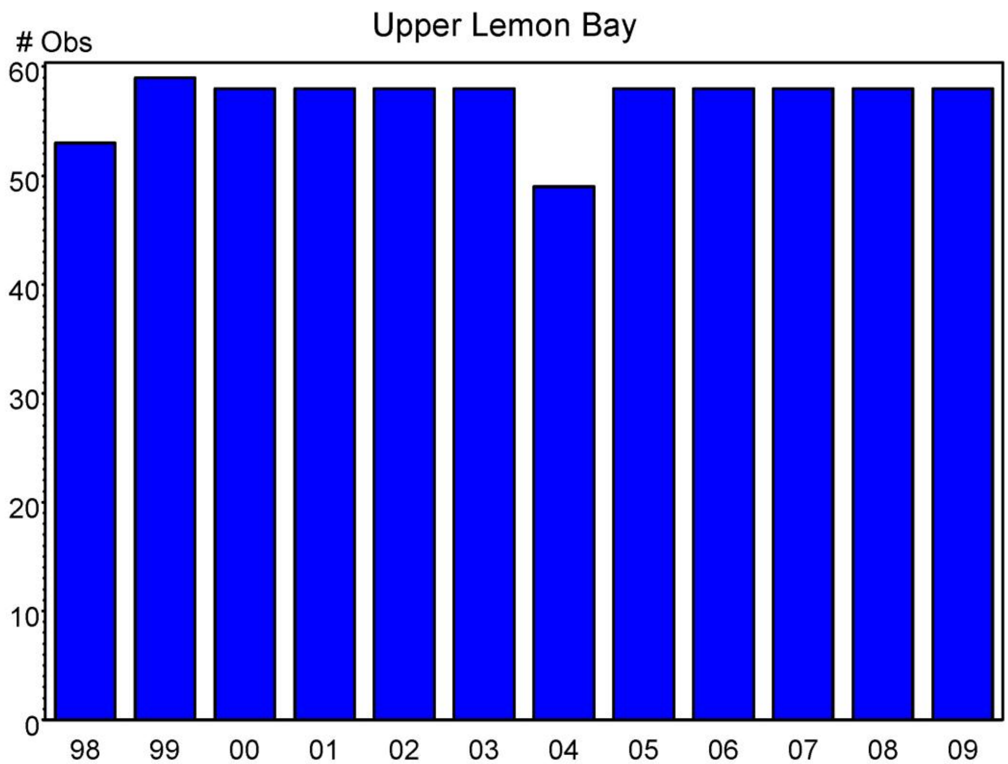

Figure 3-6. Number of total DO observations, Upper Lemon Bay.

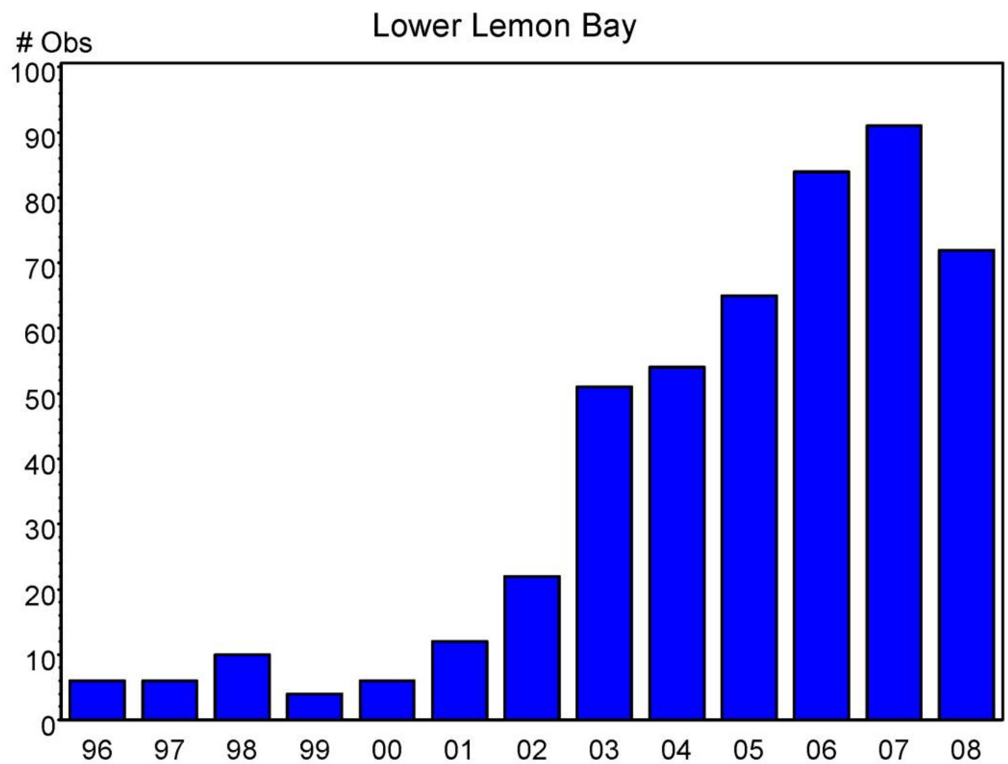

Figure 3-7. Number of total DO observations, Lower Lemon Bay.

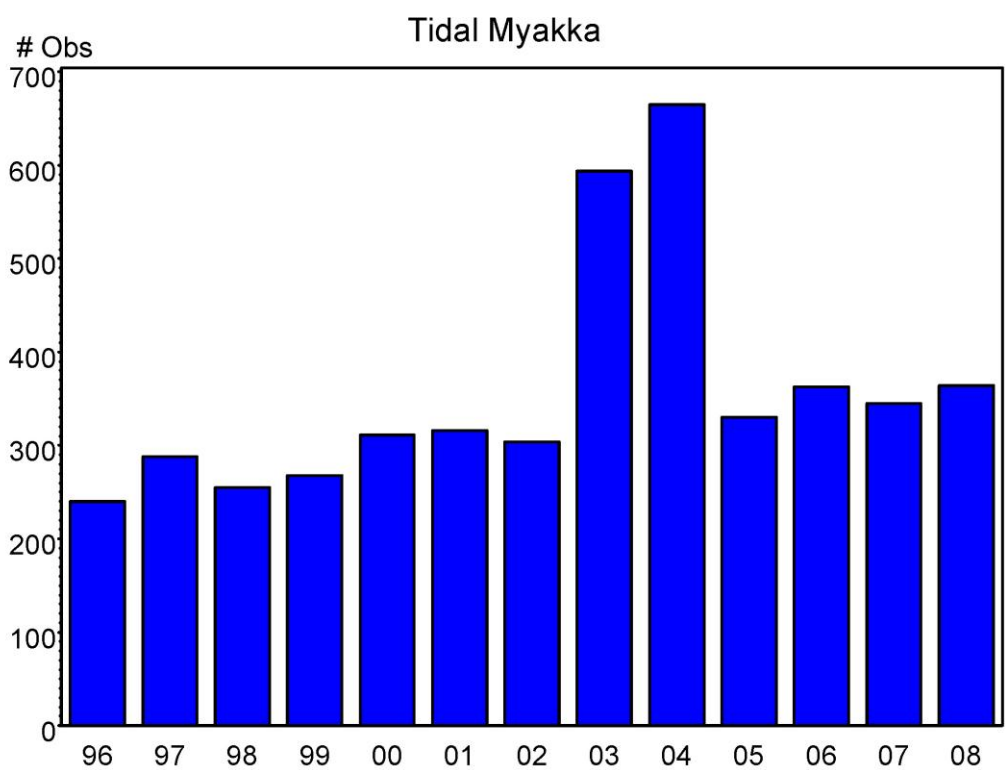

Figure 3-8. Number of total DO observations, Tidal Myakka River.

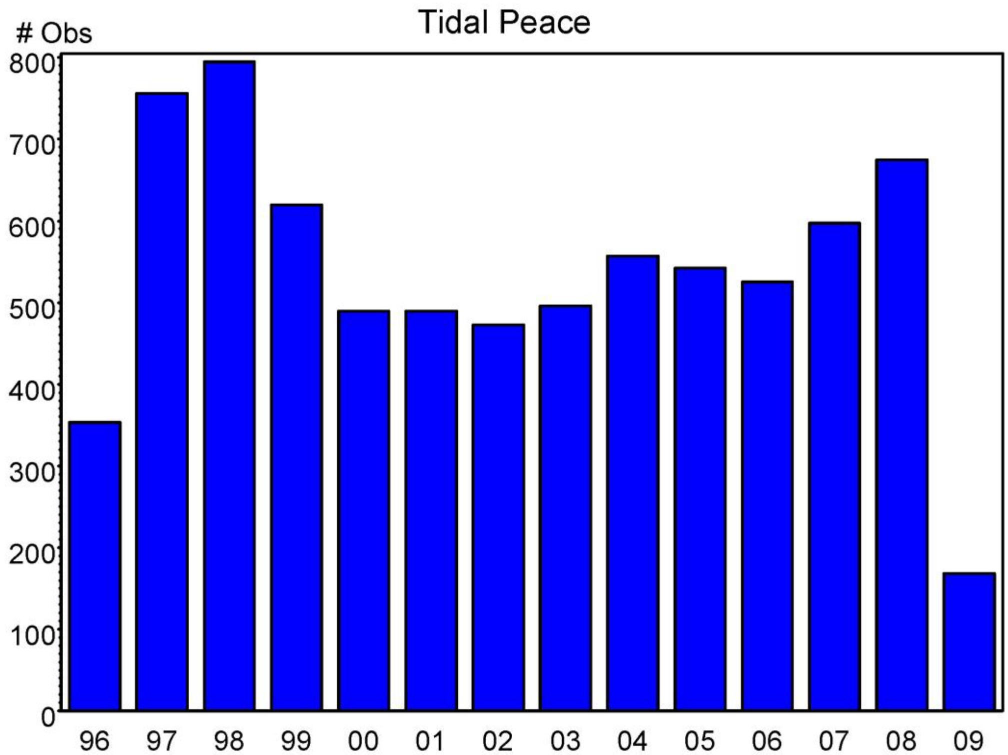

Figure 3-9. Number of total DO observations, Tidal Peace River.

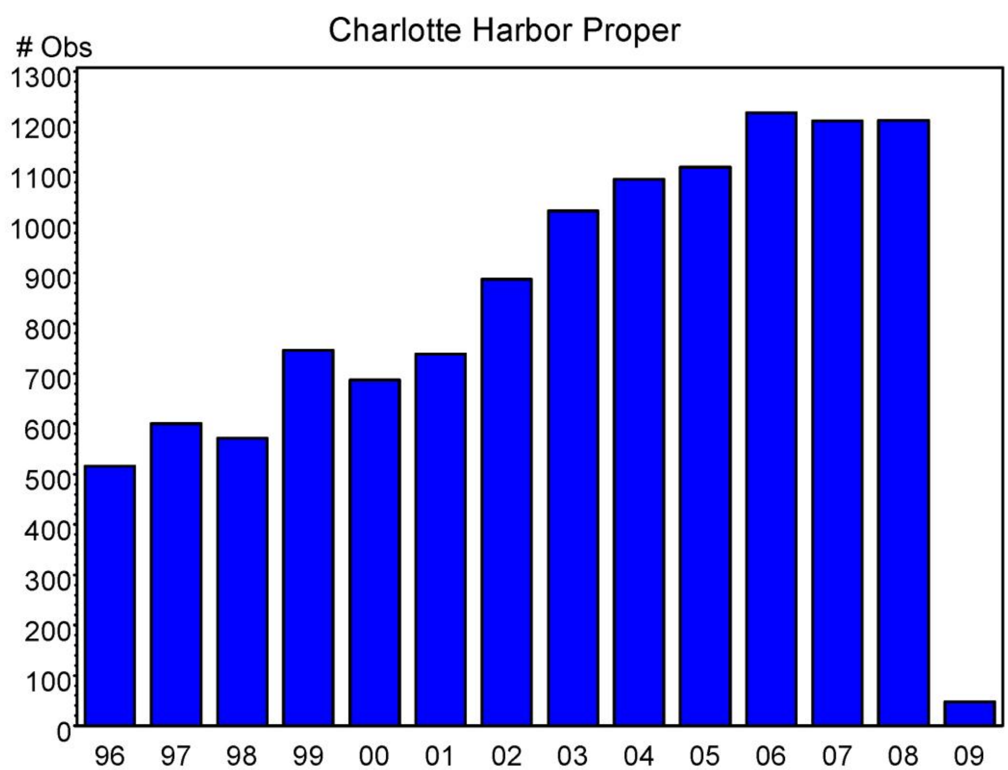

Figure 3-10. Number of total DO observations, Charlotte Harbor Proper.

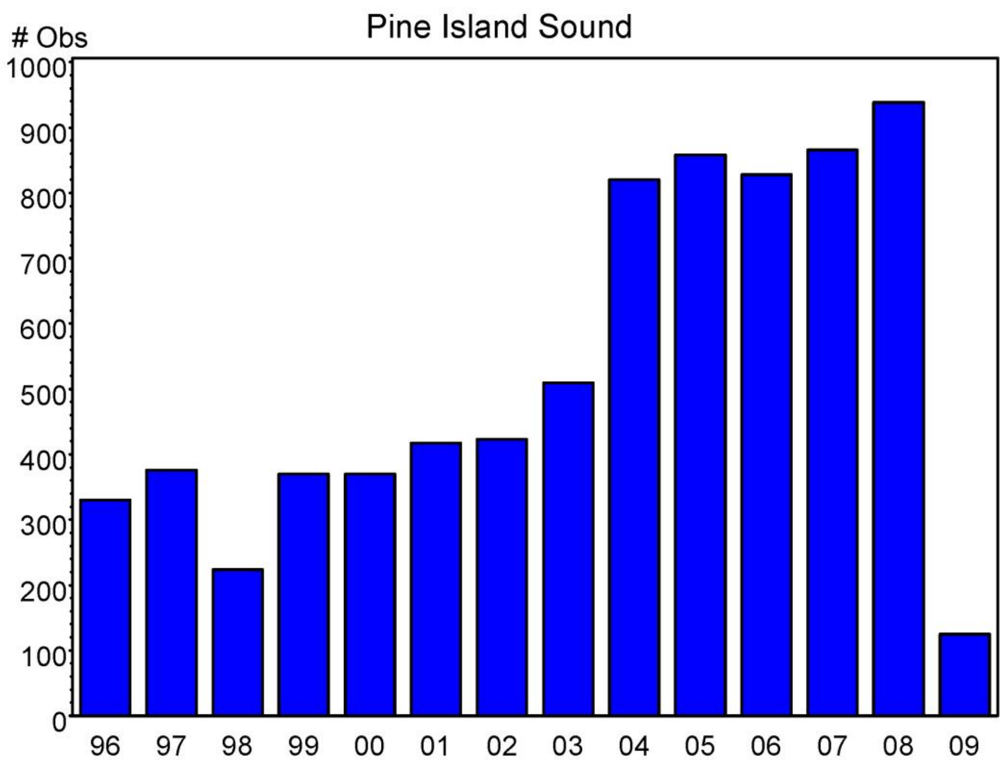

Figure 3-11. Number of total DO observations, Pine Island Sound.

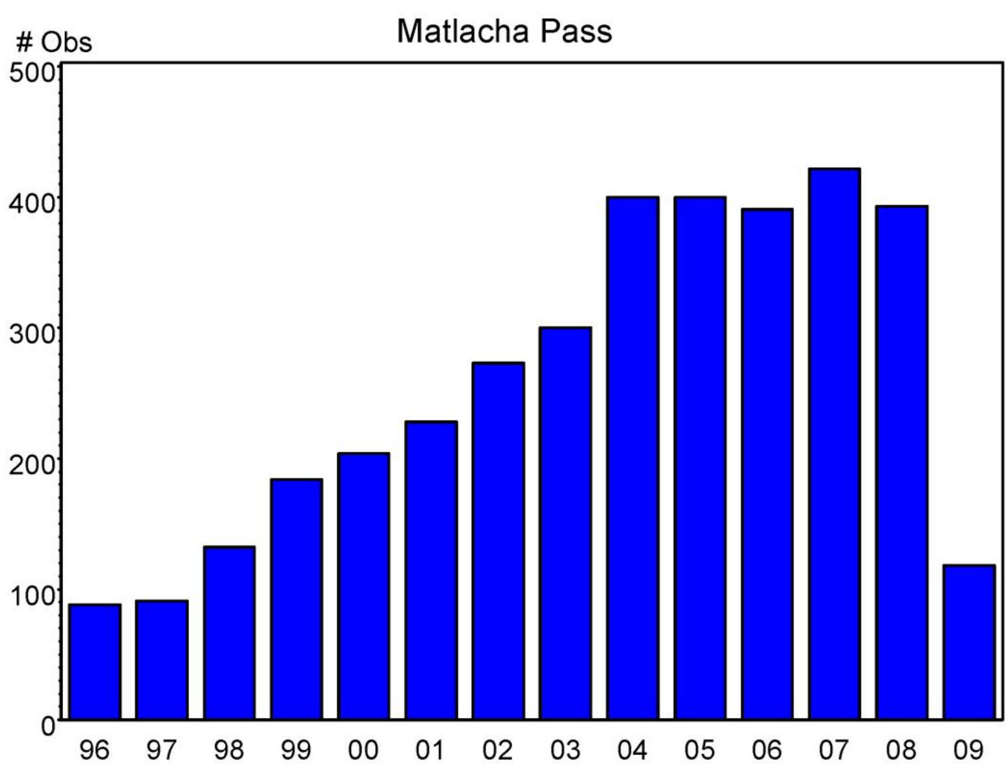

Figure 3-12. Number of total DO observations, Matlacha Pass.

