Numeric Nutrient Criteria Recommendations for the Tampa Bay Estuary

SUMMARY AND TECHNICAL SUPPORT DOCUMENTS

Prepared for:

Tampa Bay Estuary Program

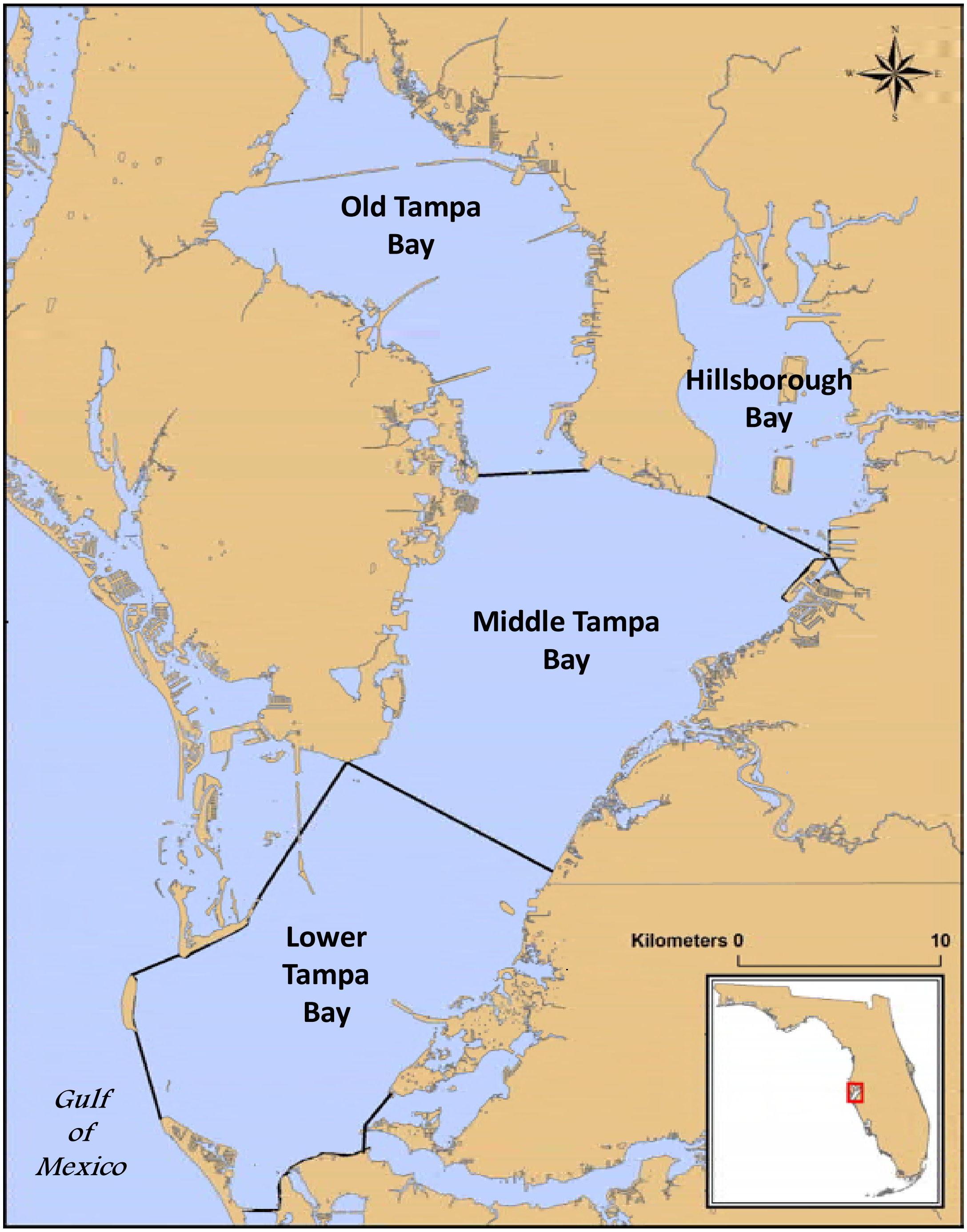
Prepared by:

Janicki Environmental, Inc.

22 February 2011

Objective

The objective of this document is to provide a summary of the recent work conducted by the Tampa Bay Estuary Program (TBEP) to provide the U.S. Environmental Protection Agency (EPA) and the Florida Department of Environmental Protection (FDEP) recommendations regarding the establishment of numeric nutrient criteria for the Tampa Bay Estuary. For reference, the following map of Tampa Bay depicts the four major bay segments referred to in this summary and the attached technical documents.



The Need for Numeric Nutrient Criteria

The FDEP began development of numeric nutrient standards in December 2001. The FDEP formed a technical advisory committee and an agency work group to assist in identifying appropriate nutrient standards. FDEP has conducted a number of workshops and meetings as well as several studies since 2002.

In 2008, several environmental groups filed suit against EPA in Federal Court alleging that EPA had determined in 1998 that Florida's current narrative nutrient standard did not comply with the Clean Water Act and that EPA had not established numeric nutrient standards pursuant to Section 303(c)(4)(B) of the Clean Water Act. As a consequence of this lawsuit, EPA sent FDEP a letter on January 14, 2009 finding that FDEP's narrative nutrient standard did not comply with the Clean Water Act and directing the State of Florida to develop numeric nutrient standards for rivers and lakes by January 2010 and estuarine and coastal waters by January 2011. EPA stated that it would adopt its own nutrient standards if FDEP could not meet these deadlines. In August 2009, the suit plaintiffs and EPA agreed to a Consent Decree formally establishing the deadlines and determined that EPA would be responsible for establishing numeric criteria for Florida waters.

Management of the Tampa Bay Estuary

The Tampa Bay Comprehensive Conservation and Management Plan (TBNEP, 1996) established the restoration of seagrass in the bay to levels estimated in the 1950s as a primary goal for overall bay restoration. In establishing and addressing this goal, a conceptual paradigm was developed to identify the primary, manageable factors thought to influence the recovery and sustainability of seagrass resources within the bay. Reduced water clarity as a result of excessive nitrogen loads to the bay and resulting light attenuation by phytoplankton responding to these loadings were the key water quality indicators by which seagrass recovery could be managed. A number of studies in the 1990s clearly established that nitrogen was the limiting nutrient in the Tampa Bay estuary and that phosphorus loadings to the bay from the enriched Bone Valley region were not controlling estuarine production.

In November 2002, the Florida Department of Environmental Protection (FDEP) concluded that the Tampa Bay Nitrogen Management Consortium's (TBNMC) nitrogen management strategy provided reasonable assurance that the state water quality criteria for nutrients would be met in Tampa Bay. Prior to this state determination, the U.S. Environmental Protection Agency (EPA) recognized a 1998 action by FDEP that proposed a total maximum load ("federally-recognized TMDL") of nitrogen that could be discharged to the bay annually and still meet state water quality standards related to nutrients. Both FDEP's reasonable assurance determination and the total maximum nitrogen loading recognized by EPA are based on statistical modeling and data analyses peer-reviewed by the TBEP, its partners, and state and federal regulators. Thus, the TBNMC's nitrogen loading targets developed for the major bay segments of Tampa Bay have been acknowledged by both FDEP and EPA as protective nutrient loads for this estuary. A five-year renewal of the Tampa Bay Reasonable Assurance (RA) was recently approved by order of the FDEP Secretary.

The Southwest Florida Water Management District recently reported on the seagrass acreage in Tampa Bay from its survey conducted in 2010. The results from this survey show an increase of approximately 3,250 acres since the 2008 survey (Figure 1). Therefore, there is tangible evidence that the TBNMC nitrogen loading strategy continues to support seagrass recovery in the Tampa Bay Estuary.

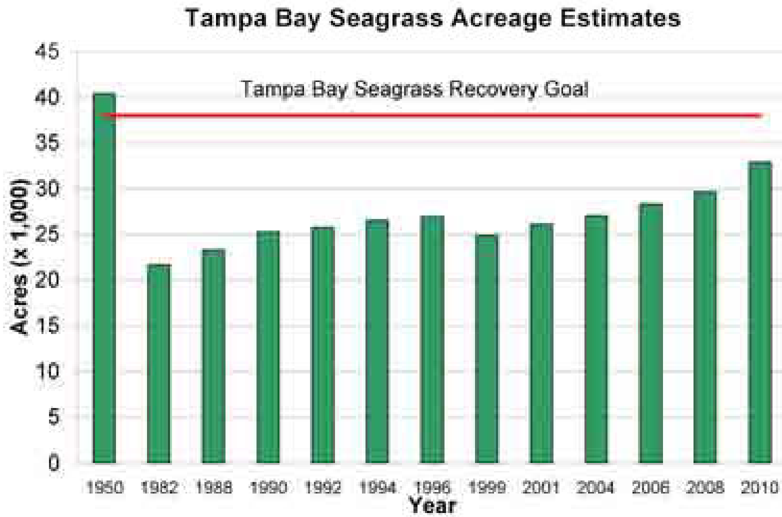


Figure 1. Tampa Bay seagrass coverage. Data source: Southwest Florida Water Management District.

Recent results from the Environmental Protection Commission of Hillsborough County ambient monitoring program indicate that the chlorophyll targets were achieved in all four bay segments of Tampa Bay in 2010 (Figure 2). Therefore, there is tangible evidence that the TBNMC nitrogen loading strategy continues to achieve water quality targets in the Tampa Bay Estuary.

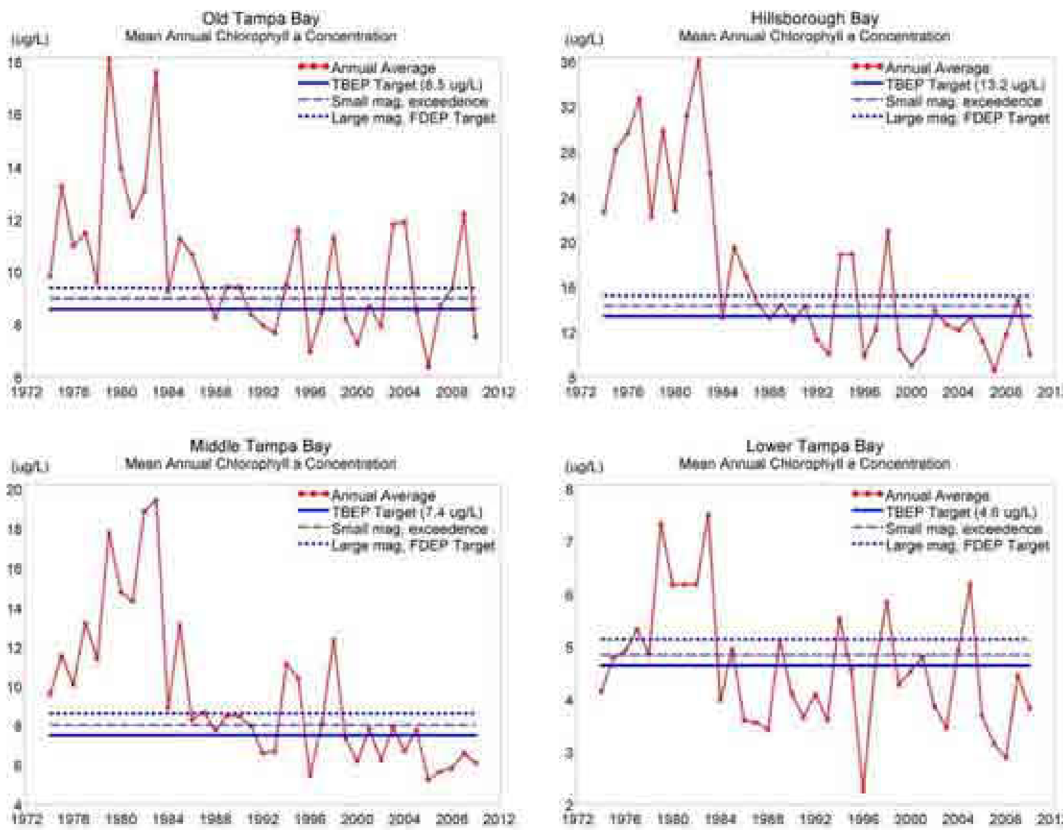


Figure 2. Tampa Bay mean annual chlorophyll *a* concentrations for each of the four major bay segments, 1974-2010. Data source: Environmental Protection Commission of Hillsborough County.

TBNMC Recommendation for Tampa Bay Numeric Nutrient Criteria

In March 2010, the TBNMC provided comments and requests regarding the development by EPA of protective loads for the Tampa Bay Estuary as it relates to establishing numeric nutrient criteria for inland waters and estuaries in Florida. As part of this effort, the TBNMC provided recommended protective nutrient loads for the Tampa Bay Estuary. The TBNMC proposed TN and TP loading criteria for the four mainstem segments of Tampa Bay as follows:

Proposed TN and TP loading criteria for the segments of Tampa Bay.		
Segment	**TN Load (tons/year)**	**TP Load (tons/year)**
Old Tampa Bay	486	104
Hillsborough Bay	1451	1093
Middle Tampa Bay	799	140
Lower Tampa Bay	349	52

EPA expectations are for both total nitrogen (TN) and total phosphorus (TP) protective loads. The recommended protective TN loads for the segments of Tampa Bay are those from the 1992-1994 period, as utilized in the Final 2009 Reasonable Assurance Addendum: Allocation & Assessment Report and in the federally-recognized Tampa Bay TMDL. The TBNMC recommended protective TP loads from the same time period in its comments and requests to the EPA in March 2010.

The TBNMC approach that has established state and federally-approved nitrogen loading targets for the estuary follows EPA's technical guidance that quantitative stressor-response relationships are the most preferred methodology in establishing numeric nutrient criteria (EPA, 2010). Multiple lines of empirical evidence justify maintaining existing TN and TP loads to the Tampa Bay Estuary. Water quality and clarity in the Bay has improved tremendously since significant management actions were initiated starting in the 1980s, seagrass acreage has increased to the highest levels observed since the 1950s and continues to increase, and economically important fish and wildlife populations have been maintained since routine monitoring programs began in the 1990s.

Continuing TBEP Input to EPA Regarding Numeric Nutrient Criteria

The TBEP, in cooperation with the Sarasota Bay Estuary Program and Charlotte Harbor National Estuary Program, supported the development of a document that identified the potential methods for the estimation of numeric nutrient criteria for southwest Florida estuaries (Janicki Environmental, 2010). This document identified several methods currently being considered by both EPA (EPA, 2010) and FDEP (2010) to establish numeric nutrient criteria for Florida estuarine waters.

In addition to the methods document, the TBEP has addressed several other issues associated with the establishment of numeric nutrient criteria for the Tampa Bay Estuary. These include:

- Expression of recommended TN and TP criteria as concentrations.
- Demonstration that the proposed criteria provide full aquatic life support, especially achievement of dissolved oxygen (DO) standards.
- The need for establishment of downstream protective values (DPVs) for terminal reaches that drain directly into Tampa Bay.
- Consideration of the influence of infrequent non-anthropogenic events, such as hurricanes and El Niño conditions, on implementation of the proposed criteria.

The following summarizes the TBEP recommendations regarding these issues. Detailed evaluations for each issue can be found in the attached documents.

- **Concentration-based Criteria**

Previous efforts by the TBEP have developed strong relationships between nutrient supply to Tampa Bay and resultant chlorophyll *a* concentrations in the bay, and between chlorophyll *a* concentrations and light availability for seagrasses. Thus, management actions have focused on controlling nitrogen loads to Tampa Bay, with measureable success as expressed by increases in a biological endpoint, seagrass acreage. The relationships are between nitrogen loads and chlorophyll *a*, however, not nitrogen concentrations in the bay and chlorophyll *a*.

TBEP recognizes that EPA intends to establish criteria for TN and TP and that these criteria may be expressed as ambient concentrations. Although the TBEP recommendations for TN and TP criteria remain the TN and TP loads reported above, recommendations for concentration-based numeric nutrient criteria consistent with the TN and TP loading recommendations have been developed and are being provided by the TBEP (Janicki Environmental, 2011a), in the event that EPA determines that loadings cannot be used as numeric nutrient criteria.

The Reference Period approach was selected to establish the proposed concentration-based numeric criteria for TN and TP. Based on a 1992-1994 reference period, segment-specific chlorophyll *a* targets have been identified and implemented as part of the Tampa Bay Nitrogen Management Strategy since 2000 (Janicki and Wade, 1996; Janicki, Wade, and Pribble, 2000). Using this similar and consistent approach, segment-specific annual geometric mean TN and TP concentrations from the 1992-1994 period were derived for this current effort. TN and TP concentration thresholds, as were developed for established, regulatory-recognized chlorophyll *a* thresholds, account for the inter-annual variability in the TN and TP concentrations observed from 1992-2009.

Application of the Reference Period approach resulted in the following recommendations for concentration-based TN and TP criteria for Tampa Bay. These criteria are:

- Old Tampa Bay TN = 0.93 mg/L TP = 0.31 mg/L
- Hillsborough Bay TN = 1.01 mg/L TP = 0.45 mg/L
- Middle Tampa Bay TN = 0.87 mg/L TP = 0.29 mg/L
- Lower Tampa Bay TN = 0.74 mg/L TP = 0.10 mg/L.

The criteria referenced above should be assessed as an annual geometric mean from long-term monthly water quality monitoring stations currently used in the state's chlorophyll a threshold assessments under the Tampa Bay RA determination. The assessment of TN and TP concentrations attainment should only occur when chlorophyll a thresholds are exceeded within a bay segment, and should coordinate with current regulatory assessments under the FDEP RA determination and EPA TMDL for TN loads in Tampa Bay. Further, compliance assessments should be conducted over five-year time frames, with no more than two consecutive years being greater than these established criteria if chlorophyll a thresholds are also exceeded during the same time period. This approach is analogous to the chlorophyll *a* threshold assessments currently being conducted under the regulatory requirements for the FDEP RA determination and EPA TMDL for Tampa Bay.

- **Aquatic Life Support - Dissolved Oxygen**

The numeric nutrient criteria to be promulgated will need to provide full aquatic life support in each estuary. The aquatic life forms specifically influenced by excessive nutrient loadings to estuaries include seagrasses (affected by reduced water clarity due to excessive chlorophyll *a* concentrations) and fish and benthic communities (affected by reduced DO conditions). Seagrass support is provided by maintenance of appropriate nutrient conditions and the resulting chlorophyll *a* concentrations as discussed above. Support of fish and benthic communities is provided by maintenance of appropriate nutrient conditions and the resulting DO conditions.

The spatial and temporal distributions of DO concentrations in Tampa Bay's major bay segments have been characterized, the principal drivers of low DO conditions in Tampa Bay have been investigated, and the relevance of the empirical distribution of DO concentrations to the FDEP's Impaired Water Rule standard for DO have been evaluated with respect to the proposed numeric nutrient criteria for the Tampa Bay Estuary (Janicki Environmental, 2011b). The following conclusions can be drawn from these efforts:

- A descriptive characterization of the spatial and temporal attributes of observed DO concentrations used over 30 years of data, collected by 4 different sampling agencies. Examination of the spatial distribution of DO samples shows that DO exceedances < 4 mg/L were always less than 10% of the samples in all segments except Hillsborough Bay, never exceeded 15% of the samples in Hillsborough Bay, and are most likely to occur in Hillsborough Bay near the mouths of the Hillsborough River and Alafia River and along the western half of Hillsborough Bay. These are deeper areas, more likely to be stratified due to freshwater inputs, and have high organic sediment content.

- The principal factor affecting DO in Tampa Bay is temperature. That is evident in both the descriptive temporal plots and in the generalized linear model assessed in the quantitative assessment of those factors affecting the probability of DO being less than 4 mg/L. The model results indicate that stratification, bottom type, and sample depth were other factors that contributed to the probability of low DO conditions (i.e., < 4 mg/L). Furthermore, it was determined that chlorophyll *a* concentrations were not a significant factor contributing to the probability of low DO conditions in Tampa Bay. In other words, the occurrence of DO values below 4 mg/L were not significantly related to observed chlorophyll *a* concentrations at the time of sampling.

- 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.

- **Downstream Protection Values**

Downstream Protection Values (DPVs) are defined by EPA as those water quality criteria in flowing waters that ensure protection of designated uses in the downstream estuarine waters as required by the Clean Water Act under 40 CFR 131.10(b). For freshwater lakes, EPA has determined that a

DPV for stream tributaries that flow into a downstream lake is either the allowable concentration or the allowable loading of TN and/or TP applied at the point of entry into the downstream waterbody (EPA Freshwater Rule, finalized December 2010). Either expression (concentration or loading) may be used for assessment and source control allocation purposes, such as TMDLs.

Based on input garnered from a January 28th, 2011, joint TBEP Technical Advisory Committee and TBNMC meeting and the adopted logic approved by EPA for DPVs for freshwater lakes, the TBEP staff contends that the existing federally-approved TMDL TN loading limits and the recommended TP loading limits meet the intent of DPVs for Tampa Bay major bay segments. Continued attainment of chlorophyll *a* thresholds in the major bay segments of Tampa Bay should provide sufficient evidence that the TN and TP contributions of tributaries draining to Tampa Bay are protective of the estuary. Therefore, the protective TN and TP loads recommended by the TBNMC in March 2010 to the EPA are sufficiently protective to attain in-bay chlorophyll *a* thresholds for Tampa Bay.

- **Recommendation for Consideration of Tidal Creeks as Unique Entities**

Questions have been raised as to whether the numeric nutrient criteria proposed for the estuary proper should apply to tidal creeks that drain to the estuary. Tidal creeks play an integral role in the ecological function of coastal estuaries (summarized in Janicki Environmental, 2011d). The treatment of tidal creeks in the implementation of the estuarine numeric nutrient criteria is, therefore, a significant issue. A thorough understanding of the ecological elements (e.g., faunal and floral species and communities), processes (e.g., primary productivity, nutrient cycling, secondary production), dynamics of tidal creeks (e.g., temporal fluctuations in dissolved oxygen) and function in exporting energy to estuarine and coastal ecotones is paramount to the establishment of ecologically appropriate nutrient criteria. Numeric nutrient criteria established for tidal creeks must consider the different ecological processes and functions that distinguish them from both from the freshwater systems upstream and the open estuary downstream. Only with careful consideration of these attributes can criteria be developed that will maintain the function of tidal creeks in support of the greater estuarine ecosystem. Recently, EPA's SAB (SAB Draft Panel Discussion, Jan. 25, 2011) concurred that tidal creeks warrant development of distinct criteria relative to the estuary proper.

Studies of Tampa Bay tidal creeks have revealed compelling evidence that these systems represent unique ecotones within the greater Tampa Bay estuary. Tidal creeks play an integral role in the ecological function of coastal estuaries as sites of high primary and secondary production, nursery and refuge habitat for several species of economically important fish and decapod crustaceans, and foraging areas for large-bodied fishes, wading birds, and other piscivorous species. Higher nutrient concentrations in tidal creeks relative to the greater estuary may be required to support the higher levels of primary and secondary production in these systems.

Analysis of fish collections in tidal creeks suggests that fishes inhabiting tidal creeks appear to be very tolerant to the typical DO conditions found in these systems. Both fish abundance and species richness data indicate that fish communities are relatively invariant to DO levels between 2-10 mg/L. There are indications that at DO concentrations below 2 mg/L, both fish abundance and species richness decline. Species richness of fish and decapod crustaceans may be a more sensitive indicator of the aquatic-life support function of tidal creeks; however, these need further quantification to eliminate the possibility that seasonal recruitment patterns of estuarine-dependent fishes are not correlated with seasonal variation in DO concentrations due to temperature.

The most desirable approach to establish numeric nutrient criteria for these systems would be to develop stressor-response models. Stressor-response models require the identification of an indicator variable that can be used to evaluate the condition of the tidal creek. Moreover, stressor-response models require identification of a threshold value above (or below) which the system would no longer fully support its designated use. It is important that the established criteria for tidal creeks also account for the fact that these systems by nature are more variable than their upstream or downstream counterparts. This variability is in part what makes these systems so productive and also so difficult to generalize. The timing and volume of freshwater inflows are physical drivers that exert a great deal of control on tidal creeks. Inflows are deterministic of salinity regimes, nutrient delivery, water depths, temperatures and the potential for salinity stratification in these systems. Inflows also may control access to these systems for both small recruit species looking for refuge and for large-bodied predators. Therefore, the quantification of the effects on inflows on these systems will be necessary both to determine appropriate criteria and in the evaluation process. The extent of tidal creeks in the Tampa Bay watershed to which these recommendations pertain include, but may not be limited to, the systems identified in the maps provided in Figure 3a,b below.

Based on the recognized need to define distinct biological endpoints for tidal tributaries and water quality criteria to support them, TBEP staff recommends the following:

- Recognize tidal tributaries as a separate waterbody class; and
- Consider setting a schedule (i.e., within 3 years) by which time endpoints and criteria will be proposed, but do not attempt to set interim or final criteria with insufficient data.

TBEP has dedicated funds to continue work in tidal tributaries in Tampa Bay and will commit to work with EPA to develop recommendations by September 2014.

Figure 3. a) Named tidal creeks within the Tampa Bay watershed.

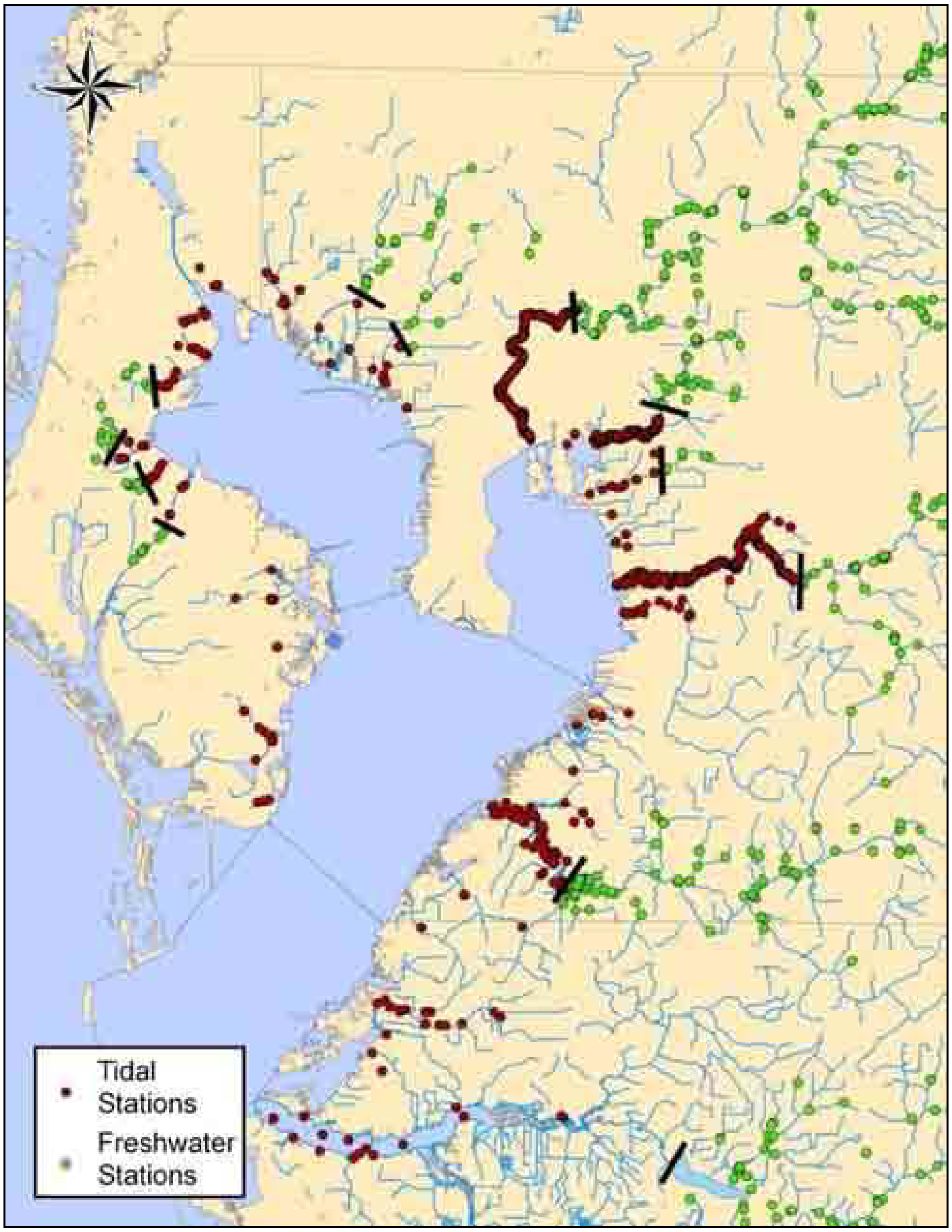


Figure 3. b) Approximate location of the upstream limit of tidal creeks and rivers as defined by empirical salinity data analysis of data from tributaries within the Tampa Bay watershed.

- **Implementation Considerations**

TBEP has addressed two key issues identified by the EPA regarding successful implementation of the proposed numeric nutrient criteria in Tampa Bay, namely the method to account for non-anthropogenic events, such as El Niño and hurricanes, and the allowable exceedance criteria (how often criteria may be exceeded before non-compliance is observed). Analyses were performed to direct input on these subjects (Janicki Environmental, 2011c), with the following conclusions:

- The annual response time to recover from the maximum monthly chlorophyll *a* concentration during a year is relatively short. Median annual response times are two months or less in all segments, and average annual response times are three months or less in all segments. This indicates that the bay recovers very quickly from normal loading events.

- The typical response times to unusual events, such as El Niño, are longer and, depending upon the timing of such events, can span over parts of two successive years.

- Comparison of the two temporal assessment schemes (1 in 3 years) vs (2 in 5 years) suggested that the 2 in 5 rule was less likely to result in a violation due solely to natural variability.

- **Final Implementation and Assessment Recommendations**

It is recommended that the assessment of compliance with the proposed numeric nutrient criteria be performed in a manner similar to that which has been proposed by TBEP for compliance with both the Tampa Bay RA determination and EPA TMDL. The goal of the estuarine numeric nutrient criteria is to provide full aquatic-life support within the estuary. The TBEP has determined that seagrasses are important indicators of desirable conditions in the bay and has defined the water-quality conditions (i.e., chlorophyll *a* concentrations) that allow for the maintenance and growth of seagrass beds in Tampa Bay. Therefore, TBEP bases its compliance assessment on the comparison of both observed chlorophyll *a* concentrations and seagrass extent to the goals that have been established. To date, this has proven to be a successful adaptive management approach for abating nutrient eutrophication in the Tampa Bay Estuary.

References

U.S. Environmental Protection Agency (EPA). 2010. Methods and Approaches for Deriving Numeric Criteria for Nitrogen/Phosphorus Pollution in Florida's Estuaries, Coastal Waters, and Southern Inland Flowing Waters.

Florida Department of Environmental Protetion (FDEP). 2010. DRAFT Overview of Approaches for Numeric Nutrient Criteria Development in Marine Waters. Division of Environmental Assessment and Restoration, Standards and Assessment Section, Florida Department of Environmental Protection, Tallahassee, FL

Hagy, J.D. 2010. Chapter 6: Numeric Nutrient Criteria Development for Protection of Downstream Estuaries. Presentation to EPA Science Advisory Board, Dec 13-14, 2010, Washington, D.C.

Janicki, A., and D. Wade. 1996. Estimating critical external nitrogen loads for the Tampa Bay Estuary: An empirically based approach to setting management targets. Tampa Bay National Estuary Program Technical Publication #06-96.
http://www.tbeptech.org/TBEP_TECH_PUBS/1996/TBEP_06_96ExternalTNLoads.pdf

Janicki, A., D. Wade, and J.R. Pribble. 2000. Developing and Establishing a Process to Track the Status of Chlorophyll-a Concentrations and Light Attenuation to Support Seagrass Restoration Goals in Tampa Bay. Tampa Bay Estuary Program Technical Report #04-00. http://www.tbeptech.org/TBEP_TECH_PUBS/2000/TBEP_04_00Chlor-A.pdf

Janicki Environmental, Inc. 2010. Empirical Approaches to Establishing Numeric Nutrient Criteria for Southwest Florida Estuaries. Report prepared for the Tampa Bay Estuary Program, Sarasota Bay Estuary Program, and Charlotte Harbor National Estuary Program by Janicki Environmental, Inc. http://www.tbeptech.org/TBEP_TECH_PUBS/2010/TBEP_05_10_SW_Florida_NEP_NNC_Methods-July_14_2010.pdf

Janicki Environmental, Inc. 2011a. Tampa Bay Numeric Nutrient Criteria: Task 1 – TN and TP Concentrations. Letter Memorandum. Prepared for Tampa Bay Estuary Program. http://www.tbeptech.org/NitrogenMgmtConsort/NNC/TBEP_NNC_TN_TP_Letter_Memo_16Feb2011.pdf

Janicki Environmental, Inc. 2011b. Tampa Bay Numeric Nutrient Criteria: Task 3 – Dissolved Oxygen. Letter Memorandum. Prepared for Tampa Bay Estuary Program. http://www.tbeptech.org/NitrogenMgmtConsort/NNC/TBEP_NNC_DO_Letter_Memo_16Feb2011.pdf

Janicki Environmental, Inc. 2011c. Tampa Bay Numeric Nutrient Criteria: Task 4 – Implementation Issues. Letter Memorandum. Prepared for Tampa Bay Estuary Program. http://www.tbeptech.org/NitrogenMgmtConsort/NNC/TBEP_NNC_Implementation_Letter_Memo_16Feb2011.pdf

Janicki Environmental, Inc. 2011d. Tampa Bay Numeric Nutrient Criteria: Tidal Creeks. Letter Memorandum. Prepared for Tampa Bay Estuary Program. http://www.tbeptech.org/NitrogenMgmtConsort/NNC/TBEP_NNC_Tidal_Creeks_Letter_Memo_16Feb2011.pdf

Tampa Bay National Estuary Program (TBNEP). 1996. Charting the Course. The Comprehensive Conservation and Management Plan for Tampa Bay. Published by the Tampa Bay National Estuary Program in cooperation with the U.S. Environmental Protection Agency, Region IV. http://www.tbep.org/tbep/download_charting_the_course.html

TAMPA BAY
Numeric Nutrient Criteria:
Task 1 - TN and TP Concentrations

Letter Memorandum

Prepared for:

Tampa Bay Estuary Program

Prepared by:

Janicki Environmental, Inc.

16 February 2011

FOREWORD

This letter memo was produced in partial fulfillment of Purchase Order #6584, TBEP Contract T-07-01 - Development of Numeric Nutrient Criteria for Tampa Bay, Task 1.

ACKNOWLEDGEMENTS

We wish to thank the partners of the Tampa Bay Estuary Program and members of the Tampa Bay Nitrogen Management Consortium for the numerous conversations providing direction and insight into concerns regarding numeric nutrient criteria establishment and appropriate methodology for developing the proposed criteria.

EXECUTIVE SUMMARY

The Tampa Bay Estuary Program (TBEP) and the Tampa Bay Nitrogen Management Consortium (TBNMC) have recommended to EPA numeric nutrient criteria for Tampa Bay as segment-specific annual total nitrogen and total phosphorus loads. EPA has noted its intention to express the numeric nutrient criteria for Tampa Bay as TN and TP concentrations. This document provides segment-specific TN and TP concentrations consistent with the TN and TP loads recommended as numeric nutrient criteria.

Establishment of numeric nutrient criteria is dependent on an understanding of the limiting nutrient within the water body of concern. For Tampa Bay, extensive data exist for evaluation of which nutrient, nitrogen or phosphorus, is limiting. Ambient water quality data strongly indicate that Tampa Bay is nitrogen limited, and this is supported by the results of nutrient addition bioassays.

Previous efforts by the TBEP have developed strong relationships between nutrient supply to Tampa Bay and resultant chlorophyll *a* concentrations in the bay, and between chlorophyll *a* concentrations and light availability for seagrasses. Thus, management actions have focused on controlling nitrogen loads to Tampa Bay, with measureable success as expressed by increases in seagrass acreage. The relationships are between nitrogen loads and chlorophyll *a*, however, not nitrogen concentrations in the bay and chlorophyll *a*.

Previous efforts to link in-bay nitrogen concentrations to chlorophyll *a* concentrations have not produced sufficient explanatory relationships for use in nitrogen concentration target setting. The current effort, driven by EPA's intention to express numeric nutrient criteria as in-bay concentrations, examines several methods to link nutrient concentrations to chlorophyll *a* concentrations and/or nutrient loads.

The final method selected for establishing proposed concentration numeric nutrient criteria for nitrogen and phosphorus was the reference period approach, based on the following rationale. Segment-specific chlorophyll *a* targets (values at this level or below indicate desirable conditions) have been established previously (Janicki and Wade, 1996). These targets were based on a 1992-1994 reference period. In 2001, a protocol for assessing whether the Tampa Bay segments were achieving these targets was developed (Janicki Environmental, 2001). This protocol, referred to as the Decision Matrix approach, considered the year-to-year variability in chlorophyll *a* concentrations and arrived at segment-specific chlorophyll *a* thresholds (values above this level indicate undesirable conditions). The threshold was the sum of the chlorophyll *a* target and 2X the standard error of the long-term chlorophyll *a* concentrations.

Using the same approach, the segment-specific annual geometric mean nitrogen and phosphorus concentrations of the 1992-1994 period were derived as commensurate with the chlorophyll *a* targets. These concentrations were increased by one standard deviation (as derived from 1992-2009 data) to develop the proposed concentration numeric nutrient criteria, which serve as the threshold concentrations in the bay.

The following conclusions are drawn from the analyses completed for this effort:

- Tampa Bay is nitrogen-limited as indicated by both ambient TN:TP ratios and nutrient addition bioassays.

- There is no discernable relationship between TN loadings and in-bay TN concentrations or between TP loadings and in-bay TP concentrations in any bay segment. This is not because loadings do not affect in-bay concentrations, but because various other confounding factors, for which sufficient data are not available, play a role in relationships between loadings and concentrations.

- On a monthly time scale, the relationships between either TN concentrations or TP concentrations and chlorophyll *a* concentrations do not explain a significant proportion of the variability in the chlorophyll *a* concentrations to support development of concentration-based numeric nutrient criteria in any bay segment.

- There are differences in TN concentrations and TP concentrations, particularly in Hillsborough Bay and Middle Tampa Bay, in those years when the chlorophyll *a* concentration thresholds are met when compared to those observed in years when the chlorophyll *a* concentration thresholds are not met. However, there is a great deal of variability within the data obtained in either group of years and these differences are not recommended as the basis for the establishment of concentration-based numeric nutrient criteria for Tampa Bay.

- The reference period approach is recommended for the establishment of concentration-based TN and TP criteria for Tampa Bay. The segment-specific annual geometric mean nitrogen and phosphorus concentrations of the 1992-1994 period were increased by one standard deviation (as derived from 1992-2009 data) to develop the proposed concentration numeric nutrient criteria. These criteria are:

-	Old Tampa Bay	TN = 0.93 mg/L	TP = 0.31 mg/L
-	Hillsborough Bay	TN = 1.01 mg/L	TP = 0.45 mg/L
-	Middle Tampa Bay	TN = 0.87 mg/L	TP = 0.29 mg/L
-	Lower Tampa Bay	TN = 0.74 mg/L	TP = 0.10 mg/L.

The criteria referenced above should be assessed as an annual geometric mean from long-term, monthly water quality monitoring stations currently used in the state's chlorophyll *a* threshold assessments under the Tampa Bay Reasonable Assurance determination. The assessment of TN and TP concentrations attainment should only occur when chlorophyll a thresholds are exceeded within a bay segment, and should coordinate with current regulatory assessments under the FDEP RA determination and EPA TMDL for TN loads in Tampa Bay. Further, compliance assessments should be conducted over five-year time frames, with no more than two consecutive years being greater than these established criteria if chlorophyll *a* thresholds are also exceeded during the same time period. This approach is analogous to the chlorophyll *a* threshold assessments currently being conducted under the regulatory requirements for the FDEP RA determination and EPA TMDL for Tampa Bay.

1.0 Introduction and Objective

The Tampa Bay Estuary Program (TBEP) and the Tampa Bay Nitrogen Management Consortium (TBNMC) have recommended numeric nutrient criteria to U.S. Environmental Protection Agency (EPA) for Tampa Bay (TBNMC, 2010). The criteria, as proposed to EPA, are segment-specific (Figure 1) and are expressed as annual total nitrogen (TN) and total phosphorus (TP) loads. These TN and TP loads are those for the reference period of 1992-1994, as discussed in the March 8, 2010 comments to EPA. However, EPA has informed the TBEP that it intends to express the numeric nutrient criteria for Tampa Bay as TN and TP concentrations.

The objective of this task is to develop segment-specific TN and TP concentrations consistent with the TN and TP loads recommended as numeric nutrient criteria by the TBEP and TBNMC. This is in keeping with recognition of the importance of maintaining consistency with existing management goals and specifically with the recent load allocations to comply with the existing TMDL for Tampa Bay.

The following provides a discussion of nutrient limitation, description of the analyses completed and the results of each analysis, and the recommended TN and TP numeric nutrient criteria, expressed as concentrations, for each of the four mainstem bay segments.

2.0 Nutrient Limitation

The establishment of numeric nutrient criteria depends upon knowledge of the nutrient most likely limiting in the waterbodies of concern. Three major factors control whether nitrogen or phosphorus is more likely to be limiting (NRC, 2000):

- the N:P ratio in external nutrient inputs;
- the preferential loss from the photic zone of nitrogen or phosphorus due to biogeochemical processes such as denitrification, sedimentation, or absorption of phosphorus; and
- the amount of nitrogen fixation.

Marine systems, including estuaries, are generally considered nitrogen limited (Thomas, 1970a,b; Ryther and Dunstan, 1971; Boynton et al., 1982; Smith, 1984; Howarth, 1988, 2008; Howarth et al., 1988a,b; Nixon et al., 1996; Howarth and Marino, 2006; Chapra, 1997; National Research Council, 2000;), although there may be times and locations when phosphorus limitation may occur (Conley, 2000; Conley et al., 2009; Malone et al., 1996).

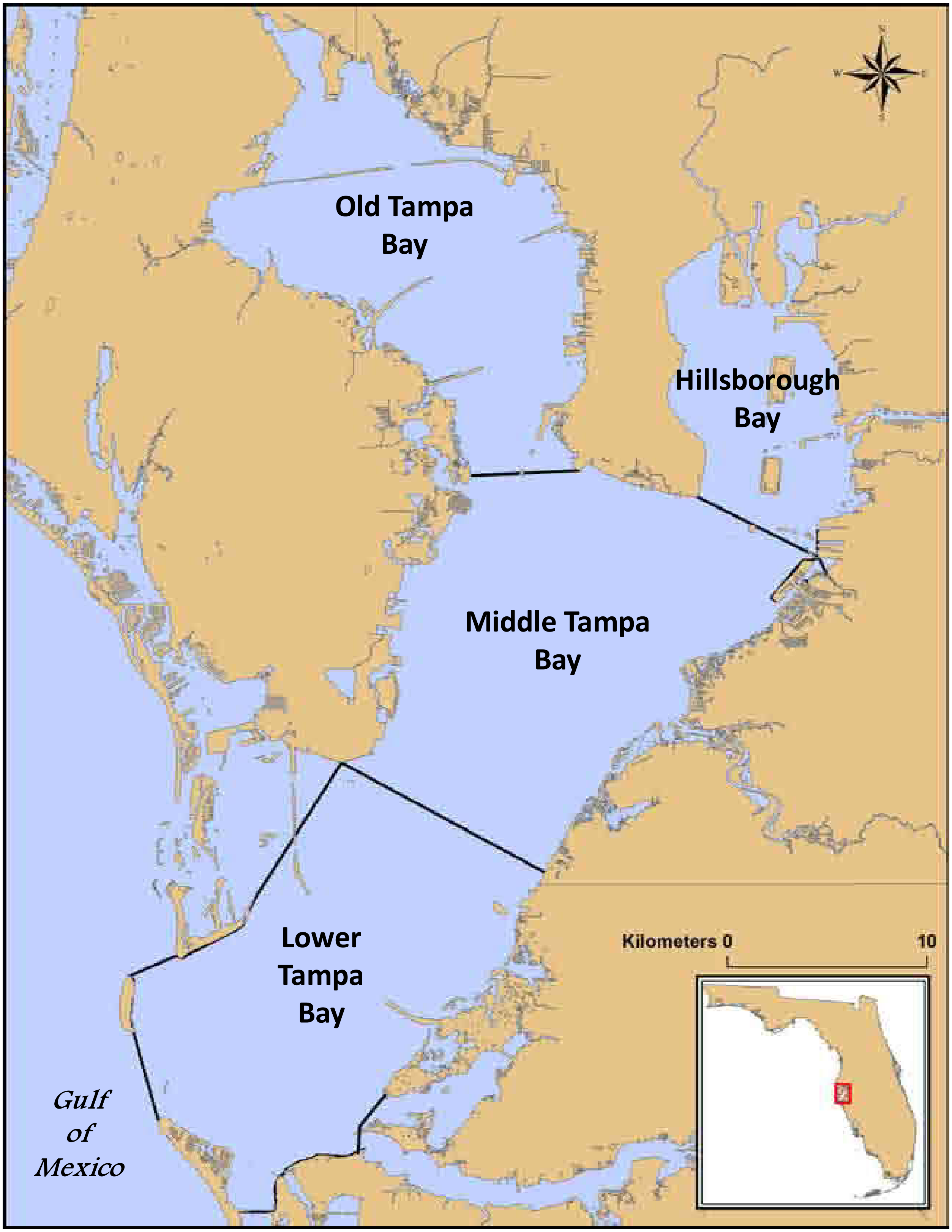


Figure 1. Tampa Bay and its four major bay segments.

Since nitrogen is considered the most likely limiting nutrient in estuarine systems, it has been identified as the primary nutrient of concern in estuarine ecosystems nationwide (Smith, 1984; NRC, 1993). As noted in Correll (1999), however, since estuaries are part of the transition zone between the open ocean and the phosphorus supplied from the land, it is possible that both phosphorus and nitrogen may be limiting in estuaries, dependent upon the time of year, location in the estuary, and nutrient supplies. Ryther and Dunstan (1971) noted the change from phosphorus limitation in freshwaters to nitrogen limitation in near-shore marine waters, although Hecky and Kilham (1988) indicated that the extent and severity of marine nitrogen limitation has not been conclusively determined, with other studies reporting estuarine phosphorus limitation in the spring and nitrogen limitation in the summer and fall (Fisher et al., 1992; Lee et al., 1996). Depending upon the relative rates of nitrogen and phosphorus supply, the limitation has been found to shift between nitrogen and phosphorus in coastal lagoons in the northeastern US (Taylor et al., 1995). It has also been documented that residence times play a significant role in determining the estuarine responses to nutrient loads ((Monson et al., 2002; Hagy et al., 2000; Borsuck et al., 2004; Boynton and Kemp, 2008).

2.1 Methods to Determine Limitation

There are two general methods that have been used to define which nutrient is limiting in a water body. They include:

- a method that depends upon ambient water quality data collected over a wide range of environmental conditions, and
- a method that involves experimental manipulation of nutrient conditions, either in the laboratory or *in situ*.

2.1.1 Ambient Water Quality Data Methods

This method depends upon a metric typically used to evaluate nutrient limitation: the nitrogen to phosphorus ratio (N:P ratio). The N:P ratio indicative of balanced conditions is typically taken to be 16:1 (molar), based on the work of Redfield (1934, 1958). This N:P ratio was based on the elemental composition of algae, under both laboratory and natural conditions. When N:P ratios are greater than 16:1 in a system, this is indicative of phosphorus limitation. However, there may be considerable variation in this ratio within an algal culture, dependent upon cell division status, light conditions, and precedent conditions (Correll, 1999; Correll and Tolbert, 1962; Terry et al., 1985).

Molar ratios of N:P are easily determined from water quality monitoring data. In freshwater systems, the N:P ratio is usually higher than 16:1, indicating that phosphorus is usually most limiting to primary production in these ecosystems (Schindler, 1977; Elser et al., 2007). This becomes evident by examining the concentrations of the forms of nitrogen and phosphorus that are available for algal uptake. Little if any dissolved inorganic phosphorus (DIP) is generally found in relatively productive freshwaters while measurable concentrations of dissolved inorganic nitrogen (DIN) remain.

Most marine systems are nitrogen limited because there are relatively low concentrations of dissolved inorganic nitrogen compared to dissolved phosphorus. Since Redfield's observations were published, research has shown that ratios from 10:1 to 20:1 for N:P are typically found in estuaries (Parsons et al., 1984). Howarth (1988) observed that the correlation between nitrogen and the primary production was better for estuaries that received nutrient concentrations with smaller N:P ratios than the one studied by Redfield. Several studies have led to the conclusion that estuaries receiving nutrient concentrations with high N:P ratios were limited by phosphorus and only those with low ratios are limited by nitrogen (Boynton et al., 1982). Boynton et al. (1982) and Howarth (1988) compiled data on the ratio of inorganic nitrogen to phosphorus in a variety of estuaries. Of the 27 studied by Howarth, 22 had N:P ratios below the Redfield ratio and may have been nitrogen limited. Because phytoplankton can assimilate some organic nutrient forms and all forms are relatively labile, it is useful to examine the ratio of total nutrient concentrations (TN:TP).

Reductions of nutrient levels in a water body will usually result in reduction in algal growth. Reducing phosphorus, however, will have no effect unless the reduction results in an N:P ratio greater than 16:1. Phosphorus would then become the limiting nutrient. In contrast, a reduction of nitrogen concentrations will result in a reduction of primary productivity when the ratio is less than 16:1. There are exceptions to this general rule. Some coastal areas are phosphorus limited due to strict phosphorus control measures or natural conditions and some freshwaters are nitrogen limited due to natural sources of phosphorus.

2.1.2 Experimental Methods

Experimental manipulation of nutrient conditions, either in the lab or *in situ,* typically involves nitrogen and phosphorus additions to either a test alga or a phytoplankton assemblage singularly and in combination. The responses to the additions determine the limiting nutrient. If growth is found only during nitrogen addition, nitrogen-limitation is indicated. Conversely, if growth is found only during phosphorus addition, phosphorus-limitation is indicated.

In situ methods have included:

- limnocorrals or bags in which nutrient additions are made and resultant growth responses are measured (Shapiro, 1980; Lynch and Shapiro, 1981; Havens and DeCosta, 1986; Perez et al., 1994);

- mesocosm studies in which water is collected and placed in separate containers or enclosures for application of separate treatments over multiple day time scales (Oviatt et al., 1986; Taylor et al., 1995); and
- whole-lake studies performed on entire lakes or portions of lakes separated by curtains (Schindler, 1974, 1975).

In Florida, as part of its TMDL process, the Florida Department of Environmental Protection (FDEP) attempts to identify the limiting nutrient(s) in impaired waterbodies. The TMDL for a specific waterbody specifies the maximum amount of the limiting nutrient that may enter the waterbody, with this limitation being defined with the aim of improving water quality. If the N:P ratio does not clearly suggest the limiting nutrient, TMDLs for both nitrogen and phosphorus are typically defined. The primary method for determining the limiting nutrient employed by the FDEP is use of existing water quality data to derive ambient N:P ratios, but more complicated methods, including field tests and laboratory algal growth potential bioassays, have been employed. Per FDEP guidelines, receiving waters with ratios less than 10:1 (molar) are considered nitrogen limited, ratios of greater than 30:1 (molar) indicate phosphorus limitation, and ratios of 10-30:1 (molar) indicate co-limitation (FDEP, 2002).

2.2 Confounding Factors

Determination of the limiting nutrient based solely on N:P ratios estimated from water quality data or from experimental uptake rates should be performed with consideration of potentially confounding effects. Algal cell interior N:P ratios and uptake rates may vary due to:

- cell division status (Correll and Tolbert, 1962),
- light intensity or light quality (Wynne and Rhee, 1986),
- light and temperature (Jahnke et ., 1986), and
- P deprivation and then subsequent availability (Sicko-Goad and Jensen, 1976).

Nutrient limitation in freshwaters, which are typically considered to be phosphorus limited, can vary seasonally. Summer nitrogen limitation in lakes can occur when photic zone inorganic nutrients are low (Elser et al., 1990). It has also been demonstrated that some estuaries show seasonal shifts in limitation (D'Elia et al., 1986; McComb et al., 1981; Conley, 2000). The best available information should be used to determine the limiting nutrient of a system before management decisions are made with the objective of improved water quality via nutrient load control.

2.3 Nutrient Limitation in Tampa Bay

Nutrient limitation in Tampa Bay has been examined using both the N:P ratio method and nutrient addition bioassays.

2.3.1 TN:TP Ratios in Tampa Bay

The average TN:TP ratios for the segments of the TBEP, both by weight and molar, were determined based on ambient water quality data, and are presented in Table 1 for the period 1981 to 2009. The ratios were calculated by first calculating the monthly ratio for each segment based on data collected by the Environmental Protection Commission of Hillsborough County (EPCHC). The mean value of these monthly values within a year was calculated and the mean of these annual values was calculated.

Table 1. Annual mean TN and TP concentrations and TN:TP in TBEP segments (1981-2009).

Bay Segment	TN (mg/L)	TP (mg/L)	TN:TP (Weight)	TN:TP (Molar)
Old Tampa Bay	0.71	0.27	3.5	7.7
Hillsborough Bay	0.79	0.45	2.1	4.6
Middle Tampa Bay	0.63	0.27	2.9	6.3
Lower Tampa Bay	0.48	0.13	4.8	10.5

All segments except Lower Tampa Bay have molar N:P ratios less than 10:1, while that for Lower Tampa Bay is just slightly greater than 10:1. According to the FDEP guidelines (FDEP, 2002), all segments would therefore be considered nitrogen-limited. While nitrogen limitation is indicated in all segments, the nutrient that is most limiting can vary seasonally (Malone et al., 1996; Conley et al., 2009), so that areas that are generally nitrogen limited may by phosphorus-limited at times. In addition to nutrient limitation, phytoplankton growth may also be light-limited during certain parts of the year (Pennock and Sharp, 1994).

Seasonal variation in nutrient limitation has been observed in other waterbodies (Fisher et al., 1992; Lee et al., 1996; Malone et al, 1996; Conley et al., 2009). Season-specific TN:TP ratios were also estimated based on the 1981-2009 data (Table 2). These estimates continue to support the conclusion that Tampa Bay is nitrogen-limited.

Table 2. Seasonal mean TN:TP ratios in TBEP segments (1981- 2009).

Bay Segment	Dry Season		Wet Season	
	TN:TP (Weight)	TN:TP (Molar)	TN:TP (Weight)	TN:TP (Molar)
Old Tampa Bay	3.6	8.0	3.2	7.1
Hillsborough Bay	2.2	4.9	1.9	4.2
Middle Tampa Bay	3.0	6.6	2.6	5.7
Lower Tampa Bay	5.1	11.3	4.2	9.2

2.3.2 Nutrient Addition Bioassays in Tampa Bay

The City of Tampa Bay Study Group routinely performed bioassays throughout Tampa Bay during 1993-2009 as part of the evaluation of the effects of discharge from the H.F. Curren wastewater facility (Johansson, 2009 – Attachment 1). Bioassays in late winter and late summer have been conducted for most of this period. The results of these 152 bioassays have supported that nitrogen is the primary limiting nutrient in the bay, with no results showing phosphorus as the limiting nutrient in the bay, including within that portion of the bay which receives the wastewater effluent. Therefore, the discharge phosphorus limitation is not required for this facility.

It is concluded that the four mainstem bay segments in Tampa Bay are nitrogen-limited. This conclusion contributed to the development of TN loading targets for Tampa Bay (Janicki and Wade, 1996), without consideration of TP loading targets in the original target setting effort. Since EPA is considering developing both TN and TP numeric nutrient criteria for Tampa Bay, the proposed numeric nutrient criteria expressed as TP loads were based on the same time period used to develop the proposed TN loading numeric nutrient criteria (comments submitted to EPA (TBNMC, 2010). Table 3 presents the recommended protective nutrient loads established by the TBNMC and proposed to EPA.

Table 3. Protective nutrient loads for the Tampa Bay estuary established by the Tampa Bay Nitrogen Management Consortium, and accepted through separate administrative action by FDEP (acceptance of the 2002 RA, 2007 RA Update & 2009 RA Addendum) and EPA (establishment of the 1998 federally-recognized TMDL for Tampa Bay).		
Bay Segment	**Tampa Bay NMC Proposed Alternative Total Nitrogen Load expressed as tons/year**	**Tampa Bay NMC Proposed Total Phosphorus Load expressed as tons/year**
Old Tampa Bay	486	104
Hillsborough Bay	1,451	1,093
Middle Tampa Bay	799	140
Lower Tampa Bay	349	52
Remainder of Lower Tampa Bay	629	112

3.0 Tampa Bay TN and TP Criteria: Analyses and Results

Multiple analyses were completed in the evaluation of potential TN and TP criteria expressed as in-bay concentrations. These include:

- examination of the relationships between TN and TP loadings to in-bay TN and TP concentrations, respectively;
- examination of relationships between monthly TN and TP concentrations with chlorophyll *a* concentrations;
- examination of relationships between annual TN and TP concentrations with chlorophyll *a* concentrations; and
- application of a reference period approach to establishing TN and TP concentration-based criteria.

The data used in these analyses are defined in Attachment 2. The following describes these analyses and the results obtained.

3.1 Evaluation of Relationships Between In-bay TN and TP Concentrations and TN and TP Loads

Since the current proposed TN and TP criteria are expressed as loads, the simplest method to propose criteria expressed as in-bay concentrations would be based on the potential relationships between in-bay TN and TP concentrations and TN and TP loads delivered to each segment. All four mainstem segments have annual TMDL TN loads recognized by both EPA and DEP. If significant relationships are found between the nutrient loads and their respective in-bay concentrations, then the proposed numeric nutrient criteria loads could be expressed as concentrations.

Monthly segment-specific TN and TP concentrations were merged with monthly segment-specific TN and TP loads resulting in a dataset of monthly values of TN and TP concentrations and loads. Plots of these data were inspected, with TN and TP concentrations as functions of TN and TP loads, respectively, including various lag and cumulative load effects. Graphical results for each segment are provided in Attachment 3 (TN) and Attachment 4 (TP). The relationships examined are between the in-bay nutrient concentrations and the following:

- Current months load,
- Previous month load,
- Cumulative loads over current and previous month, and
- Cumulative loads over current and two previous months.

The graphical representations of the relationships were then used to guide evaluation of relationships between TN and TP concentrations and loads that may explain large proportions of the monthly variation in concentrations.

No relationships were found between TN concentrations and potential TN load explanatory variables that explained more than 20% of the variation in TN concentrations in Hillsborough Bay or more than 10% of the variation in concentrations in the other three bay segments (Table 4). In Old Tampa Bay, the natural log-transformed three-month cumulative TN load explained only 7% of the variation in in-bay TN concentrations. In Hillsborough Bay, the natural log-transformed two-month cumulative TN load explained 33% of the variation in in-bay TN concentrations. In Middle Tampa Bay, 10% of the variation in in-bay TN concentrations was explained by the natural log-transformed three-month cumulative TN load, and 20% of the variation in in-bay TN concentrations in Lower Tampa Bay was explained by the natural log-transformed cumulative three-month TN load. This suggests that there are some in-bay processes (e.g., sedimentation, denitrification, and transport within the bay and exchange with the Gulf of Mexico) that affect the relationship between the TN loads and the resultant in-bay TN concentrations in Tampa Bay.
The relationships between TP concentrations and potential TP loading explanatory variables that were found varied appreciably among bay segments (Table 3). In Old Tampa Bay, the natural log-transformed three-month cumulative TP load explained 44% of the variation in TP concentrations. In Hillsborough Bay, the natural log-transformed current month TP load explained 33% of the variation in in-bay TP concentrations. In Middle Tampa Bay, 47% of the variation in TP concentrations was explained by the natural log-transformed three-month cumulative TP load, and 20% of the variation in TP concentrations in Lower Tampa Bay was explained by the natural log-transformed cumulative three-month TP load.

The results of these analyses do not provide adequate evidence to support recommendations for TN and TP concentration criteria based on the relationships between the in-bay nutrient concentrations and the nutrient loads to those segments.

Table 4. Best-fit regressions of TN and TP concentrations on TN and TP loads, respectively.

Segment – Variable	Regression	p > F	r^2
Old Tampa Bay – [TN]	$[TN] = 0.19 + 0.112 *$ln Cumulative 3-Month TN Load	<0.0001	0.07
Old Tampa Bay – [TP]	$[TP] = -0.32 + 0.15 *$ln Cumulative 3-Month TP Load	<0.0001	0.44
Hillsborough Bay – [TN]	$[TN] = -0.25 + 0.189 *$ln Cumulative 2-Month TN Load	<0.0001	0.20
Hillsborough Bay – [TP]	$[TP] = 0.32 + 0.0008 *$ln Current Month TP Load	<0.0001	0.33
Middle Tampa Bay – [TN]	$[TN] = 0.5 + 0.0005 *$ln Cumulative 3-Month TN Load	<0.0001	0.10
Middle Tampa Bay – [TP]	$[TP] = -0.08 + 0.089 *$ln Cumulative 3-Month TP Load	<0.0001	0.47
Lower Tampa Bay – [TN]	$[TN] = 0.3 + 0.036 *$ln Cumulative 3-Month TN Load	<0.0141	0.02
Lower Tampa Bay – [TP]	$[TP] = 0.1 + 0.0005 *$ln Cumulative 3-Month TP Load	<0.0001	0.20

3.2 Evaluation of Relationships Between Chlorophyll *a* and TN and TP Concentrations

The second data analysis approach examined the potential relationships between chlorophyll *a* concentrations and either TN or TP concentrations in each bay segment. Chlorophyll *a* thresholds have been established by the TBEP as part of the nitrogen management plan for the bay. If significant relationships are found, then the chlorophyll *a* thresholds could be used to determine the corresponding nutrient concentrations for use as numeric nutrient criteria. There are two temporal scales that can be examined – monthly and annual.

3.2.1 Evaluation of Relationships Between Monthly Chlorophyll *a* and TN and TP Concentrations

Initially, monthly segment-specific chlorophyll *a* and nutrient (TN and TP) concentrations were plotted. A series of variables based on the ambient TN and TP concentrations, including various lag concentrations, was examined. Graphical results are provided in Attachments 5 (TN) and 6 (TP) for each segment as scatter plots of chlorophyll *a* and the following:

- Current month TN and TP concentration,
- Previous month TN and TP concentration,
- Average of current and previous months TN and TP concentrations, and
- Average of current and two previous months TN and TP concentrations,

The graphical representations of the relationships were then used to guide evaluation of relationships between chlorophyll *a* and TN and TP concentrations that may explain the monthly variation in chlorophyll *a* concentrations.

No relationships were found between chlorophyll *a* and TN concentrations that explained more than 24% of the variation in chlorophyll *a* (maximum r^2 = 0.24) (Table 5). In Old Tampa Bay, the mean two-month TN concentration explained 12% of the variation in in-bay chlorophyll *a* concentrations. In Hillsborough Bay, the same-month TN concentration explained 33% of the variation in in-bay chlorophyll *a* concentrations. In Middle Tampa Bay, 17% of the variation in in-bay chlorophyll *a* concentrations was explained by the same-month TN concentration, and only 6% of the variation in in-bay chlorophyll *a* concentrations in Lower Tampa Bay was explained by the same-month TN concentration.

No relationships were found between chlorophyll *a* and TP concentrations that explained more than 27% of the variation in chlorophyll *a* concentrations (Table 5). In Old Tampa Bay, the same-month TP concentration explained 15% of the variation in in-bay chlorophyll *a* concentrations. In Hillsborough Bay, the mean two-month TP concentration explained 17% of the variation in in-bay chlorophyll a concentrations. In Middle Tampa Bay and Lower Tampa, the same-month TP concentration explained 27% and 12%,respectively, of the variation in in-bay chlorophyll *a* concentrations.

Table 5. Best-fit regressions of monthly chlorophyll *a* concentrations on TN and TP concentrations.			
Segment – Variable	Regression	p > F	r^2
Old Tampa Bay – TN	chl *a* =3.78 + 7.34*Mean 2-month TN Concentration	<0.0001	0.12
Old Tampa Bay – TP	chl *a* =5.51 + 14.94*Mean TP Concentration	<0.0001	0.15
Hillsborough Bay – TN	chl *a* =1.22 + 15.7* Mean TN Concentration	<0.0001	0.24
Hillsborough Bay – TP	chl *a* =6.82+15.65*Mean 2-month TP Concentration	<0.0001	0.17
Middle Tampa Bay – TN	chl *a* = 2.75 + 7.45* Mean TN Concentration	<0.0001	0.17
Middle Tampa Bay – TP	chl *a* = 3.45 + 15.59*Mean TP Concentration	<0.0001	0.27
Lower Tampa Bay – TN	chl *a* =3.02 + 2.9* Mean TN Concentration	<0.0003	0.06
Lower Tampa Bay – TP	chl *a* = 2.97 + 10.22*Mean TP Concentration	<0.0001	0.12

The results of these analyses do not provide adequate evidence to support recommendations for TN and TP concentration criteria based on the relationships between the in-bay chlorophyll *a* concentrations and the in-bay TN and TP concentrations in these segments.

3.2.2 Evaluation of Relationships Between Annual Chlorophyll *a* and TN and TP Concentrations

The relationships between annual mean chlorophyll *a* and annual mean TN and TP concentrations were examined as a potential means of developing nutrient criteria. The annual mean TN and TP concentrations were classified according to whether the annual chlorophyll *a* threshold in a given segment was met or not. Based on this classification, the TN and TP concentrations for those years in which the threshold was met could be compared to those TN and TP concentrations for those years when the threshold was exceeded (Figures 2-9).

The results of this analysis indicate that on an annual basis, there are differences in the in-bay TN concentrations during years in which the threshold chlorophyll *a* targets are met and those in which they are not met. This is particularly the case in Hillsborough Bay and Middle Tampa Bay. Similar differences were found between the TP concentrations in those years in which the threshold chlorophyll *a* targets are met and those in which they are not met. However, these differences are not as discrete as seen in the TN concentrations.

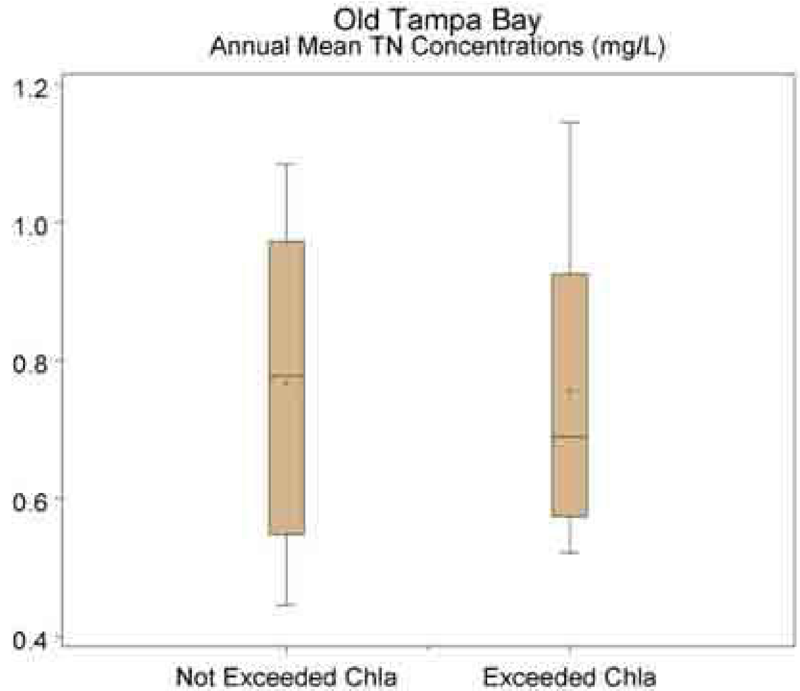


Figure 2. Comparison of TN concentrations in Old Tampa Bay in those years when the chlorophyll *a* thresholds were exceeded and those years when the chlorophyll *a* thresholds were not exceeded.

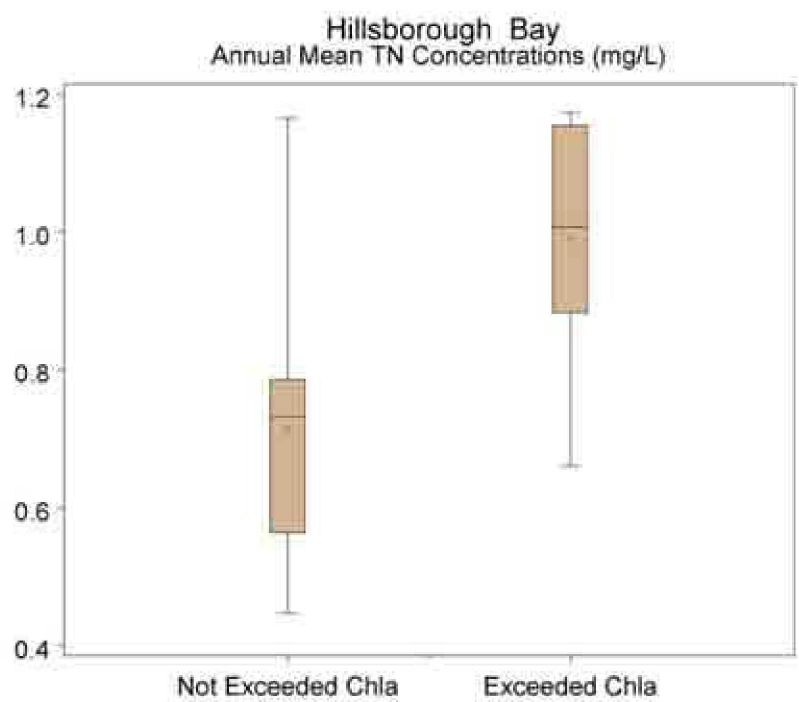


Figure 3. Comparison of TN concentrations in Hillsborough Bay in those years when the chlorophyll *a* thresholds were exceeded and those years when the chlorophyll *a* thresholds were not exceeded.

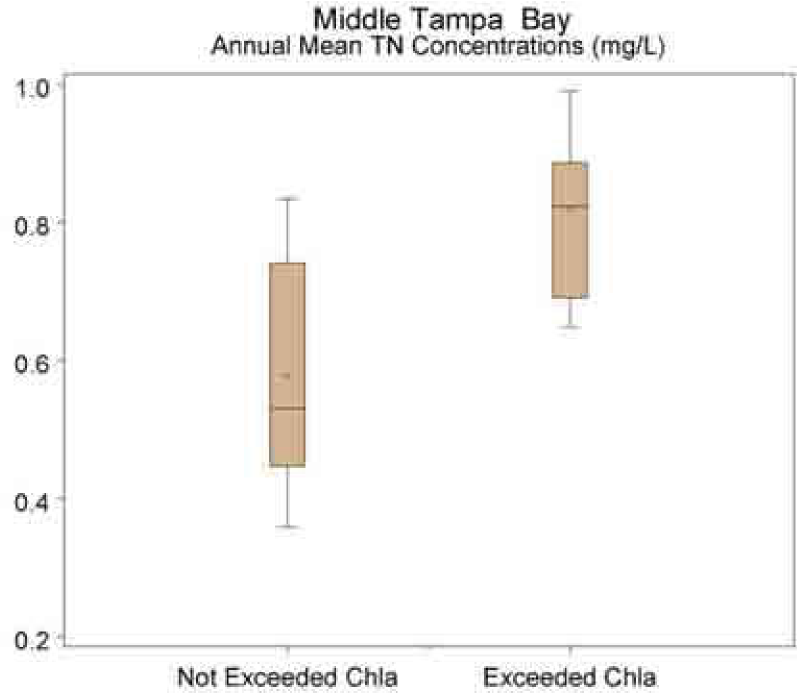


Figure 4. Comparison of TN concentrations in Middle Tampa Bay in those years when the chlorophyll *a* thresholds were exceeded and those years when the chlorophyll *a* thresholds were not exceeded.

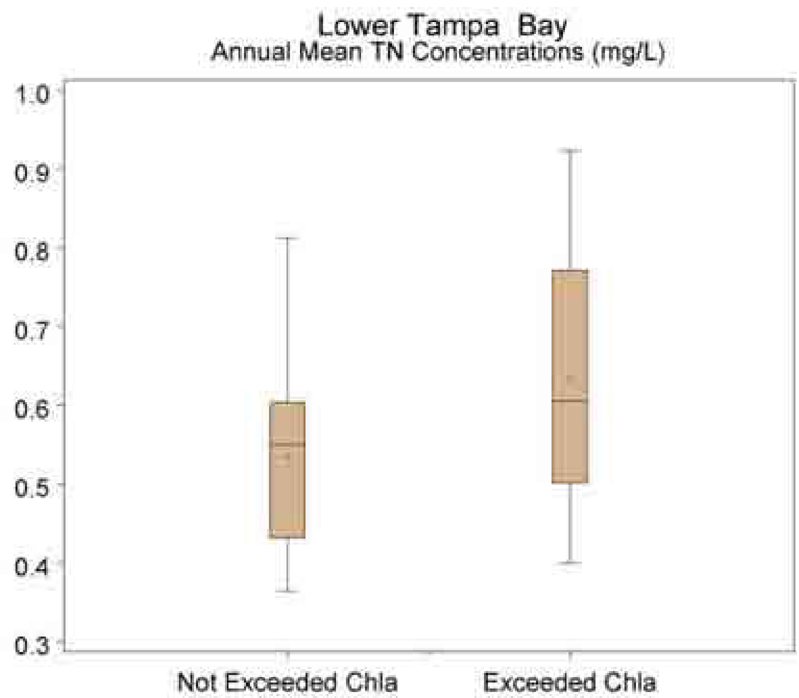


Figure 5. Comparison of TN concentrations in Lower Tampa Bay in those years when the chlorophyll *a* thresholds were exceeded and those years when the chlorophyll *a* thresholds were not exceeded.

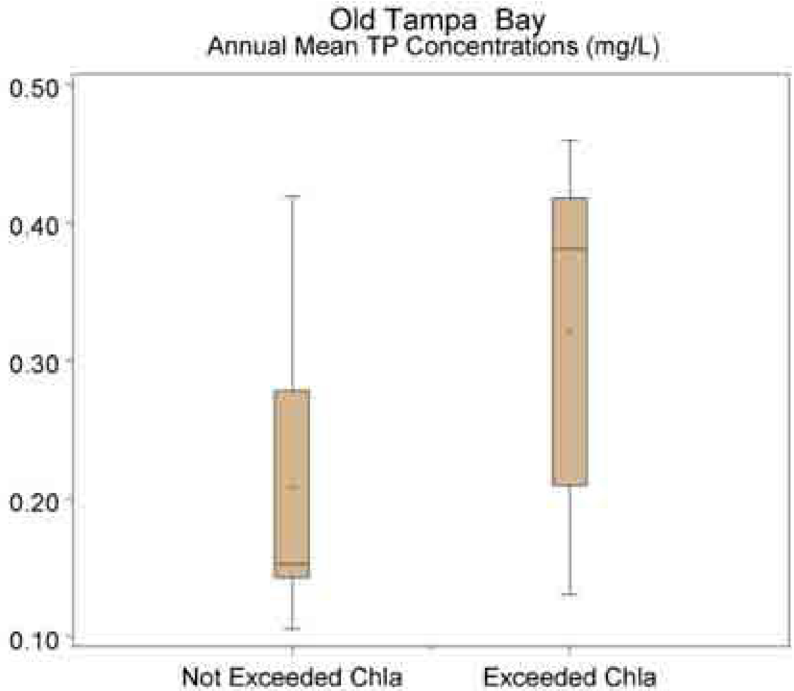


Figure 6. Comparison of TP concentrations in Old Tampa Bay in those years when the chlorophyll *a* thresholds were exceeded and those years when the chlorophyll *a* thresholds were not exceeded.

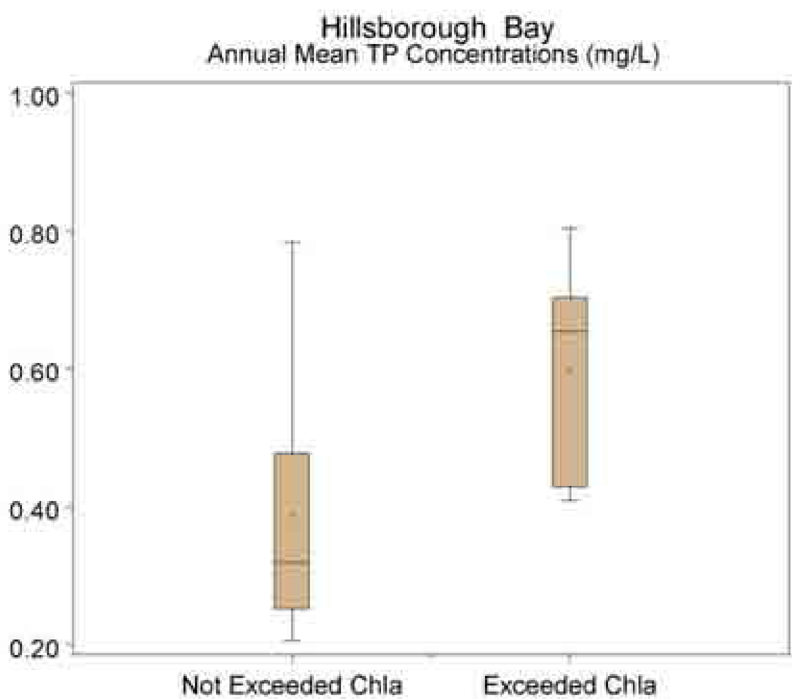


Figure 7. Comparison of TP concentrations in Hillsborough Bay in those years when the chlorophyll *a* thresholds were exceeded and those years when the chlorophyll *a* thresholds were not exceeded.

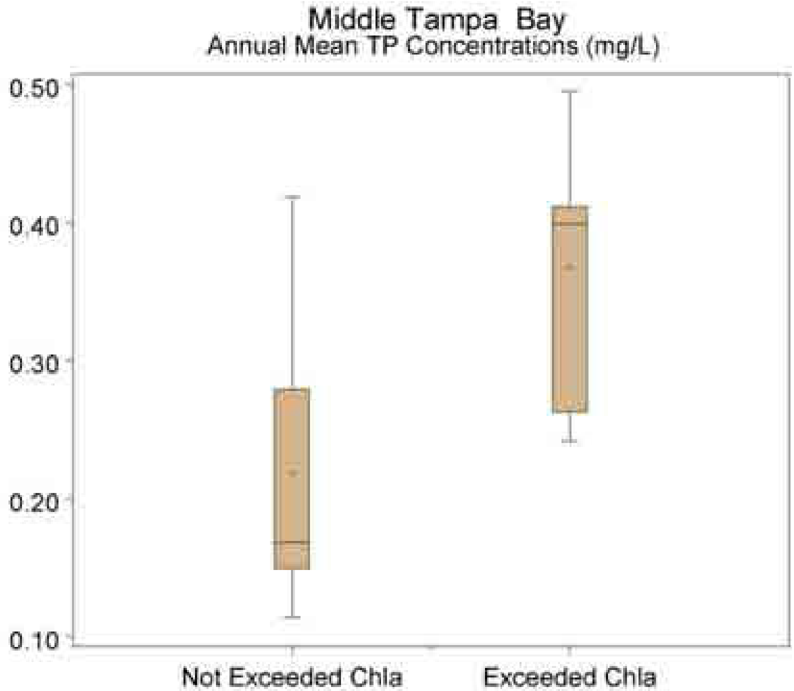


Figure 8. Comparison of TP concentrations in Middle Tampa Bay in those years when the chlorophyll *a* thresholds were exceeded and those years when the chlorophyll *a* thresholds were not exceeded.

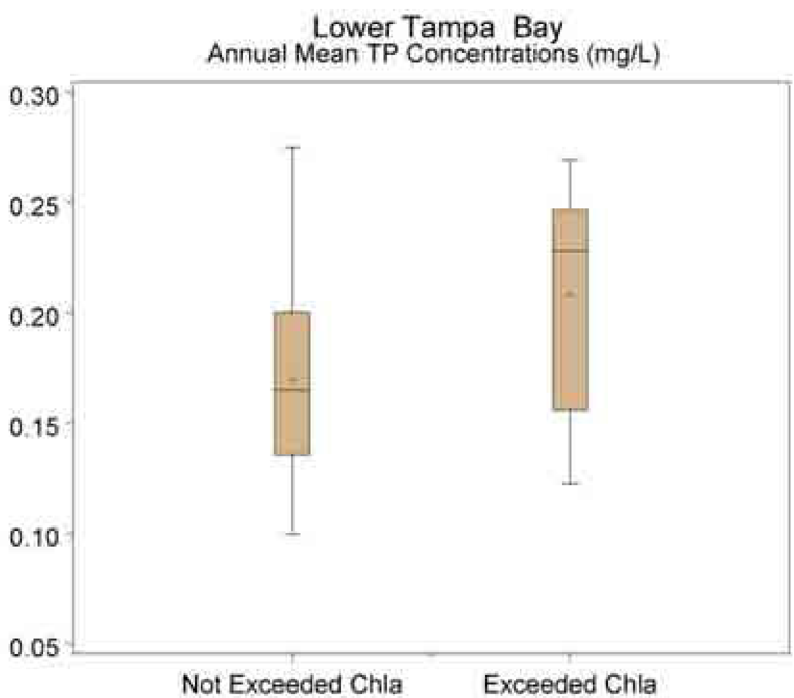


Figure 9. Comparison of TP concentrations in Lower Tampa Bay in those years when the chlorophyll *a* thresholds were exceeded and those years when the chlorophyll *a* thresholds were not exceeded.

3.3 Reference Period TN and TP Concentrations as Concentration Criteria

The analyses described above indicated that while there were significant relationships between monthly nutrient concentrations and loads, and between monthly chlorophyll *a* and nutrient concentrations, these relationships explained very little of the observed variation in the dependent constituent. The evaluations of annual average chlorophyll *a* and annual TN and TP concentrations did provide evidence that for some segments, there were differences in nutrient concentrations between those periods in which chlorophyll a targets were met and those in which they were exceeded. Based on these findings, establishment of nutrient criteria should be linked to the annual chlorophyll *a* and loading targets already established for Tampa Bay.

The fourth approach to developing concentration-based numeric nutrient criteria is the reference period approach. Segment-specific chlorophyll *a* **targets** (values at this level or below indicate desirable conditions) have been previously established (Janicki and Wade, 1996). These targets were based on a 1992-1994 reference period. In 2000, a protocol for assessing whether the Tampa Bay segments were achieving these targets was developed (Janicki and Pribble, 2000). This protocol, referred to as the Decision Matrix approach, considered the year-to-year variability in chlorophyll a concentrations and arrived at segment-specific chlorophyll *a* **thresholds** (values above this level indicate undesirable conditions). The threshold was the sum of the chlorophyll a target and 2X the standard error of the long-term chlorophyll *a* concentrations. FDEP has adopted these thresholds to assess compliance with the Tampa Bay Reasonable Assurance.

Following this approach, numeric nutrient criteria for the four bay segments can be estimated. The 1992-1994 annual geometric mean concentrations are:

- Old Tampa Bay TN = 0.75 mg/L TP = 0.25 mg/L
- Hillsborough Bay TN = 0.82 mg/L TP = 0.37 mg/L
- Middle Tampa Bay TN = 0.69 mg/L TP = 0.24 mg/L
- Lower Tampa Bay TN = 0.57 mg/L TP = 0.08 mg/L

The following are the standard deviations of the mean annual TN and TP concentrations from the 1992-2009 period (which includes all years since the chlorophyll a concentration and TN loading targets were established):

- Old Tampa Bay TN = 0.18 mg/L TP = 0.06 mg/L
- Hillsborough Bay TN = 0.19 mg/L TP = 0.08 mg/L
- Middle Tampa Bay TN = 0.18 mg/L TP = 0.05 mg/L
- Lower Tampa Bay TN = 0.17 mg/L TP = 0.02 mg/L

In the same manner as the chlorophyll a thresholds were developed for Tampa Bay as described above, the proposed concentration-based TN and TP criteria are defined as the sum of the concentration targets and the standard deviation of the long-term mean annual TN and TP concentrations. Table 6 presents these proposed criteria.

Table 6. Proposed numeric nutrient criteria based on geometric mean of annual concentrations for the period 1992-1994 and the standard deviation of the long-term TN and TP concentrations.		
Segment	**TN Concentration (mg/L)**	**TP Concentration (mg/L)**
Old Tampa Bay	0.93	0.31
Hillsborough Bay	1.01	0.45
Middle Tampa Bay	0.87	0.29
Lower Tampa Bay	0.74	0.10

The proposed TN and TP concentration criteria are compared to the observed geometric mean annual TN and TP concentrations in Figures 10 through 17. The horizontal lines represent the proposed criteria; the data to the right of the vertical lines depict the TN and TP concentrations since the establishment of the reference period (1992-1994).

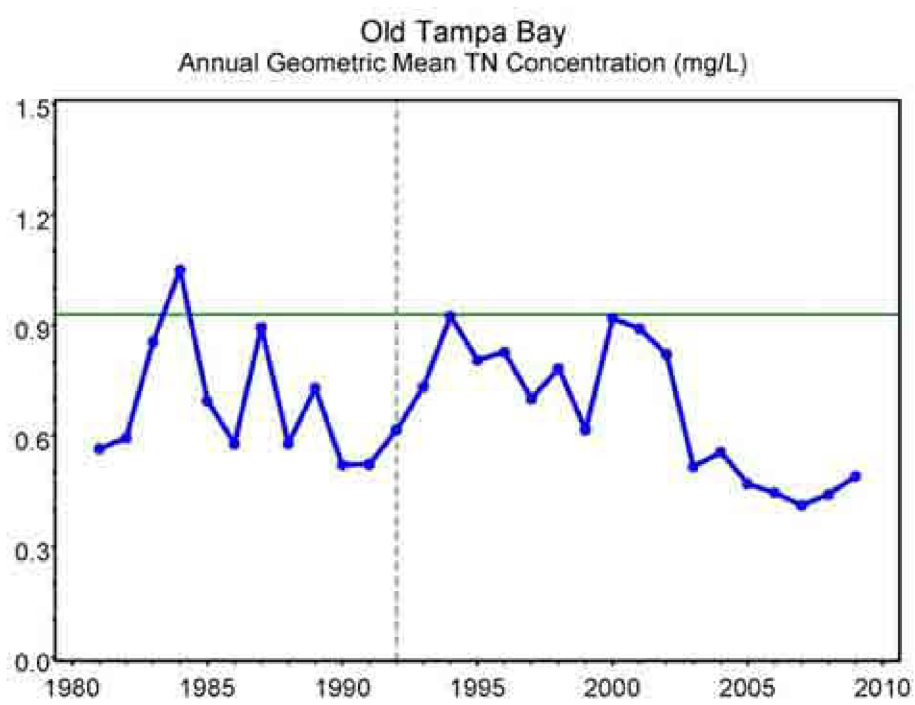


Figure 10. Comparison of proposed TN concentration criterion for Old Tampa Bay to the annual geometric mean TN concentrations from 1981 through 2009.