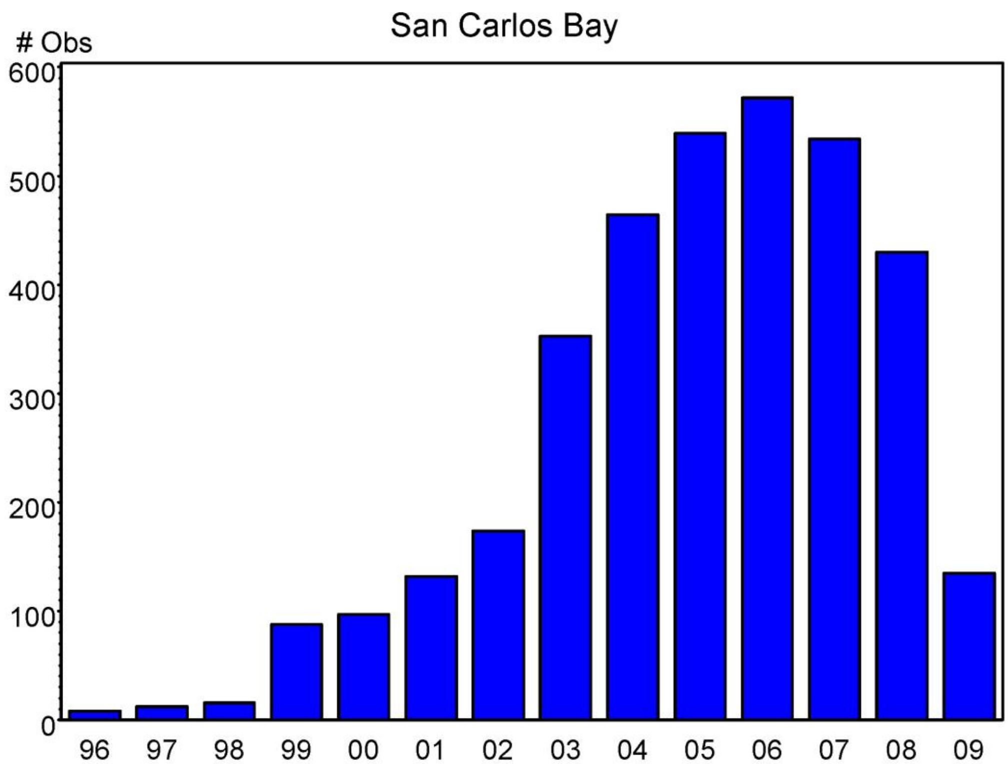

Figure 3-13. Number of total DO observations, San Carlos Bay.

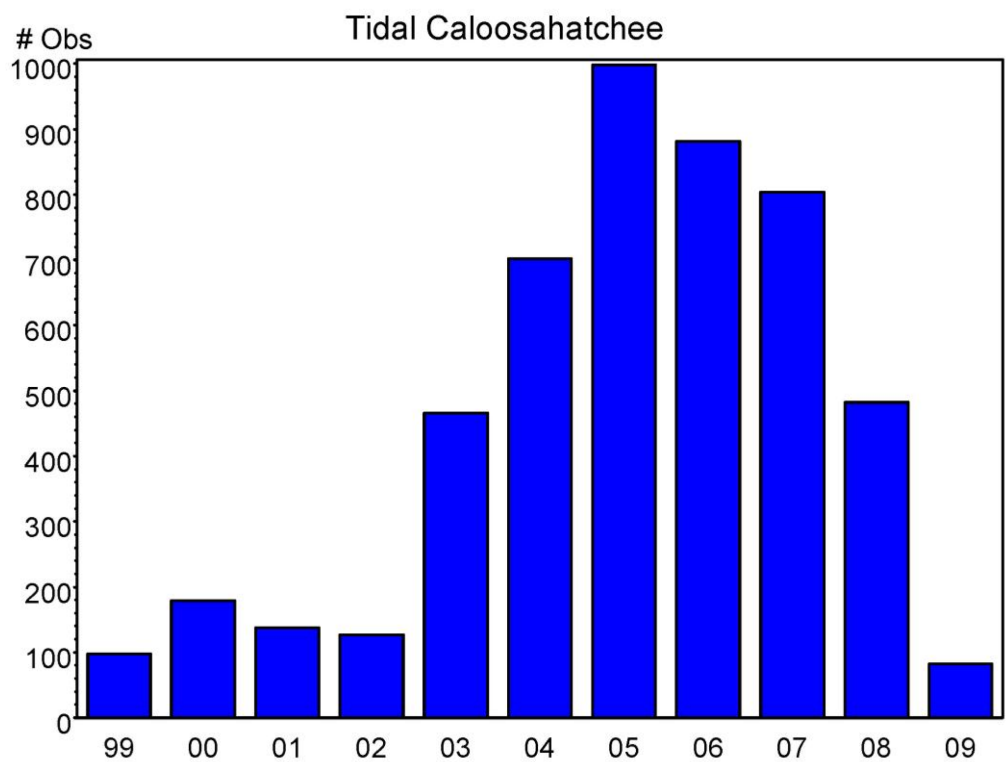

Figure 3-14. Number of total DO observations, Tidal Caloosahatchee River.

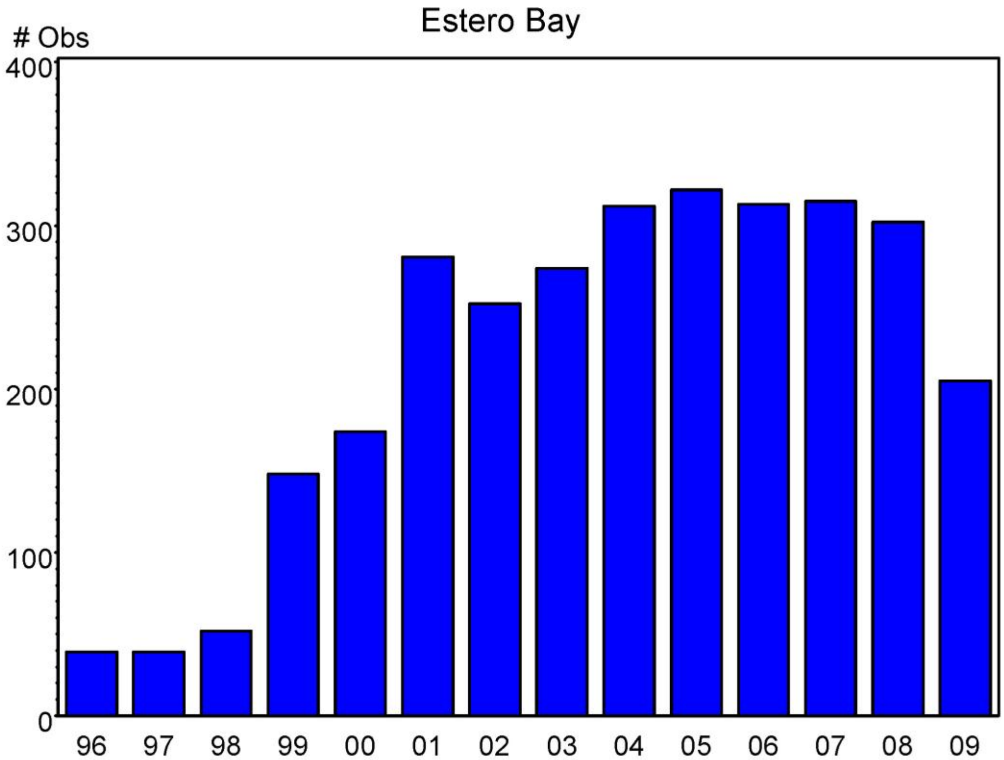

Figure 3-15. Number of total DO observations, Estero Bay.

4.0 APPROACH

Descriptive and quantitative analytical techniques were applied in this assessment. The data were mapped using ArcGIS (ESRI, 2009) to allow examination of the spatial representation of the sampling within the CHNEP area. Spatial and temporal variation in DO was investigated using a series of ArcGIS maps and descriptive plots. An exploratory data analysis was conducted to investigate the factors affecting dissolved oxygen concentrations in the bay segments using logistic regression models to estimate the probability of a dissolved oxygen value less than 4 mg/l as a function of potential drivers of dissolved oxygen in the segments of the CHNEP area.

5.0 RESULTS

In this section, the following results are presented:

- examination of the temporal in DO exceedances in each segment,
- examination of the spatial patterns in DO in each segment, and
- analysis of the factors affecting the probability of DO exceedances.

5.1 Temporal Patterns in DO exceedences

The first step in the analysis was to examine the temporal patterns in DO concentrations in each bay segment. Time series plots of all DO measurements are presented in Figures 5-1 through 5-11. A different symbol was used for the different sampling programs. As expected, the seasonal pattern of lower DO concentrations in the warmer summer months and higher DO concentrations in the colder winter months is seen in all segments. As discussed in Section 1.0, the FDEP has established the state water quality standards (FAC 62.302) to protect the designated uses of Florida waterbodies. The state standard for DO is greater than or equal to 4 mg/l in predominantly marine waters at all times. The IWR declares a predominantly marine waterbody to be impaired if DO is less than 4 mg/l more than 10% of the time (i.e., a 10% exceedance). Therefore, a horizontal reference line at 4 mg/l is presented on the time series plots to aid the reader in identifying measurements that are less than the 4 mg/l. Additionally, vertical reference lines are presented to assist the reader in identifying the 2003-2007 reference period.

In order to determine if the segments are meeting the DO threshold, the annual exceedance percentage (i.e., the proportion of the total number of DO samples collected within a year that are less than 4 mg/l) for each segment is presented in Figures 5-12 through 5-22. The data presented in these figures include all DO samples from all programs regardless of sample depth.

Of the eleven segments, five segments (Upper Lemon Bay, Tidal Myakka, Tidal Peace, Matlacha Pass, and Tidal Caloosahatchee) had at least one year in which the annual proportion of DO < 4 mg/l was greater than 10%. The remaining six segments did not have any years with a DO exceedence. Of all the segments, San Carlos Bay had the fewest number of DO observations < 4 mg/l.

The within-year variation in the percentage of samples less than 4 mg/l for each bay segment is shown in Figures 5-23 through 5-33. The influence of temperature and salinity on the capacity of estuarine water to hold oxygen is evident. There are very few values below 4 mg/l in winter months (November – March), while in summer months (June – September) a higher preponderance of observations with a DO value below 4 mg/l is documented in all segments. As noted in the annual exceedence percentages, San Carlos Bay has the lowest percentage of DO exceedences with a maximum exceedence of 6.3% in September.

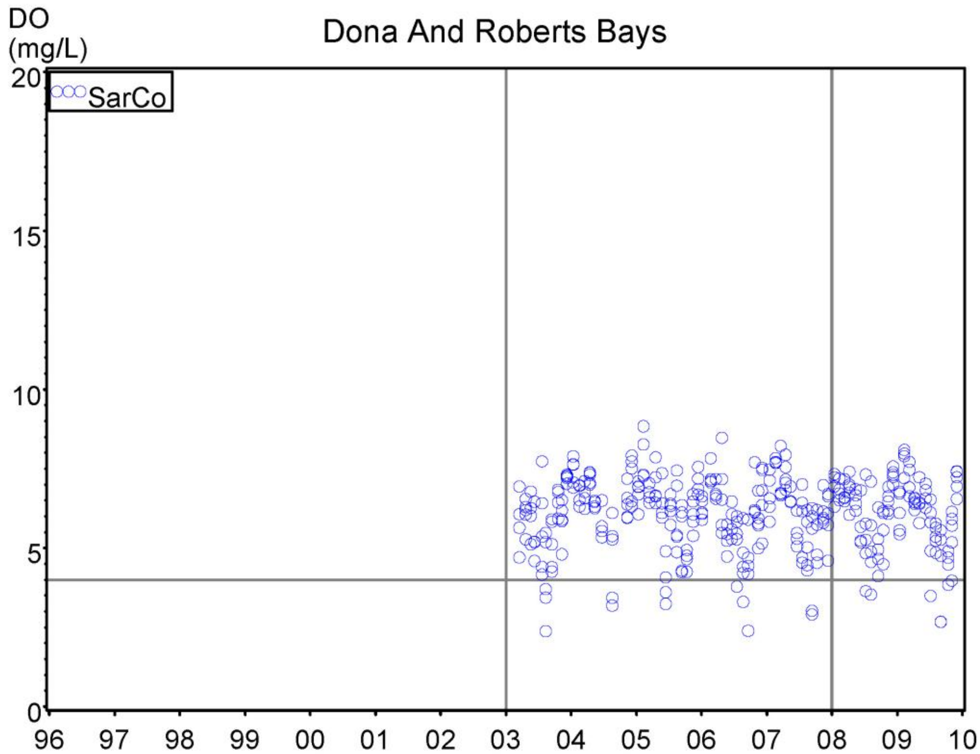

Figure 5-1. Time series of DO concentrations, Dona and Roberts Bays.

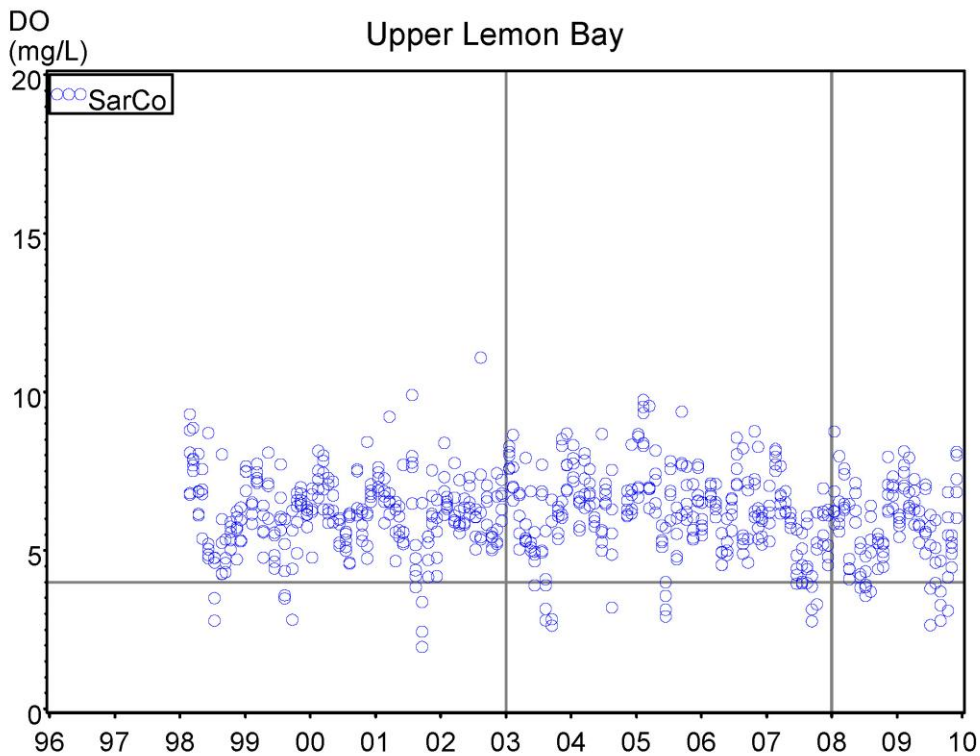

Figure 5-2. Time series of DO concentrations, Upper Lemon Bay.

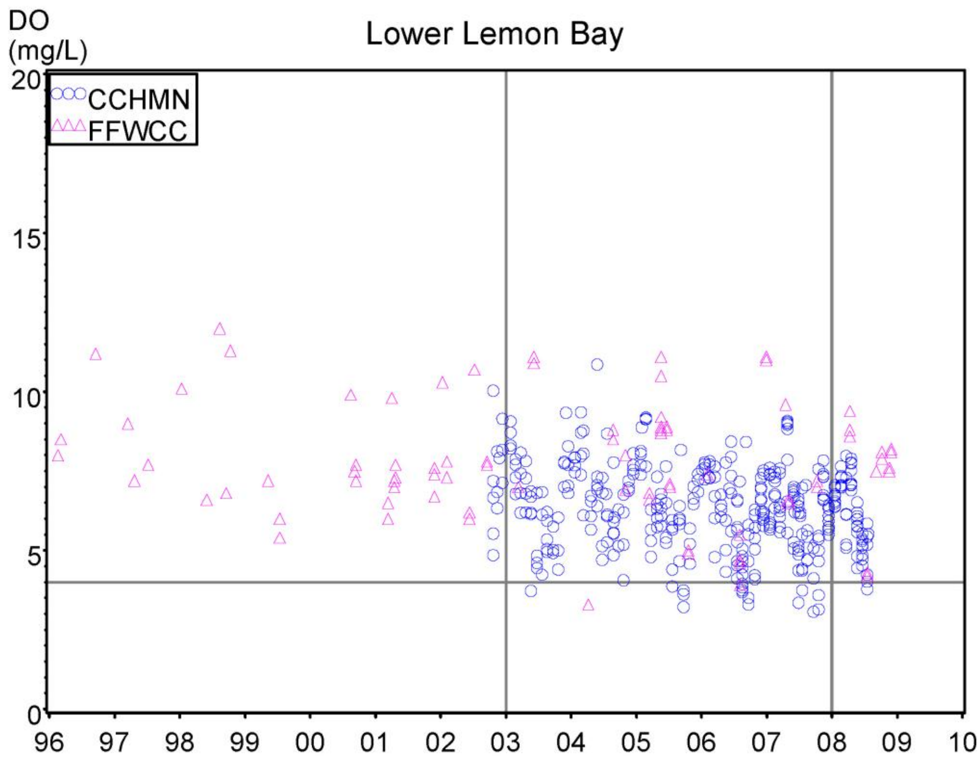

Figure 5-3. Time series of DO concentrations, Lower Lemon Bay.