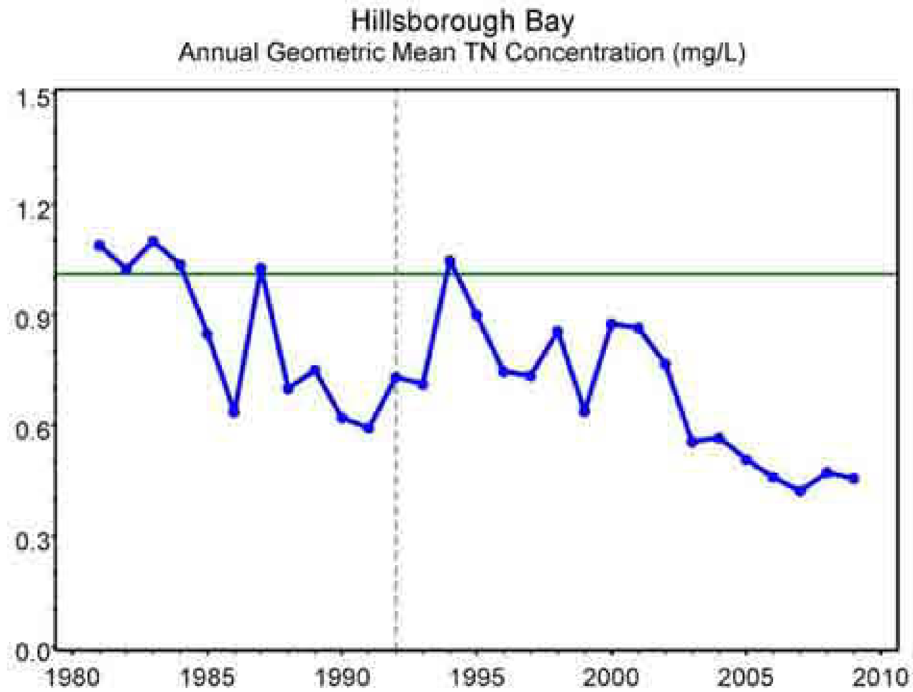


Figure 11. Comparison of proposed TN concentration criterion for Hillsborough Bay to the annual geometric mean TN concentrations from 1981 through 2009.

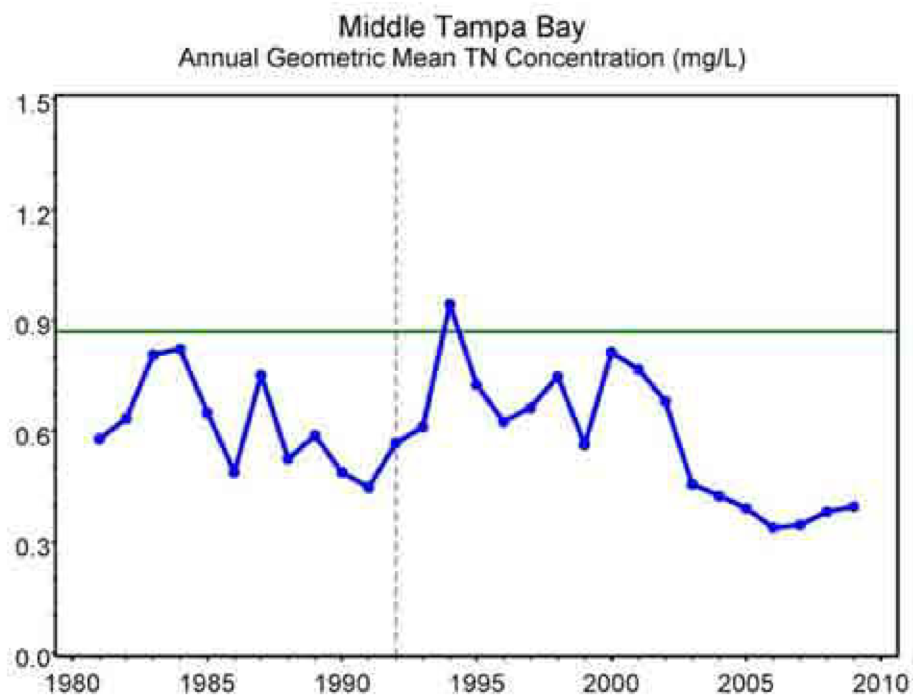


Figure 12. Comparison of proposed TN concentration criterion for Middle Tampa Bay to the annual geometric mean TN concentrations from 1980 through 2009.

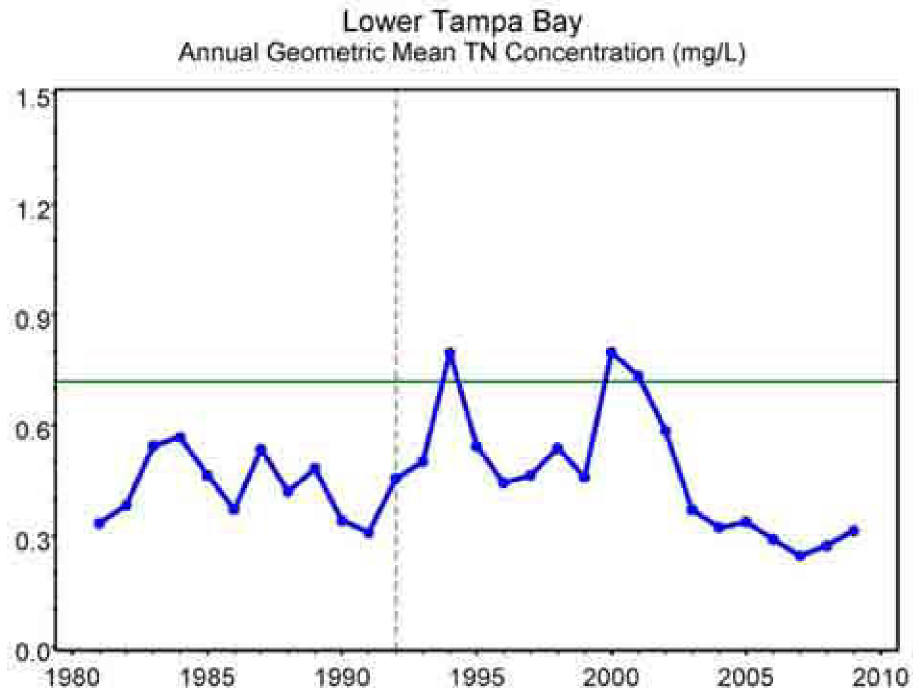


Figure 13. Comparison of proposed TN concentration criterion for Lower Tampa Bay to the annual geometric mean TN concentrations from 1980 through 2009.

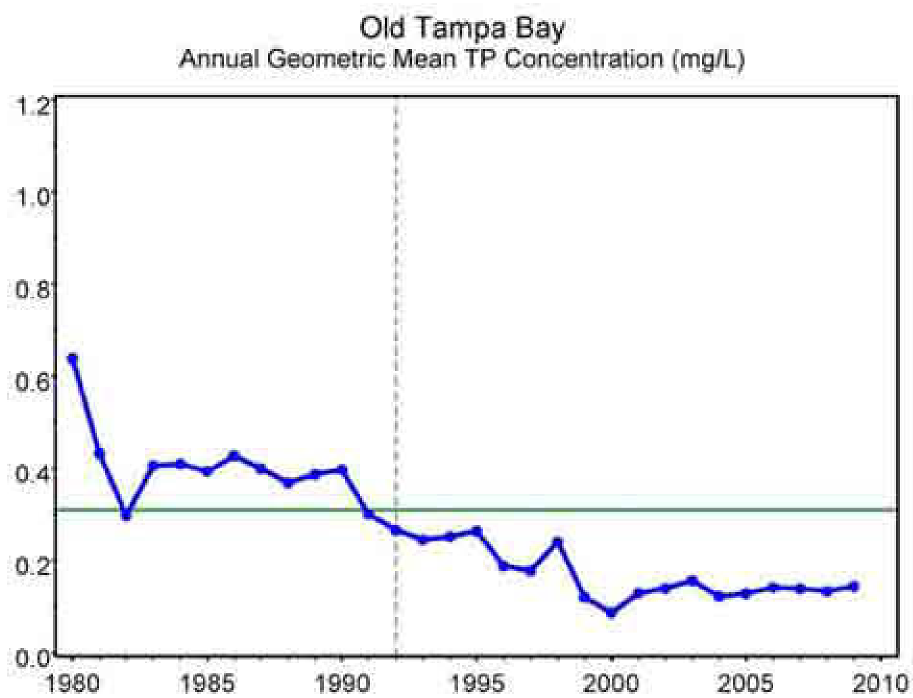


Figure 14. Comparison of proposed TP concentration criterion for Old Tampa Bay to the annual geometric mean TP concentrations from 1980 through 2009.

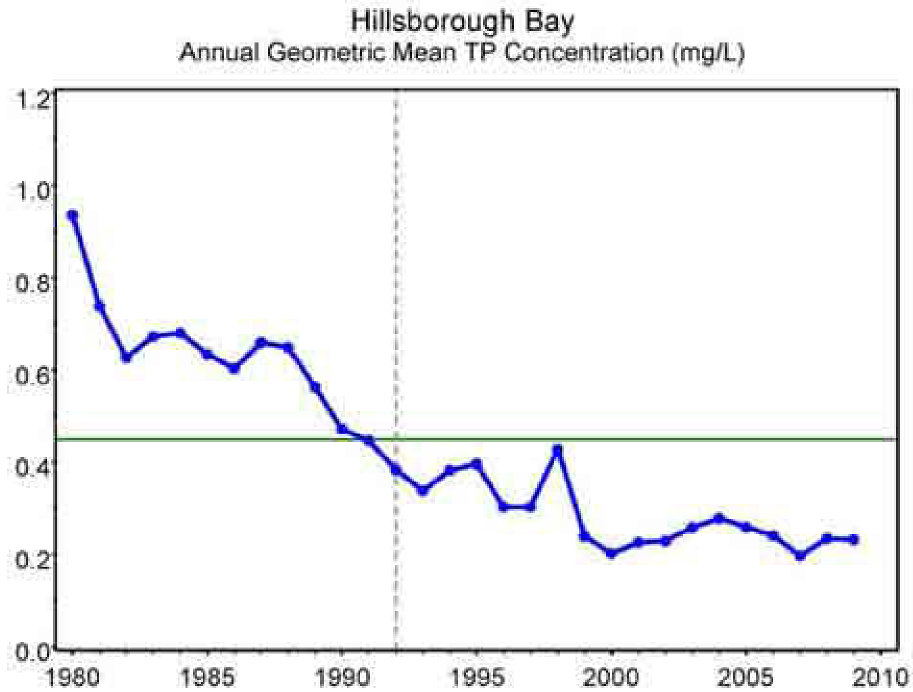


Figure 15. Comparison of proposed TP concentration criterion for Hillsborough Bay to the annual geometric mean TP concentrations from 1980 through 2009.

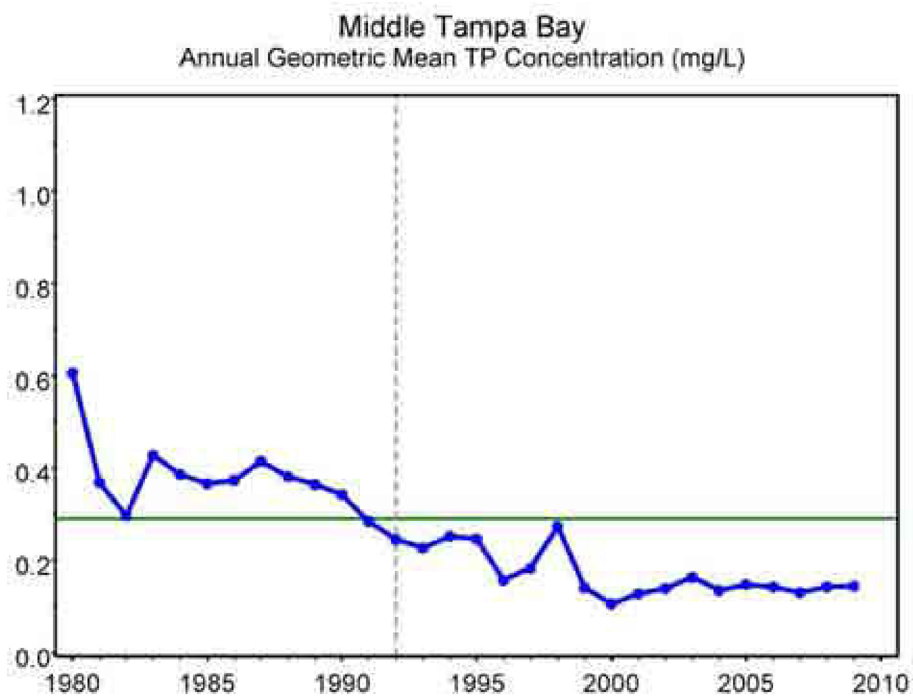


Figure 16. Comparison of proposed TP concentration criterion for Middle Tampa Bay to the annual geometric mean TP concentrations from 1980 through 2009.

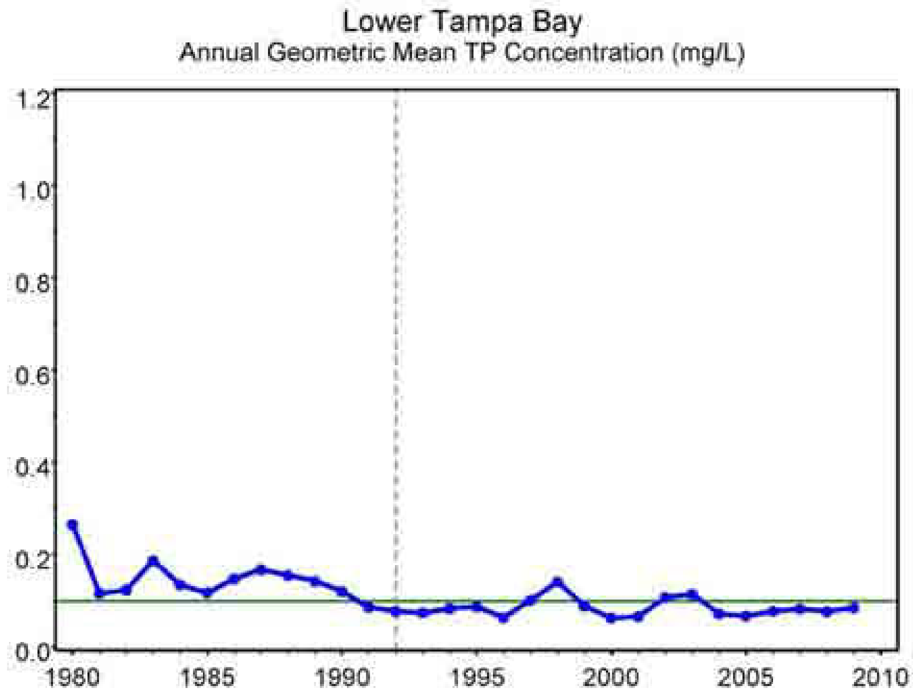


Figure 17. Comparison of proposed TP concentration criterion for Lower Tampa Bay to the annual geometric mean TP concentrations from 1980 through 2009.

4.0 Conclusions

The following conclusions can be drawn from the analyses and results discussed above:

- Tampa Bay is nitrogen-limited as indicated by both ambient TN:TP ratios and nutrient addition bioassays.

- There is no discernable relationship between TN loadings and in-bay TN concentrations or between TP loadings and in-bay TP concentrations in any bay segment. This is not because loadings do not affect in-bay concentrations, but because various other confounding factors, for which sufficient data are not available, play a role in relationships between loadings and concentrations

- On a monthly time scale, the relationships between either TN concentrations or TP concentrations and chlorophyll *a* concentrations do not explain a significant proportion of the variability in the chlorophyll *a* concentrations to support development of concentration-based numeric nutrient criteria in any bay segment.

- There are differences in TN concentrations and TP concentrations, particularly in Hillsborough Bay and Middle Tampa Bay, in those years when the chlorophyll *a* concentration thresholds are met when compared to those observed in years when the chlorophyll *a* concentration thresholds are not met. However, there is a great deal of variability within the data obtained in either group of years and these differences are not recommended as the basis for the establishment of concentration-based numeric nutrient criteria for Tampa Bay.

- The reference period approach is recommended for the establishment of concentration-based TN and TP criteria for Tampa Bay. The segment-specific annual geometric mean nitrogen and phosphorus concentrations of the 1992-1994 period were increased by one standard deviation (as derived from 1992-2009 data) to develop the proposed concentration numeric nutrient criteria. These criteria are:

-	Old Tampa Bay	TN = 0.93 mg/L	TP = 0.31 mg/L
-	Hillsborough Bay	TN = 1.01 mg/L	TP = 0.45 mg/L
-	Middle Tampa Bay	TN = 0.87 mg/L	TP = 0.29 mg/L
-	Lower Tampa Bay	TN = 0.74 mg/L	TP = 0.10 mg/L.

5.0 References

Borsuck, M.E., C.A.Stow, and K.E. Reckhow. 2004. Confounding effect of flow on estuarine response to nitrogen loading. Jour. Environ. Eng. 130:605-614.

Boynton, W.R. and W.M. Kemp. 2008. Estuaries. pp. 809-856. In: Nitrogen in the Marine Environment. 2nd Edition. Capone, D.G., Bronk, D.A., Mulholland, M.R., and Carpenter, E.J. (eds.), Elsevier Inc., Burlington, Massachusetts.

Boynton, W.R., W.M. Kemp, and C.W. Keefe. 1982. A comparative analysis of nutrients and other factors influencing estuarine phytoplankton production. In: Estuarine Comparisons. Kennedy, V.S. (ed.). Academic Press, San Diego.

Chapra, S.C. 1997. Surface Water-Quality Modeling, McGraw-Hill, New York, N.Y.

Conley, D.J. 2000. Biogeochemical nutrient cycles and nutrient management strategies. Hydrobiologia. 410:87-96.

Conley, D.J., H.W. Paerl, R.W. Howarth, D.F. Boesch, S.P. Seitzinger, K.E. Havens, C. Lancelot, and G.E. Likens. 2009. Controlling Eutrophication: Nitrogen and Phosphorus. Science. 323:1014-1015.

Correll, D.L. 1999. Phosphorus: A rate limiting nutrient in surface waters. Poultry Science. 78:674-682.

Correll, D.L., and N.E. Tolbert. 1962. Ribonucleic acid-polyphosphate from algae. I. Isolation and physiology. Plant Physiol. 37:627-636.

D'Elia, C.F., J.G. Sanders, and W.R. Boynton. 1986. Nutrient enrichment studies in a coastal plain estuary: Phytoplankton growth in large-scale continuous cultures. Can. J. Fish. Aquat. Sci. 43:397-406.

Elser, J.J., E.R. Marzolf, and C.R. Goldman. 1990. Phosphorus and nitrogen limitation of phytoplankton growth in the freshwaters of North America: a review and critique of experimental enrichments. Can. J. Fish. Aquat. Sci. 47:1468-1477.

Elser, J.J., M.E.S. Bracken, L.L Cleland, D.S. Gruner, W.S. harpole, H. Hillebrand, J.T. Ngai, E.W. Seabloom, J.B. Shurin, and J.E. Smith. 2007. Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. Ecology Letters 10, doi: 10.1111/j.1461-0248.2007.01113x.

FDEP. 2002. Unpublished guidelines for determining nutrient limitations in waterbodies under the Impaired Waters Rule. Watershed Assessment Division. Tallahassee.

Fisher, T.R., E.R. Peele, J.W. ammerman, and L.W. Harding, Jr. 1992. Nutrient limitation of phytoplankton in Chesapeake Bay. Mar. Ecol. Prog. Ser. 82:51-63.

Hagy, J.D., L.P. Sanford, and W.R. Boynton. 2000. Estimation of net physical transport and hydraulic residence times for a coastal plain estuary using box models. Estuaries. 23:328-340.

Havens, K.E., and J. DeCosta. 1986. A comparison of phytoplankton responses to nutrient additions in acidic and circumneutral pH lakewater. Hydrobiologia. 137:211-222.

Hecky, R.E., and P. Kilham. 1988. Nutrient limitation of phytoplankton in freshwater and marine environment: A review of recent evidence on the effects of enrichment. Limnol. Oceanogr. 33:796-822.

Howarth, R.W. 1988. Nutrient limitation of net primary productivity in marine ecosystems. Annual Review of Ecology and Systematics. 19:89-110.

Howarth, R. W. 2008. Coastal nitrogen pollution: A review of sources and trends globally and regionally. Harmful Algae. 8:14-20.

Howarth, R.W., and R. Marino. 2006. Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: Evolving views over three decades. Limnol. Oceanogr. 51:364-376.

Howarth, R.W., R. Marino, J. Land, and J.J. Cole. 1988a. Nitrogen fixation in freshwater, estuarine, and marine ecosystems. 1. Rates and importance. Limnol. Oceanogr. 33:669-687.

Howarth, R.W., R. Marino, and J.J. Cole. 1988b. Nitrogen fixation in freshwater, estuarine, and marine ecosystems. 2. Biogeochemical controls. Limnol. Oceanogr. 33:688-701.

Jahnke, J., H.J. Rick, and L. Aletsee. 1986. On the light and temperature dependence of the minimum and maximum phosphorus contents in cells of the marine plankton diatom *Thalassiosira rotula* Meunier. J. Plankton Res. 8:549-555.

Janicki, A.J., and J.R. Pribble. 2000. Establishing a process for tracking chlorophyll-a concentrations and light attenuation in Tampa Bay. Tampa Bay National Estuary Program Technical Publication #04-00.

Janicki, A., and D. Wade. 1996. Estimating critical external nitrogen loads for the Tampa Bay Estuary: An empirically based approach to setting management targets. Tampa Bay National Estuary Program Technical Publication #06-96.

Johansson, J.O.R. 2009. Nutrient enrichment studies of natural phytoplankton populations in Tampa Bay: A summary of results June 1993 to August 2009. City of Tampa Wastewater Department Bay Study Group.

Lee, Y.S., T. Seiki, T. Mukai, K. Takimoto, and M. Okada. 1996. Limiting nutrients of phytoplankton community in Hiroshima Bay, Japan. Water Res. 30:1490-1494.

Lynch, M., and J. Shapiro. 1981. Predation, enrichment, and phytoplankton community structure. Limnol. Oceanogr. 26:86-102.

Malone, T.C., D.J. Conley, T.R. Fisher, P.M. Glibert, L.W. Harding, and K.G. Sellner. 1996. Scales of Nutrient-Limited Phytoplankton Productivity in Chesapeake Bay. Estuaries. Vol. 19, No. 2. Dedicated Issue: Nutrients in Coastal Waters. pp. 371-385.

McComb, A.J., R.P. Atkins, P.B. Birch, and R.J. Lukatelich. 1981. Eutrophication in the Peel-Harvey estuarine system, Western Australia. In: Estuaries and Nutrients. Nielsen, B.J., and L.E. Cronin (eds). Humana Press. Clifton, NJ, p 569-582.

Monsen, N.E., J.E. Cloern, and L.V. Lucus. 2002. A comment on the use of flushing time, residence time, and age as transport time scales. Limnol. Oceanogr. 47:1545-1553.

National Research Council (NRC), 2000. Clean Coastal Waters: Understanding and Reducing the Effects of Nutrient Pollution. National Academy Press. Washington, D.C.

National Research Council (NRC), 1993. Managing wastewater in coastal urban areas. National Academy Press. Washington, D.C.

Nixon, S.W., et al. (15 co-authors). 1996. The fate of nitrogen and phosphorus at the land-sea margin of the North Atlantic Ocean. Biogeochemistry. 35:141-180.

Oviatt, C.A., A.A. Keller, P.A. Sampou, and L.L. Beatty. 1986. Patterns of productivity during eutrophication: a mesocosm experiment. Mar. Ecol. Prog. Ser. 28:69-80.

Parsons, T.R., Y. Maita, and C.M. Lalli. 1984. A manual of chemical and biological methods for seawater analysis. Pergamon Press.

Pennock, J.R., and J.H. Sharp. 1994. Temporal alternation between light- and nutrient-limitation of phytoplankton production in a coastal plain estuary. Mar. Ecol. Prog. Ser. 111:275-288.

Perez, E.A.A., J. DeCosta, and K.E. Havens. 1994. The effects of nutrient addition and pH manipulation in bag experiments on the phytoplankton of a small acidic lake in West Virginia, USA. Hydrobiologia. 291:93-103.

Redfield, A.C. 1934. On the proportion of organic derivatives in sea water and their relation to the composition of plankton. James Johnstone Memorial Volume. Liverpool University Press. pp. 176-192.

Redfield, A.C. 1958. The biological control of chemical factors in the environment. Am. Sci. 46:205-222.

Ryther, J.H., and W.M. Dunstan. 1971. Nitrogen, phosphorus, and eutrophication in the coastal marine environment. Science. 171:1008–1013.

Schindler, D.W. 1974. Eutrophication and recovery in experimental lakes: Implications for lake management. Science. 184:897-899.

Schindler, D.W. 1975. Whole-lake eutrophication experiments with phosphorus, nitrogen and carbon. Verh. Int. Verein. Limnol. 19:3221-3231.

Schindler, D.W. 1977. The evolution of phosphorus limitations in lakes. Science. 195:260-262.

Shapiro, J. 1980. The importance of trophic-level interactions to the abundance and species composition of algae in lakes. In: Hypertrophic Ecosystems, Developments in Hydrobiology. Barica, J. and L.R. Mur (eds). Junk, The Netherlands Vol. 2. pp.105-116.

Sicko-Goad, L., and T.E. Jensen. 1976. Phosphate metabolism in blue-green algae. II. Changes in phosphate distribution during starvation and the "polyphosphate overplus" phenomenon in *Plectonema boryanum*. Am. J. Bot. 63:183-188.

Smith, S.V. 1984. Phosphorus versus nitrogen limitation in the marine environment. Limnol. Oceanogr. 29:1149-1160.

Tampa Bay Nitrogen Management Consortium (TBNMC). 2010. Letter to Water Docket, U.S. Environmental Protection Agency, March 8, 2010.

Taylor, D., S. Nixon, S. Granger, and B. Buckley. 1995. Nutrient limitation and the eutrophication of coastal lagoons. Mar. Ecol. Prog. Ser. 127:235-244.

Terry, K.L., J. Hirate, and E.A. Laws. 1985. Light-, nitrogen-, and phosphorus-limited growth of *Phaeodactylum tricornutum* Bohlin strain TFX-1: chemical composition, carbon partitioning, and the diel periodicity of physiological processes. J. Exp. Mar. Biol. Ecol. 86:85-100.

Thomas, W. H. 1970a. On nitrogen deficiency in tropical parameters in poor and rich water. Limnol. Oceanogr. 15:380-385.

Thomas, W. H. 1970b. Effect of ammonium and nitrate concentration on chlorophyll increases in natural tropical Pacific phytoplankton populations. Limnol. Oceanogr. 15:386-394.

Wynne, D., and G.Y. Rhee. 1986. Effects of light intensity and quality on the relative N and P requirement (the optimum N:P ratio) of marine planktonic algae. J. Plankton Res. 8:91-103.

Attachment 1
Results of City of Tampa Bay Study Group Bioassays (Johansson, 2009)

NUTRIENT ENRICHMENT STUDIES OF NATURAL PHYTOPLANKTON POPULATIONS IN TAMPA BAY

A SUMMARY OF RESULTS
JUNE 1993 TO AUGUST 2009

J.O.R. JOHANSSON
THE CITY OF TAMPA
WASTEWATER DEPARTMENT
BAY STUDY GROUP

NOVEMBER 16, 2009

NUTRIENT ENRICHMENT STUDIES OF NATURAL PHYTOPLANKTON POPULATIONS IN TAMPA BAY. A SUMMARY OF RESULTS JUNE 1993 TO AUGUST 2009

INTRODUCTION

The Bay Study Group (BSG) has been conducting nutrient enrichment studies (bioassays) on natural phytoplankton populations at four locations in Tampa Bay since 1993 (Figure 1). This report will summarize findings for all tests that have been performed to date, from June 1993 through August 2009.

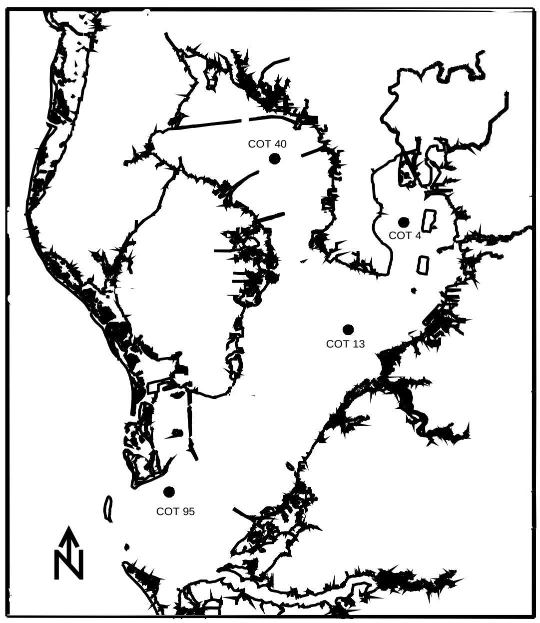


Figure 1. Phytoplankton nutrient bioassay monitoring stations in Tampa Bay.

METHODS

The bioassays have been performed on the natural phytoplankton population collected from surface waters of the four stations, with one station located in each of the four major segment of Tampa Bay, as shown below:

- Hillsborough Bay - COT4
- Old Tampa Bay - COT40
- Middle Tampa Bay - COT13
- Lower Tampa Bay - COT95

Bioassay measurements were performed on a quarterly schedule from June 1993 through August 1995 for all stations except COT95. At this station monthly tests were conducted during the first year of the program. From February 1996 to the present, bioassays have been performed twice per year, during late winter and late summer.

The bioassay method used is similar to a method used in Chesapeake Bay waters (see Fisher et al. 1992a and b). An outline of the specific method used by the BSG is provided here.

A large volume of surface water is collected for the following nutrient treatments. Each treatment is conducted in duplicate on 3l samples:

- Controls (no nutrient addition).
- N-additions (NH3-N added to reach a final concentration in the sample of near 50uM).
- P-additions (PO4-P added to reach a final concentration in the sample of near 5uM).
- N+P-additions (combination of the N-additions and P-additions).

The treatment samples are incubated under natural sunlight in ambient bay water temperatures for an appropriate incubated period (usually 48h for the late winter and 24h for the late summer tests).

The growth response of the natural phytoplankton community to the different treatments is determined through measurements in changes of algal biomass, measured as chlorophyll-a.

Paired t-test statistics ($p<0.05$) and non-statistical evaluations of treatment responses are used to interpret the bioassay results and to group the growth response to the nutrient additions into the following response categories:

- Exclusive N limitation: (1) the addition of P induced no response relative the control, and (2) the addition of N alone had virtually the same effect as the addition of N+P.
- Primary N limitation: (1) the addition of P alone induced little response relative the control, (2) the addition of N alone induced a response, and (3) the addition of N+P induced the largest response.
- Balanced NP limitation: (1) the addition of N and P alone induced no response relative the control, (2) the addition of N+P induced a large response.
- Exclusive P limitation: (1) the addition of N induced no response relative the control, and (2) the addition of P alone had virtually the same effect as the addition of N+P.
- Primary P limitation: (1) the addition of N alone induced little response relative the control, (2) the addition of P alone induced a response, and (3) the addition of N+P induced the largest response.
- No response to any nutrient addition, indicating nutrient saturation, light limitation, and/or insufficient incubation time.

RESULTS

A total of 152 bioassay experiments have been conducted since the start of the program in June 1993.

The growth response of the natural phytoplankton community to the different nutrient treatments were grouped into the response categories described above. The result of these analyses is summarized in Table 1.

Table 1. Results from natural phytoplankton nutrient bioassays in the four major subsections of Tampa Bay, 1993 – 2009.

Bioassay response	Hillsborough Bay COT4	Old Tampa Bay COT40	Middle Tampa Bay COT13	Lower Tampa Bay COT95
Exclusive N limitation	29	25	28	39
Primary N limitation	2	2	2	1
Balanced	0	0	0	0
Exclusive P limitation	0	0	0	0
Primary P limitation	0	0	0	0
No response	0	3	0	0

DISCUSSION AND CONCLUSION

One-hundred-fifty-two natural phytoplankton community nutrient limitation experiments have been conducted in Tampa Bay by the BSG from 1993 to the present. The strong nitrogen dependence by the Tampa Bay phytoplankton community is obvious in all four bay segments; of the 152 bioassay tests conducted to date, 149 indicate that nitrogen was the stronger limiting nutrient. None of the 152 tests have indicated that phosphorous was the stronger limiting nutrient. However, three tests in OTB have shown a lack of phytoplankton growth response by either N or P additions.

REFERENCES

Fisher, T.R., A.B. Gustafson, K.G. Sellner, and R.B. Lacouture.1992a. Nutrient bioassays in Chesapeake Bay to assess nutrients limiting algal growth. Progress Rep. MD Dept. of the Environment, Jan. 1992, Baltimore, MD.

Fisher, T.R., E.R. Peele, J.W. Ammerman, and L.W. Harding, Jr. 1992b. Nutrient limitation of phytoplankton in Chesapeake Bay. Mar. Ecol. Prog. Ser., 82:51-63.

Attachment 2
Data Sources

The following data sources were used in the analyses performed for this task:

- The water quality data were obtained from the Environmental Protection Commission of Hillsborough County (EPCHC). Their sampling program collects surface samples on a monthly basis from the following series of fixed stations. Among others, the primary analytes included:
  - Chlorophyll a
  - TN
  - TP
  - Salinity.

Old Tampa Bay	Hillsborough Bay	Middle Tampa Bay	Lower Tampa Bay
46	44	11	25
60	70	9	23
64	52	81	21
47	6	84	91
65	71	33	90
63	7	32	24
66	55	13	95
40	08	14	92
41	73	82	93
67	80	28	
50		16	
38		19	
51			
68			
36			

- The TN and TP loading estimates were obtained from a series of reports produced for the TBEP (1985-2002) and FDEP (2003-2007). These are:

Zarbock, H., A. Janicki, D. Wade, D. Heimbuch, and H. Wilson. 1994. Estimates of Total Nitrogen, Total Phosphorus, and Total Suspended Solids Loadings to Tampa Bay, Florida. Technical Publication #04-94 of the Tampa Bay National Estuary Program. Prepared by Coastal Environmental, Inc. Prepared for Tampa Bay National Estuary Program. St. Petersburg, FL.

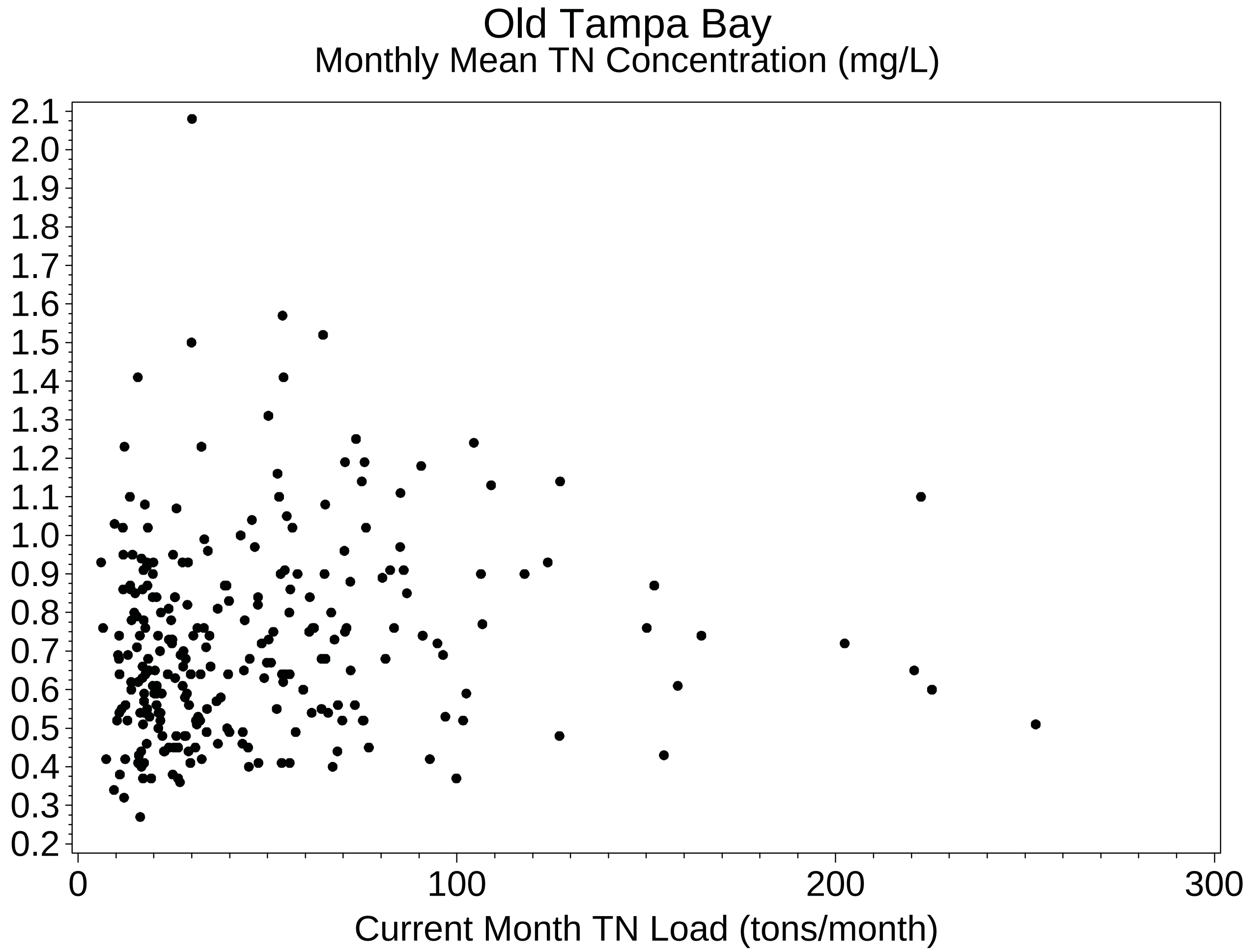
Zarbock, H.W., A.J. Janicki, and S.S. Janicki. 1996. Estimates of Total Nitrogen, Total Phosphorus, and Total Suspended Solids Loadings to Tampa, Bay, Florida. Technical Appendix: 1992-94 Total Nitrogen Loadings to Tampa Bay. Technical Publication #19-96 of the Tampa Bay National Estuary Program. Prepared by Coastal Environmental, Inc. Prepared for Tampa Bay National Estuary Program. St. Petersburg, FL.

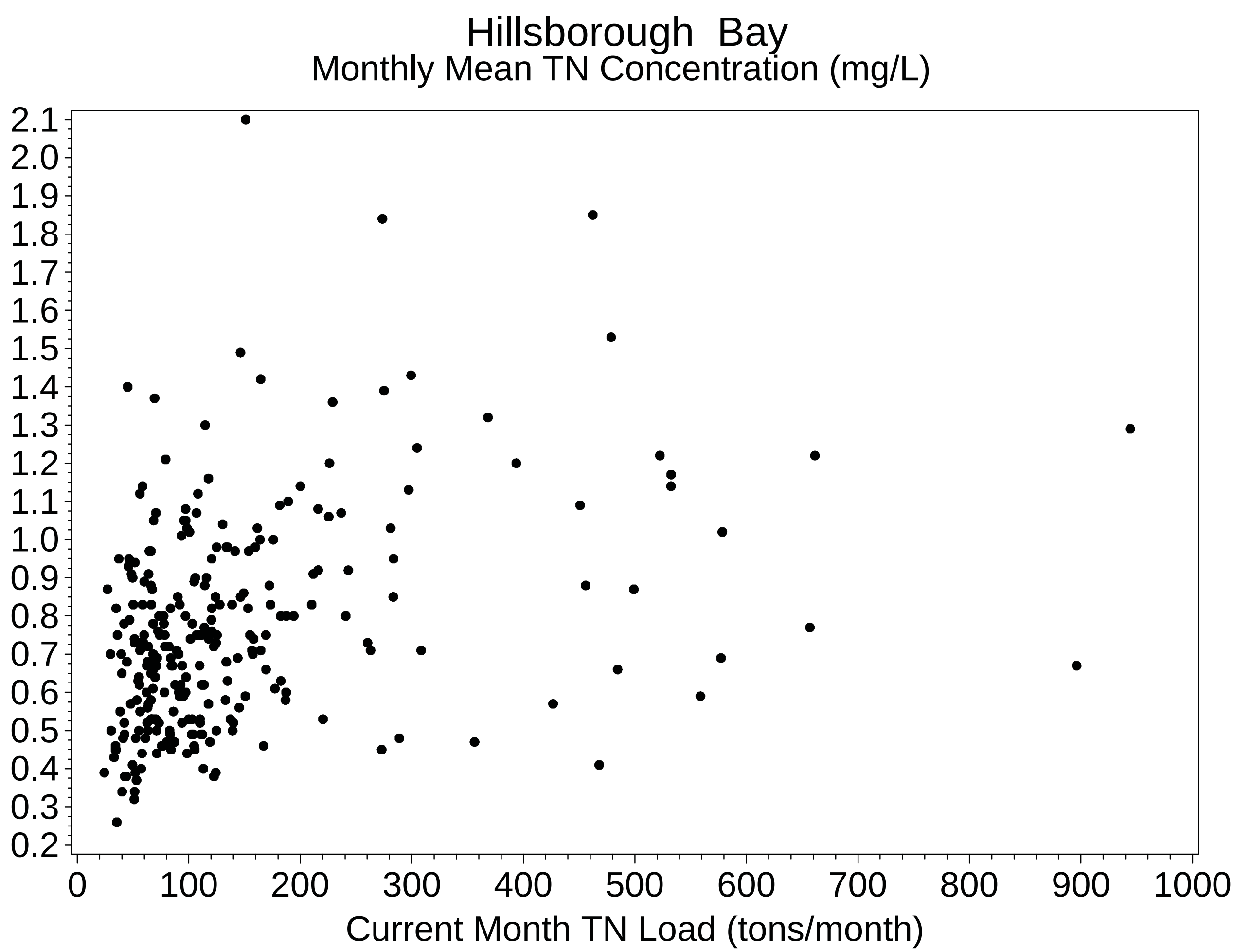
Pribble, R., A. Janicki, H. Zarbock, S. Janicki, and M. Winowitch. 2001. Estimates of Total Nitrogen, Total Phosphorus, Total Suspended Solids, and Biochemical Oxygen Demand Loadings to Tampa, Bay, Florida: 1995-1998. Technical report #05-01 of the Tampa Bay Estuary Program. Prepared by Janicki Environmental, Inc. Prepared for Tampa Bay Estuary Program. St. Petersburg, FL.

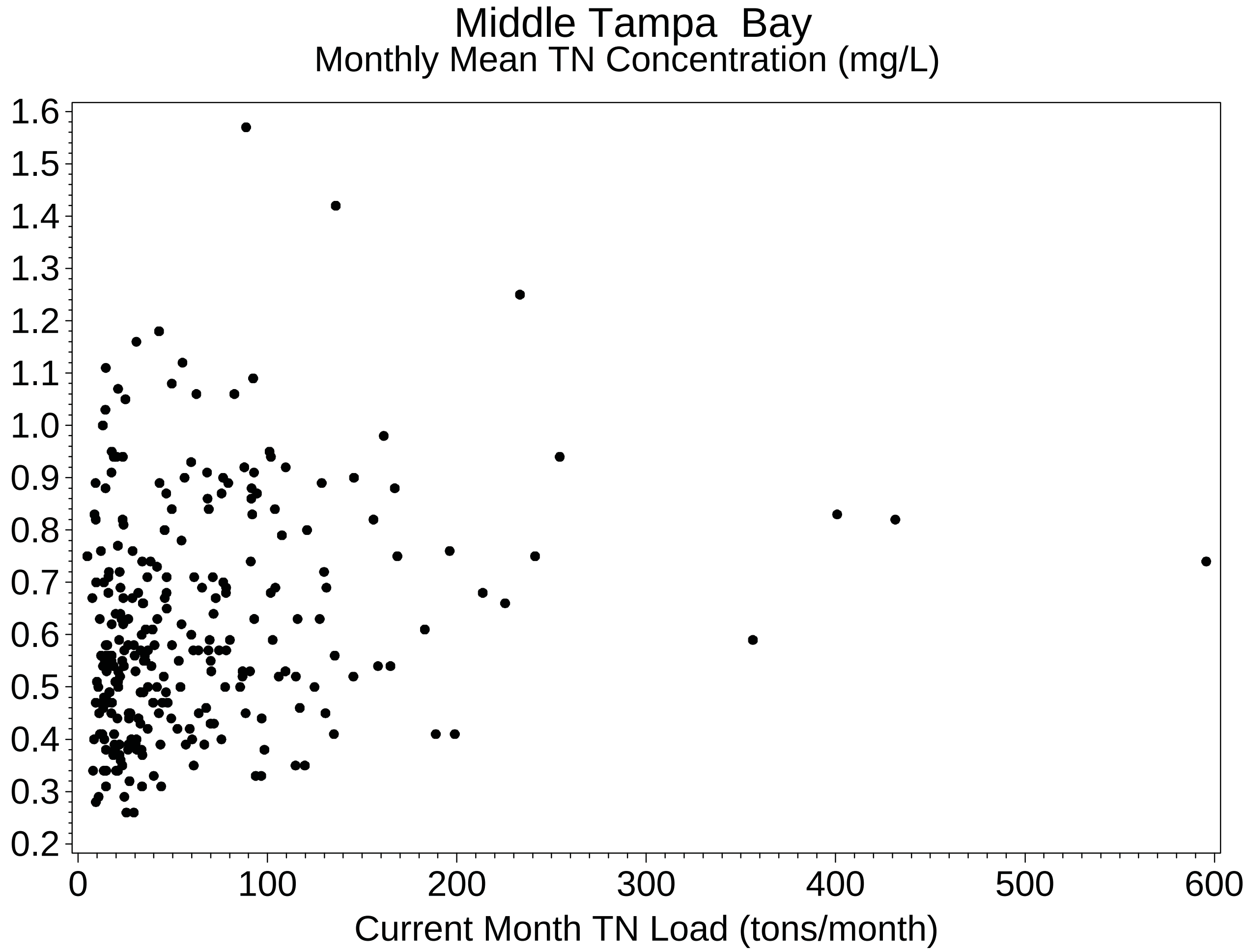
Poe, A., K. Hackett, S. Janicki, R. Pribble, and A. Janicki. 2005. Estimates of Total Nitrogen, Total Phosphorus, Total Suspended Solids, and Biochemical Oxygen Demand Loadings to Tampa Bay, Florida: 1999-2003. Technical Report #02-05 of the Tampa bay Estuary Program. Prepared by Janicki Environmental, Inc. Prepared for Tampa Bay National Estuary Program. St. Petersburg, FL.

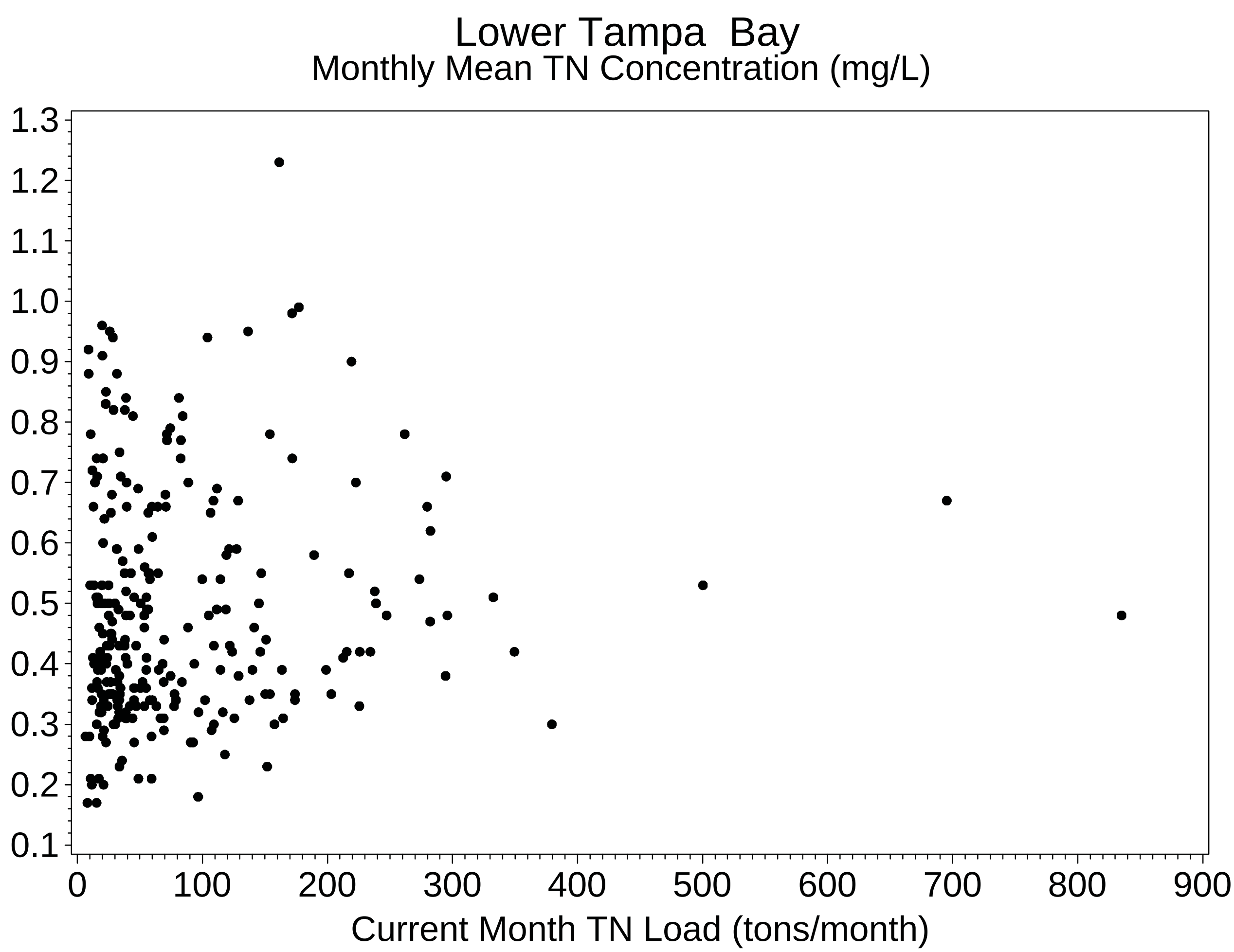
Janicki Environmental, Inc. 2008. Estimates of Total Nitrogen, Total Phosphorus, Total Suspended Solids, and Biochemical Oxygen Demand Loadings to Tampa Bay, Florida: 2004-2007. Prepared by Janicki Environmental, Inc. Prepared for Florida Department of Environmental Protections. Tallahassee, FL.

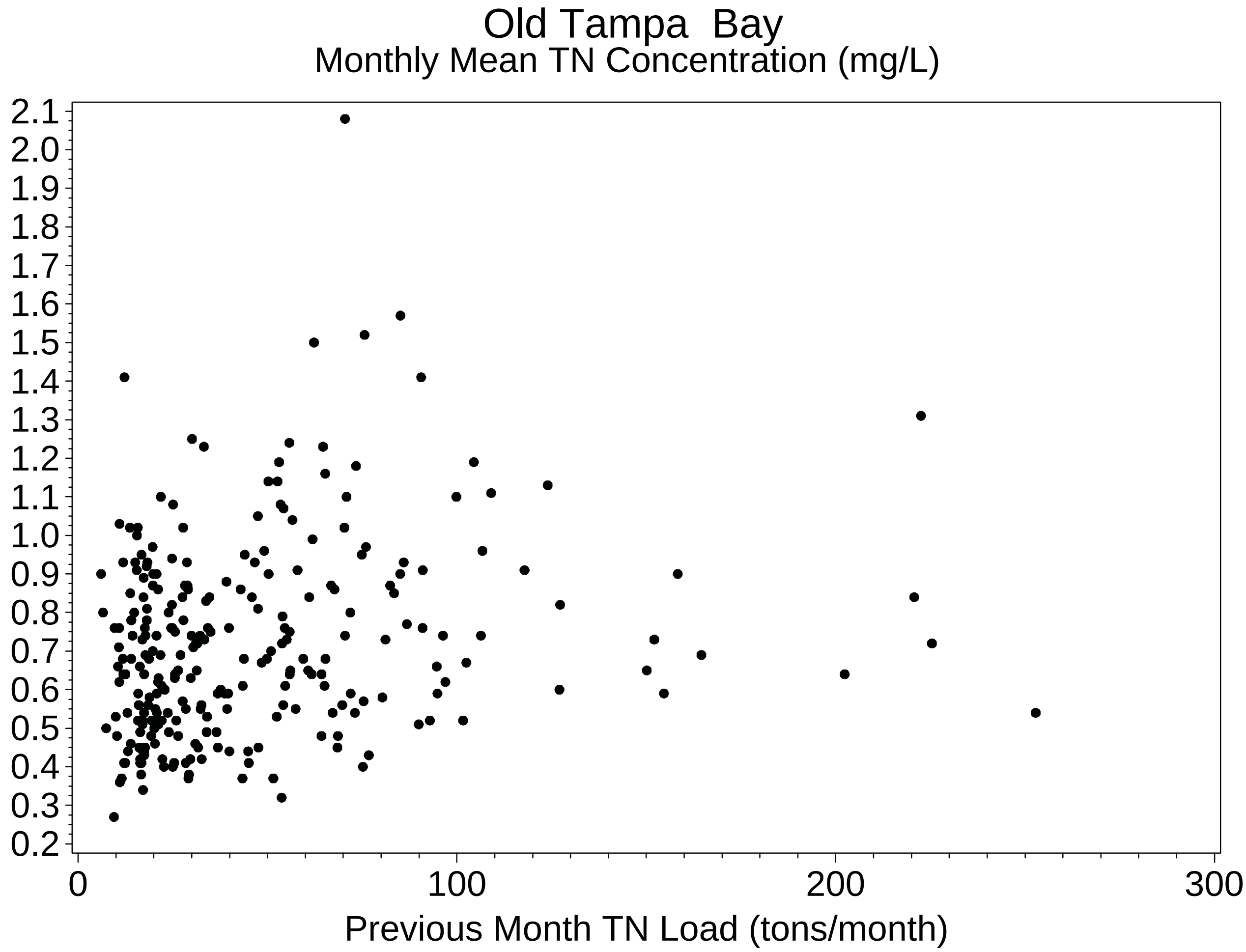
Attachment 3
Monthly TN Concentrations and Monthly TN Loads


Old Tampa Bay
Monthly Mean TN Concentration (mg/L)
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
100
200
300
Current Month TN Load (tons/month)

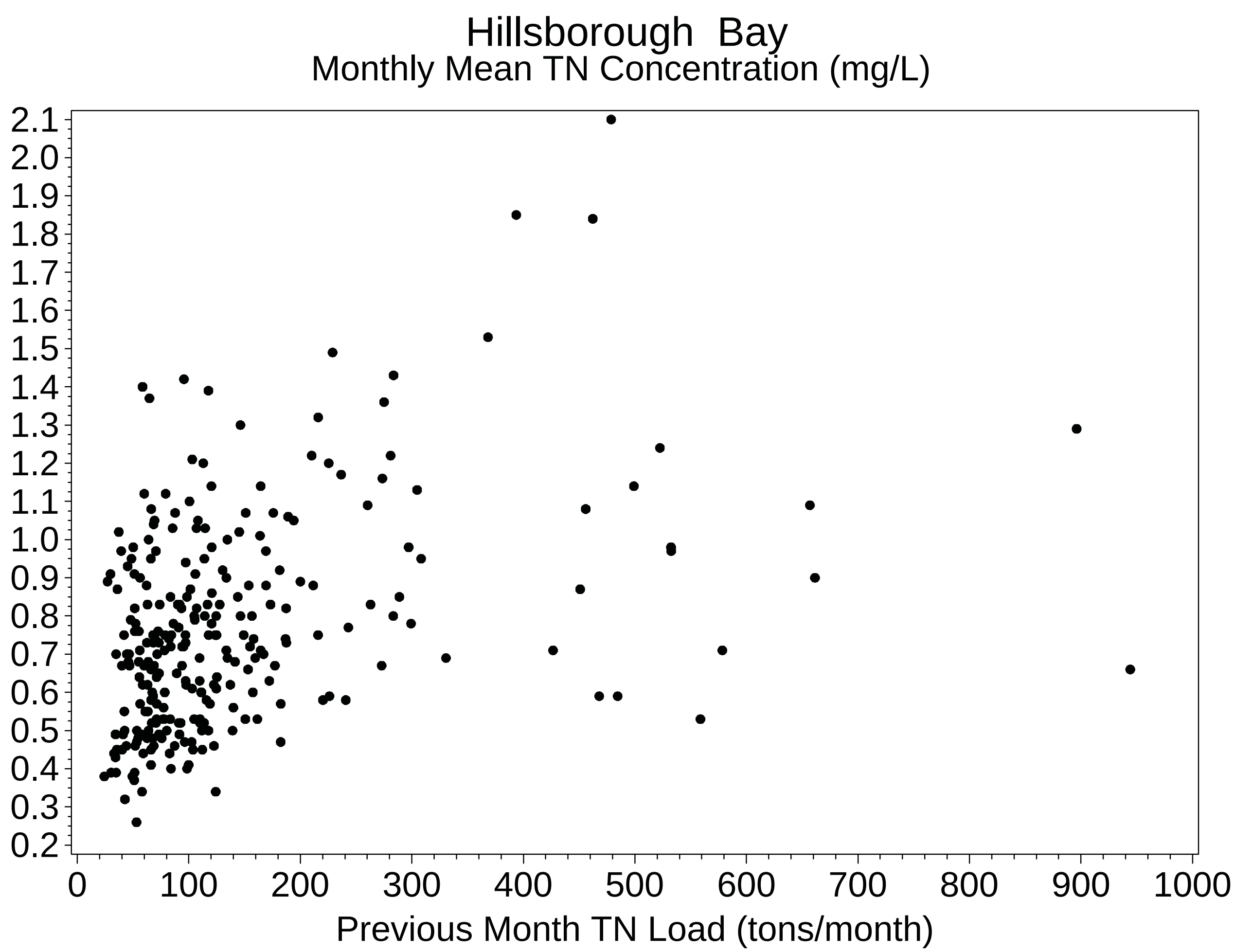

Hillsborough Bay
Monthly Mean TN Concentration (mg/L)
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
100
200
300
400
500
600
700
800
900
1000
Current Month TN Load (tons/month)


Middle Tampa Bay
Monthly Mean TN Concentration (mg/L)
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
100
200
300
400
500
600
Current Month TN Load (tons/month)

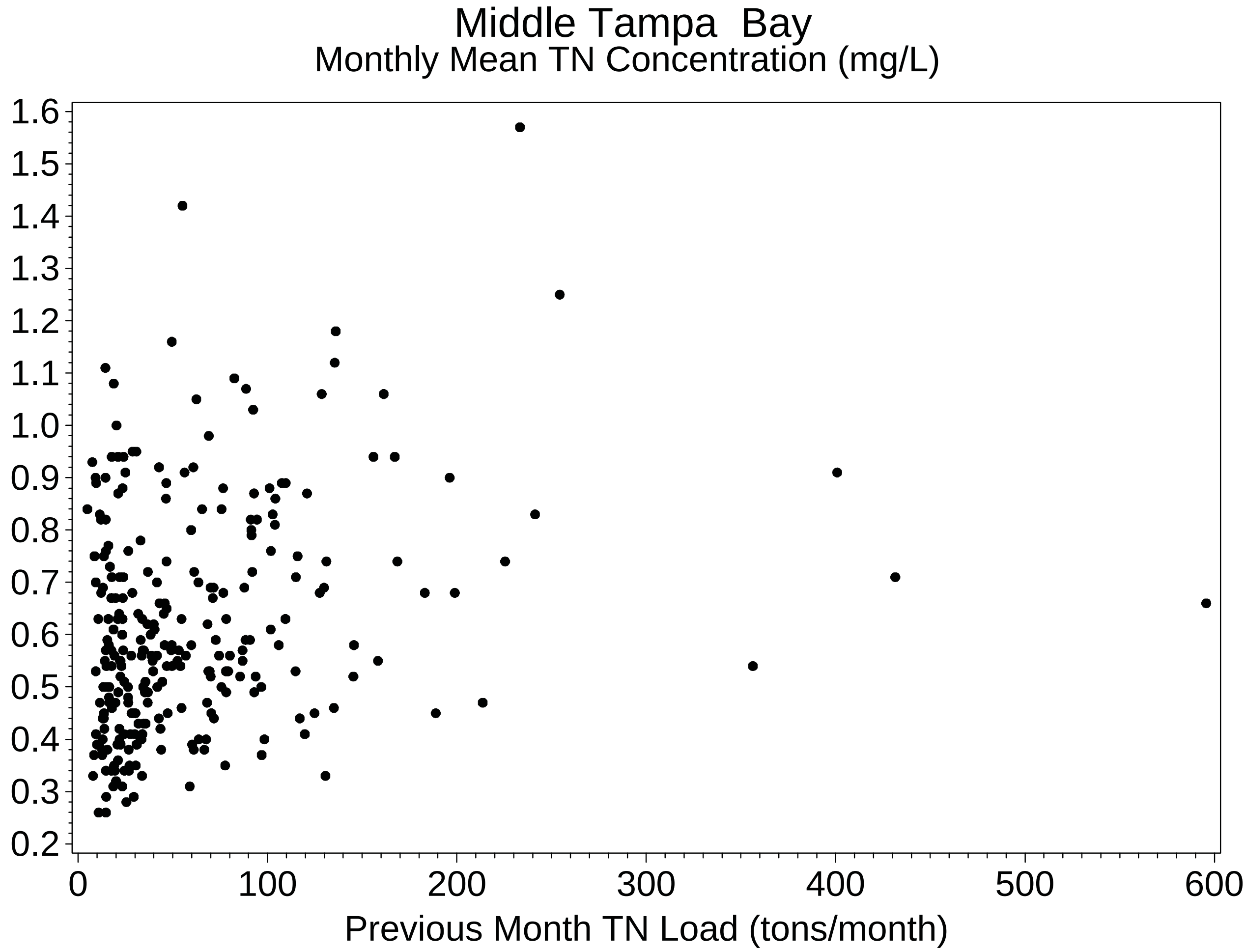

Lower Tampa Bay
Monthly Mean TN Concentration (mg/L)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
100
200
300
400
500
600
700
800
900
Current Month TN Load (tons/month)

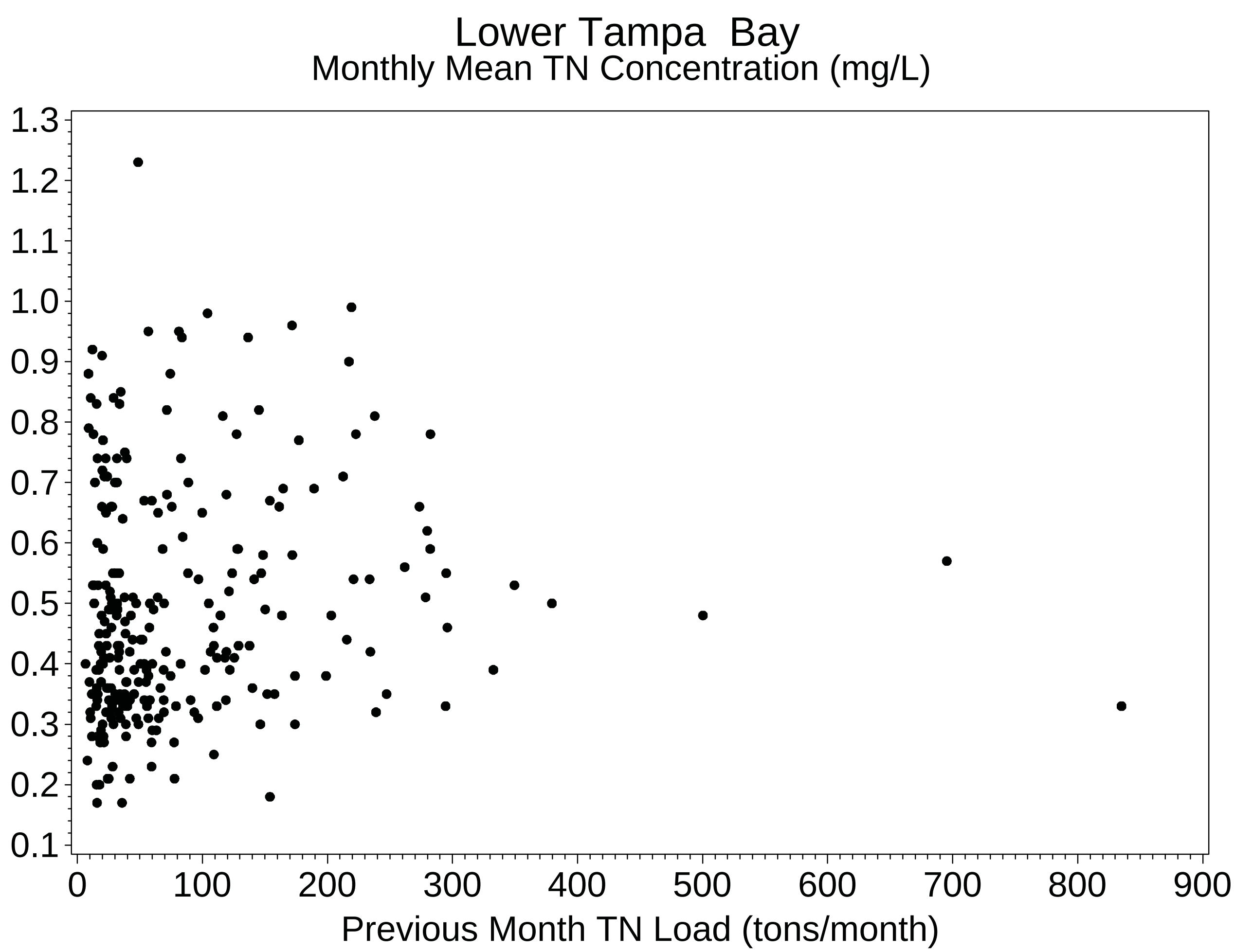


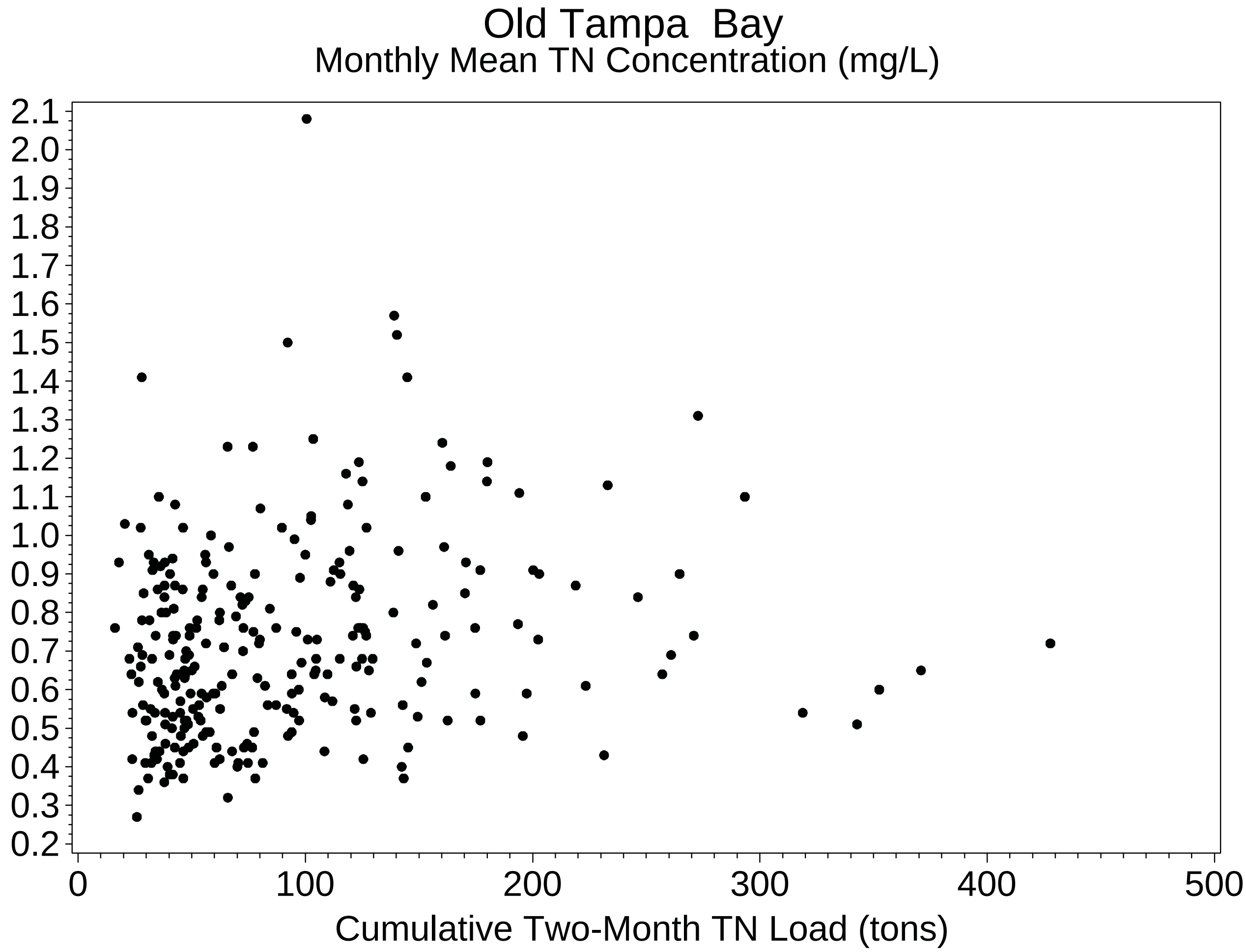
Old Tampa Bay
Monthly Mean TN Concentration (mg/L)
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
100
200
300
Previous Month TN Load (tons/month)

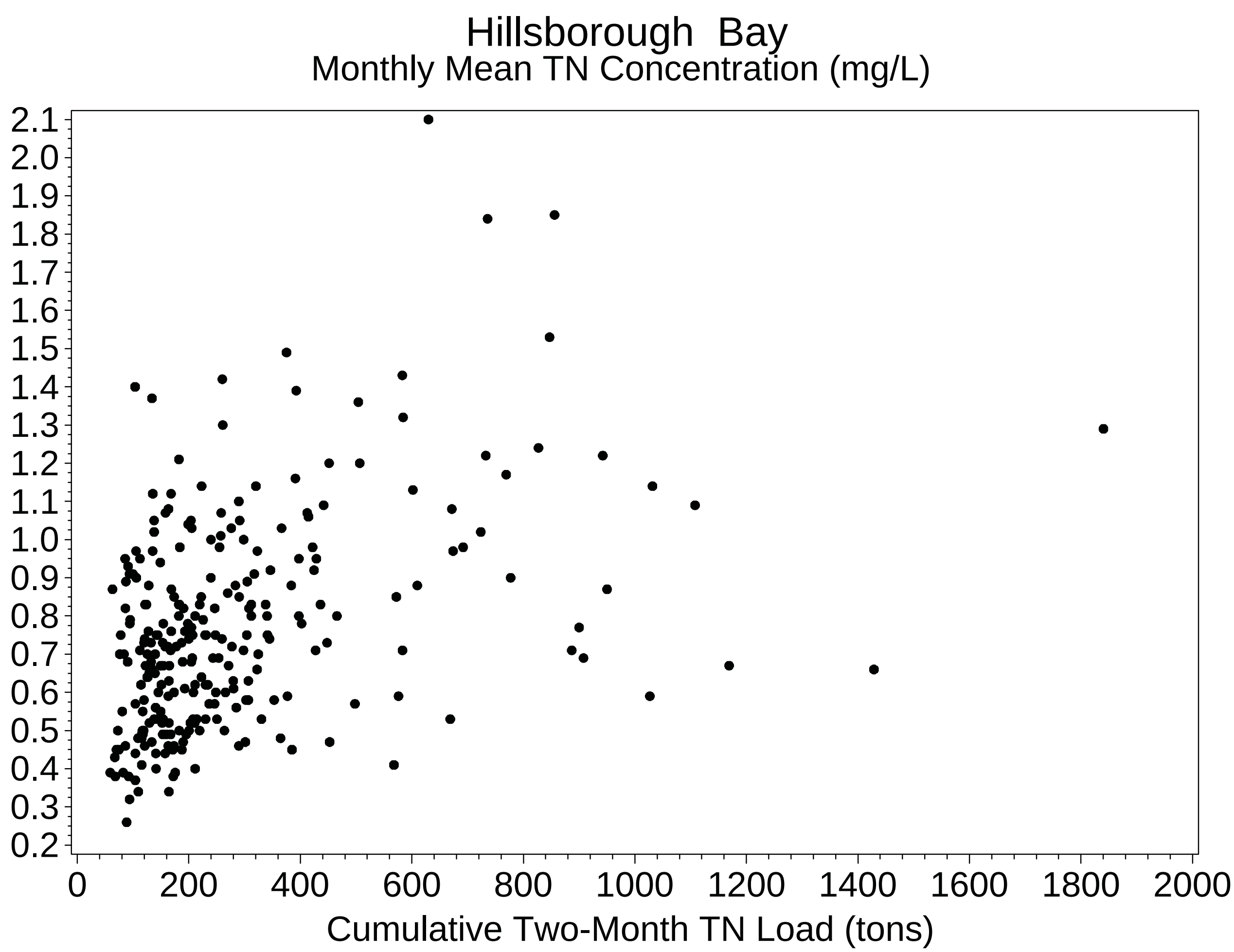


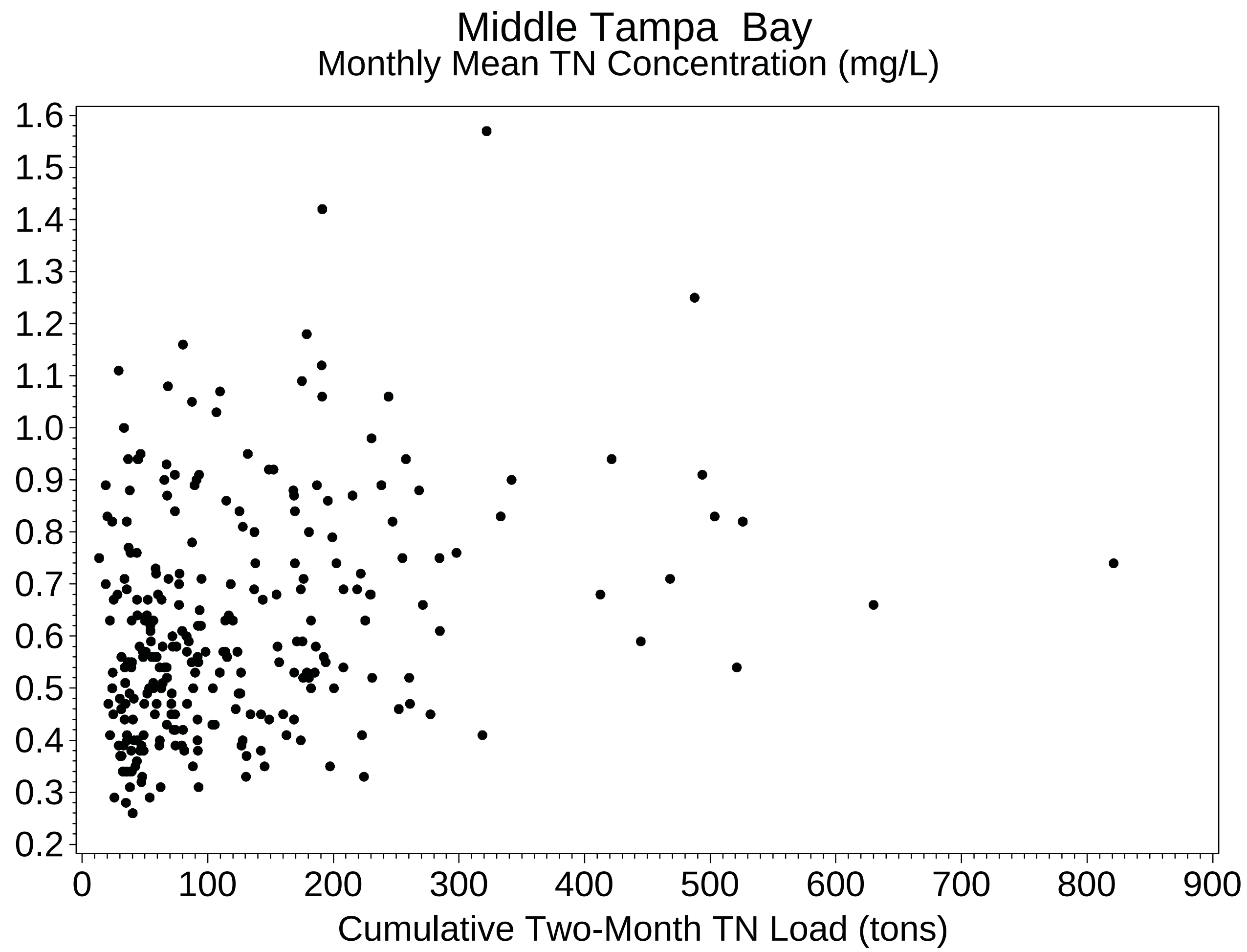
Hillsborough Bay
Monthly Mean TN Concentration (mg/L)
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
100
200
300
400
500
600
700
800
900
1000
Previous Month TN Load (tons/month)

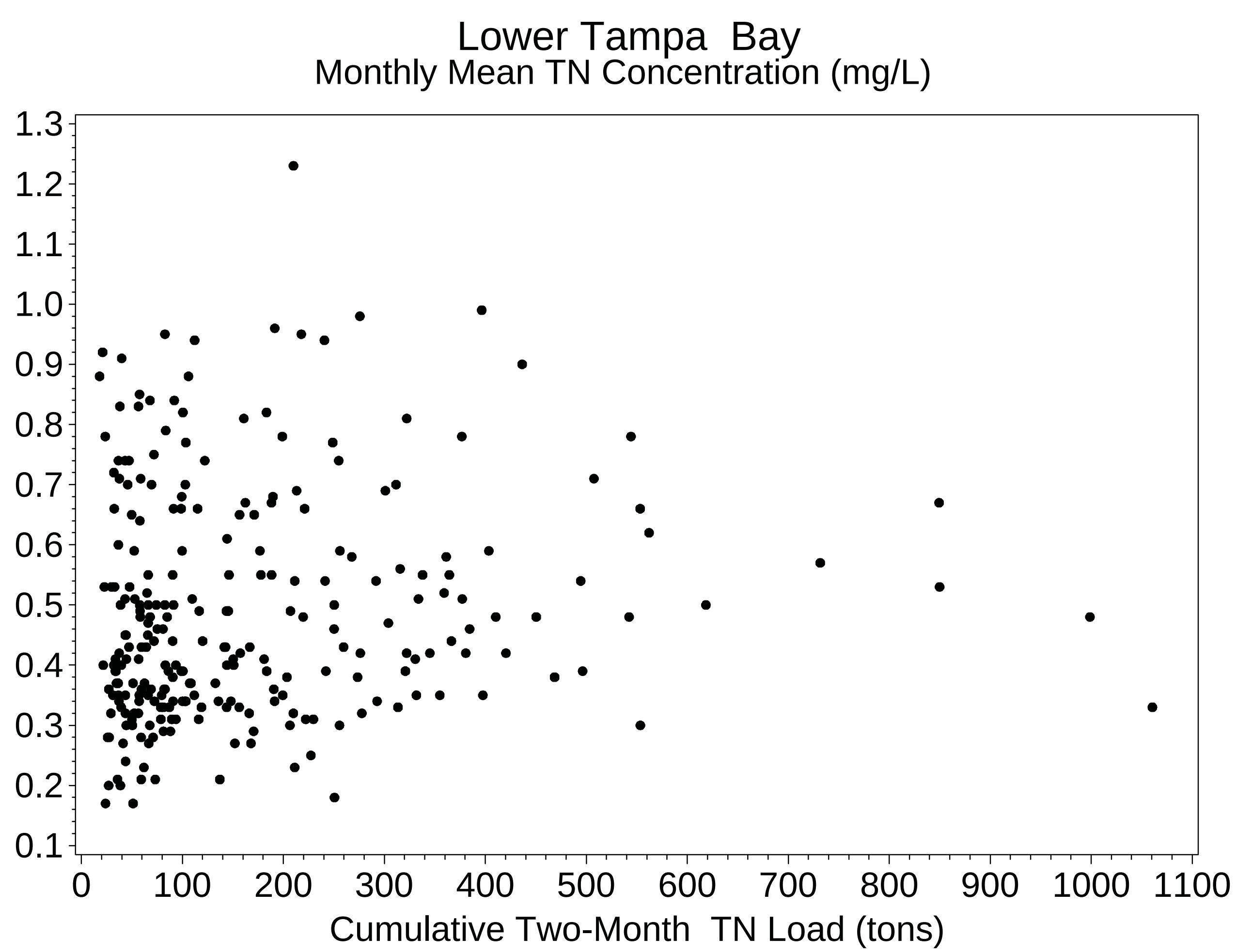

Middle Tampa Bay
Monthly Mean TN Concentration (mg/L)
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
100
200
300
400
500
600
Previous Month TN Load (tons/month)

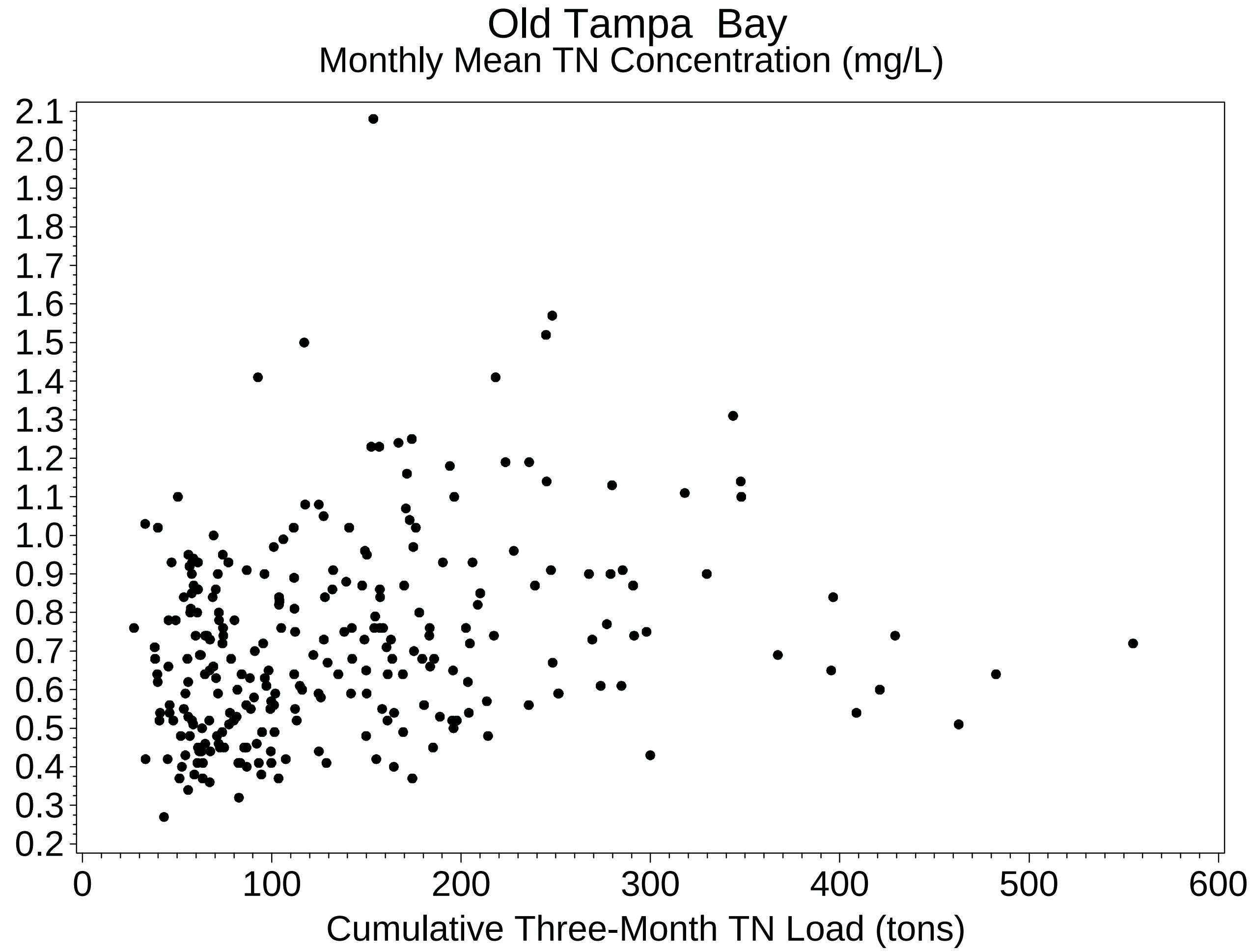

Lower Tampa Bay
Monthly Mean TN Concentration (mg/L)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
100
200
300
400
500
600
700
800
900
Previous Month TN Load (tons/month)

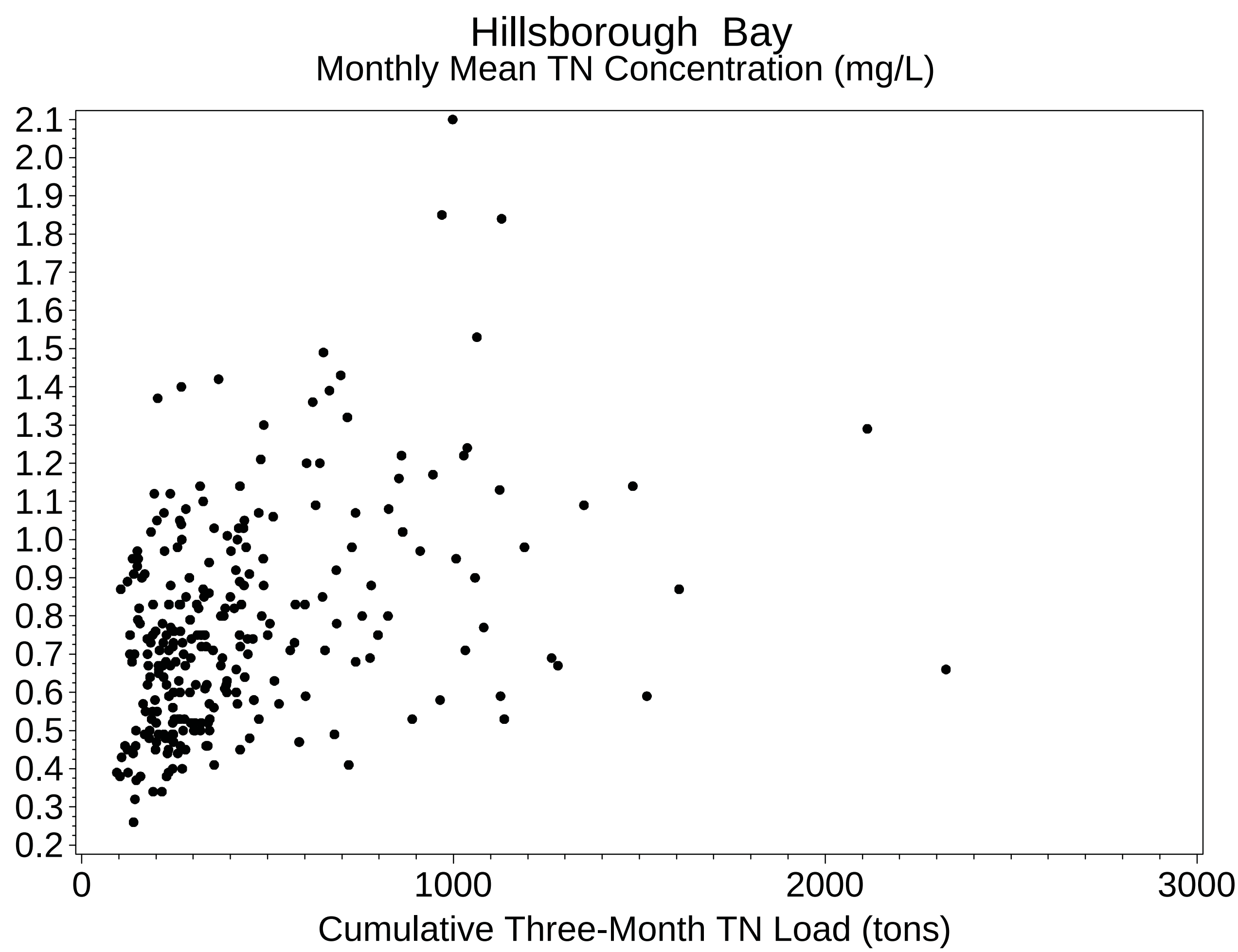

Old Tampa Bay
Monthly Mean TN Concentration (mg/L)
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
100
200
300
400
500
Cumulative Two-Month TN Load (tons)

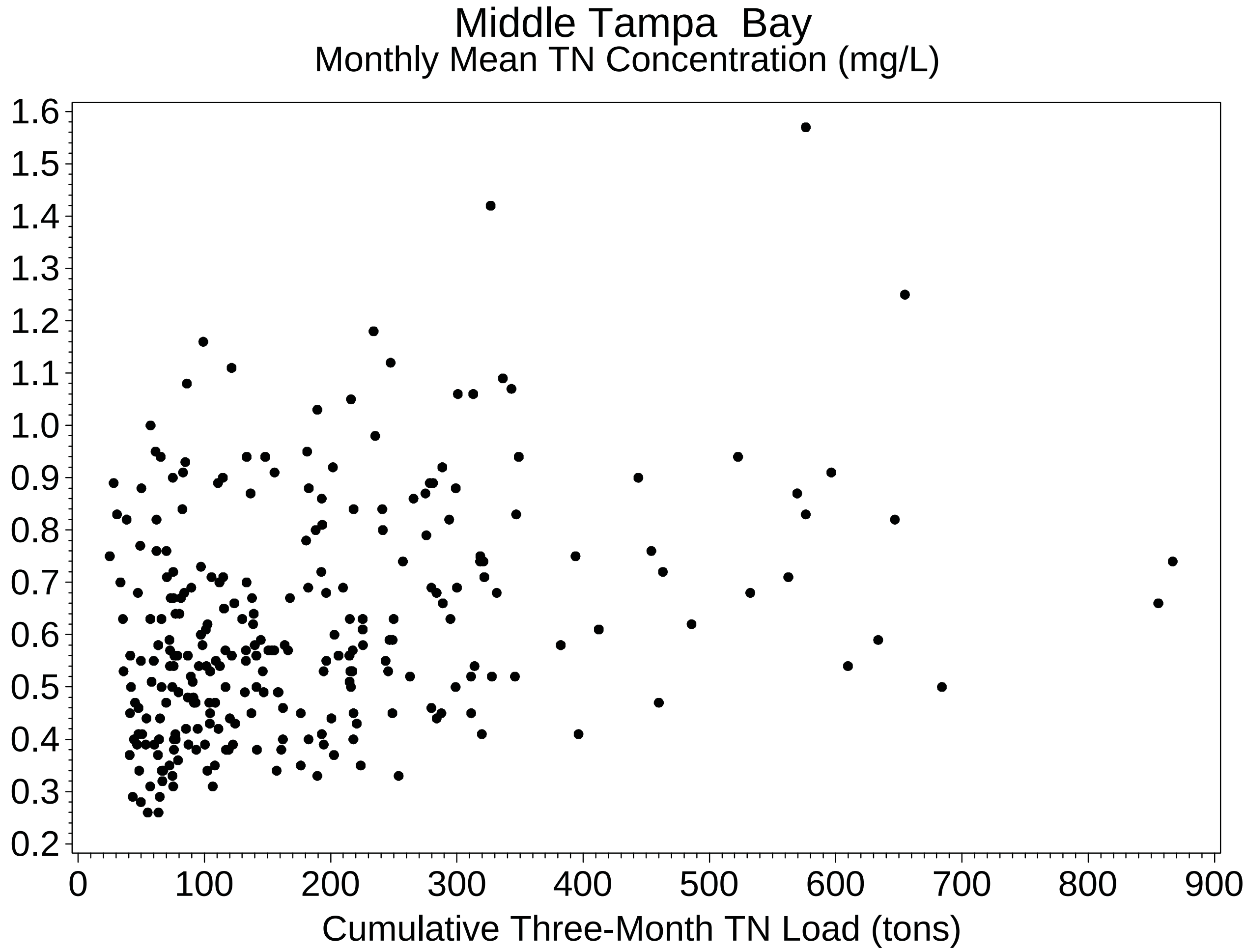

Hillsborough Bay
Monthly Mean TN Concentration (mg/L)
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Cumulative Two-Month TN Load (tons)

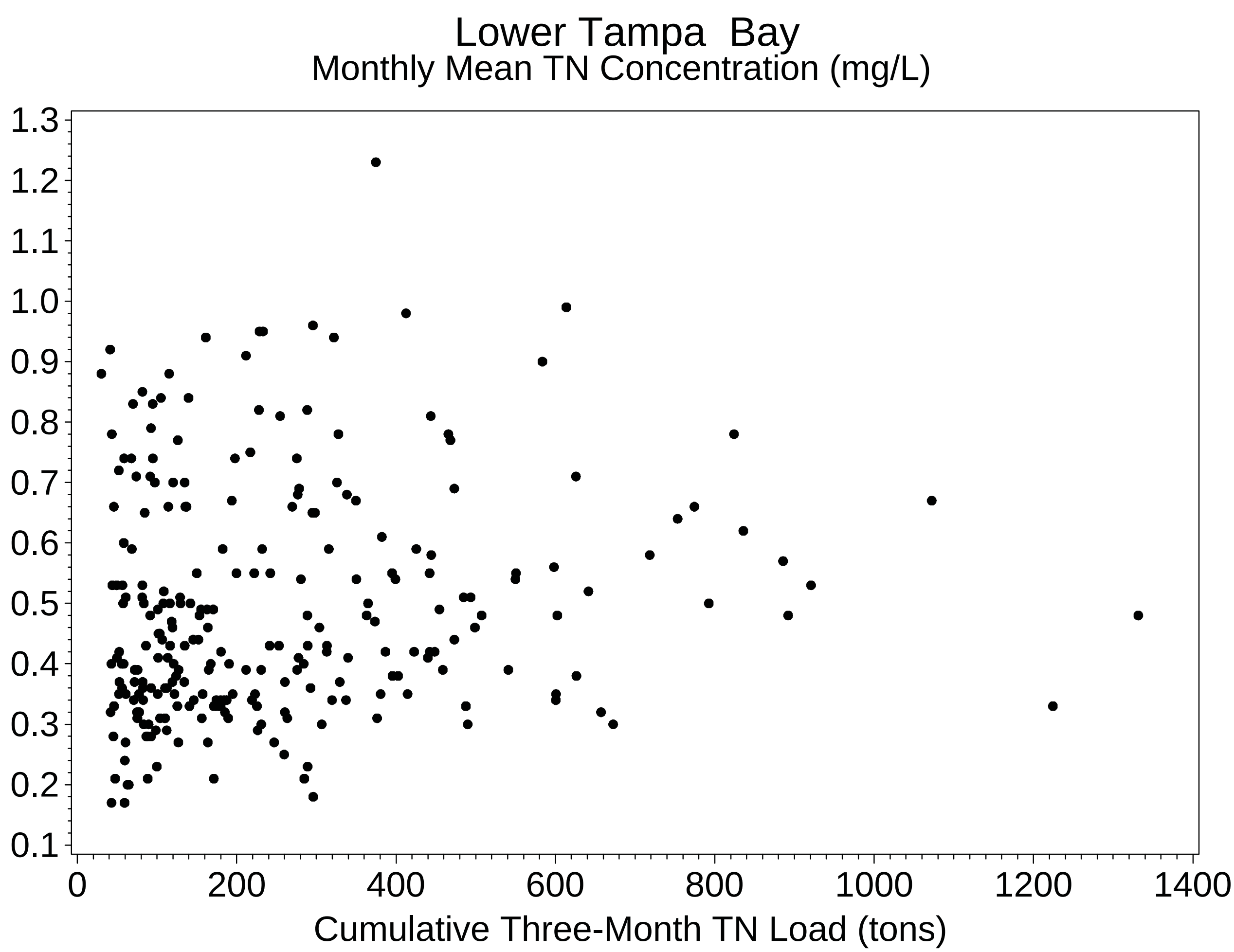

Middle Tampa Bay
Monthly Mean TN Concentration (mg/L)
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
100
200
300
400
500
600
700
800
900
Cumulative Two-Month TN Load (tons)

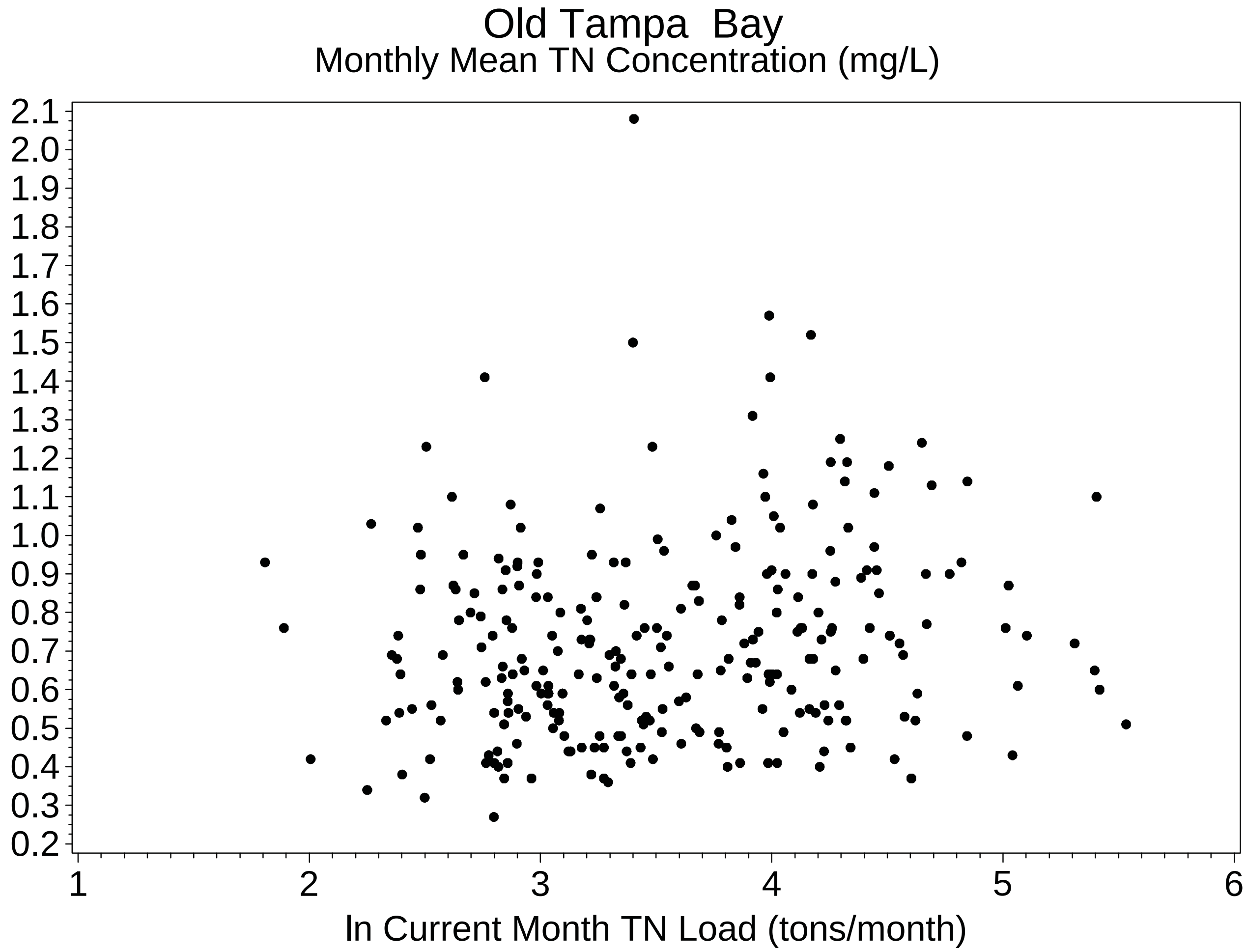

Lower Tampa Bay
Monthly Mean TN Concentration (mg/L)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
100
200
300
400
500
600
700
800
900
1000
1100
Cumulative Two-Month TN Load (tons)


Old Tampa Bay
Monthly Mean TN Concentration (mg/L)
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
100
200
300
400
500
600
Cumulative Three-Month TN Load (tons)

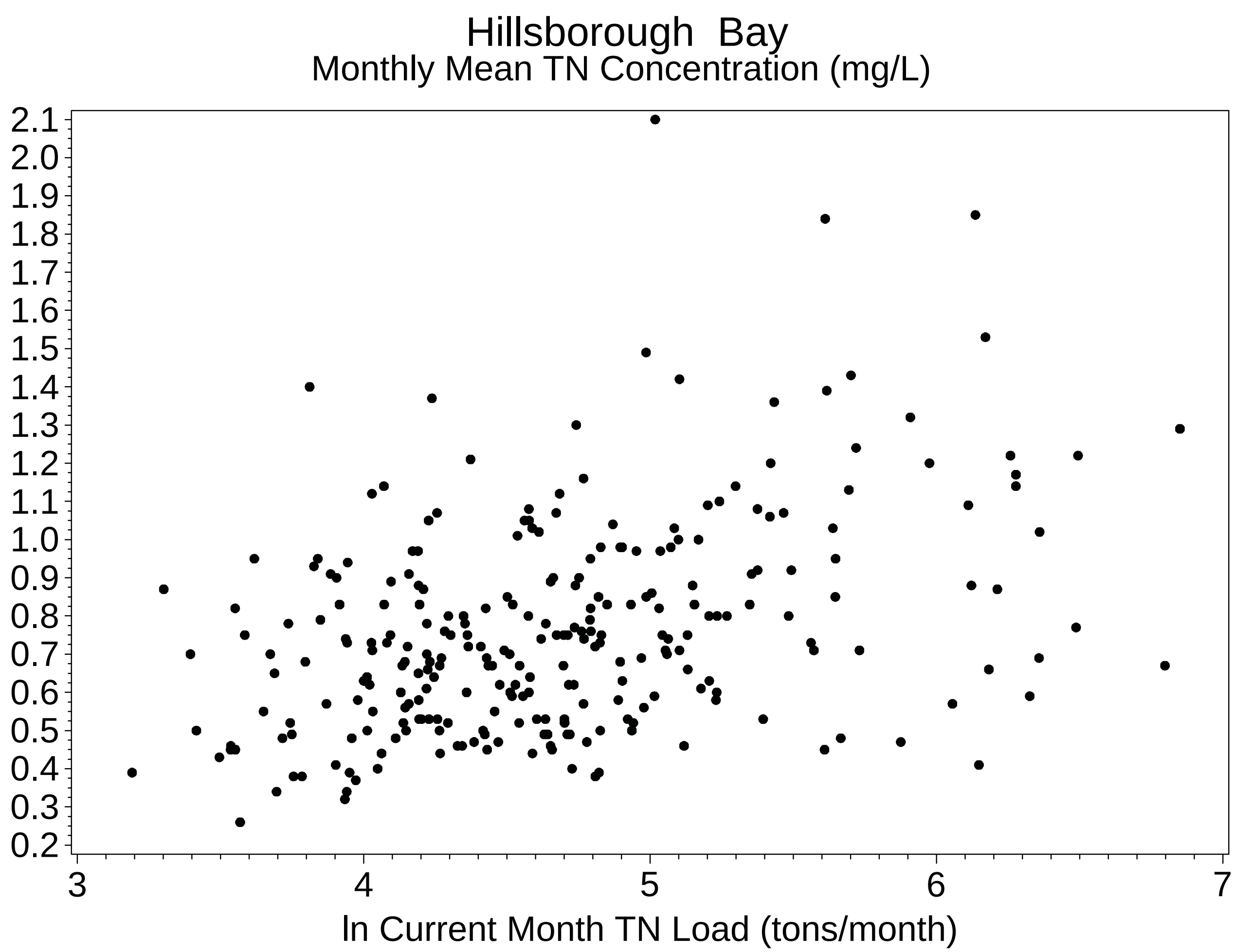

Hillsborough Bay
Monthly Mean TN Concentration (mg/L)
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
1000
2000
3000
Cumulative Three-Month TN Load (tons)


Middle Tampa Bay
Monthly Mean TN Concentration (mg/L)
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
100
200
300
400
500
600
700
800
900
Cumulative Three-Month TN Load (tons)

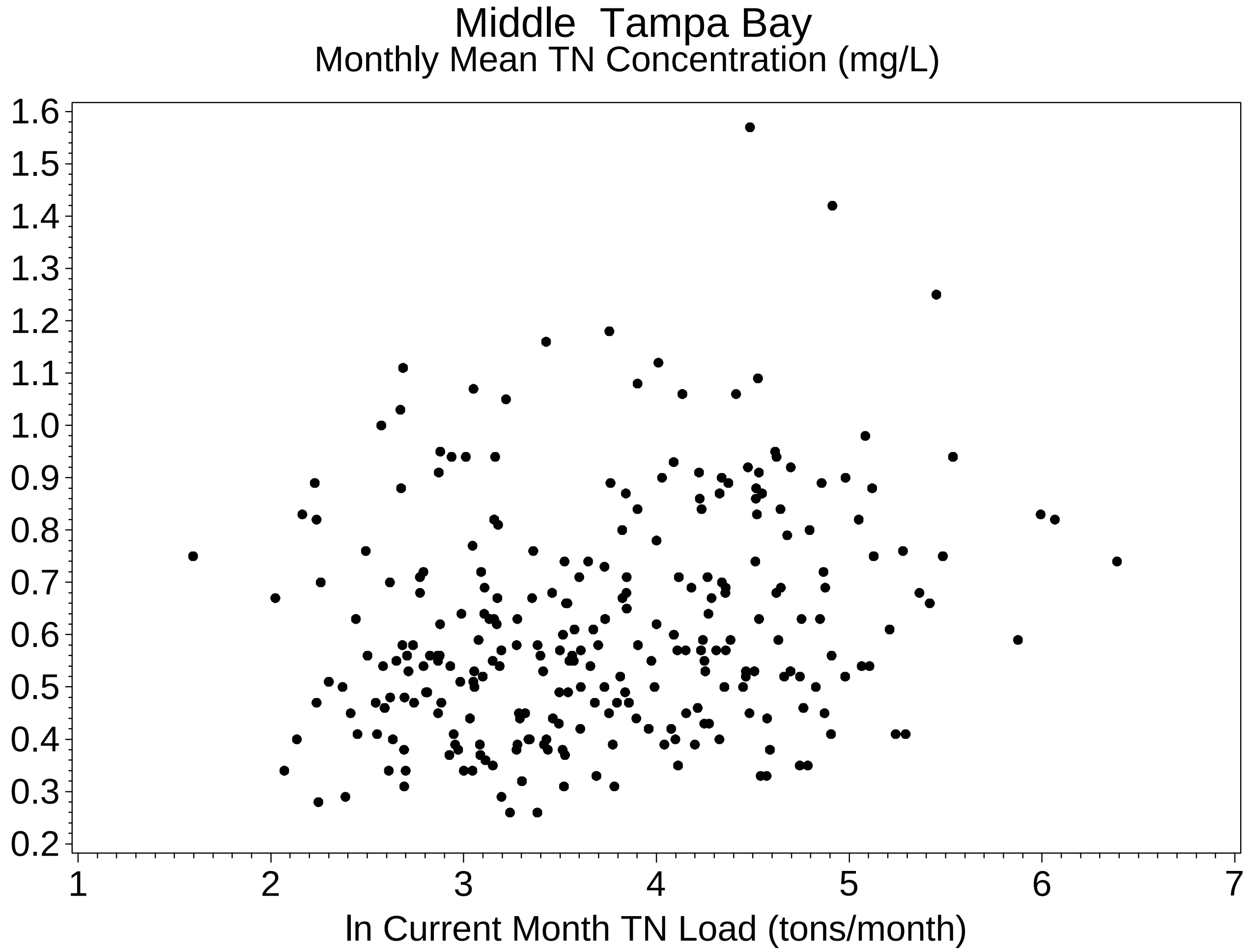

Lower Tampa Bay
Monthly Mean TN Concentration (mg/L)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
200
400
600
800
1000
1200
1400
Cumulative Three-Month TN Load (tons)

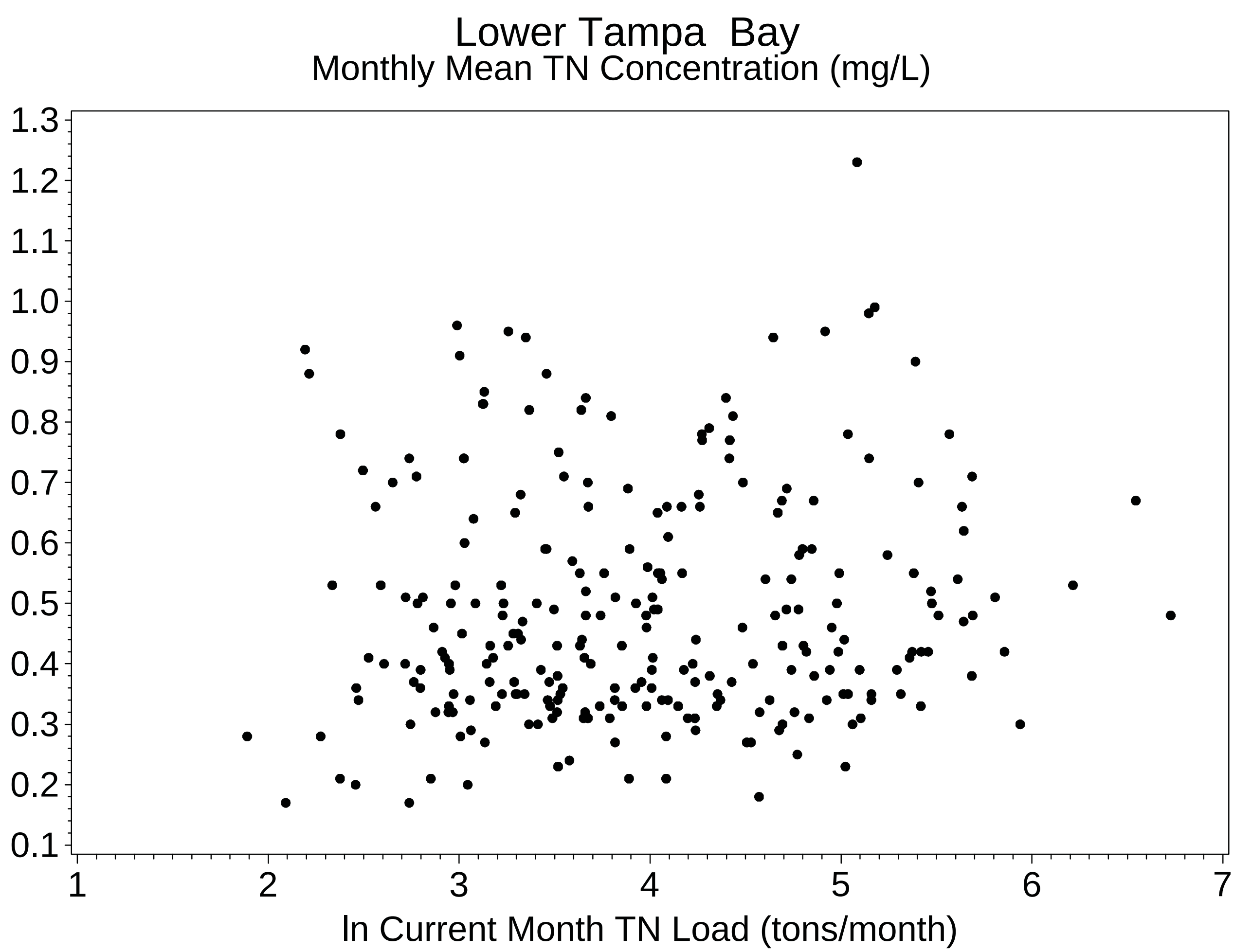


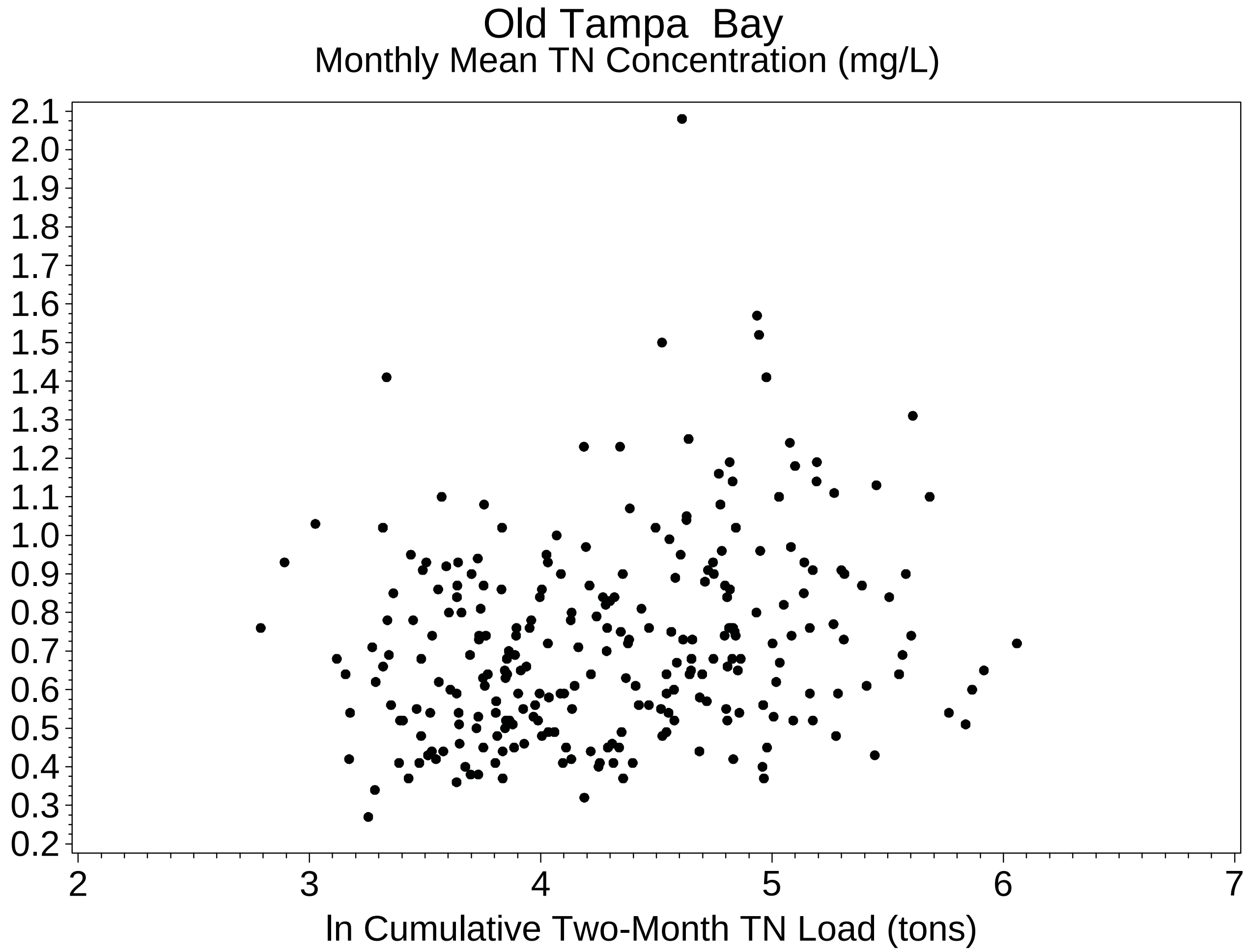
Old Tampa Bay
Monthly Mean TN Concentration (mg/L)
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1
2
3
4
5
6
ln Current Month TN Load (tons/month)

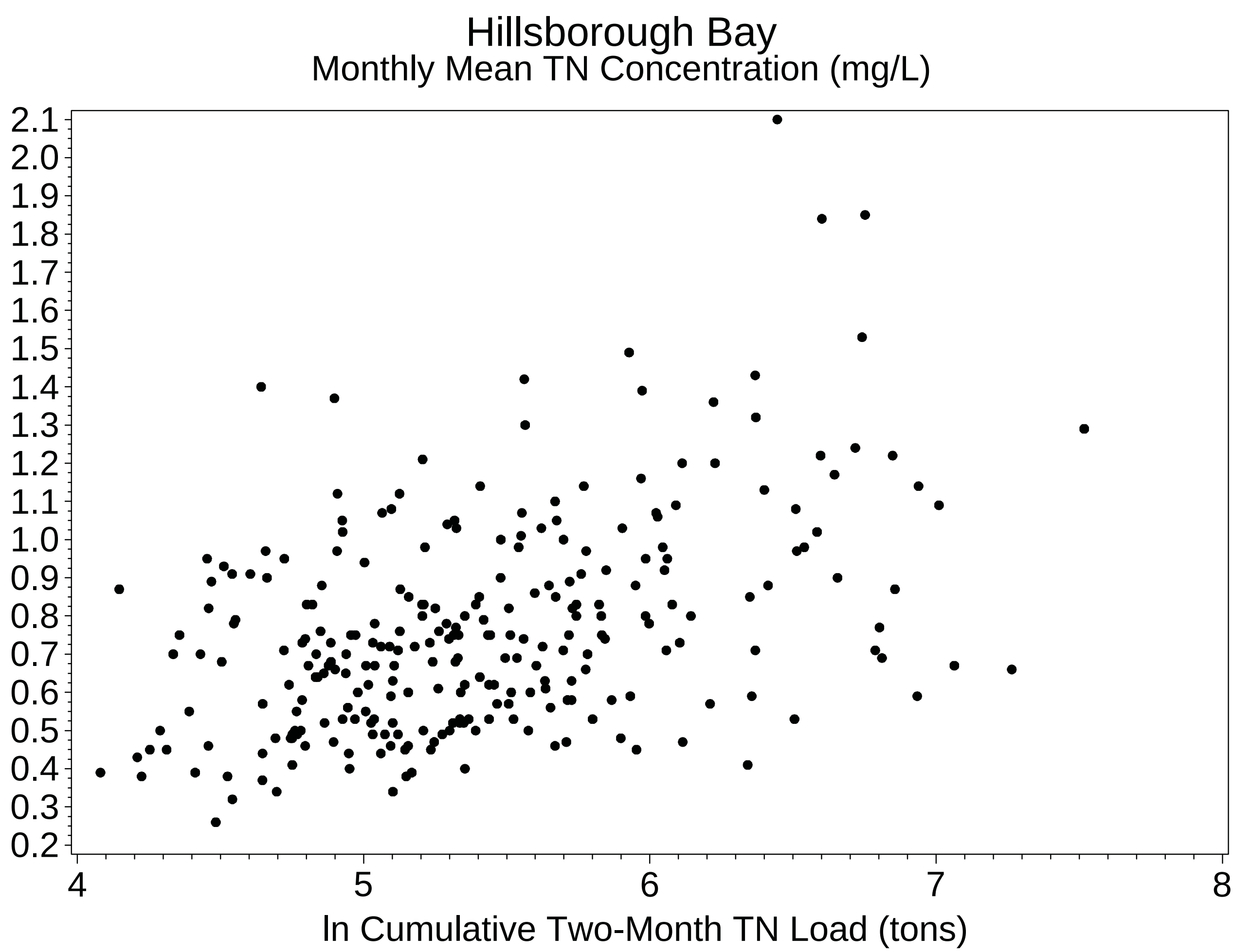


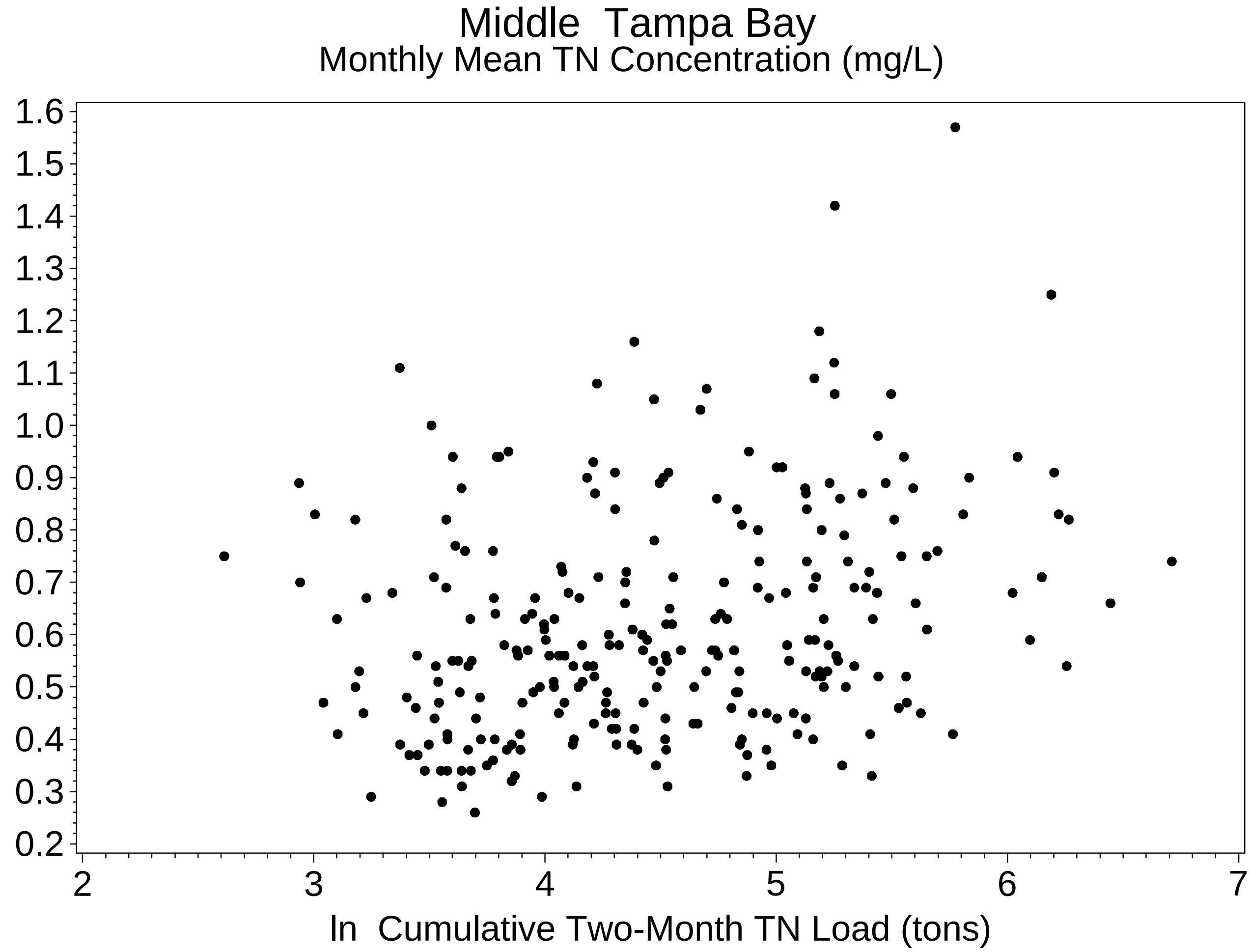
Hillsborough Bay
Monthly Mean TN Concentration (mg/L)
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
3
4
5
6
7
ln Current Month TN Load (tons/month)

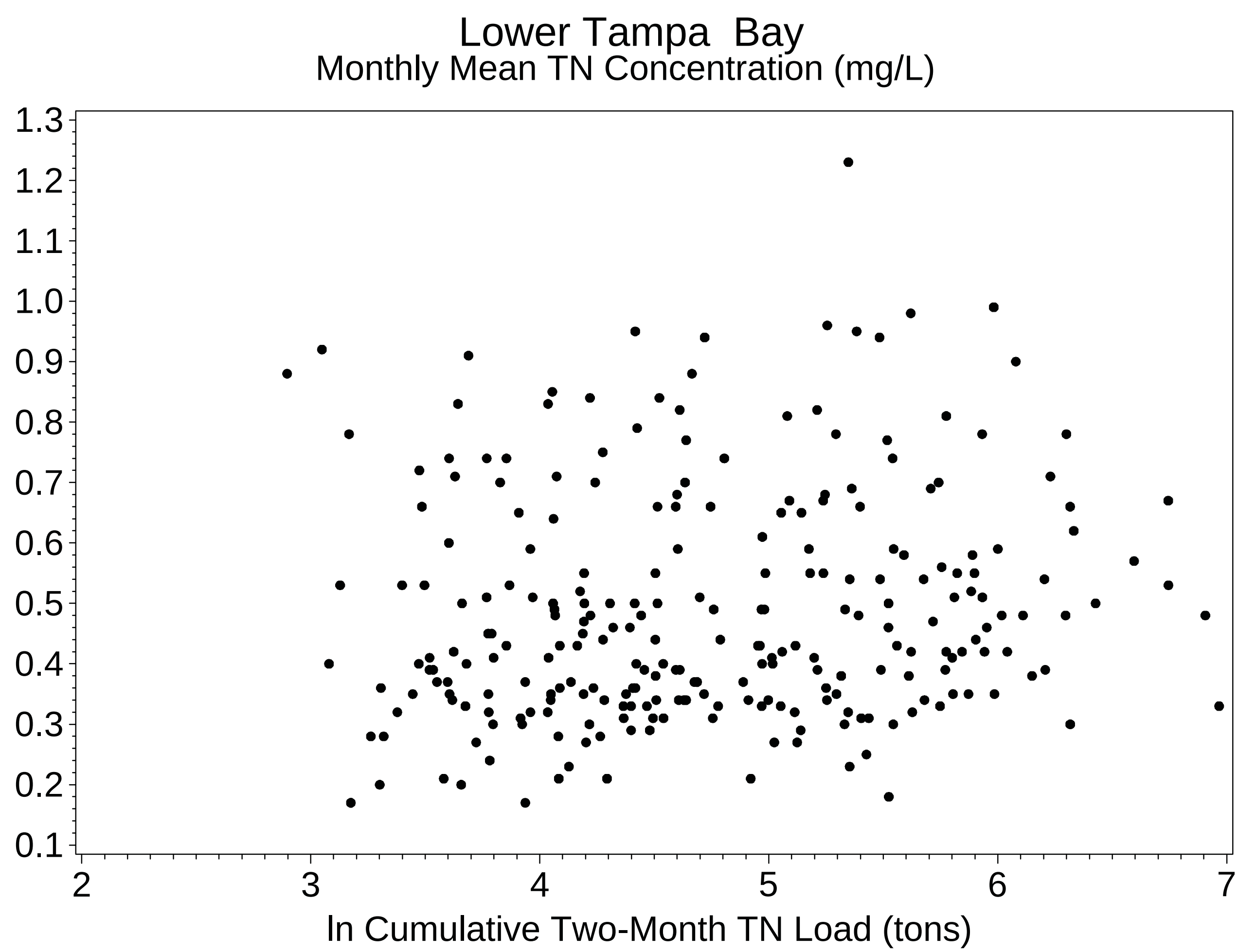

Middle Tampa Bay
Monthly Mean TN Concentration (mg/L)
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1
2
3
4
5
6
7
ln Current Month TN Load (tons/month)

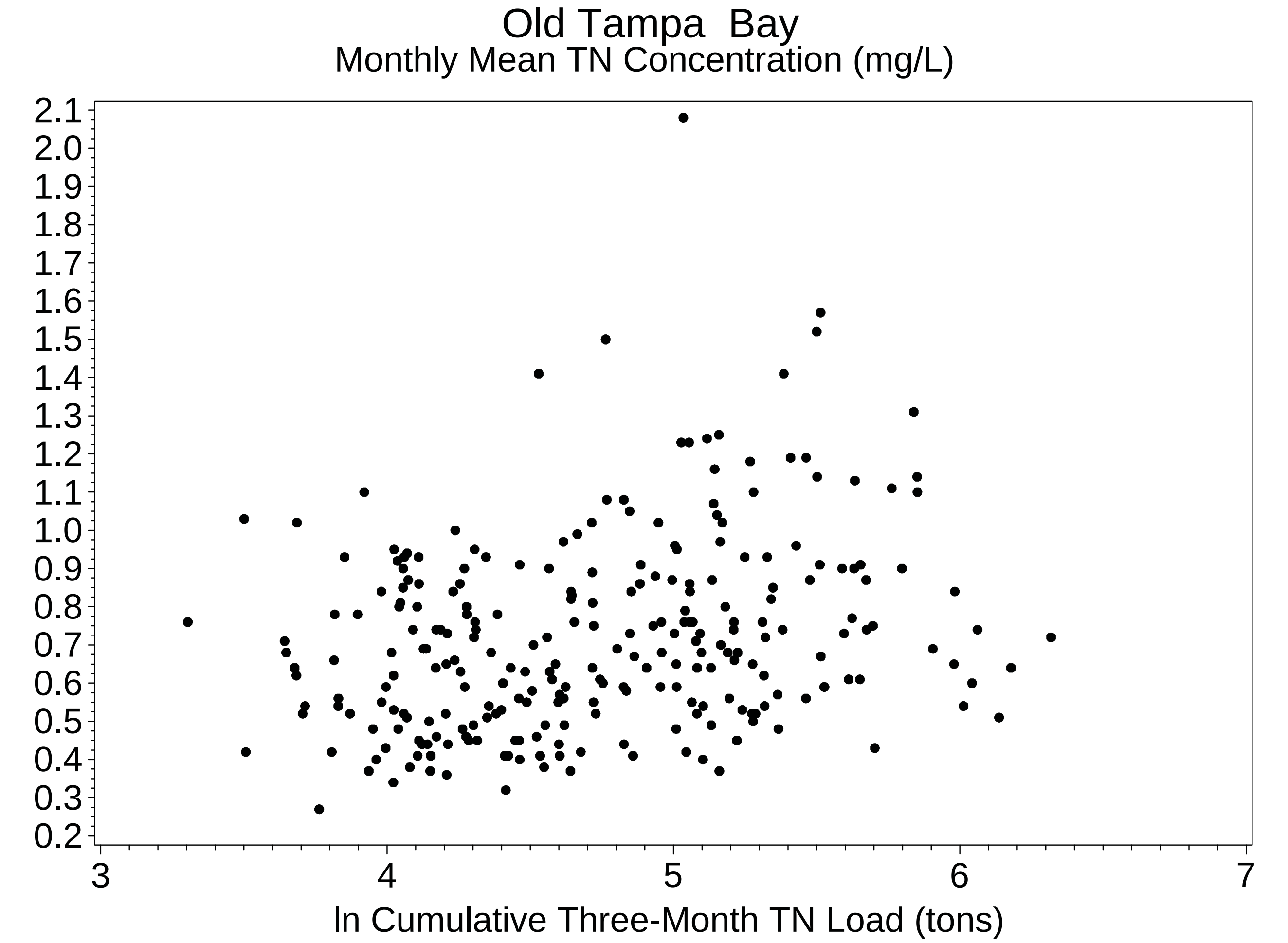

Lower Tampa Bay
Monthly Mean TN Concentration (mg/L)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1
2
3
4
5
6
7
ln Current Month TN Load (tons/month)

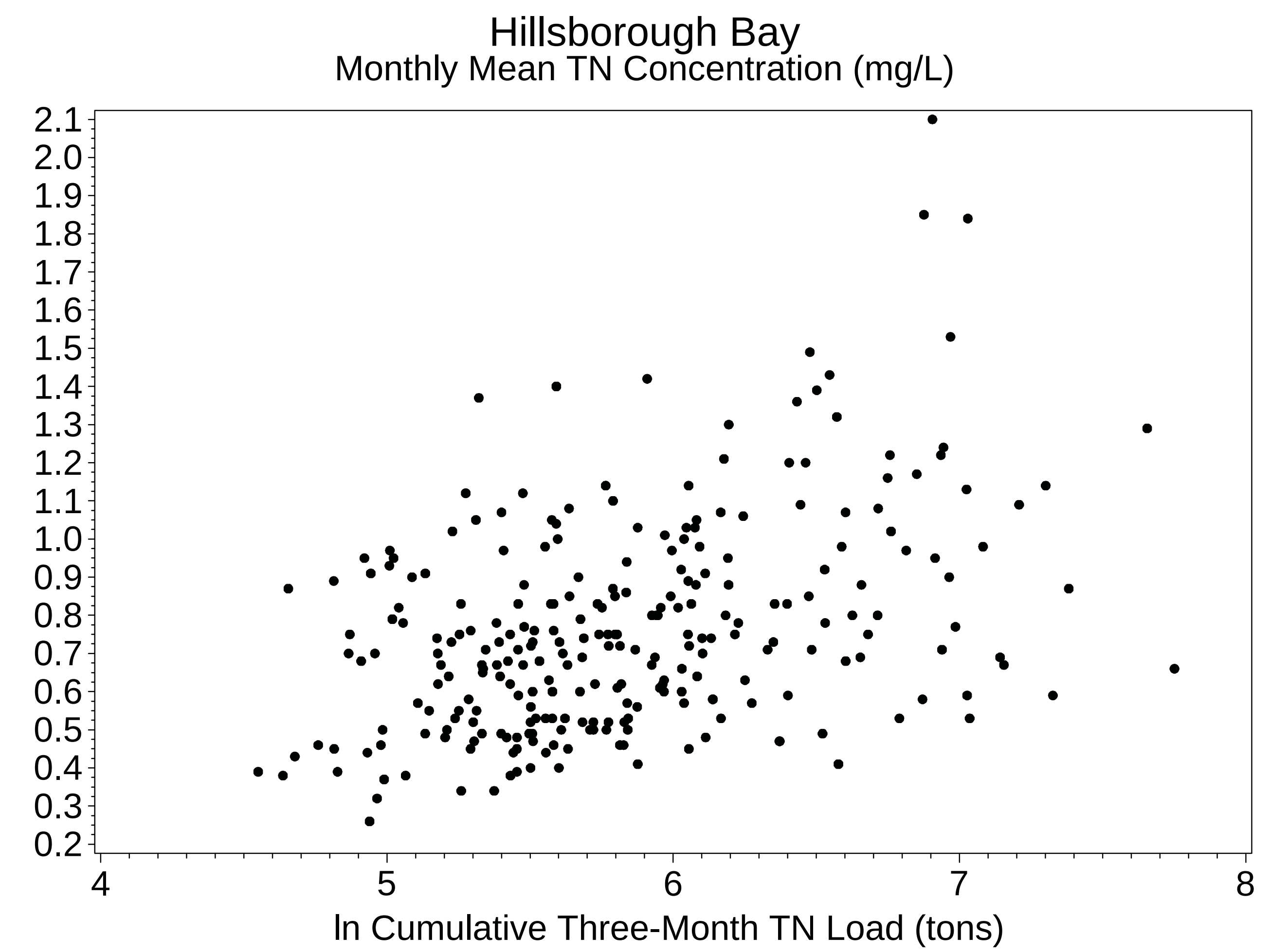

Old Tampa Bay
Monthly Mean TN Concentration (mg/L)
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
2
3
4
5
6
7
ln Cumulative Two-Month TN Load (tons)

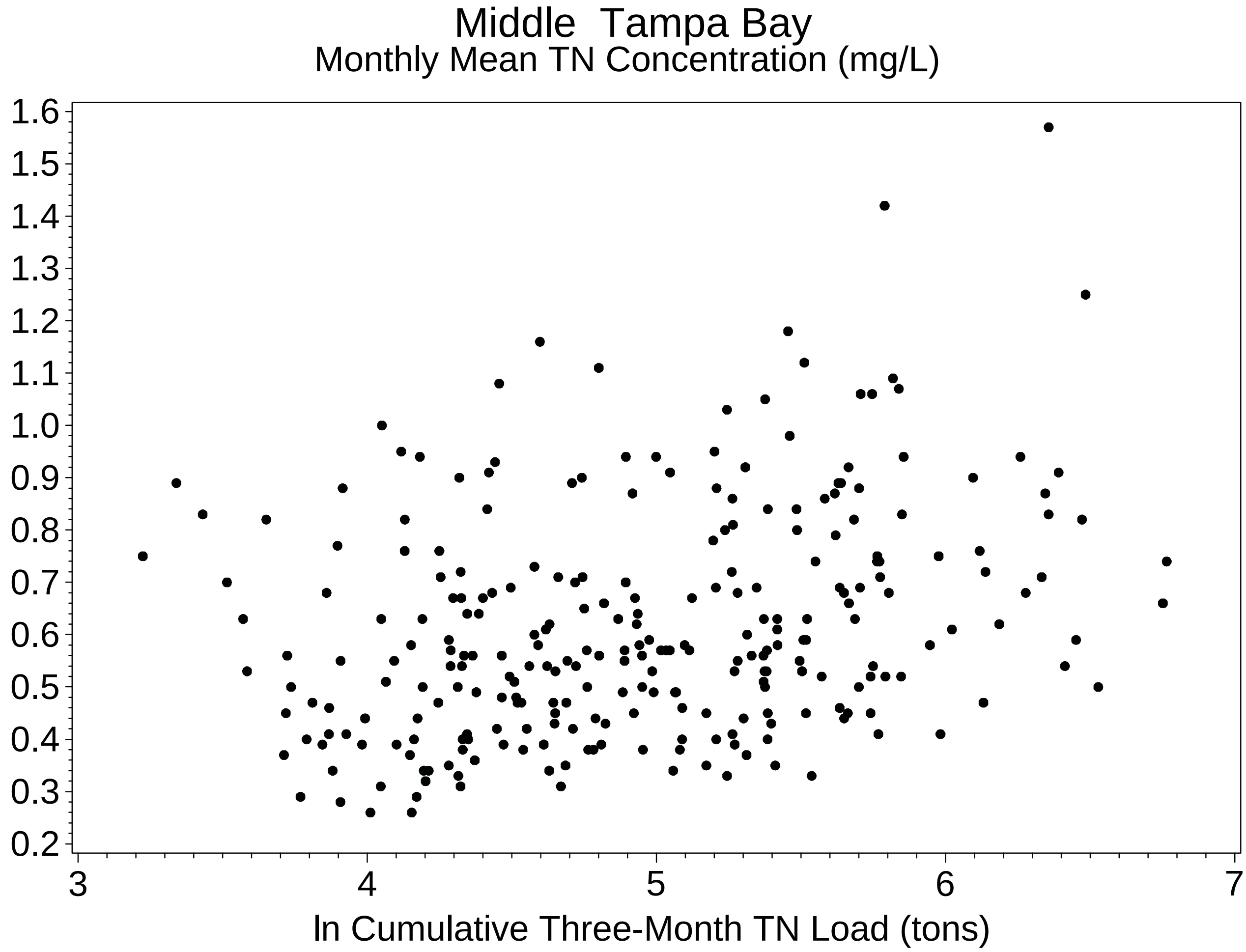

Hillsborough Bay
Monthly Mean TN Concentration (mg/L)
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
4
5
6
7
8
ln Cumulative Two-Month TN Load (tons)

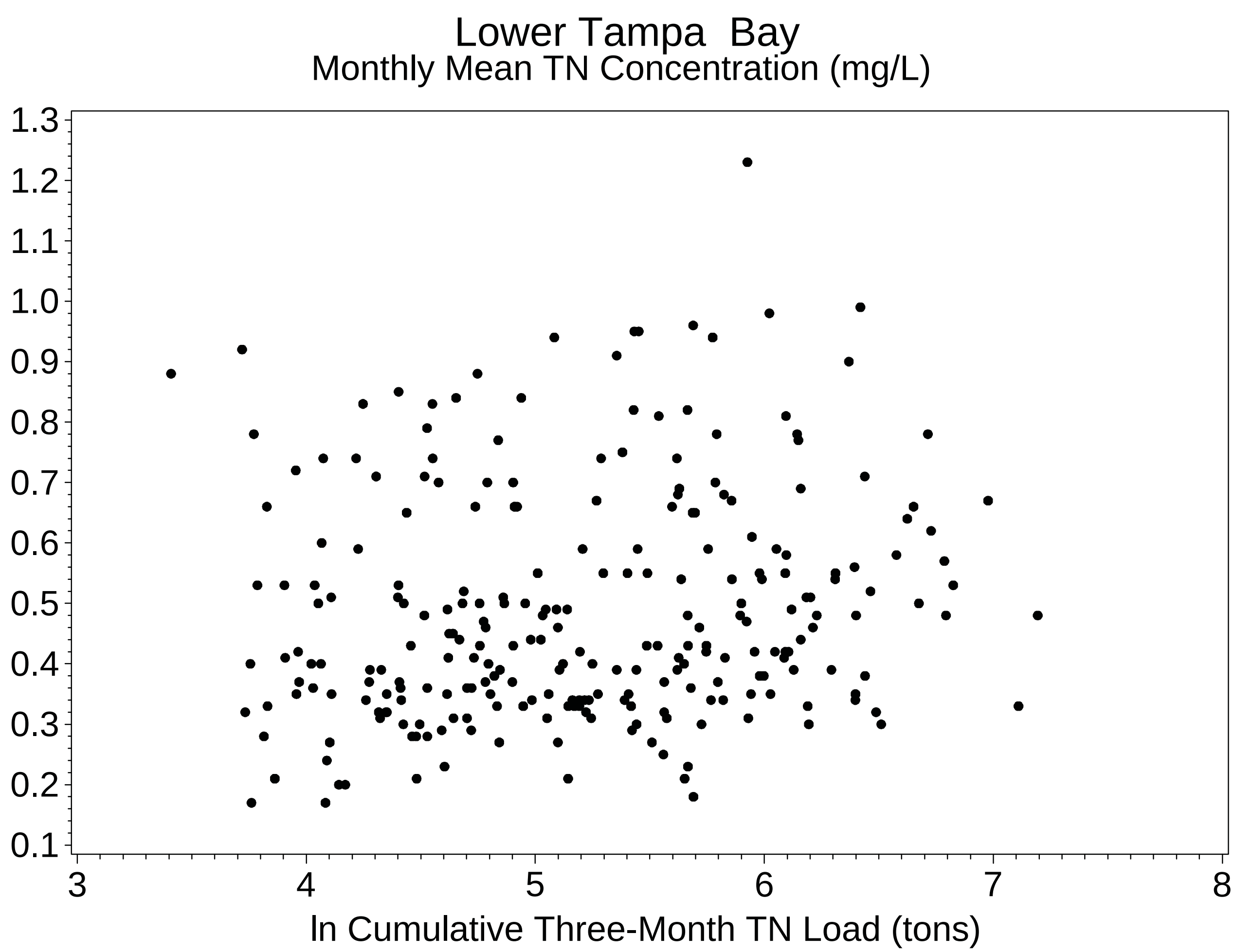

Middle Tampa Bay
Monthly Mean TN Concentration (mg/L)
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
2
3
4
5
6
7
ln Cumulative Two-Month TN Load (tons)


Lower Tampa Bay
Monthly Mean TN Concentration (mg/L)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
2
3
4
5
6
7
ln Cumulative Two-Month TN Load (tons)

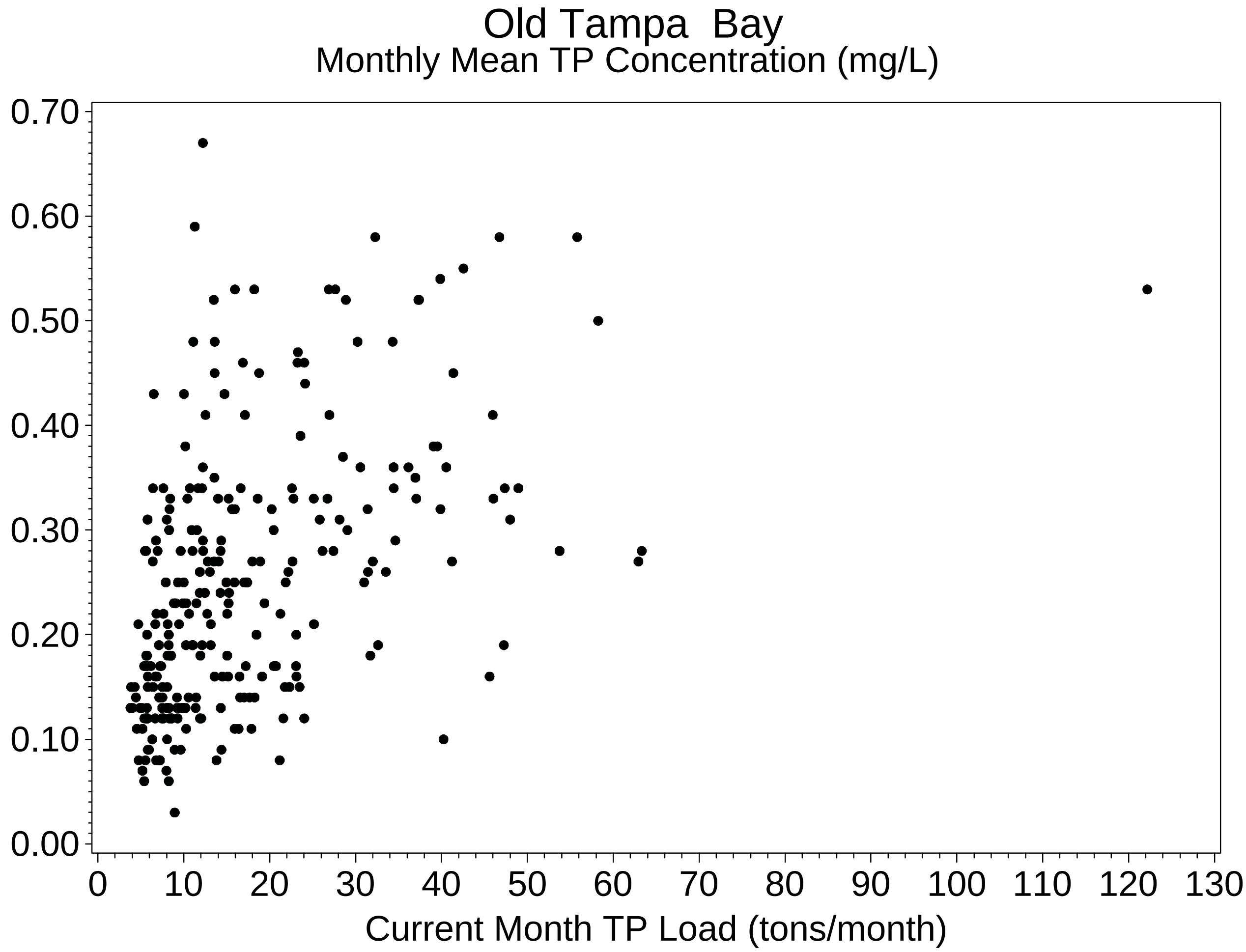

Old Tampa Bay
Monthly Mean TN Concentration (mg/L)
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
3
4
5
6
7
ln Cumulative Three-Month TN Load (tons)

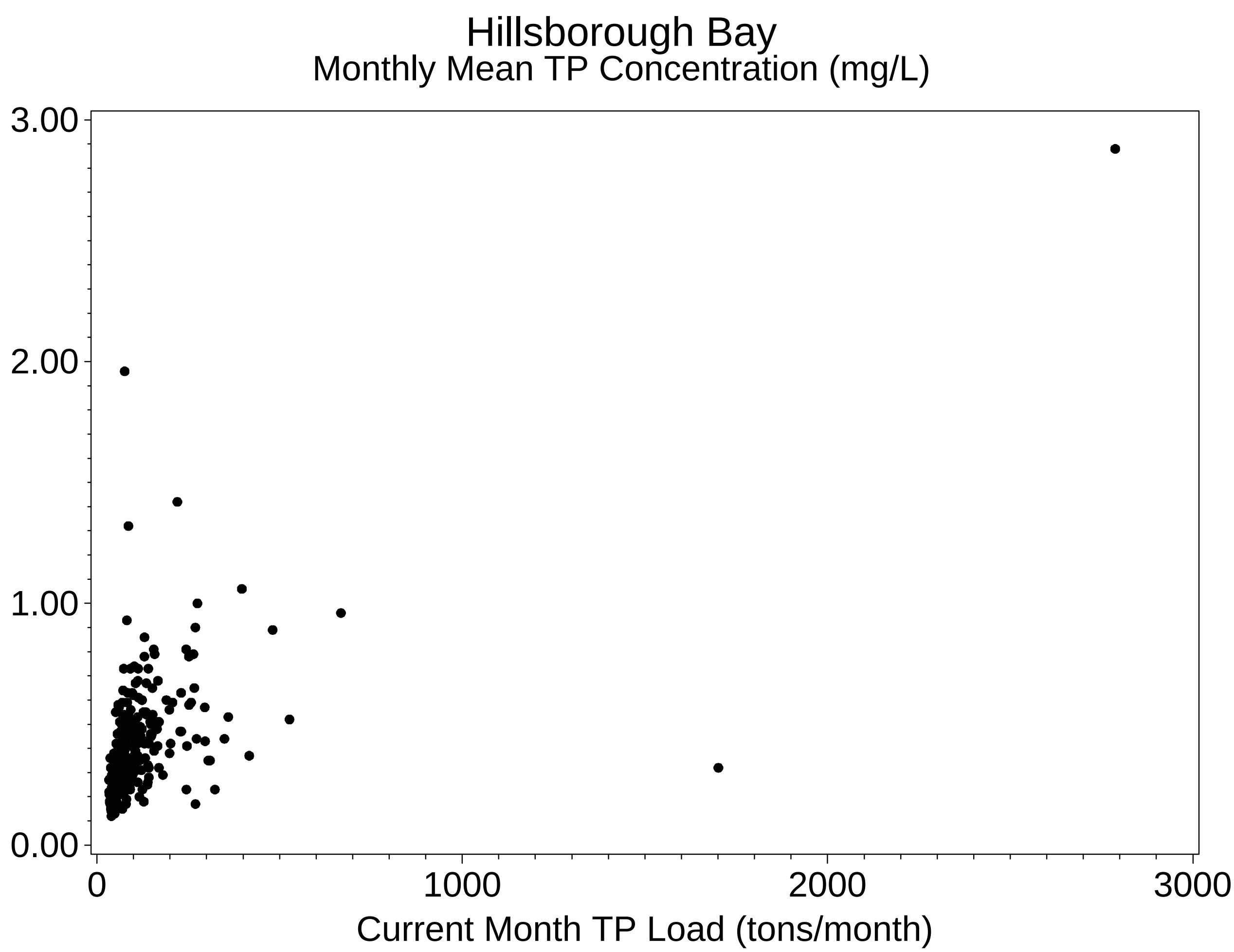

Hillsborough Bay
Monthly Mean TN Concentration (mg/L)
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
4
5
6
7
8
ln Cumulative Three-Month TN Load (tons)

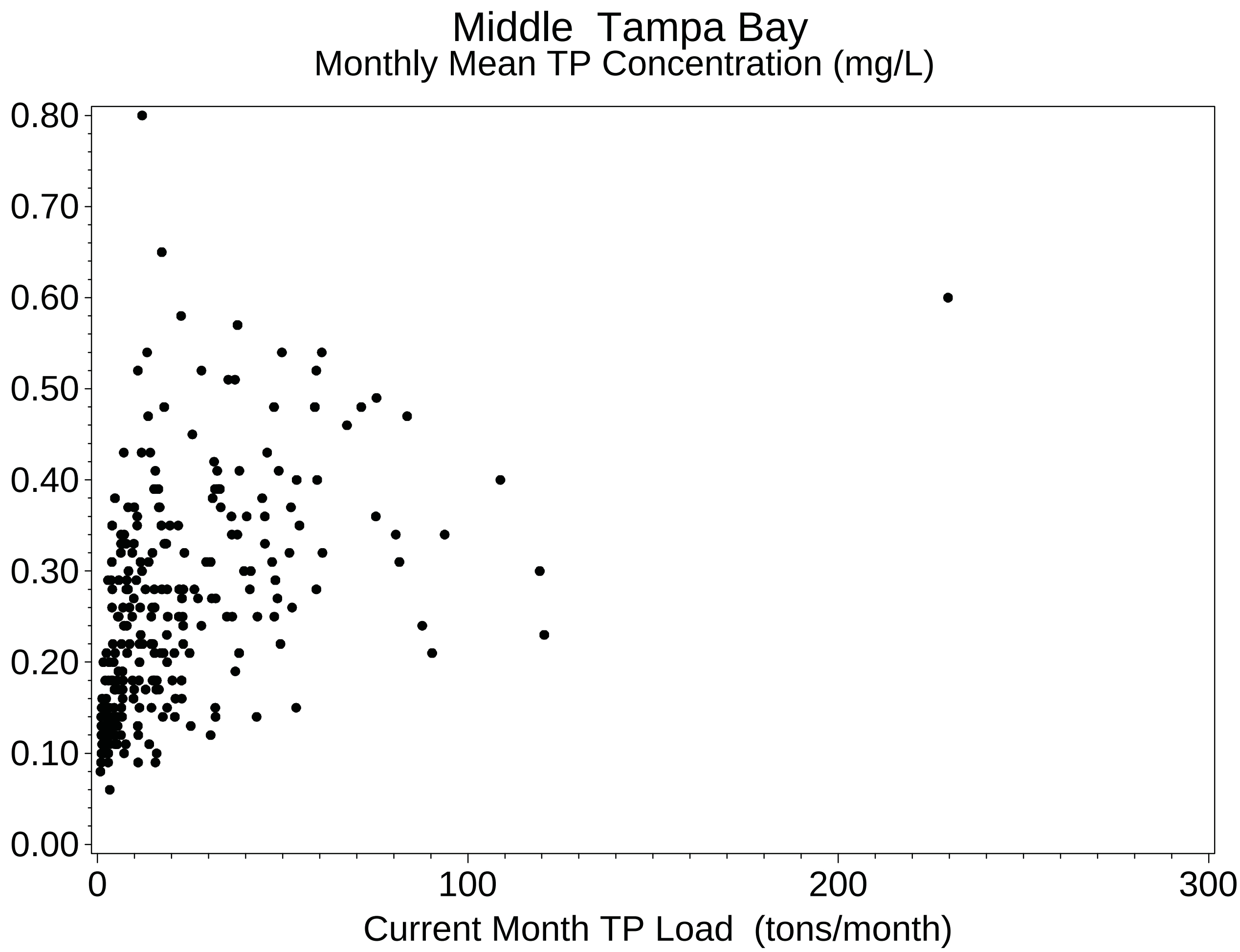

Middle Tampa Bay
Monthly Mean TN Concentration (mg/L)
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
3
4
5
6
7
ln Cumulative Three-Month TN Load (tons)

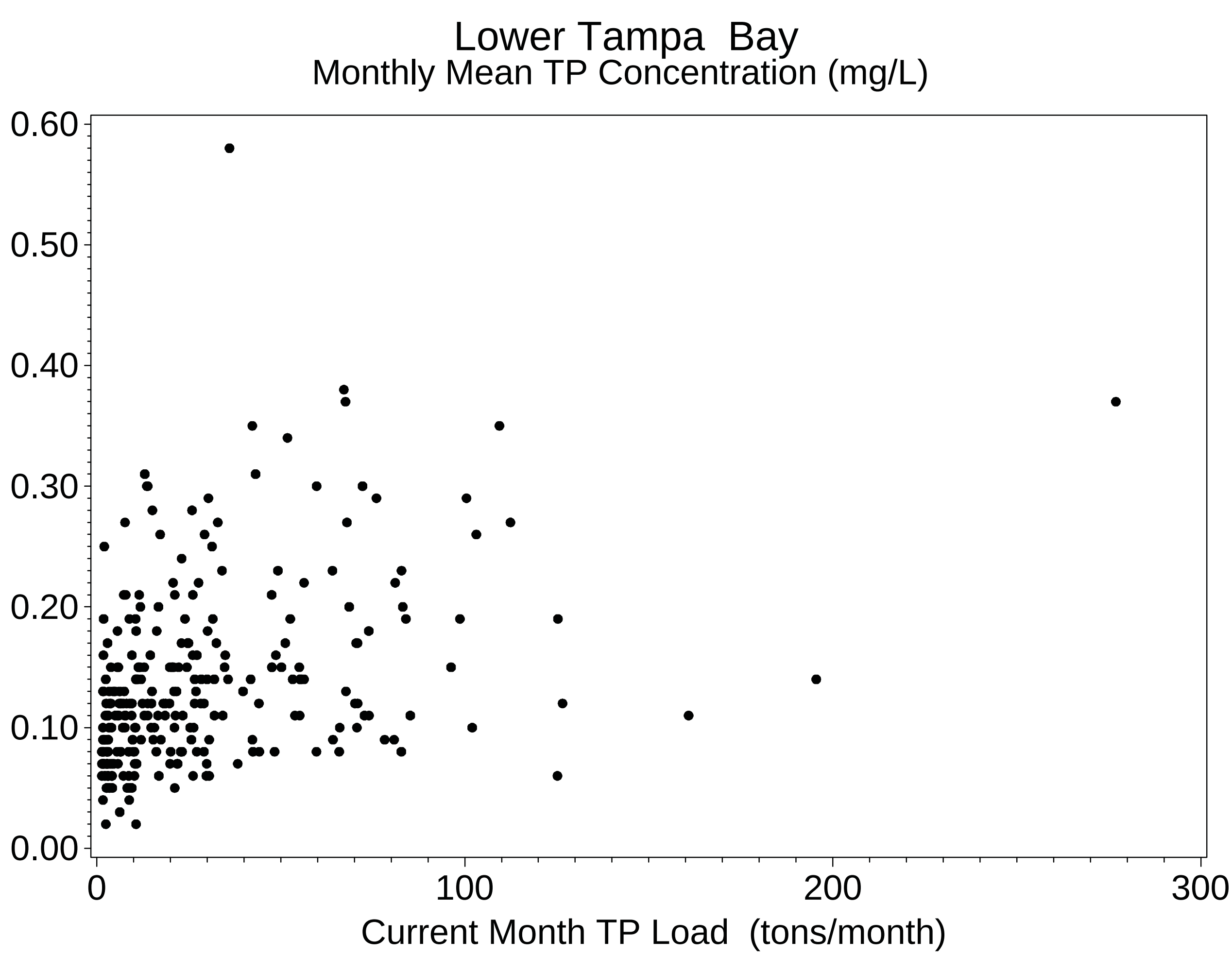

Lower Tampa Bay
Monthly Mean TN Concentration (mg/L)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
3
4
5
6
7
8
ln Cumulative Three-Month TN Load (tons)

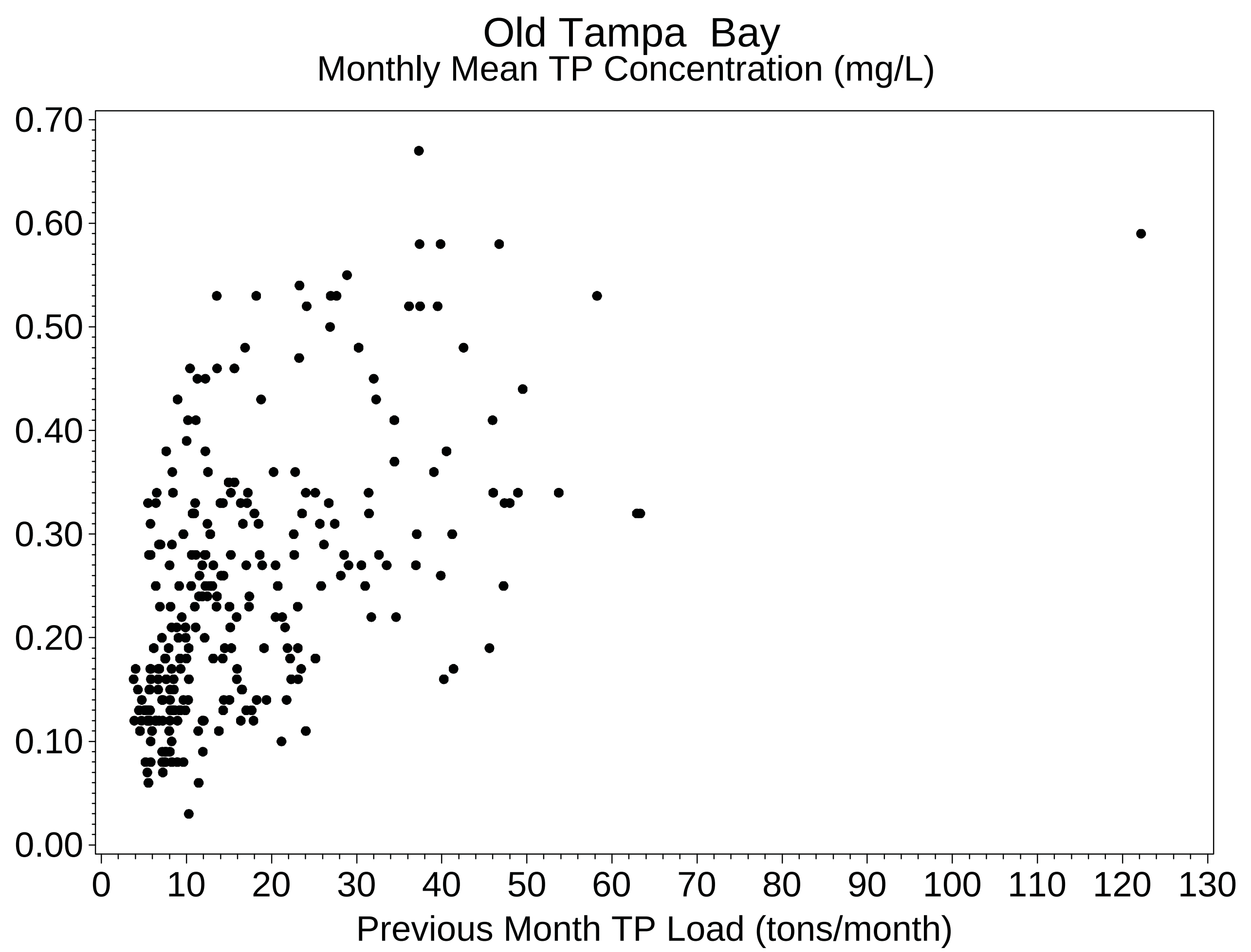
Attachment 4
Monthly TP Concentrations and Monthly TP Loads

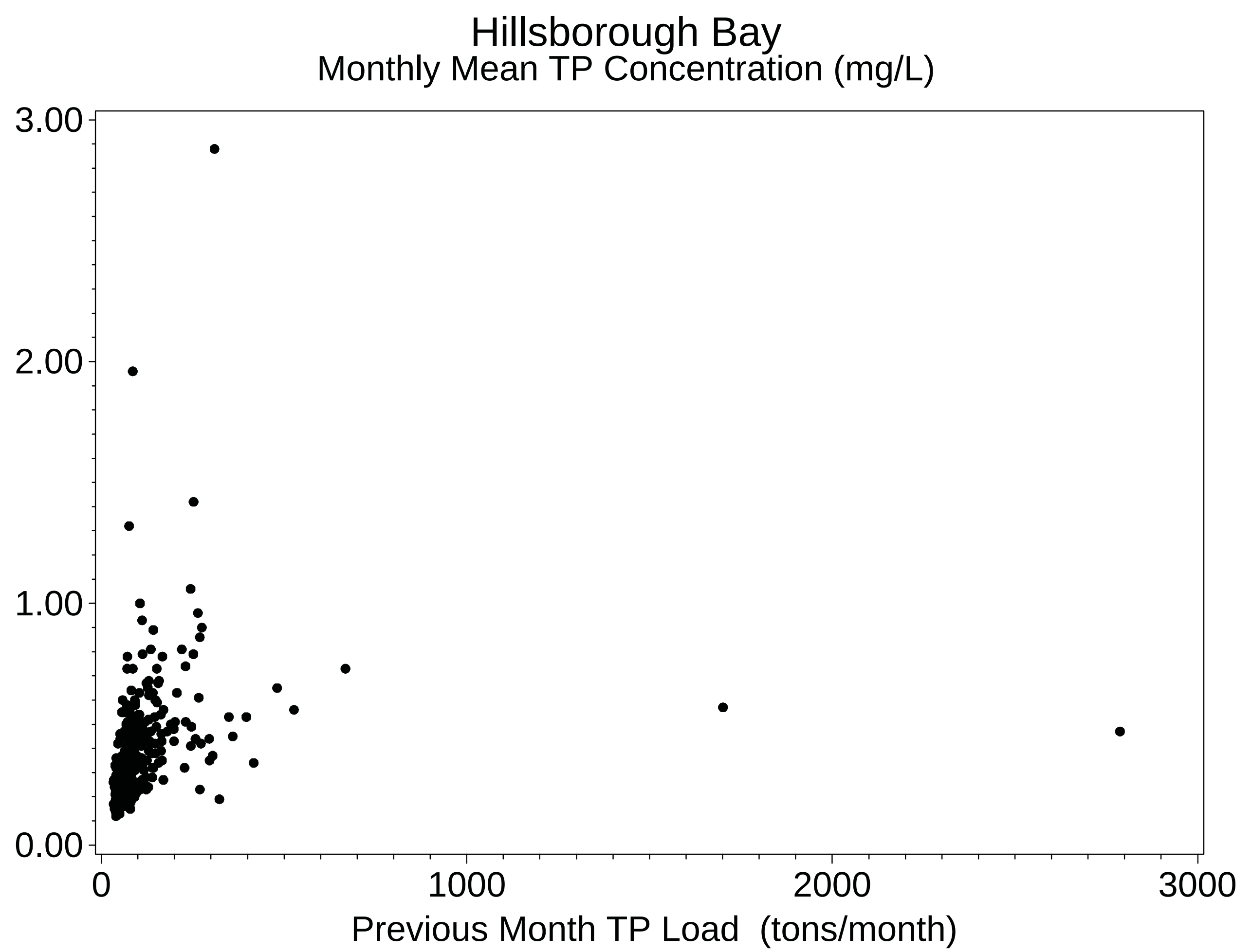

Old Tampa Bay
Monthly Mean TP Concentration (mg/L)
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0 10 20 30 40 50 60 70 80 90 100 110 120 130
Current Month TP Load (tons/month)

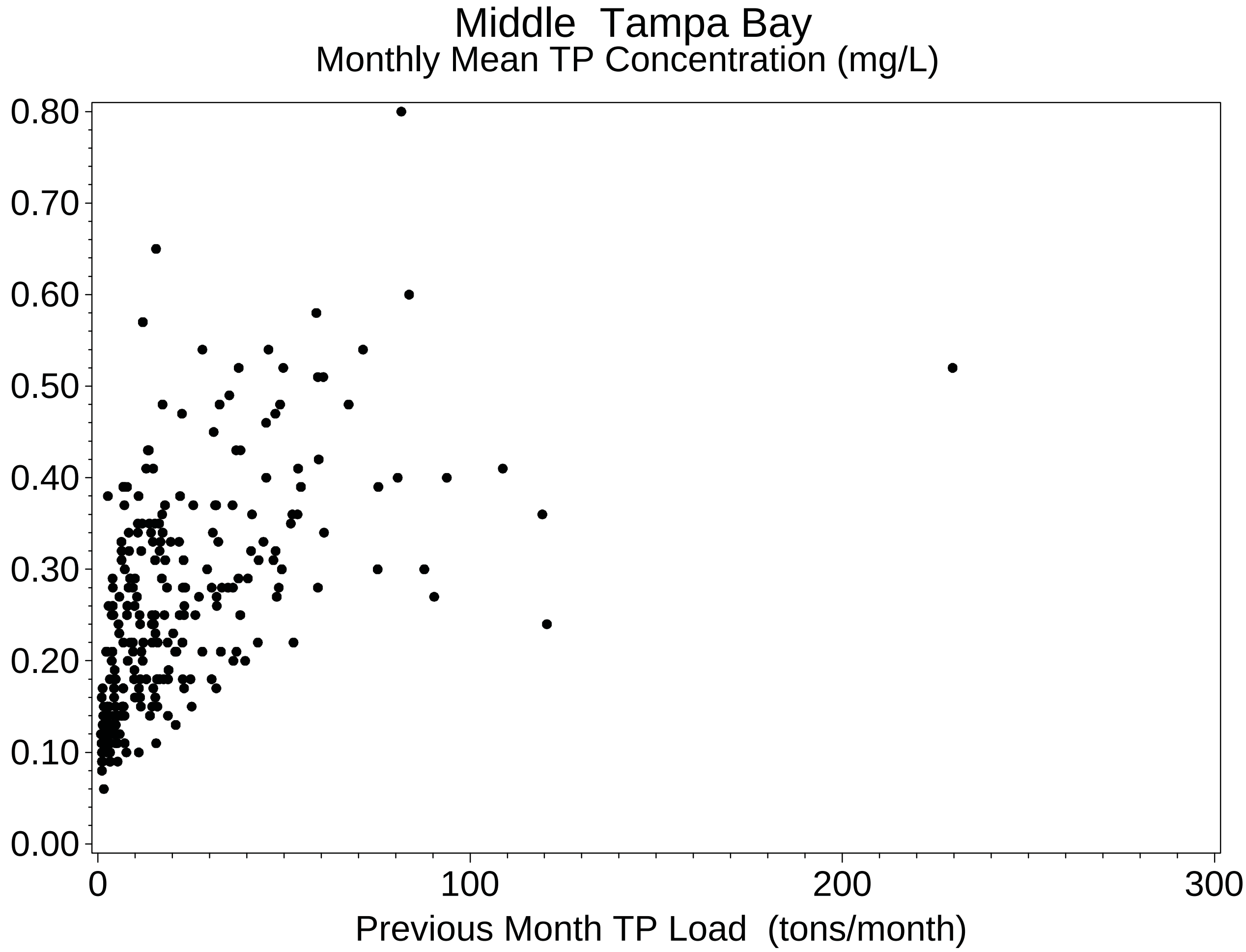

Hillsborough Bay
Monthly Mean TP Concentration (mg/L)
3.00
2.00
1.00
0.00
0 1000 2000 3000
Current Month TP Load (tons/month)

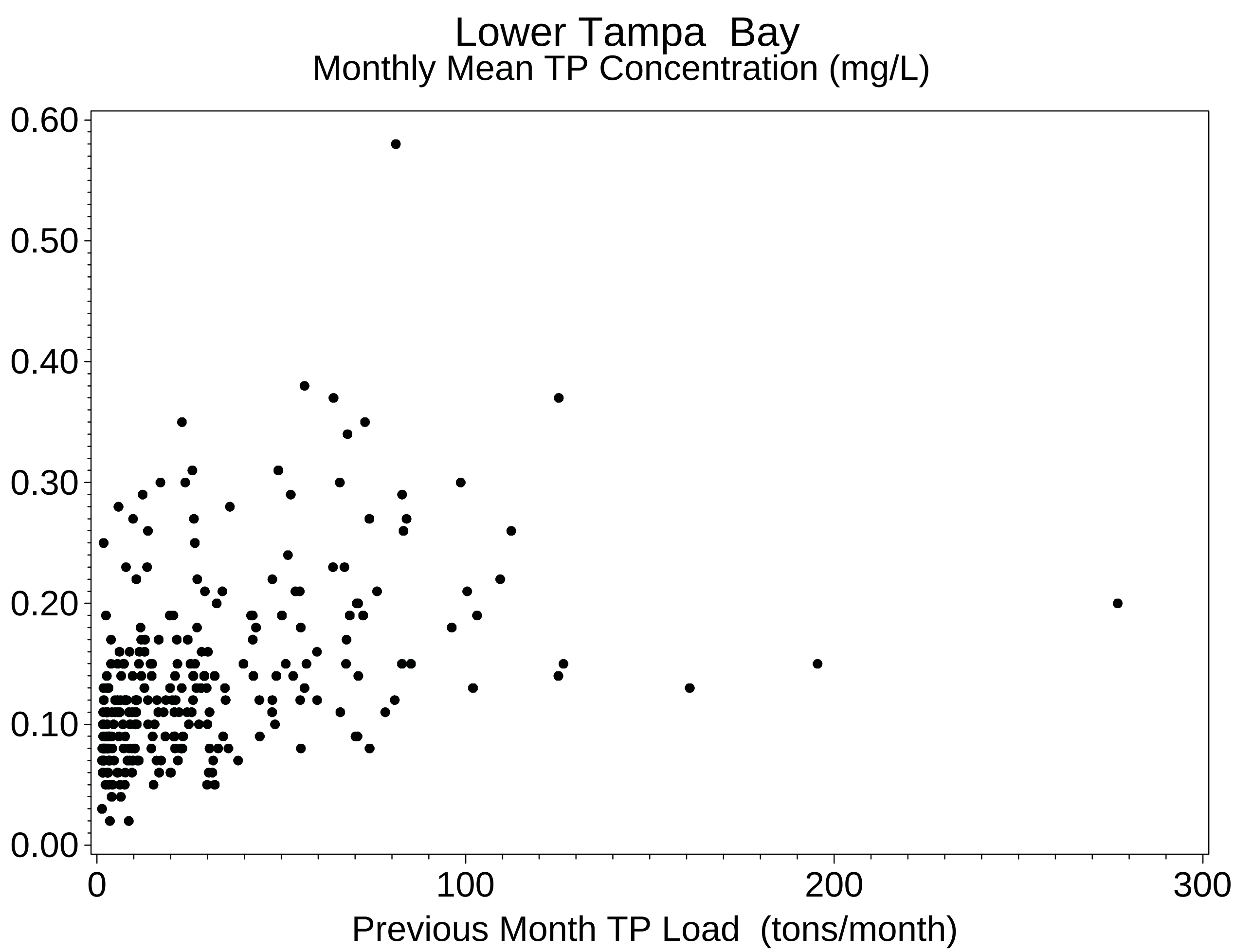

Middle Tampa Bay
Monthly Mean TP Concentration (mg/L)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
100
200
300
Current Month TP Load (tons/month)