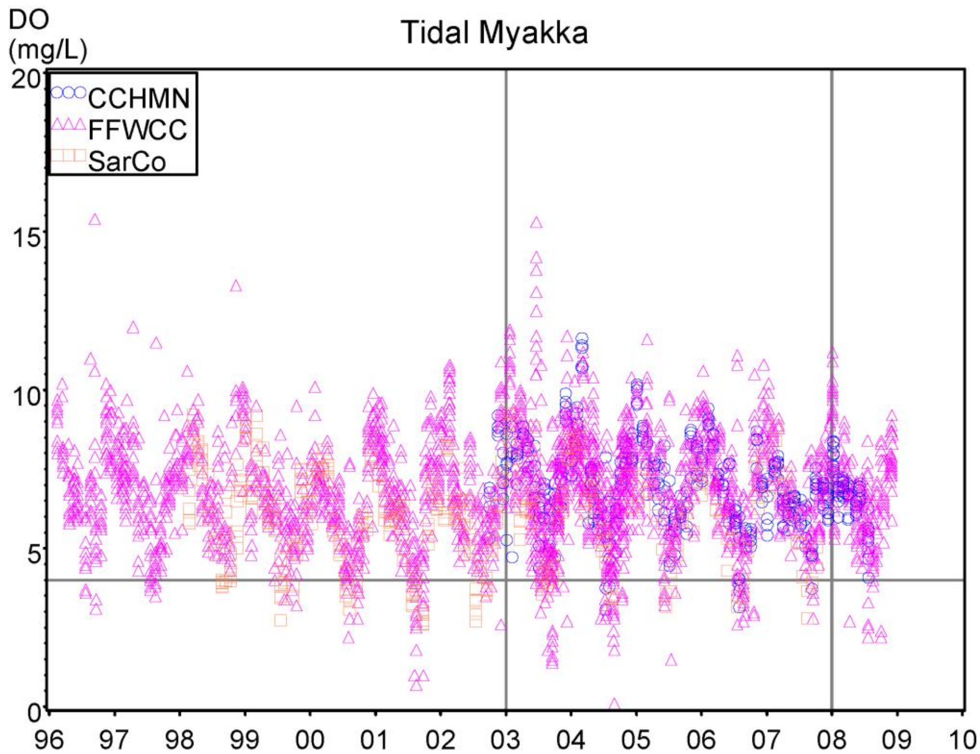

Figure 5-4. Time series of DO concentrations, Tidal Myakka River.

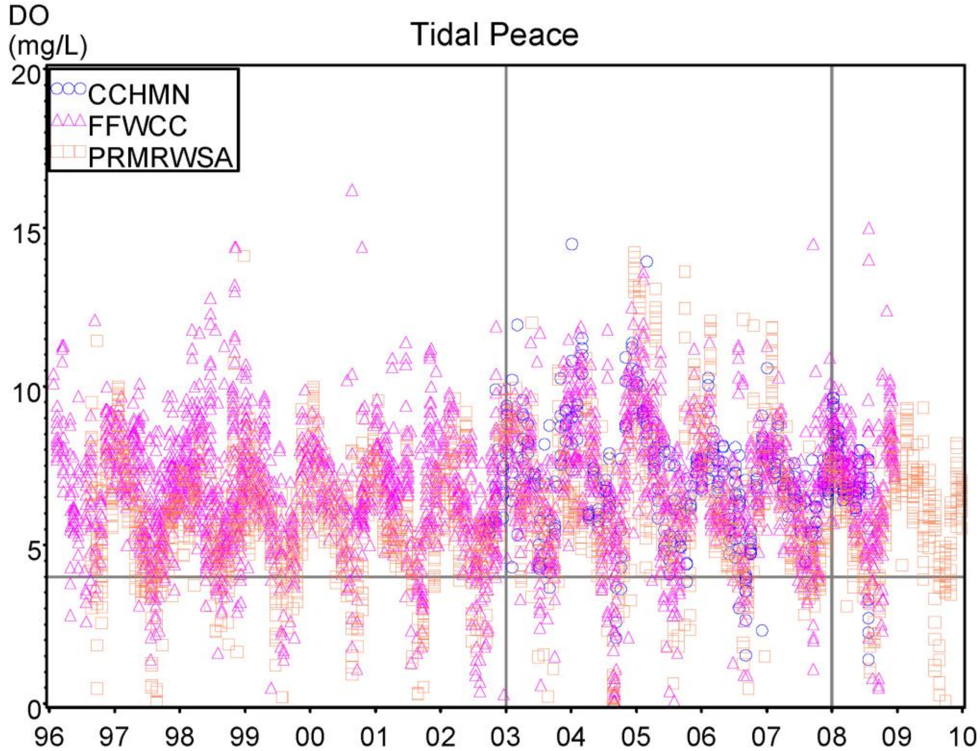

Figure 5-5. Time series of DO concentrations, Tidal Peace River.

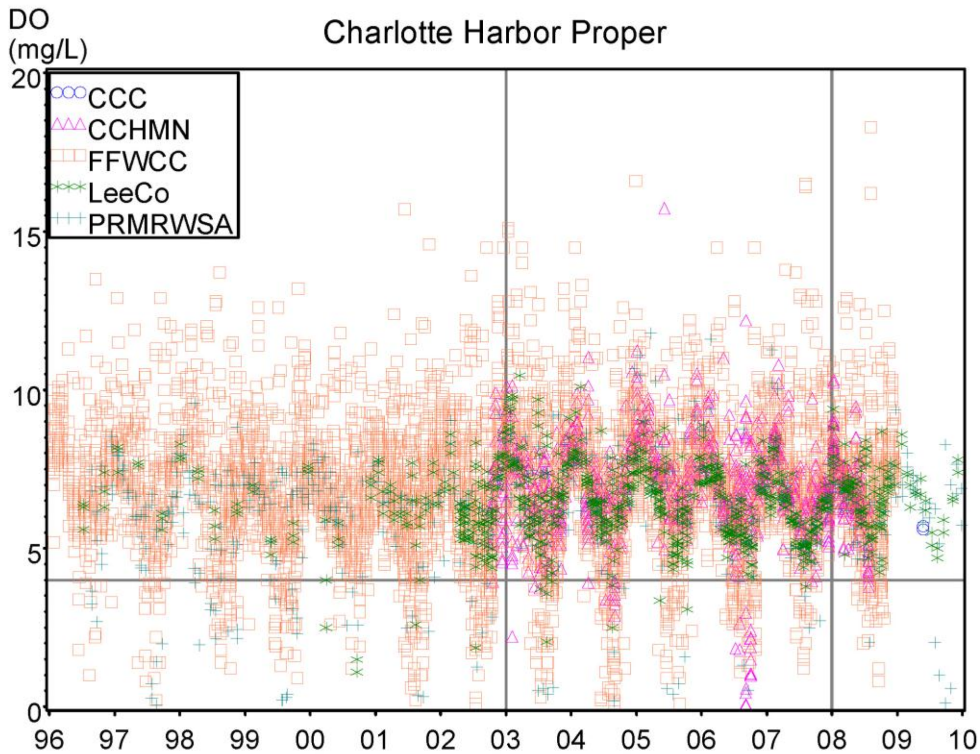

Figure 5-6. Time series of DO concentrations, Charlotte Harbor Proper.

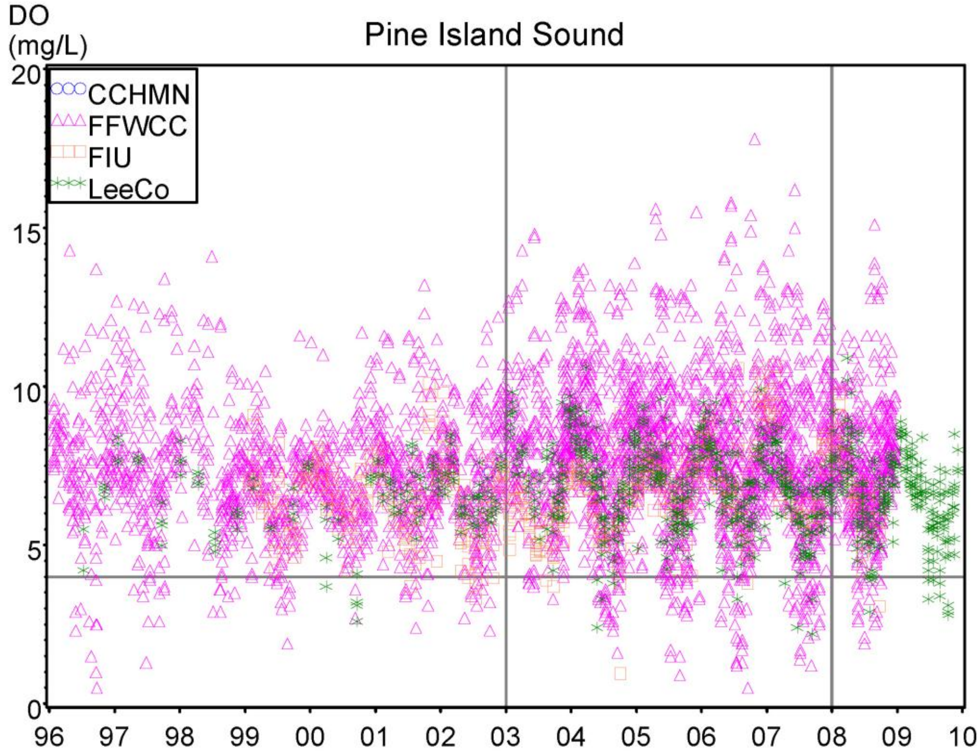

Figure 5-7. Time series of DO concentrations, Pine Island Sound.

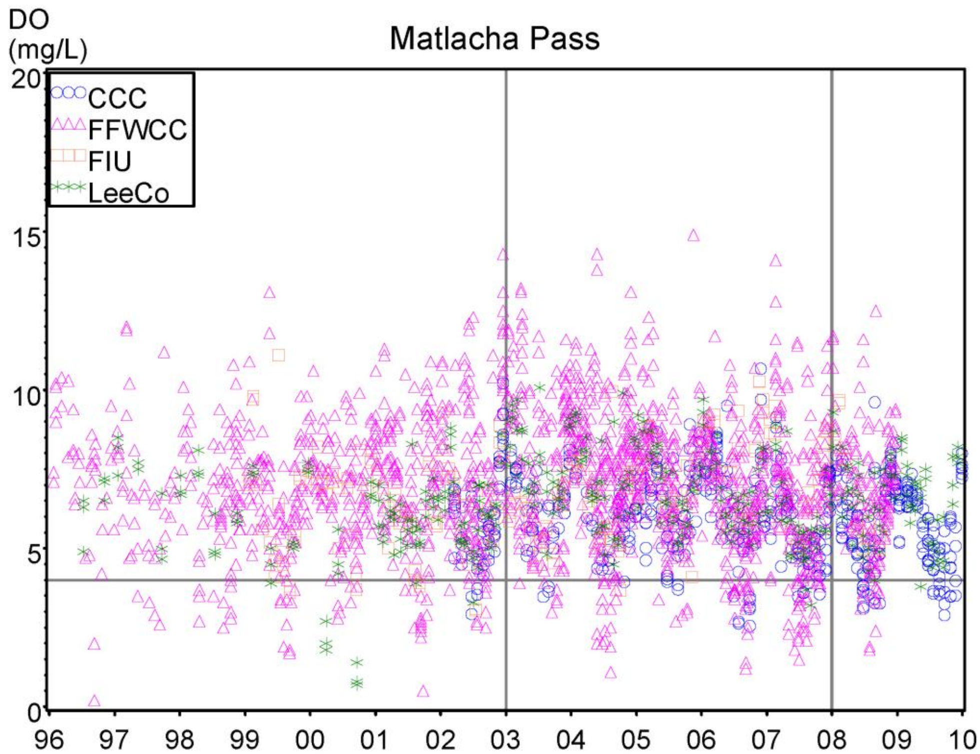

Figure 5-8. Time series of DO concentrations, Matlacha Pass.

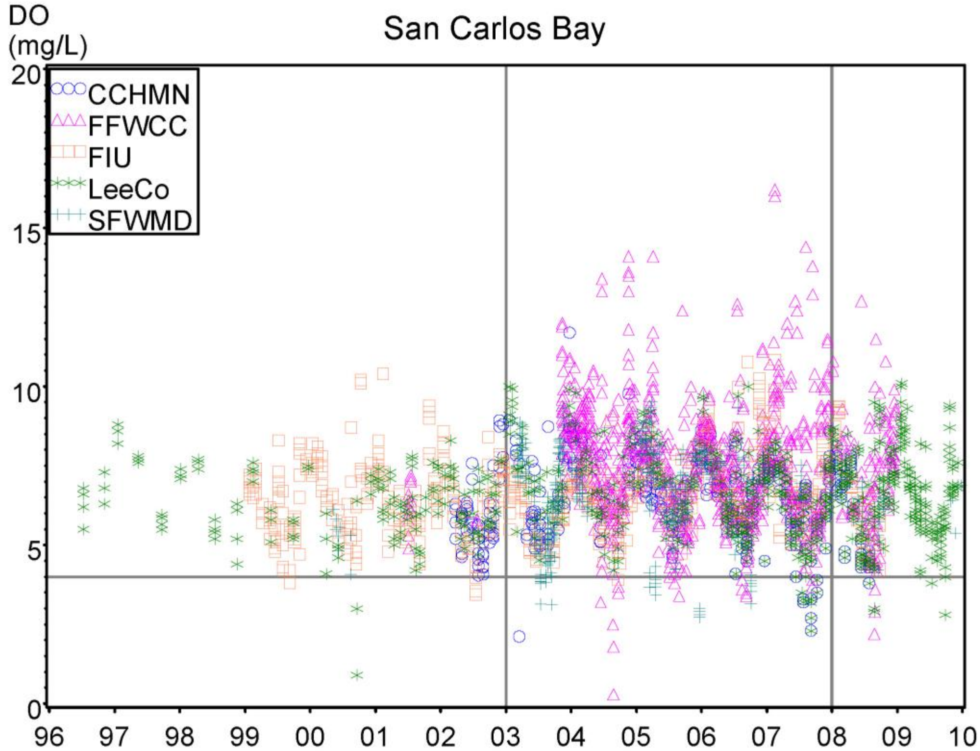

Figure 5-9. Time series of DO concentrations, San Carlos Bay.

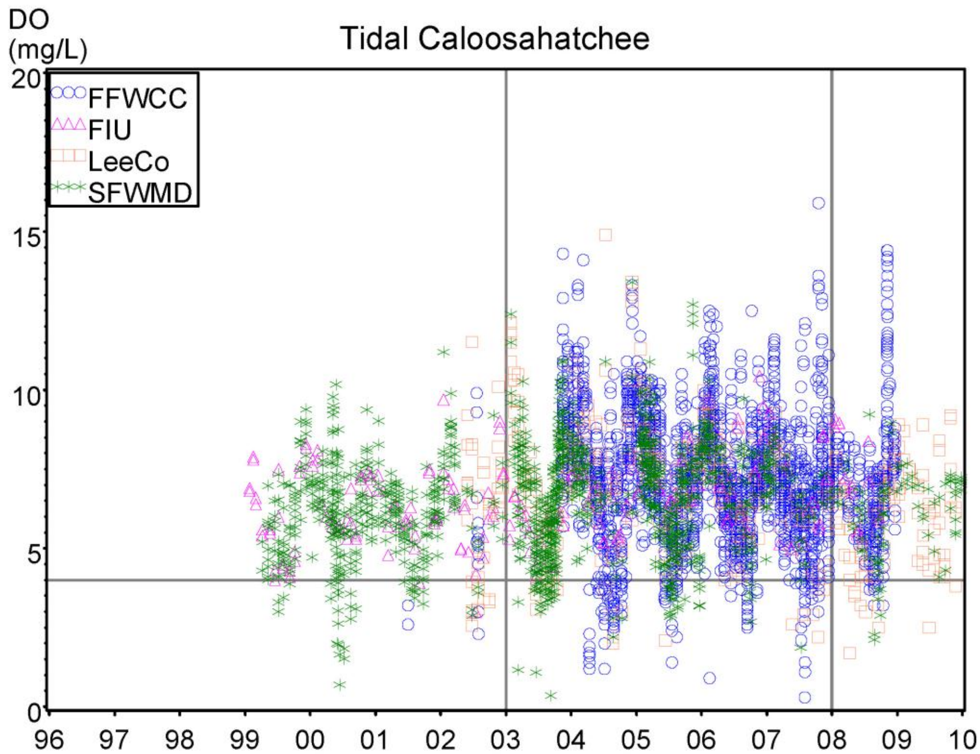

Figure 5-10. Time series of DO concentrations, Tidal Caloosahatchee River.

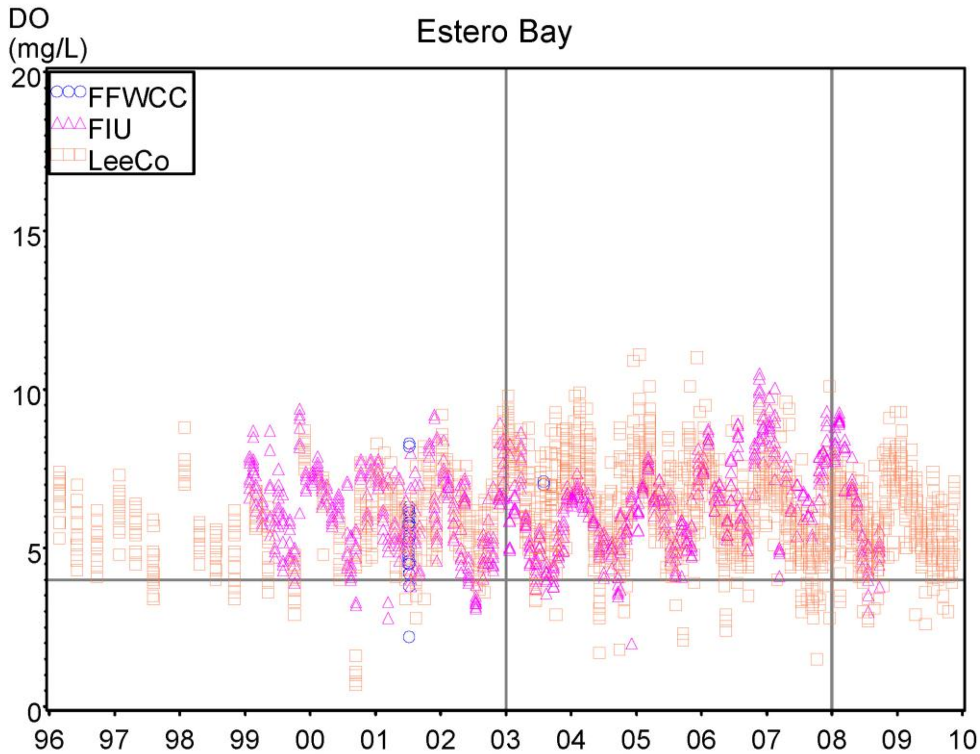

Figure 5-11. Time series of DO concentrations, Estero Bay.