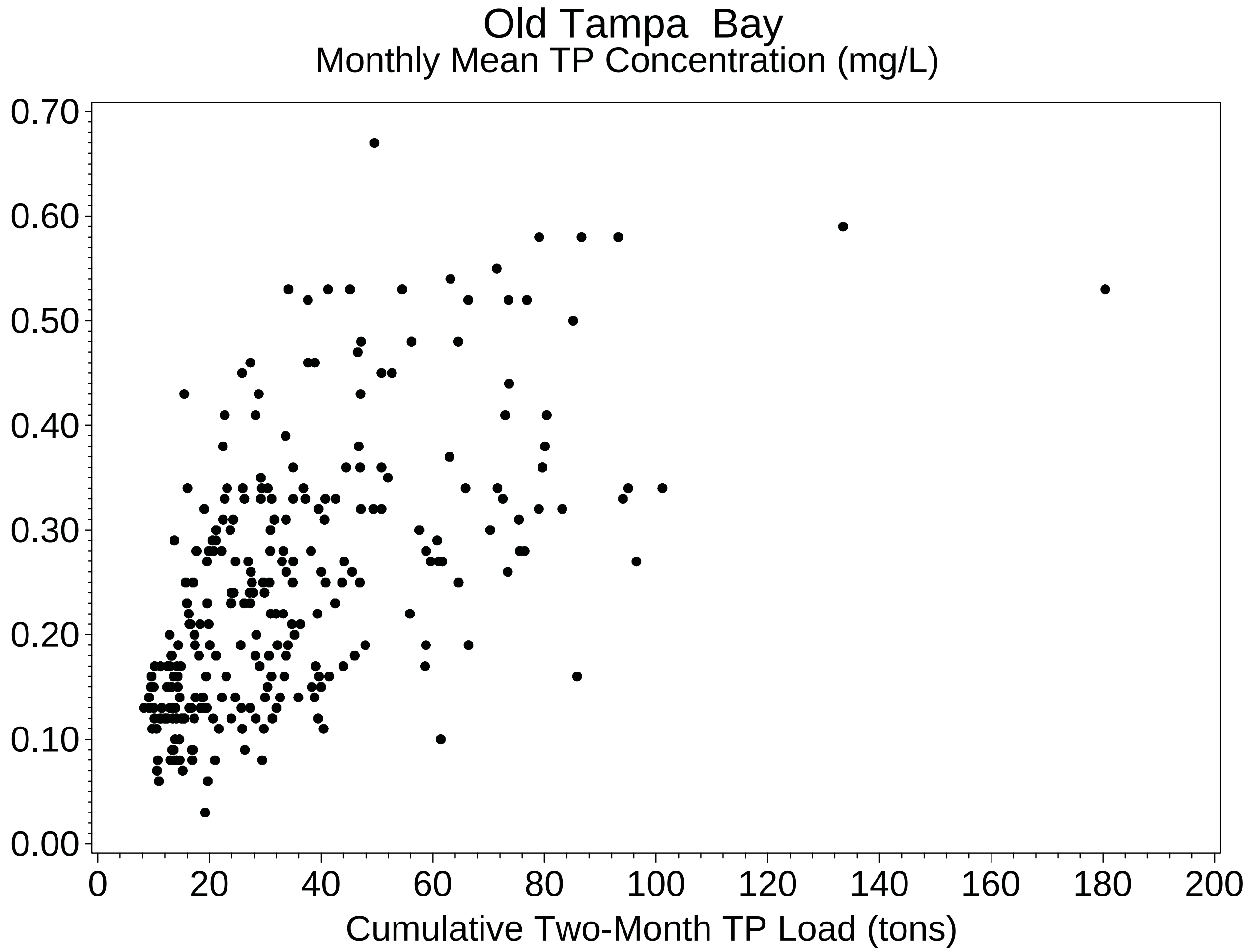

Lower Tampa Bay
Monthly Mean TP Concentration (mg/L)
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
100
200
300
Current Month TP Load (tons/month)

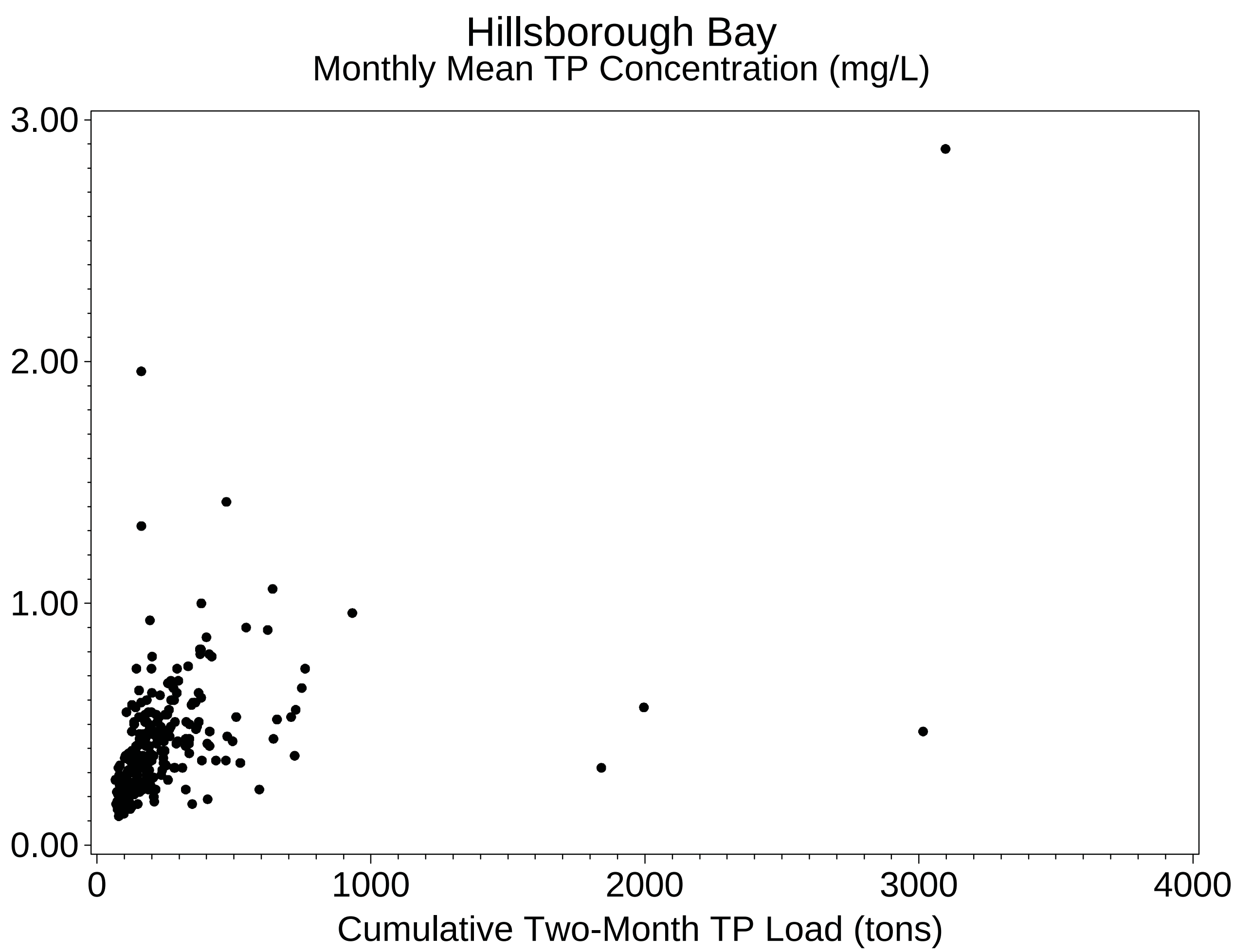

Old Tampa Bay
Monthly Mean TP Concentration (mg/L)
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
10
20
30
40
50
60
70
80
90
100
110
120
130
Previous Month TP Load (tons/month)

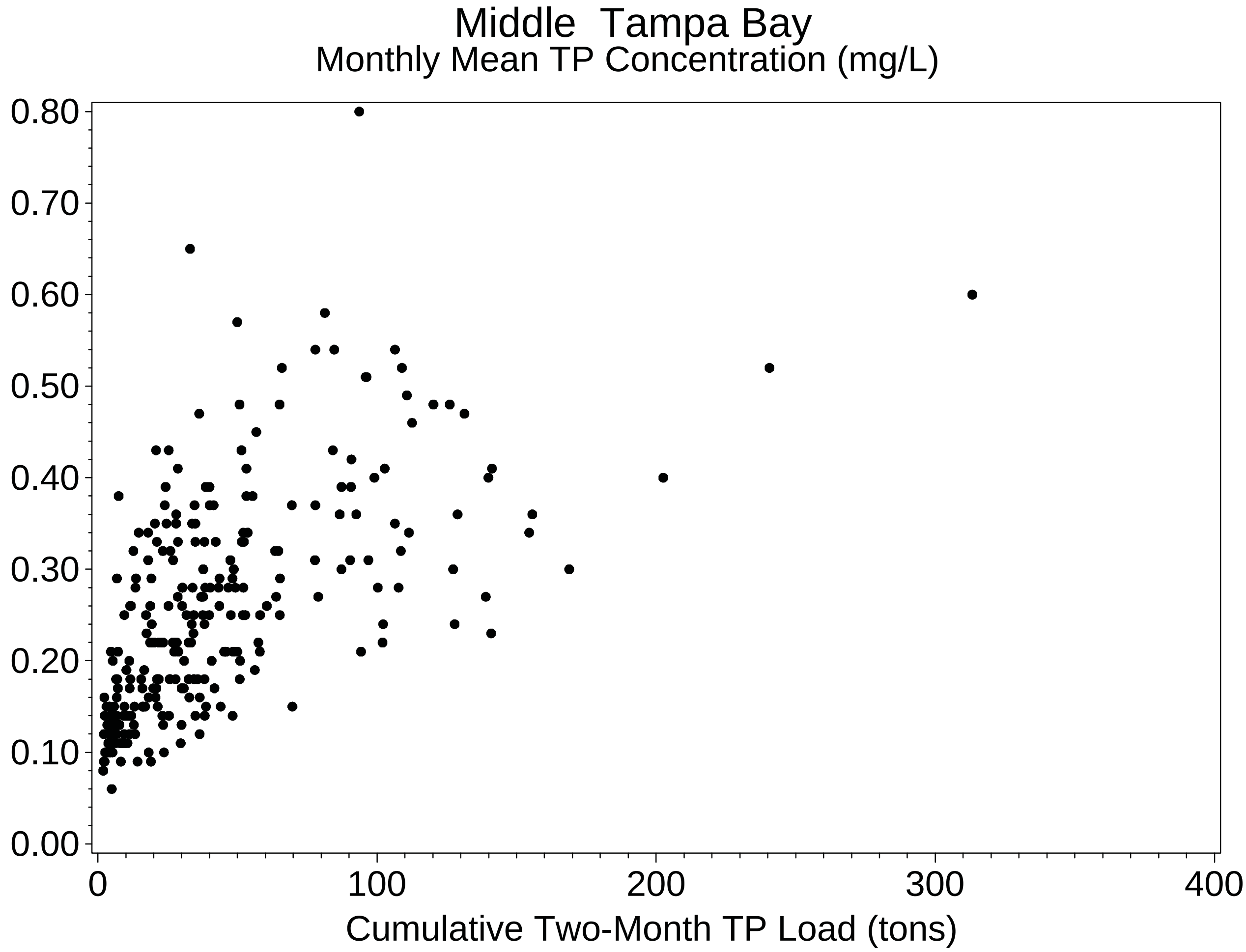

Hillsborough Bay
Monthly Mean TP Concentration (mg/L)
3.00
2.00
1.00
0.00
0
1000
2000
3000
Previous Month TP Load (tons/month)

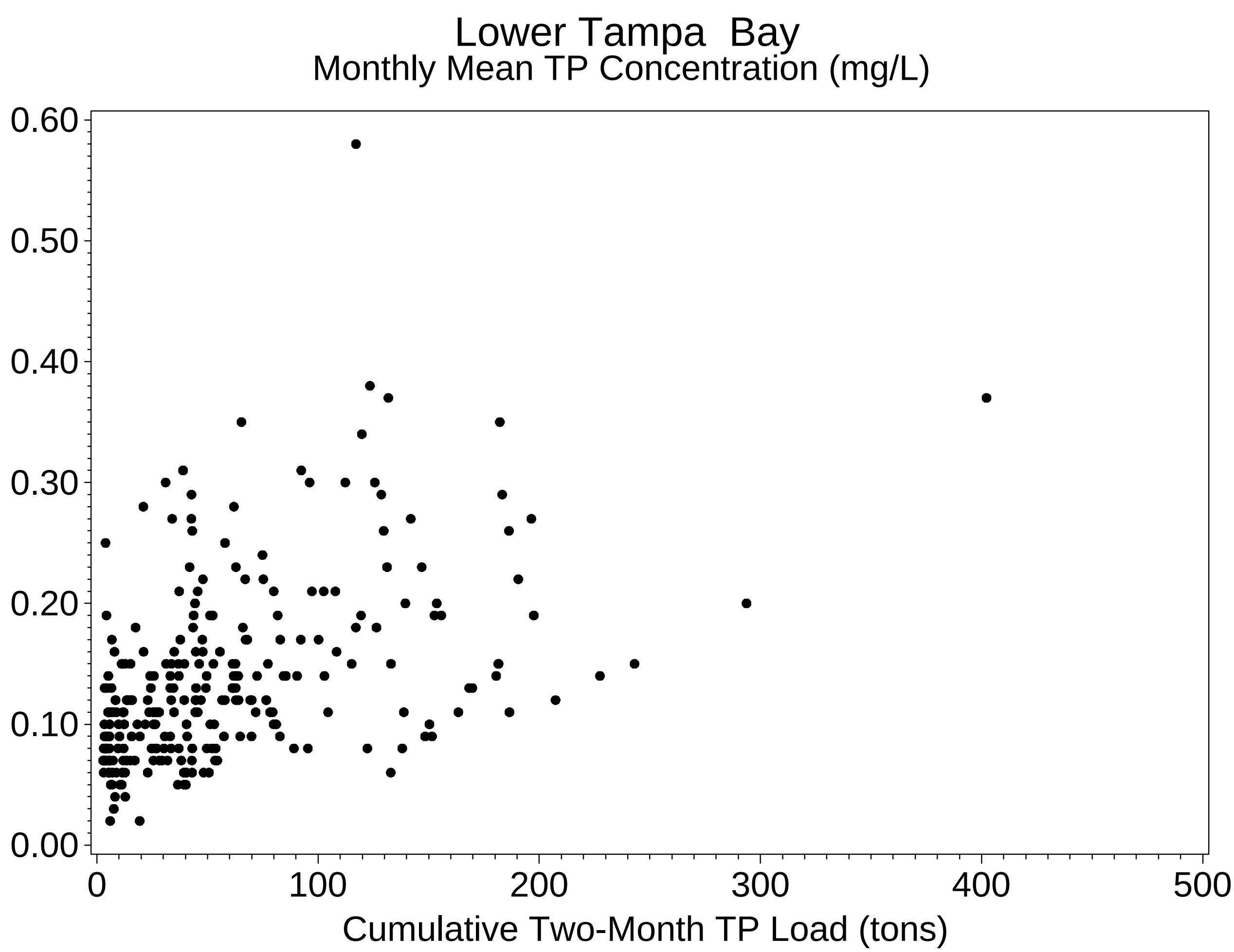

Middle Tampa Bay
Monthly Mean TP Concentration (mg/L)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
100
200
300
Previous Month TP Load (tons/month)

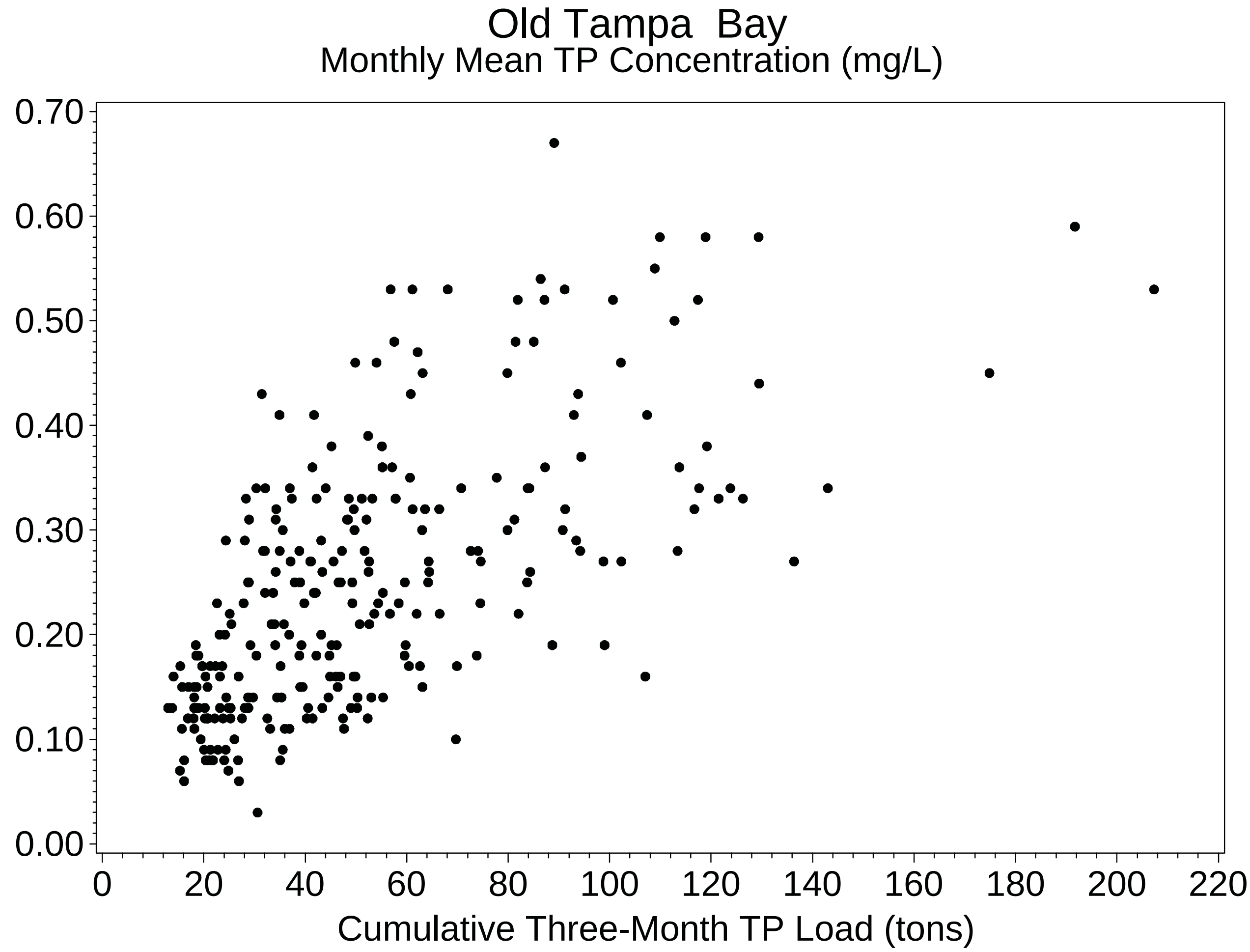

Lower Tampa Bay
Monthly Mean TP Concentration (mg/L)
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
100
200
300
Previous Month TP Load (tons/month)

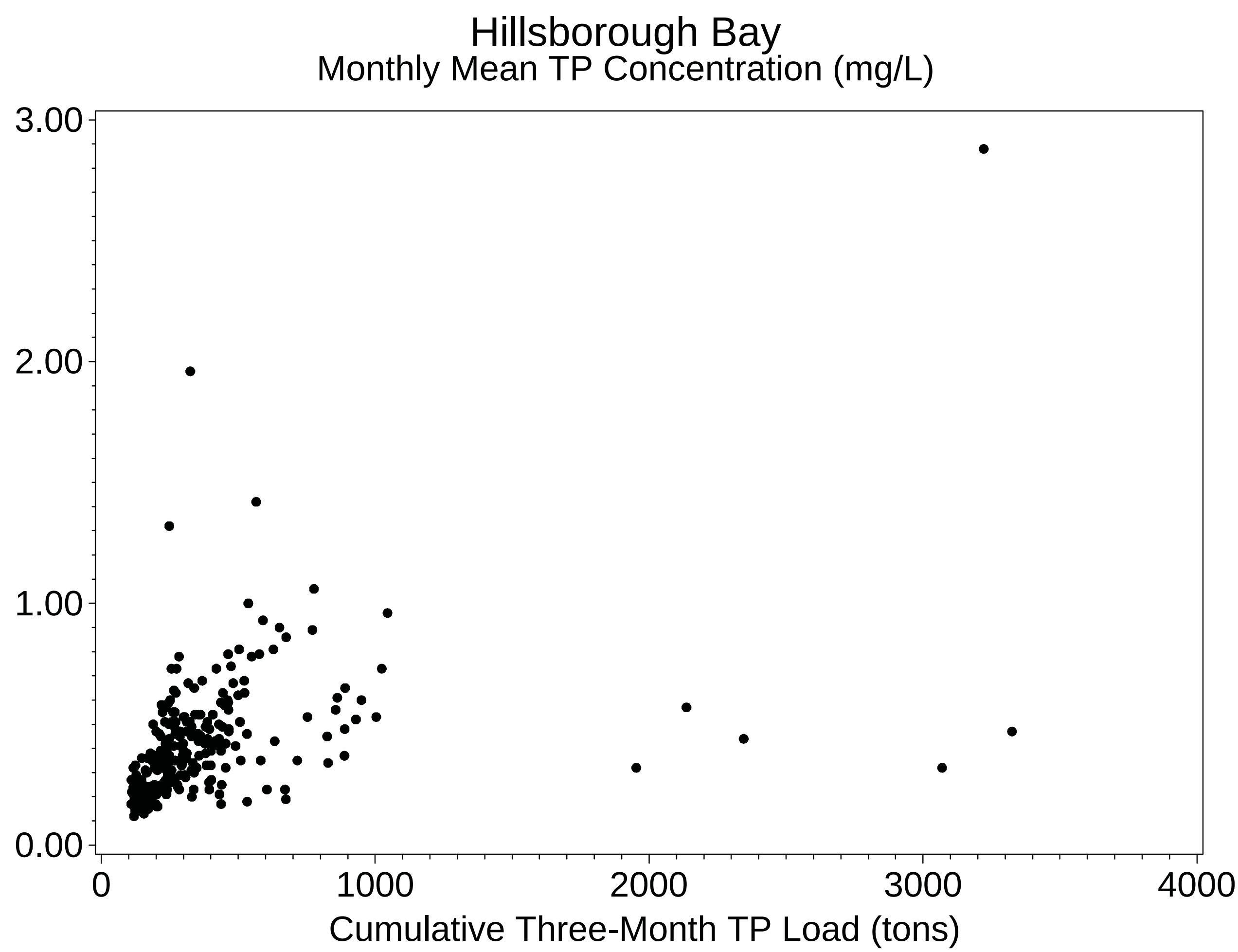

Old Tampa Bay
Monthly Mean TP Concentration (mg/L)
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
20
40
60
80
100
120
140
160
180
200
Cumulative Two-Month TP Load (tons)

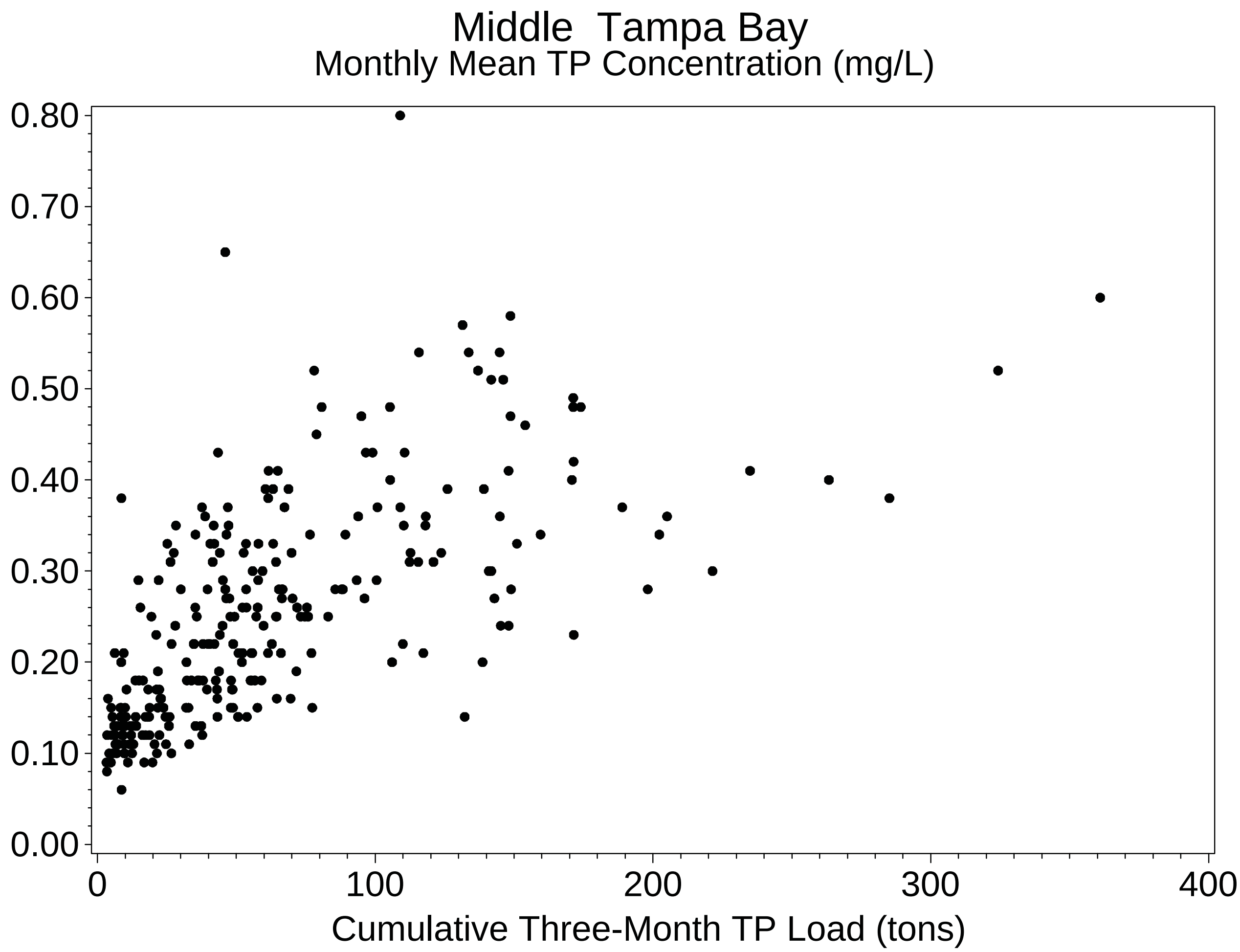

Hillsborough Bay
Monthly Mean TP Concentration (mg/L)
3.00
2.00
1.00
0.00
0
1000
2000
3000
4000
Cumulative Two-Month TP Load (tons)


Middle Tampa Bay
Monthly Mean TP Concentration (mg/L)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
100
200
300
400
Cumulative Two-Month TP Load (tons)

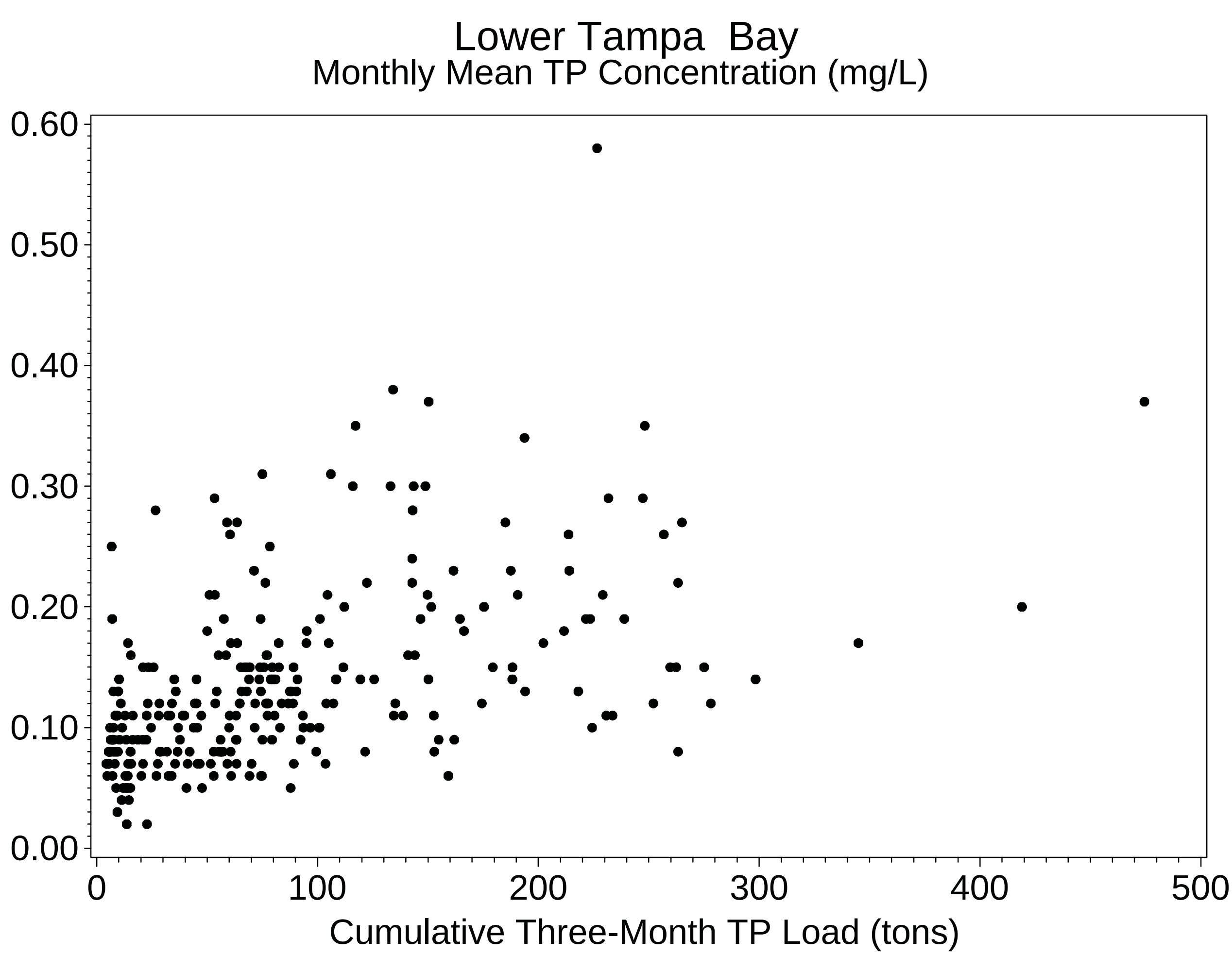

Lower Tampa Bay
Monthly Mean TP Concentration (mg/L)
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
100
200
300
400
500
Cumulative Two-Month TP Load (tons)


Old Tampa Bay
Monthly Mean TP Concentration (mg/L)
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
20
40
60
80
100
120
140
160
180
200
220
Cumulative Three-Month TP Load (tons)

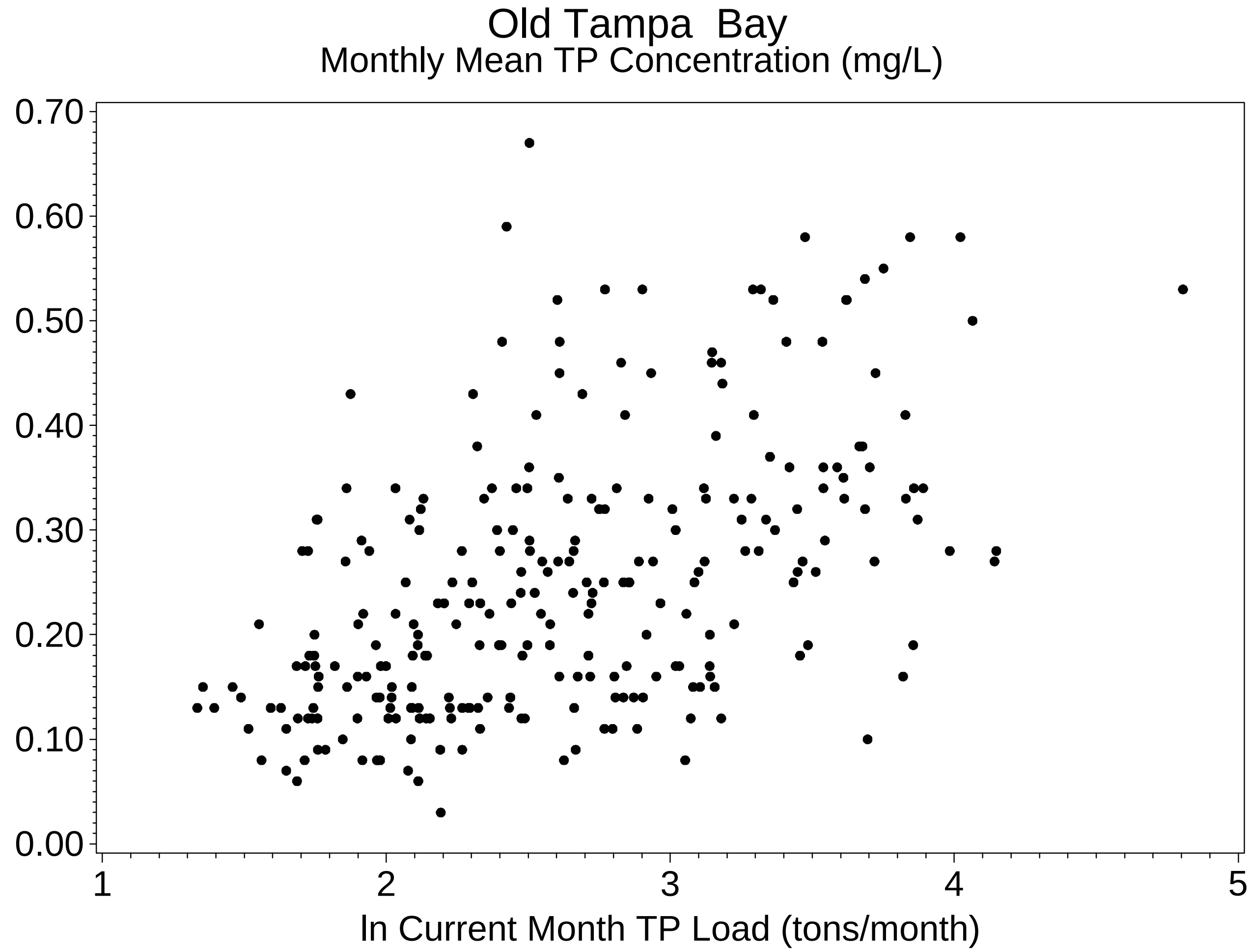

Hillsborough Bay
Monthly Mean TP Concentration (mg/L)
3.00
2.00
1.00
0.00
0
1000
2000
3000
4000
Cumulative Three-Month TP Load (tons)

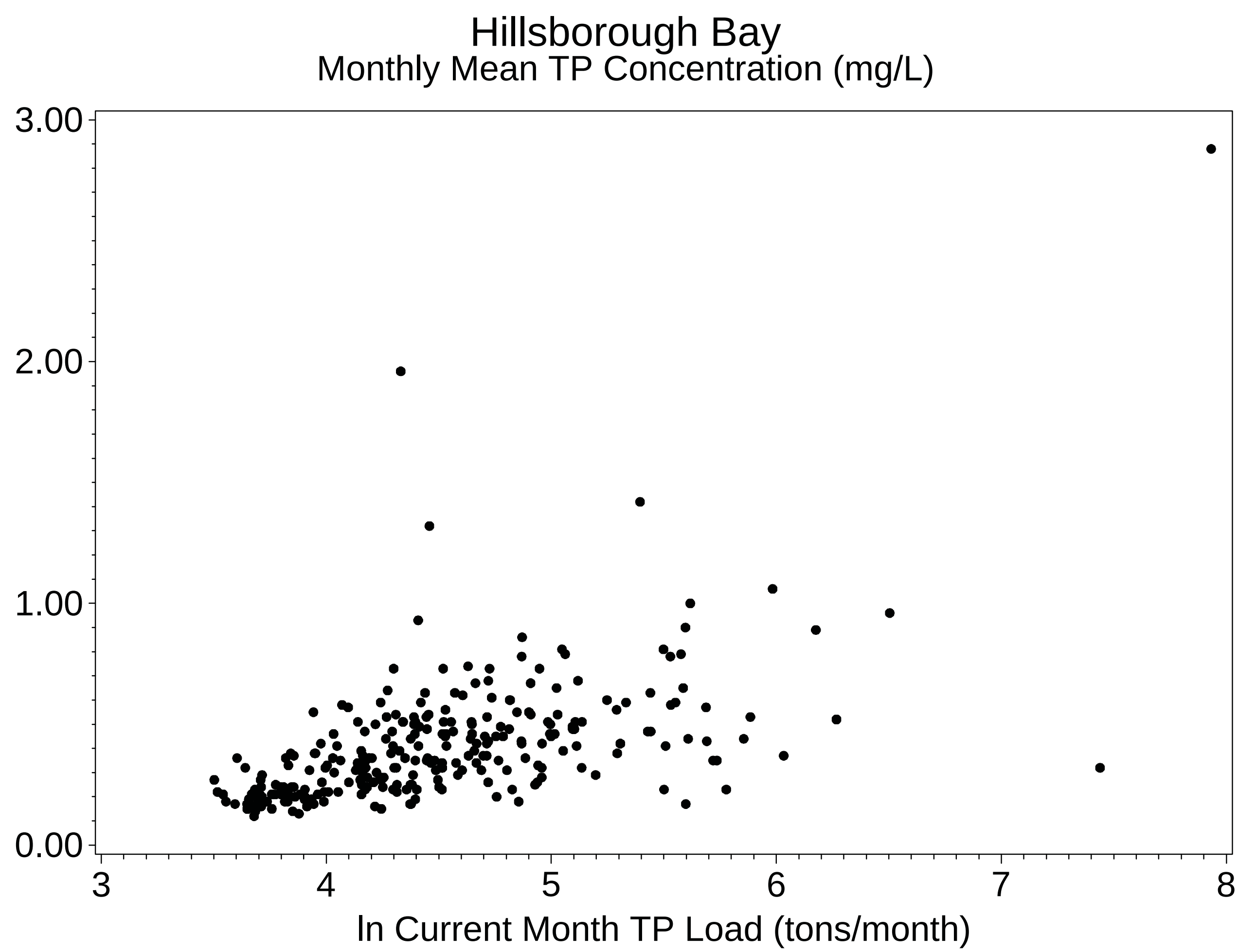


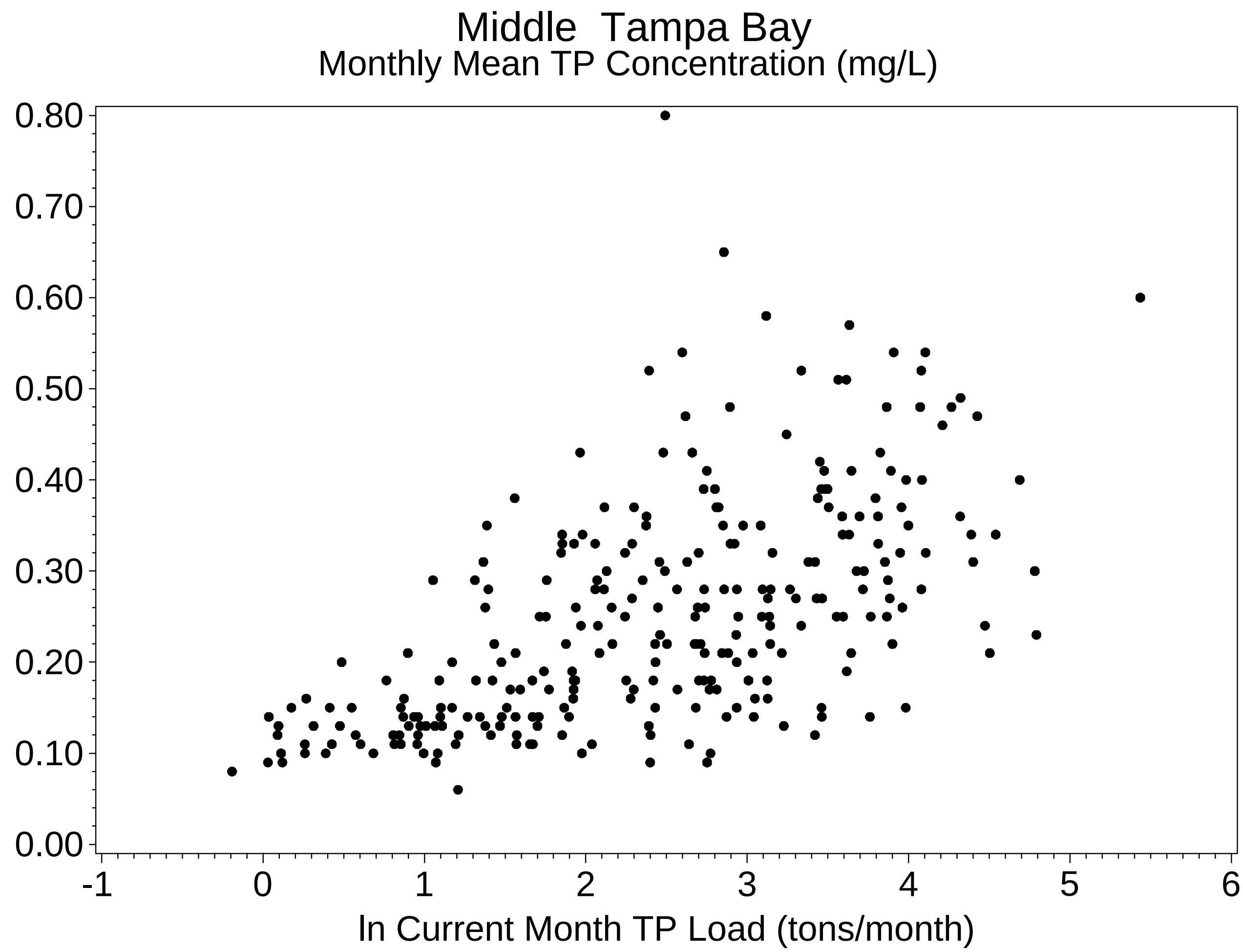
Middle Tampa Bay
Monthly Mean TP Concentration (mg/L)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
100
200
300
400
Cumulative Three-Month TP Load (tons)



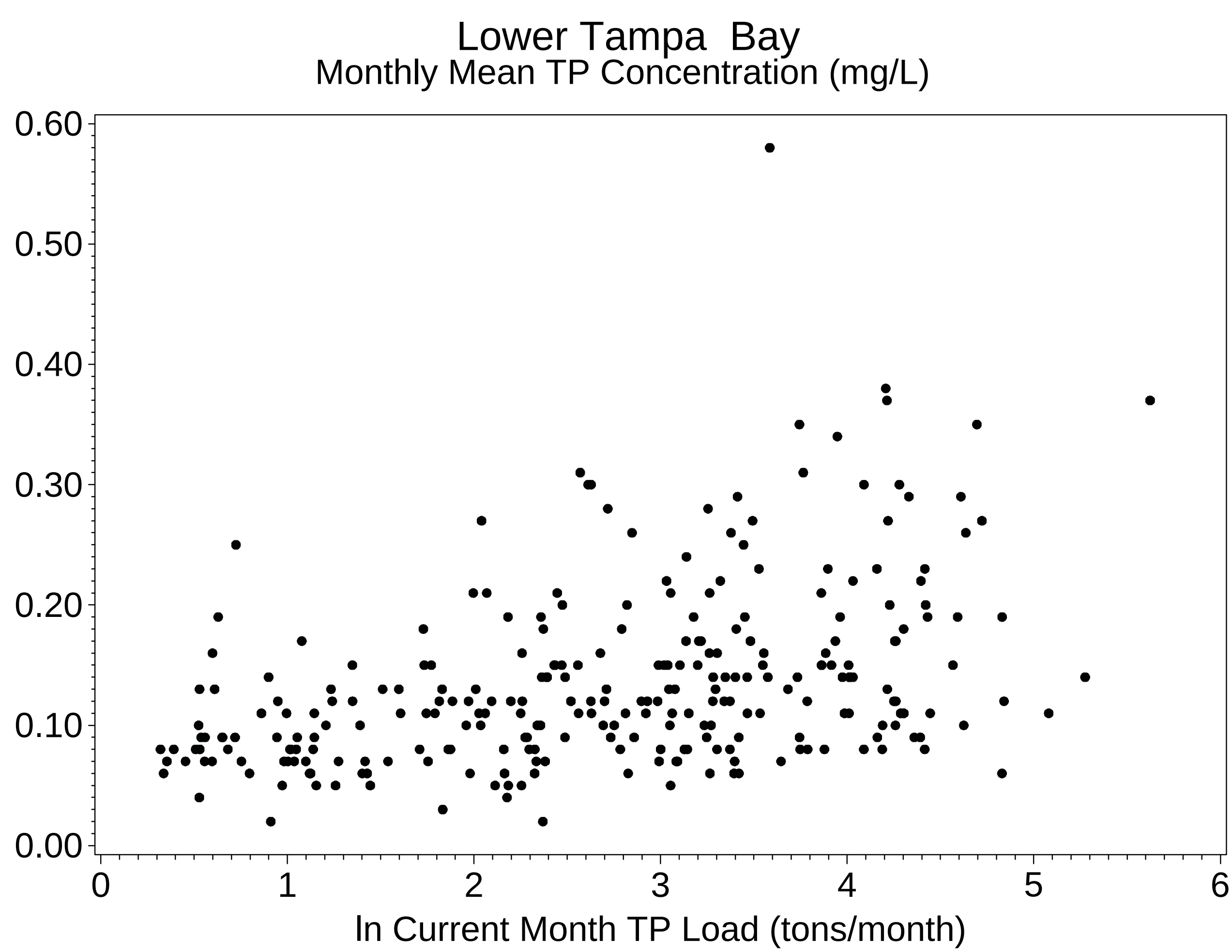
Lower Tampa Bay
Monthly Mean TP Concentration (mg/L)
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
100
200
300
400
500
Cumulative Three-Month TP Load (tons)


Old Tampa Bay
Monthly Mean TP Concentration (mg/L)
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
2
3
4
5
ln Current Month TP Load (tons/month)

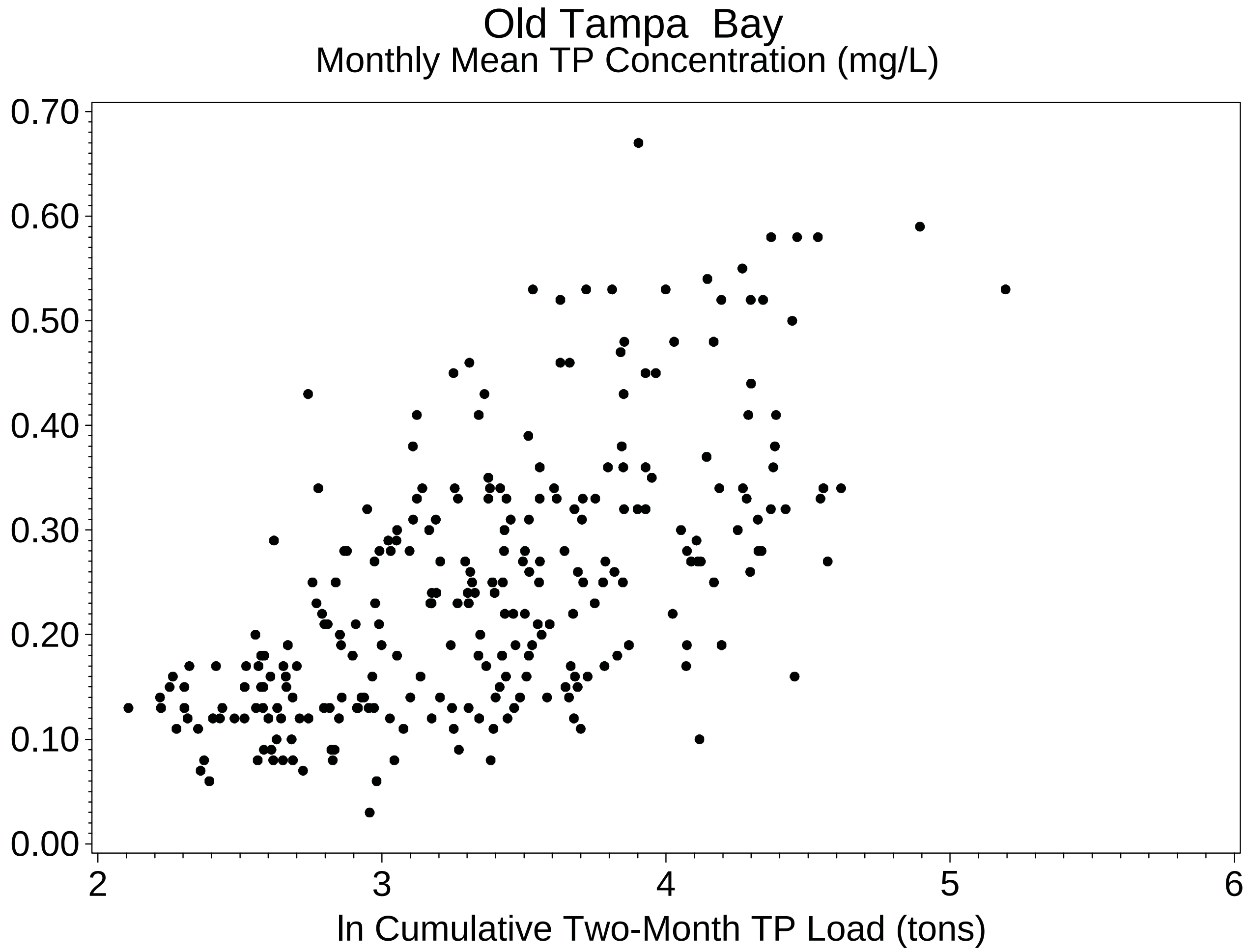

Hillsborough Bay
Monthly Mean TP Concentration (mg/L)
3.00
2.00
1.00
0.00
3
4
5
6
7
8
ln Current Month TP Load (tons/month)



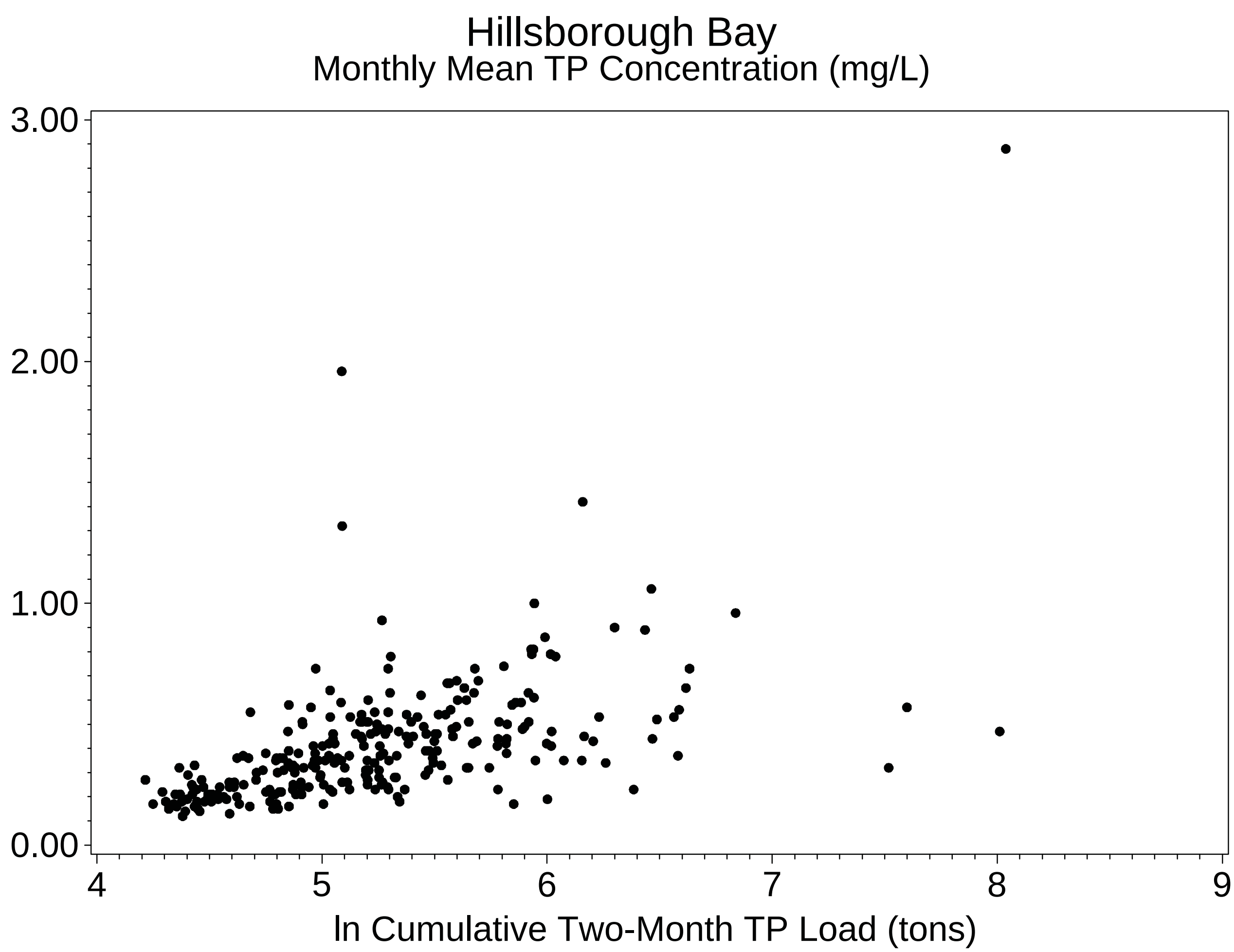
Middle Tampa Bay
Monthly Mean TP Concentration (mg/L)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-1
0
1
2
3
4
5
6
ln Current Month TP Load (tons/month)



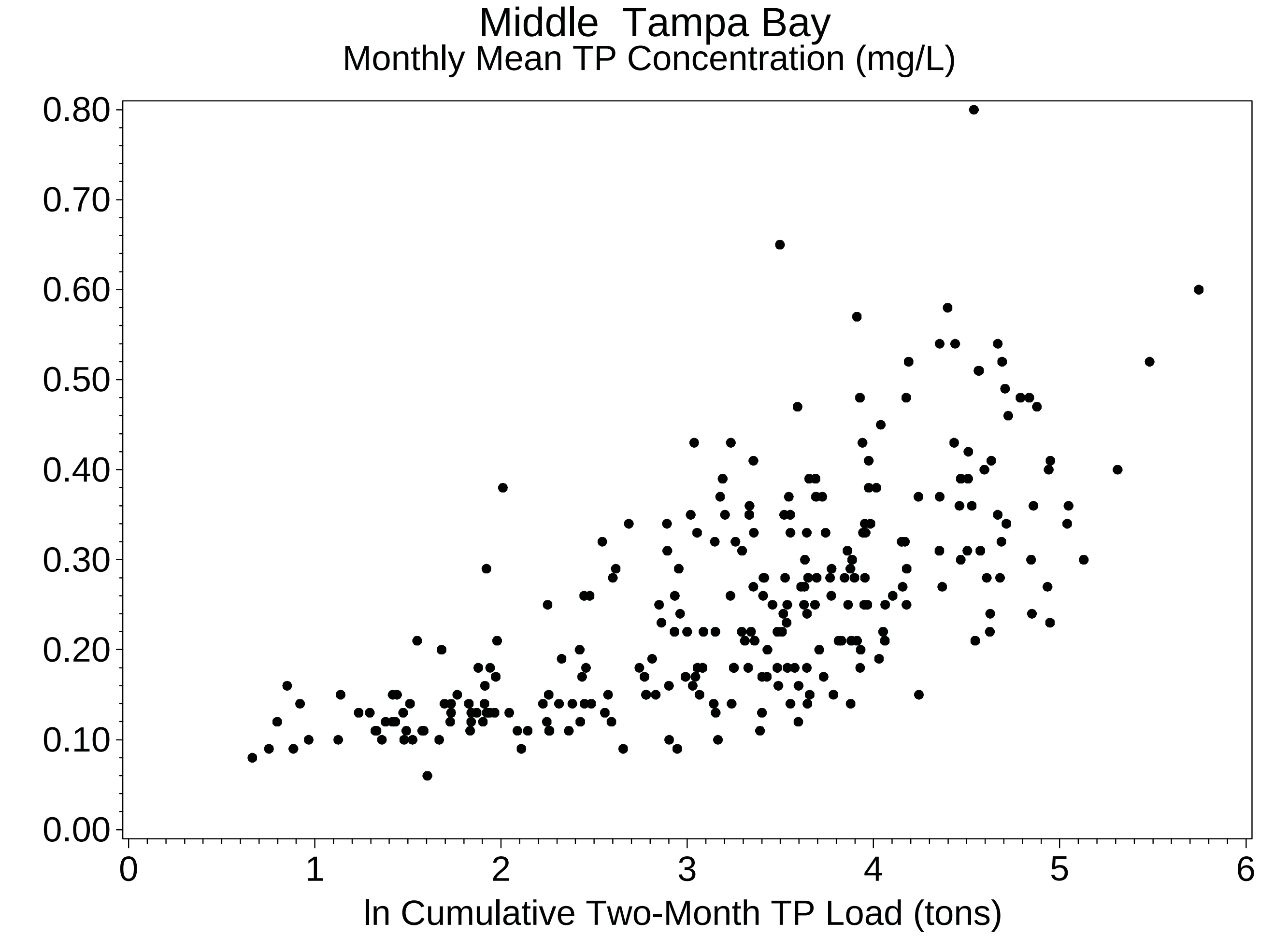
Lower Tampa Bay
Monthly Mean TP Concentration (mg/L)
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
1
2
3
4
5
6
ln Current Month TP Load (tons/month)



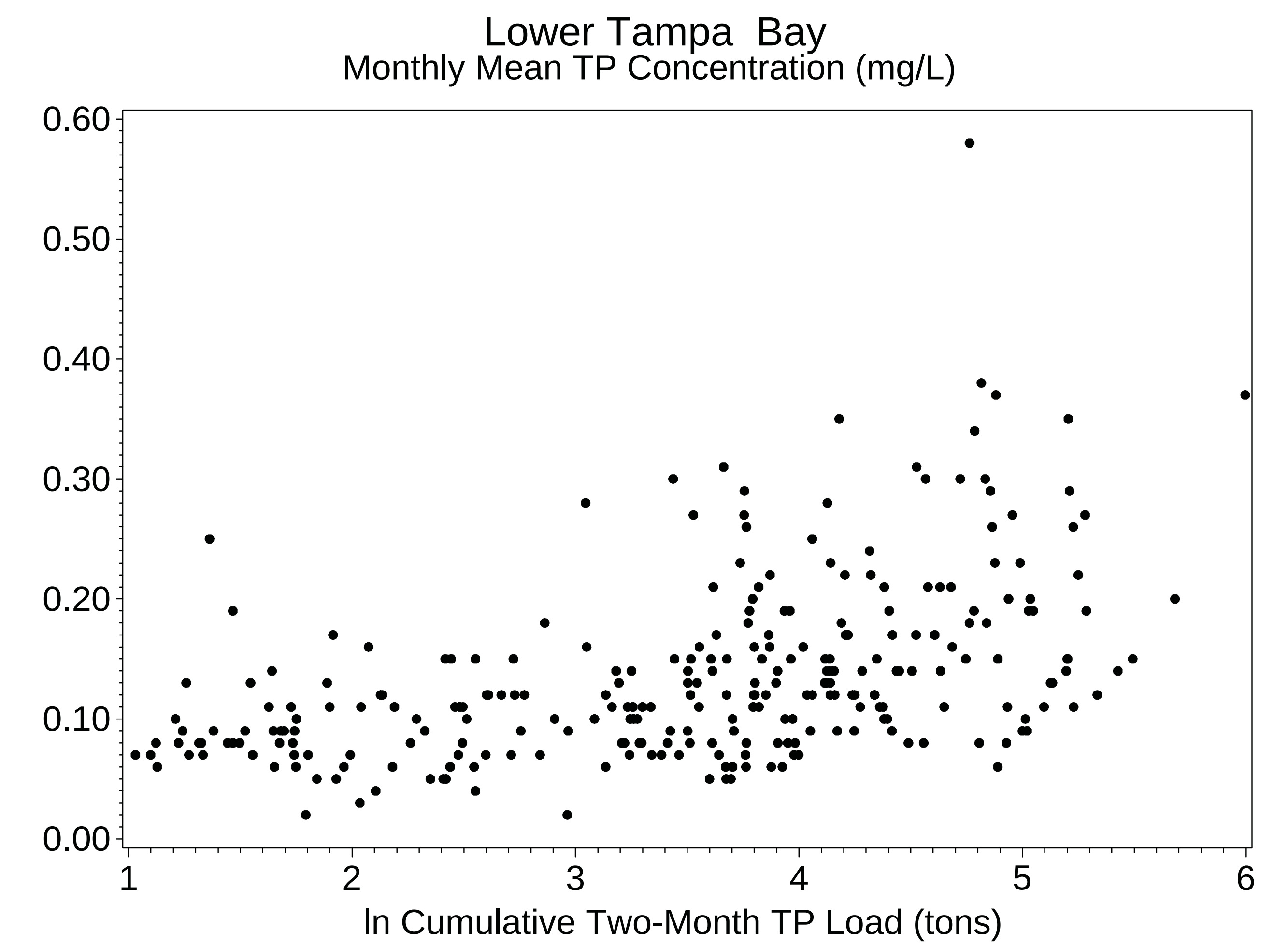
Old Tampa Bay
Monthly Mean TP Concentration (mg/L)
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
2
3
4
5
6
ln Cumulative Two-Month TP Load (tons)



Hillsborough Bay
Monthly Mean TP Concentration (mg/L)
3.00
2.00
1.00
0.00
4
5
6
7
8
9
ln Cumulative Two-Month TP Load (tons)

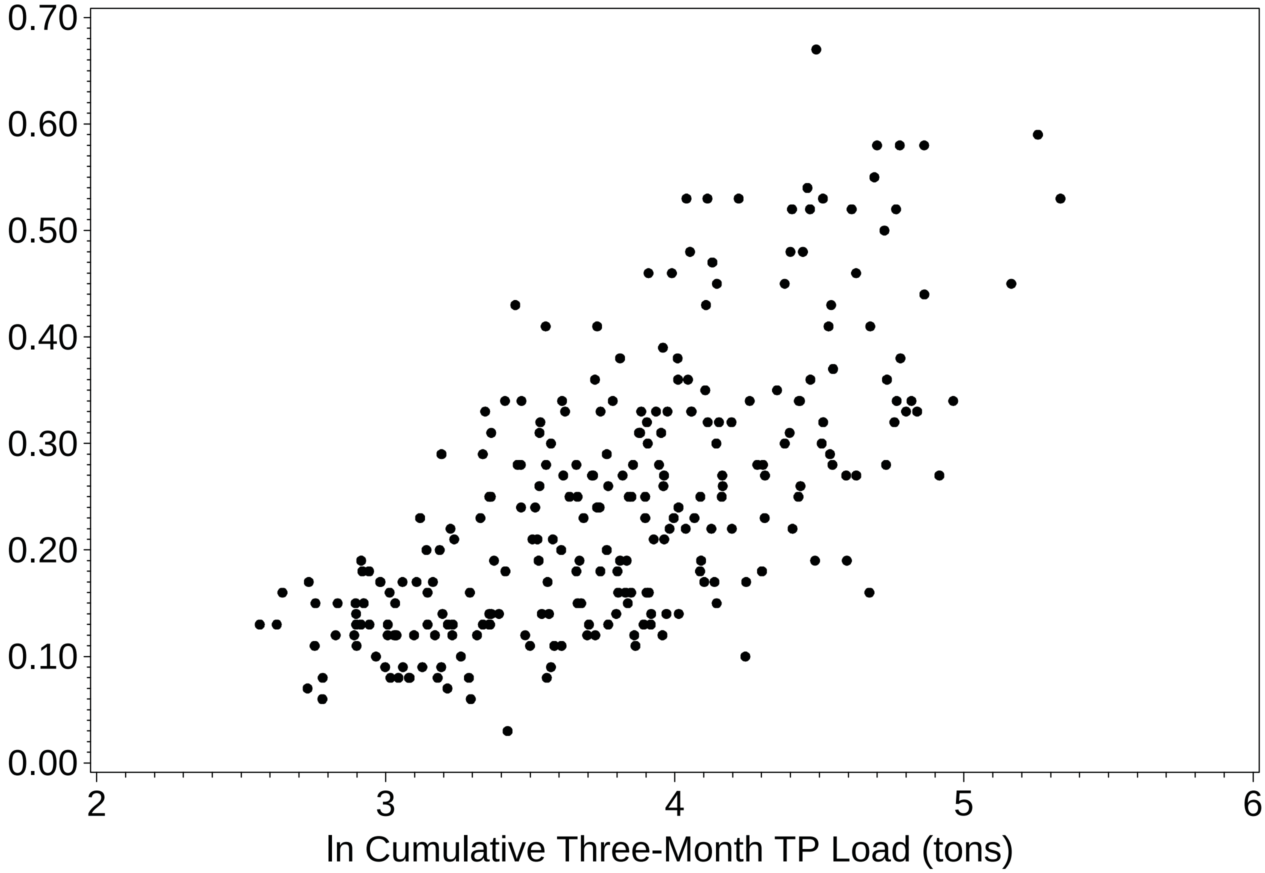


Middle Tampa Bay
Monthly Mean TP Concentration (mg/L)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
1
2
3
4
5
6
ln Cumulative Two-Month TP Load (tons)

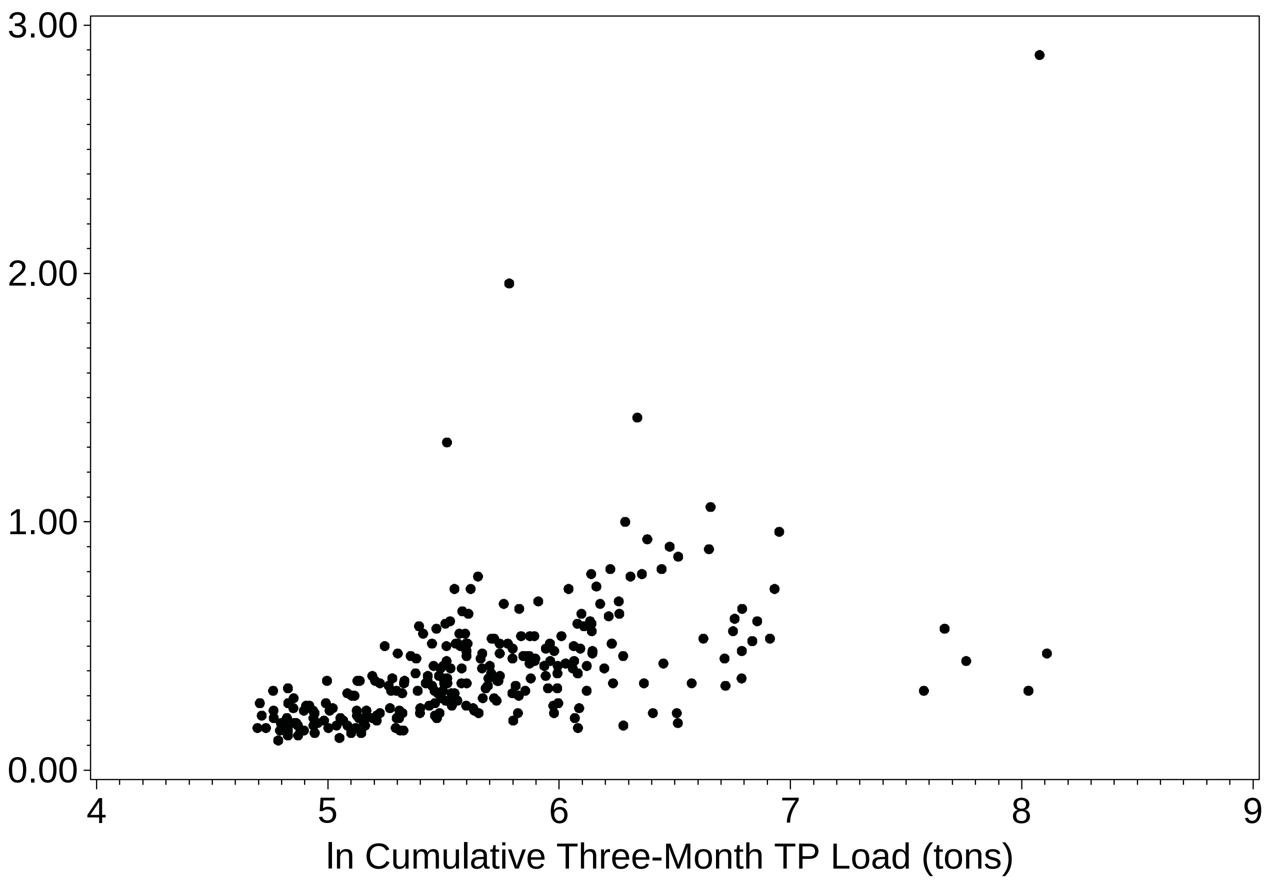


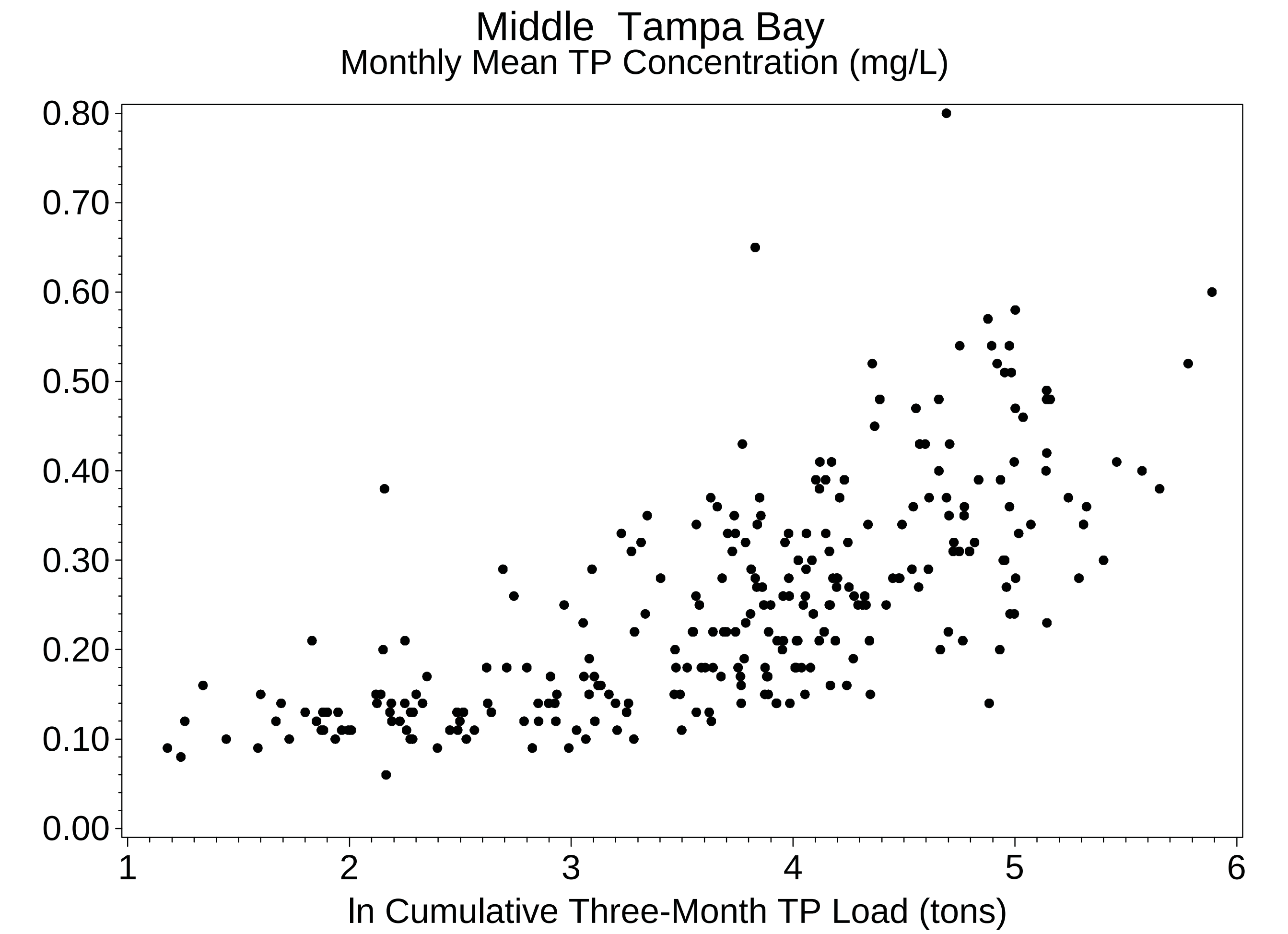
Lower Tampa Bay
Monthly Mean TP Concentration (mg/L)
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
2
3
4
5
6
ln Cumulative Two-Month TP Load (tons)

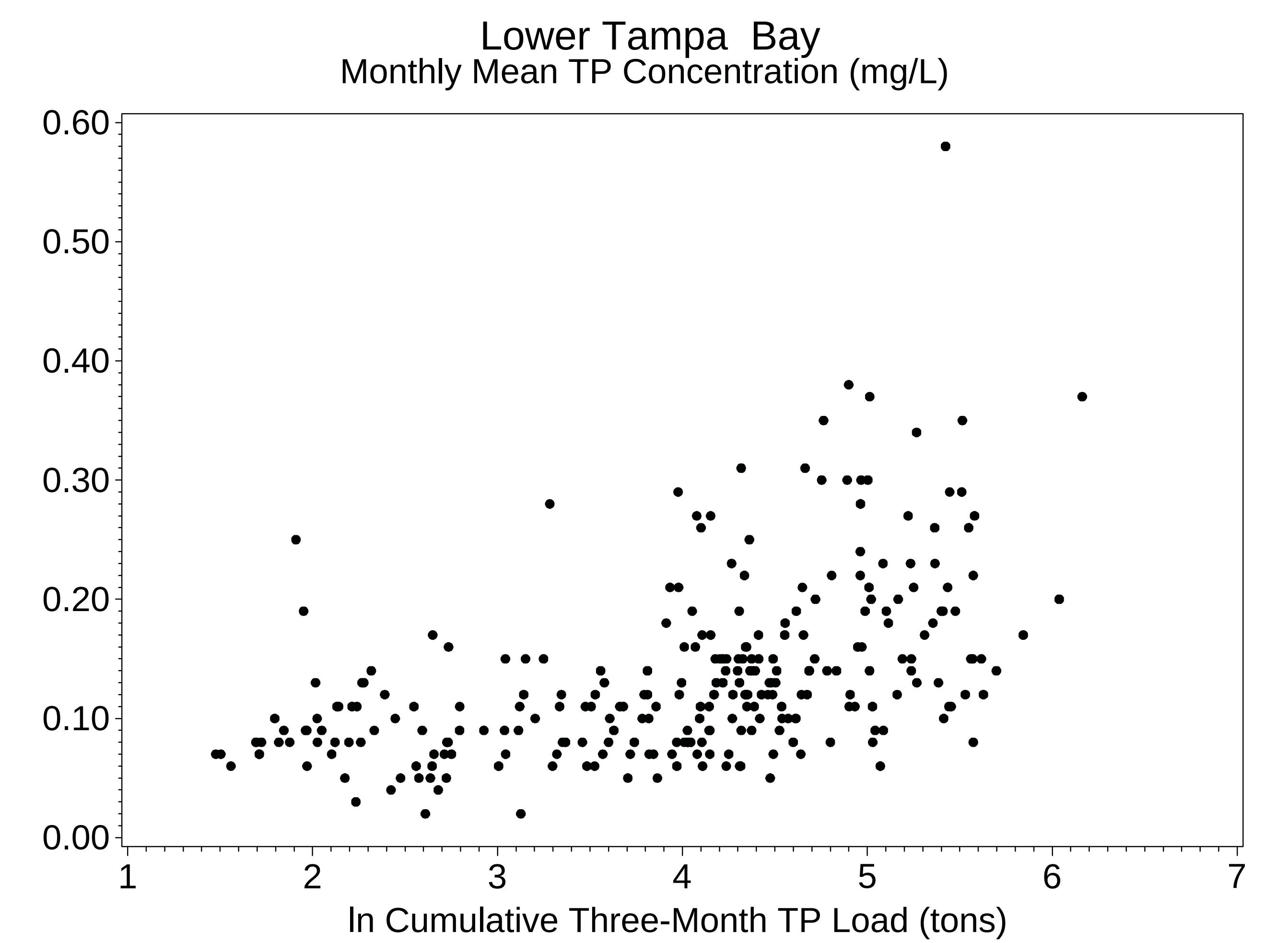
Old Tampa Bay
Monthly Mean TP Concentration (mg/L)



Hillsborough Bay
Monthly Mean TP Concentration (mg/L)

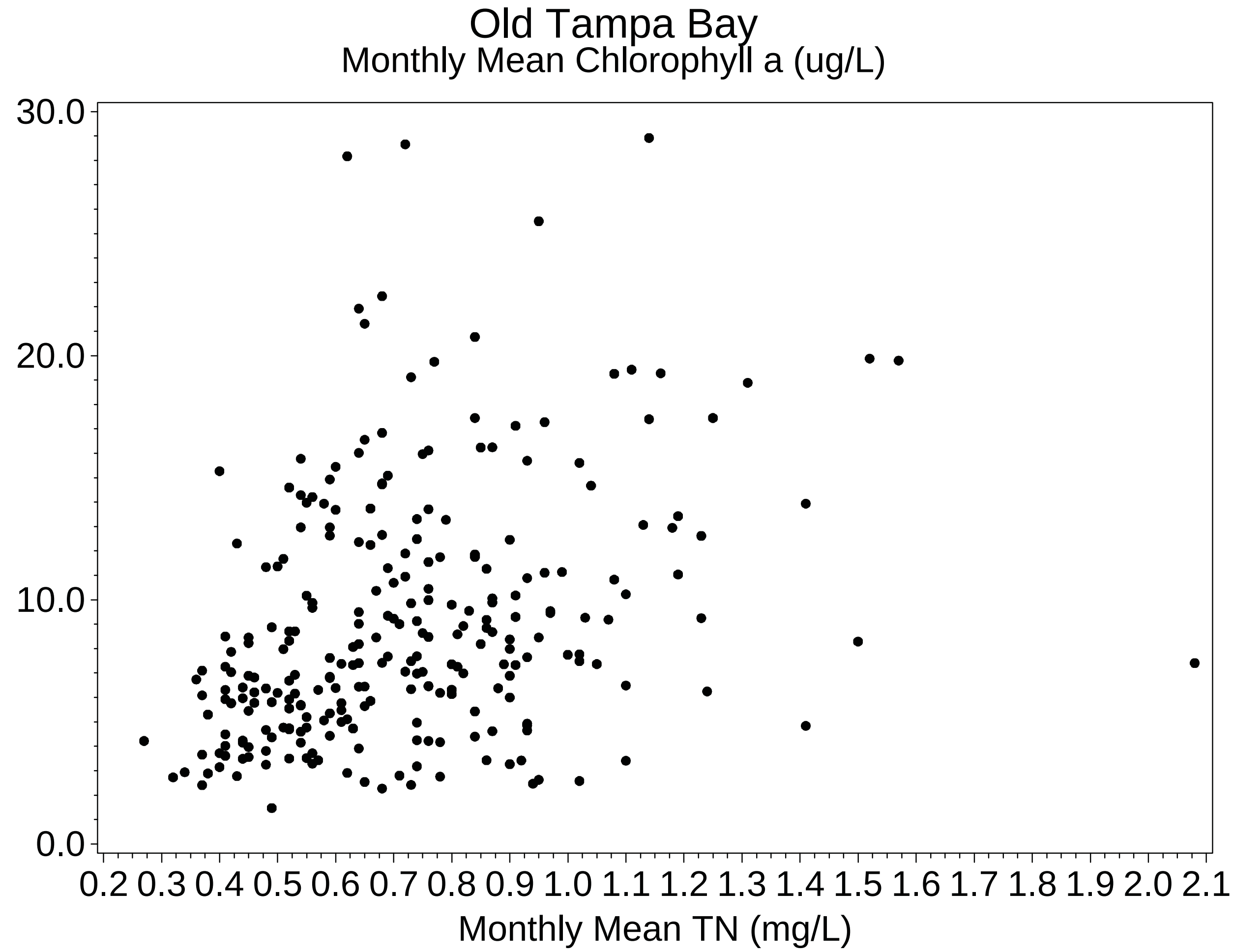


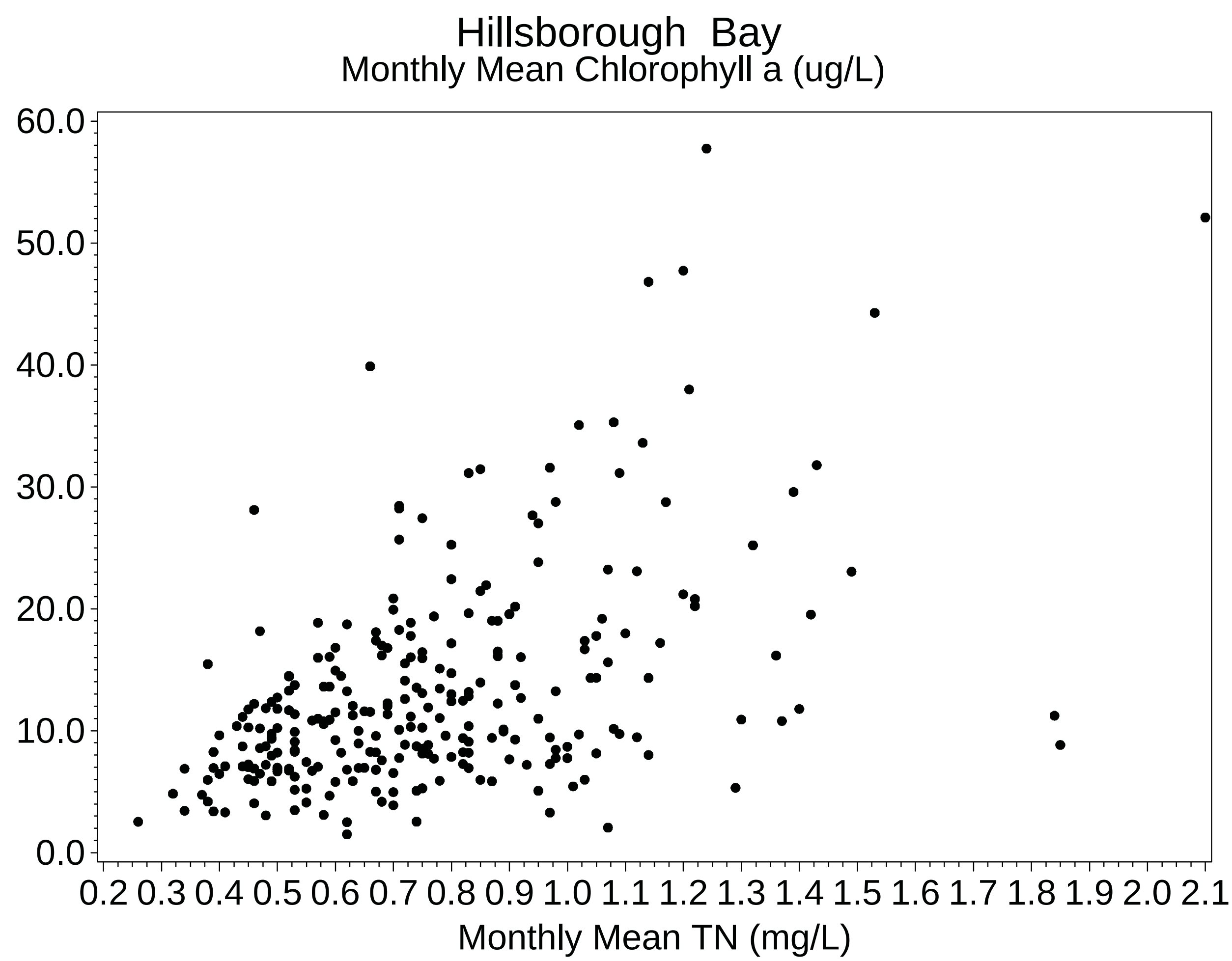

Middle Tampa Bay
Monthly Mean TP Concentration (mg/L)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
2
3
4
5
6
ln Cumulative Three-Month TP Load (tons)