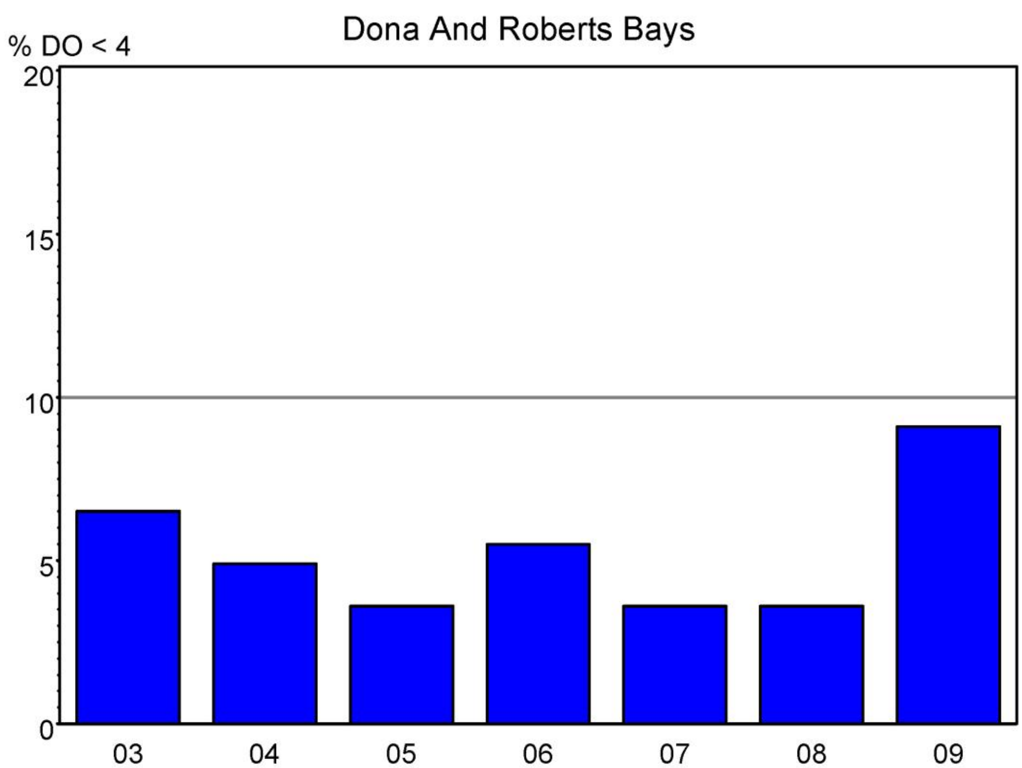

Figure 5-12. Percent of DO exceedences by year, Dona and Roberts Bays.

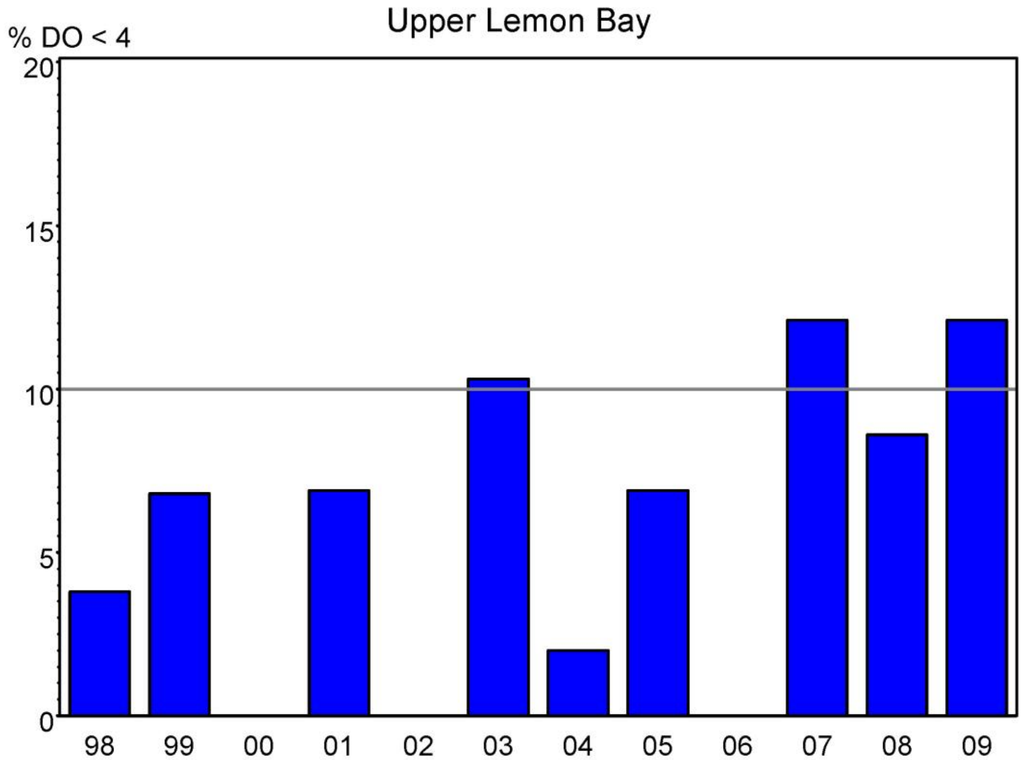

Figure 5-13. Percent of DO exceedences by year, Upper Lemon Bay.

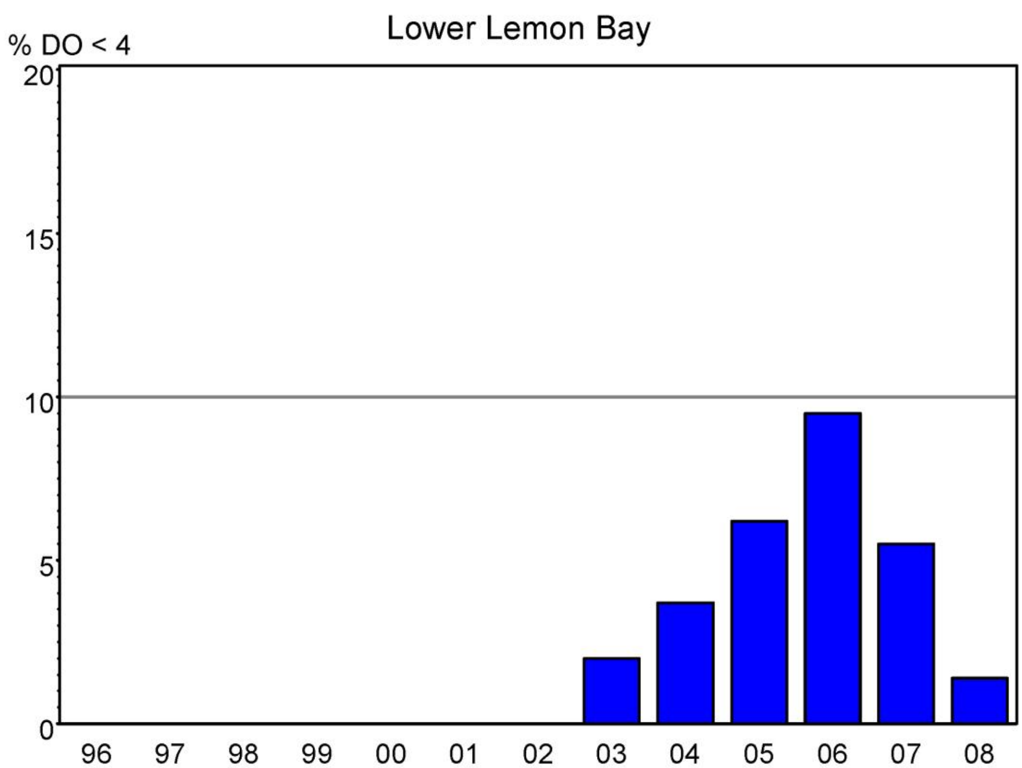

Figure 5-14. Percent of DO exceedences by year, Lower Lemon Bay.

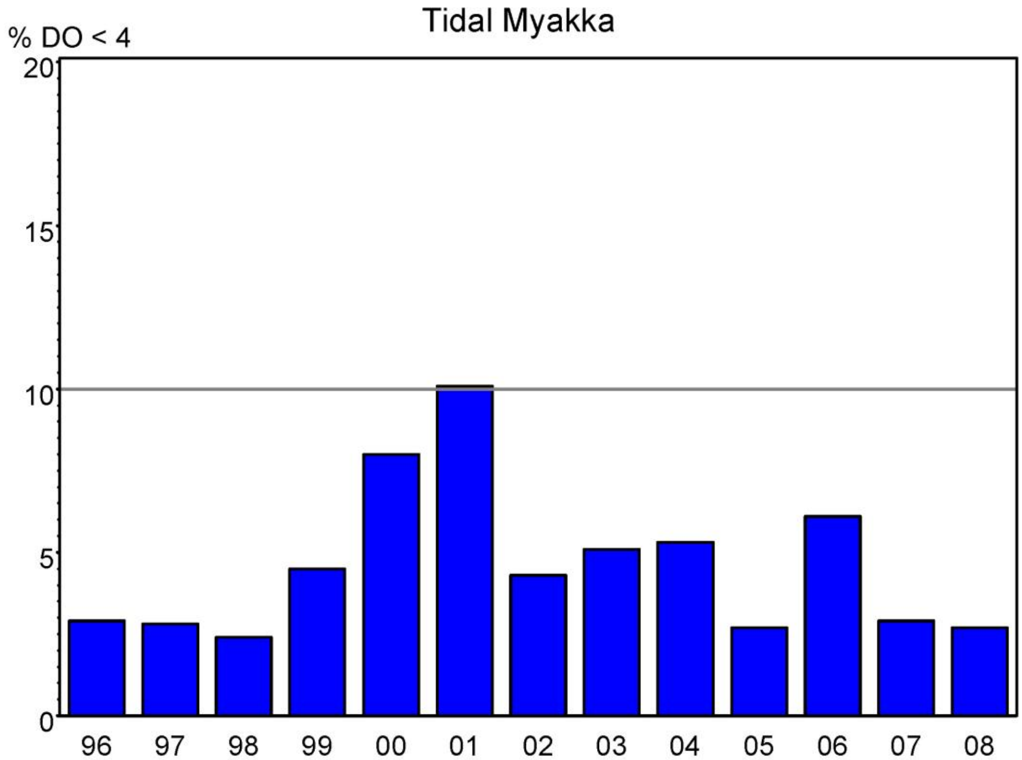

Figure 5-15. Percent of DO exceedences by year, Tidal Myakka River.

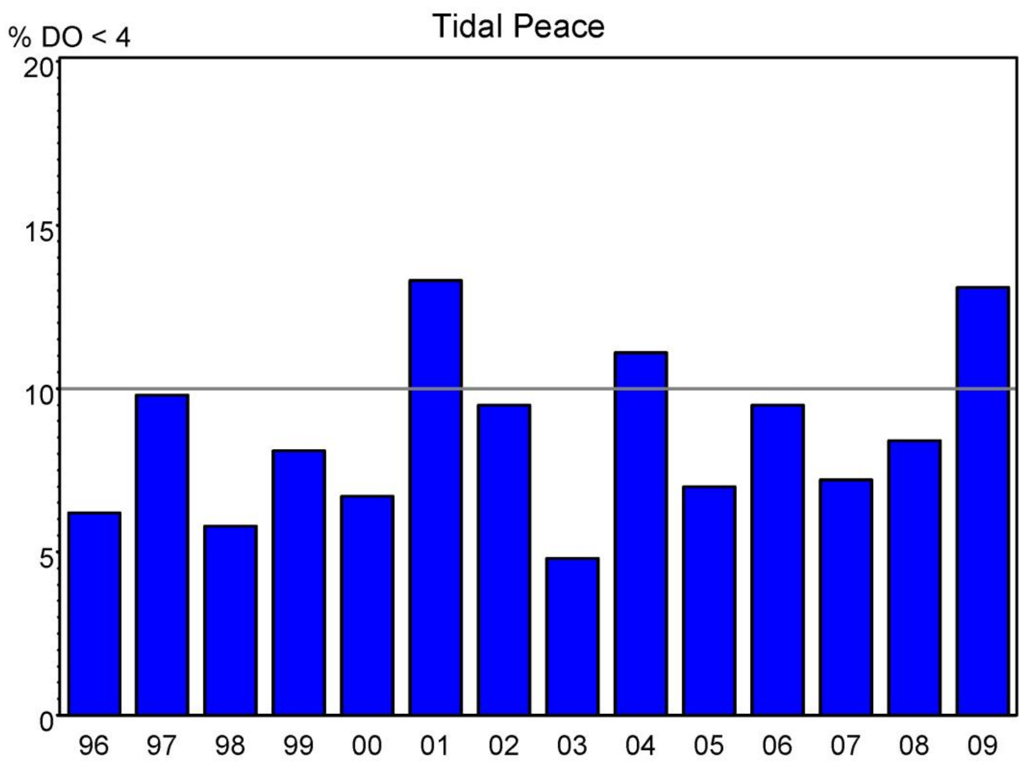

Figure 5-16. Percent of DO exceedences by year, Tidal Peace River.

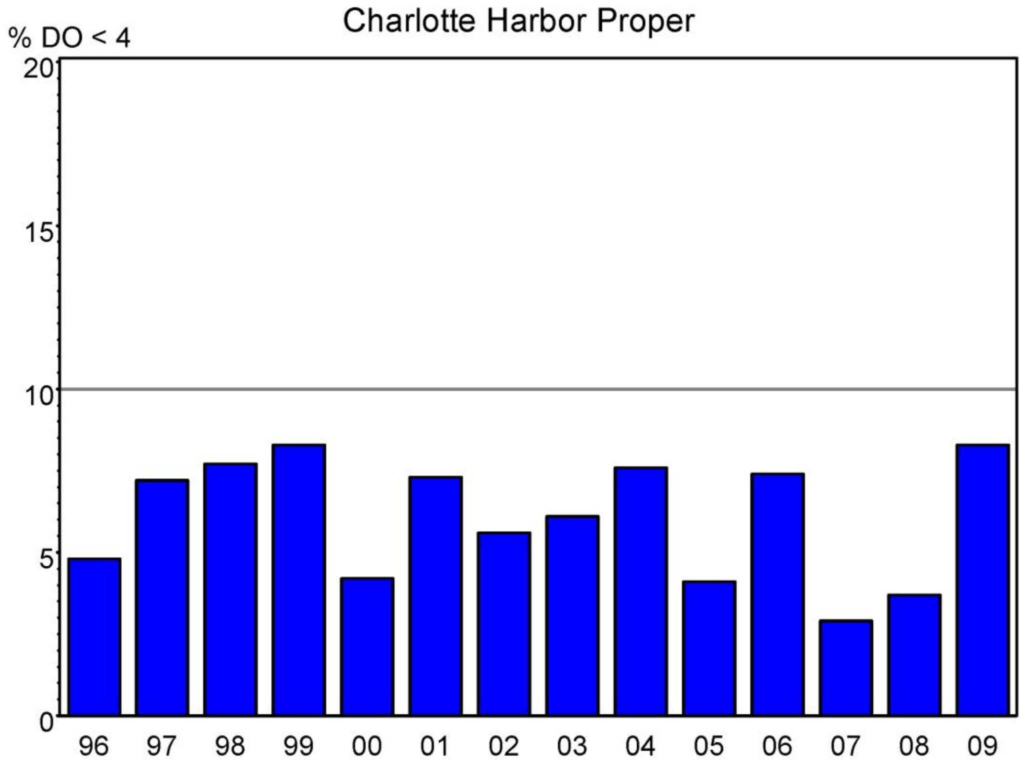

Figure 5-17. Percent of DO exceedences by year, Charlotte Harbor Proper.

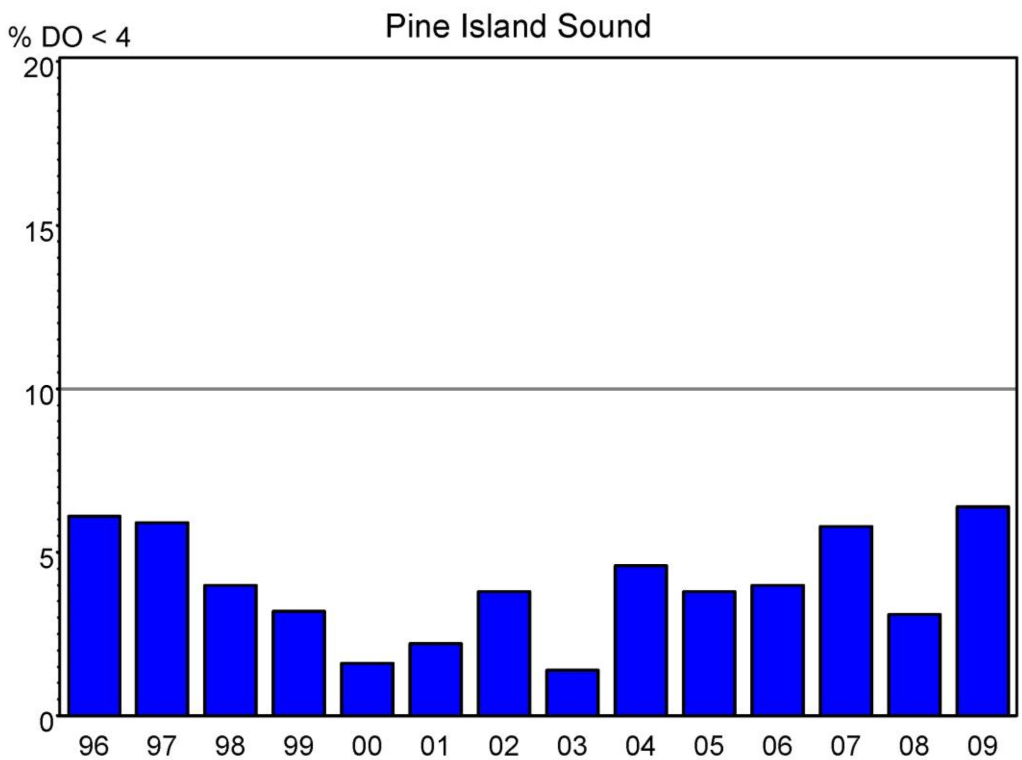

Figure 5-18. Percent of DO exceedences by year, Pine Island Sound.

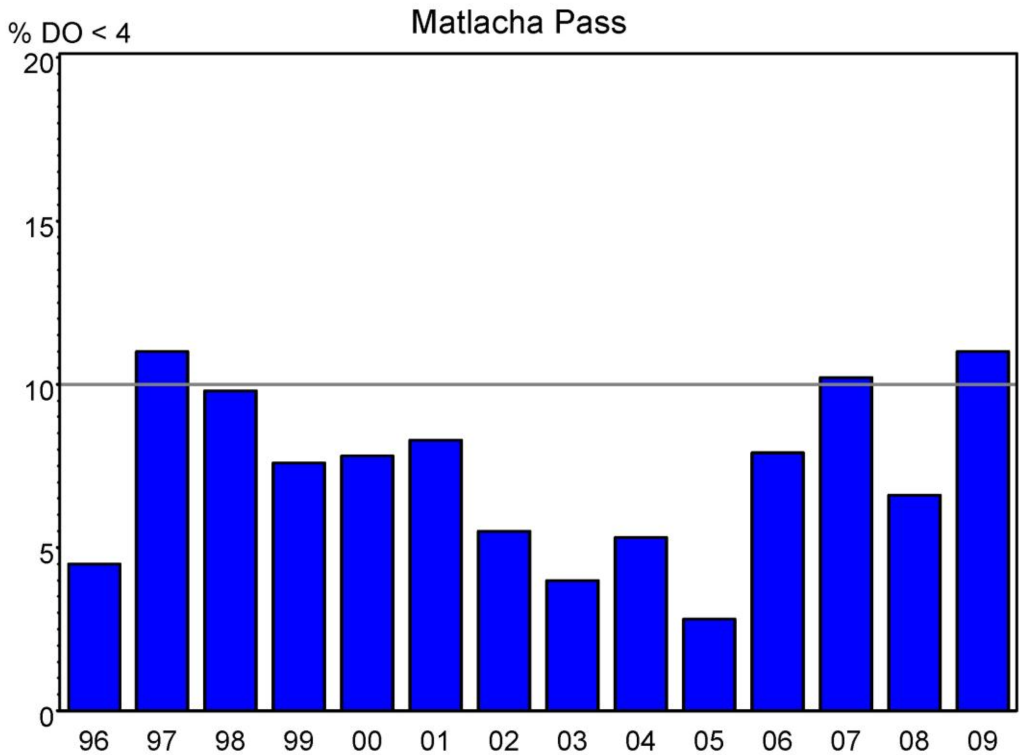

Figure 5-19. Percent of DO exceedences by year, Matlacha Pass.

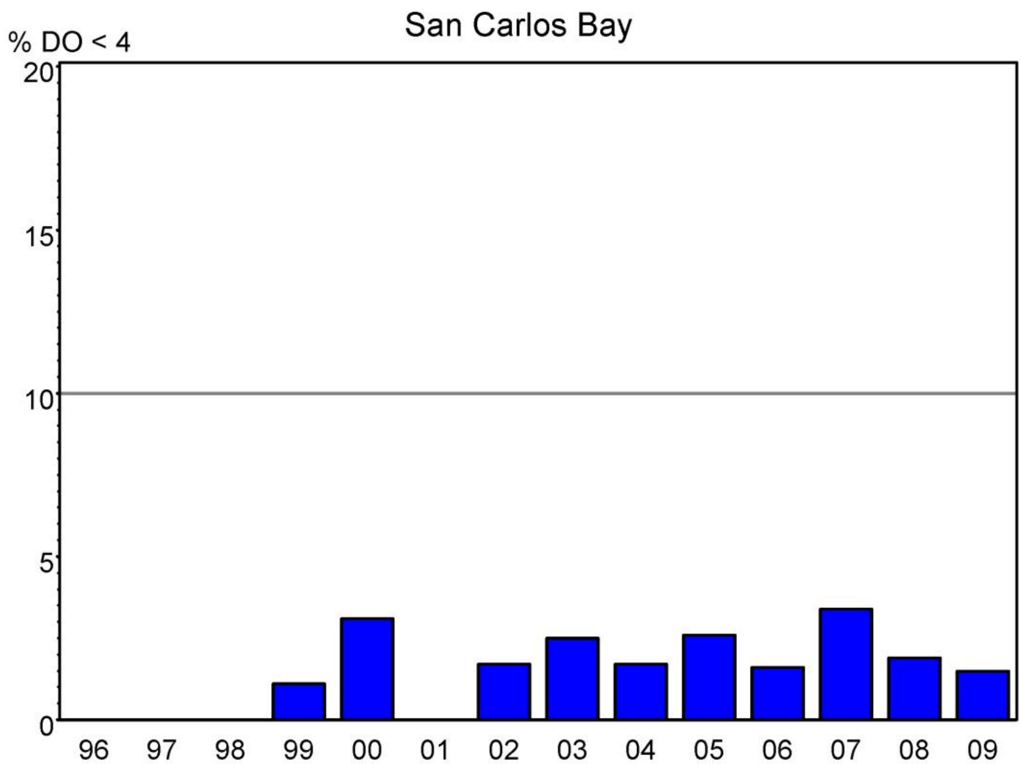

Figure 5-20. Percent of DO exceedences by year, San Carlos Bay.

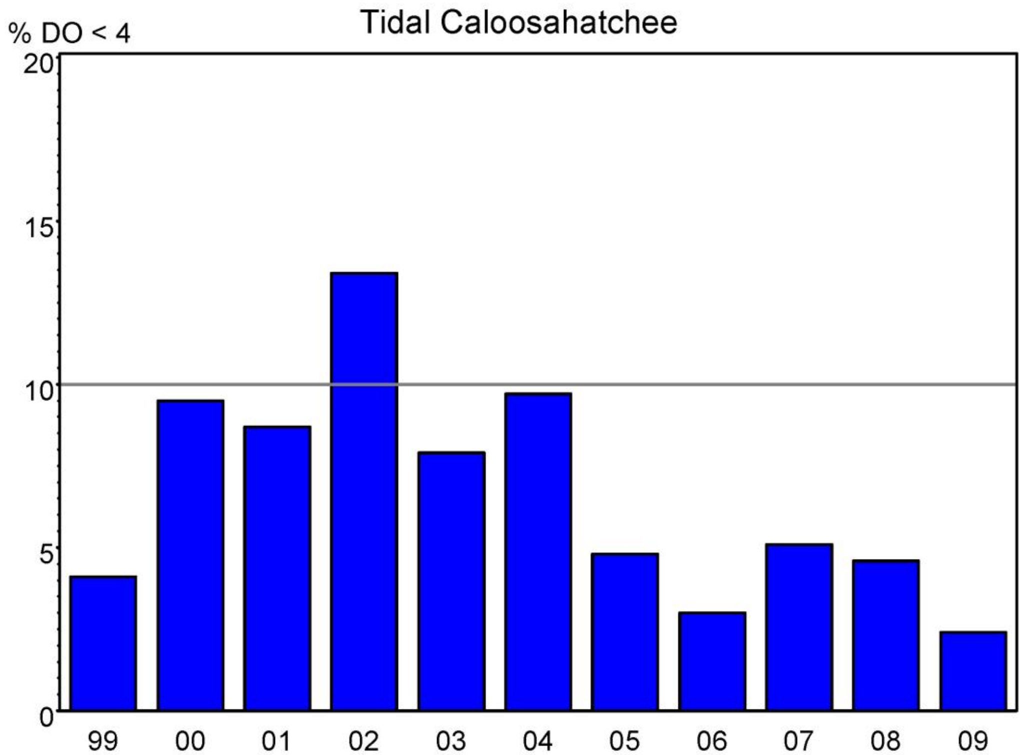

Figure 5-21. Percent of DO exceedences by year, Tidal Caloosahatchee River.

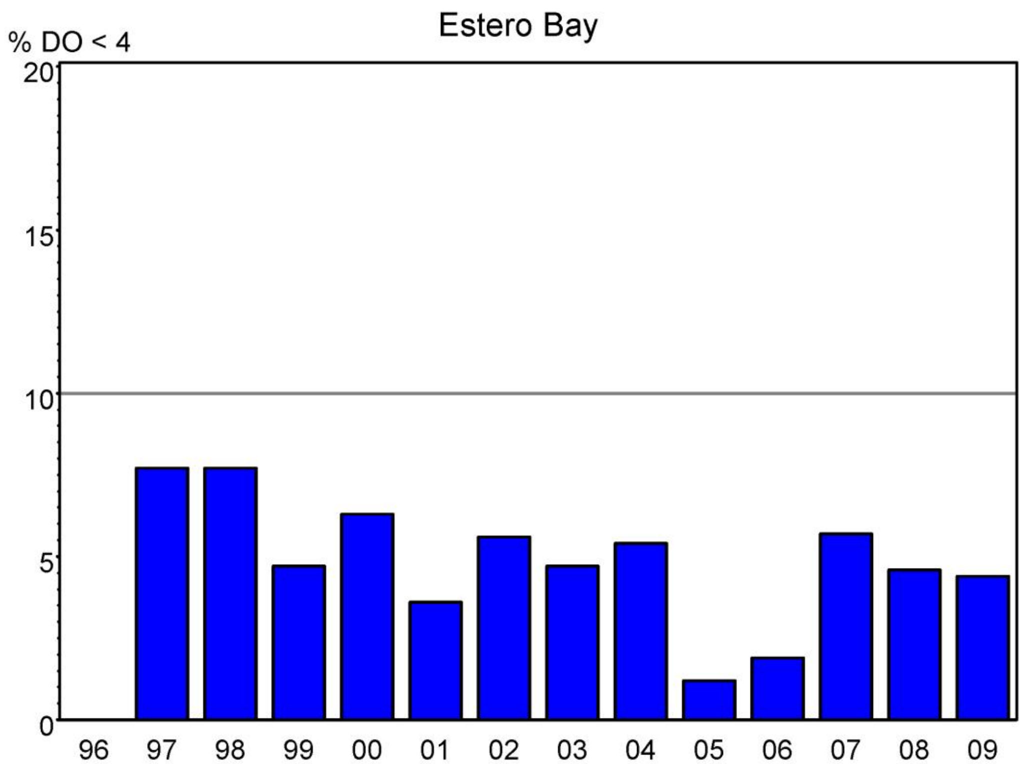

Figure 5-22. Percent of DO exceedences by year, Estero Bay.

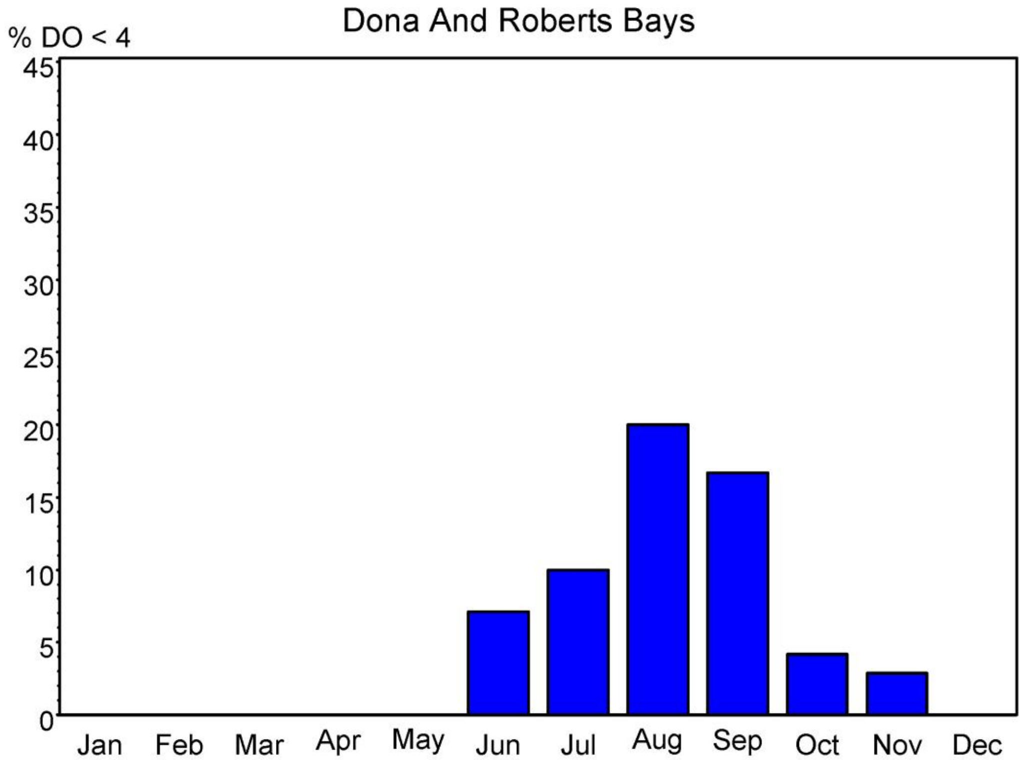

Figure 5-23. Percent of DO exceedences by calendar month, Dona and Roberts Bays.

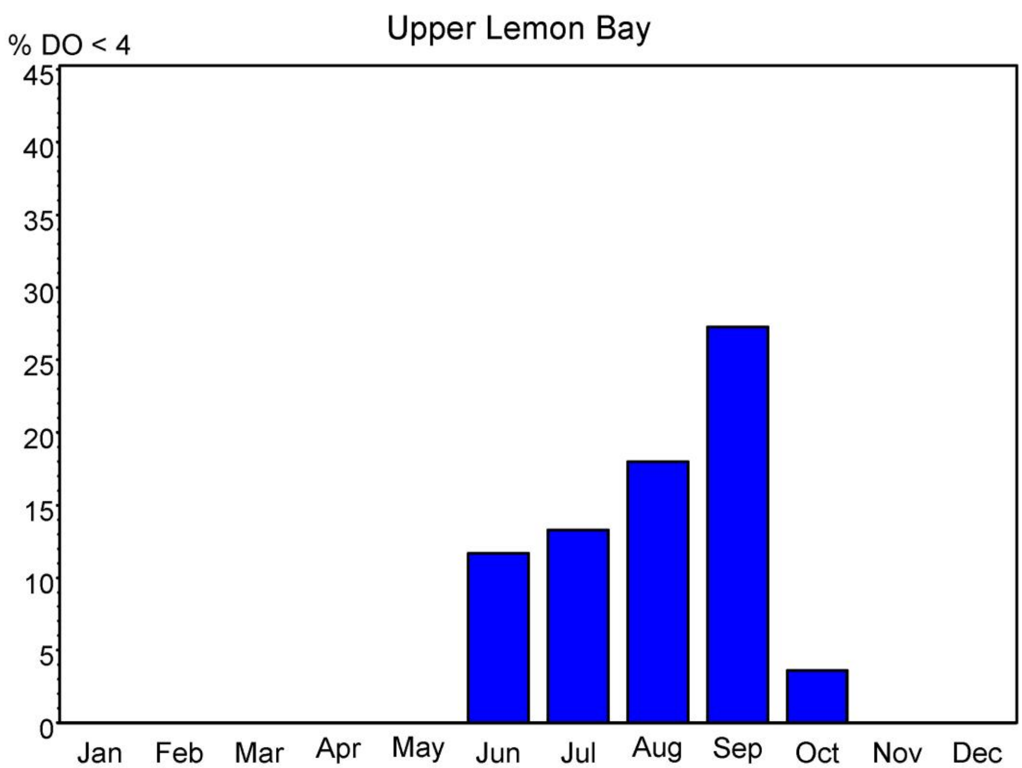

Figure 5-24. Percent of DO exceedences by calendar month, Upper Lemon Bay.

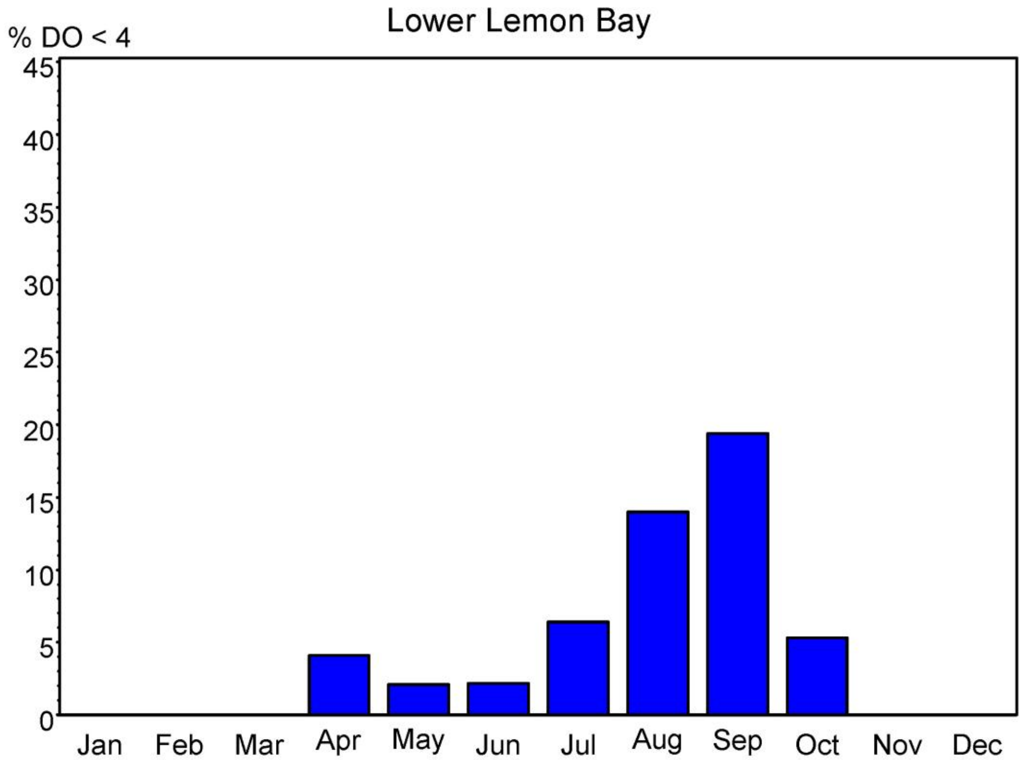

Figure 5-25. Percent of DO exceedences by calendar month, Lower Lemon Bay.