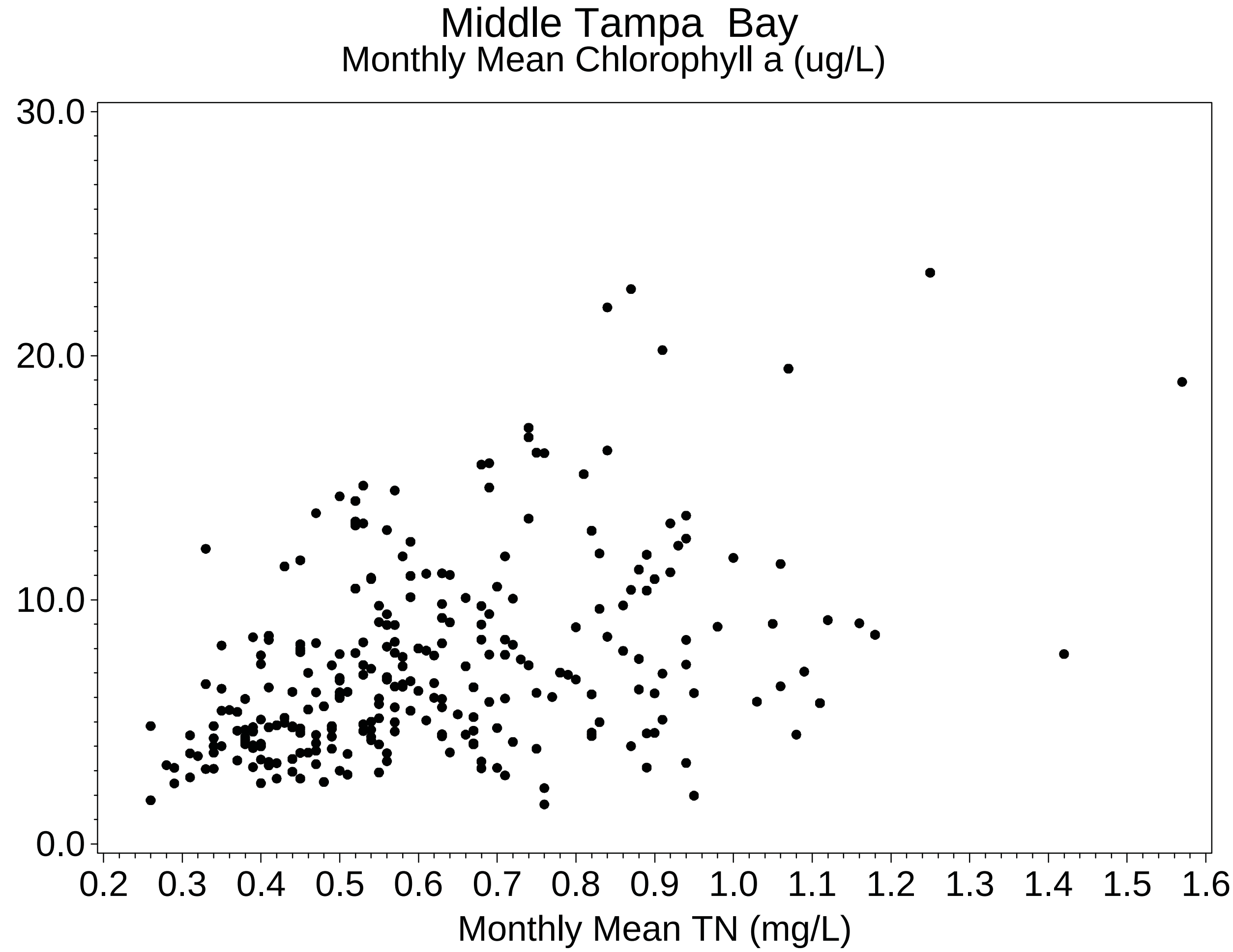

Lower Tampa Bay
Monthly Mean TP Concentration (mg/L)
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
2
3
4
5
6
7
ln Cumulative Three-Month TP Load (tons)

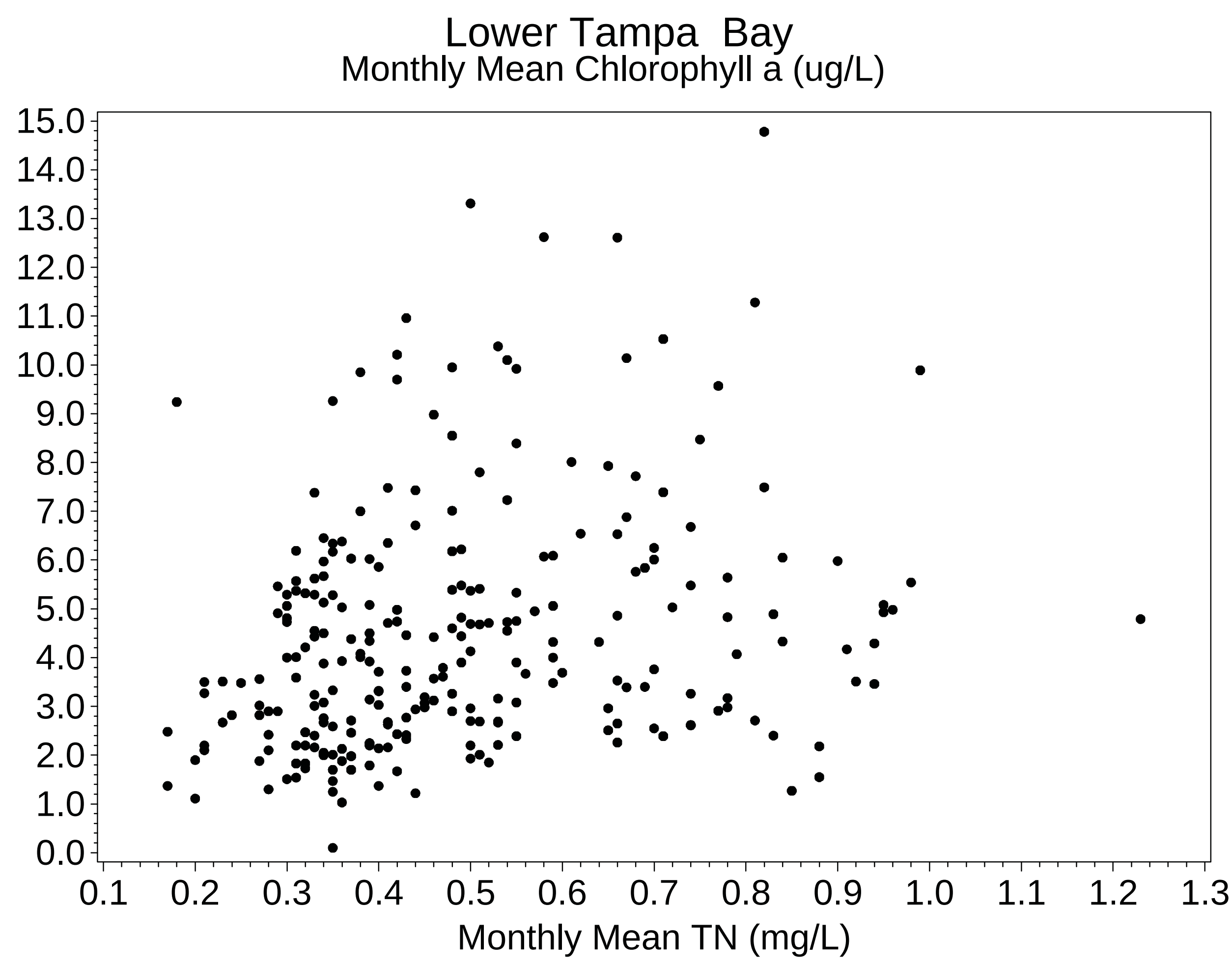
Attachment 5

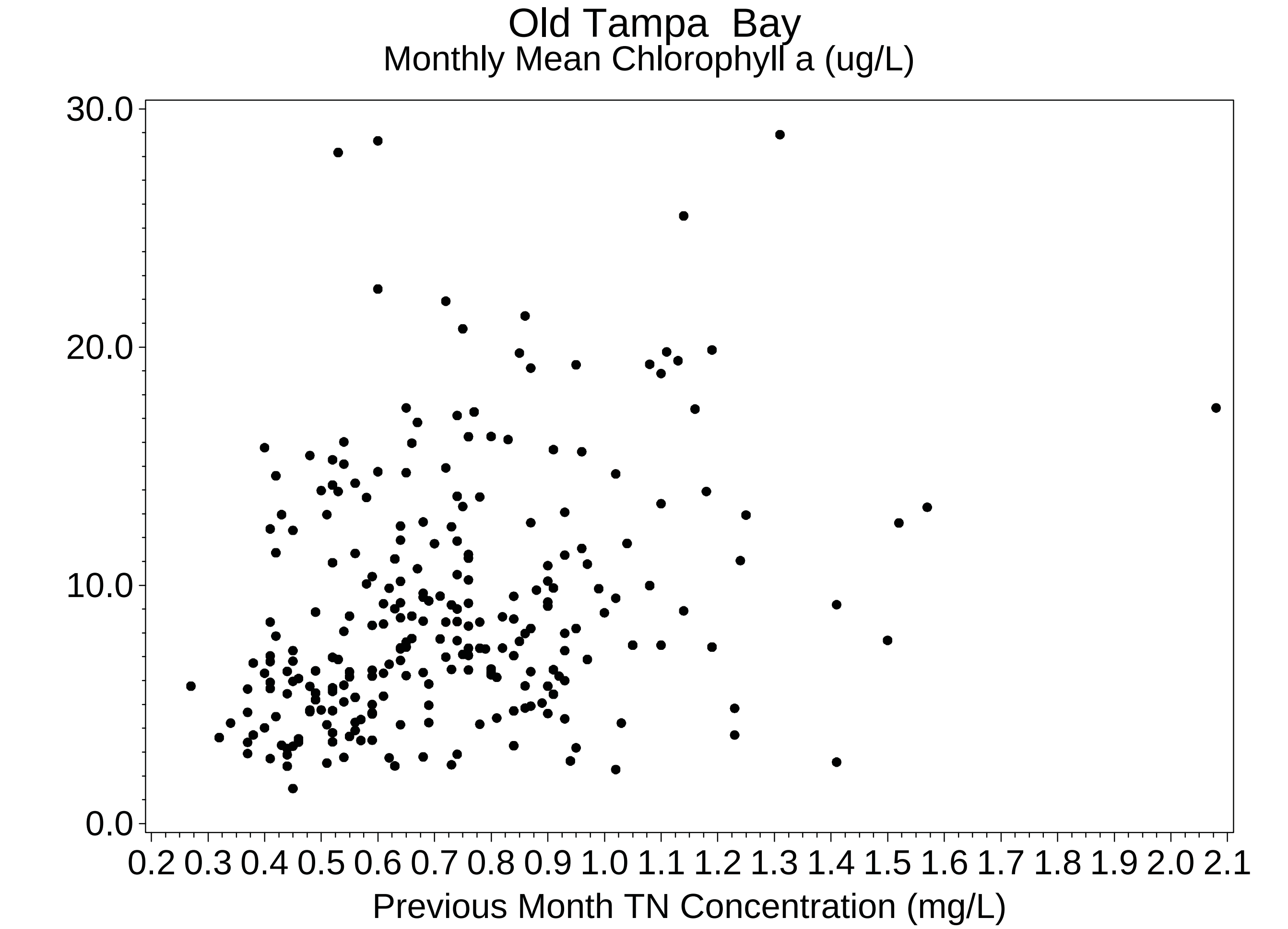
Monthly Chlorophyll *a* Concentrations and Monthly TN Concentrations

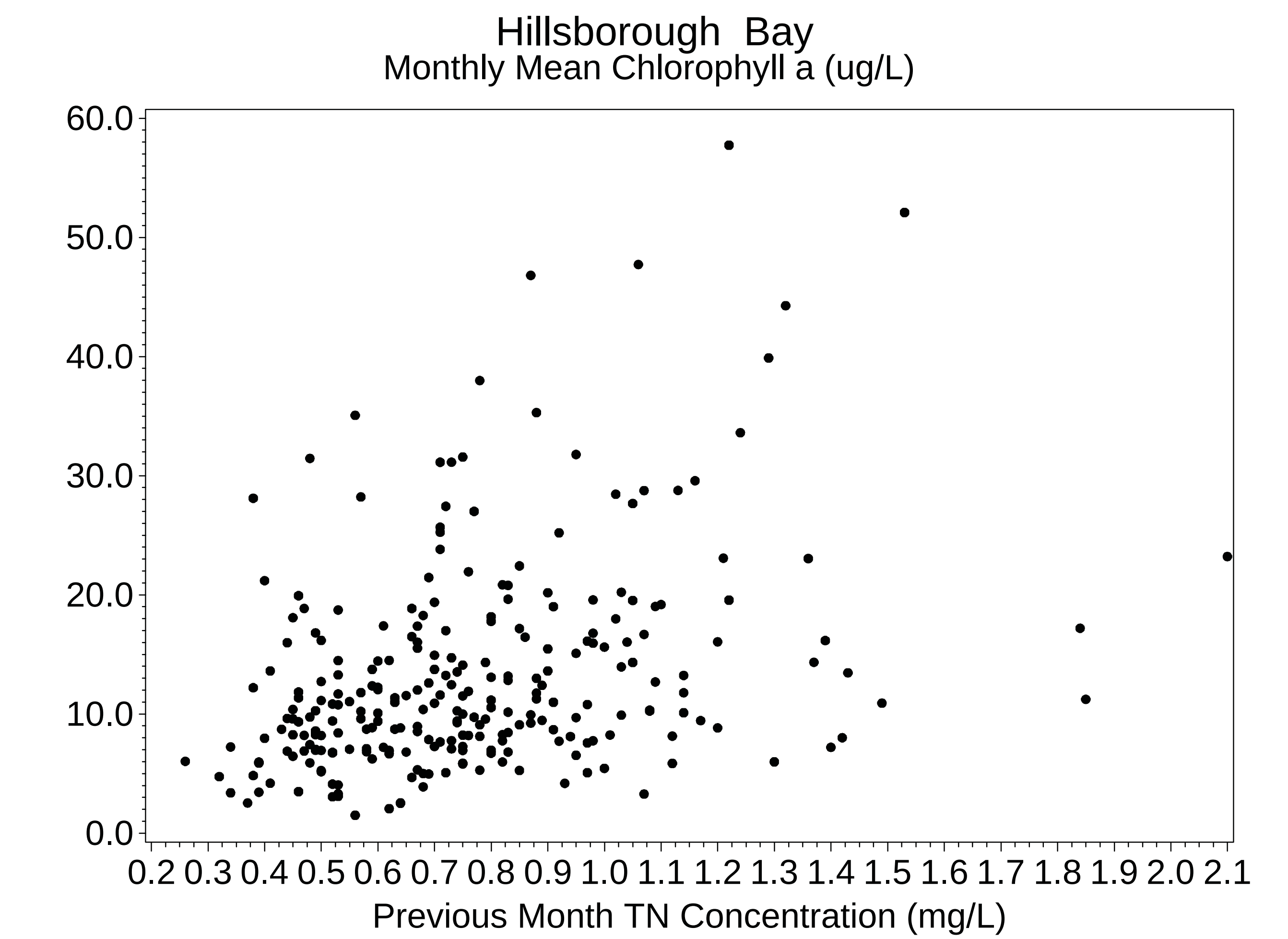

Old Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
30.0
20.0
10.0
0.0
0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1
Monthly Mean TN (mg/L)

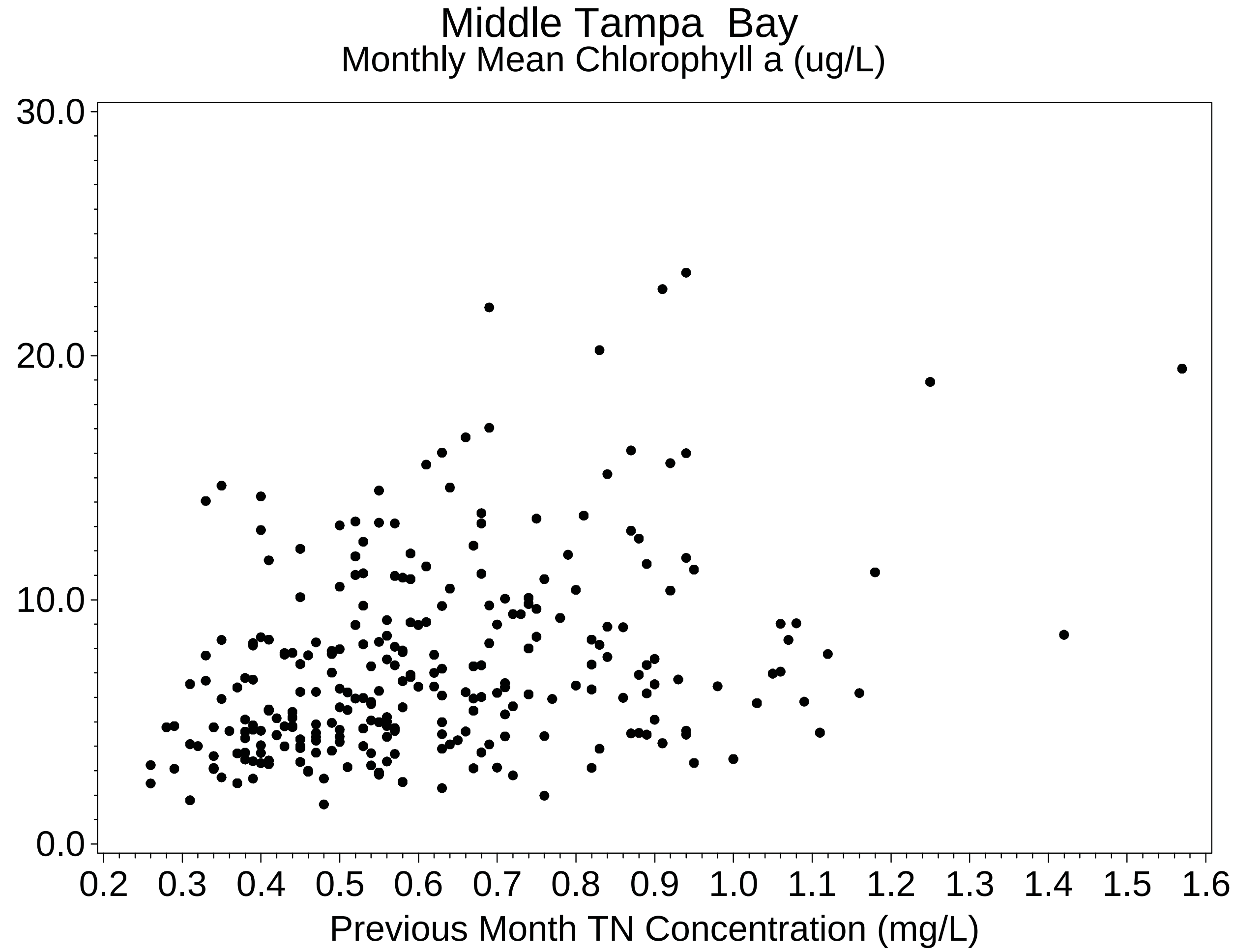

Hillsborough Bay
Monthly Mean Chlorophyll a (ug/L)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1
Monthly Mean TN (mg/L)

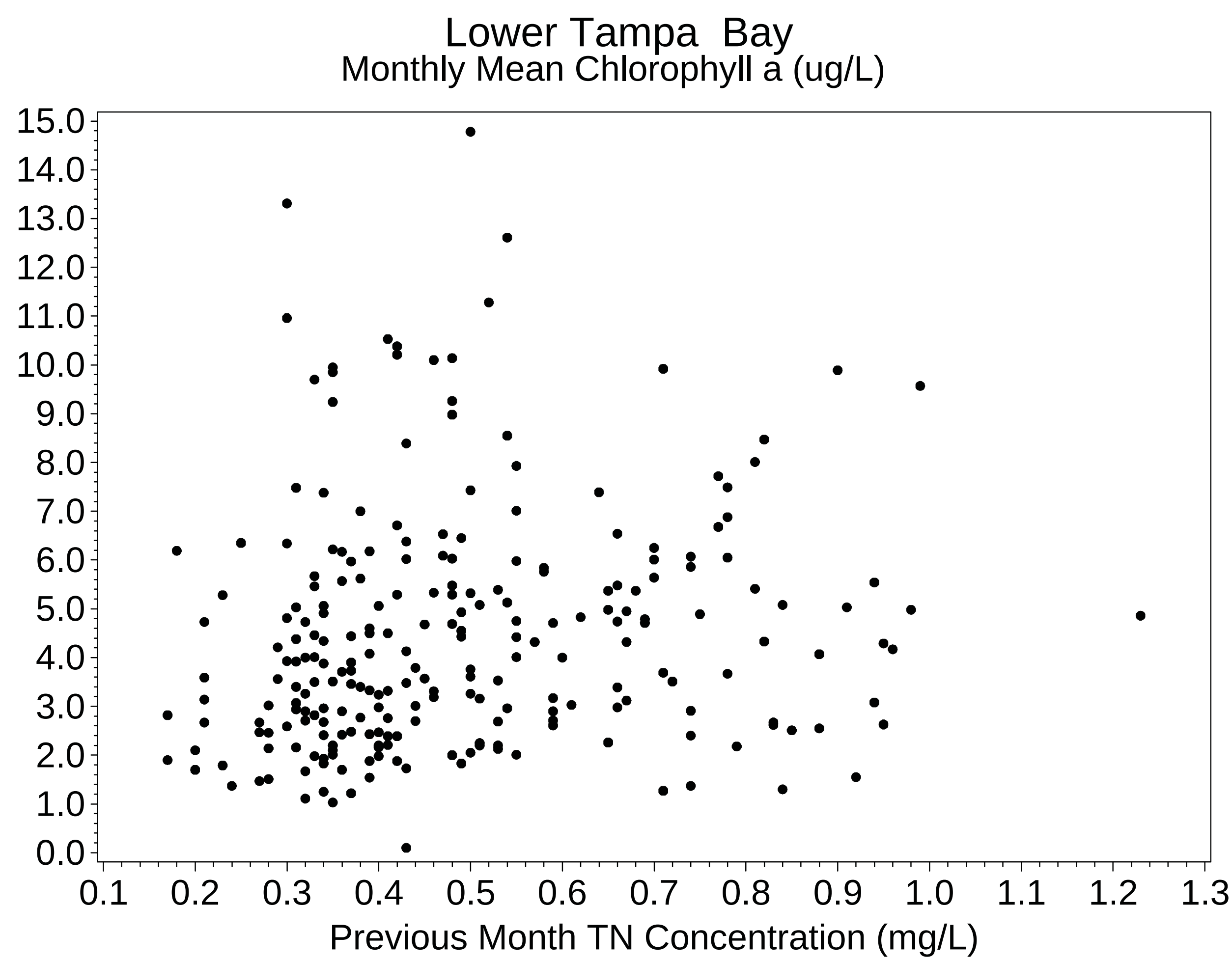

Middle Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
30.0
20.0
10.0
0.0
0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6
Monthly Mean TN (mg/L)

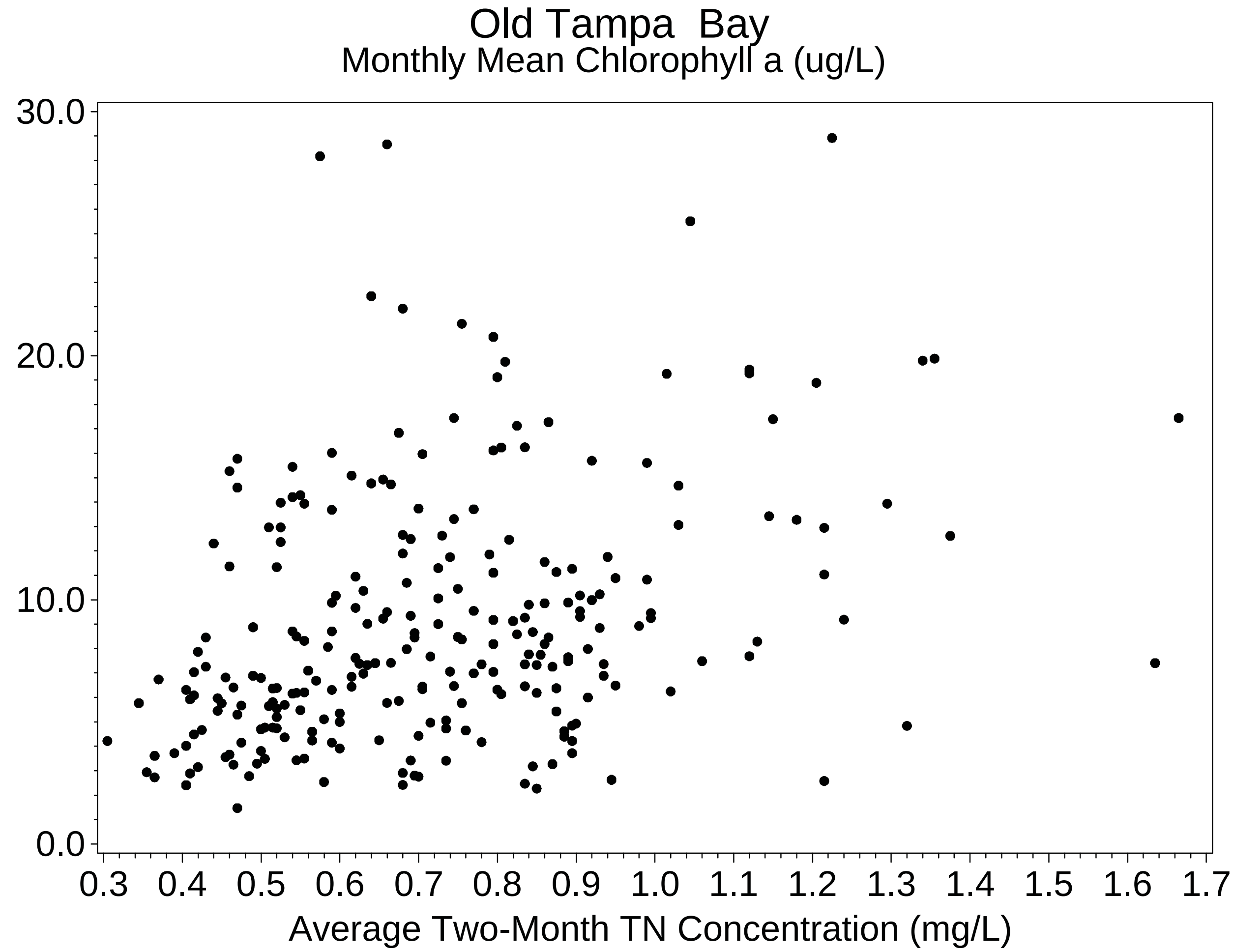

Lower Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3
Monthly Mean TN (mg/L)

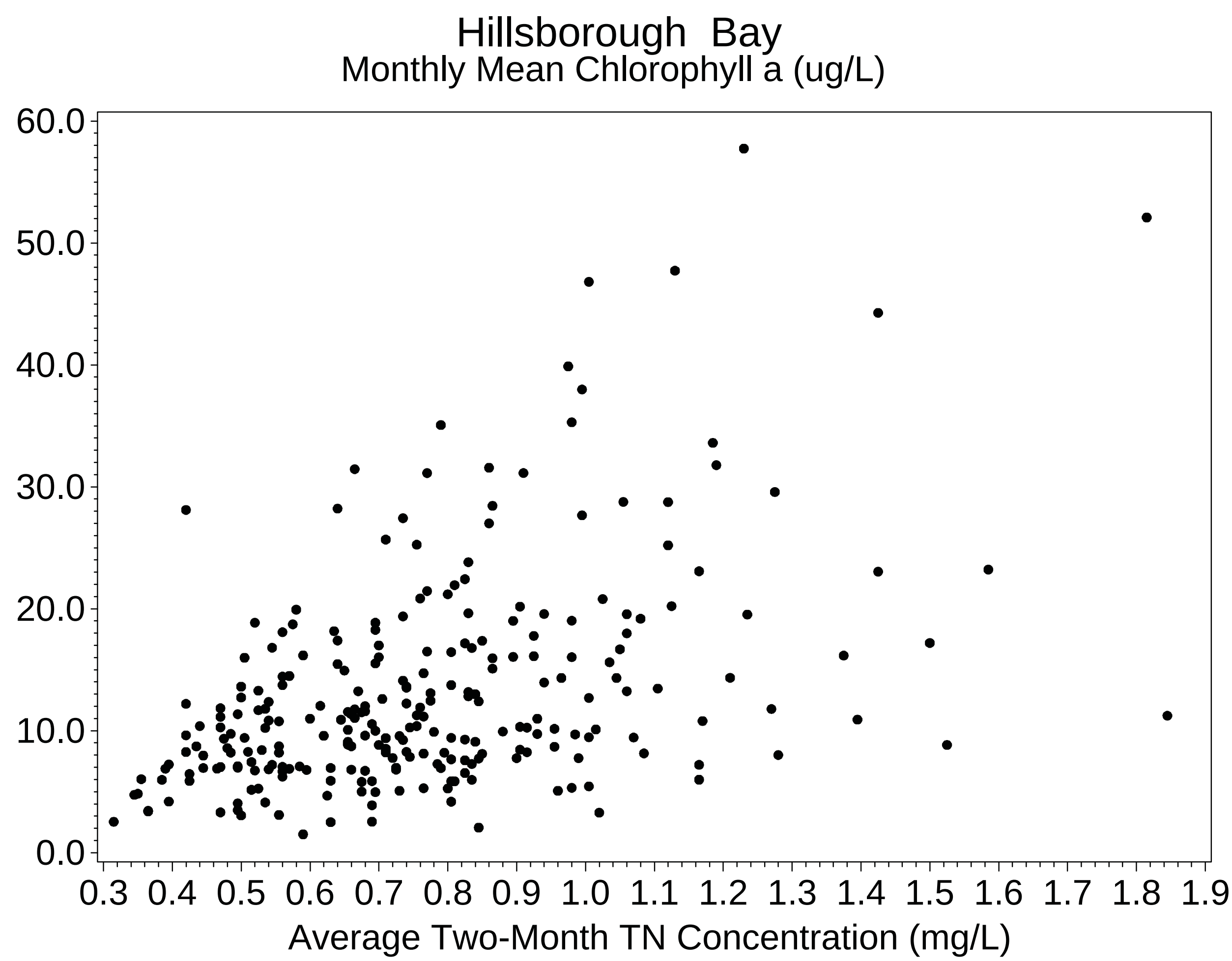

Old Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
30.0
20.0
10.0
0.0
0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1
Previous Month TN Concentration (mg/L)

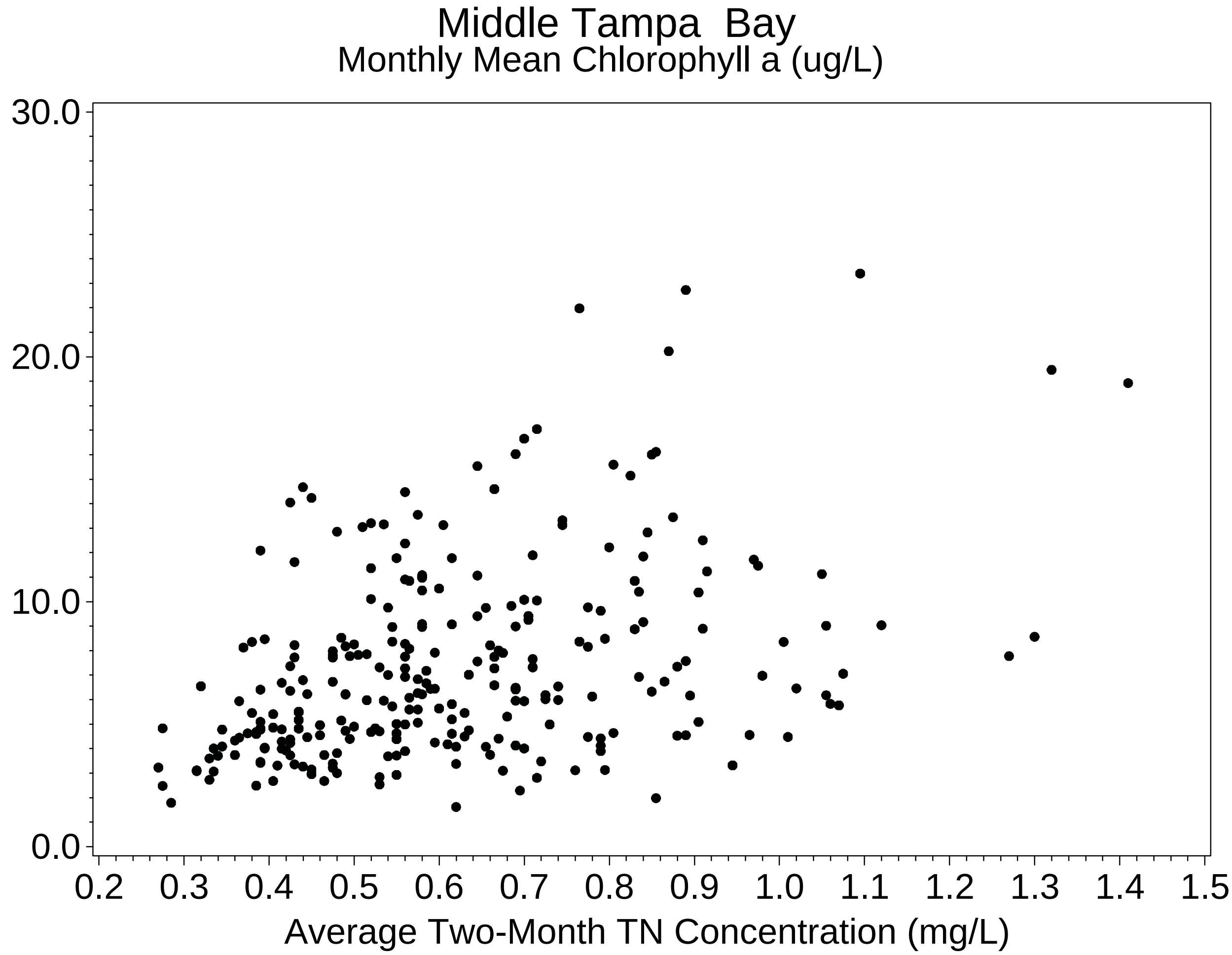

Hillsborough Bay
Monthly Mean Chlorophyll a (ug/L)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1
Previous Month TN Concentration (mg/L)

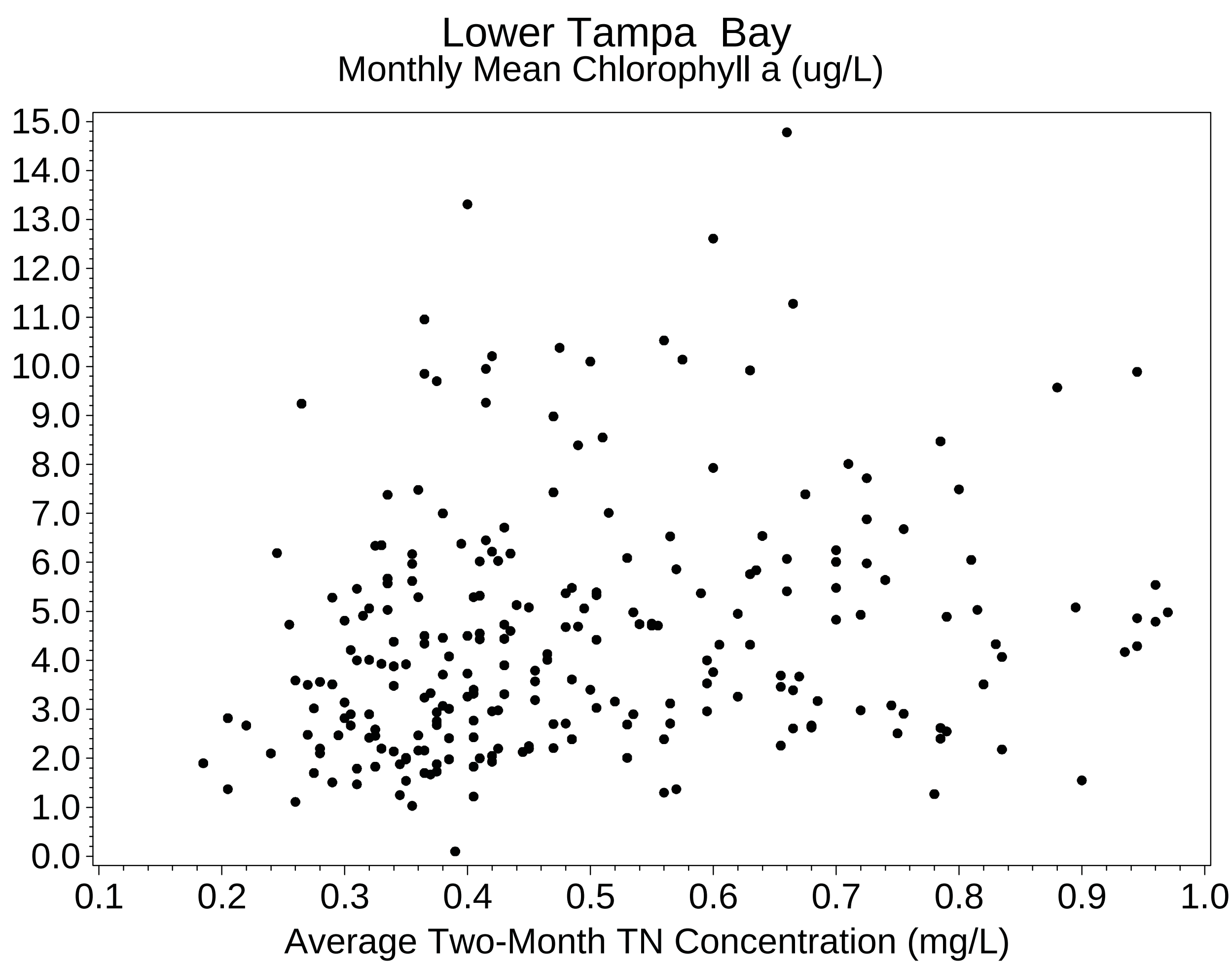

Middle Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
30.0
20.0
10.0
0.0
0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6
Previous Month TN Concentration (mg/L)

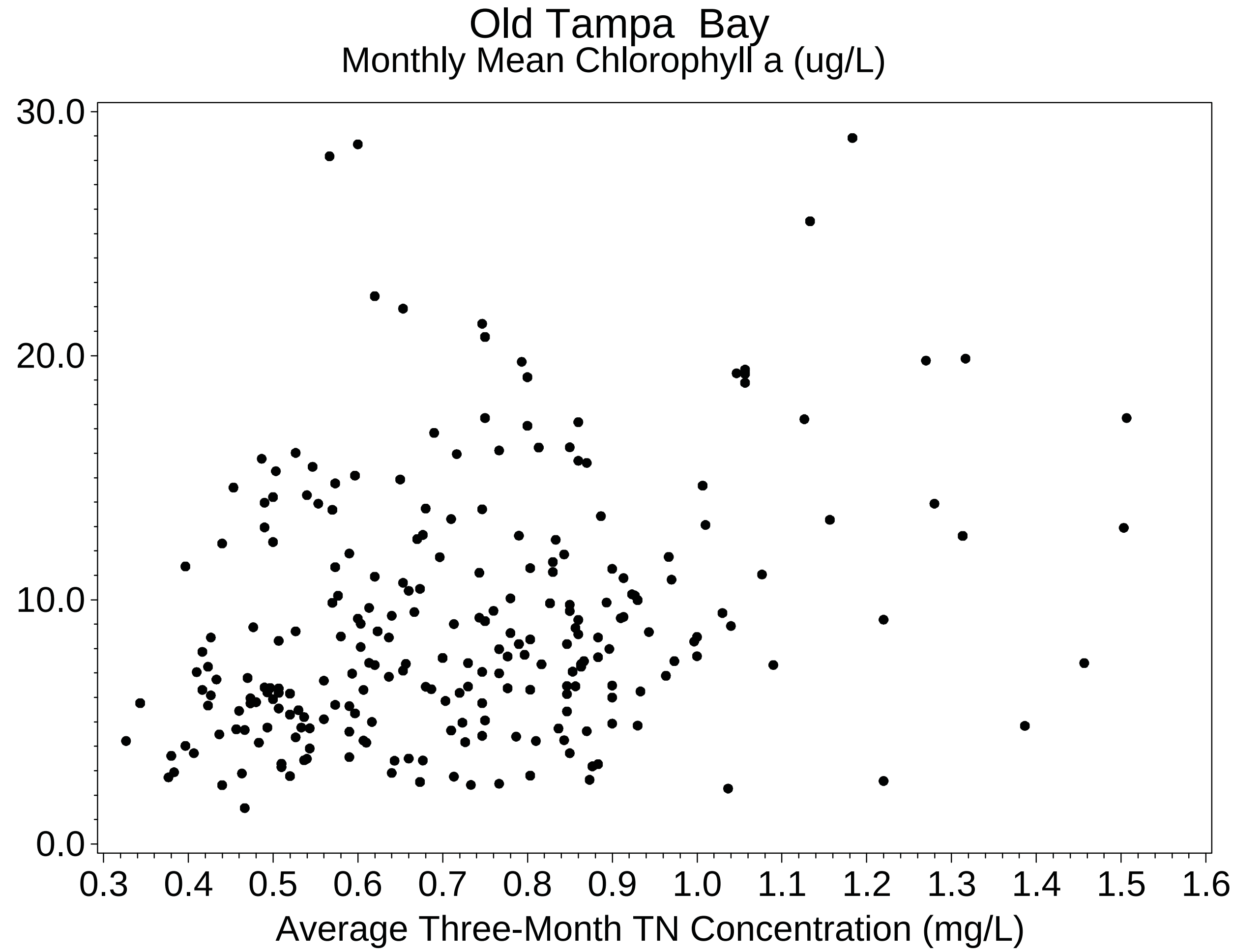

Lower Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3
Previous Month TN Concentration (mg/L)


Old Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
30.0
20.0
10.0
0.0
0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7
Average Two-Month TN Concentration (mg/L)

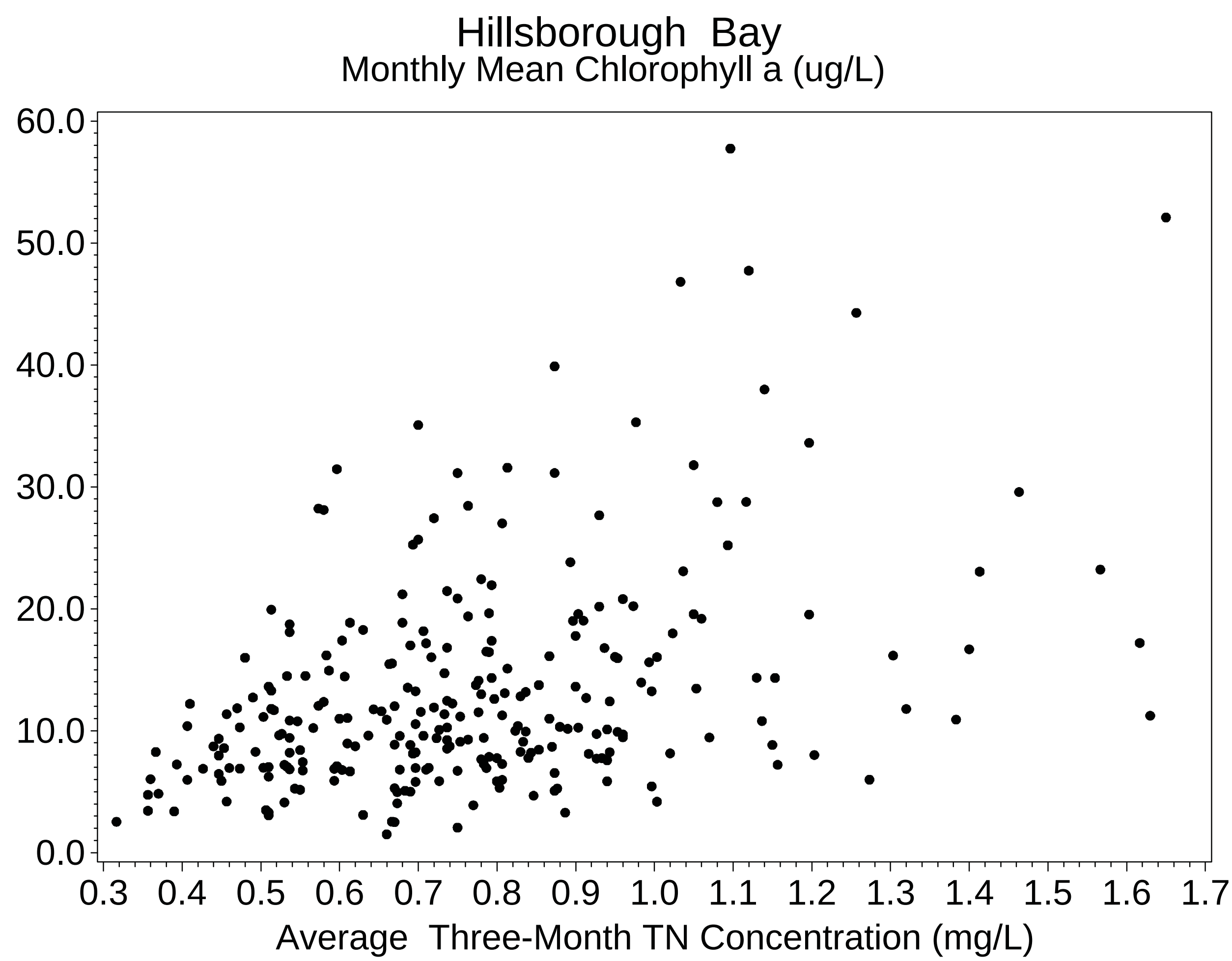

Hillsborough Bay
Monthly Mean Chlorophyll a (ug/L)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9
Average Two-Month TN Concentration (mg/L)


Middle Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
30.0
20.0
10.0
0.0
0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5
Average Two-Month TN Concentration (mg/L)

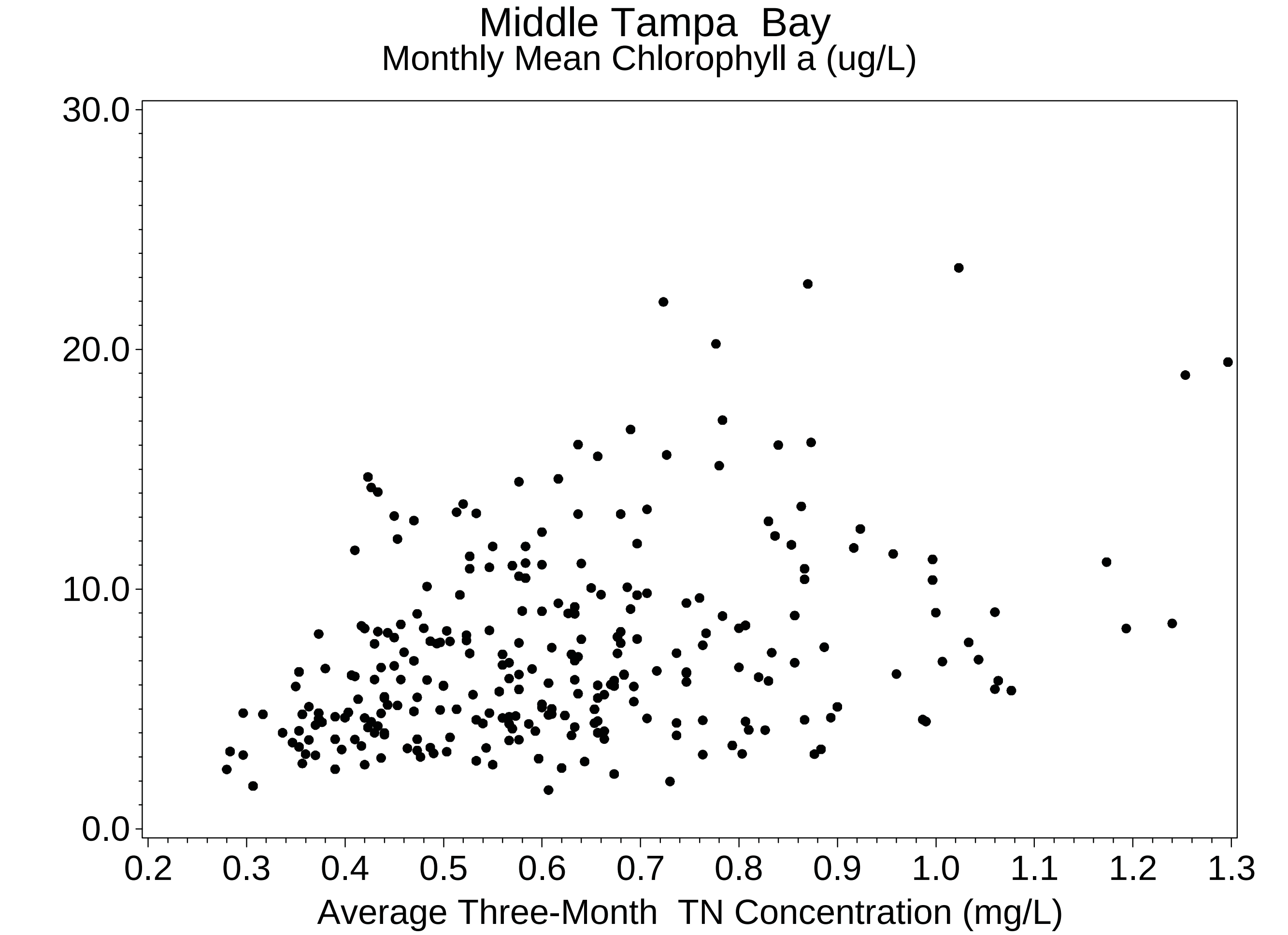

Lower Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Average Two-Month TN Concentration (mg/L)

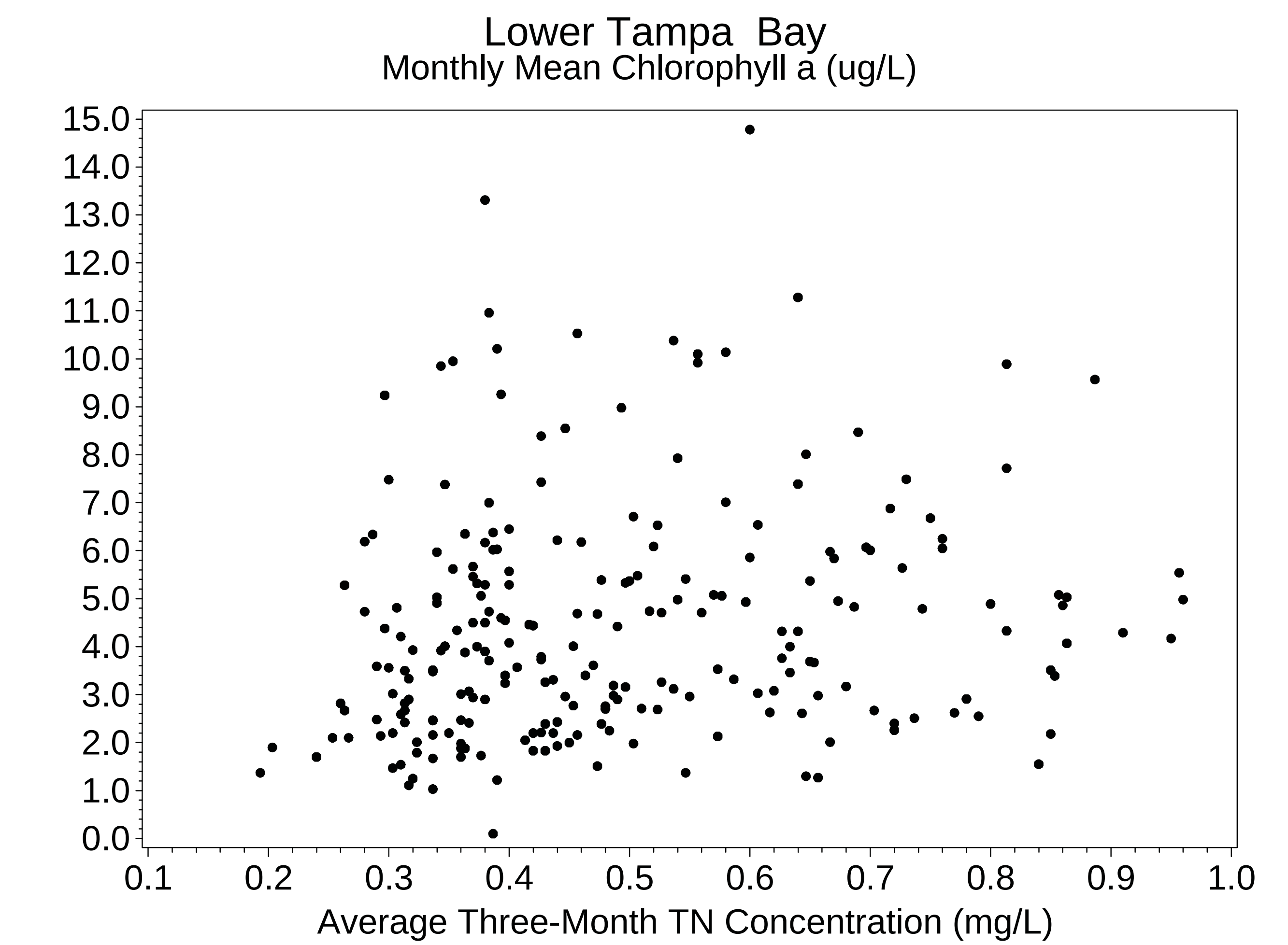


Old Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
30.0
20.0
10.0
0.0
0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6
Average Three-Month TN Concentration (mg/L)



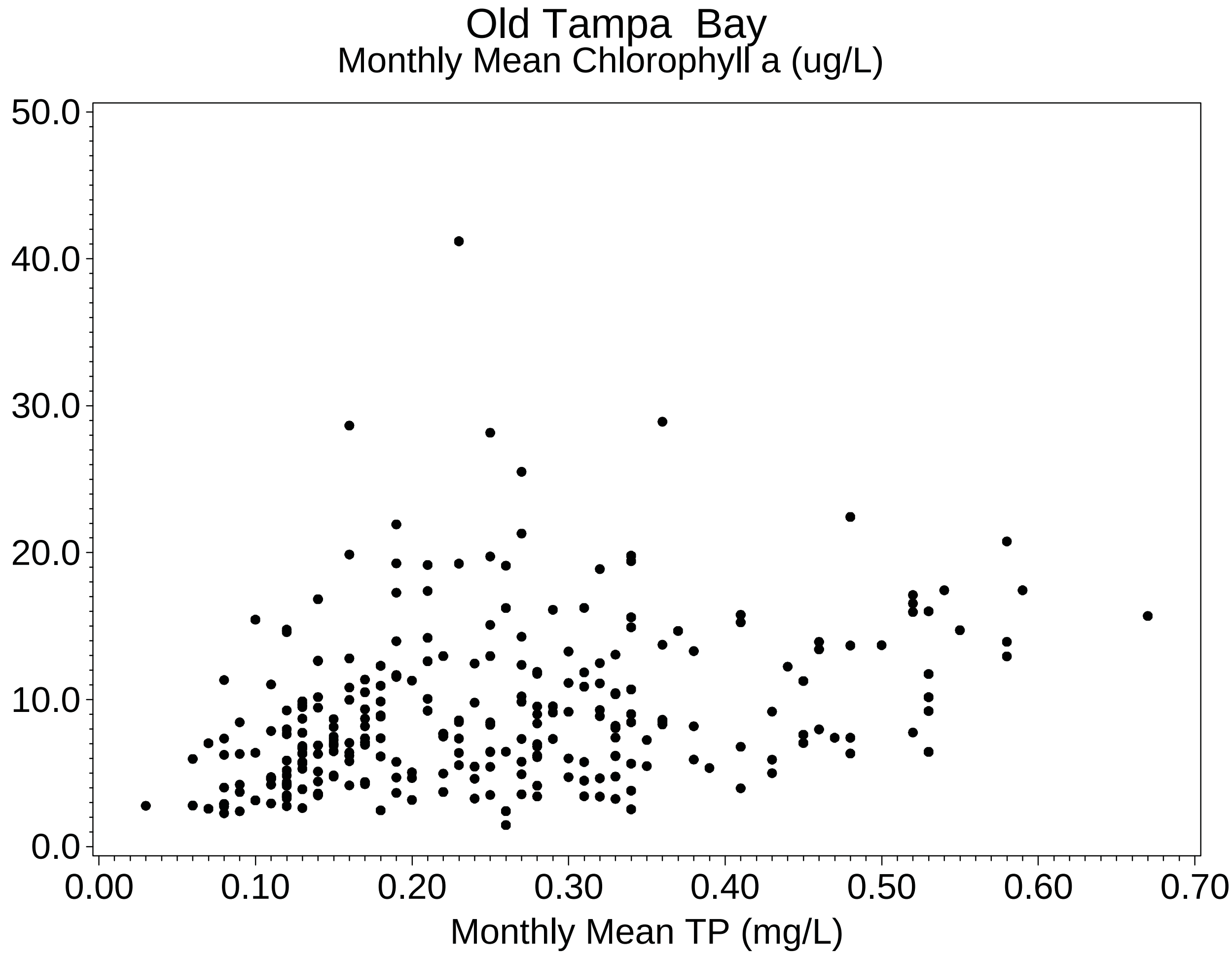
Hillsborough Bay
Monthly Mean Chlorophyll a (ug/L)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7
Average Three-Month TN Concentration (mg/L)

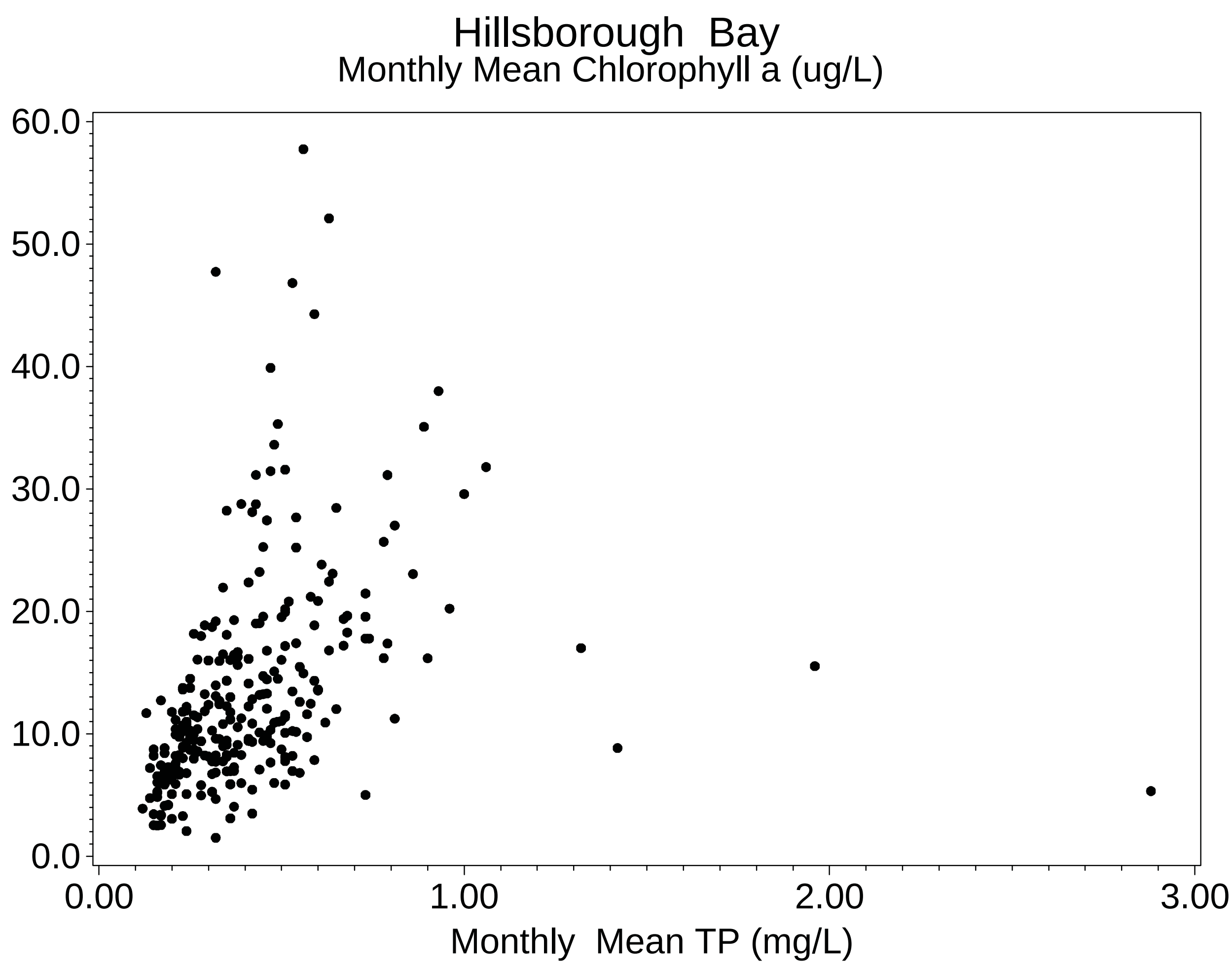

Middle Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
30.0
20.0
10.0
0.0
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
Average Three-Month TN Concentration (mg/L)

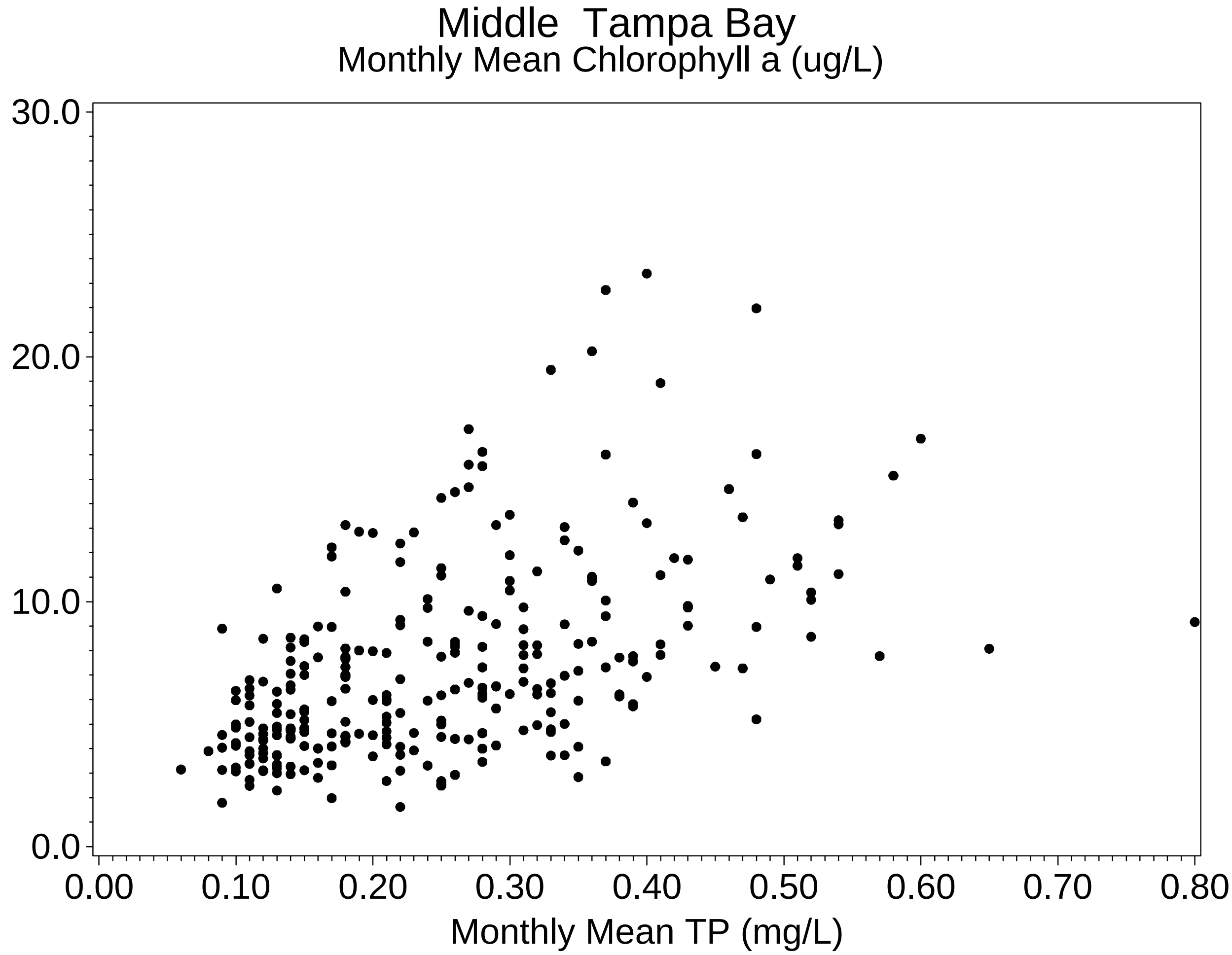

Lower Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Average Three-Month TN Concentration (mg/L)

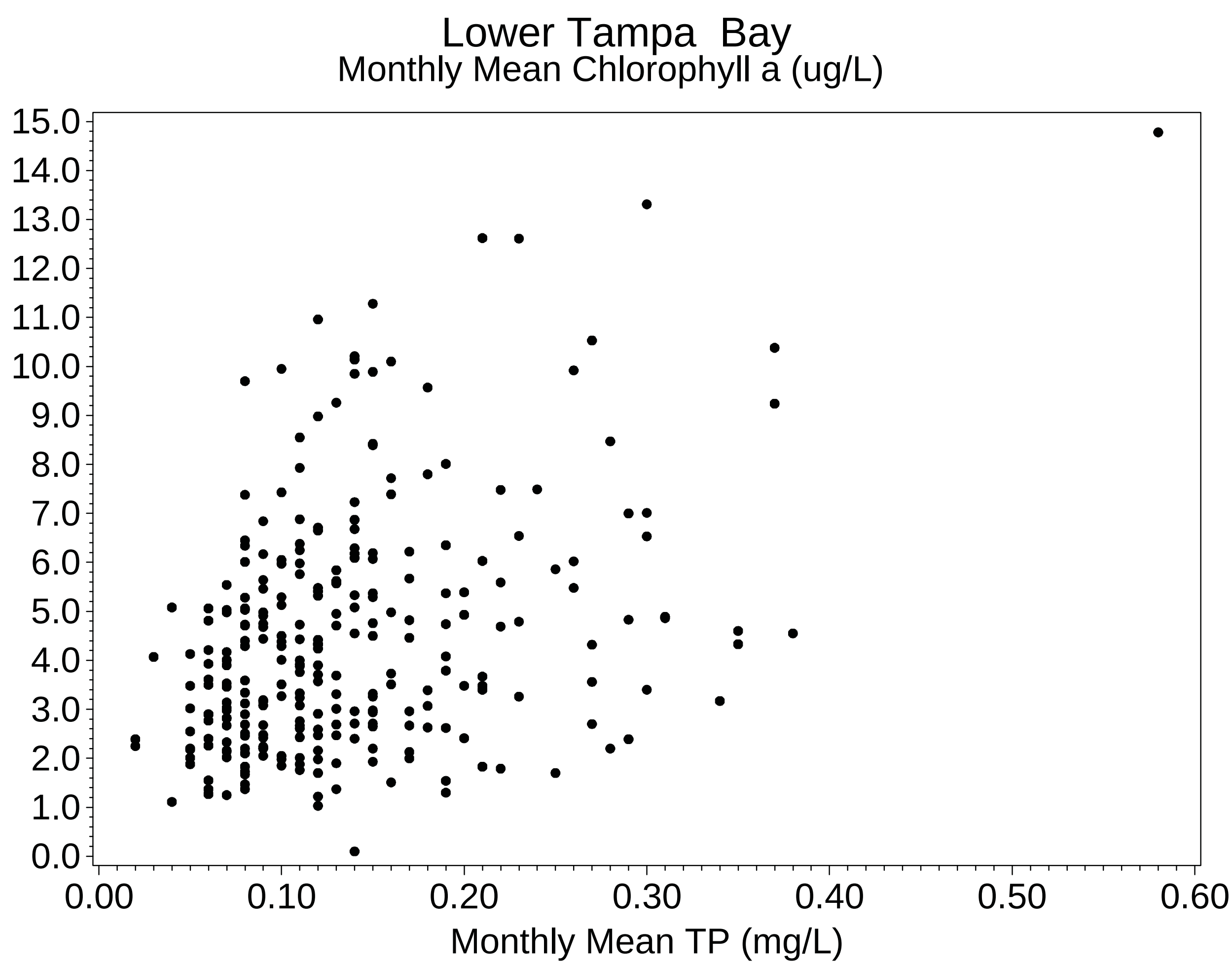
Attachment 6

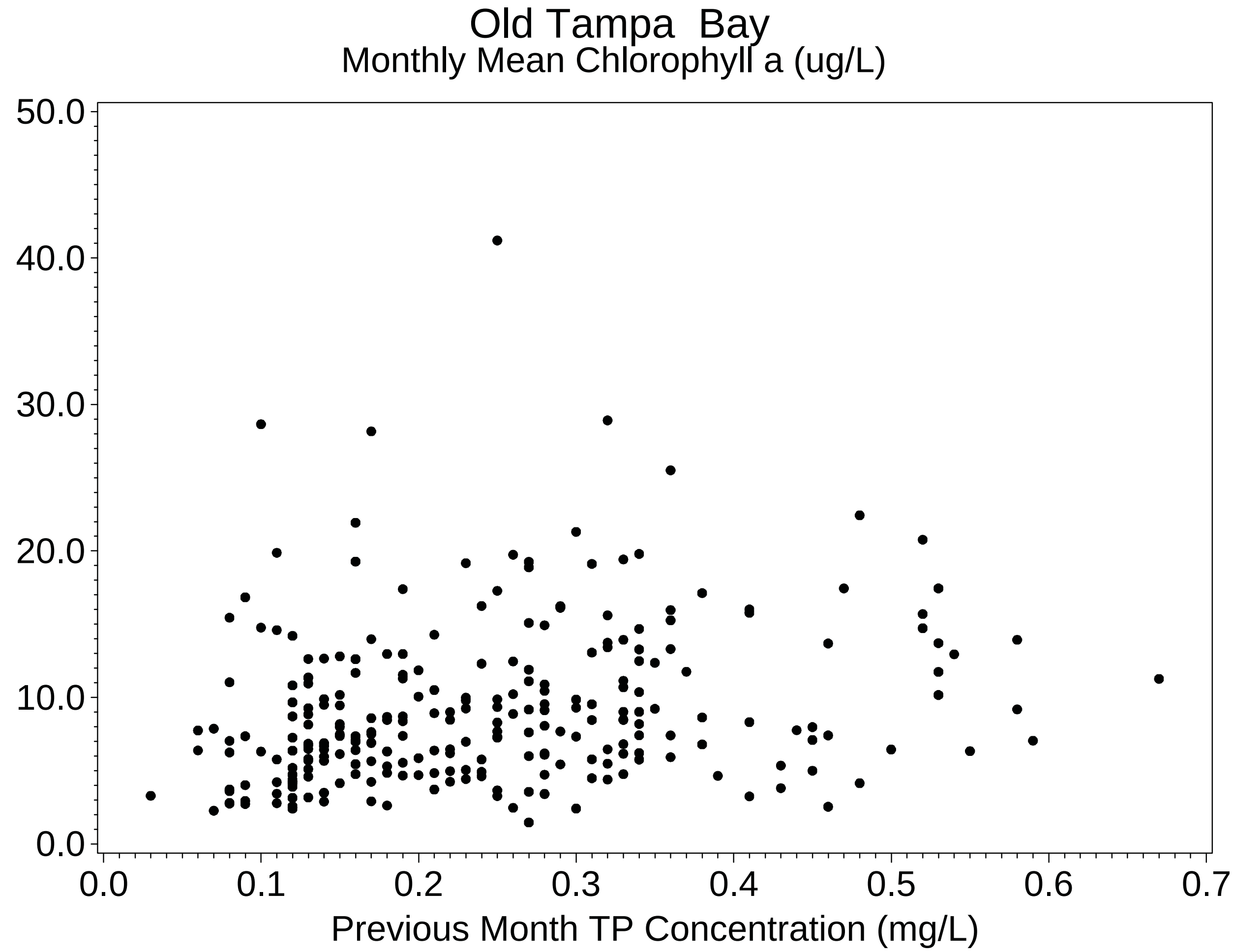
Monthly Chlorophyll *a* Concentrations and Monthly TP Concentrations

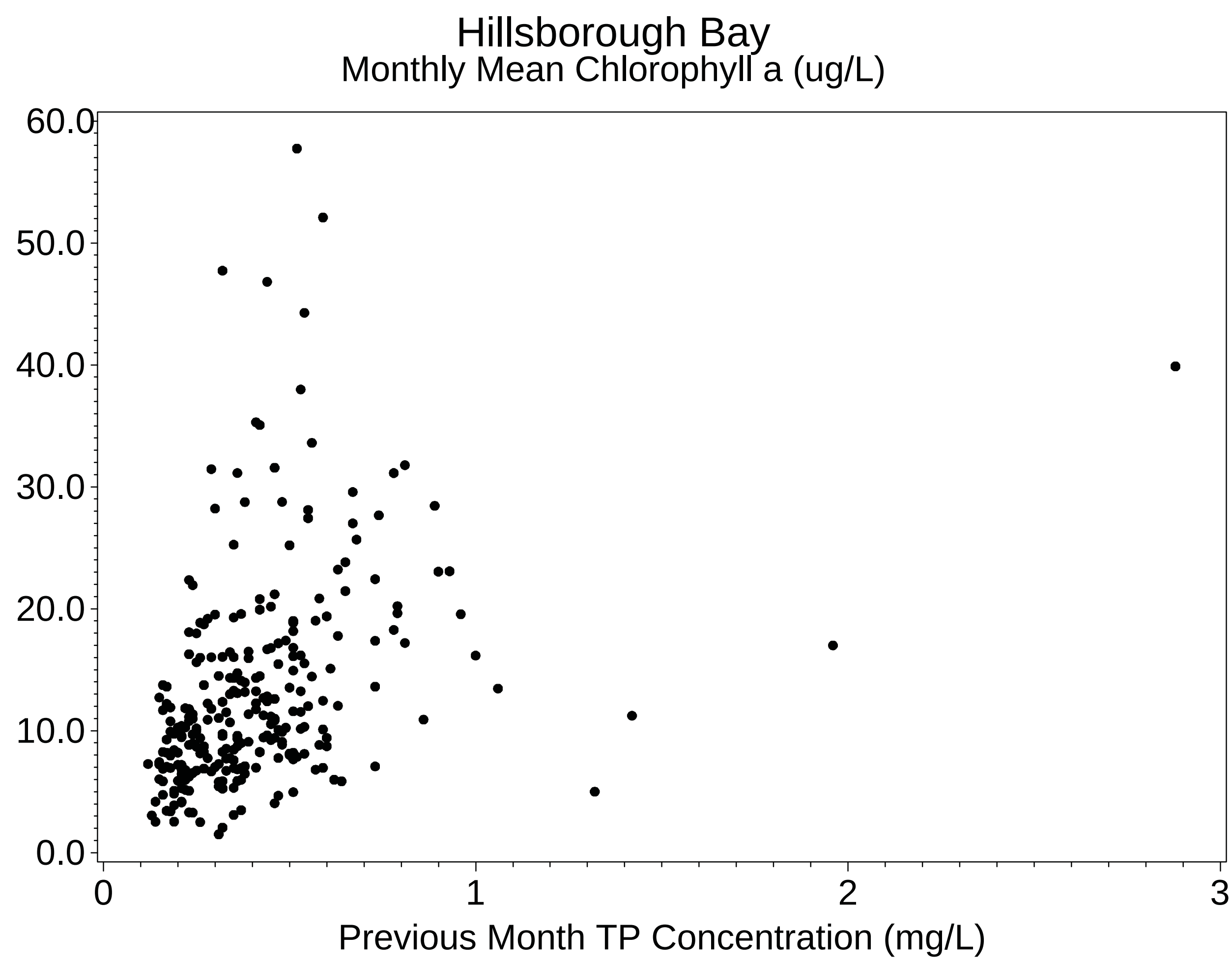

Old Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
50.0
40.0
30.0
20.0
10.0
0.0
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
Monthly Mean TP (mg/L)

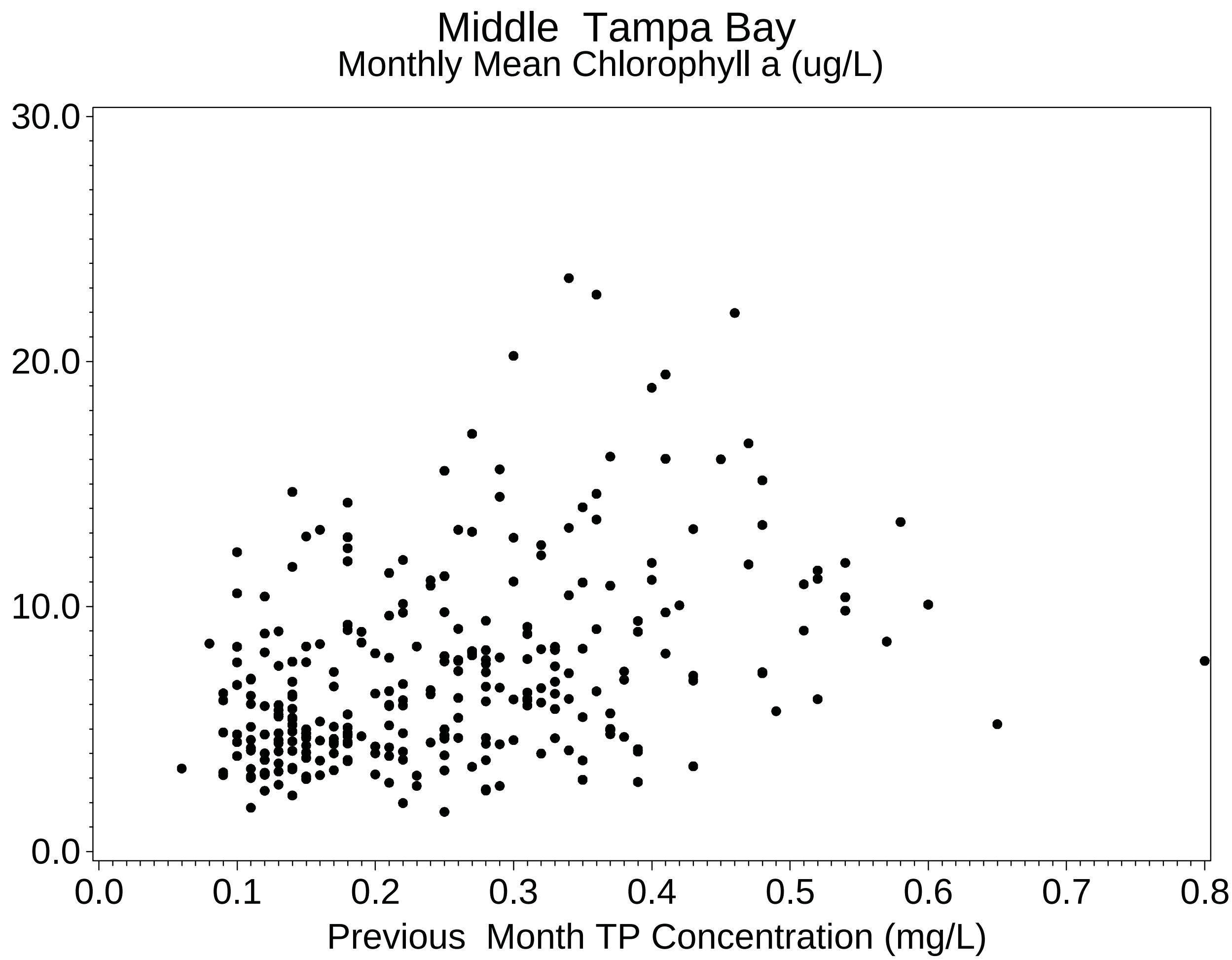

Hillsborough Bay
Monthly Mean Chlorophyll a (ug/L)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.00
1.00
2.00
3.00
Monthly Mean TP (mg/L)

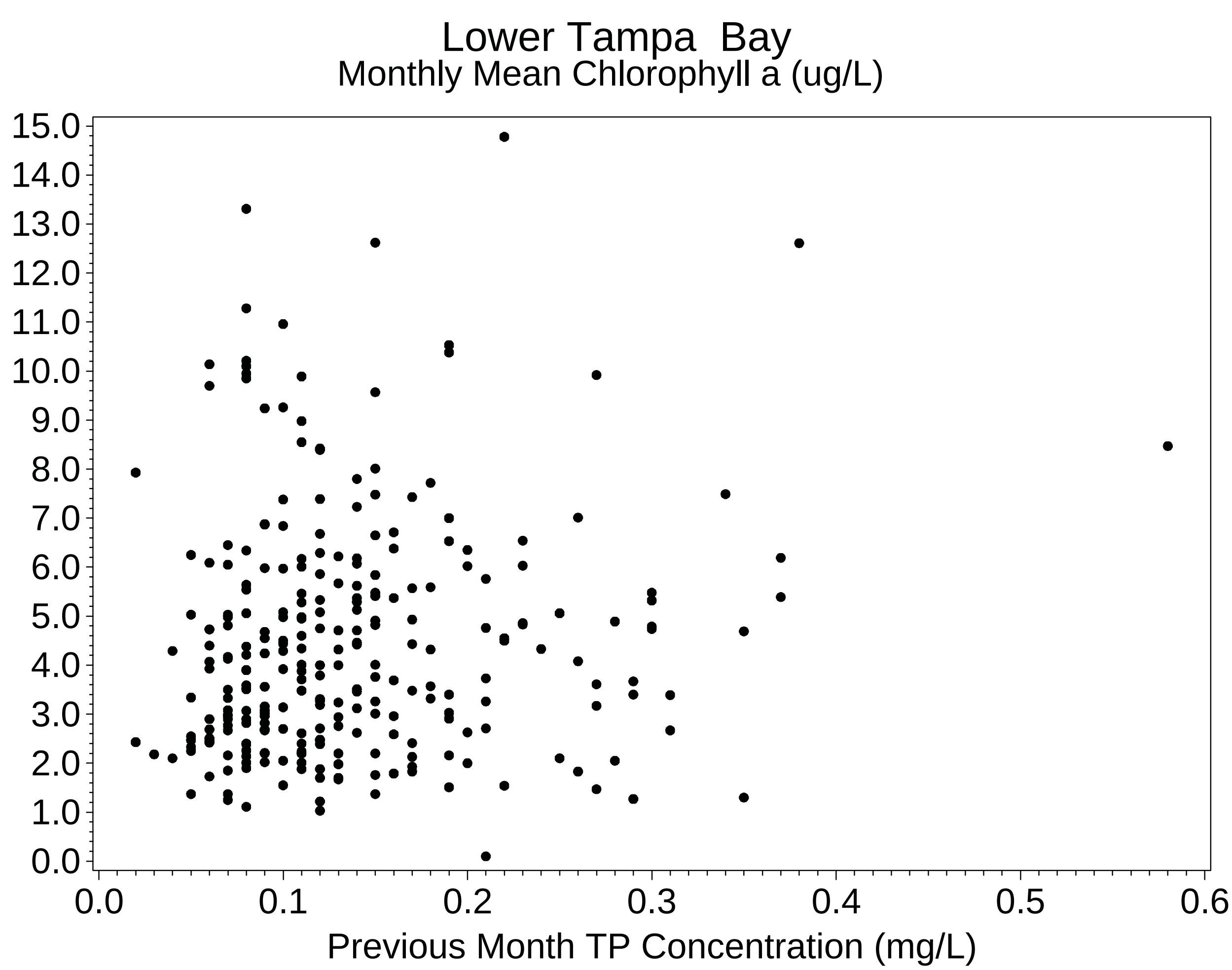

Middle Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
30.0
20.0
10.0
0.0
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80
Monthly Mean TP (mg/L)

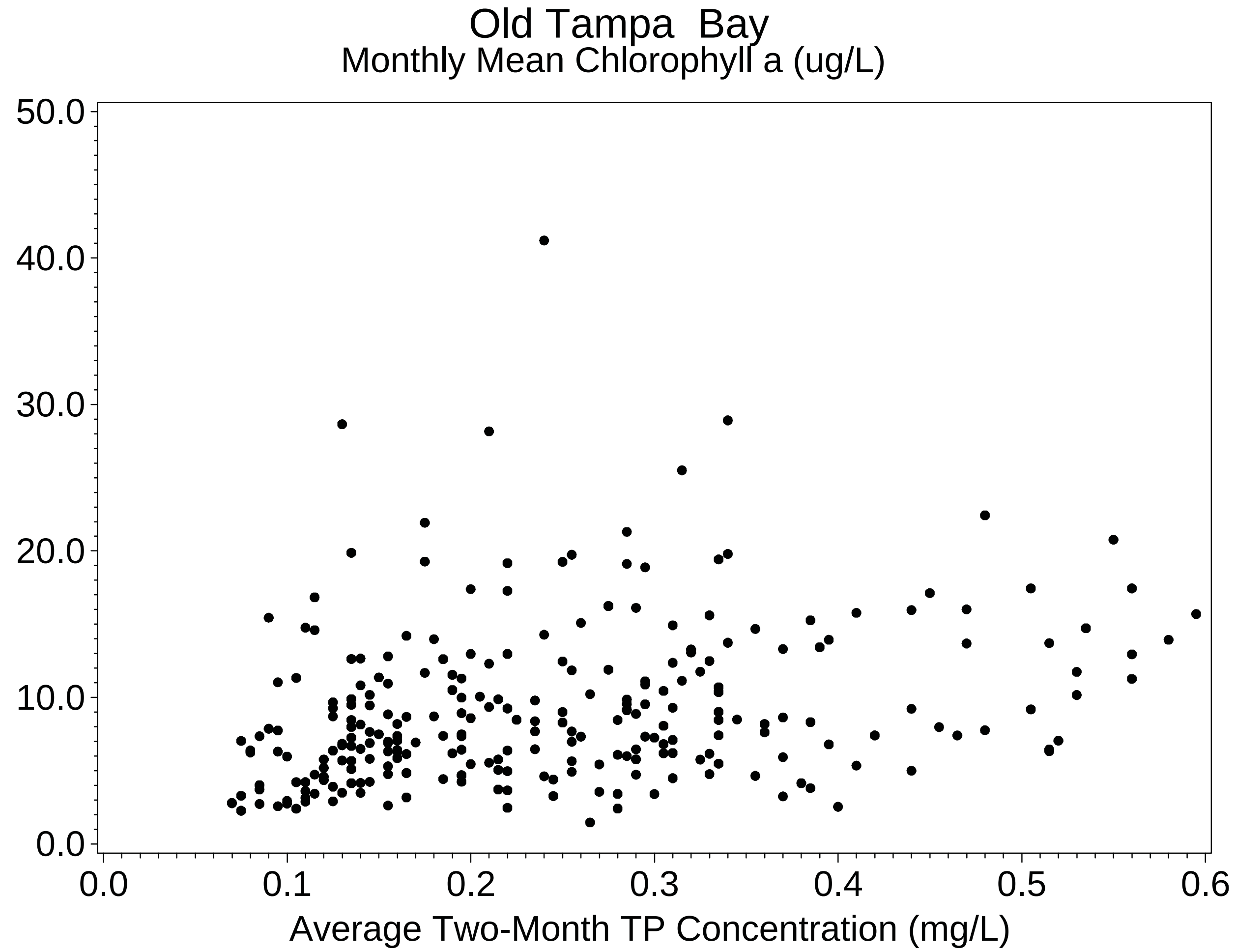

Lower Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.00 0.10 0.20 0.30 0.40 0.50 0.60
Monthly Mean TP (mg/L)