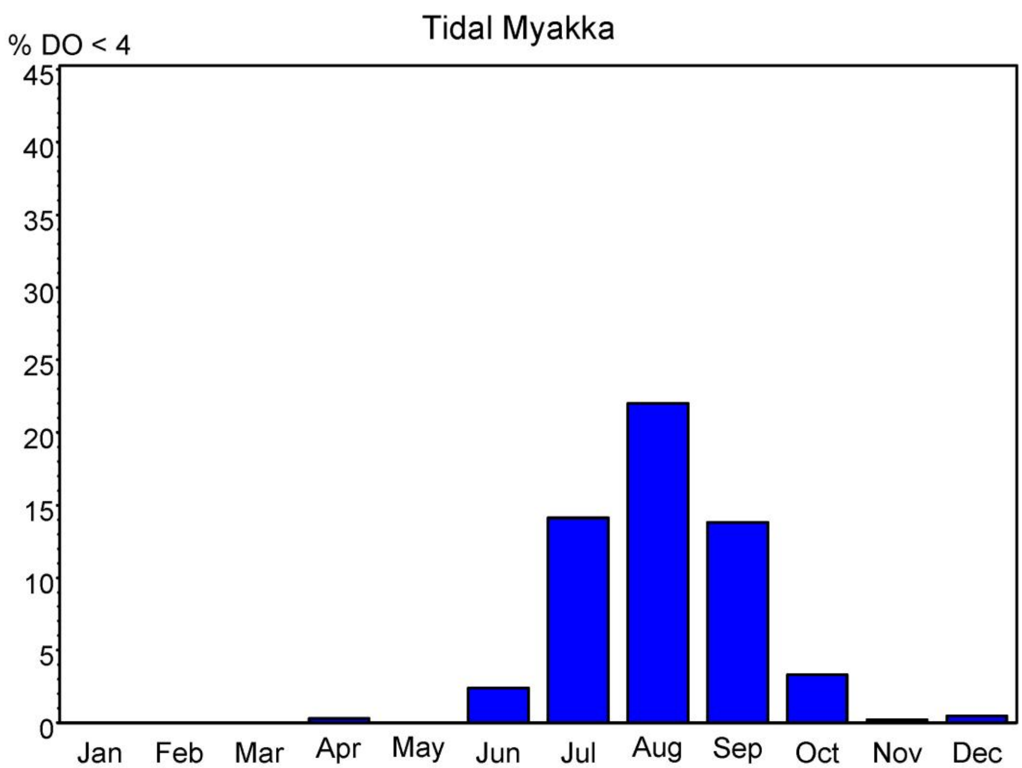

Figure 5-26. Percent of DO exceedences by calendar month, Tidal Myakka River.

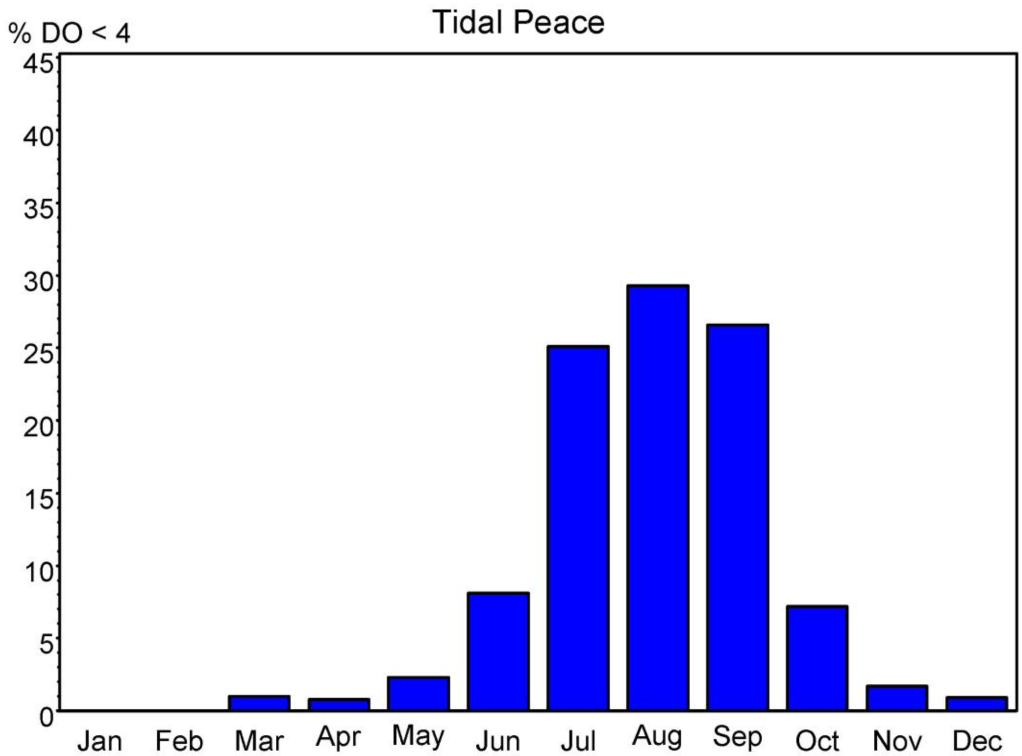

Figure 5-27. Percent of DO exceedences by calendar month, Tidal Peace River.

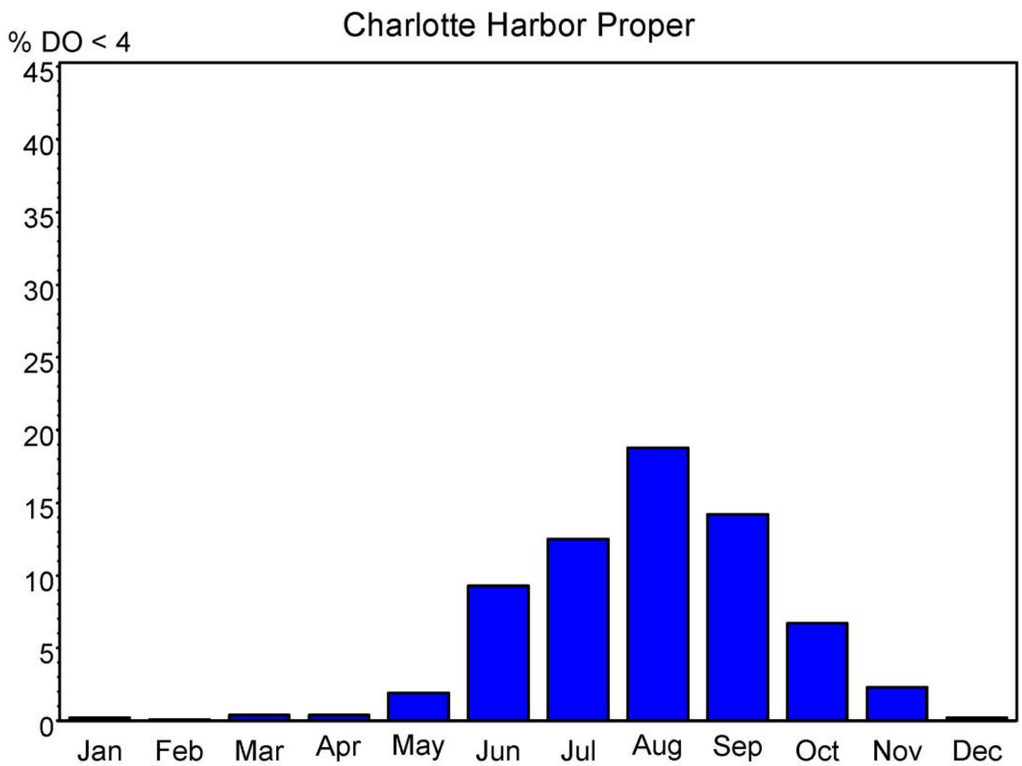

Figure 5-28. Percent of DO exceedences by calendar month, Charlotte Harbor Proper.

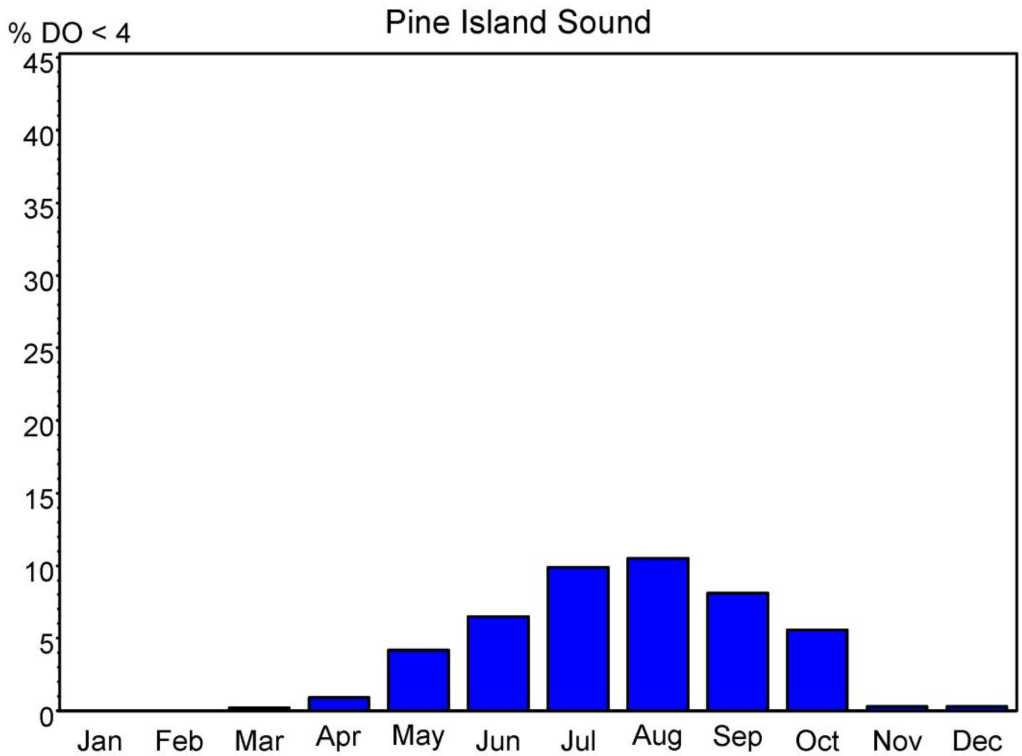

Figure 5-29. Percent of DO exceedences by calendar month, Pine Island Sound.

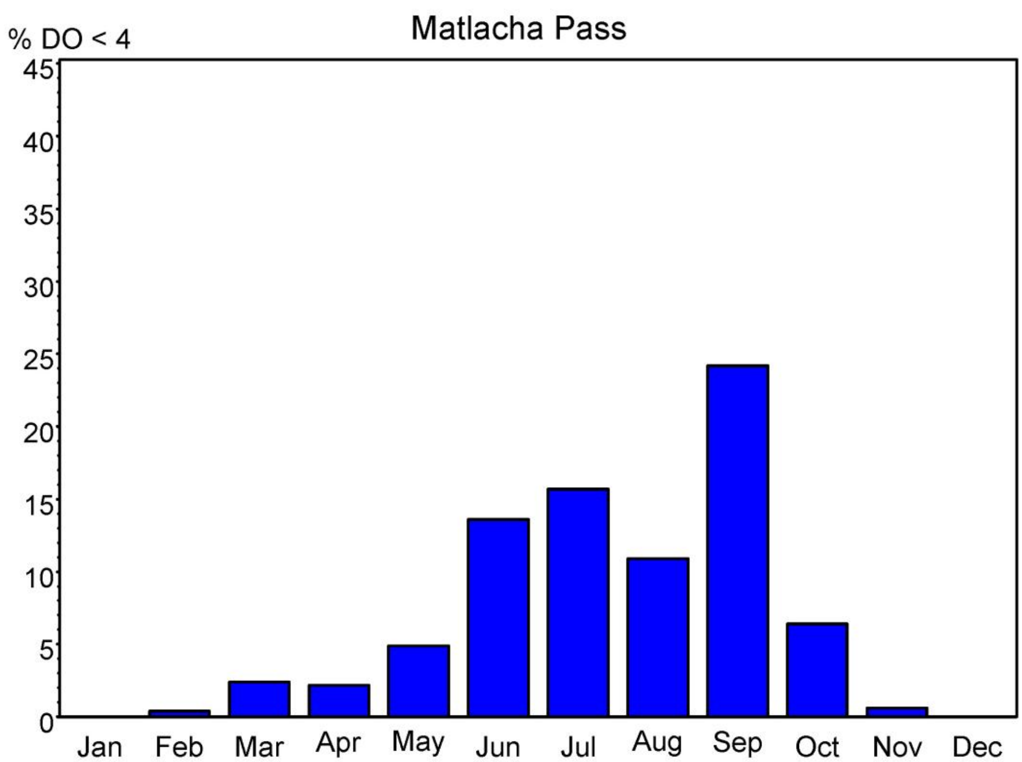

Figure 5-30. Percent of DO exceedences by calendar month, Matlacha Pass.

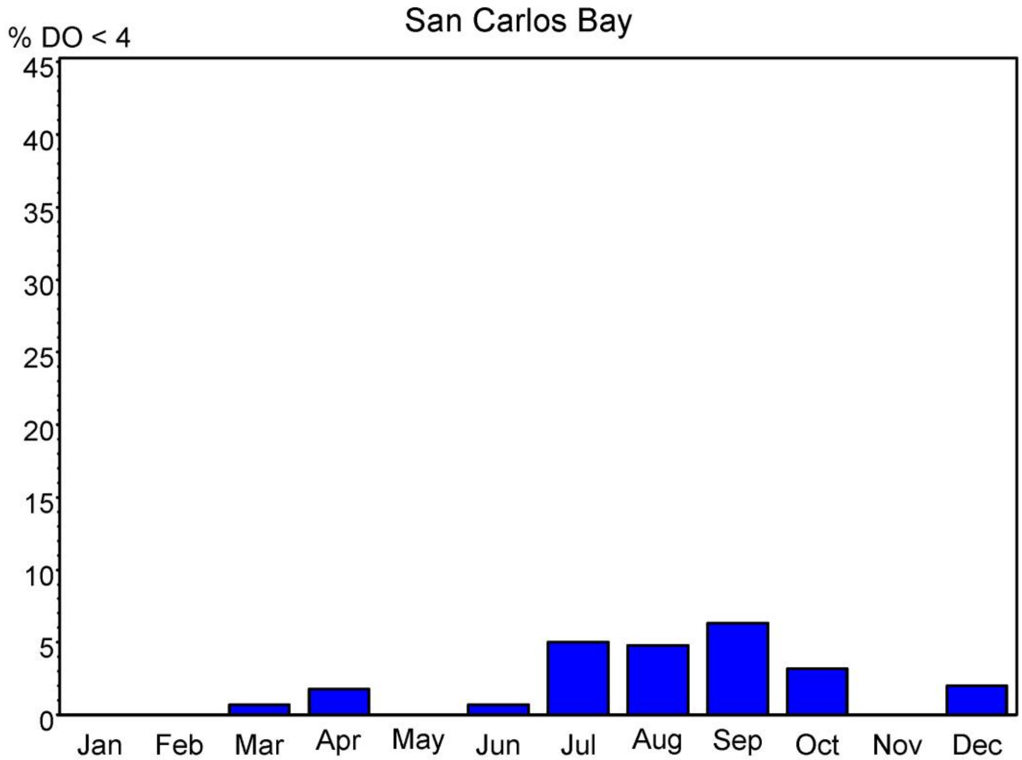

Figure 5-31. Percent of DO exceedences by calendar month, San Carlos Bay.

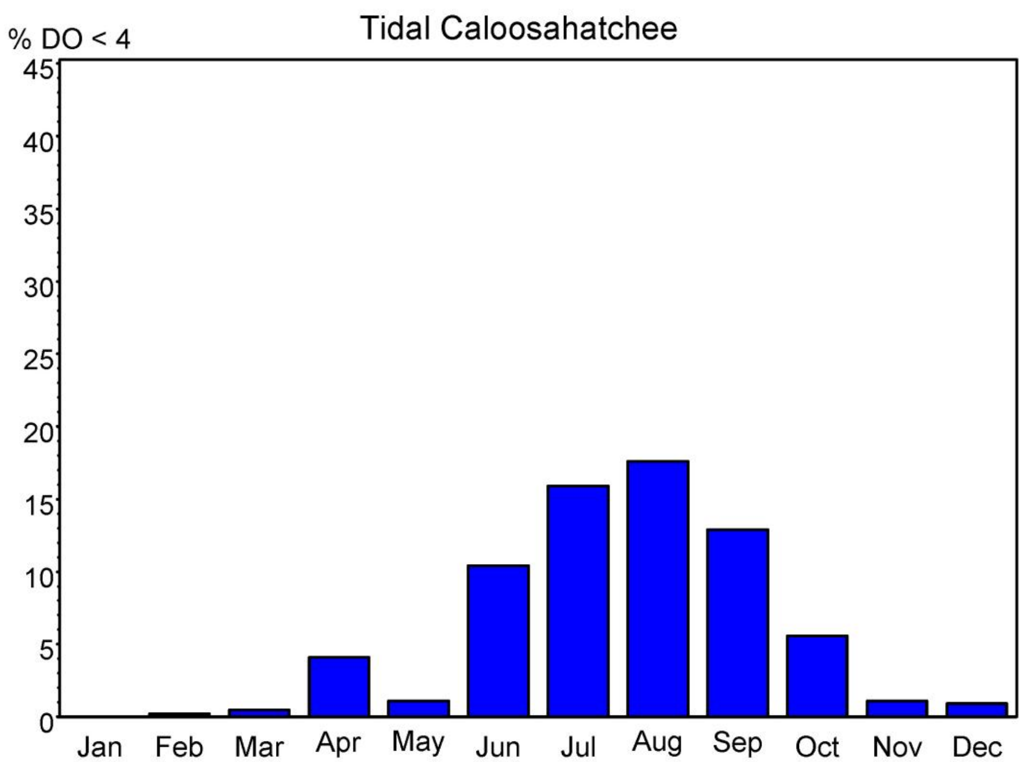

Figure 5-32. Percent of DO exceedences by calendar month, Tidal Caloosahatchee River.

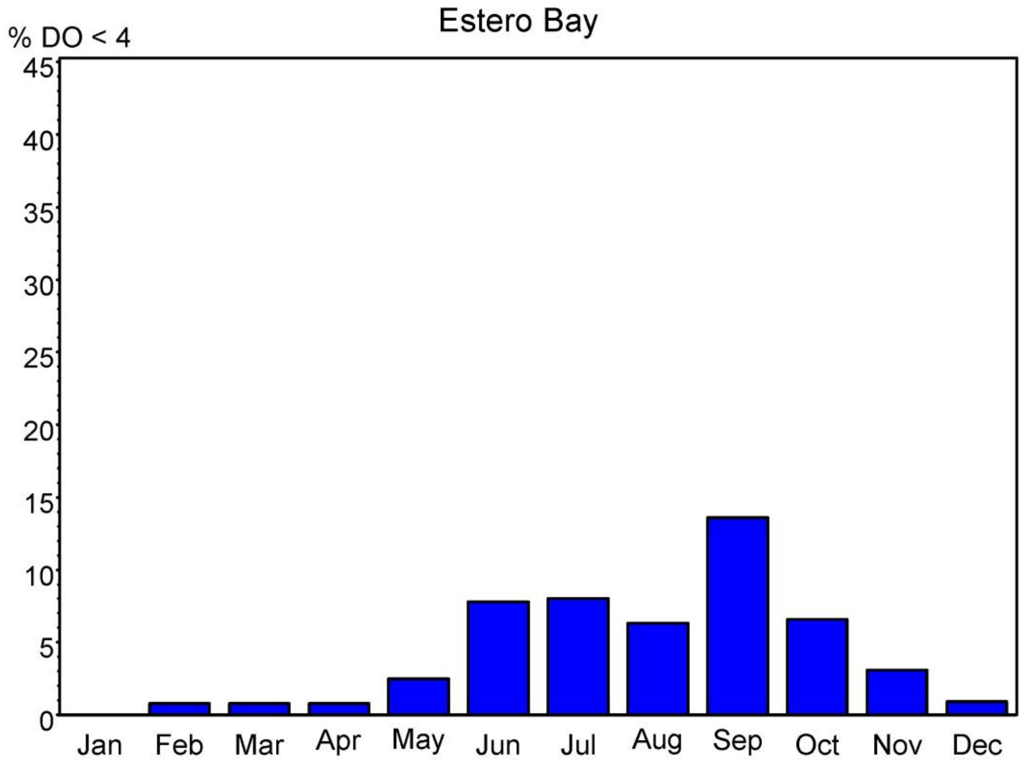

Figure 5-33. Percent of DO exceedences by calendar month, Estero Bay.

5.2 Spatial Patterns in DO exceedences

In order to better understand the spatial variation in DO among segments, a box and whisker plot of DO measurements by segment is presented in Figure 5-34. The box represents the interquartile range (25^{th}, 50^{th} [median], and 75^{th} percentiles), while the whiskers represent the minimum and maximum DO measurements. The average DO for the segment is represented by the blue dot. The average DO ranged from 6.1 mg/l in Dona and Roberts Bays to 7.3 mg/l in Pine Island Sound. Variability was somewhat lower in the northern segments (Dona and Roberts Bays, Upper Lemon Bay, and Lower Lemon Bay) where the lowest DO concentration was 1.96 mg/l and the highest DO concentration was 12 mg/l. The greatest variability was seen in Charlotte Harbor Proper (0.05 – 18.3 mg/l) and Pine Island Sound (0.5 – 17.8 mg/l). The 25^{th} percentile DO concentrations ranged from 5.2 mg/l (Estero Bay) to 6.2 mg/l (Pine Island Sound), meaning that at least 75% of the DO measurements were greater than 5.2 mg/l in all segments.

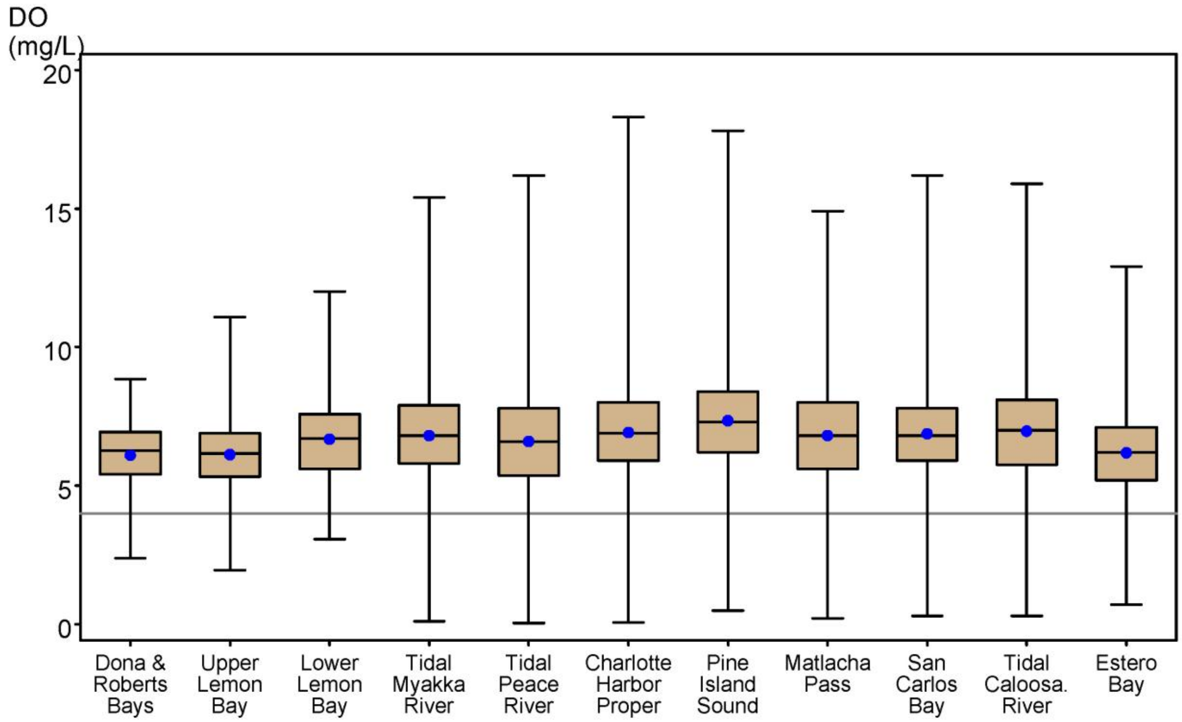

Figure 5-34. Distribution of DO values in each of the CHNEP segments.

To identify areas with a higher potential for DO exceedences, the spatial distribution of DO values throughout each segment was investigated during the warmest months of the year when low DO values are most likely to occur (Figures 5-23 through 5-33). DO samples from all depths, collected from June through September, were mapped in ArcGIS for the Upper portion of the CHNEP area (Figure 5-35 including Dona and Roberts Bays, Upper Lemon Bay, and Lower Lemon Bay), northern rivers and Charlotte Harbor (Figure 5-36 including the Tidal Myakka River, Tidal Peace River, and Charlotte Harbor Proper), and lower Charlotte Harbor (Figure 5-37 including Pine Island Sound, Matlacha Pass, San Carlos Bay, Tidal Caloosahatchee River, and Estero Bay). The sampling points were labeled using a graduated scale from 0 to 4 by 1.0 mg/l increments and those over 4 mg/l were labeled as a single color (blue). When sample points fell on top of one another the lowest value was displayed to denote the lowest value recorded in that area. Therefore, it is important to note that this map does not represent typical conditions but rather is meant to highlight areas that may be susceptible to a low DO occurrence under certain circumstances. These circumstances are further investigated later in this document.

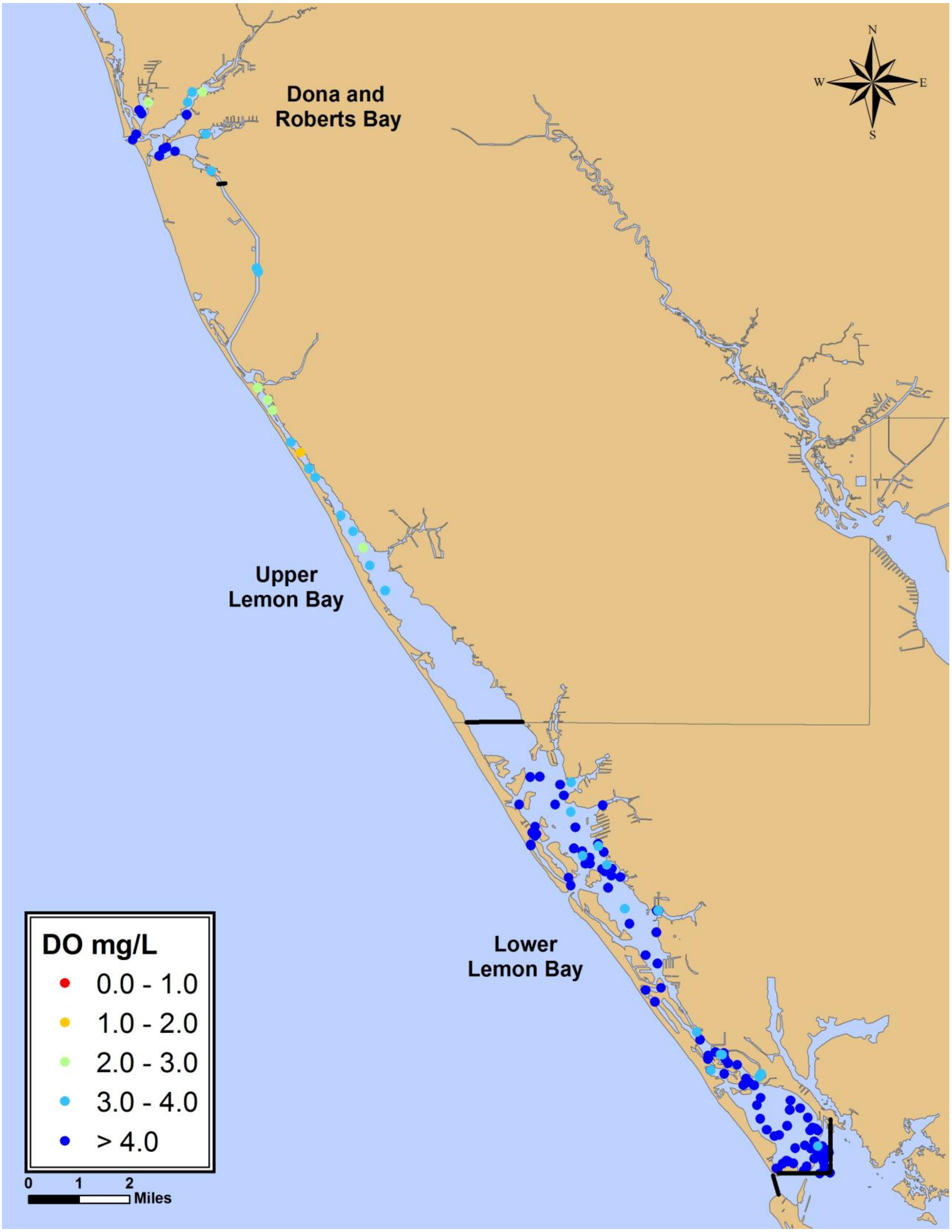

Figure 5-35. Spatial distribution of DO during summer months (June-September) for the northern portion of the CHNEP area.

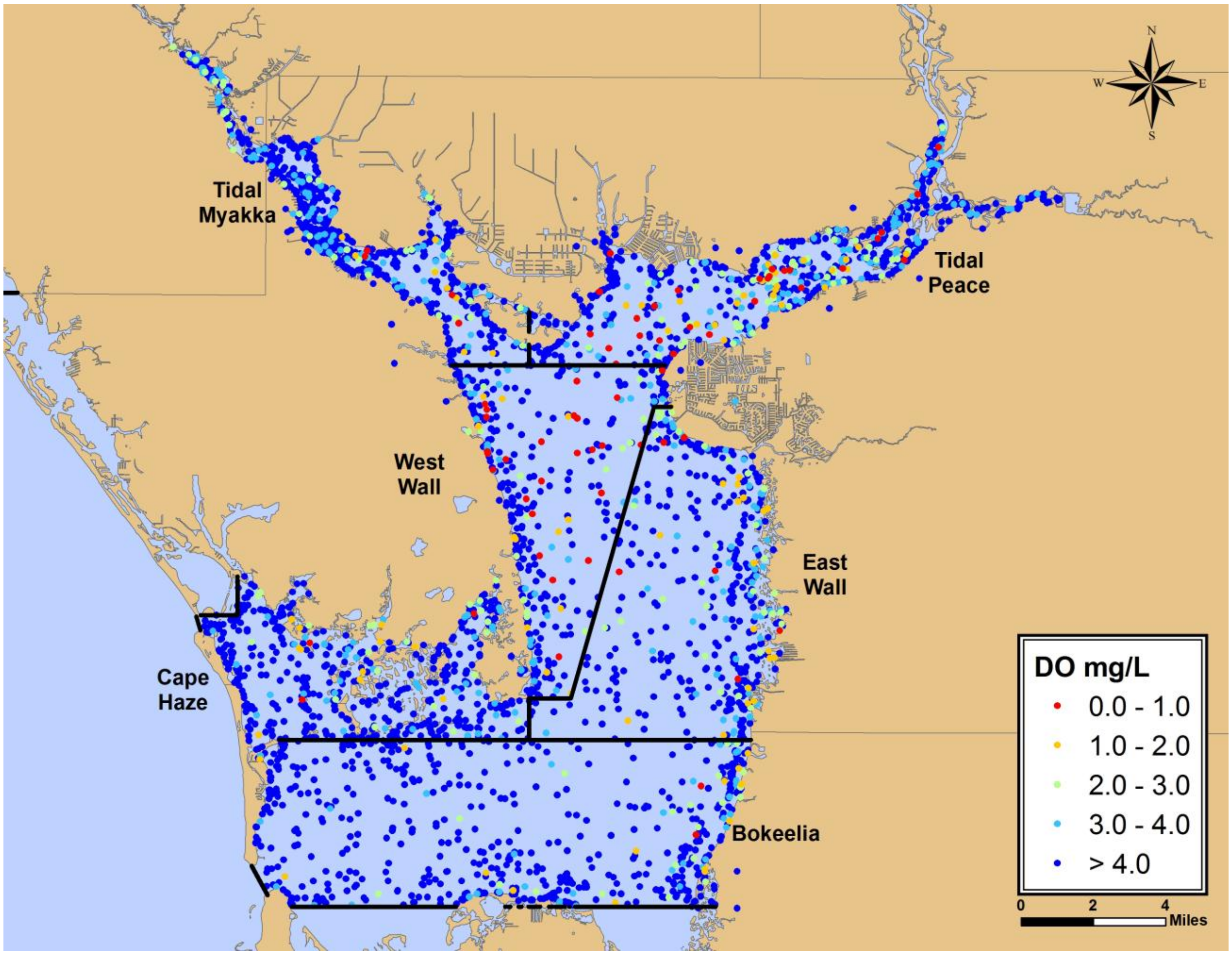

Figure 5-36. Spatial distribution of DO during summer months (June-September) for Tidal Myakka, Tidal Peace, and Charlotte Harbor Proper.

A summary of DO measurements by segment for the months of June through September is presented in Table 5-1. As with the maps, the data in the table represent the percentage of DO observations during the June through September period for different DO ranges (0-1 mg/l, 1-2 mg/l, 2-3 mg/l, 3-4 mg/l, and > 4mg/l). The majority of DO measurements less than 2 mg/l occurred in the Tidal Peace River and Charlotte Harbor Proper. Even though these data represent the season that typically has the lowest DO concentrations, three segments (Lower Lemon Bay, Matlacha Pass, and San Carlos Bay) have greater than 90% of the DO measurements greater than 4 mg/l. With the exception of Tidal Peace River and Charlotte Harbor Proper, the majority of the observations less than 4 mg/l during the June through September period were in the 3-4 mg/l range.