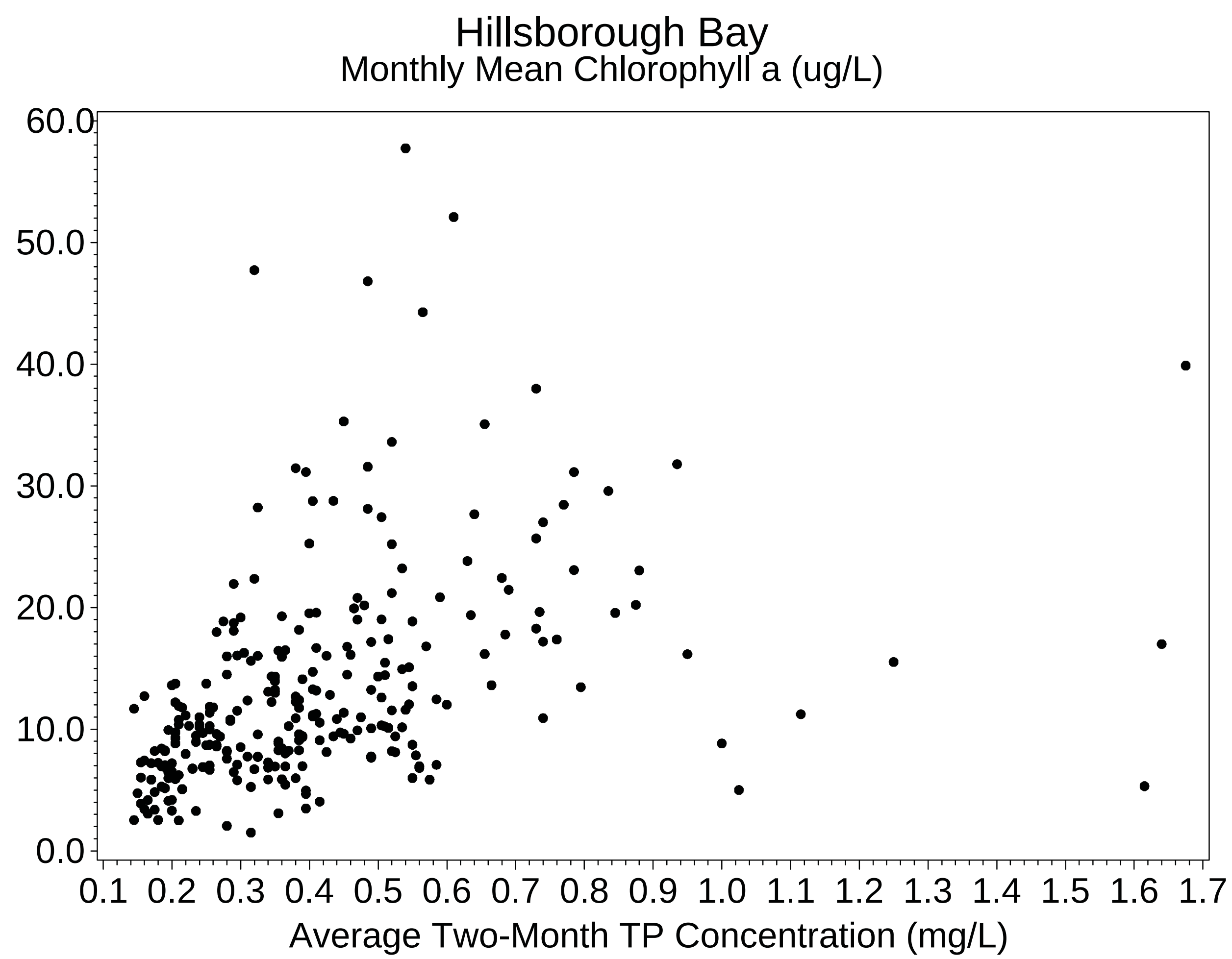

Old Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
50.0
40.0
30.0
20.0
10.0
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Previous Month TP Concentration (mg/L)

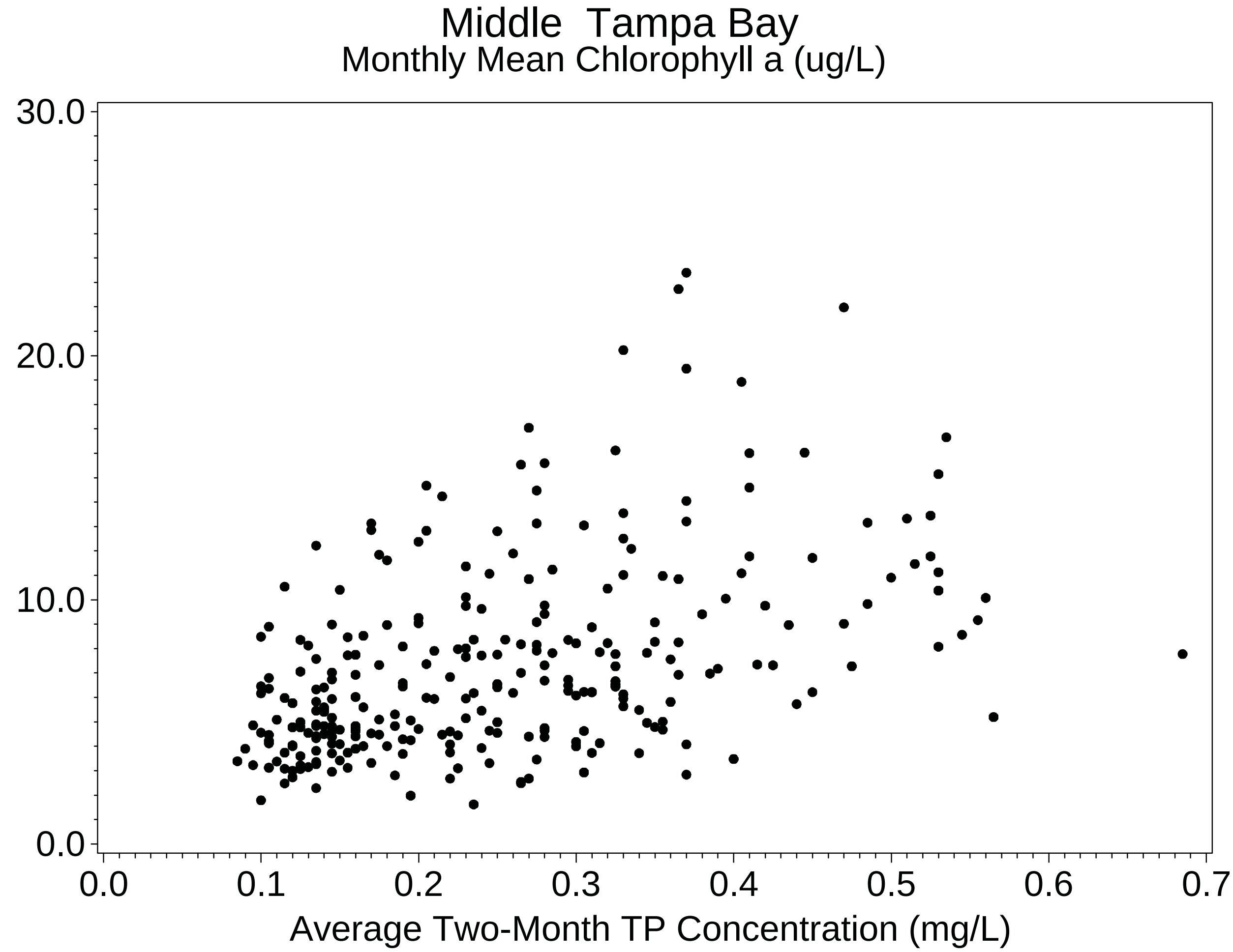

Hillsborough Bay
Monthly Mean Chlorophyll a (ug/L)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0
1
2
3
Previous Month TP Concentration (mg/L)


Middle Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
30.0
20.0
10.0
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Previous Month TP Concentration (mg/L)

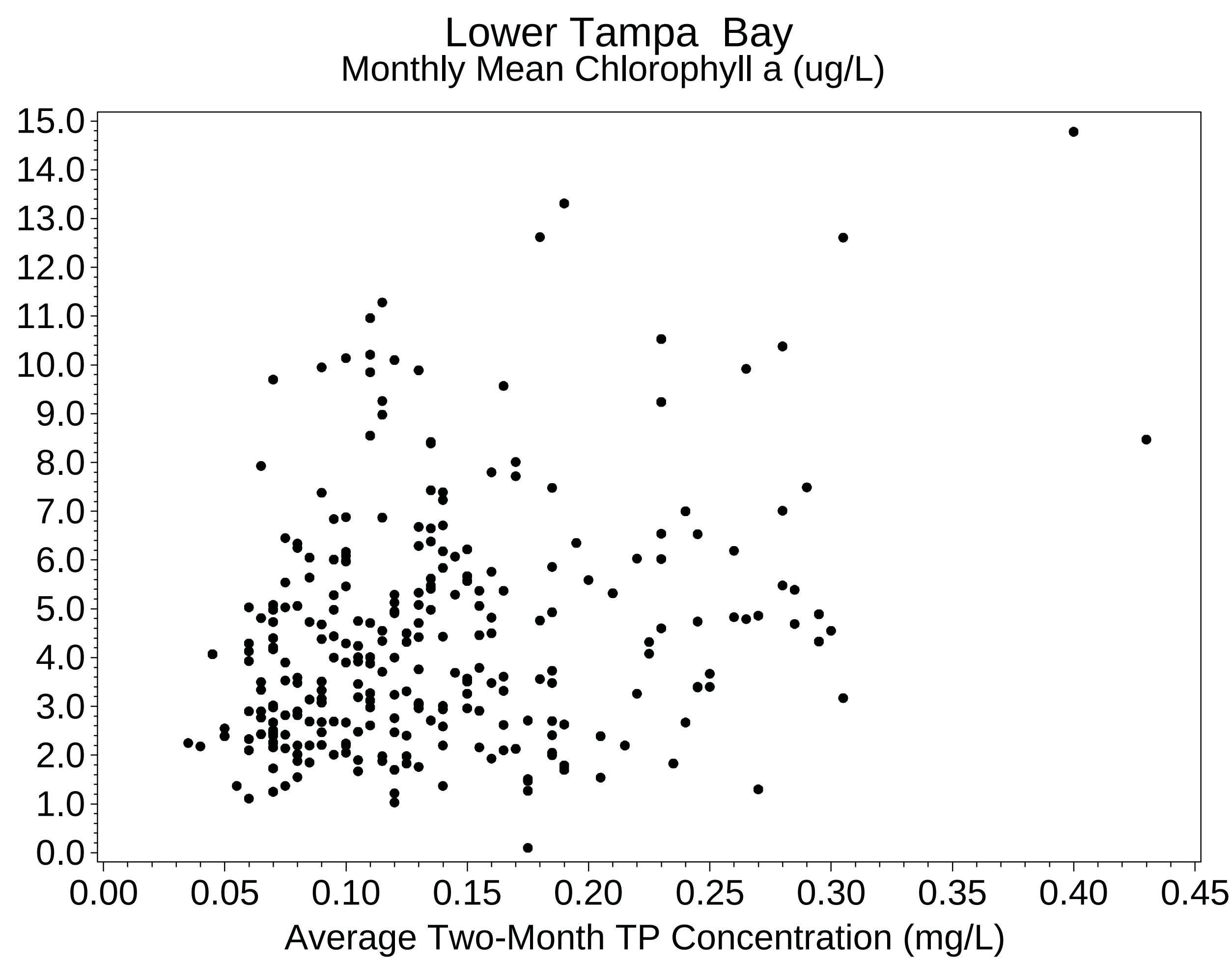

Lower Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Previous Month TP Concentration (mg/L)


Old Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
50.0
40.0
30.0
20.0
10.0
0.0
0.0 0.1 0.2 0.3 0.4 0.5 0.6
Average Two-Month TP Concentration (mg/L)

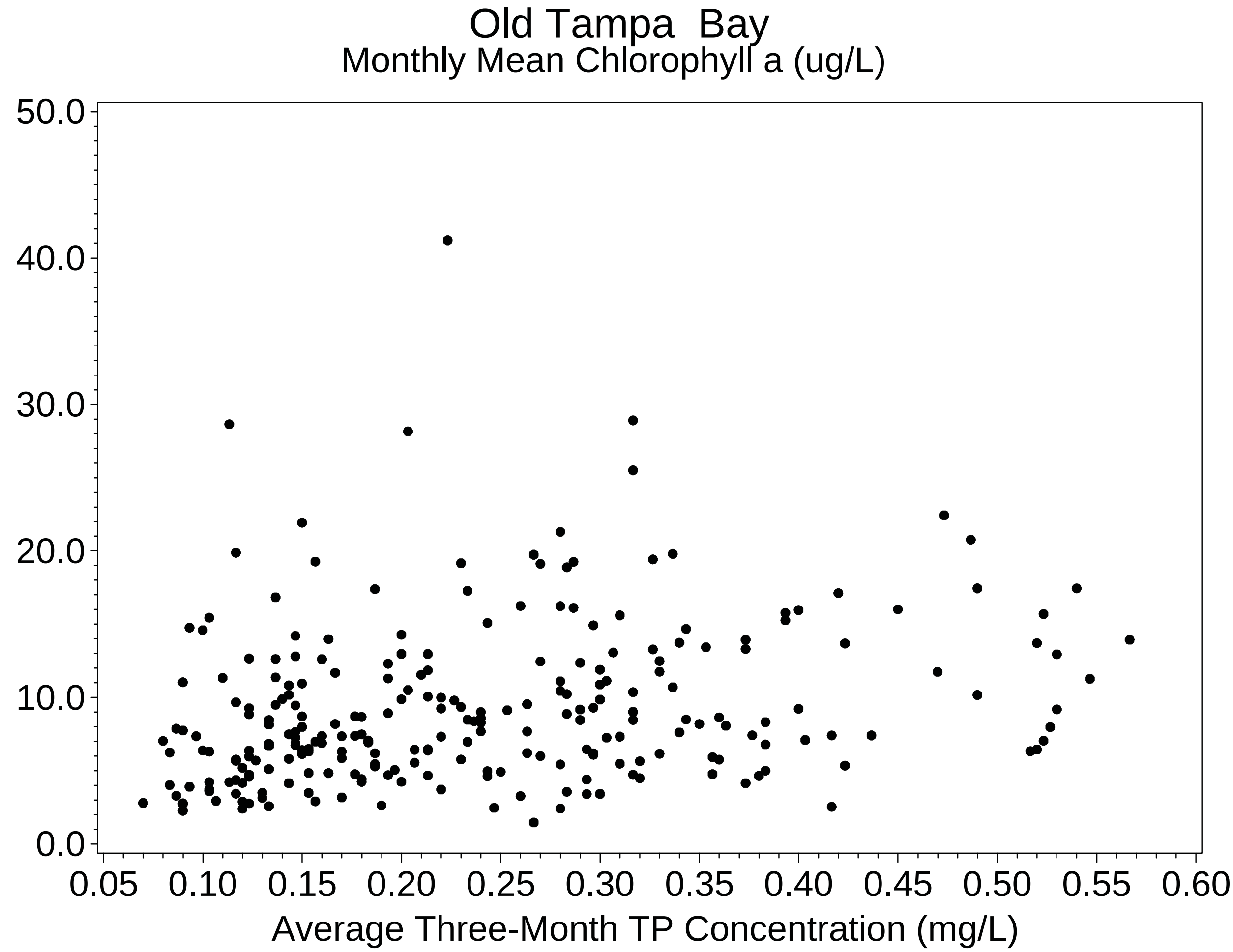

Hillsborough Bay
Monthly Mean Chlorophyll a (ug/L)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7
Average Two-Month TP Concentration (mg/L)

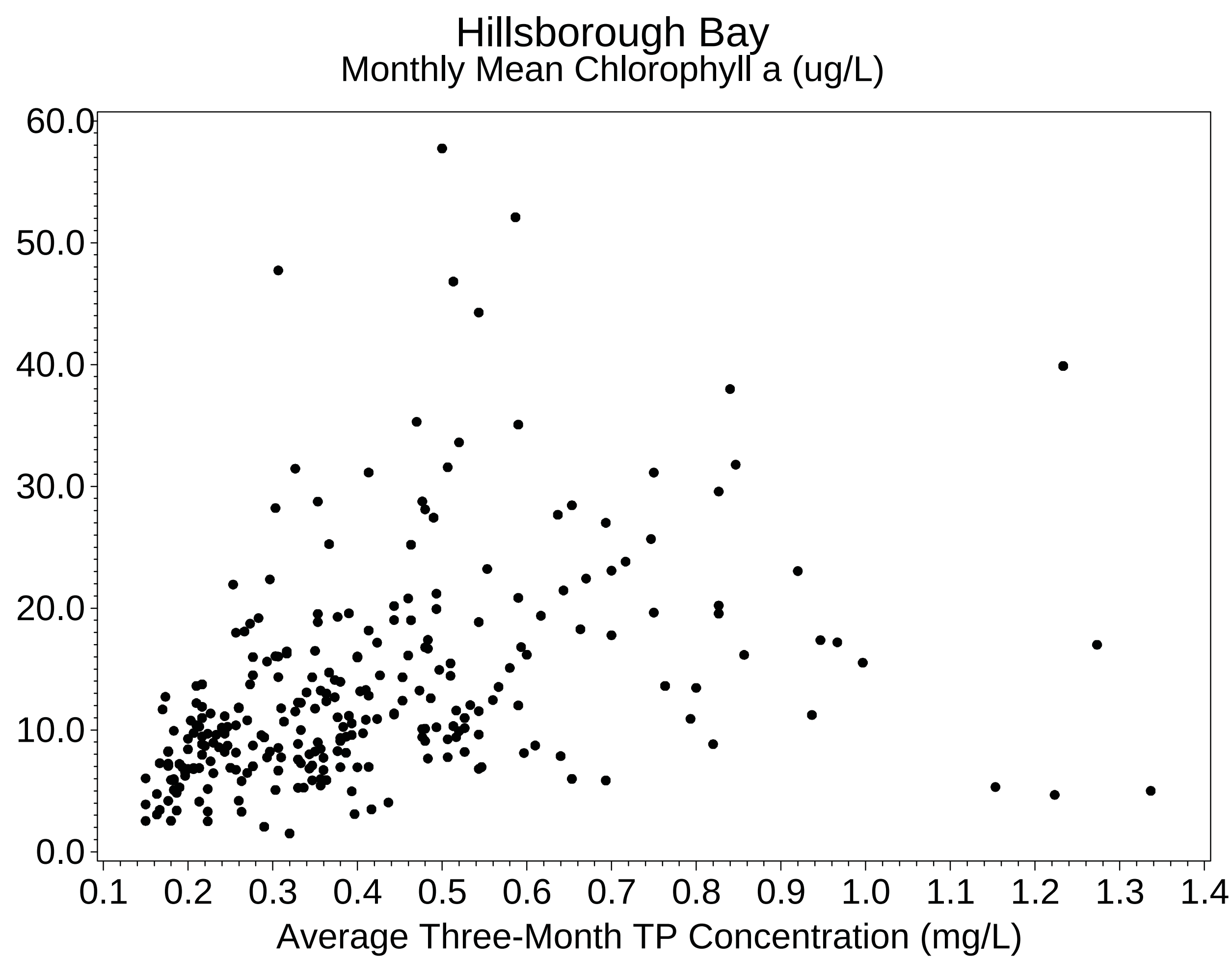


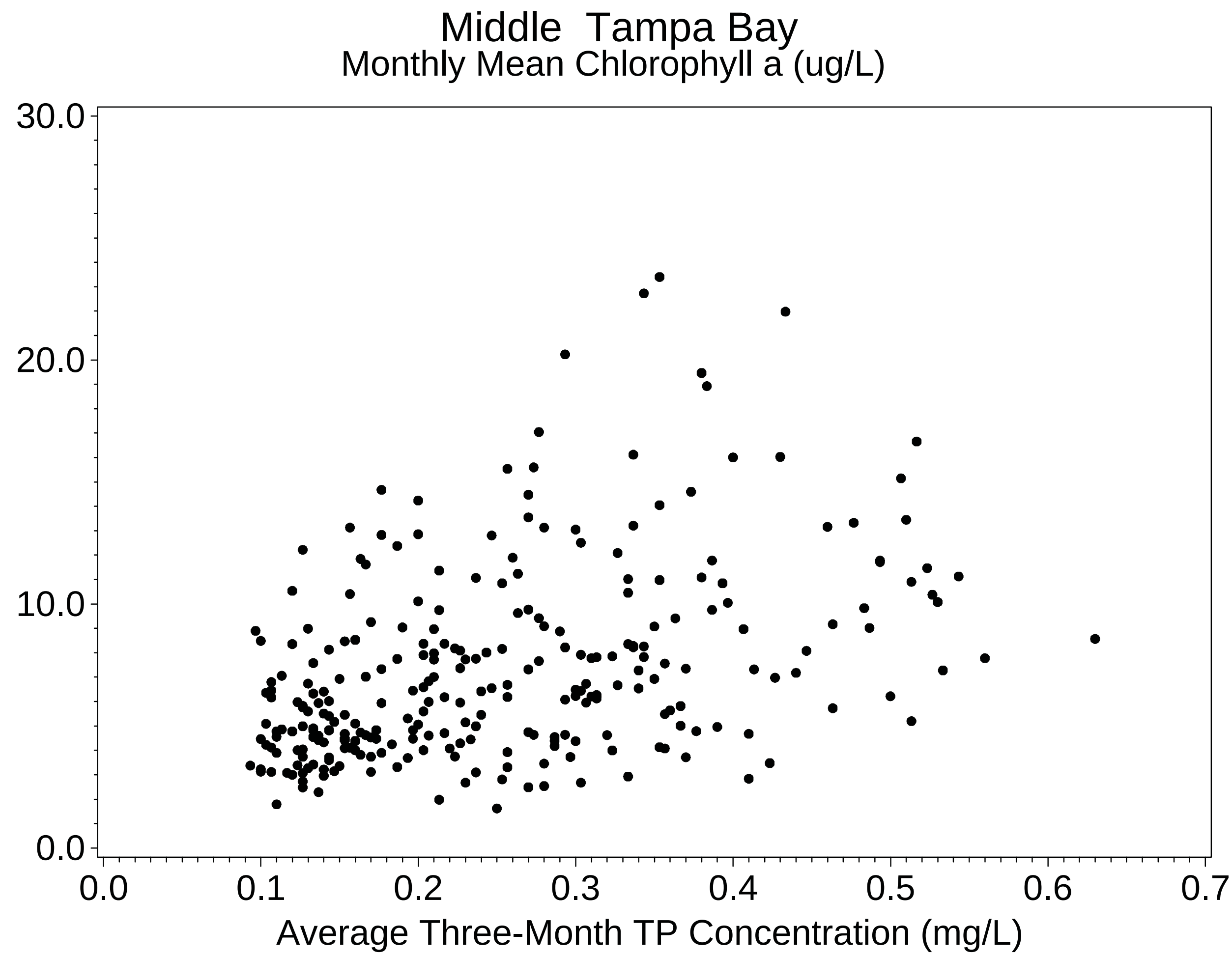
Middle Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
30.0
20.0
10.0
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Average Two-Month TP Concentration (mg/L)

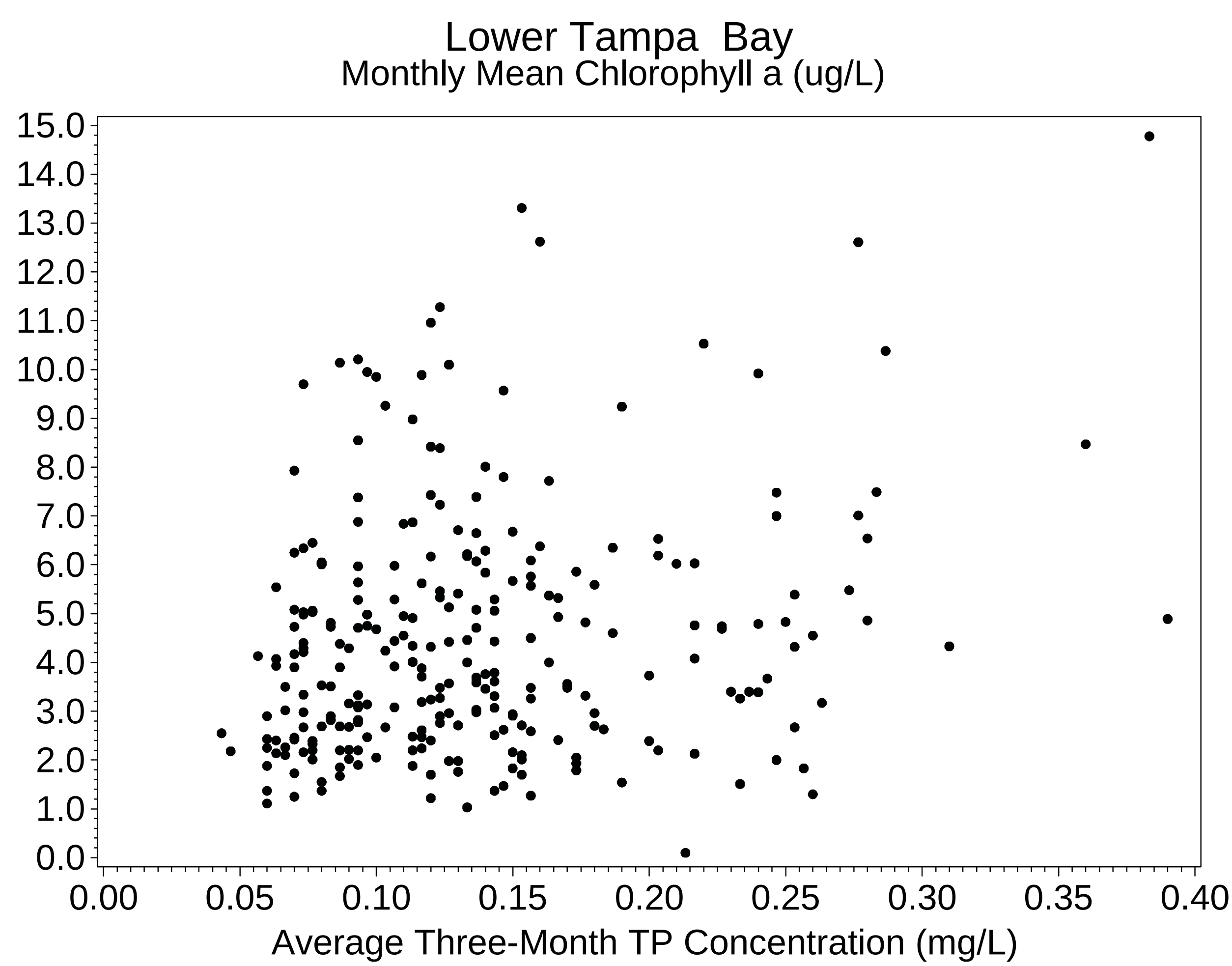


Lower Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
Average Two-Month TP Concentration (mg/L)


Old Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
0.0
10.0
20.0
30.0
40.0
50.0
0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60
Average Three-Month TP Concentration (mg/L)


Hillsborough Bay
Monthly Mean Chlorophyll a (ug/L)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4
Average Three-Month TP Concentration (mg/L)


Middle Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
30.0
20.0
10.0
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Average Three-Month TP Concentration (mg/L)


Lower Tampa Bay
Monthly Mean Chlorophyll a (ug/L)
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Average Three-Month TP Concentration (mg/L)

TAMPA BAY
Numeric Nutrient Criteria:
Task 3 – Dissolved Oxygen

Letter Memorandum

Prepared for:

Tampa Bay Estuary Program

Prepared by:

Janicki Environmental, Inc.

16 February 2011

FOREWORD

This letter memo was produced in partial fulfillment of Purchase Order #6584, TBEP Contract T-07-01 - Development of Numeric Nutrient Criteria for Tampa Bay, Task 2.

ACKNOWLEDGEMENTS

We wish to thank the partners of the Tampa Bay Estuary Program and members of the Tampa Bay Nitrogen Management Consortium for the numerous conversations providing direction and insight into concerns regarding numeric nutrient criteria establishment and appropriate methodology for developing the proposed criteria.

EXECUTIVE SUMMARY

The objective of this task was to characterize dissolved oxygen (DO) concentrations in Tampa Bay's major bay segments, assess principal drivers of DO exceedances in Tampa Bay and evaluate the relevance of the empirical distribution of DO concentrations to the Florida Department of Environmental Protection's Impaired Water Rule standard for DO with respect to the development of recently proposed numeric nutrient criteria for the Tampa Bay estuary (Janicki Environmental, 2011). The assessment included a descriptive characterization of the spatial and temporal attributes of observed DO concentrations using over 30 years of data, four different sampling agencies, and over 17,000 individual data points.

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

- The empirical evidence presented here suggests that all major segments of Tampa Bay are meeting full aquatic life support with respect to DO.

- Examination of the spatial distribution of DO samples shows that DO exceedances < 4 mg/L are most likely to occur in Hillsborough Bay near the mouths of the Hillsborough and Alafia Rivers, and along the western half of Hillsborough Bay. These are deeper areas, more likely to be stratified due to freshwater inputs, and have high organic sediment content.

- The principal factor affecting DO in Tampa Bay is temperature. That is evident in both the descriptive temporal plots and in the generalized linear model assessed in the quantitative assessment of those factors affecting the probability of DO being less than 4 mg/L. The model results indicate that stratification, bottom type, and sample depth were other factors that contributed to the probability of low DO conditions (i.e., < 4 mg/L). Furthermore, it was determined that chlorophyll *a* concentrations were not a significant factor contributing to probability of low DO conditions in Tampa Bay. In other words, the occurrence of DO values below 4 mg/L were not significantly related to observed chlorophyll *a* concentrations at the time of sampling.

- 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 support with respect to DO.

1.0 Introduction and Objective

The Tampa Bay Estuary Program (TBEP) and the Tampa Bay Nitrogen Management Consortium (TBNMC) have recommended numeric nutrient criteria to U.S. Environmental Protection Agency (EPA) for Tampa Bay (TBNMC, 2010). The criteria, as proposed to EPA, are segment-specific (Figure 1) and are expressed as annual total nitrogen (TN) and total phosphorus (TP) loads. These TN and TP loads are those for the reference period of 1992-1994, as discussed in the March 8, 2010 comments to EPA. The numeric nutrient criteria proposed for the Tampa Bay estuary must provide full aquatic life support within the estuary. The primary response variable used to establish the proposed numeric nutrient criteria is chlorophyll *a* concentrations. Dissolved oxygen (DO) can be used as an additional indicator of eutrophic conditions (EPA, 2001) and can serve as an indicator of habitat suitability for a wide range of aquatic fauna (e.g., fishes and benthic invertebrates).

The Florida Department of Environmental Protection (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).

The conceptual model applied by FDEP in establishing this 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. 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 the consequent increase in 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 Tampa Bay with respect to the development of recently proposed numeric nutrient criteria for the Tampa Bay estuary (Janicki Environmental, 2011). This study also explores evidence that the FDEP conceptual model described above is currently relevant in the Tampa Bay estuary. In particular, this assessment investigated the relationship between the percentage of DO exceedances in each of Tampa Bay's four major bay segments and the threshold values for chlorophyll *a* established as part of an overall nutrient control strategy for Tampa Bay (Greening and Janicki, 2006). Descriptive and quantitative analyses were used to evaluate the effects of known drivers of DO including temperature, depth, bottom type, stratification, chlorophyll *a* concentrations and the percentage of DO exceedances.

2.0 Data Sources

The data sources for this assessment included:

- Environmental Protection Commission of Hillsborough County (EPCHC),
- Pinellas County Department of Environmental Management (PCDEM),
- Manatee County Department of Environmental Management (MCDEM), and
- Florida Fish and Wildlife Conservation Commission's Fisheries Independent Monitoring Program (FIM) program.

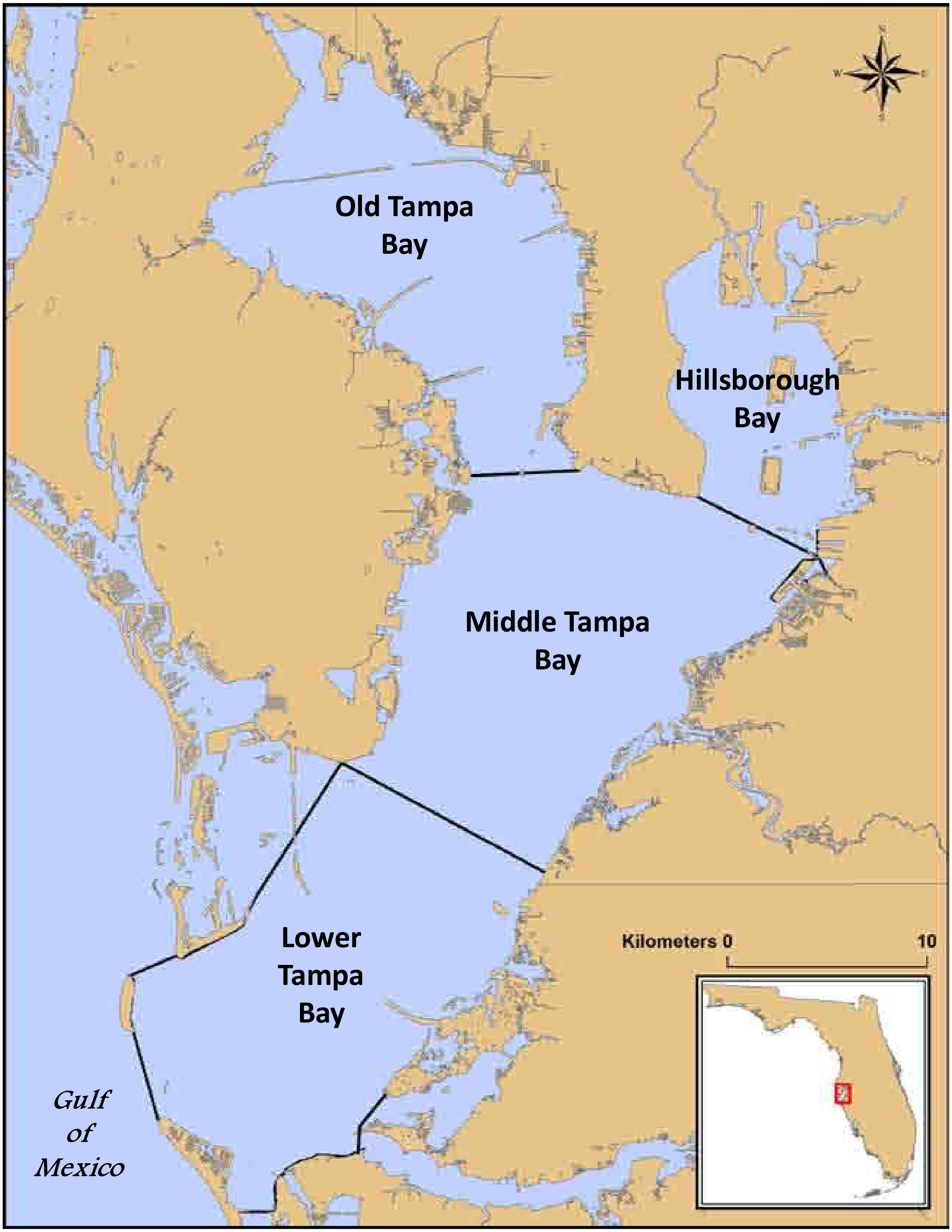


Figure 1. Tampa Bay and its four major bay segments.

Monthly fixed station water quality data have been collected by the EPCHC from 1974 to present at 54 fixed station locations throughout Tampa Bay (Figure 2). Sediment chemistry data were obtained by the Tampa Bay Estuary Program's benthic monitoring program that uses a probabilistic survey design with sampling taking place in a late summer index period of each year (Figure 3). Water quality data from Pinellas County and Manatee County were used in the assessment within their jurisdictional boundaries (Figure 4). These data are taken routinely with quarterly sampling at fixed stations in Manatee County and 8 or 9 sampling dates per year in Pinellas County since 2003 using a probabilistic design. Hydrographic and DO data from the Florida Fish and Wildlife Conservation Commission's Fisheries Independent Monitoring Program (FIM) program were also obtained and analyzed. These data were collected concurrently with monthly fisheries samples throughout Tampa Bay collected using a probabilistic design since 1996 (Figure 5). Together the data represent over 17,000 individual samples.

3.0 Approach

Descriptive and quantitative analytical techniques were applied in this assessment. The data were mapped using ArcGIS (ESRI, 2009) for each program to allow examination of the spatial representation of the sampling within Tampa Bay. Spatial and temporal variation in DO was represented using a series of ArcGIS plots and descriptive figures. Annual segment average chlorophyll *a* concentrations and the percentage of DO exceedances (defined as a DO value below 4 mg/L) were calculated and displayed as time series plots for each segment. The percent silt-clay values from benthic collections between 1993 and 2008 were used to create a bottom contour of sediment silt-clay content in Tampa Bay. Inverse distance weighting was used to interpolate between empirical observations of silt-clay assuming that individual observations are representative of a specific but unknown area surrounding the sample and which has not changed substantially over the study period. These interpolated silt-clay values were mapped and values assigned to each fixed station location from the EPCHC water quality monitoring program database described above.

The quantitative assessment consisted of developing an empirical regression model to estimate the probability of a bottom dissolved oxygen value less than 4 mg/L as a function of hypothesized major drivers of dissolved oxygen in Tampa Bay. These drivers included temperature, bottom depth, the interpolated silt-clay values, chlorophyll *a*, surface salinity, and a measure of stratification calculated as the rate of change between surface and bottom salinity as a function of depth. A generalized linear mixed-effects model was developed for this assessment. The model estimates the probability of a DO exceedance (i.e., a DO $<$ 4.0 mg/L) as a function of several predictor variables. The fixed effect model equivalent is a logistic regression model; a class of generalized linear models. The incorporation of random effects in the model specification was important for several reasons. The specification of random effects components allows for:

- generalization of the results to spaces within a segment other than the fixed station location since the station effect is now specified as the realization of a probability distribution,
- the incorporation of a covariance structure to describe the hierarchical design of the sampling program where stations within a segment are sampled on the same day and therefore may be correlated, and
- the correlation that arises from repeated sampling at a fixed location which has inherent characteristics to be captured.

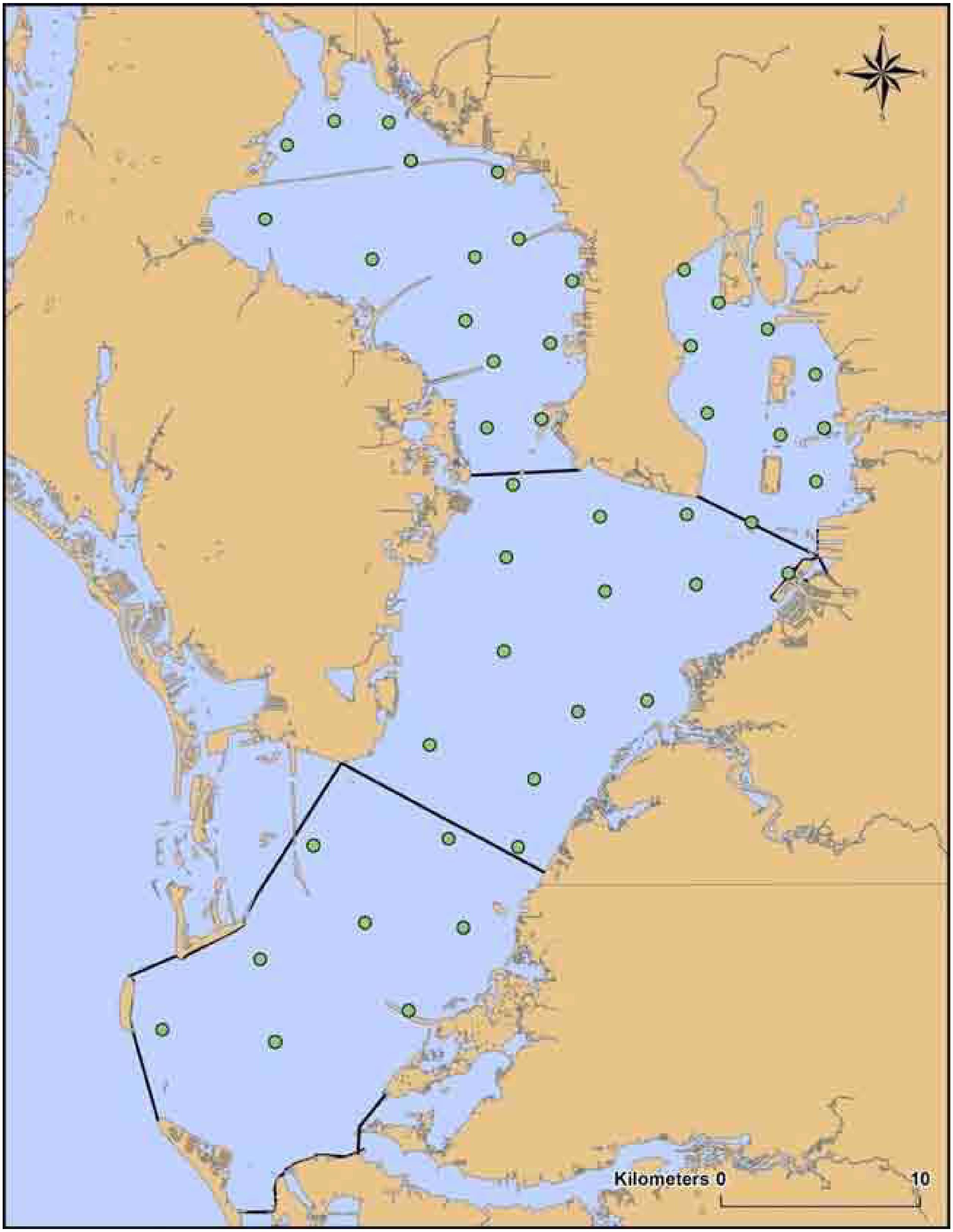


Figure 2. Sampling locations from EPC fixed stations in Tampa Bay sampled since 1974.

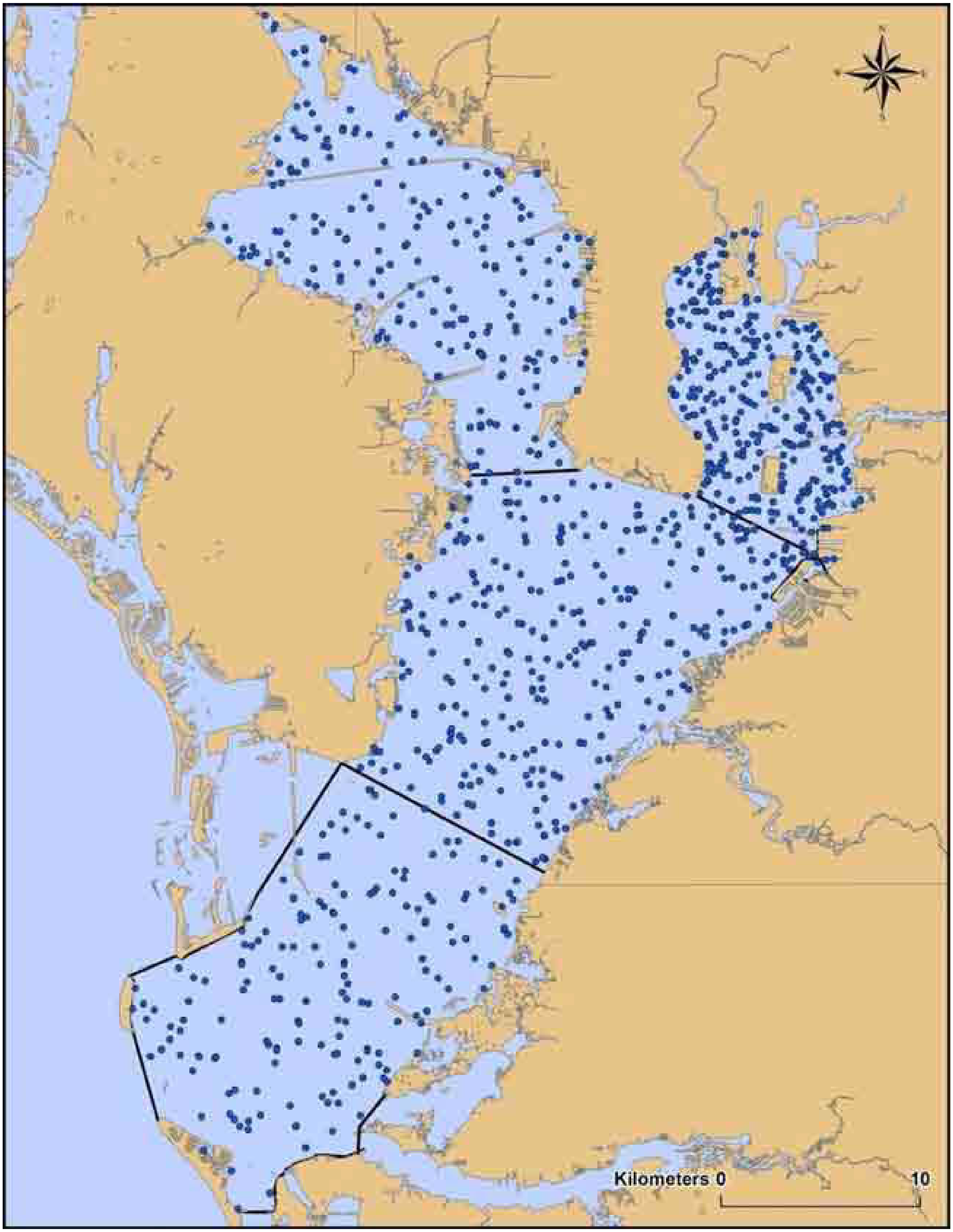


Figure 3. Sampling locations from EPC benthic collections between 1993-2008.

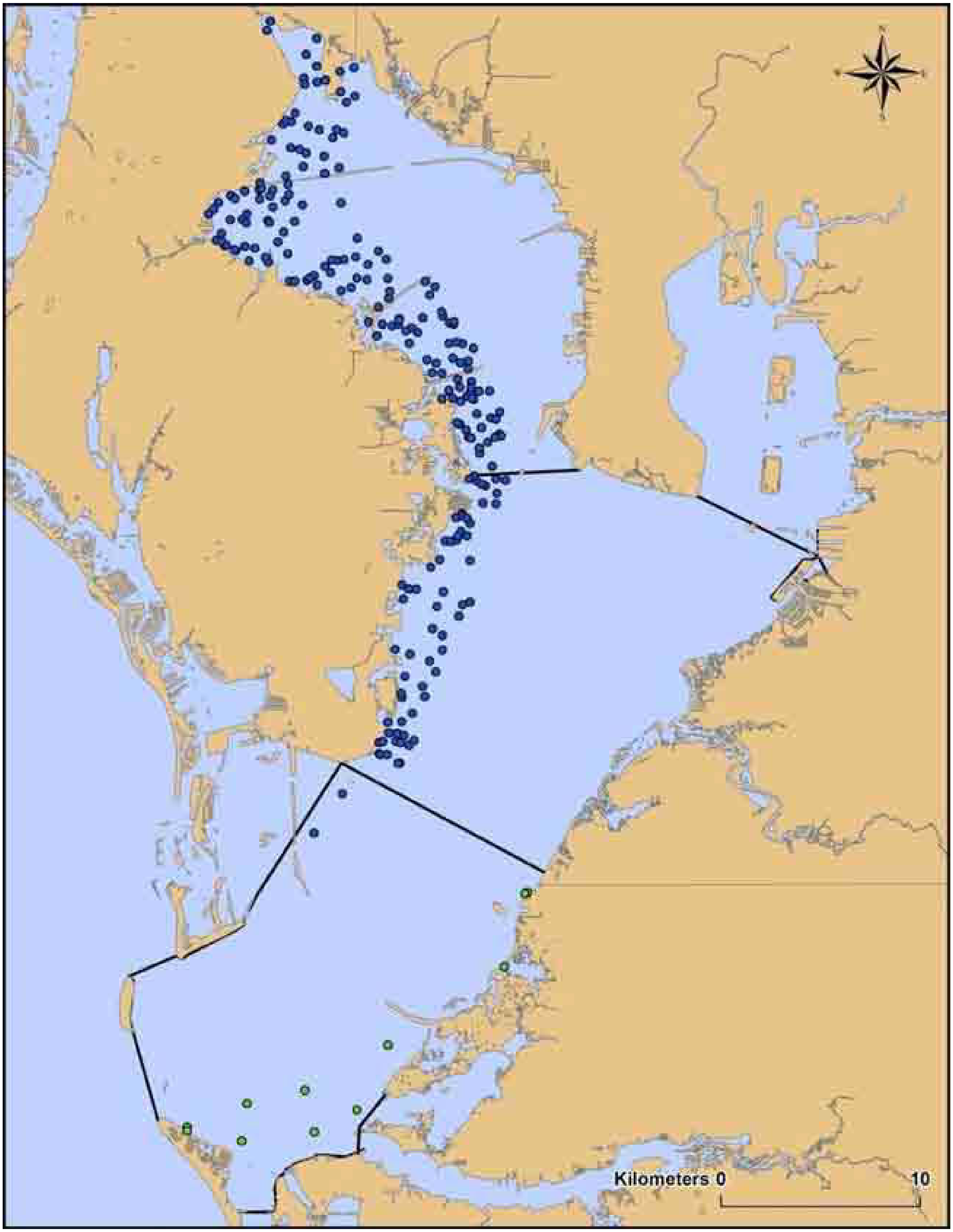


Figure 4. Sampling locations from Pinellas County DEM (blue circles) and Manatee County DEM (green circles).

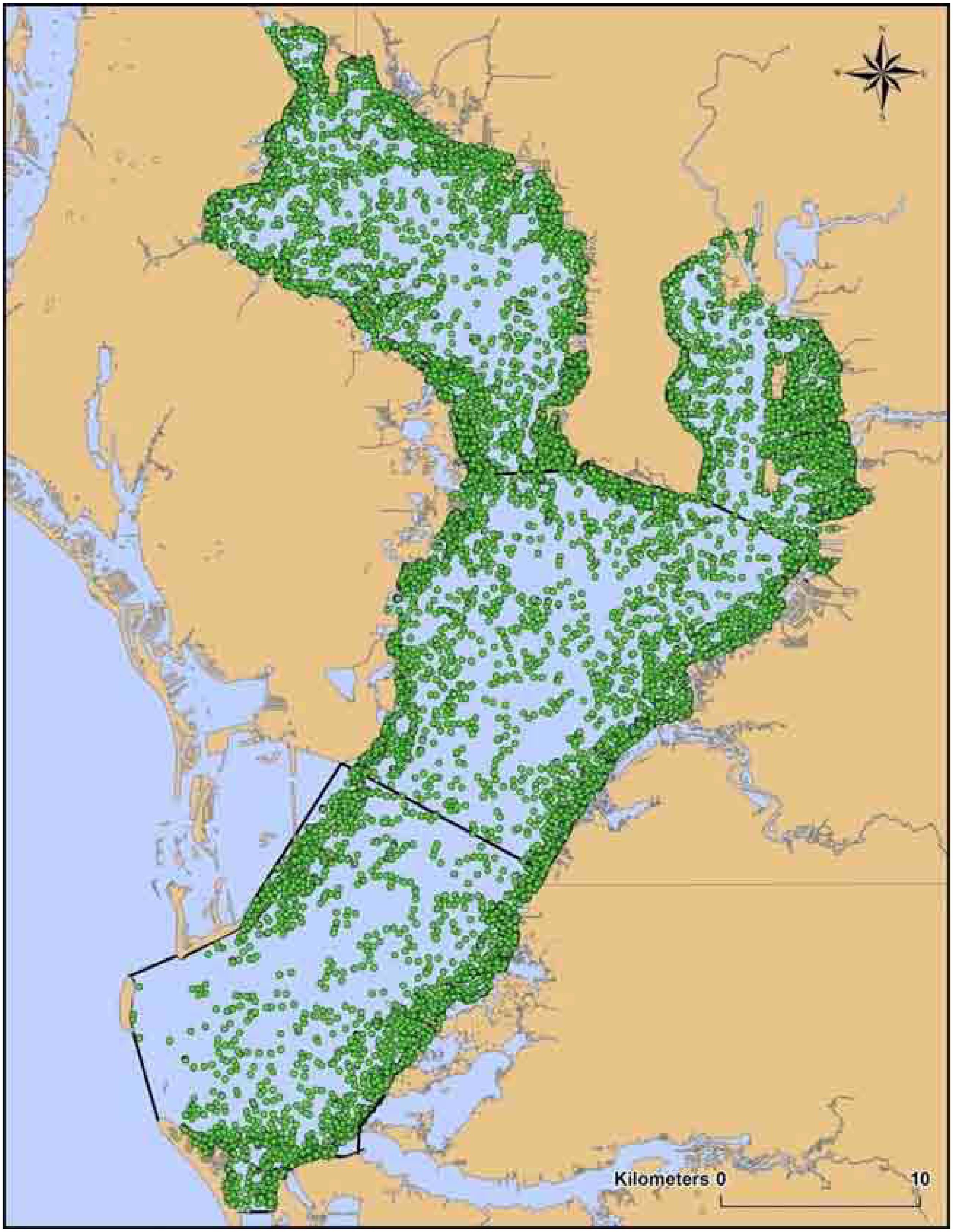


Figure 5. Fisheries Independent Monitoring (FIM) sampling locations between 1996 and 2009.

These aspects of the sampling design are important considerations when evaluating the effects of potential explanatory variables on the DO exceedance probability. Traditional statistical model inference relies on the assumption of sample independence among others. When samples are not independent, the statistical test to evaluate the significance of model parameters are biased leading to a likely overestimate of the significance of a factor in the model. The random effects component accounts for this correlation and adjusts the p values of the statistical test to account for these artifacts. The likelihood ratio test was used to confirm the improvement of the model by the incorporation of the random effects components.

The GLIMMIX procedure (SAS v9.2; SAS Institute, 2008) was used to estimate the probability of a DO exceedance by specifying the logit link function and the binomial distribution for the error term. The correlation structure of the random effects was based on the assumption of compound symmetry as described in the GLIMMIX users Guide (SAS Institute, 2008) though other covariance patterns may also be appropriate.

The generalized mixed-effects model formulation is:

$$y \mid u \sim N(X\beta + Zu, R)$$

$$where: \; u \sim N(0, G)$$

X and Z are known design matrices

R and G are unknown variance components specified by the random effects

To model the binomial responses of a DO exceedance, the inverse (logit) link function is specified and the fixed effects components are estimated as a linear model through the logit:

$$\text{logit}(P_{ij}) = \beta_0 + \beta_1 * x_1 + \beta_2 * x_2 + \beta_3 * x_3 + \beta_4 * x_4 + \beta_5 * x_5 + \beta_6 * x_6$$

$$where: \; \text{logit}(P_{ij}) = \log\left(\frac{P_{ij}}{1-P_{ij}}\right)$$

The fixed effects coefficients, $\beta_1 .. \beta_6$, are estimated by the model associated with the drivers described above. The random effects components are used to specify the hierarchical effects within segment *j* and the repeated measures effect of an individual station *ij*, respectively. Exponentiation of the fixed effects coefficients results in an odds ratio estimate defining the rate of change in the odds per unit change in the predictor. The likelihood ratio test was used to identify the model improvement by the incorporation of the random effects.

Descriptive assessment of the biotic effects were conducted to examine the distribution of metrics describing the abundance, species richness and diversity of fishes and benthic invertebrates as a function of DO exceedances based on data collected by the EPCHC and FIM programs. Only DO data collected at the time of biological sampling were used for this examination. Descriptive boxplots are provided that compare the distribution of the metric described above in years when greater than 10% of the observations had a DO measure below 4 mg/L in Hillsborough Bay, the only segment where DO's were below 4 mg/L more than 10% of the time in any year.

4.0 Results

This section presents the following results:

- examination of the temporal in DO exceedances in each segment,
- examination of the spatial patterns in DO in each segment,
- analysis of the factors affecting the probability of DO exceedances in Tampa Bay, and
- examination of the relationship between fish and benthic community structure with the occurrence of DO exceedances.

4.1 DO exceedances – temporal patterns

The first step in the analysis was to examine the temporal patterns in DO exceedances in each bay segment. 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 plotted in Figures 6 through 9. The data presented in these figures include all DO samples from all programs regardless of sample depth. Only in Hillsborough Bay was there any year that exceeded 10% of the values below 4 mg/L and in these years the exceedance percentage was never higher than 15%.

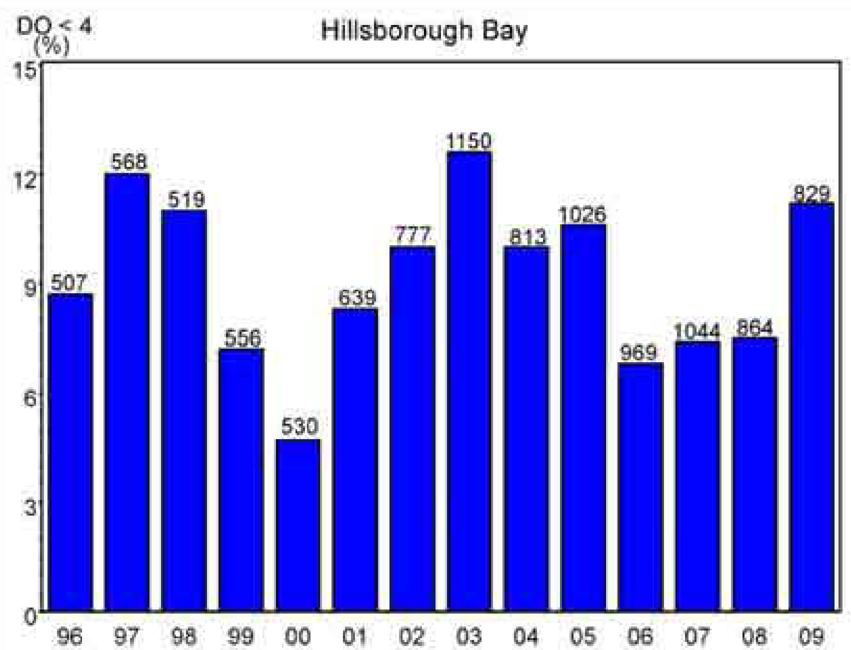


Figure 6. Annual percentage of DO values less than 4 mg/L in Hillsborough Bay. The number of samples shown above each bar.

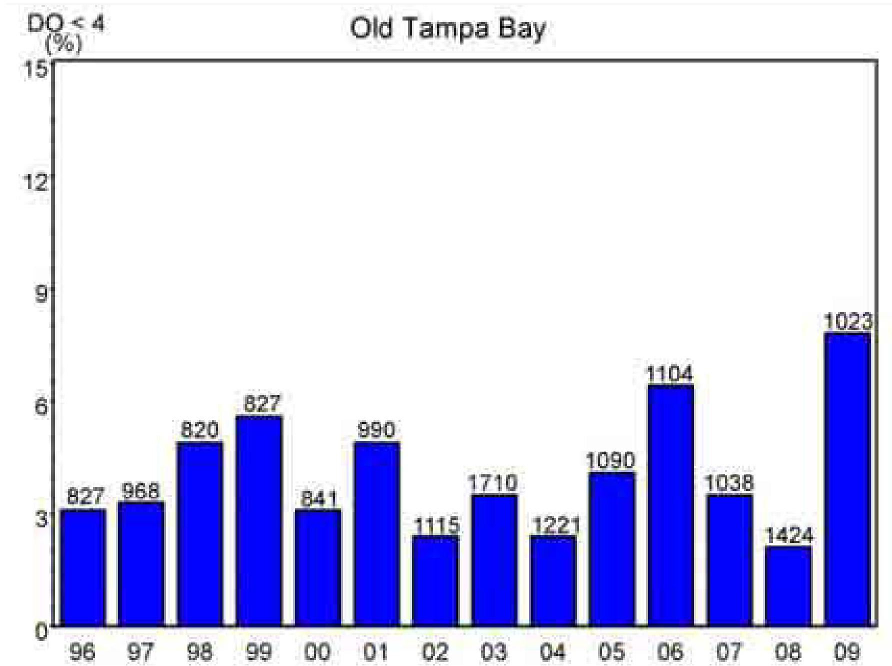


Figure 7. Annual percentage of DO values less than 4 mg/L in Old Tampa Bay. The number of samples shown above each bar.

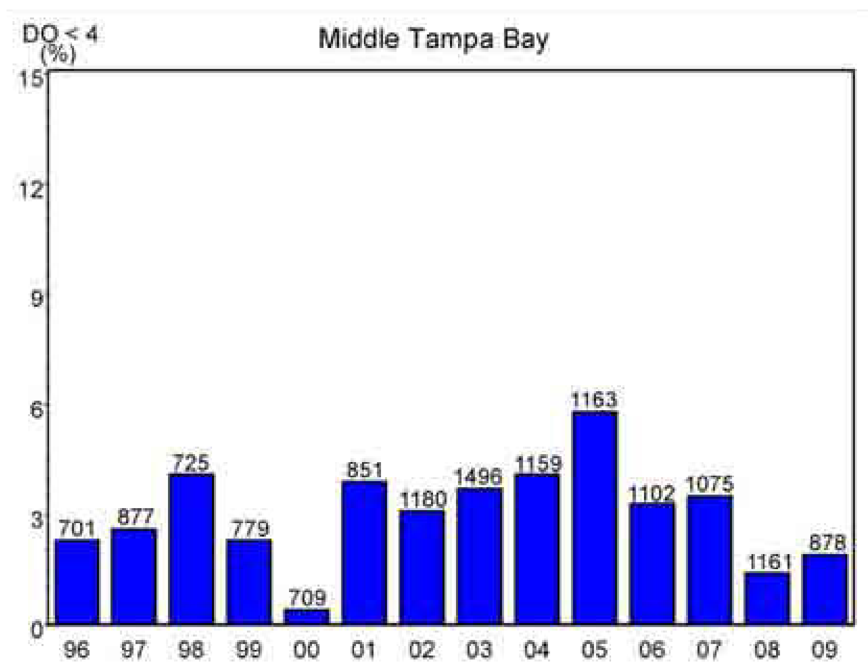


Figure 8. Annual percentage of DO values less than 4 mg/L in Middle Tampa Bay. The number of samples shown above each bar.

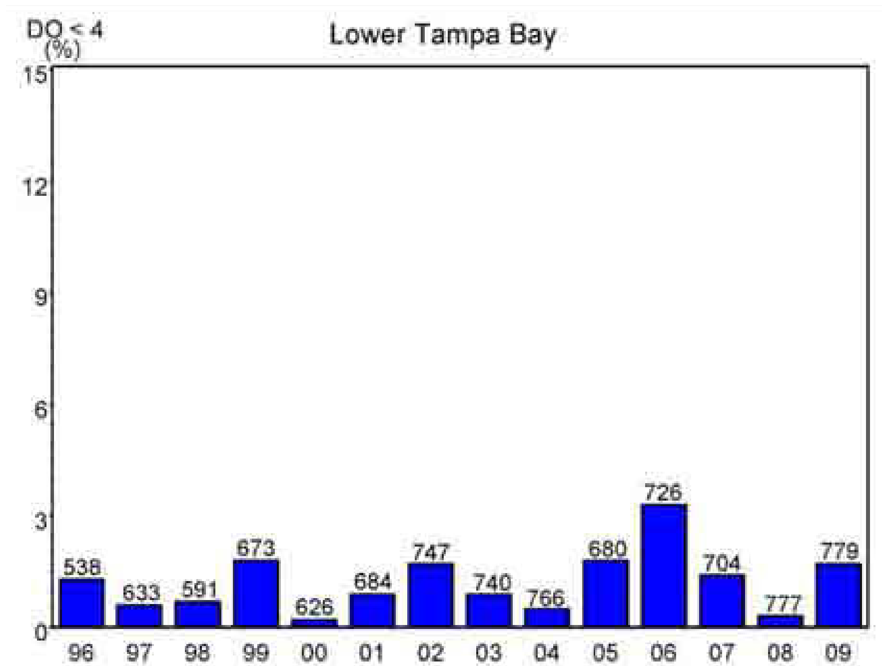


Figure 9. Annual percentage of DO values less than 4 mg/L in Lower Tampa Bay. The number of samples shown above each bar.

The within-year variation in the percentage of samples less than 4 mg/L for each bay segment is shown in Figures 10 through 13. The data presented in these figures include all DO samples from all programs regardless of sample depth. 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, while in summer months there is a higher preponderance of observations with a DO values below 4 mg/L. Hillsborough Bay was the only segment where the percentage of DO values < 4 mg/L exceeded 10% in any month.

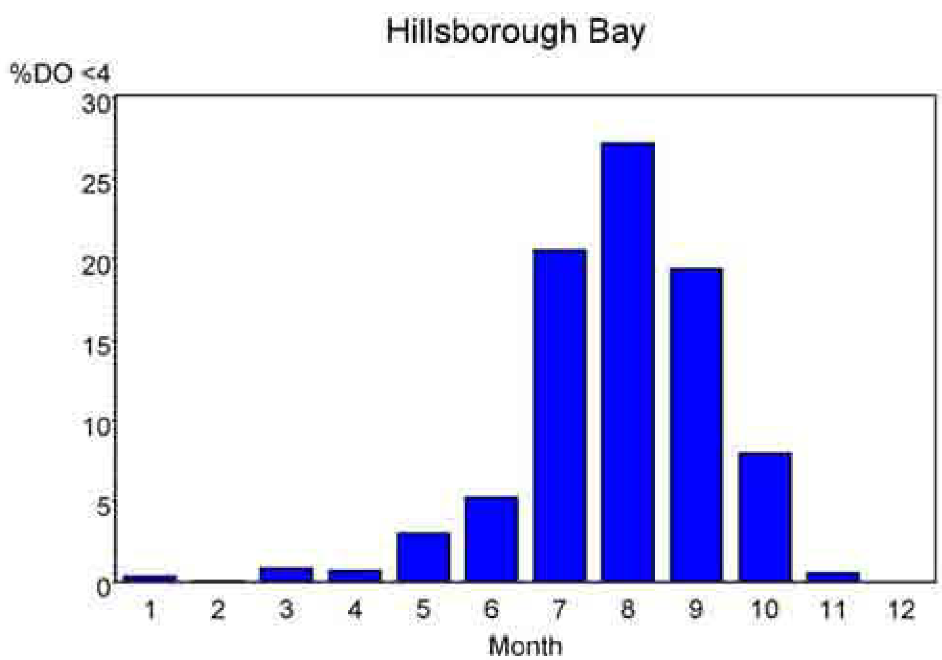


Figure 10. Seasonal distribution of DO exceedances across all years in Hillsborough Bay.

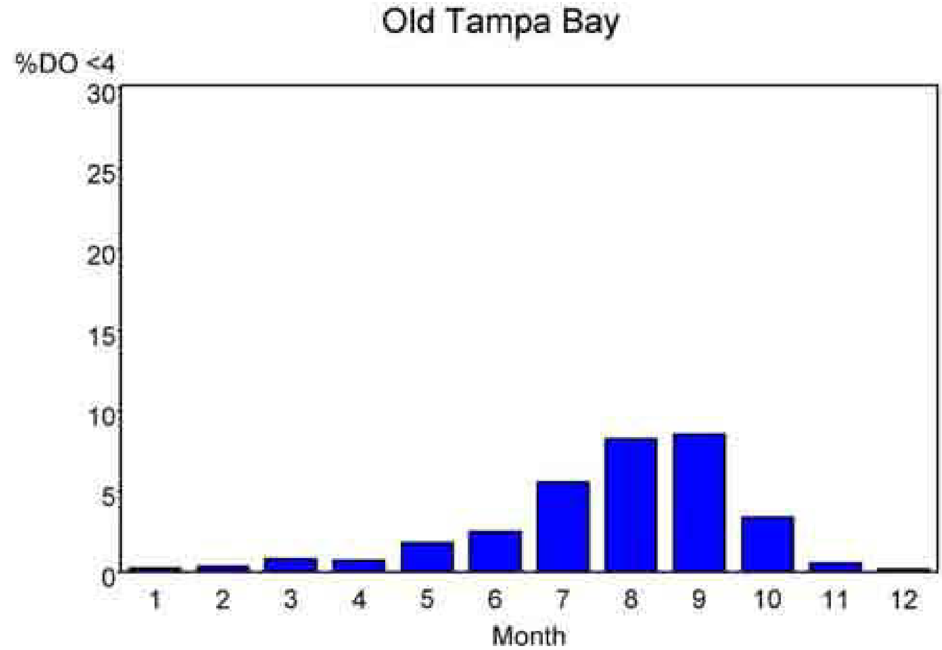


Figure 11. Seasonal distribution of DO exceedances across all years in Old Tampa Bay.

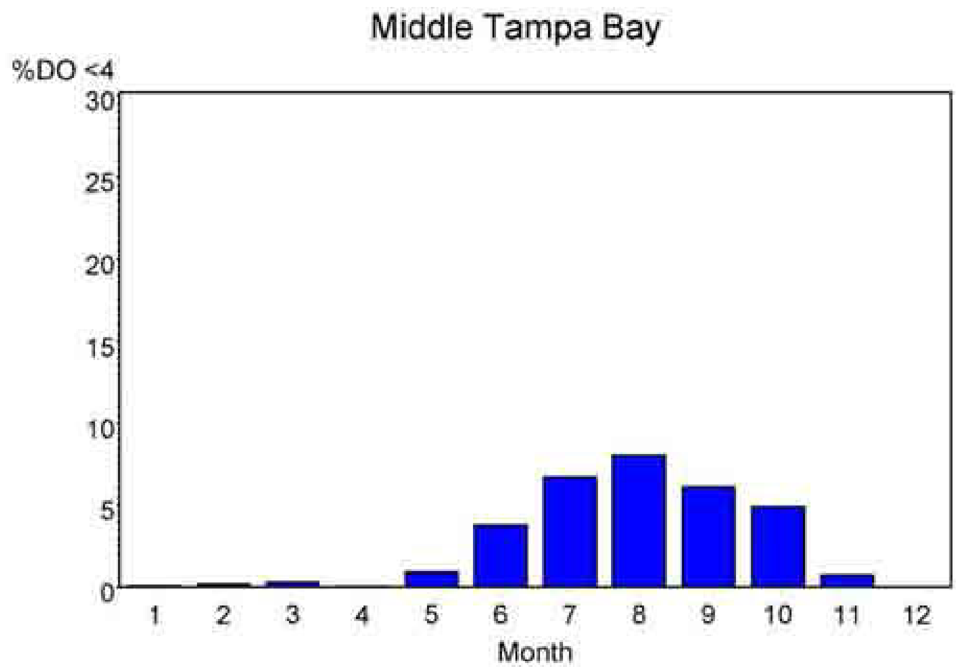


Figure 12. Seasonal distribution of DO exceedances across all years in Middle Tampa Bay.

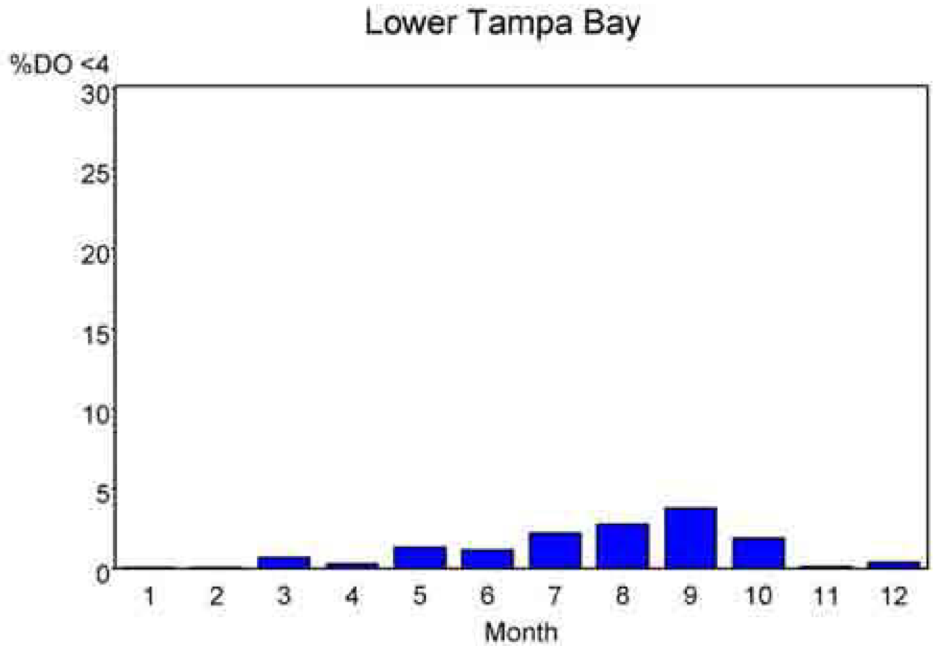


Figure 13. Seasonal distribution of DO exceedances across all years in Lower Tampa Bay.

4.2 DO exceedances – spatial patterns

While on a bay segment scale there were few instances when the percentage of DO values less than 4 mg/L exceeded 10% in a given year, there may be smaller scale areas where the probability of low DO conditions might be higher. In these smaller areas, confounding factors (e.g., water quality, depth, salinity, etc.) can affect the probability of low DO conditions.

To identify areas with a higher potential for DO exceedances in Tampa Bay, the spatial distribution of DO values throughout the bay was investigated. All DO data (irrespective of depth) collected during July, August, and September by all programs were mapped in ArcGIS. 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) (Figure 14). 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. For comparison, an additional map is provided using samples taken between November and March to represent winter conditions in Tampa Bay (Figure 15).

Examination of these maps indicates the following:

- The preponderance of DO values below 4 mg/L are found in Hillsborough Bay.
- Many of these values in Hillsborough Bay are found near the mouth of the Alafia and Hillsborough rivers.
- Many of the DO observations below 4 mg/L occurred in shallow waters along the shoreline of Tampa Bay.

- There are few DO values below 4 mg/L in Old Tampa Bay, Middle Tampa Bay, and Lower Tampa Bay.

Attachment 1 presents a series of maps depicting the spatial DO distributions within each year for each bay segment.

Sediments in Hillsborough Bay have higher silt-clay content than the sediments in the rest of Tampa Bay as shown on an interpolated contour plot of EPC sediment data (Figure 16). These areas of higher silt clay content generally coincide with areas in Hillsborough Bay where lower DO values were observed. Johansson and Squires (1989) summarized previous sediment characterizations within Tampa Bay which described an extremely similar pattern to the contour plot of Figure 16 suggesting that these areas of higher organic sediments are due at least in part to circulation within Hillsborough Bay as described by Goodwin 1989. Higher organic sediment content in Hillsborough Bay was attributed to eutrophic conditions in Hillsborough Bay resulting from previously excessive point source and non-point source discharges as well as nutrient and sediment inputs contributed by the Hillsborough and Alafia rivers (Johansson and Squires 1989). The accumulation of organic material in Hillsborough Bay sediments was described as a function of unconsumed primary production and waste material from consumers captured in areas with water depths greater than 10 feet and weak circulation patterns (Johansson and Squires 1989).

The silt-clay results are not surprising and are consistent with well-documented studies of Hillsborough Bay. The increased biological oxygen demand associated with deposition and decomposition of organic material on the bottom likely contributes to the observed lower DO values in these locations as seen in the summer DO plots (Figure 15).

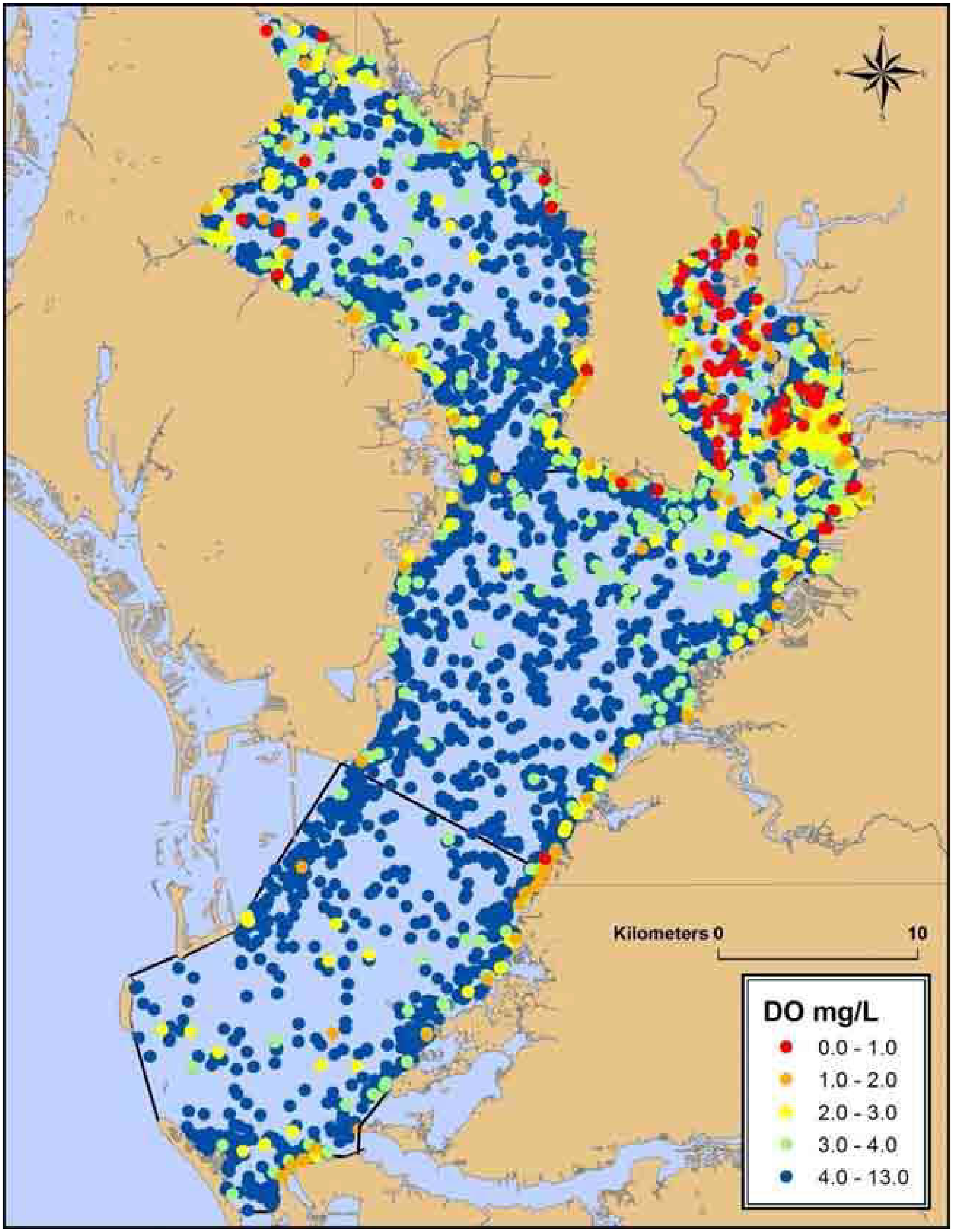


Figure 14. Spatial distribution of DO showing spatial susceptibility during summer months (July-August) by highlighting the lowest DO value recorded in a particular area.

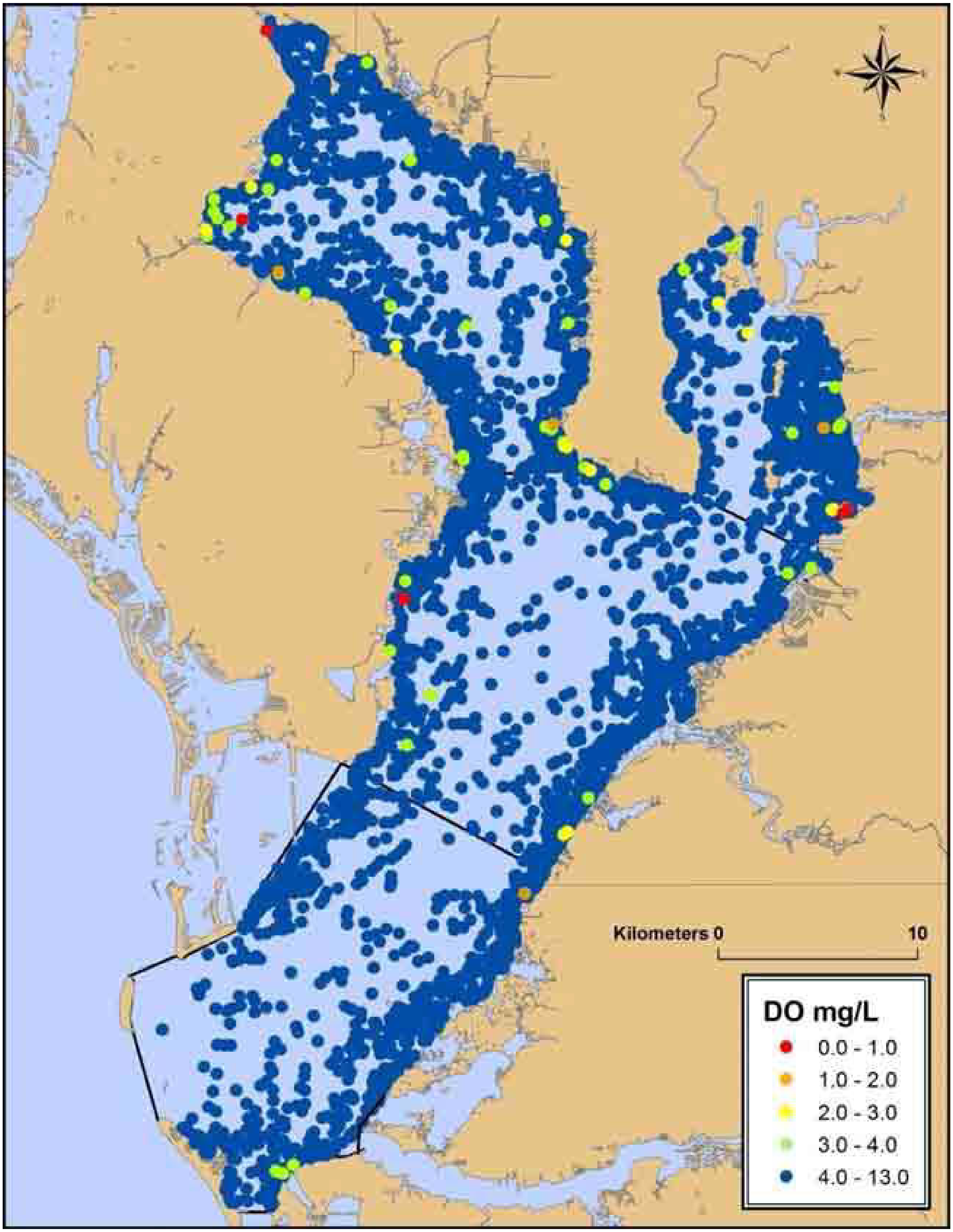


Figure 15. Spatial distribution of DO showing spatial susceptibility during winter months (November-March) by highlighting the lowest DO value recorded in a particular area.

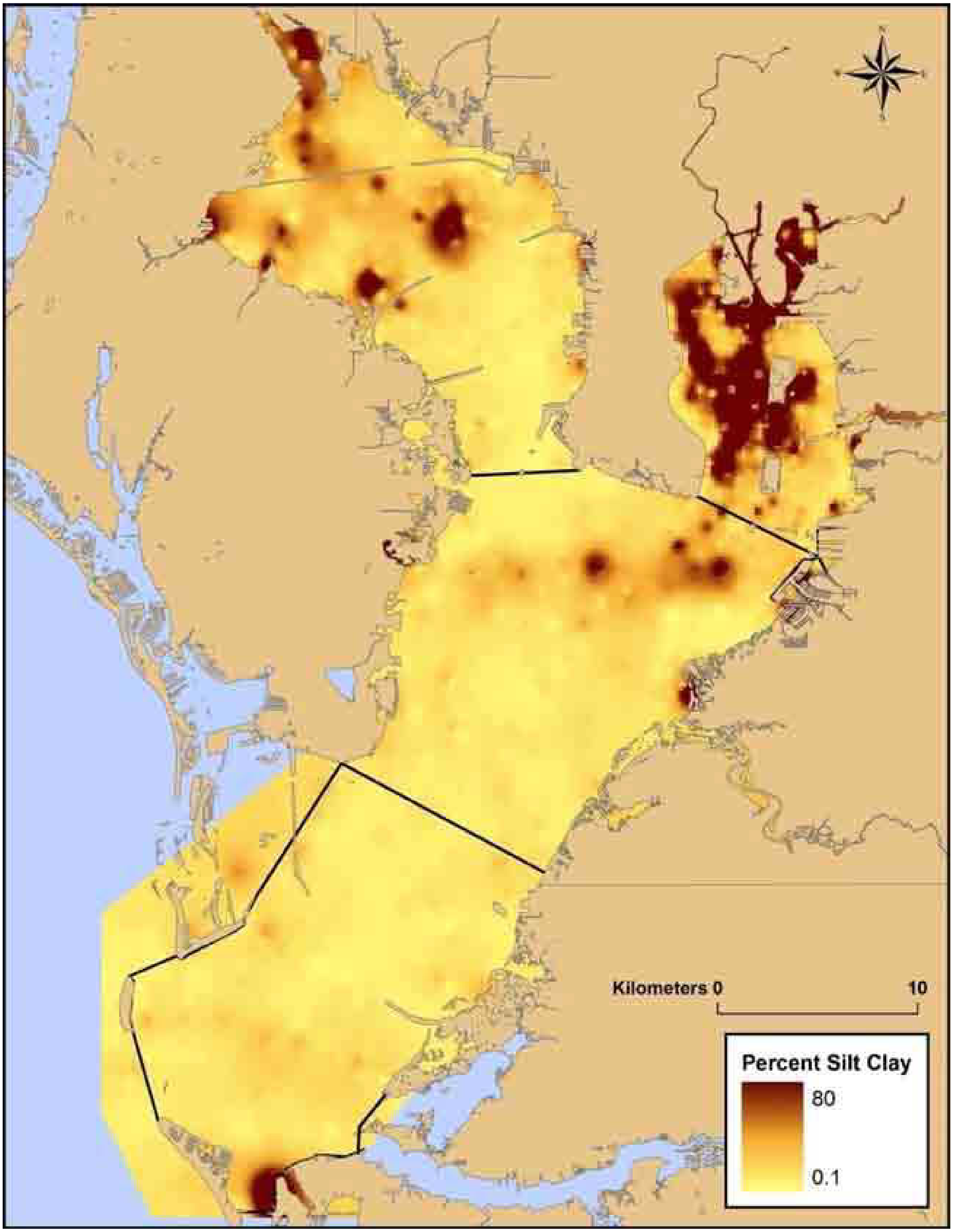


Figure 16. Contour plot of silt-clay content from data collected by the EPC benthic program.