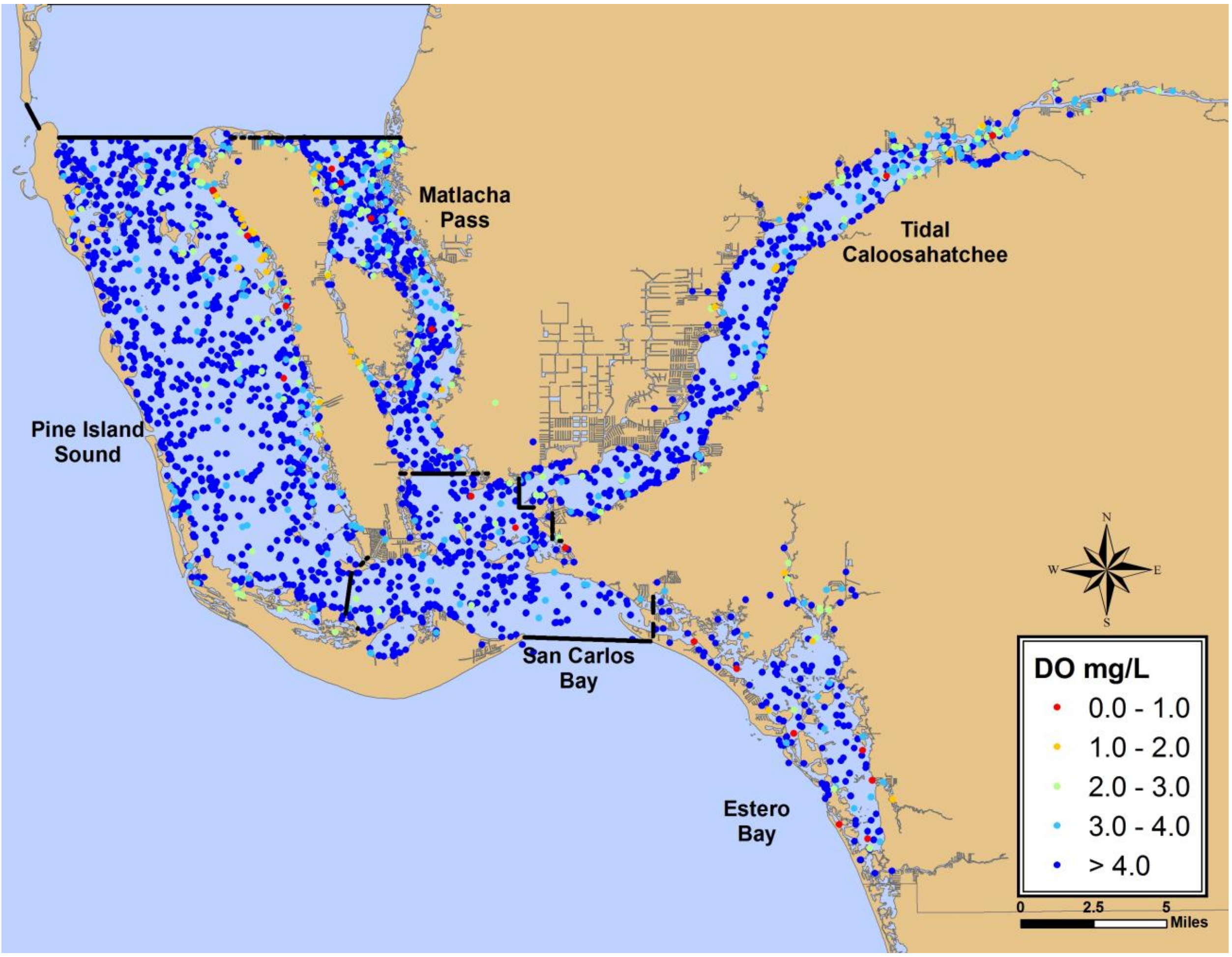

Figure 5-37. Spatial distribution of DO during summer months (June-September) for the southern portion of the CHNEP area.

Table 5-1. Summary of DO observations by segment for the months June through September.

Bay Segment	# of Observations	% of observations: 0-1 mg/l	1-2 mg/l	2-3 mg/l	3-4 mg/l	>4 mg/l
Dona and Roberts Bays	123	0.0%	0.0%	4.1%	9.8%	86.2%
Upper Lemon Bay	225	0.0%	0.4%	4.4%	12.0%	83.1%
Lower Lemon Bay	167	0.0%	0.0%	0.0%	9.6%	90.4%
Tidal Myakka	1541	0.3%	0.6%	2.7%	10.8%	85.7%
Tidal Peace	2423	2.5%	2.7%	4.9%	12.8%	77.1%
Charlotte Harbor Proper	3978	1.6%	2.3%	3.5%	7.2%	85.4%
Matlacha Pass	2519	0.2%	1.1%	2.4%	5.6%	90.7%
Pine Island Sound	1211	0.4%	1.5%	4.5%	10.9%	82.7%
San Carlos Bay	1237	0.2%	0.1%	0.9%	3.6%	95.2%
Tidal Caloosahatchee	1676	0.2%	0.8%	3.2%	11.2%	84.7%
Estero Bay	1094	0.6%	0.4%	1.3%	7.9%	89.9%

Examination of these maps and data indicates the following:

- While DO concentrations less than 4 mg/l are found throughout the CHNEP area, the majority of DO concentrations less than 2 mg/l were in the Tidal Peace River and Charlotte Harbor Proper.
- The northern segments (Dona and Roberts Bays, Upper Lemon Bay, and Lower Lemon Bay) have fewer DO values less than 2 mg/l than other segments and have less variability
- For all segments except the Tidal Peace River and Charlotte Harbor Proper, the majority of the observations less than 4 mg/l during the June through September period were in the 3-4 mg/l range.

5.3 Factors Affecting DO Exceedences

As discussed in Section 1.0, the conceptual model applied by FDEP in establishing the DO standard is that excess nutrients from anthropogenic sources result in algal blooms which in turn result in increased organic deposition and decomposition which in turn lead to reduced DO concentrations. Symptoms of eutrophication include excess primary production, deposition and decomposition of phytodetritus and consequently increased biological oxygen demand which reduces the DO content of estuarine waters (Nixon, 1995). The objective of this effort was to assess the percentage of state standard exceedances in DO and assess drivers of DO exceedances in the segments of the CHNEP area with respect to the development of recently proposed numeric nutrient criteria for the Sarasota Bay estuary (Janicki Environmental, 2011a; 2011b). In order to better understand the factors that influence DO, a series of regressions were developed.

A preliminary ordinary least squares regression analysis of DO and potential explanatory variables revealed that an increase in temperature was the main driver of lower DO concentrations ($Pr > F < 0.0001$, $r^2 = 0.32$) for the CHNEP area. While this information is useful, further analysis was required to better understand what influences the probability of DO concentrations less than 4 mg/l in individual segments. To this end, a series of stepwise logistic regressions were developed for individual segments to identify the explanatory variables that influence the probability of a DO concentration less than 4 mg/l.

The parameter estimates, resulting odds ratio estimates, chi-square values, and Hosmer & Lemeshow Goodness-of-Fit Test output are provided in Table 5-2. The relative effect of individual parameter estimates on the change in probability of observing a DO < 4 mg/l can be assessed using either the odds ratio estimate or the chi-square values associated with the significance test. An odds ratio of 1 is equivalent to a rate of change of 0 and indicates a variable has little influence on the predicted probability. For example, for Dona and Roberts Bays the odds ratio for temperature is 1.312. Therefore, for a one unit increase in temperature, there is a 31% increase in the probability of a DO concentration less than 4 mg/l occurring.

In all segments, temperature is the primary factor that is positively correlated with a DO exceedence (a DO concentration < 4 mg/l). Though chlorophyll is included in the models of three segments (Tidal Myakka, Pine Island Sound, and Tidal Caloosahatchee), in Tidal Myakka and Tidal Caloosahatchee an increase in chlorophyll leads to a decrease in the probability of a DO exceedence. This contradicts the conceptual model proposed by FDEP and discussed in Section 1.0. Output from the Hosmer & Lemeshow Goodness-of-Fit Test is used to assess the fit of the models. As can be seen in the first column of the table, there is no evidence of a lack of fit in the models except for Upper Lemon Bay, Tidal Peace River, and Charlotte Harbor Proper.

Table 5-2. Logistic regression parameter estimates including odds ratios, significance levels, and overall model goodness-of-fit (Hosmer and Lemeshow). The response variable is the probability of a bottom DO < 4 mg/l.

Bay Segment (Hosmer & Lemeshow Goodness-of-Fit Test)	Parameter	Coefficient	Odds Ratio	Chi-square	Pr > Chi-square
Dona and Roberts Bays (Pr > ChiSq 0.86)	Color	0.1047	1.009	45.5	<0.0001
	Temperature	0.2062	1.312	14.1	0.0002
Upper Lemon Bay (Pr > ChiSq 0.01)	Color	0.0116	1.012	43.4	<0.0001
	Temperature	0.1347	1.144	24.6	<0.0001
Lower Lemon Bay (Pr > ChiSq 0.06)	Color	0.0262	1.027	41.1	<0.0001
	Temperature	0.0860	1.090	12.9	0.0003
Tidal Myakka (Pr > ChiSq 0.22)	Color	0.0112	1.011	225.9	<0.0001
	Temperature	0.5840	1.793	29.6	<0.0001
	Chlorophyll	-0.2083	0.812	15.7	<0.0001
Tidal Peace (Pr > ChiSq 0.004)	Temperature	0.2398	1.192	88.5	<0.0001
	Color	0.0043	1.004	21.6	<0.0001
Charlotte Harbor Proper (Pr > ChiSq 0.05)	Temperature	0.1376	1.148	62.8	<0.0001
	Color	0.0064	1.004	21.6	<0.0001
Matlacha Pass (Pr > ChiSq 0.54)	Temperature	0.2058	1.228	31.7	<0.0001
Pine Island Sound (Pr > ChiSq 0.62)	Chlorophyll	0.0520	1.053	9.7	0.0019
	Temperature	0.0907	1.095	3.7	0.0537
San Carlos Bay (Pr > ChiSq 0.43)	Temperature	0.1822	1.200	15.4	<0.0001
	Color	-0.0126	0.987	2.9	0.0866
Tidal Caloosahatchee (Pr > ChiSq 0.29)	Color	0.0133	1.013	115.9	<0.0001
	Temperature	0.2479	1.281	20.4	<0.0001
	Chlorophyll	-0.0591	0.943	8.1	0.0045
Estero Bay (Pr > ChiSq 0.16)	Temperature	0.1468	1.158	46.0	<0.0001
	Color	0.0125	1.013	17.5	<0.0001

As was discussed in Section 2.0, Camp, Dresser, and McKee (1998) found that salinity stratification was prevalent during periods of low DO concentrations in the Tidal Peace River and Charlotte Harbor. Salinity stratification is known to result in depressed dissolved oxygen layers as a freshwater lens builds on surface waters restricting the exchange of bottom water with the atmosphere. To investigate the degree to which salinity stratification occurs in the CHNEP area, the difference between bottom and surface salinity was calculated from every observation where both surface and bottom values were recorded (generally where depths were greater than 1 meter). The data are summarized in Table 5-3. Statistics could not be calculated for Dona and Roberts Bays and Upper Lemon Bay as only surface samples were reported. As expected, the degree of stratification varies widely in the CHNEP area as some segments have major freshwater inflows and others have relatively little freshwater inflow. The segments with the largest freshwater inflows (Tidal Peace, Tidal Caloosahatchee, and San Carlos Bay) had the greatest stratification while Lower Lemon Bay and Pine Island Sound had the least stratification.

Table 5-3. Summary statistics of stratification (bottom salinity – surface salinity) by segment.

Bay Segment	50th Percentile	75th Percentile	90th Percentile	95th Percentile	99th Percentile
Dona and Roberts Bays	n/a	n/a	n/a	n/a	n/a
Upper Lemon Bay	n/a	n/a	n/a	n/a	n/a
Lower Lemon Bay	0.0	0.1	0.2	0.4	2.0
Tidal Myakka	0.0	0.3	1.6	3.1	6.6
Tidal Peace	0.2	2.2	7.1	10.1	16.3
Charlotte Harbor Proper	0.0	0.3	1.9	4.2	10.8
Matlacha Pass	0.0	0.1	1.1	3.4	9.0
Pine Island Sound	0.0	0.1	0.7	2.0	5.7
Tidal Caloosahatchee	0.0	1.0	3.7	5.8	11.7
San Carlos Bay	0.2	1.4	6.1	8.8	14.5
Estero Bay	0.0	0.3	2.1	5.0	8.8

There was evidence of a lack of fit in the models developed for several of the segments, therefore, additional models were developed. These models estimate the probability of a bottom DO less than 4 mg/l as a function of several explanatory variables, including salinity stratification. The parameter estimates, resulting odds ratio estimates, chi-square values, and Hosmer & Lemeshow Goodness-of-Fit Test output are provided in Table 5-4 for Charlotte Harbor Proper and Tidal Peace River (Upper Lemon Bay was not included because of a lack of salinity stratification data). There was no evidence of a lack of fit in the models. Temperature and stratification were the main drivers of DO exceedences in these two segments. Chlorophyll was not a significant predictor of bottom DO exceedences in either of the models.

Table 5-4.	**Summary of DO observations by segment for the months June through September.**				
Bay Segment (Hosmer & Lemeshow Goodness-of-Fit Test)	**Parameter**	**Coefficient**	**Odds Ratio**	**Chi-square**	**Pr > Chi-square**
Tidal Peace (Pr > ChiSq 0.84)	Temperature	0.4888	1.630	92.1	<0.0001
	Stratification	0.1996	1.221	30.9	<0.0001
	Color	0.0034	1.003	4.0	0.0451
Charlotte Harbor Proper (Pr > ChiSq 0.79)	Stratification	0.4448	1.560	102.2	<0.0001
	Temperature	0.5643	1.758	46.9	<0.0001
	Color	0.0160	0.999	3.6	0.0573

6.0 CONCLUSIONS

The following conclusions can be drawn from the analyses presented above:

- The empirical evidence presented above suggests that the majority of CHNEP segments are meeting full aquatic life uses with respect to the current state DO standards. Six segments (Dona and Roberts Bays, Lower Lemon Bay, Charlotte Harbor Proper, Pine Island Sound, San Carlos Bay, and Estero Bay) had no annual DO exceedences. Of the five segments that had exceedences, Tidal Myakka and Tidal Caloosahatchee had a single exceedence while Upper Lemon Bay, Tidal Peace, and Matlacha Pass had three exceedences each. Examination of spatial distribution revealed no strong tendencies for DO less than 4 mg/l. However, the probability of DO values less than 2 mg/l was highest in the Tidal Peace and the upper portion of Charlotte Harbor Proper. Previous work by Camp, Dresser & McKee (1998) revealed that stratification was more prevalent when low DO concentrations occurred in the Tidal Peace and Charlotte Harbor. Logistic regression models developed for this report confirm that stratification is one of the principle drivers of DO exceedences in the Tidal Peace and Charlotte Harbor.

- The principal factor affecting DO in the segments of the CHNEP is temperature. This fact is evident in both the descriptive time-series plots and the results of ordinary least-squares regression.

- Additional models were developed to identify the explanatory variables that contribute to the probability of DO exceedences at the segment level. In all segments, temperature is the primary factor that is positively associated with a DO exceedence (a DO concentration < 4 mg/l). Though chlorophyll is included in the models of three segments (Tidal Myakka, Pine Island Sound, and Tidal Caloosahatchee), in Tidal Myakka and Tidal Caloosahatchee an increase in chlorophyll leads to a decrease in the probability of a DO exceedence. This contradicts the conceptual model proposed by FDEP that excess nutrients from anthropogenic assaults result in algal blooms which result in increased organic deposition and decomposition which in turn lead to reduced DO concentrations.

- There was evidence of a lack of fit in the models developed for several of the segments, therefore additional models were developed for these segments. These models estimate the probability of a bottom DO less than 4 mg/l as a function of several explanatory variables, including salinity stratification. There was no evidence of a lack of fit in the additional models. Temperature and stratification were the main drivers of DO exceedences in Tidal Peace and Charlotte Harbor Proper. Chlorophyll was not a significant predictor of bottom DO exceedences in either of the segments.

- Based on the weight-of-evidence presented here, it is reasonable to conclude that the proposed numeric nutrient criteria, which are based on a reference period approach, are protective of full aquatic life uses with respect to current state DO standards.

7.0 LITERATURE CITED

Camp Dresser & McKee Inc. 1998. The Study of Seasonal and Spatial Patterns of Hypoxia in Upper Charlotte Harbor.

Duffey, R., R. E. Leary, and J. Ott. 2007. Charlotte Harbor and Estero Bay Aquatic Preserves Water Quality Status and Trends for 1998 – 2005. Charlotte Harbor Estuaries Volunteer Water Quality Monitoring Network 7 Year Results Final Report. Prepared for: Charlotte Harbor National Estuary Program.

Environmental Systems Research Institute (ESRI), Inc. 2009. ArcGIS Version 9.2. Redlands, CA: 1999-2009.

Janicki Environmental, Inc. 2011a. Development of Numeric Nutrient Criteria for the Estuarine Waters of the Charlotte Harbor National Estuary Program, Task 7: Numeric Nutrient Criteria Development, Interim Report 6. Prepared for: Charlotte Harbor National Estuary Program.

Janicki Environmental, Inc. 2011b. Charlotte Harbor Numeric Nutrient Criteria: Task 8 - TN and TP Loading and Concentration Based Criteria, Draft Letter Memorandum. Prepared for: Charlotte Harbor National Estuary Program.

Mallin, M. A., M. H. Posey, M. R. McIver, D. C. Parsons, S. H. Ensign, and T. D. Alphin. 2002. Impacts and recovery from multiple hurricanes in a Piedmont-Coastal Plain river system. Bioscience 52:999-1010.

Mallin, M. A., M. H. Posey, G. C. Shank, M. R. McIver, S. H. Ensign, and T. D. Alphin. 1999. Hurricane effects on water quality and benthos in the Cape Fear watershed: Natural and anthropogenic impacts. Ecological Applications 9:350-362.

McPherson, B. F., R. T. Montgomery, and E. E. Emmons. 1990. Phytoplankton productivity and biomass in the Charlotte Harbor estuarine system, Florida. Water Research Bulletin. 26:787-800.

Nixon, S. W. 1995. Coastal marine eutrophication: A definition, social causes, and future concerns. Ophelia. 41:199-219.

Tilmant, J. T., R. W. Curry, R. Jones, A. Szmant, J. C. Zieman, M. Flora, M. B. Robblee, D. Smith, R. W. Snow, and H. Wanless. 1994. Hurricane Andrew's effect on marine resources. Bioscience 44:230-237.

Tomasko, D. A., C. Anastasiou, and C. Kovach. 2006. Dissolved Oxygen Dynamics in Charlotte Harbor and Its Contributing Watershed, in Response to Hurricanes Charley, Frances, and Jeanne- Impacts and Recovery. Estuaries and Coasts. 932-938.

Turner, R. E., N.N. Rabalais, B. Fry, N. Atilla, C.S. Milan, J. M. Lee, C. Normandeau, T. A. Oswald, E. M. Swenson, D. A. Tomasko. 2006. Paleo-indicators and water quality changes in the Charlotte Harbor estuary (Florida). Limnol. Oceanogr. 51 (1, part 2) 518-533.

United States Environmental Protection Agency (USEPA). 2001. Nutrient Criteria Technical Guidance Manual. Estuarine and Coastal Marine Waters. EPA-822-B-01-003. U.S. Environmental Protection Agency, Office of Water, Washington, DC.