To investigate the relationship between primary production and DO in Tampa Bay, the EPCHC fixed station data collected between 1974 and 2009 was used to calculate annual average chlorophyll *a* concentrations and annual DO exceedance frequencies in each bay segment over the entire period of record (Figures 17-20). The analysis was restricted to EPCHC data because they included concurrent DO (from all depths) and chlorophyll *a* concentrations throughout the period of record. A visual comparison of the time series plots suggests little correspondence between annual chlorophyll averages (green broken line) and DO exceedance frequencies (blue solid line) within each segment. The Pearson correlation statistic (Rho) confirmed a lack of relationship in any segment (p values > 0.05). However, it is clear in all segments that a reduction in chlorophyll *a* concentrations was evident after 1985 following implementation of regulatory actions that controlled wastewater and stormwater impacts to Tampa Bay (Greening and Janicki, 2006). During this same time period, the annual percentage of DO exceedances remained variable, and did not trend in either direction over the same time period. It should be noted that data used in this analysis show that the percentage of DO values < 4 mg/L consistently remained below 10% in all bay segments.

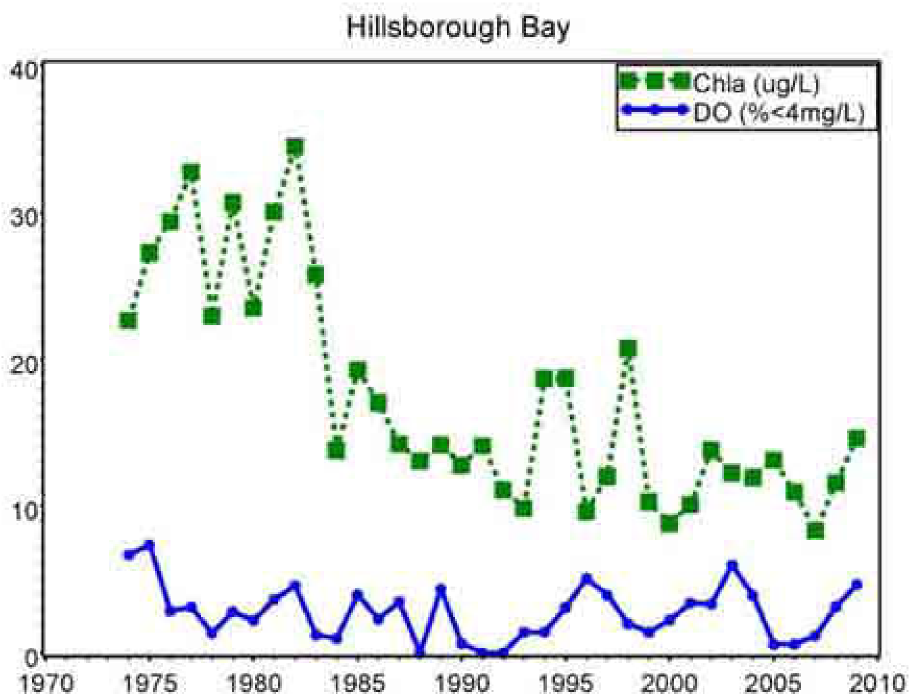


Figure 17. Time series of annual segment average chlorophyll *a* concentrations (μg/l) (broken green line) and annual segment percentage of DO values below 4 (mg/L) (solid blue line) in Hillsborough Bay between 1974 and 2009, as collected at EPCHC fixed stations.

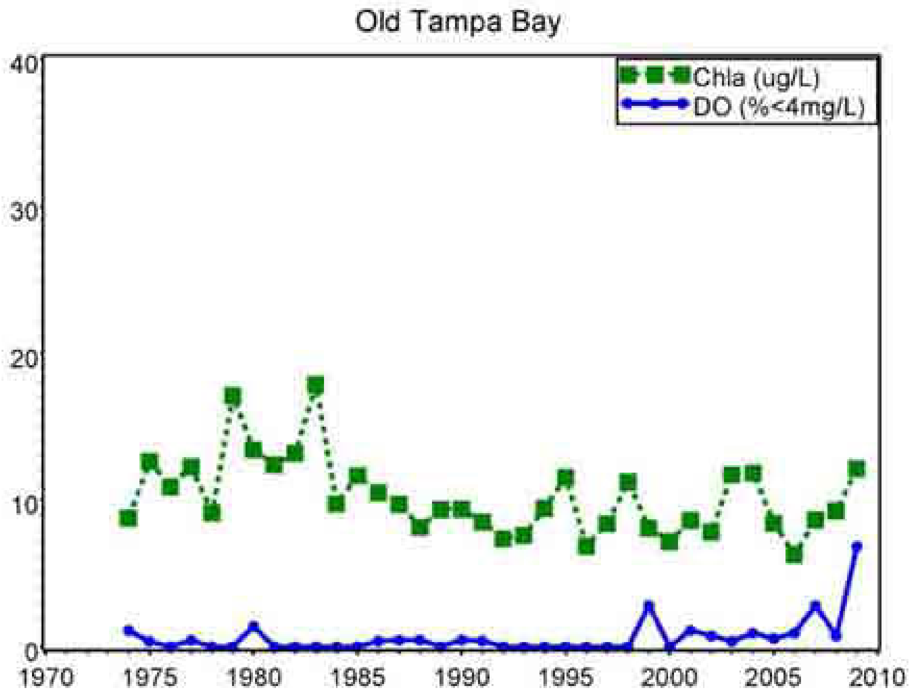


Figure 18. Time series of annual segment average chlorophyll *a* concentrations (μg/l) (broken green line) and annual segment percentage of DO values below 4 (mg/L) (solid blue line) in Old Tampa Bay between 1974 and 2009, as collected at EPCHC fixed stations.

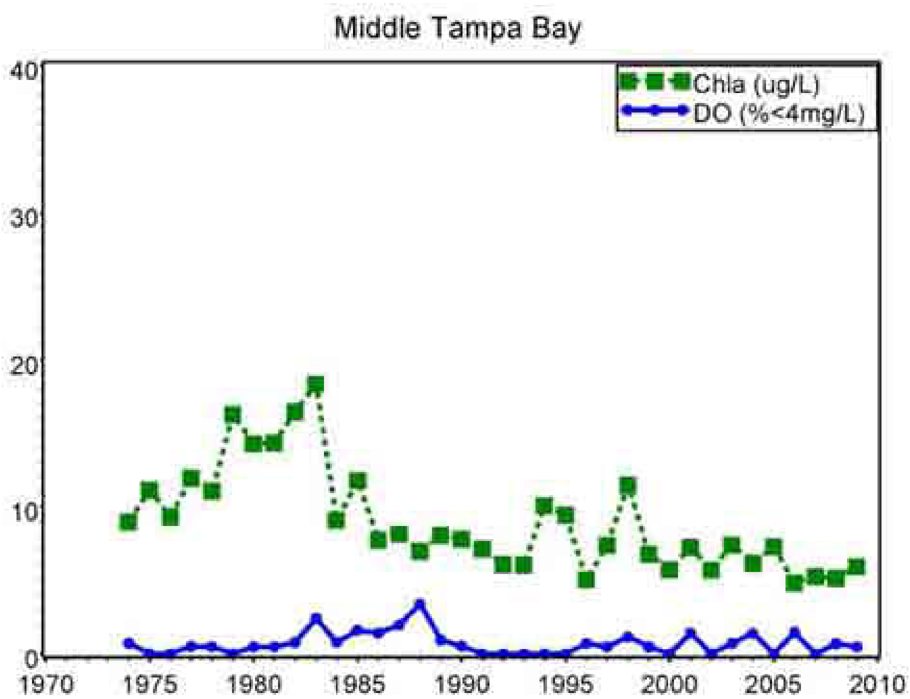


Figure 19. Time series of annual segment average chlorophyll *a* concentrations (μg/l) (broken green line) and annual segment percentage of DO values below 4 (mg/L) (solid blue line) in Middle Tampa Bay between 1974 and 2009, as collected at EPCHC fixed stations.

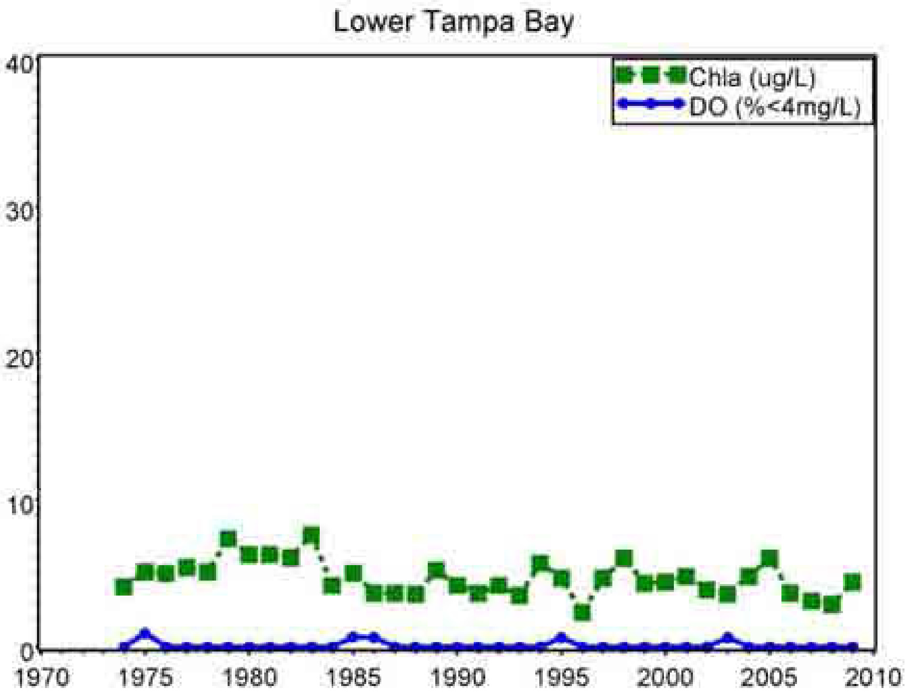


Figure 20. Time series of annual segment average chlorophyll *a* concentrations (μg/l) (broken green line) and annual segment percentage of DO values below 4 (mg/L) (solid blue line) in Lower Tampa Bay between 1974 and 2009, as collected at EPCHC fixed stations.

4.3 Modeling Contributing Factors Affecting Dissolved Oxygen

As described above, a generalized linear mixed-effects model was constructed to identify the principal factors (including physical and water quality factors) affecting the probability of observing a bottom DO value less than 4 mg/L. The EPCHC fixed station data collections from 1974 through 2009 were used for this analysis since both DO and chlorophyll *a* concentration measurements were taken concurrently. The model was constructed using all months (full model) and separately using a subset of data collected between July and August. The parameter estimates, resulting odds ratio estimates, and p-values are provided in Table 1. The relative effect of individual parameter estimates on the change in probability of observing a bottom DO < 4 mg/L can be assessed using either the odds ratio estimate or the F 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.

Model results suggest that temperature, the degree of salinity stratification between surface and bottom waters, sample depth, and sediment silt-clay content were the primary factors positively associated with the probability of a bottom DO exceedance. In neither model was chlorophyll *a* concentration a significant predictor of a bottom DO exceedance.

Therefore, physical influences have a greater influence on the probability of observing a low DO value than observed chlorophyll *a* concentrations. These results agree with the descriptive assessment of the ambient DO data and provide additional weight-of-evidence that DO values < 4 mg/L in Tampa Bay are affected more by physical processes than nutrient-driven processes.

Therefore, any numeric nutrient criteria that are proposed as being protective of primary production for the attainment of seagrass targets would be equally protective for DO conditions within the bay.

Table 1. Fixed effects parameter estimates from GLIMMIX model output with associated odds ratios and significance levels for full model (top) and model for summer only (bottom). The response variable is the probability of a bottom DO < 4 mg/L.

Parameter	Coefficient	Odds Ratio	F Value	Prob>F
Intercept	-19.962			
Percent silt-clay	0.130	1.138	11.550	0.001
Bottom depth	0.339	1.403	57.550	<.0001
Stratification	0.308	1.360	47.070	<.0001
Chlorophyll *a*	0.004	1.004	3.150	NS
Surface Salinity	-0.030	0.971	7.520	0.006
Bottom temperature	0.456	1.578	324.540	<.0001
Summer Only				
Parameter	Coefficient	Odds Ratio	F Value	Prob>F
Intercept	-14.441			
Percent silt-clay	0.119	1.126	14.390	0.000
Bottom depth	0.229	1.257	12.110	0.001
Stratification	0.321	1.379	24.690	<.0001
Chlorophyll *a*	0.003	1.003	0.850	NS
Surface Salinity	0.010	1.010	0.330	NS
Bottom temperature	0.271	1.311	17.090	<.0001

4.4 Relationships between Fish and Benthic Community Structure and Dissolved Oxygen in Tampa Bay

Data for both the fish and benthic communities were available in Tampa Bay and provided an opportunity to examine the potential relationships between community structure and DO conditions-. For benthic communities, the TBEP designed and implemented a bay-wide probabilistic benthic sampling program in 1993 (Coastal Environmental, 1993). Benthic samples are collected during a late summer index period following methods developed by the EPA Estuarine Environmental Monitoring and Assessment Program (EMAP). For fish and nekton communities, the Florida Fish and Wildlife Commission (FFWCC) began the Fisheries Independent Monitoring Program (FIM) in 1989 with seasonal monitoring. In 1996, the program switched to monthly monitoring using a stratified random sampling design. The FIM program uses small seines to collect juvenile and small bodied fishes in water depths of 1.8 meters or less. Trawls are used to collect samples in deeper waters. Larger sub-adult and adult fishes are collected using 183-meter haul seines (along shorelines) and purse seines (in open bay waters less than 3.3 meters deep). Generally, 25 samples are collected with each gear type in Tampa Bay each month and physical chemistry and habitat information is recorded along with each sample.

Examination of the benthic data included calculation and depiction of the annual mean number of taxa/sample, mean number of individuals/sample, and mean species diversity (H′) for those years in which the percentage of all DO samples < 4 mg/L exceeds 10% and those years when the percentage of all DO samples < 4 mg/L is less than 10% (this classification was based on all available DO data). Figures 21-23 present the results of this examination for Hillsborough Bay, the only segment that displayed any year with DO exceedances greater than 10%. Clearly, there were no demonstrable differences in the number of taxa, number of individuals, or species diversity between those years in which the percentage of DO samples < 4 mg/L exceeds 10% and those years when the percentage of DO samples < 4 mg/L is less than 10% in Hillsborough Bay.

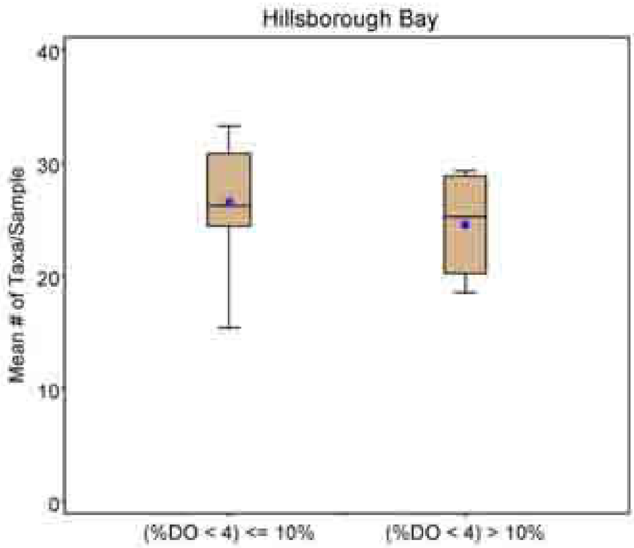


Figure 21. Comparison of the mean number of benthic taxa/sample in Hillsborough Bay for those years in which the percentage of DO samples < 4 mg/L exceeds 10% and those years when the percentage of DO samples < 4 mg/L is less than 10%. The DO classification was based on all available DO data.

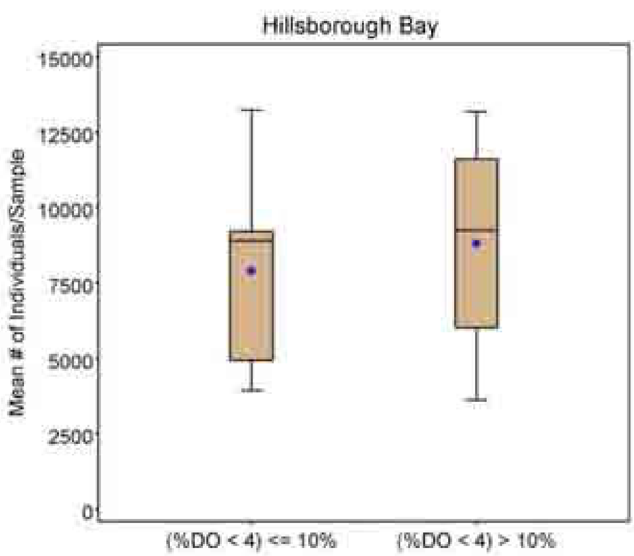


Figure 22. Comparison of the mean number of benthic individuals/sample in Hillsborough Bay for those years in which the percentage of DO samples < 4 mg/L exceeds 10% and those years when the percentage of DO samples < 4 mg/L is less than 10%. The DO classification was based on all available DO data.

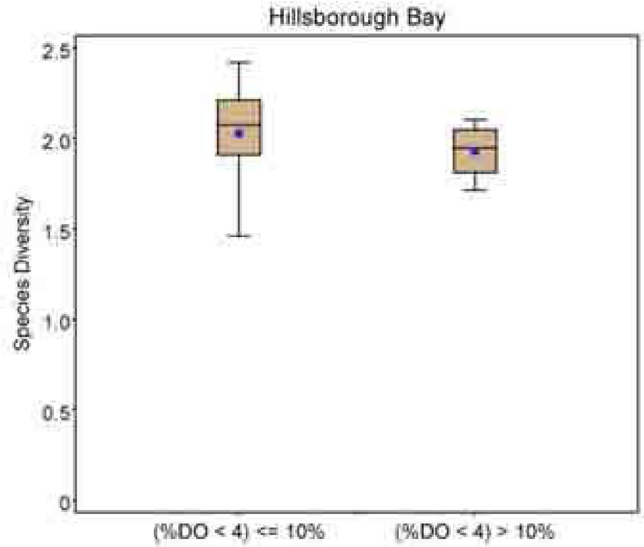


Figure 23. Comparison of the mean benthic species diversity/sample in Hillsborough Bay for those years in which the percentage of DO samples < 4 mg/L exceeds 10% and those years when the percentage of DO samples < 4 mg/L is less than 10%. The DO classification was based on all available DO data.

Likewise, the fish data were examined using the annual mean species richness, number of fish/haul, and mean species diversity (H') to compare those years in which the percentage of DO samples < 4 mg/L exceeded 10% and those years when the percentage of all DO samples < 4 mg/L was lower than 10%. Figures 24-26 present the results of this examination for Hillsborough Bay, the only segment that displayed any year with all DO exceedances greater than 10%. Each figure presents the results for 4 gear types: 20 m seines, 183 m seines, 183 m purse seines, and 6 m trawls. As was the case with the benthic metrics, there were no significant differences in the species richness, number of fish/haul, or fish species diversity between those years in which the percentage of all DO samples < 4 mg/L exceeds 10% and those years when the percentage of all DO samples < 4 mg/L is less than 10% in Hillsborough Bay. Attachment 2 presents a series of bivariate plots of fish species richness, number of fish/haul, and fish species diversity as a function of bottom DO observed at the time of sampling.

These results indicate that the Hillsborough Bay benthic and fish community structure did not differ in years when DO exceedances were greater than 10% from that observed in years in which exceedances were below 10%.

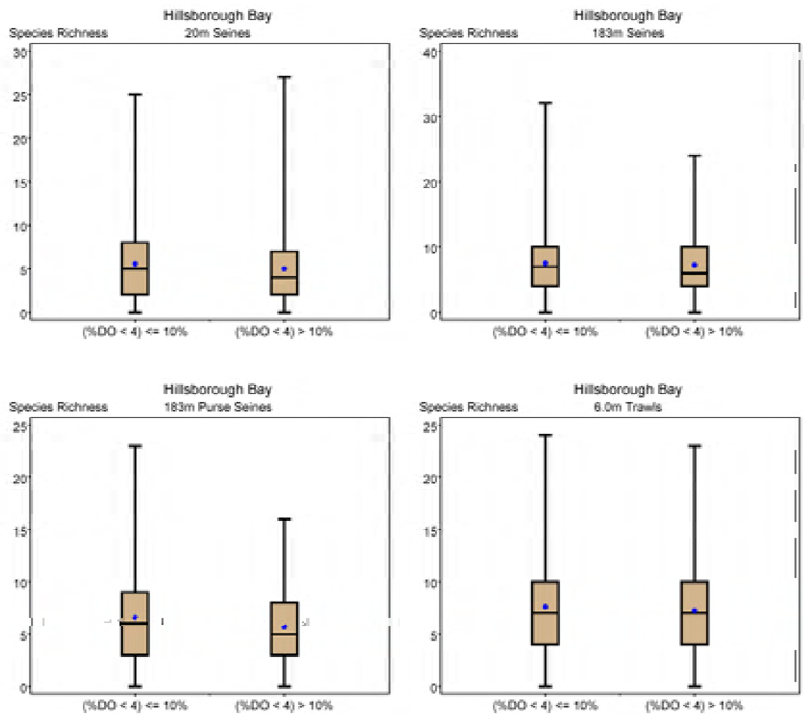


Figure 24. Comparison of the mean fish species richness in Hillsborough Bay for those years in which the percentage of DO samples < 4 mg/L exceeds 10% and those years when the percentage of DO samples < 4 mg/L is less than 10%. DO data are from samples taken concurrently with fish collections.

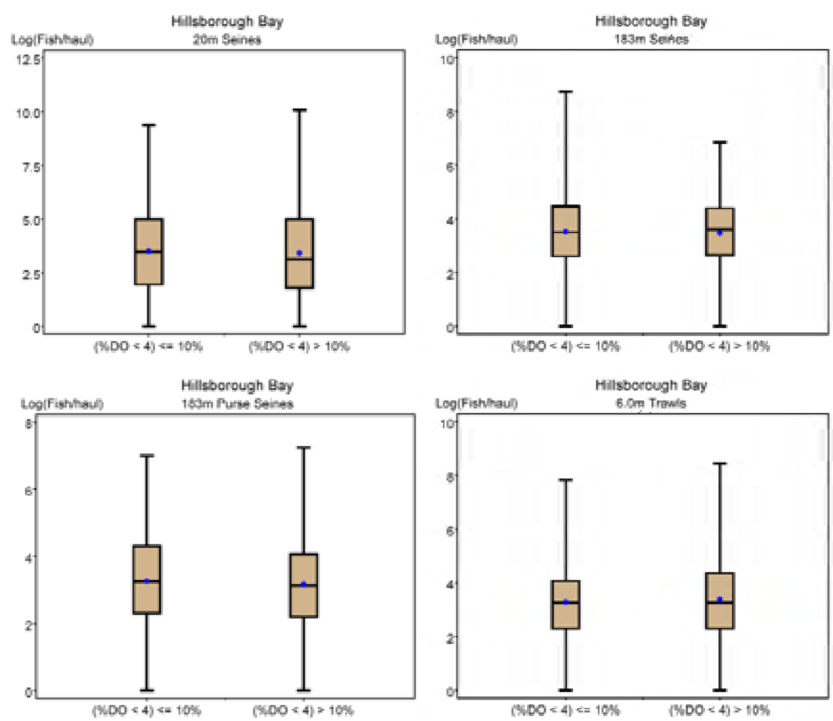


Figure 25. Comparison of the mean number of fish/haul in Hillsborough Bay for those years in which the percentage of DO samples < 4 mg/L exceeds 10% and those years when the percentage of DO samples < 4 mg/L is less than 10%. DO data are from samples taken concurrently with fish collections.

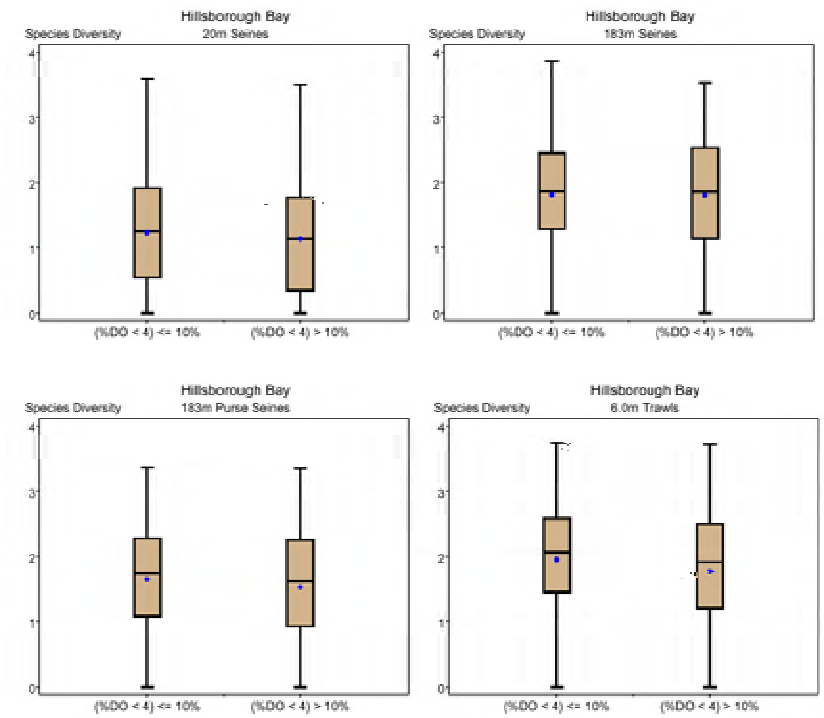


Figure 26. Comparison of the mean fish species diversity in Hillsborough Bay for those years in which the percentage of DO samples < 4 mg/L exceeds 10% and those years when the percentage of DO samples < 4 mg/L is less than 10%. DO data are from samples taken concurrently with fish collections.

5.0 Conclusions

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

- The empirical evidence presented here suggests that all major segments of Tampa Bay are meeting full aquatic life support with respect to DO. Examination of the spatial distribution of DO samples shows that DO exceedances < 4 mg/L are most likely to occur in Hillsborough Bay near the mouths of the Hillsborough and Alafia Rivers, and along the western half of Hillsborough Bay. These are deeper areas, more likely to be stratified due to freshwater inputs, and have high organic sediment content. These issues in Hillsborough Bay are well-understood and have been the subject of much research as described by Johansson and Squires (1989). The dredging of Hillsborough Bay to accommodate large container vessels and cruise ships has changed circulation patterns in Hillsborough Bay as described by Goodwin (1989). These conditions in combination with historically excessive point source and nonpoint source loadings and natural sediment transport from the Hillsborough and Alafia rivers have resulted in the accumulation of organic sediments in these areas. At the time of the National Oceanic and Atmospheric Administration's (NOAA) [Estuary-of-the-Month] special issue publication series featuring Tampa Bay and Sarasota Bay (NOAA, 1989), selective dredging was considered as a remediation measure for these sediments. Estevez (1989) countered that natural biological processes in the sediments would remediate the effects of the organic-rich sediments, if given enough time and continued nutrient load reductions and sediment exchange processes were realized (Greening and Janicki, 2006). While high organic sediments remain in parts of Hillsborough Bay, sediment nutrient fluxes have been decreasing in Hillsborough Bay (Janicki Environmental, 2010) indicating that the sediments are becoming less of a nutrient source than when Hillsborough Bay was experiencing the eutrophic conditions of the 1970's and early 1980's.

- The principal factor affecting DO in Tampa Bay is temperature. That is evident in both the descriptive temporal plots and in the generalized linear model utilized in the quantitative assessment of those factors affecting the probability of DO being less than 4 mg/L. The model results indicate that stratification, bottom type, and sample depth were other factors that contributed to the probability of low DO conditions (i.e., < 4 mg/L). Furthermore, it was determined that chlorophyll *a* concentrations were not a significant factor contributing to the probability of low DO conditions in Tampa Bay. In other words, the occurrence of DO values below 4 mg/L were not significantly related to observed chlorophyll *a* concentrations at the time of sampling.

- 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 support with respect to DO.

6.0 References

Coastal Environmental, Inc. 1993. A Monitoring Program to Assess Environmental Changes in Tampa Bay, FL. Technical Publication #02-93 of the Tampa Bay National Estuary Program. Prepared by Coastal Environmental, Inc. (A.P. Squires, A.J. Janicki, D.G. Heimbuch, and H.T. Wilson).

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

Estevez, E. D. 1989. Water Quality Trends and Issues, Emphasizing Tampa Bay. In: NOAA Estuary of the Month Seminar Series 11: Tampa and Sarasota Bays: Issues, Resources, Status and Management. Ed. E.D. Estevez. pp 65-88. U.S. Department of Commerce. Washington, D.C.

Florida Fish and Wildlife Conservation Commission (FFWCC). 2010. Fisheries Independent Monitoring uses a Stratified Random Sampling. http://research.myfwc.com/features/view_article.asp?id=20074.

Goodwin, C. R. 1989. Circulation of Tampa and Sarasota Bays. In: NOAA Estuary of the Month Seminar Series 11: Tampa and Sarasota Bays: Issues, Resources, Status and Management. Ed. Estevez. pp 49-64. U.S Department of Commerce, Washington D.C.

Greening, H. and A. Janicki. 2006. Toward reversal of eutrophic conditions in a subtropical estuary: Water quality and seagrass response to nitrogen loading reductions in Tampa Bay, Florida, USA. Environmental Management. 38:163-178.

Janicki, A, R. Pribble, and M. Winowitch. 2001. Estimation of the Spatial and Temporal Nature of Hypoxia in Tampa Bay, Florida. Technical Report #09-01 of the Tampa Bay Estuary Program. Prepared by Janicki Environmental, Inc.

Janicki Environmental, Inc. 2010. Draft Technical Memorandum. Tampa Bay Assimilative Capacity Screening Analysis. Prepared for Tampa Bay Estuary Program.

Janicki Environmental, Inc. 2011. Tampa Bay Numeric Nutrient Criteria: Task 1 – TN and TP Concentrations. Letter Memorandum. Prepared for Tampa Bay Estuary Program.

Johansson, J.O.R. and A.P. Squires. 1989. Surface sediments and their relationship to water quality in Hillsborough Bay, a highly impacted subdivision of Tampa Bay. Florida. In: NOAA Estuary of the Month Seminar Series 11: Tampa and Sarasota Bays: Issues, Resources, Status and Management. Ed. Estevez. pp 129-143. U.S Department of Commerce, Washington D.C.

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

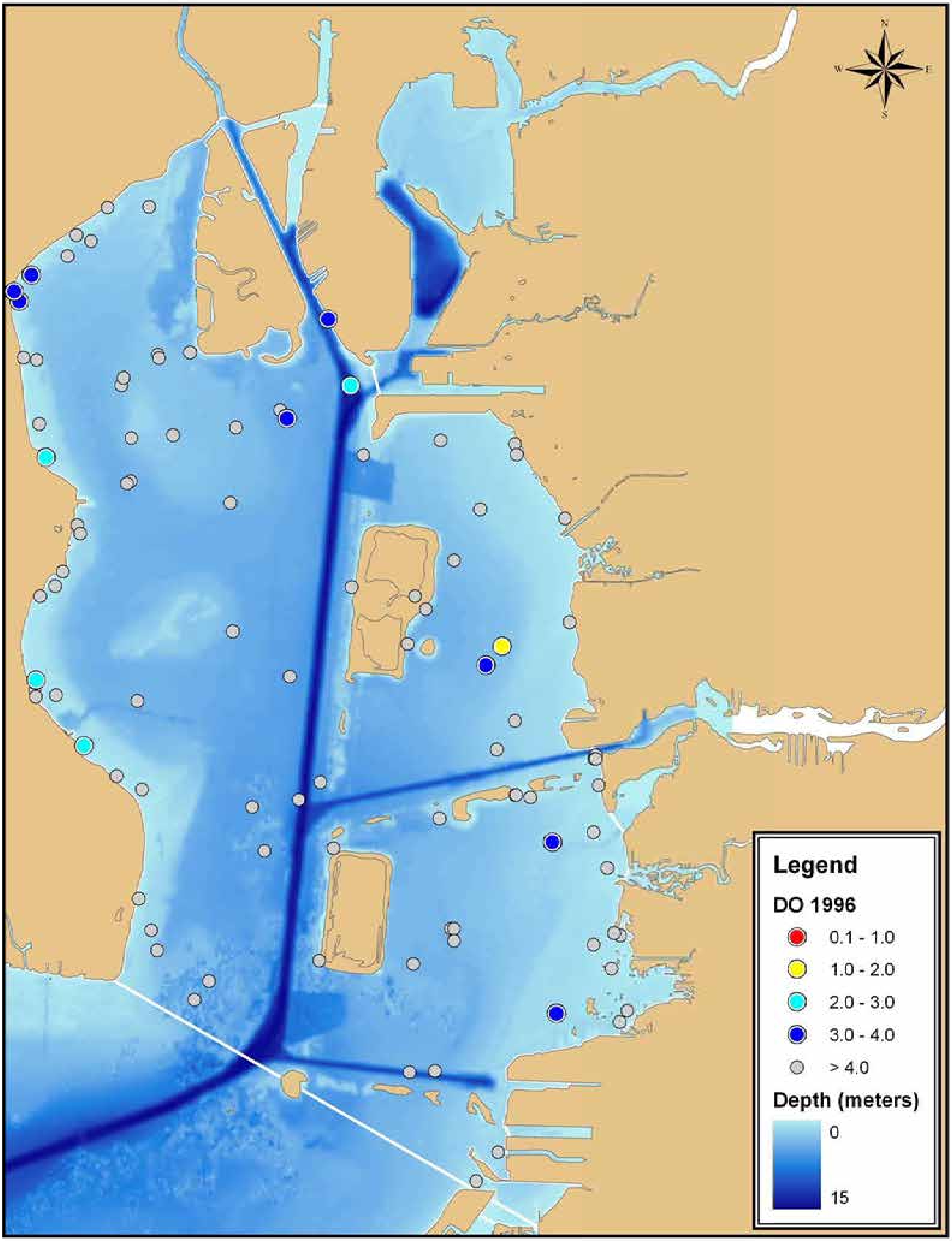
National Oceanic and Atmospheric Administration (NOAA). 1989. NOAA Estuary of the Month Seminar Series 11: Tampa and Sarasota Bays: Issues, Resources, Status and Management. Ed. Estevez. pp 65-88. U.S Department of Commerce, Washington D.C.

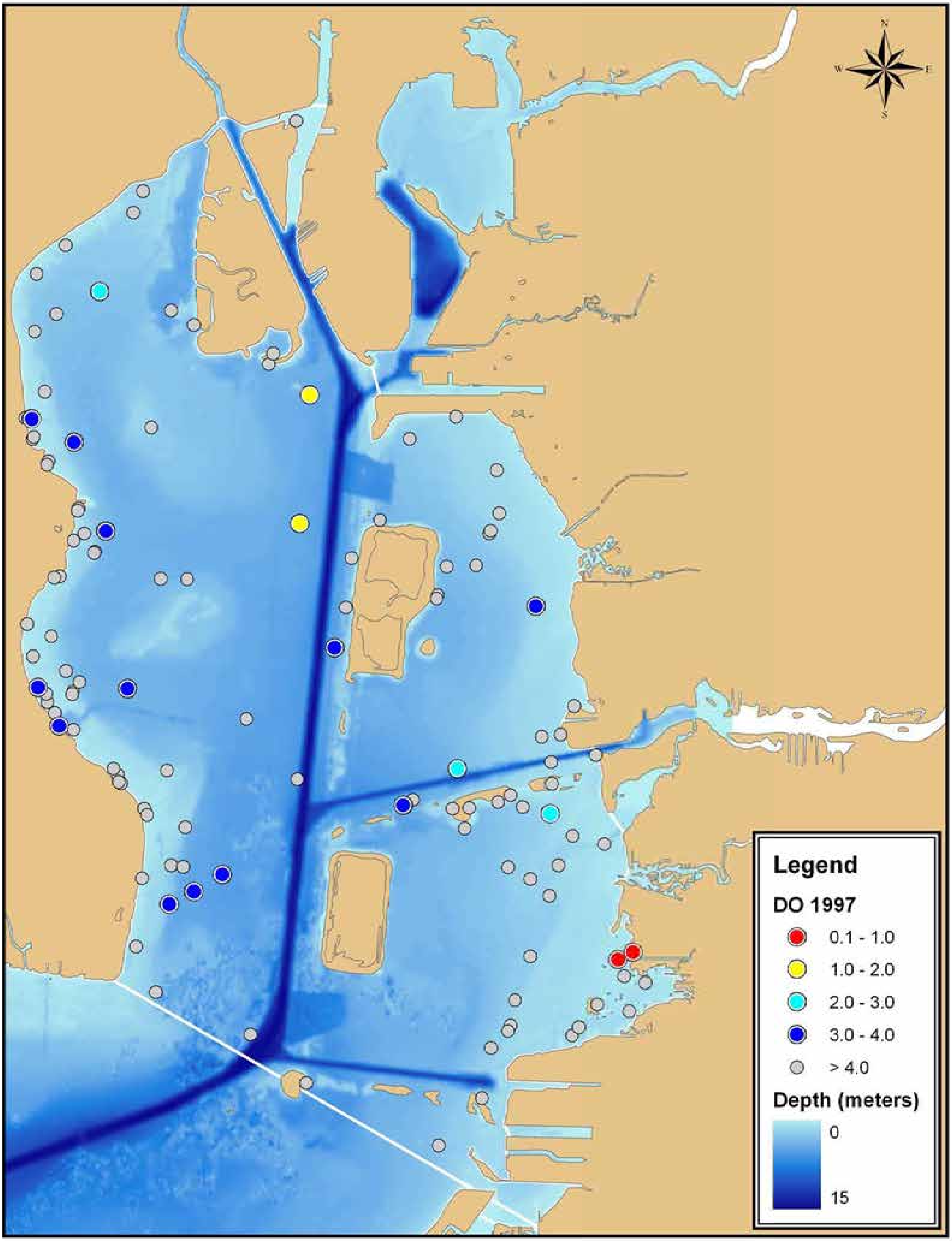
Statistical Analysis Systems (SAS®) 2008. Version 9.2. Cary, North Carolina.

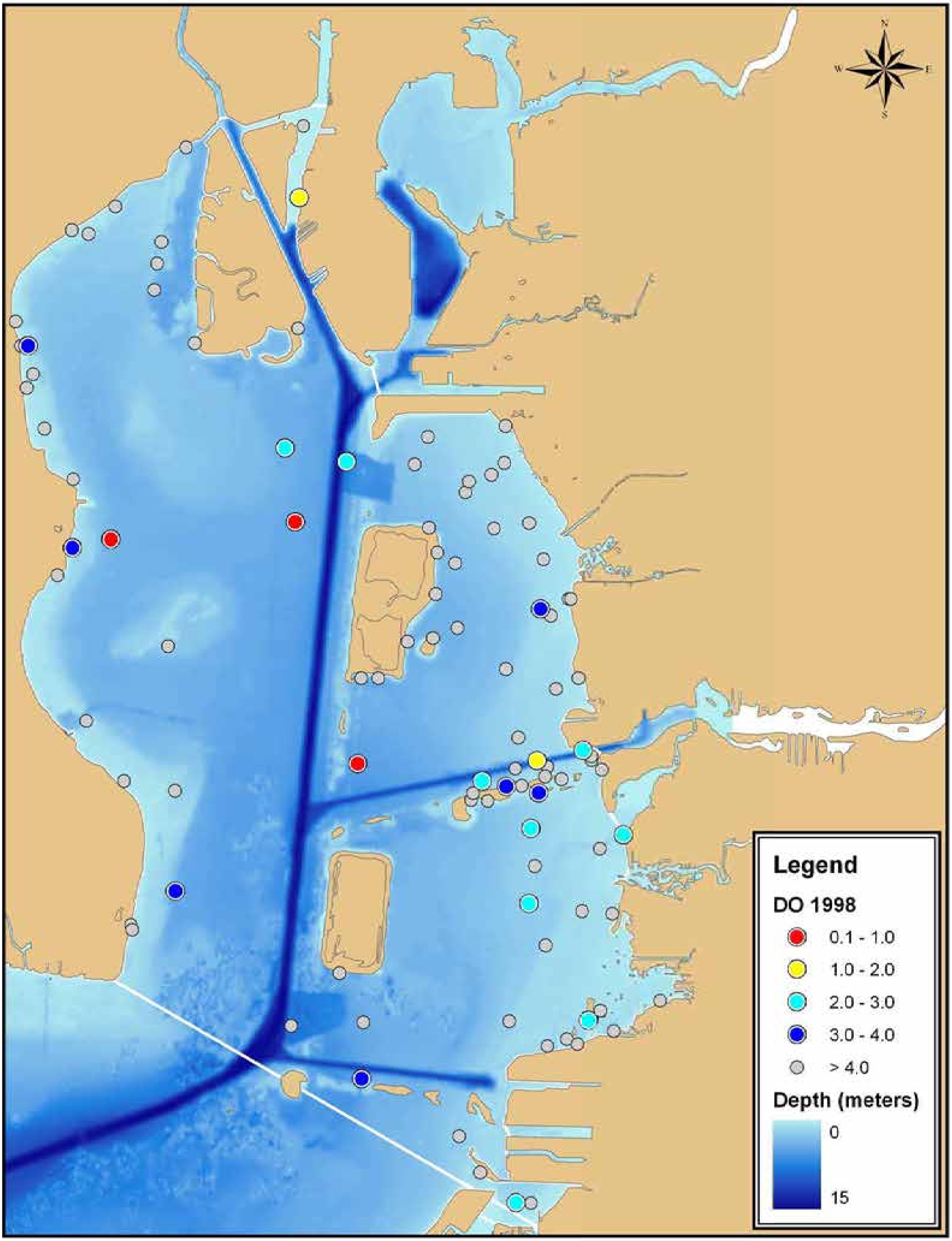
SAS Institute Inc. 2008. *SAS/STAT® Version 9.2 Users Guide*. Cary, North Carolina: SAS Institute Inc.

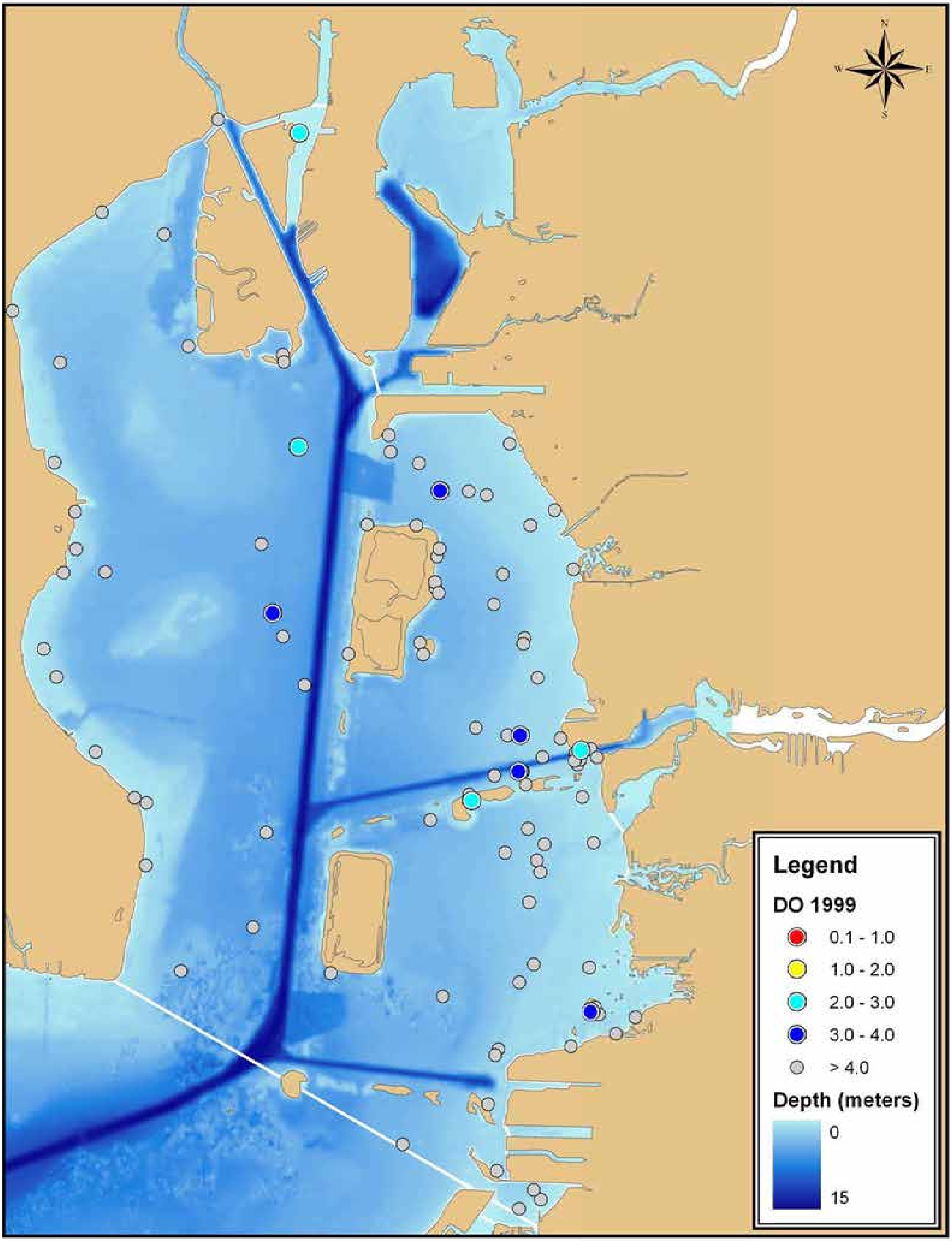
Attachment 1

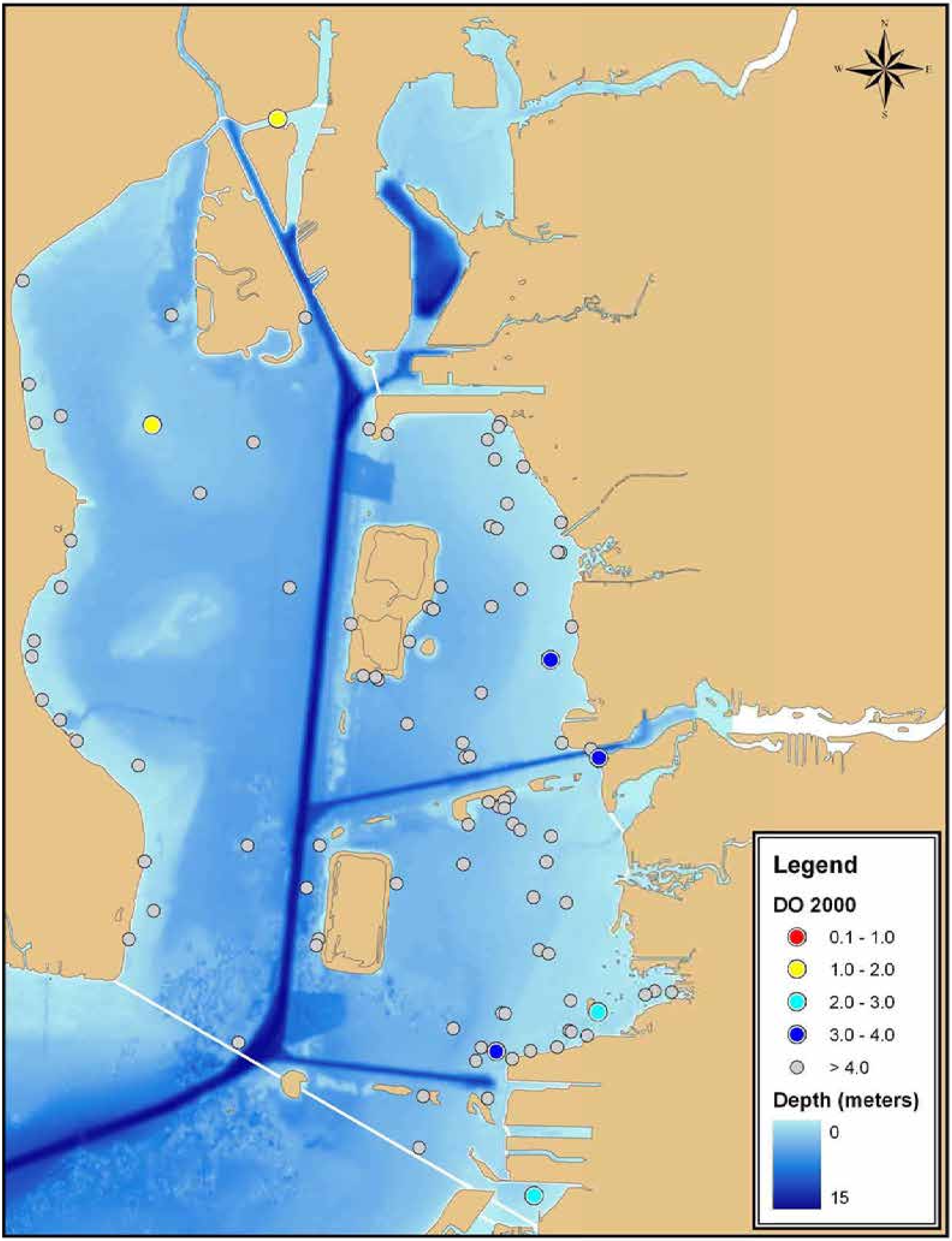
Annual Spatial Distribution of DO Data for Each Major Bay Segment


N
W
E
S
Legend
DO 1996
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

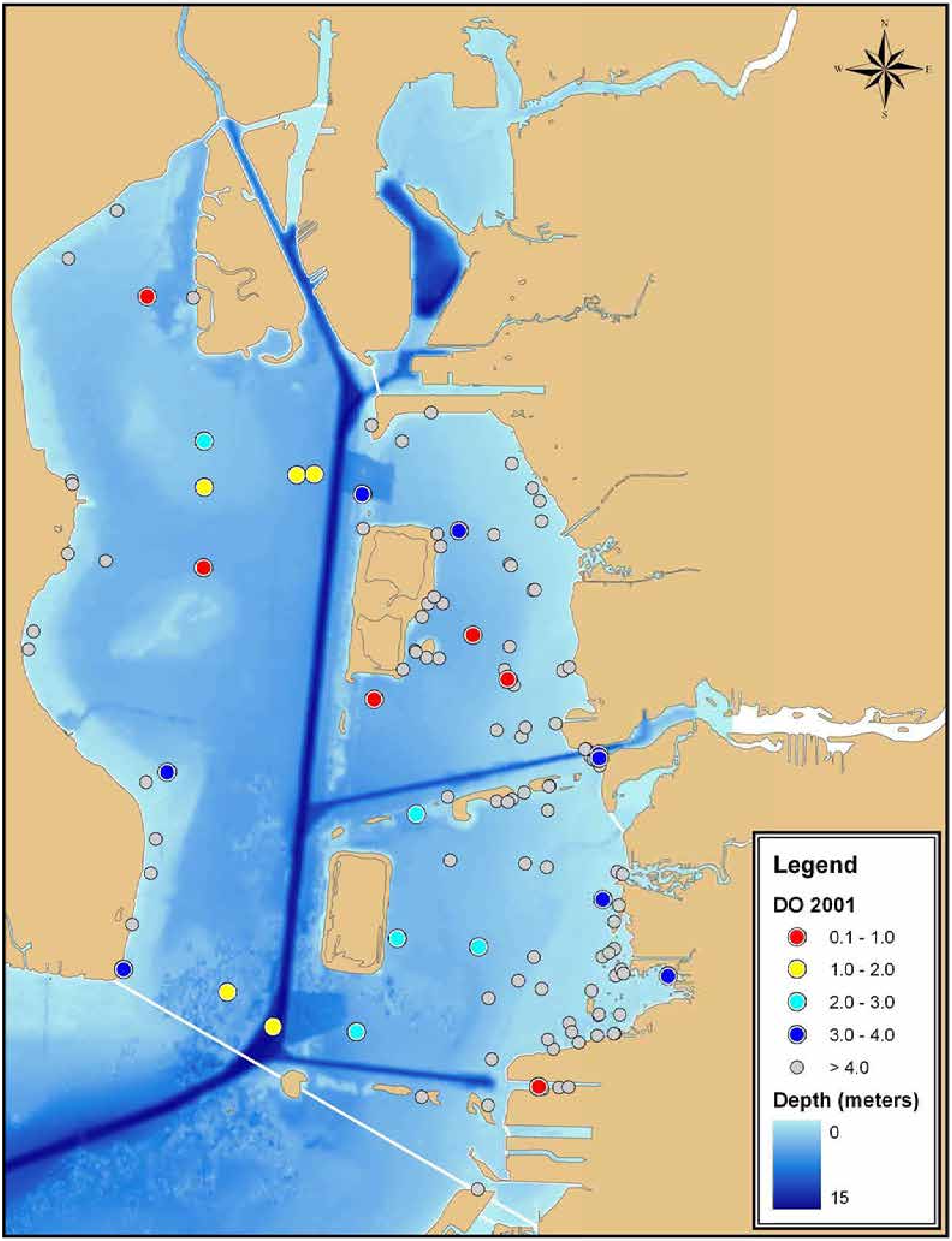

N
W
E
S
Legend
DO 1997
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

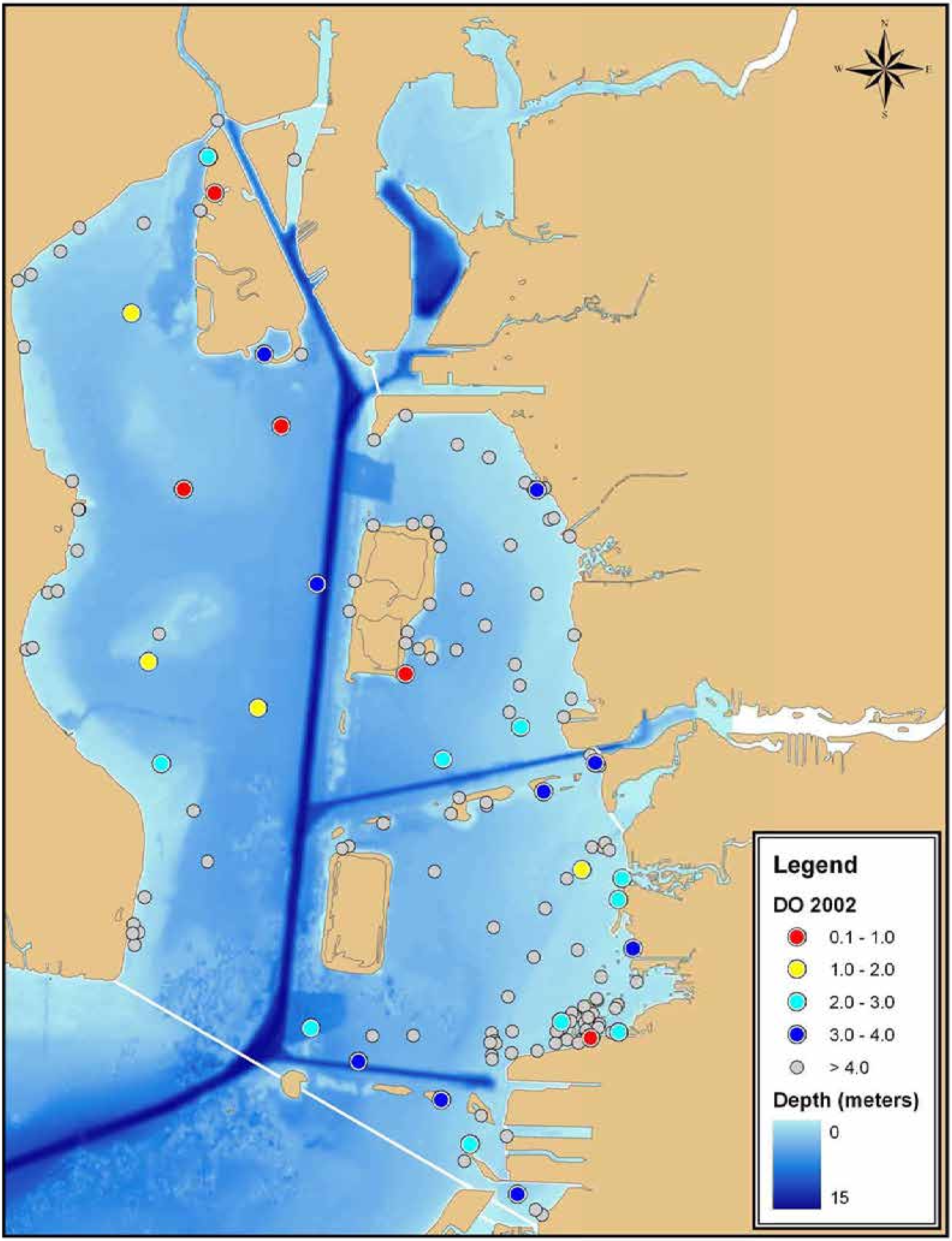

N
S
E
W
Legend
DO 1998
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

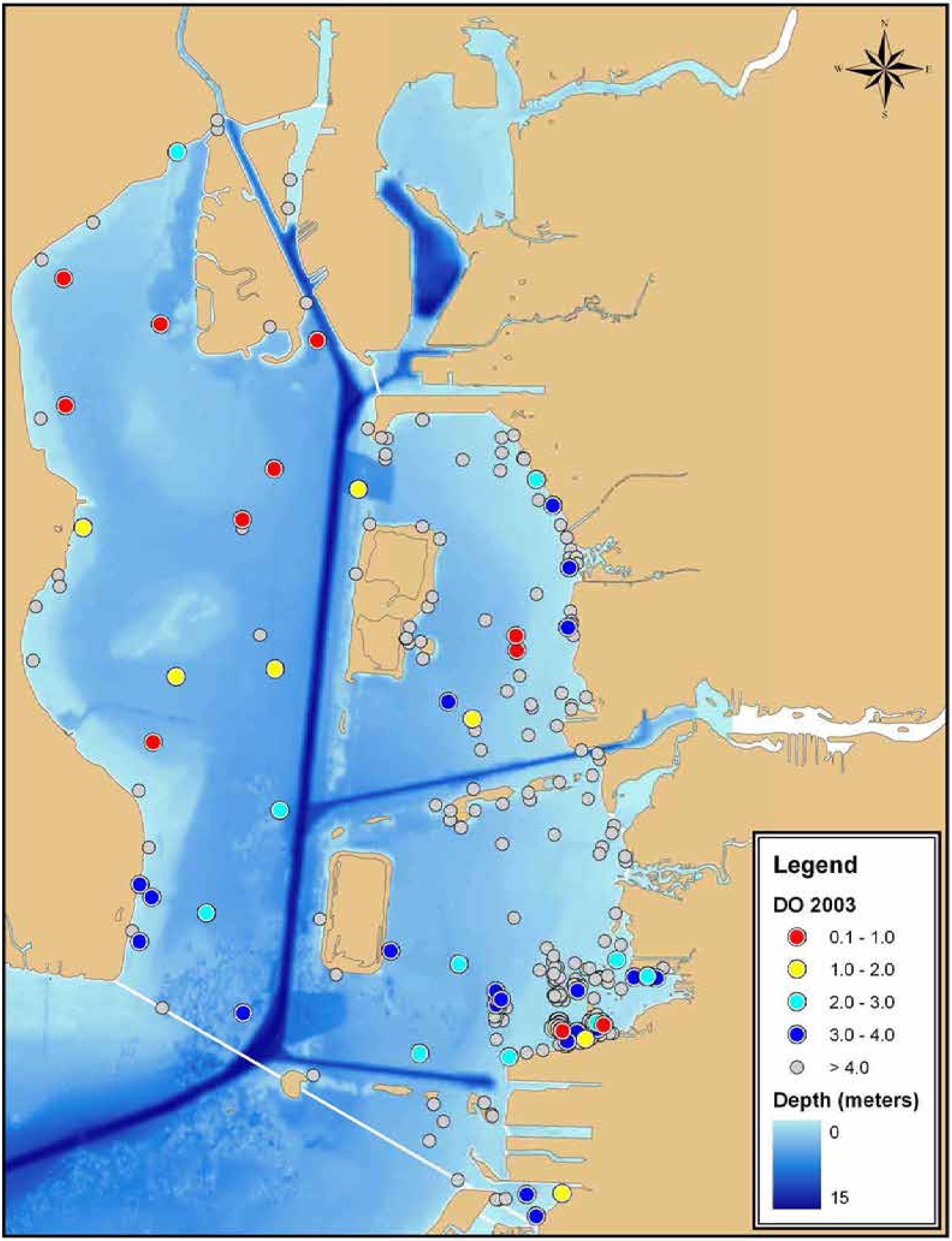

N
S
W
E
Legend
DO 1999
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

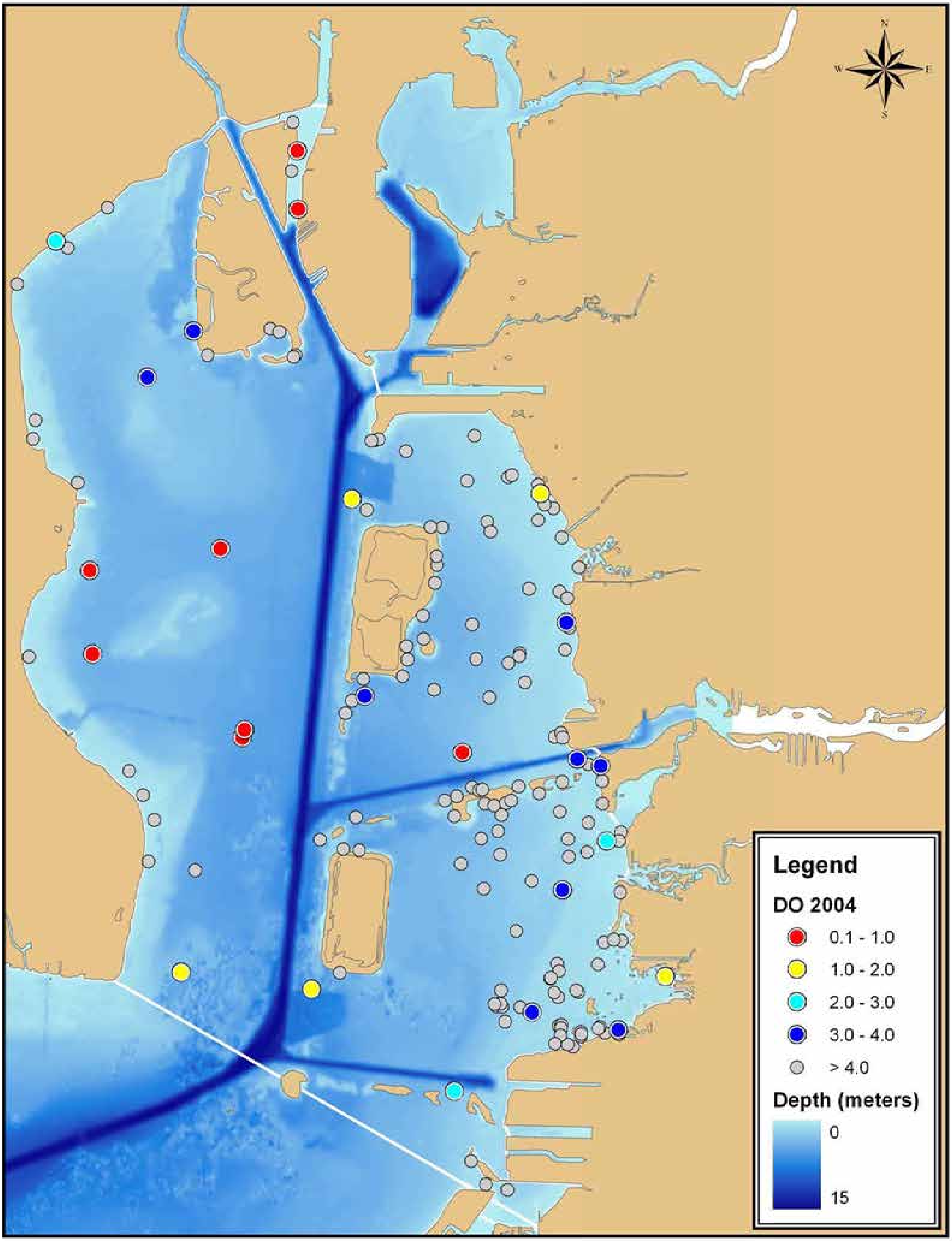


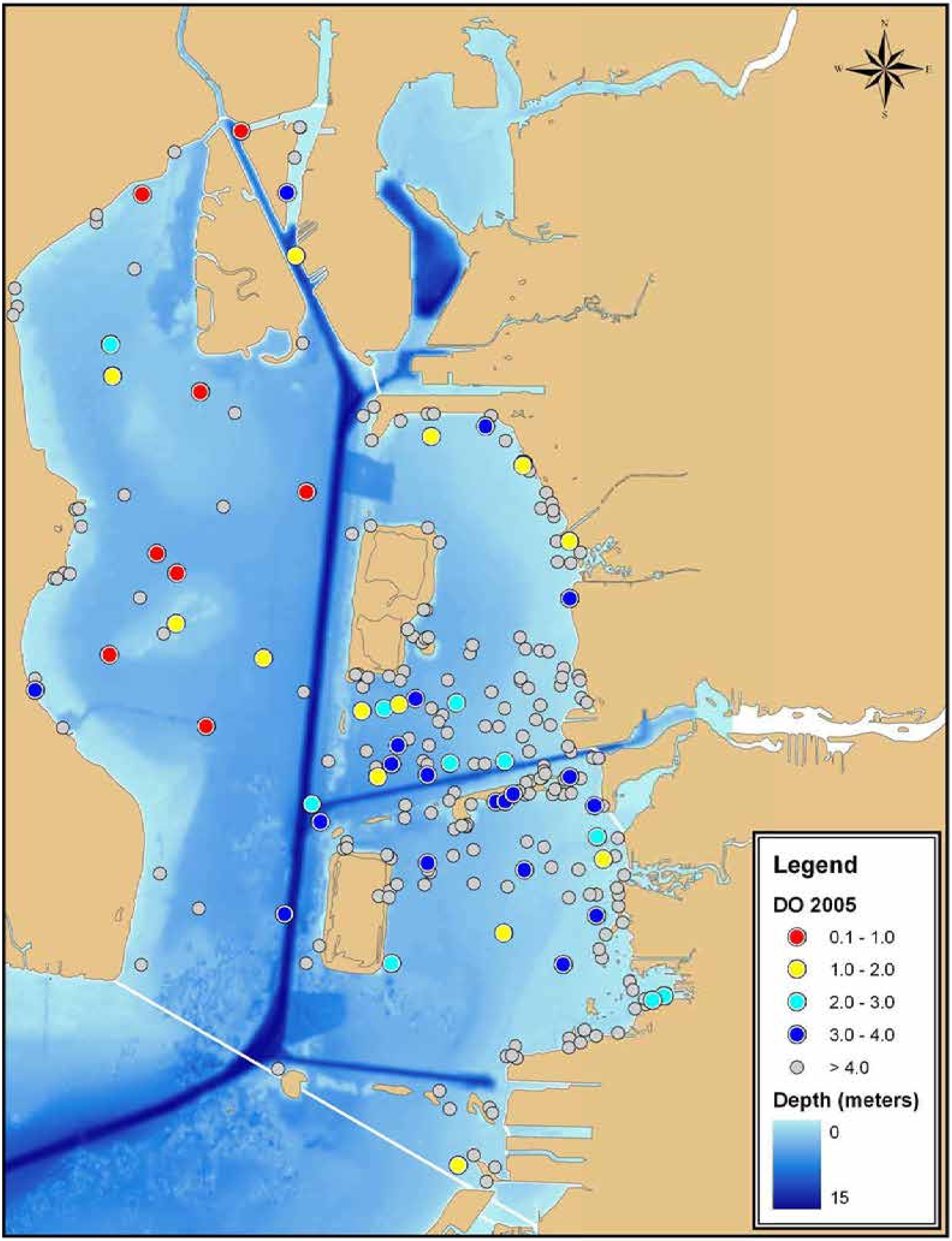
N
W
E
S
Legend
DO 2000
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

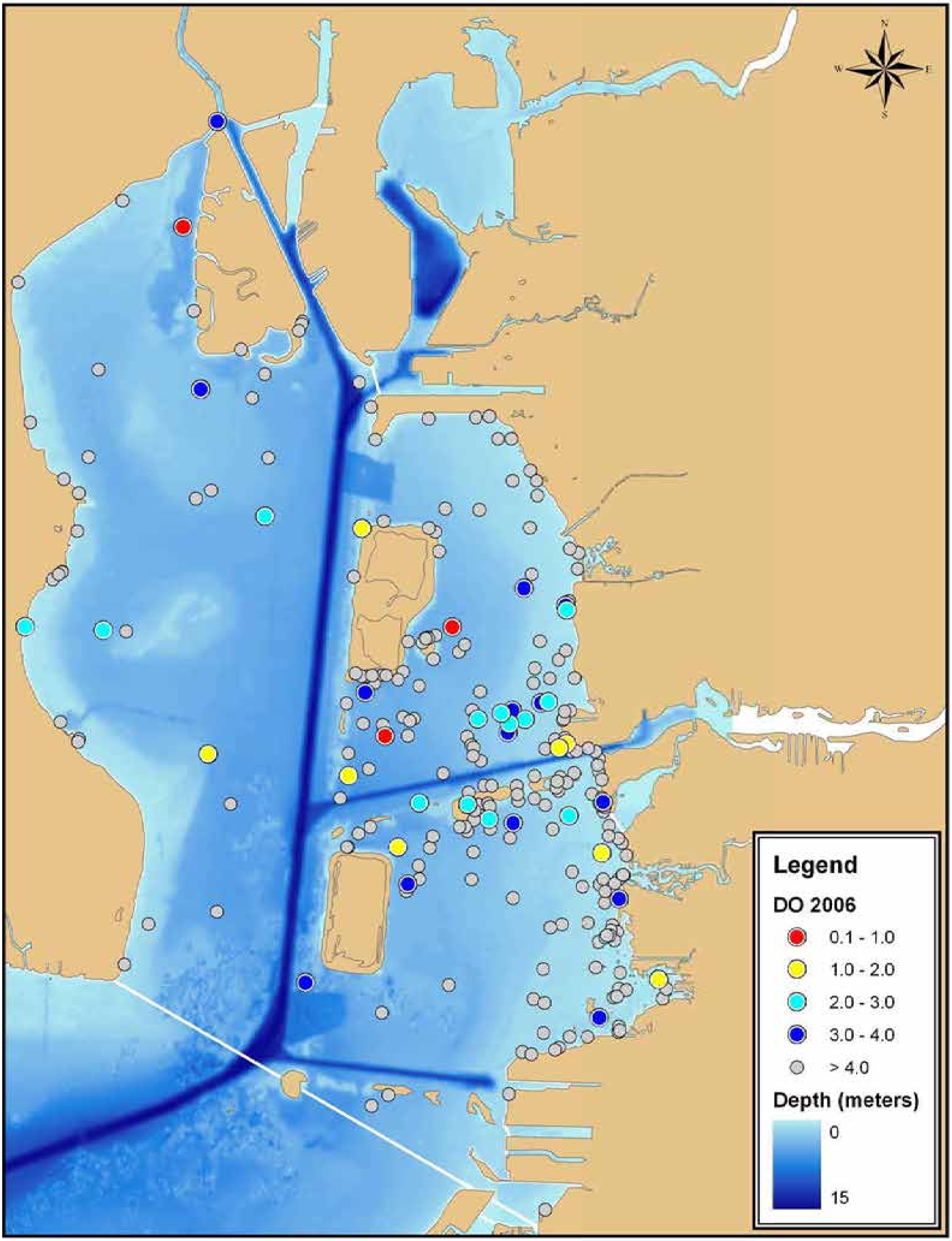

N
W
E
S
Legend
DO 2001
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

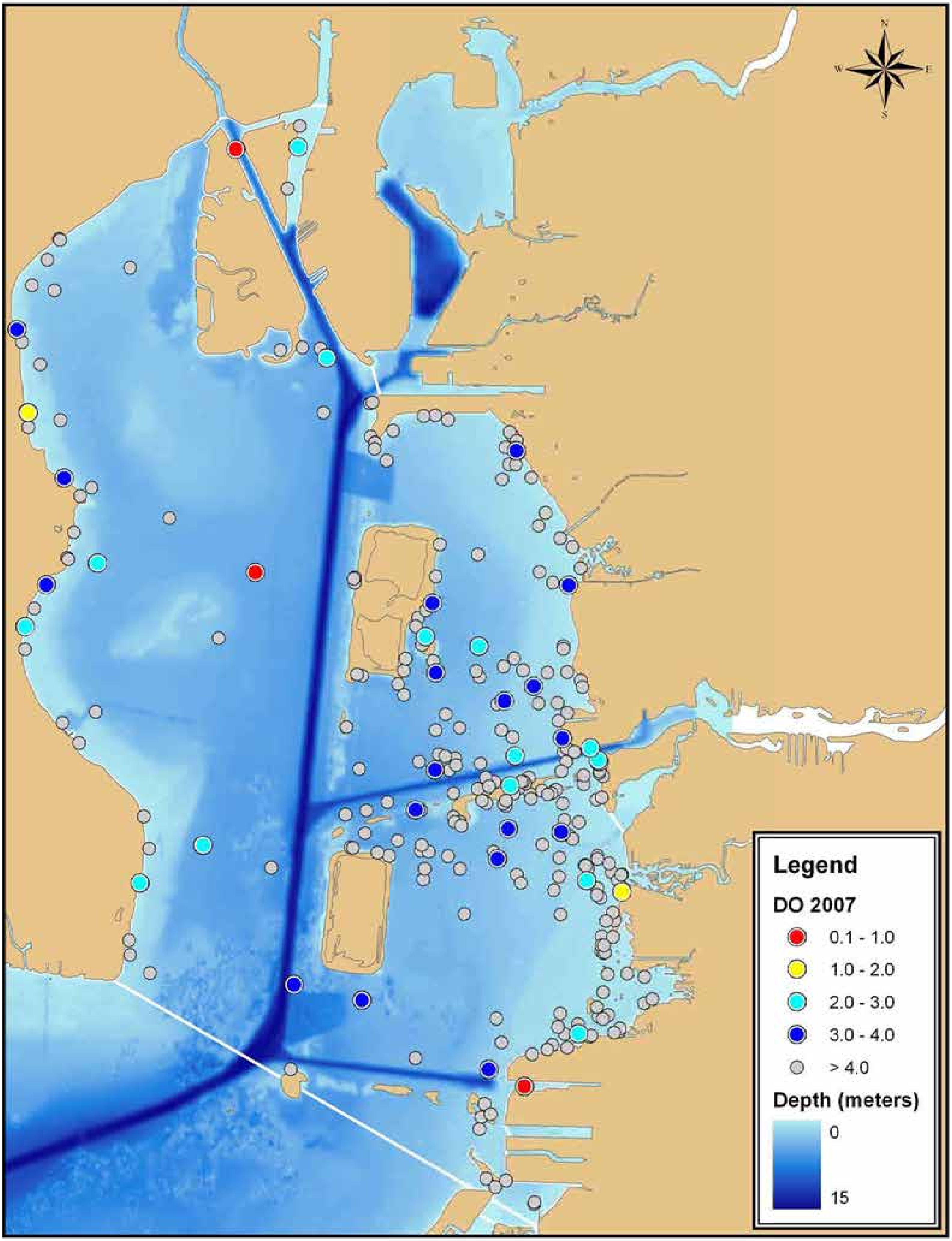

N
W
E
S
Legend
DO 2002
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15


N
S
E
W
Legend
DO 2003
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

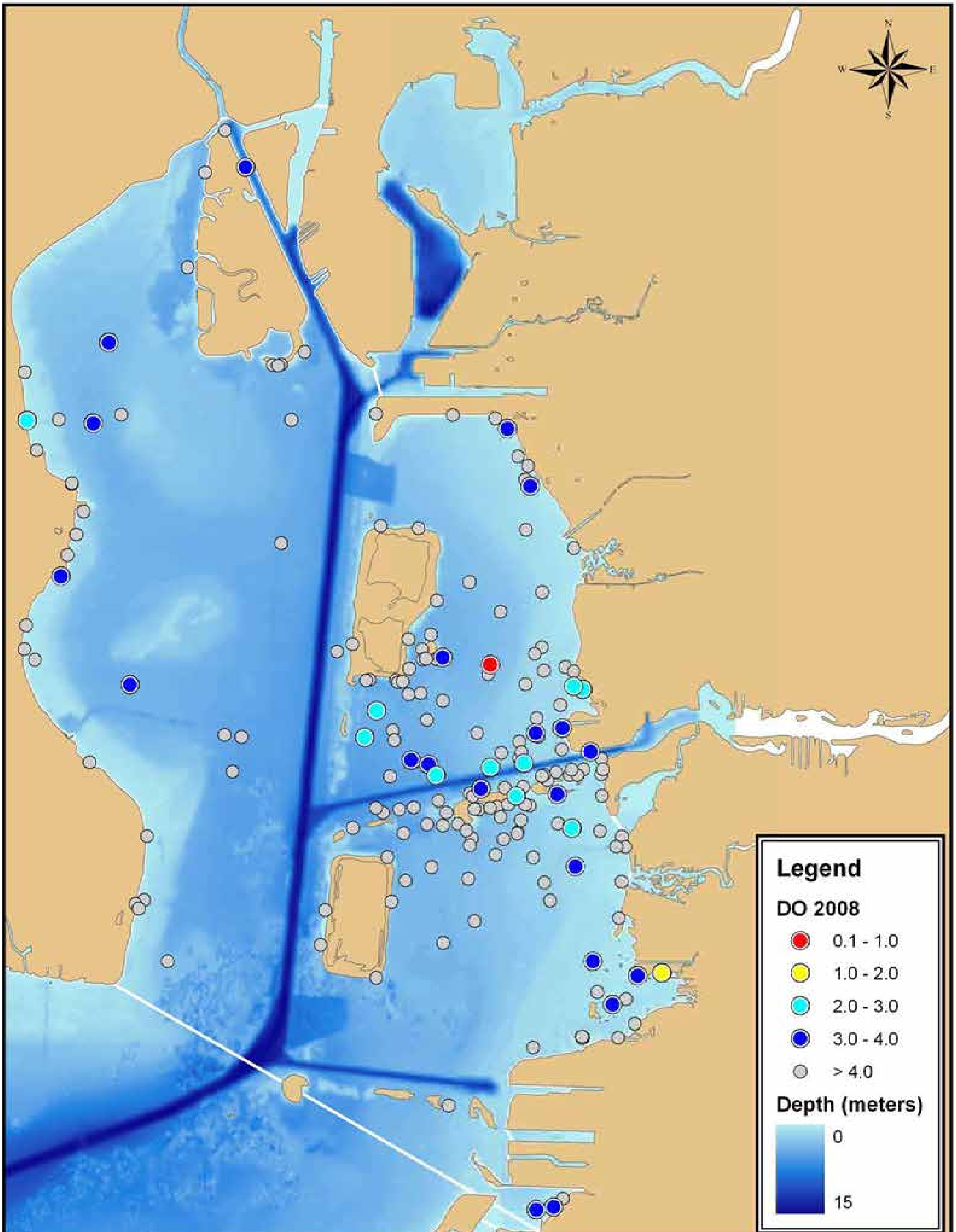

N
S
E
W
Legend
DO 2004
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

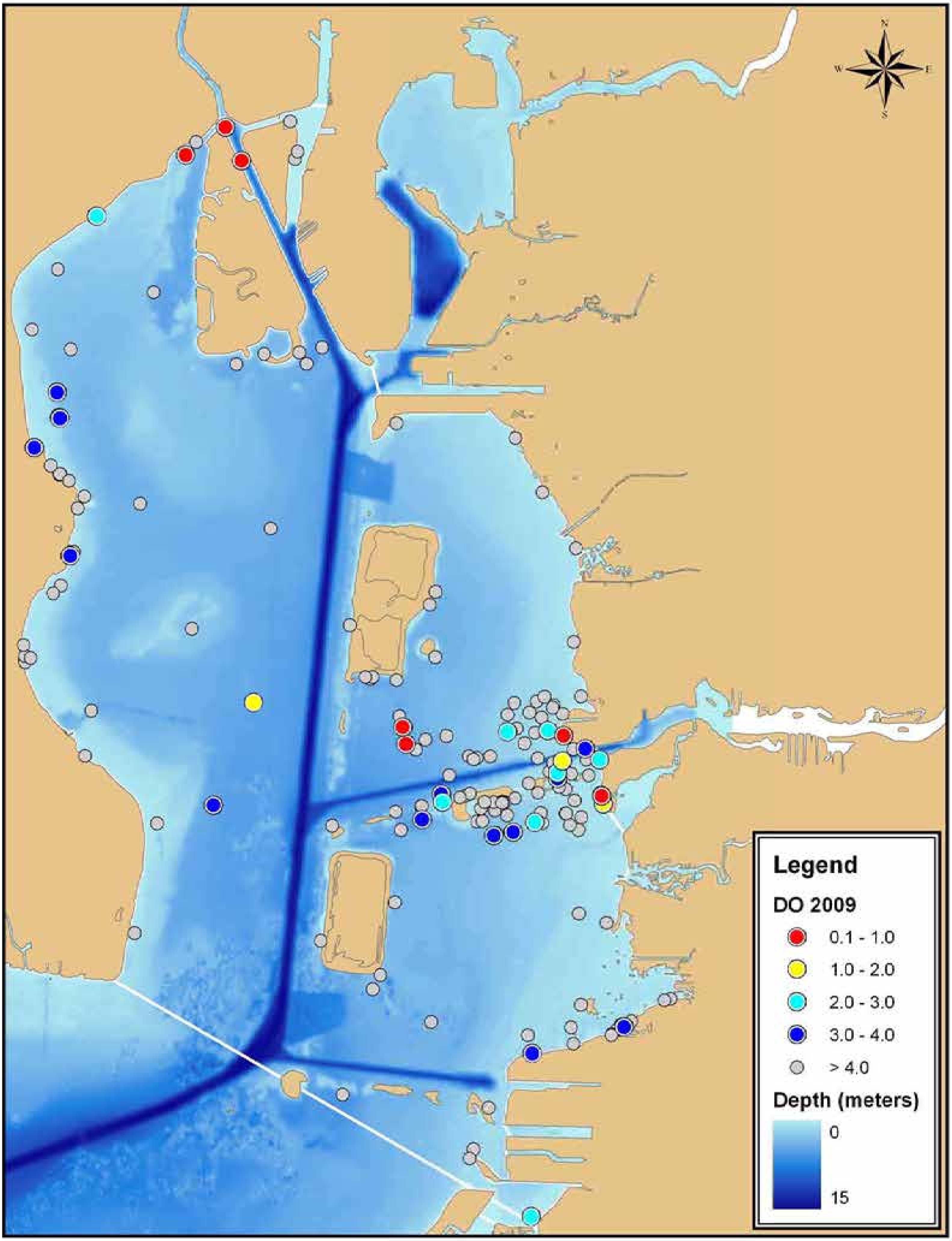

N
S
W
E
Legend
DO 2005
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

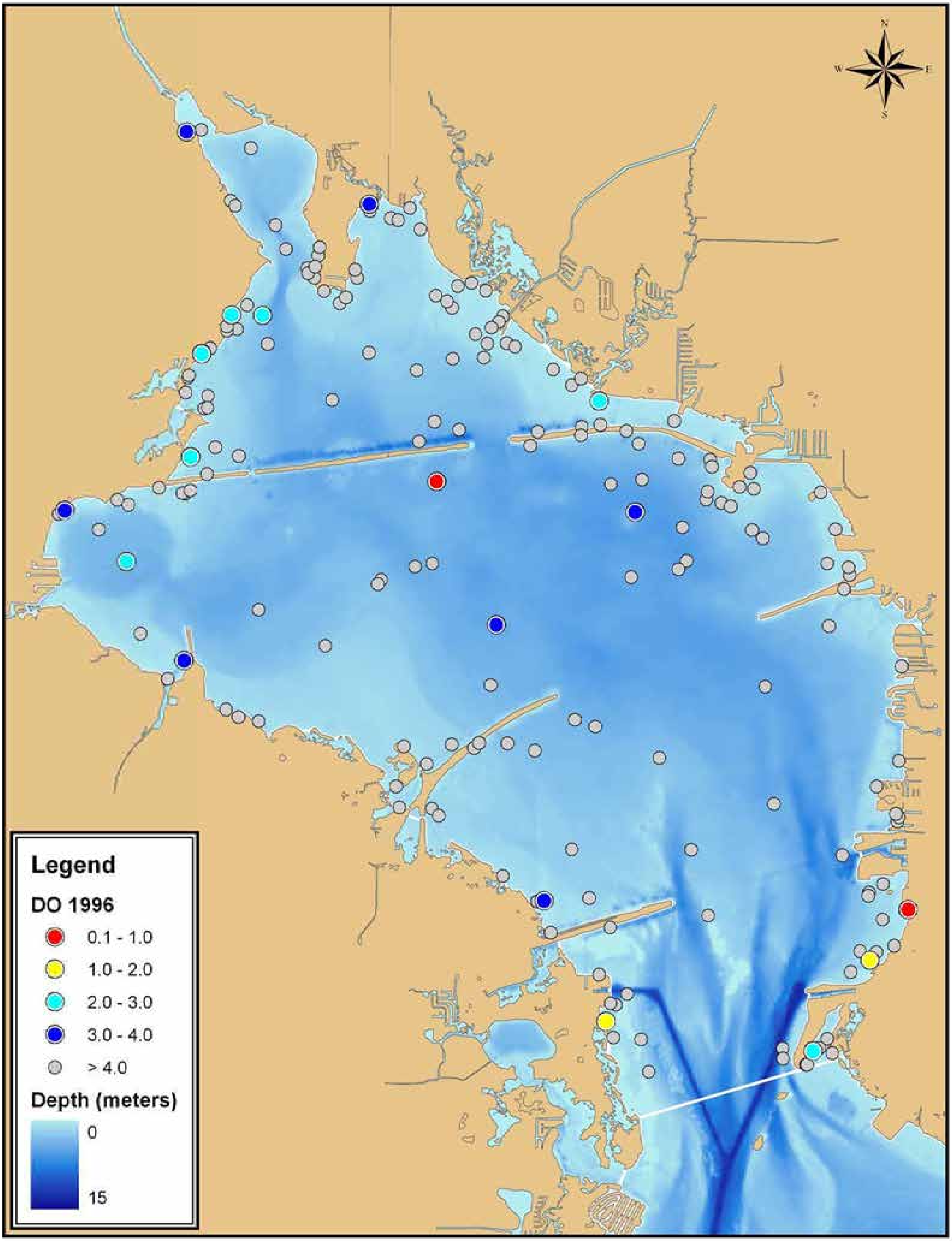

N
S
E
W
Legend
DO 2006
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15



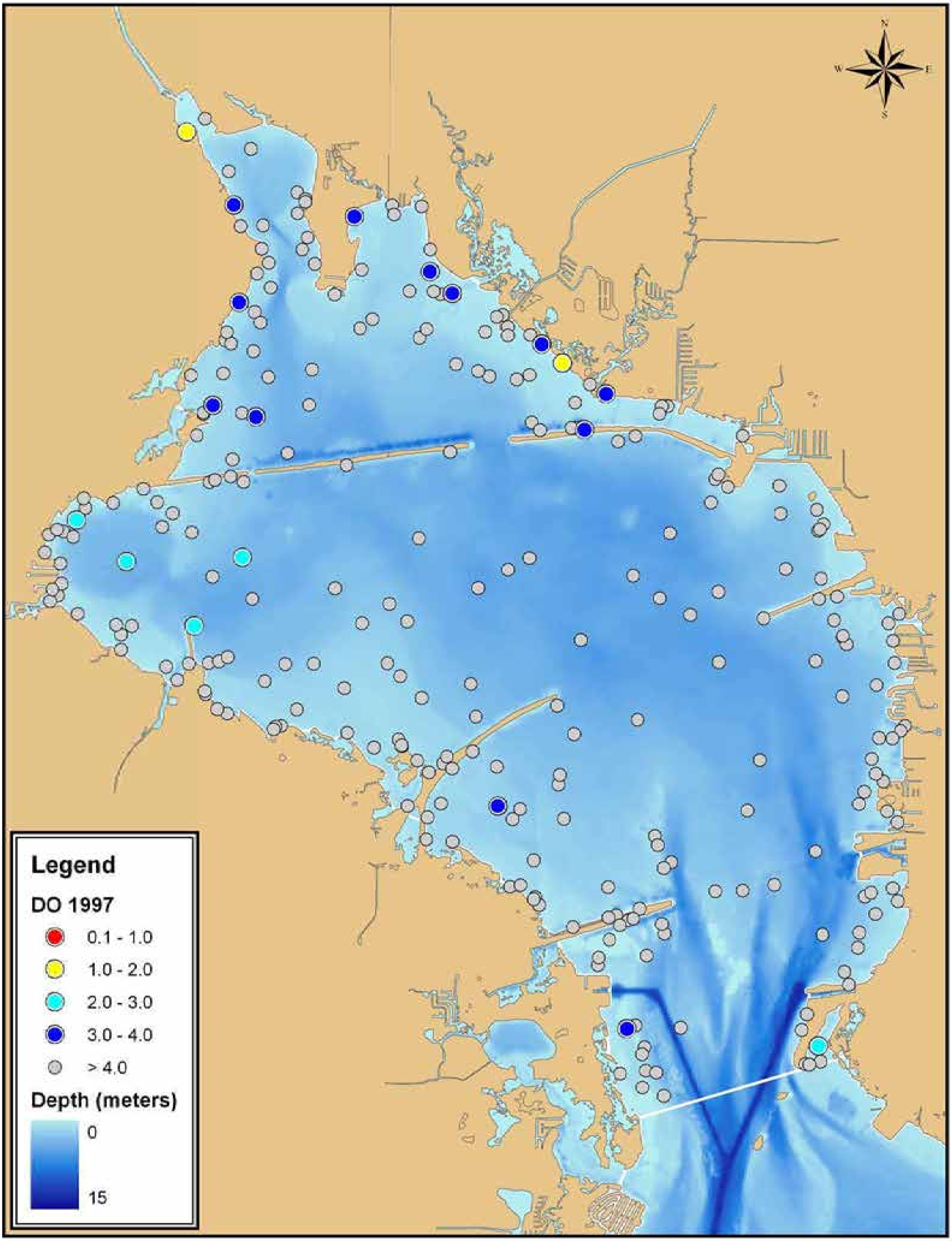
N
S
E
W
Legend
DO 2007
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15


N
W
E
S
Legend
DO 2008
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

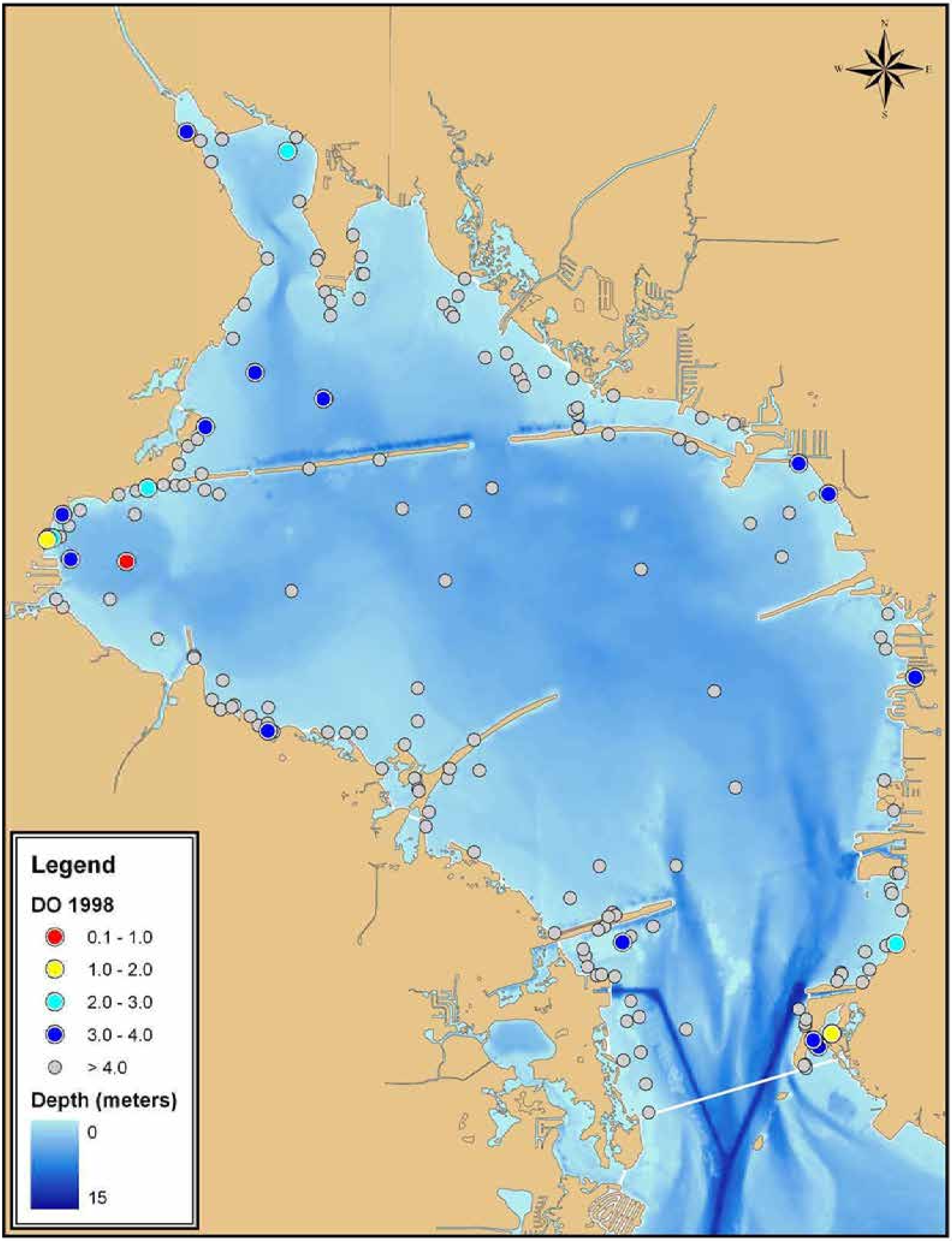

N
S
E
W
Legend
DO 2009
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

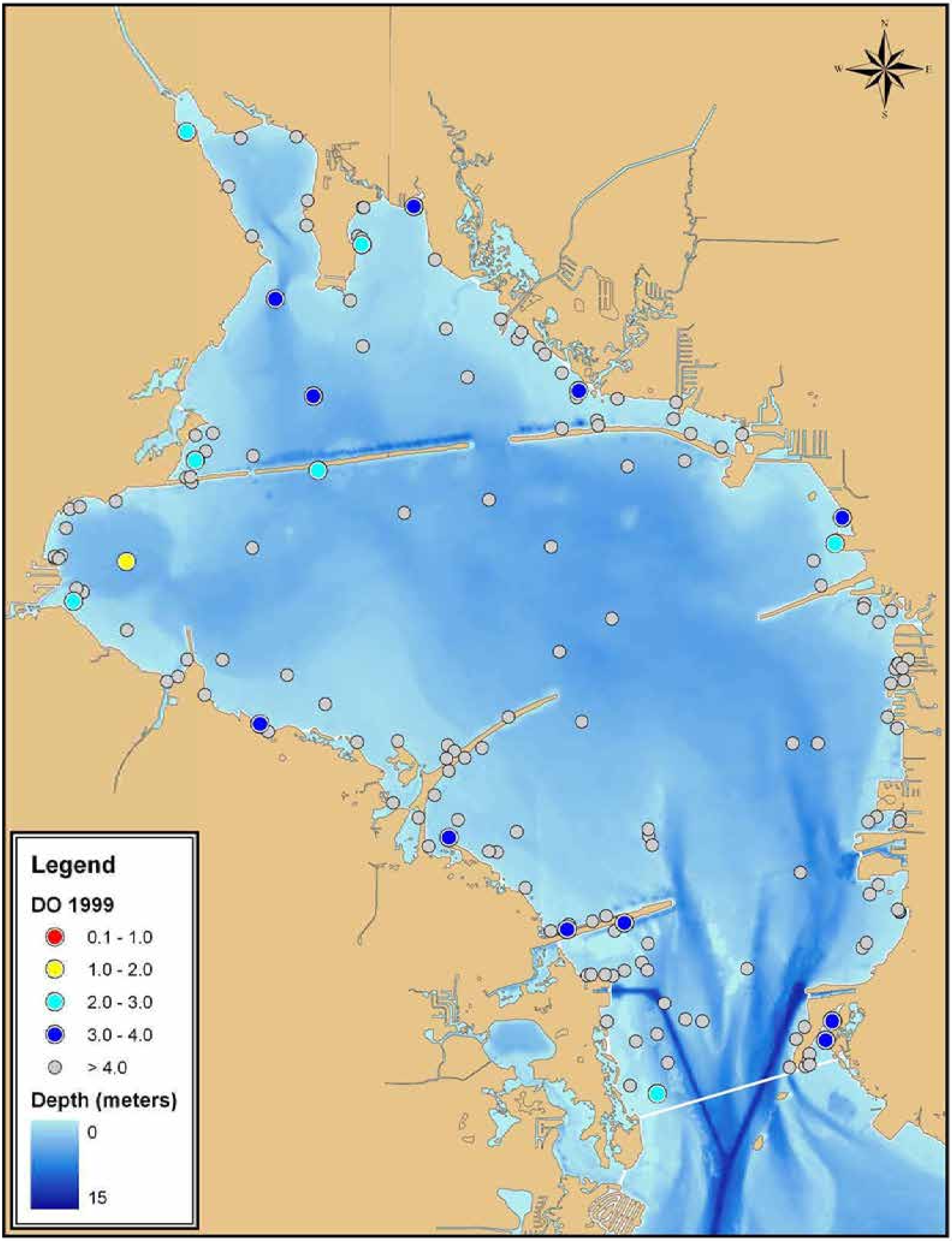


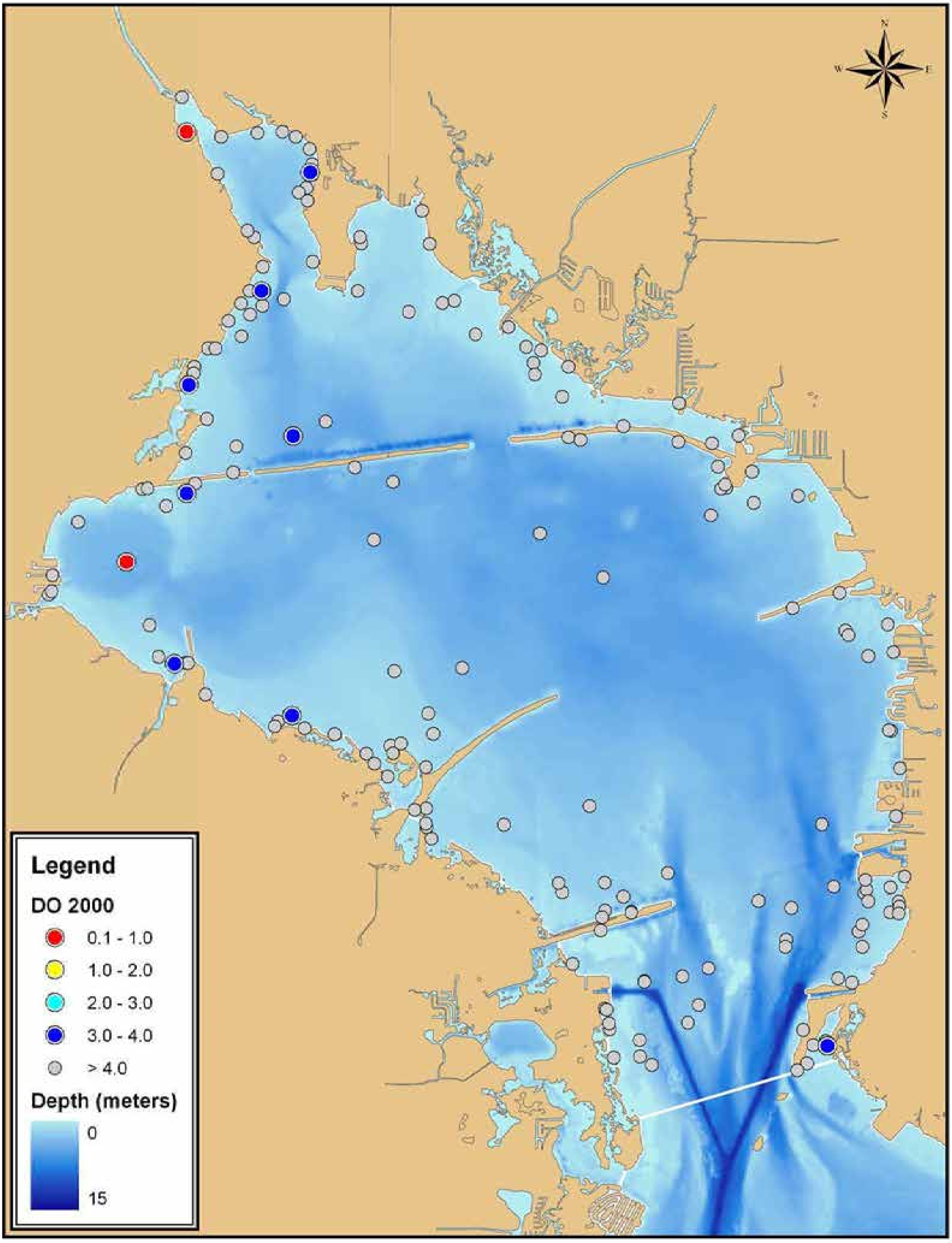
N
S
E
W
Legend
DO 1996
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

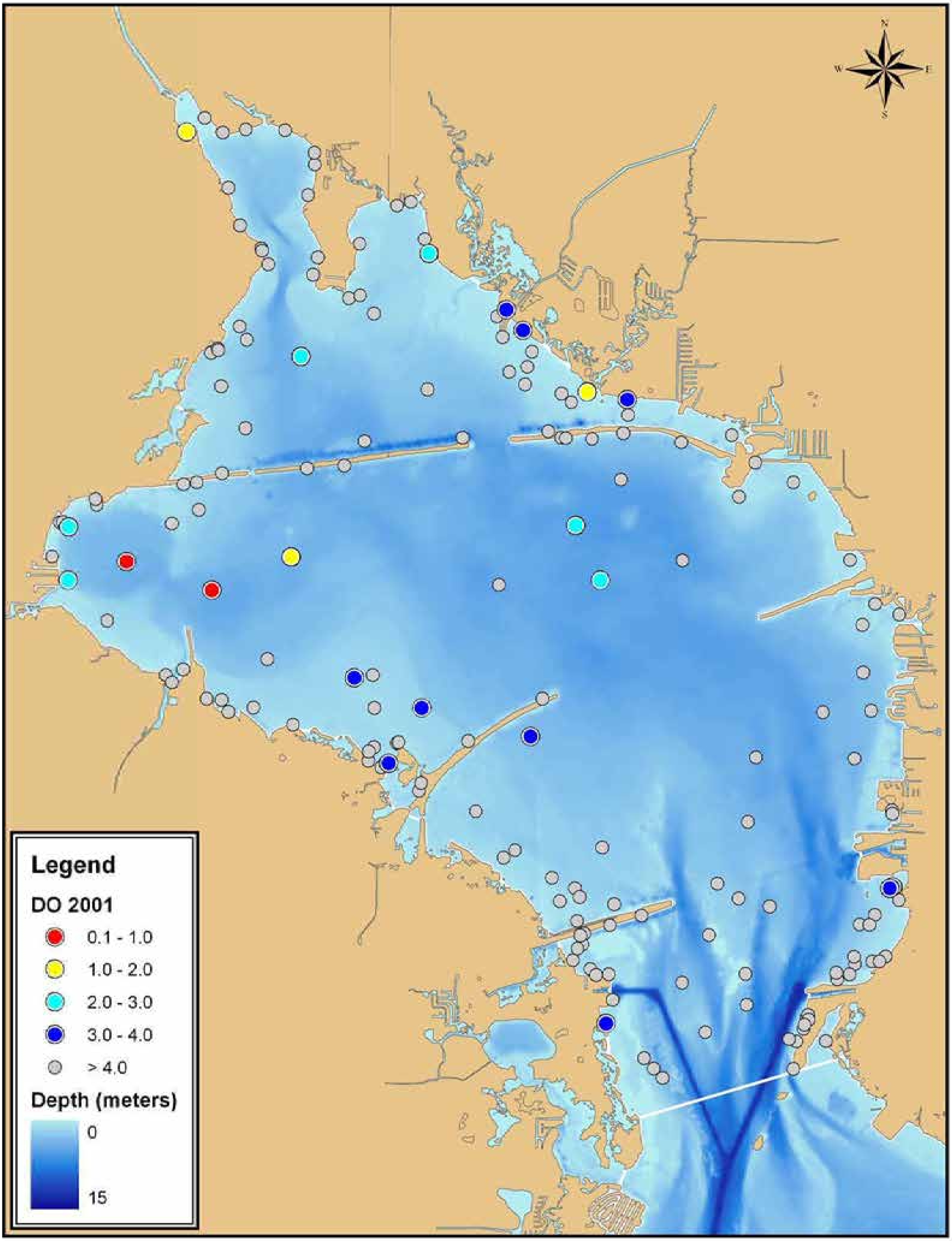


N
W
E
S
Legend
DO 1997
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

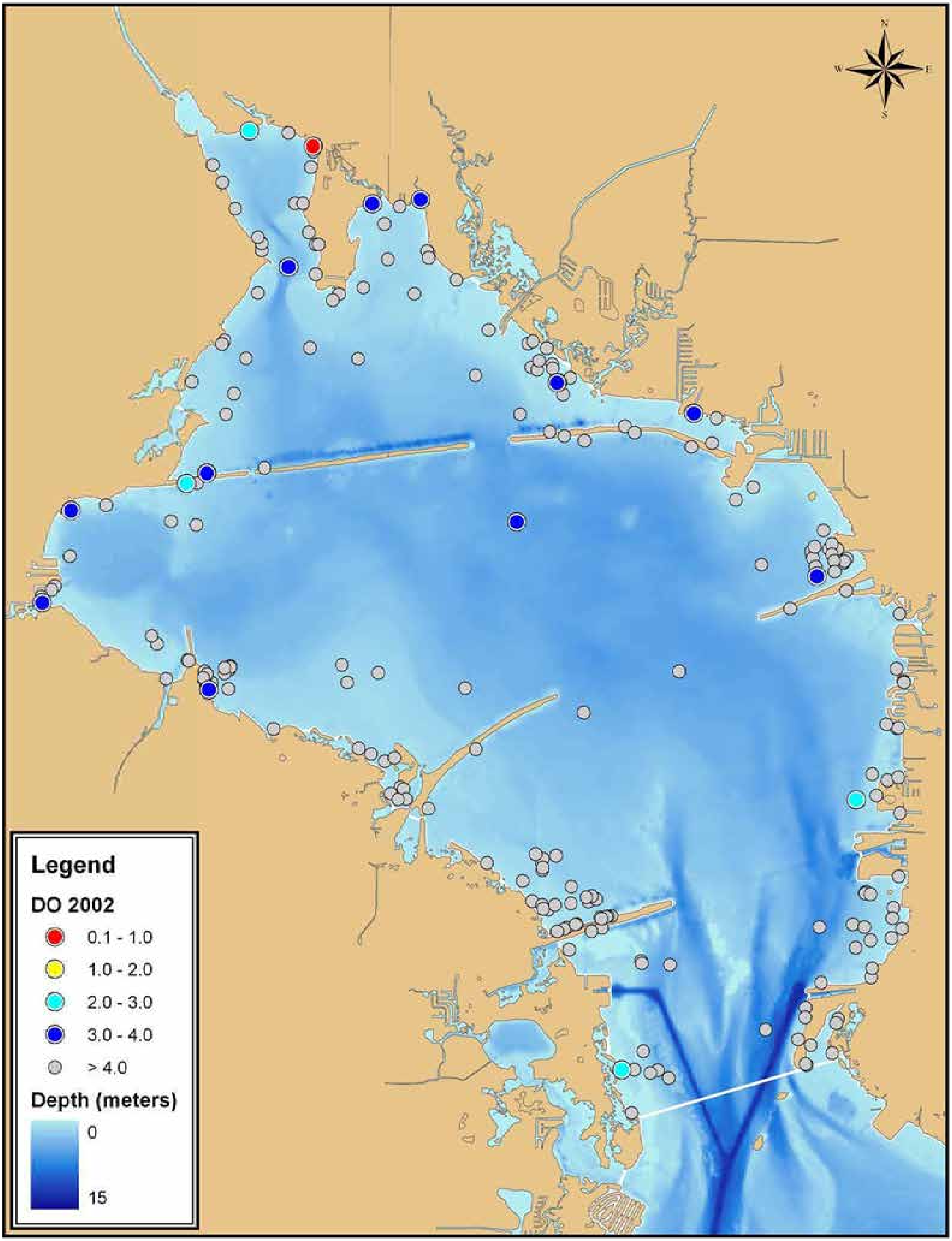

N
W
E
S
Legend
DO 1998
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

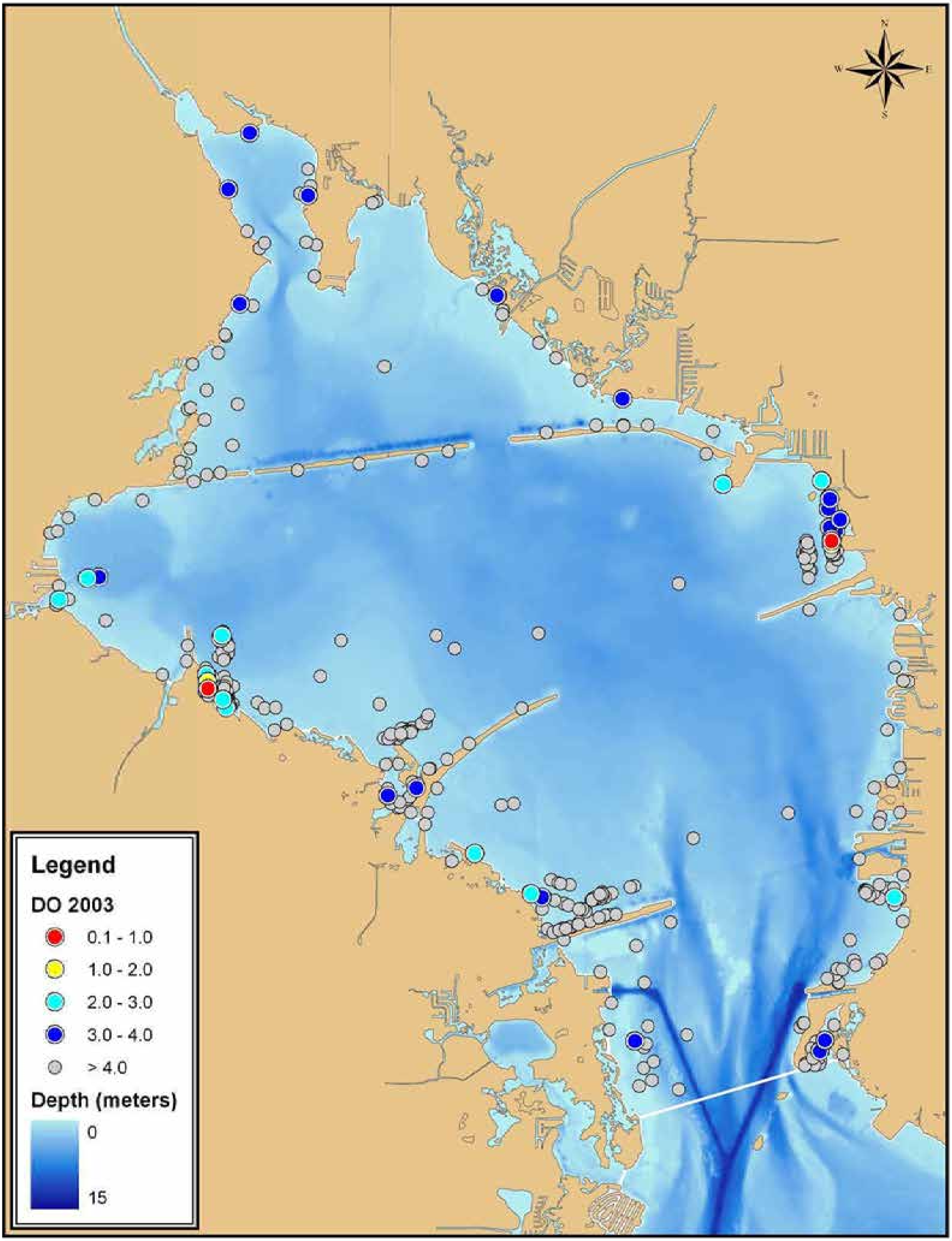

N
S
E
W
Legend
DO 1999
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

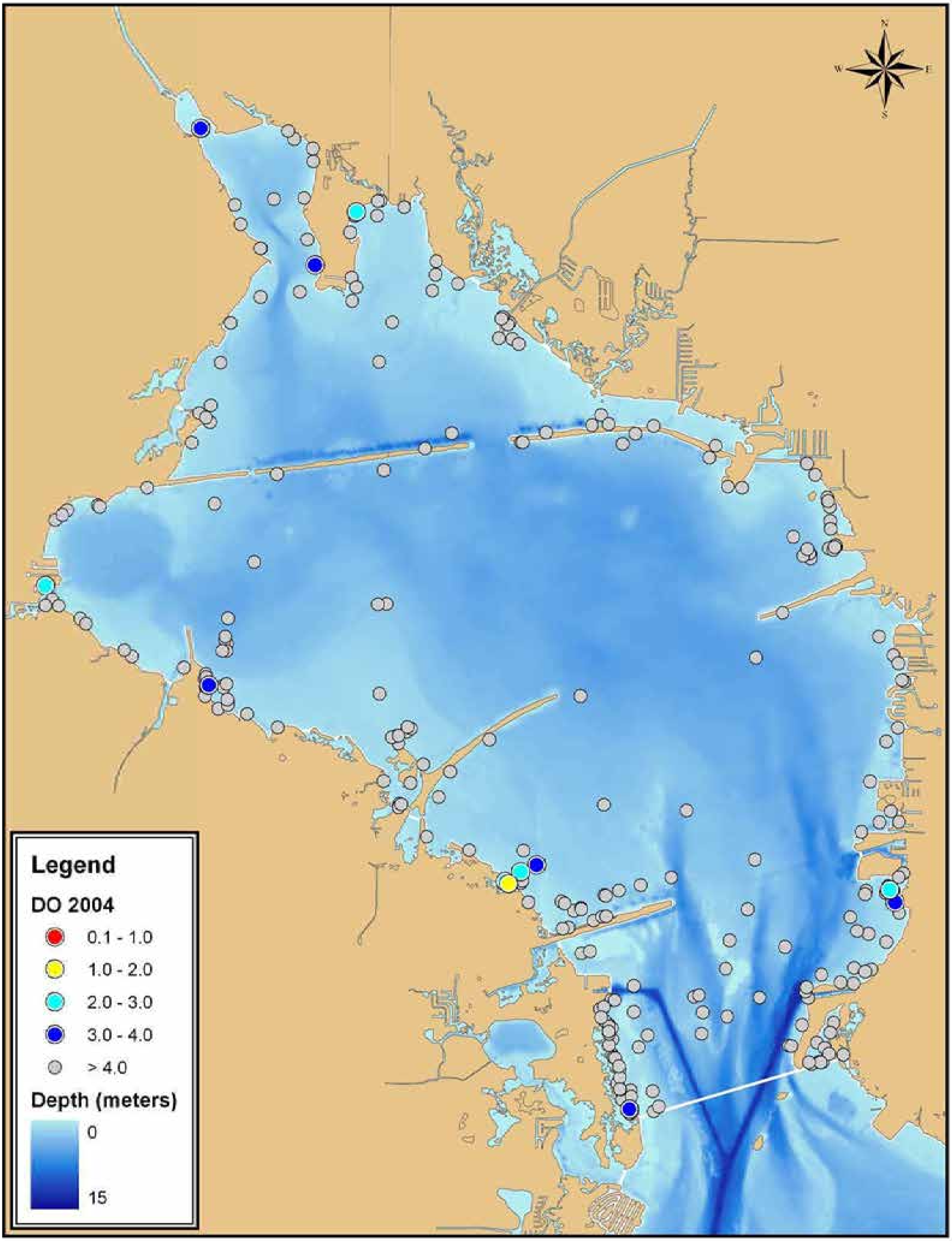

N
S
E
W
Legend
DO 2000
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

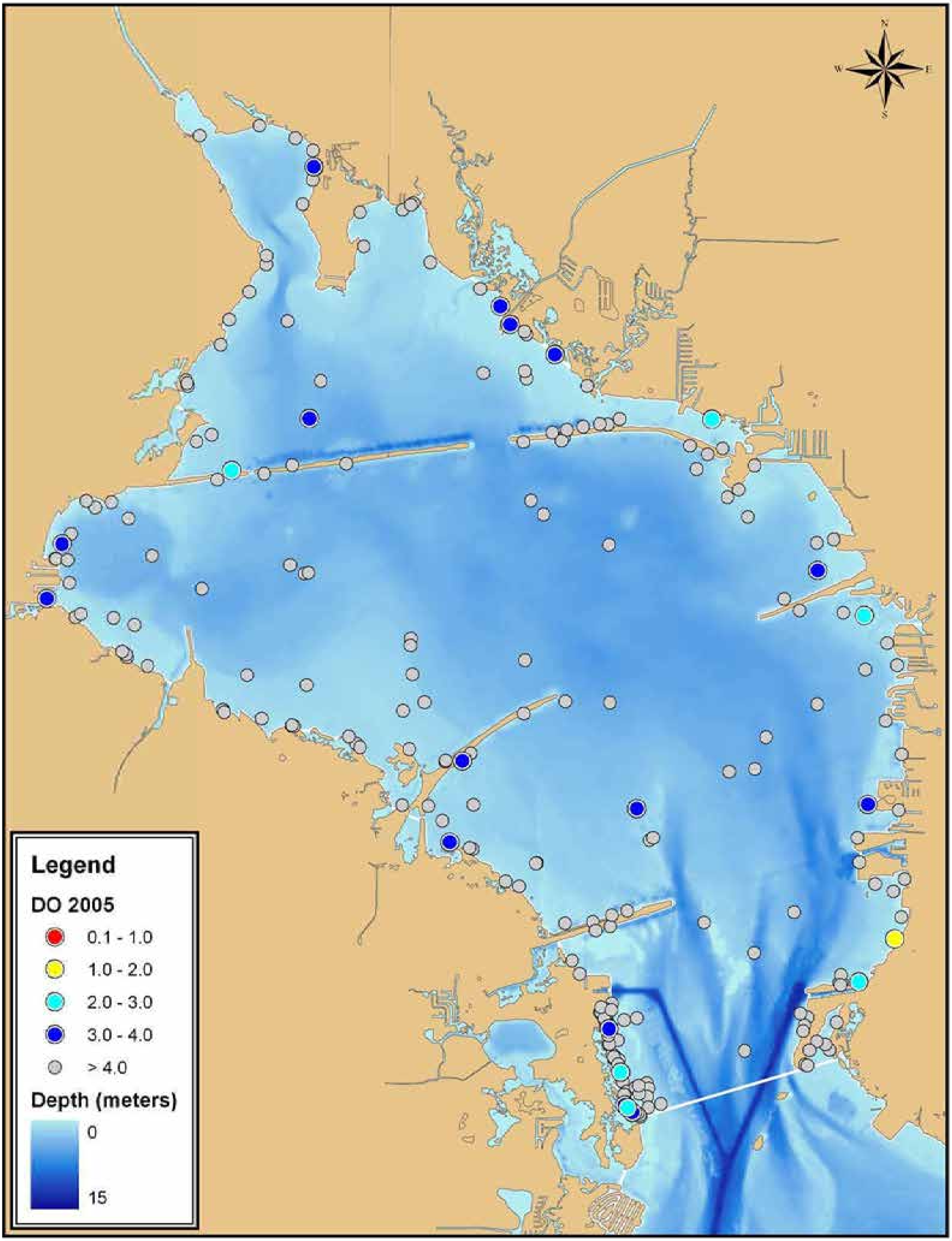


N
S
E
W
Legend
DO 2001
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

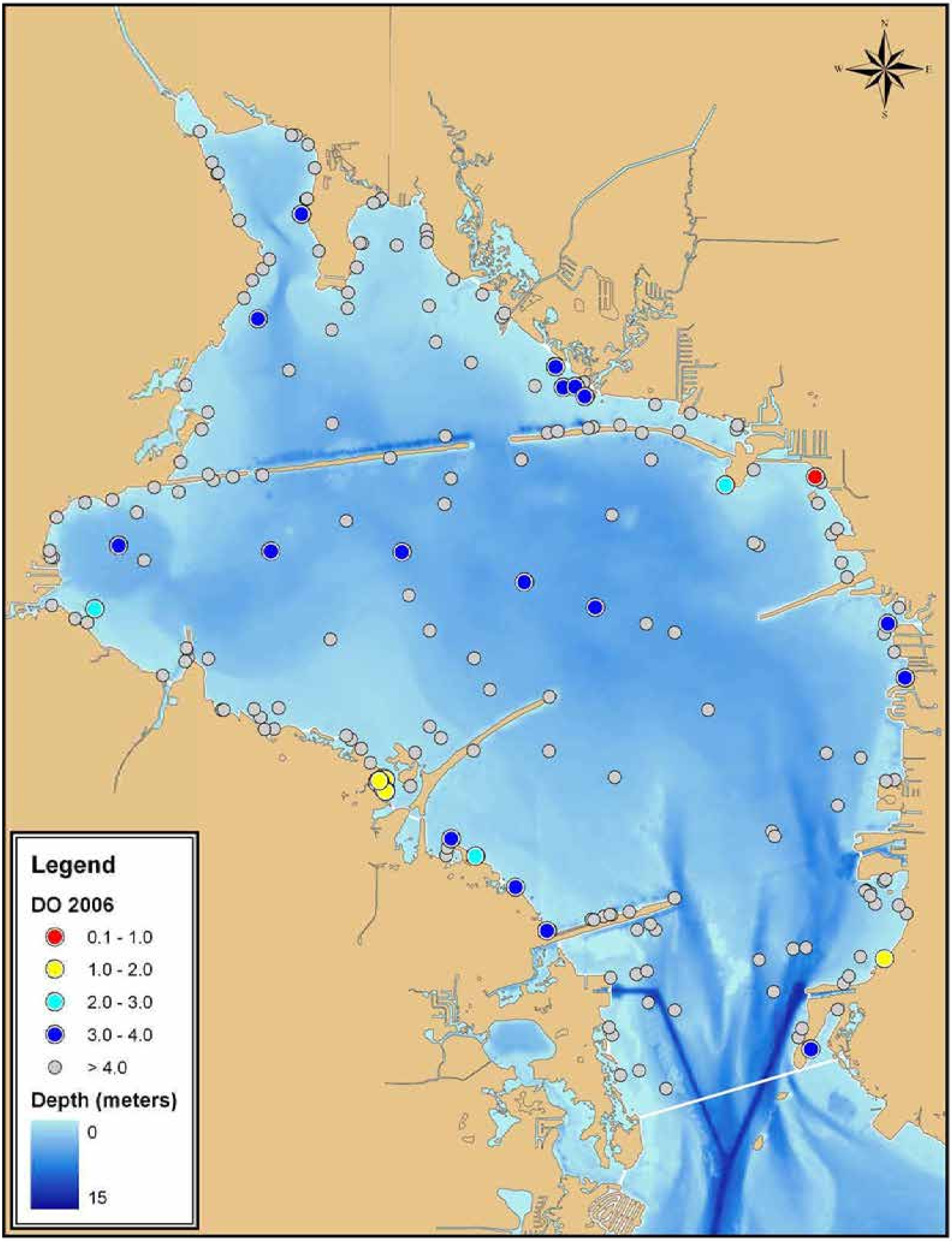

N
W
E
S
Legend
DO 2002
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

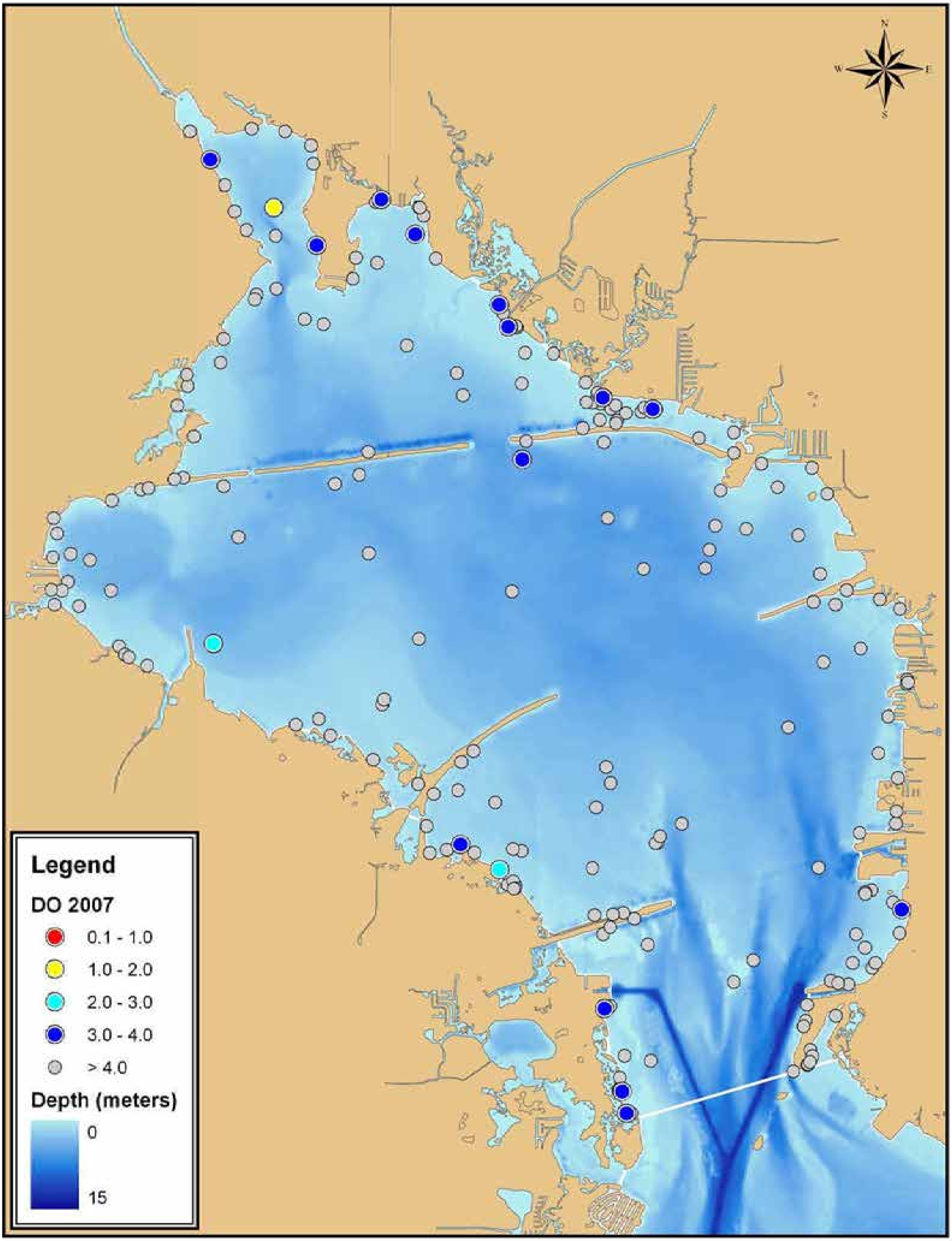

N
W
E
S
Legend
DO 2003
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

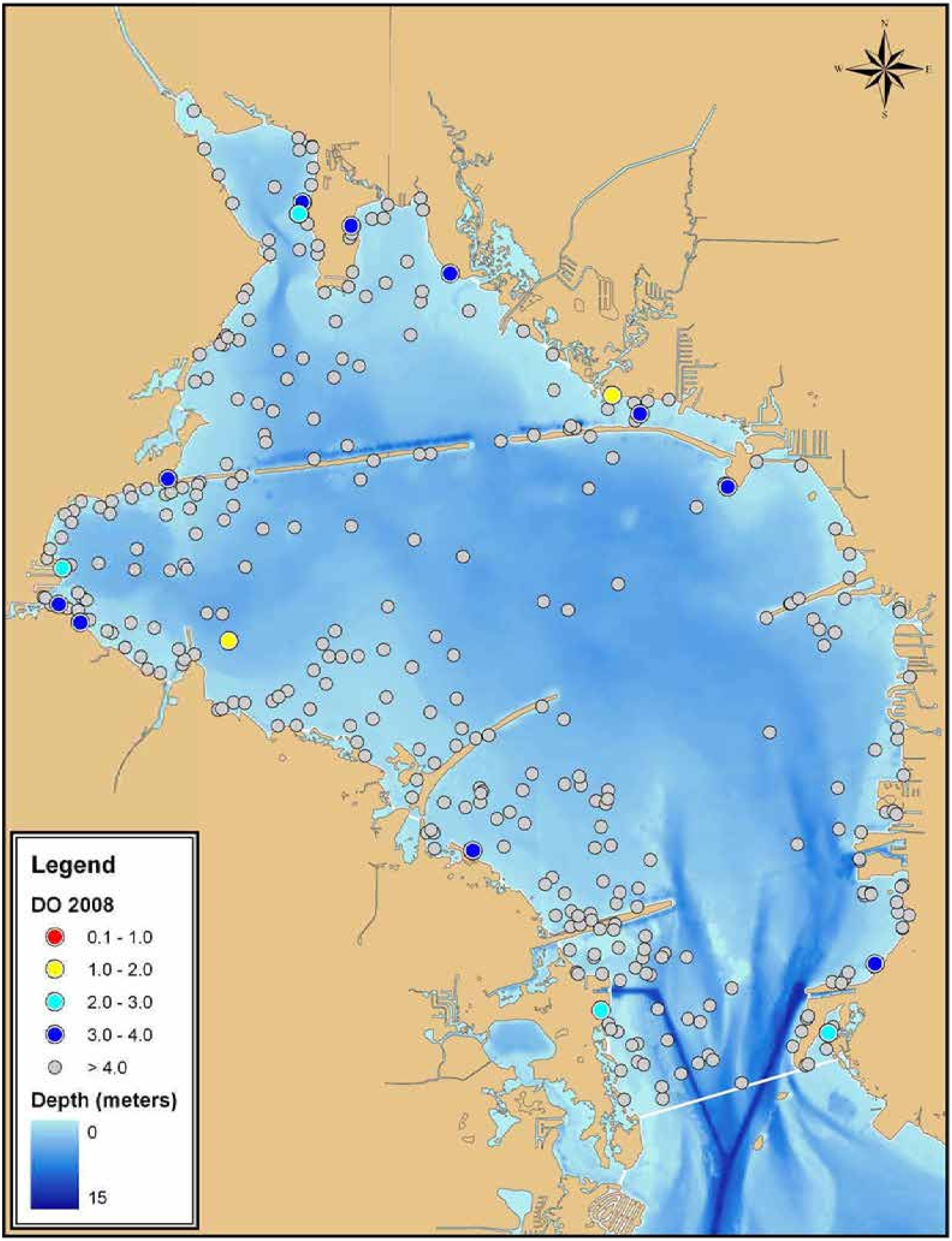

N
S
E
W
Legend
DO 2004
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15



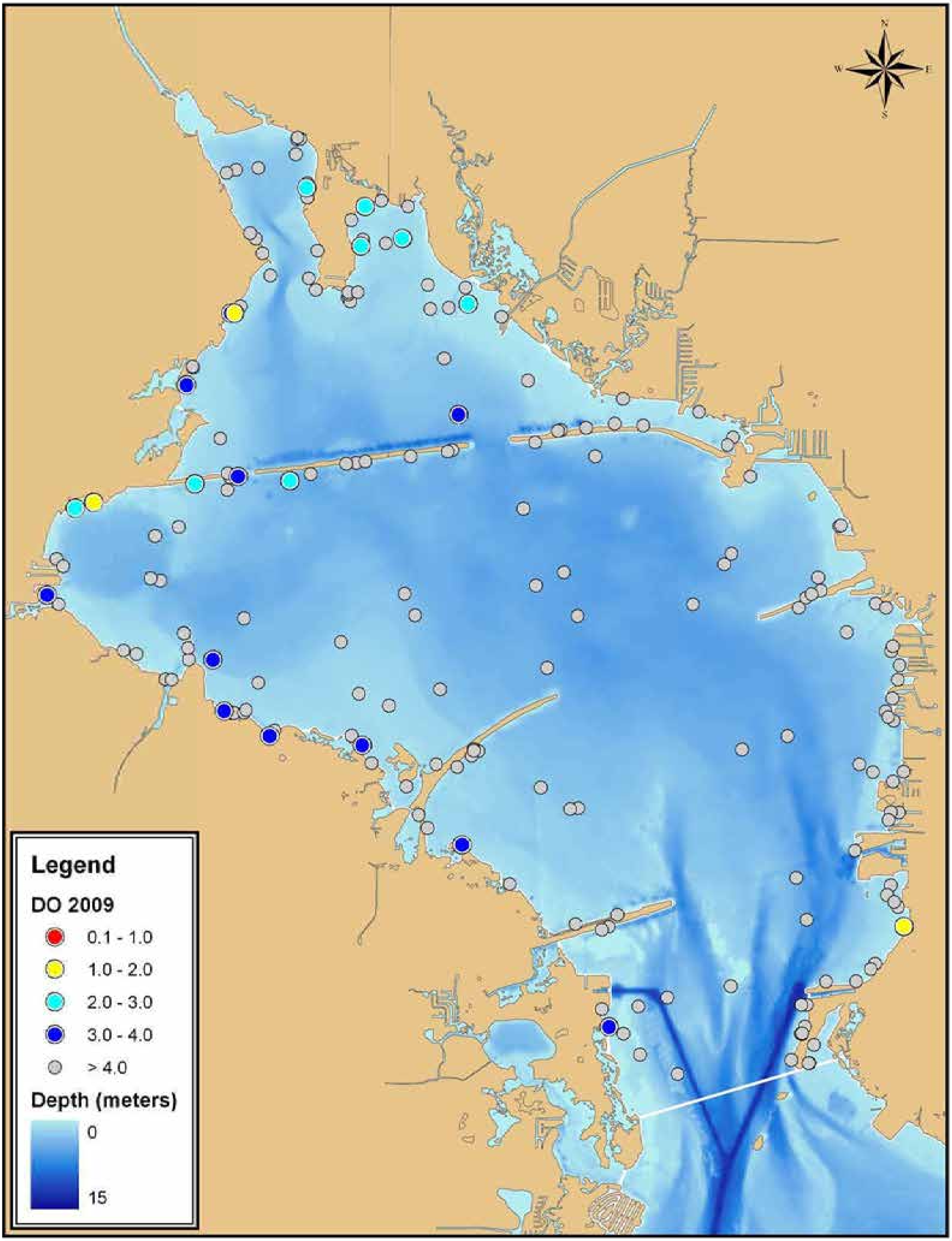
N
S
E
W
Legend
DO 2005
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

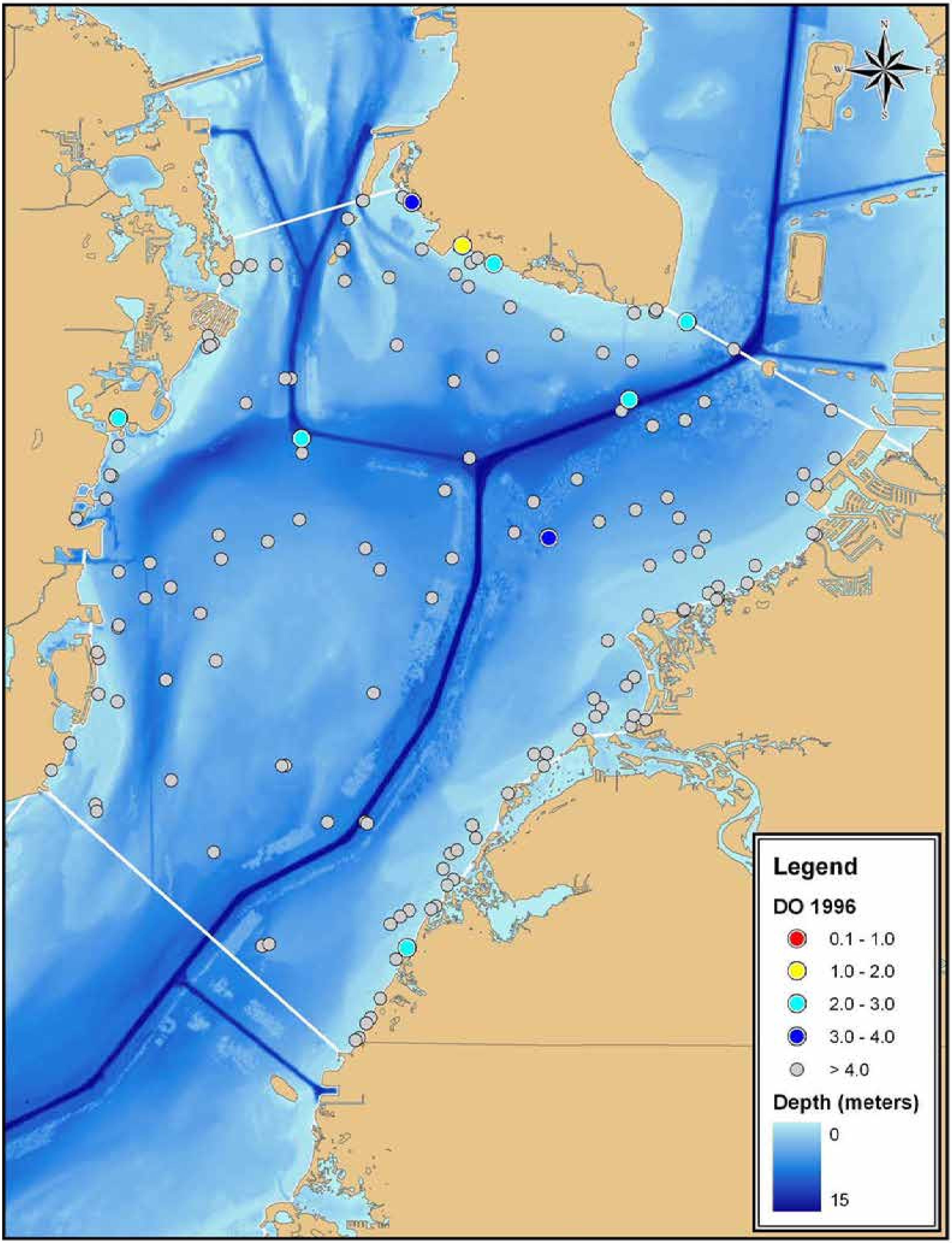

N
S
W
E
Legend
DO 2006
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

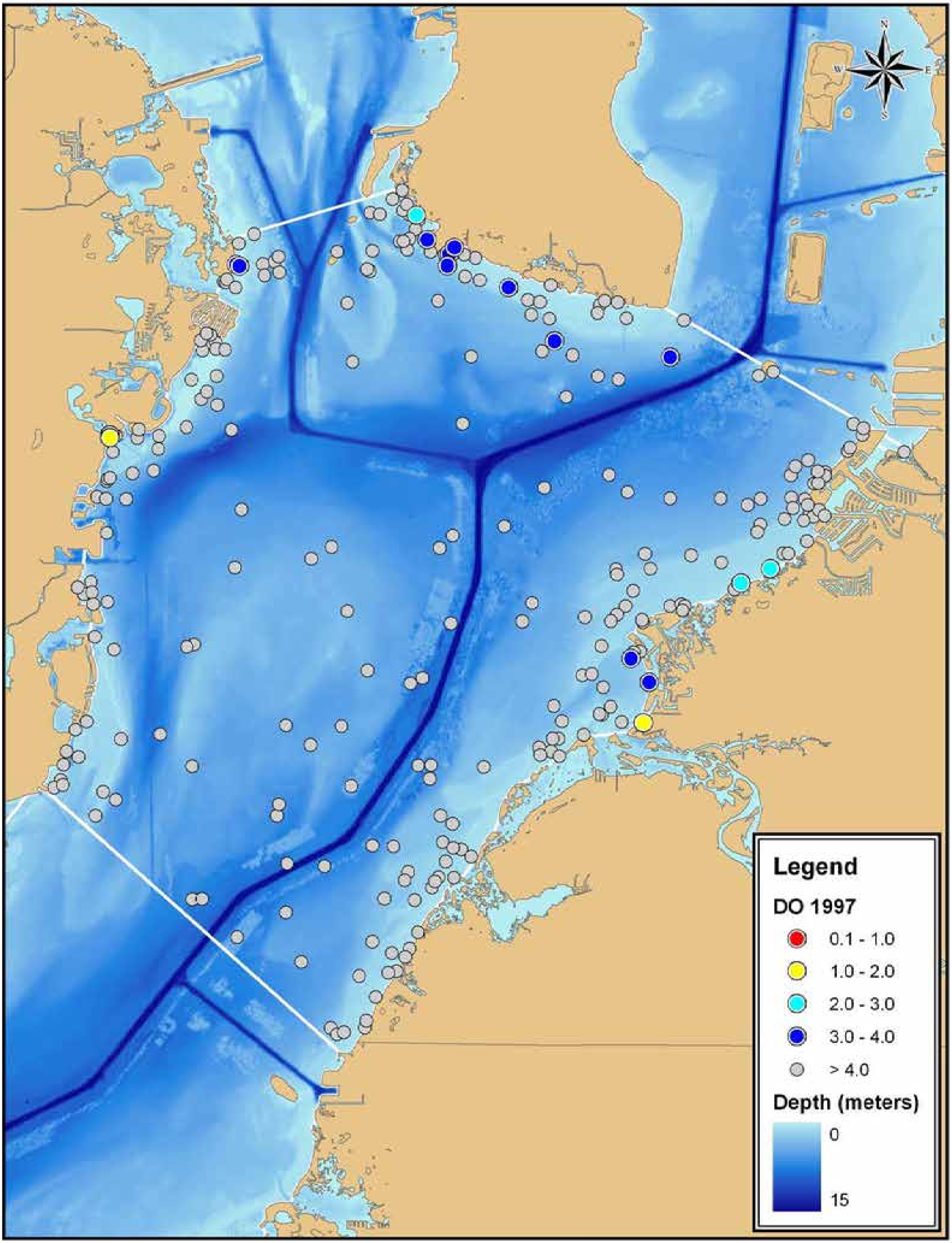

N
W
E
S
Legend
DO 2007
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

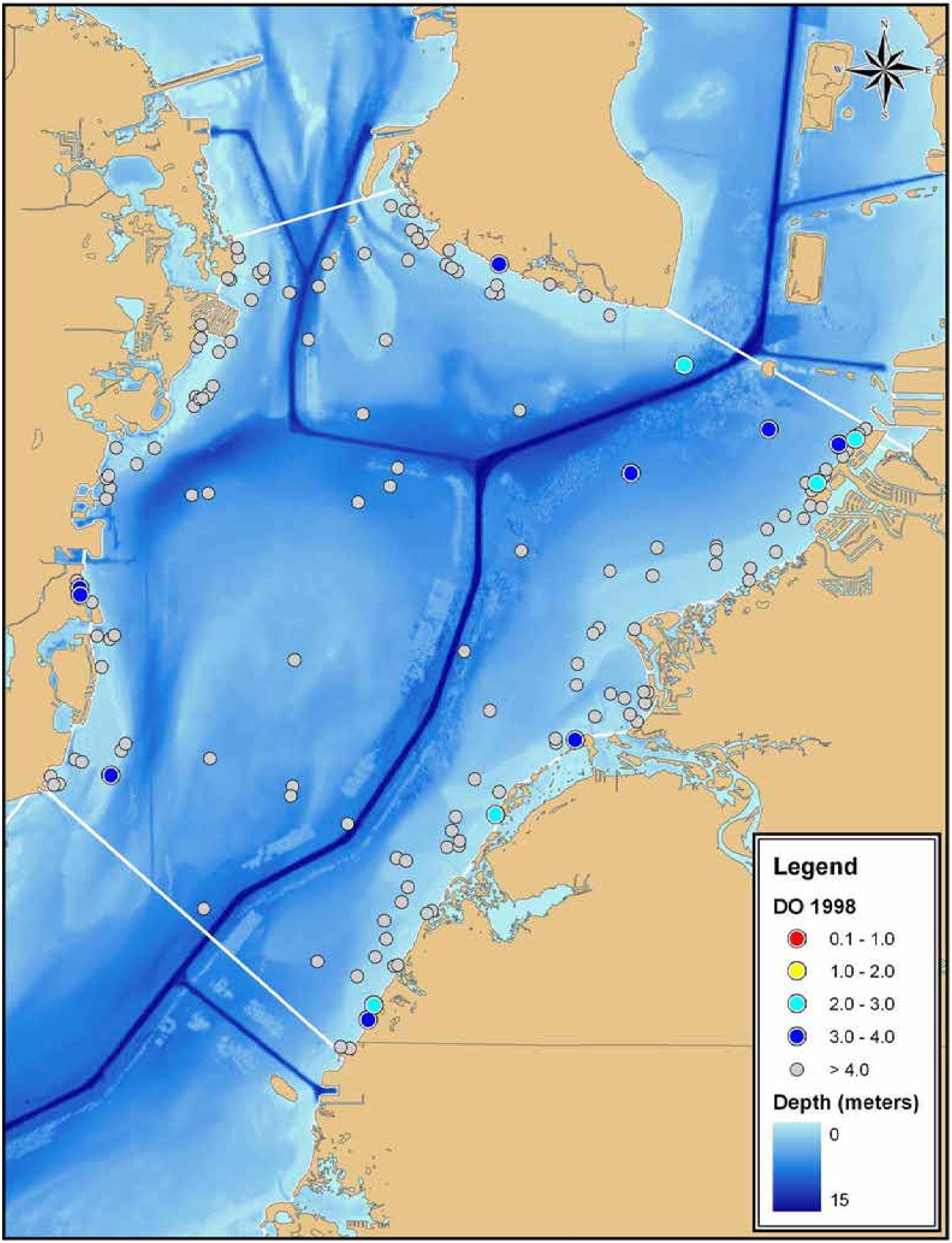


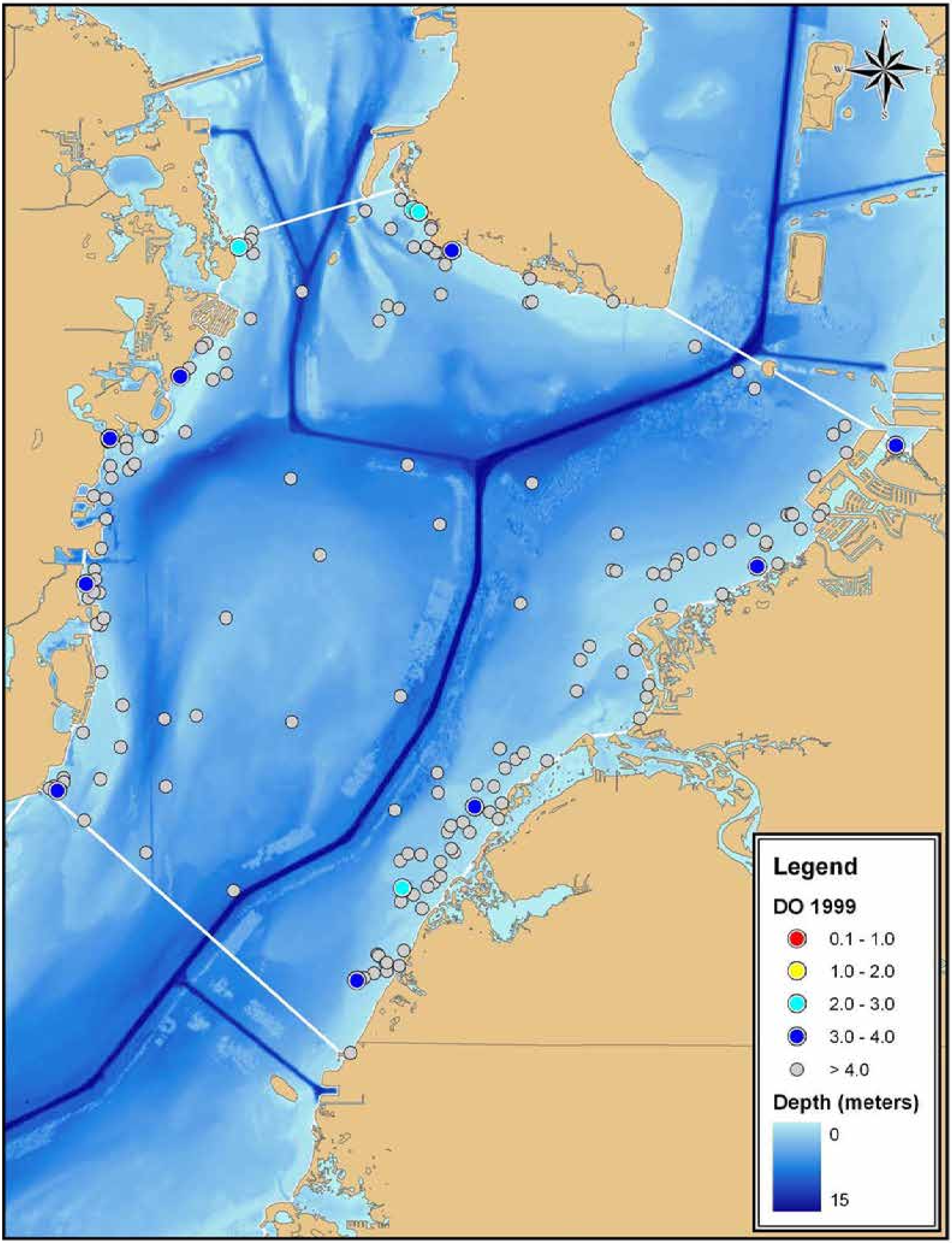
N
W
E
S
Legend
DO 2008
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

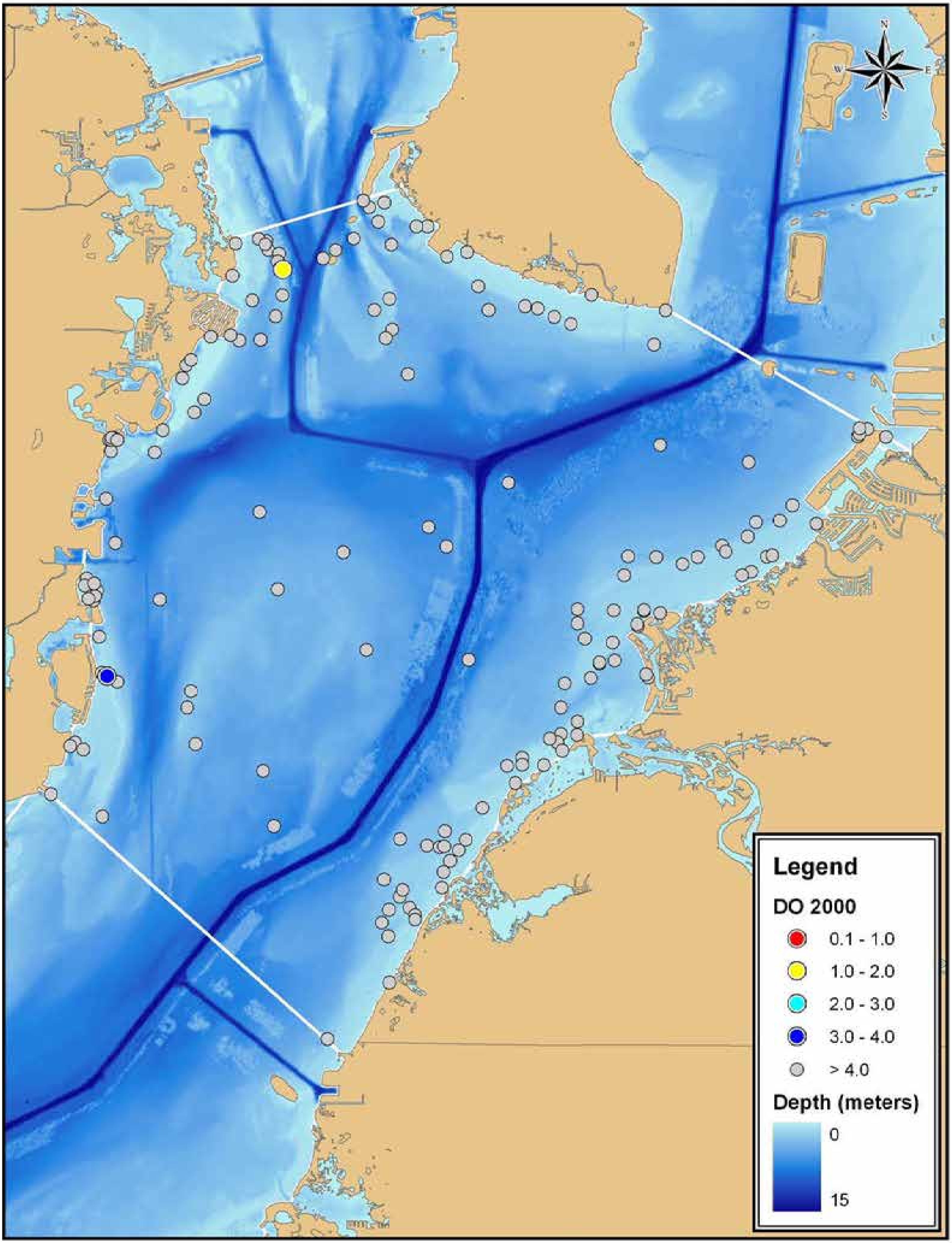

N
S
W
E
Legend
DO 2009
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

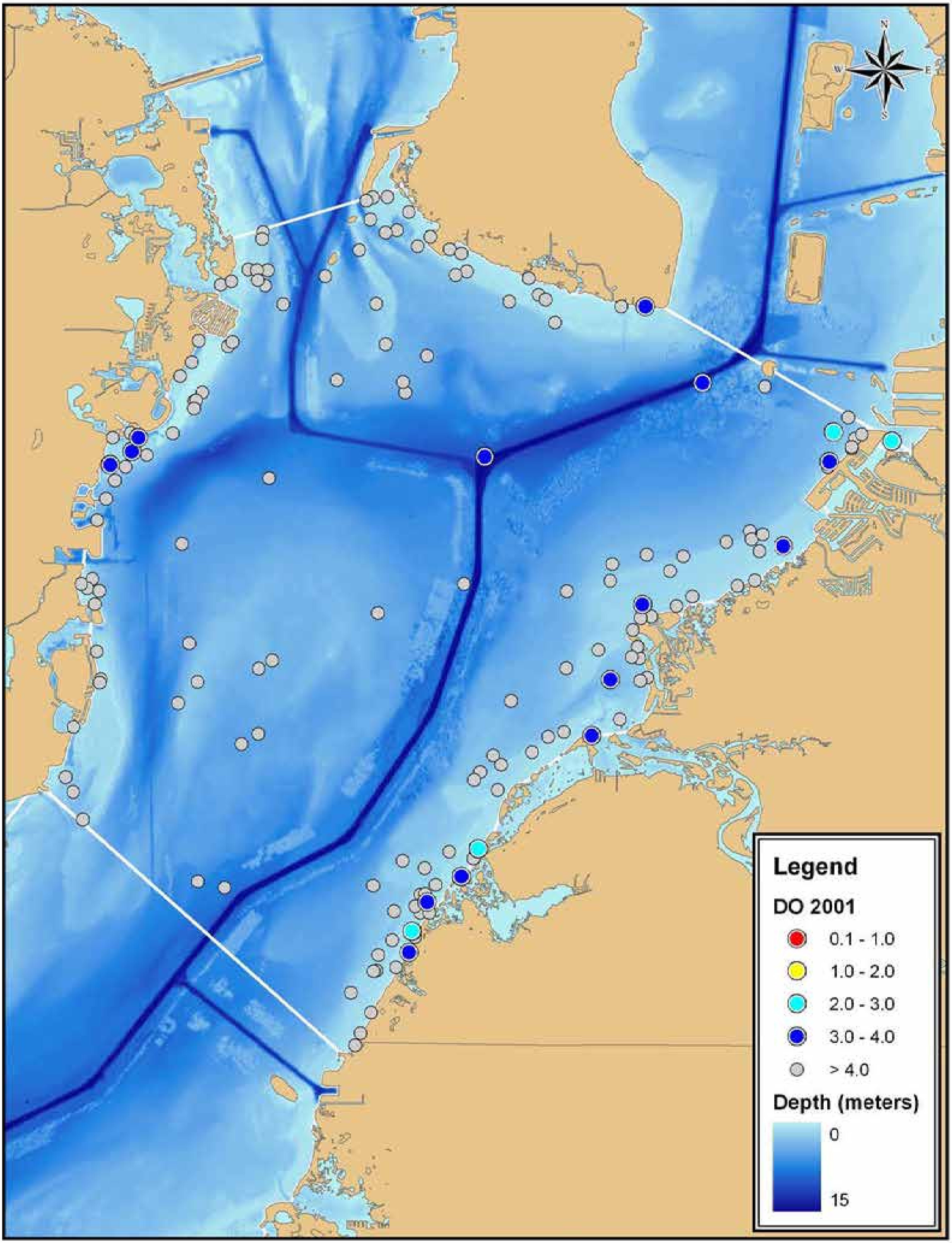

N
S
E
W
Legend
DO 1996
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

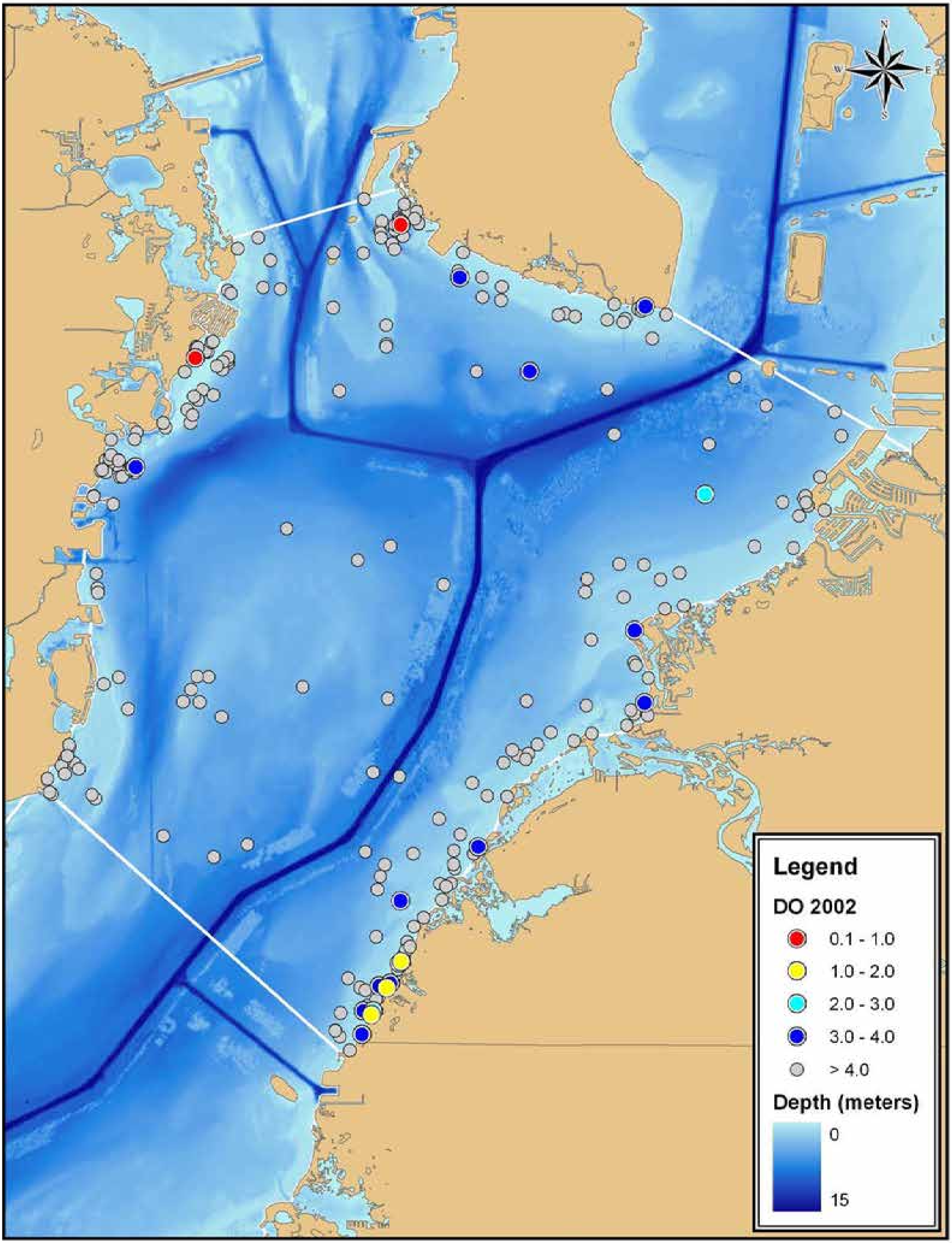

N
S
E
W
Legend
DO 1997
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

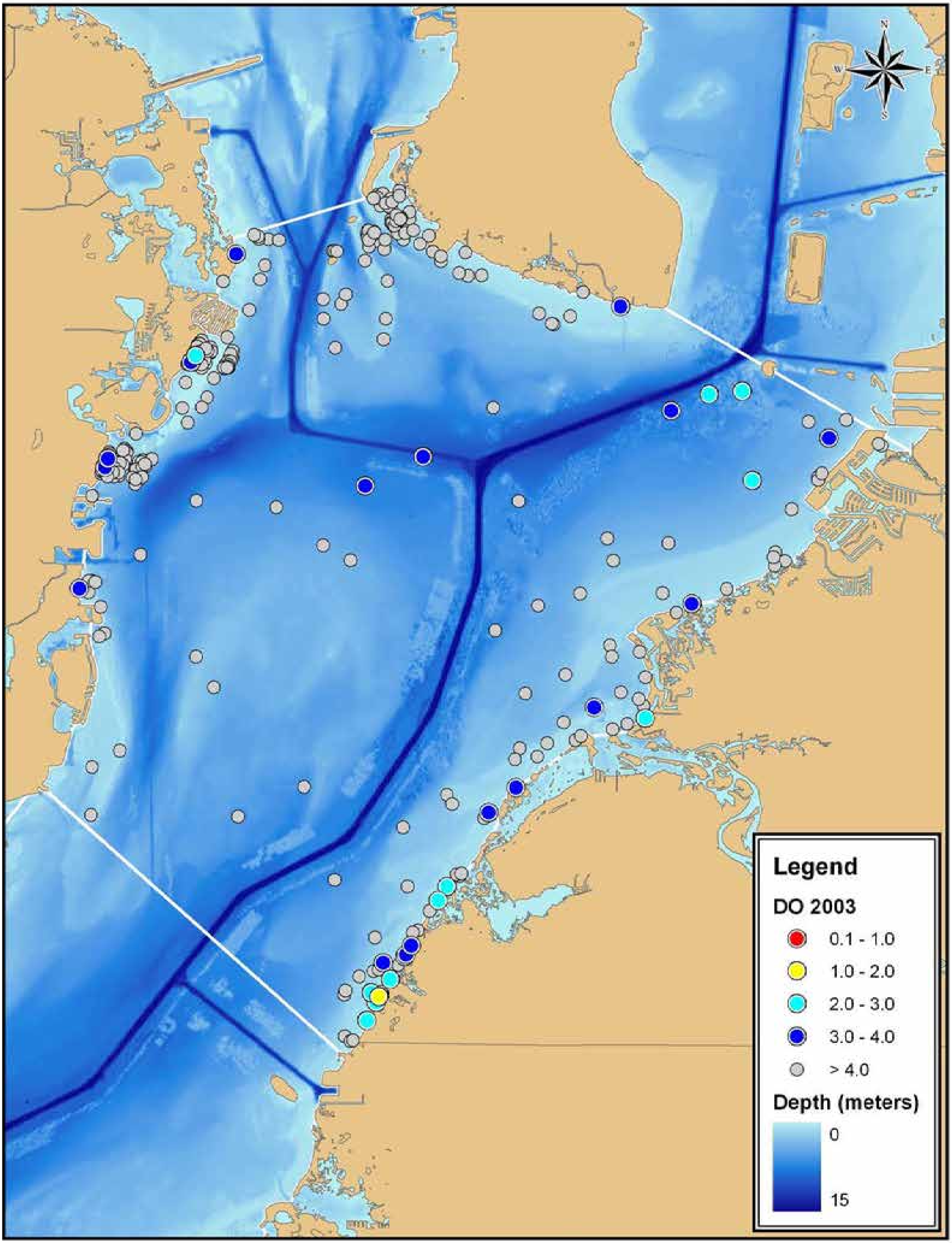

N
S
E
W
Legend
DO 1998
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15


N
S
E
W
Legend
DO 1999
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

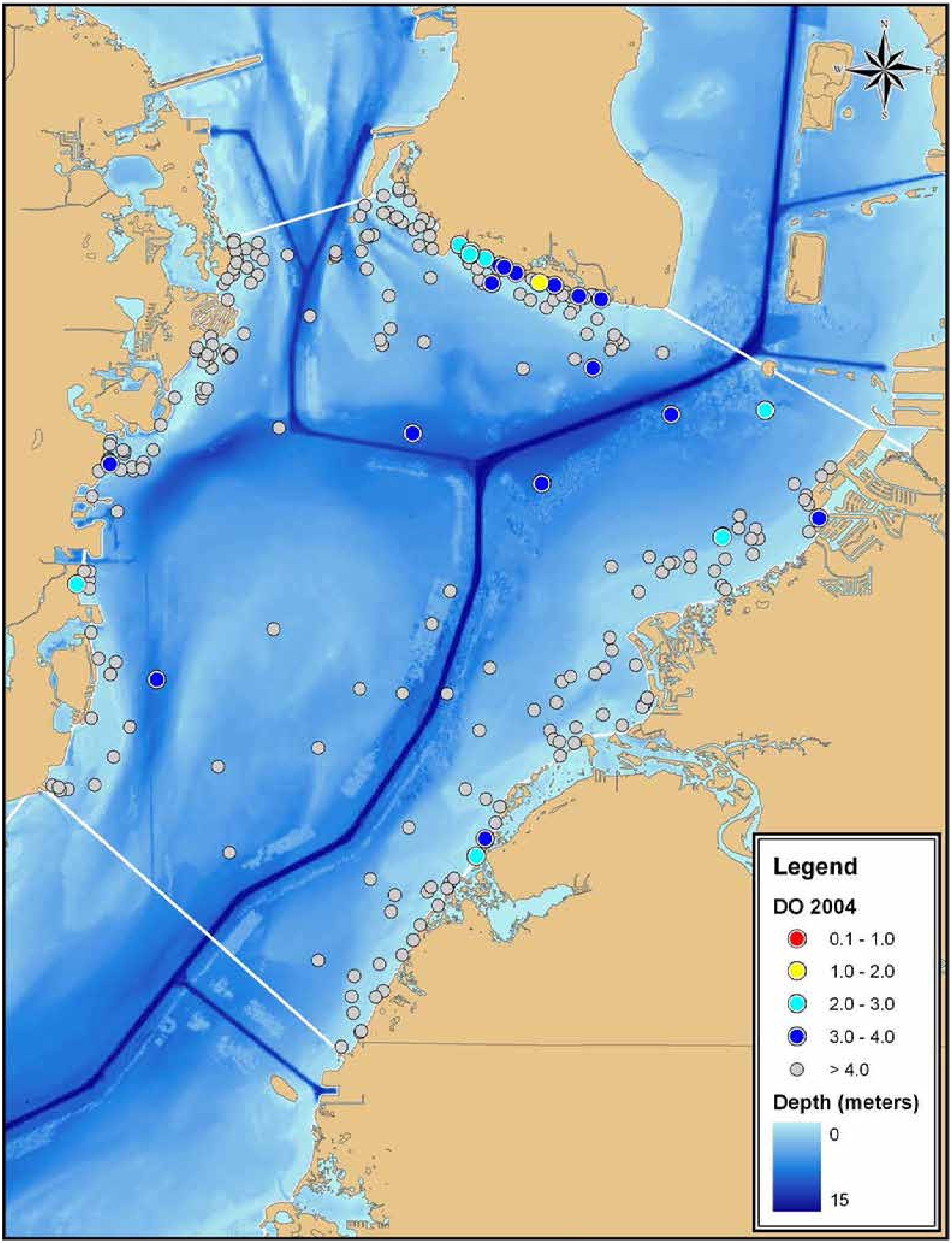

N
S
E
W
Legend
DO 2000
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

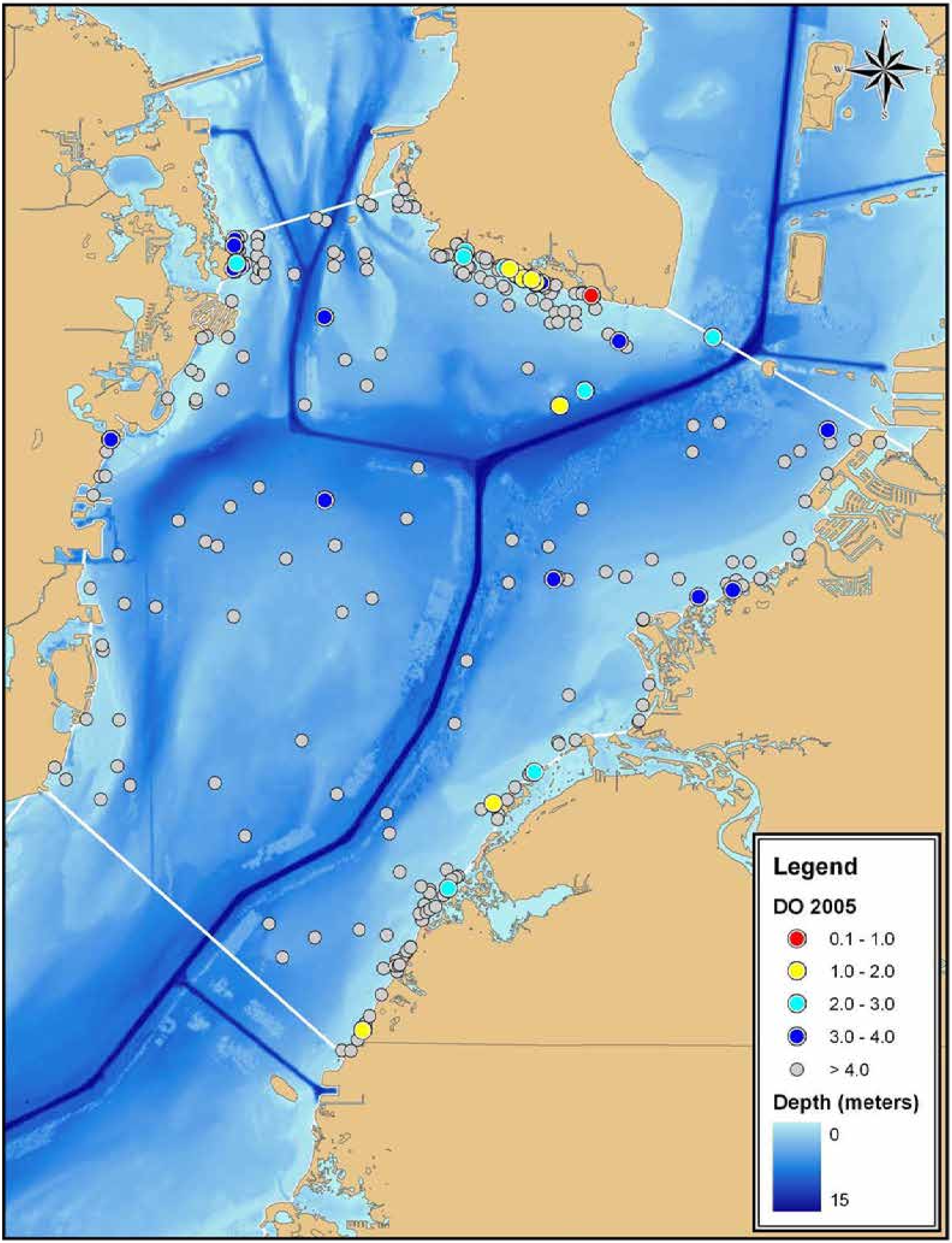

N
S
E
W
Legend
DO 2001
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

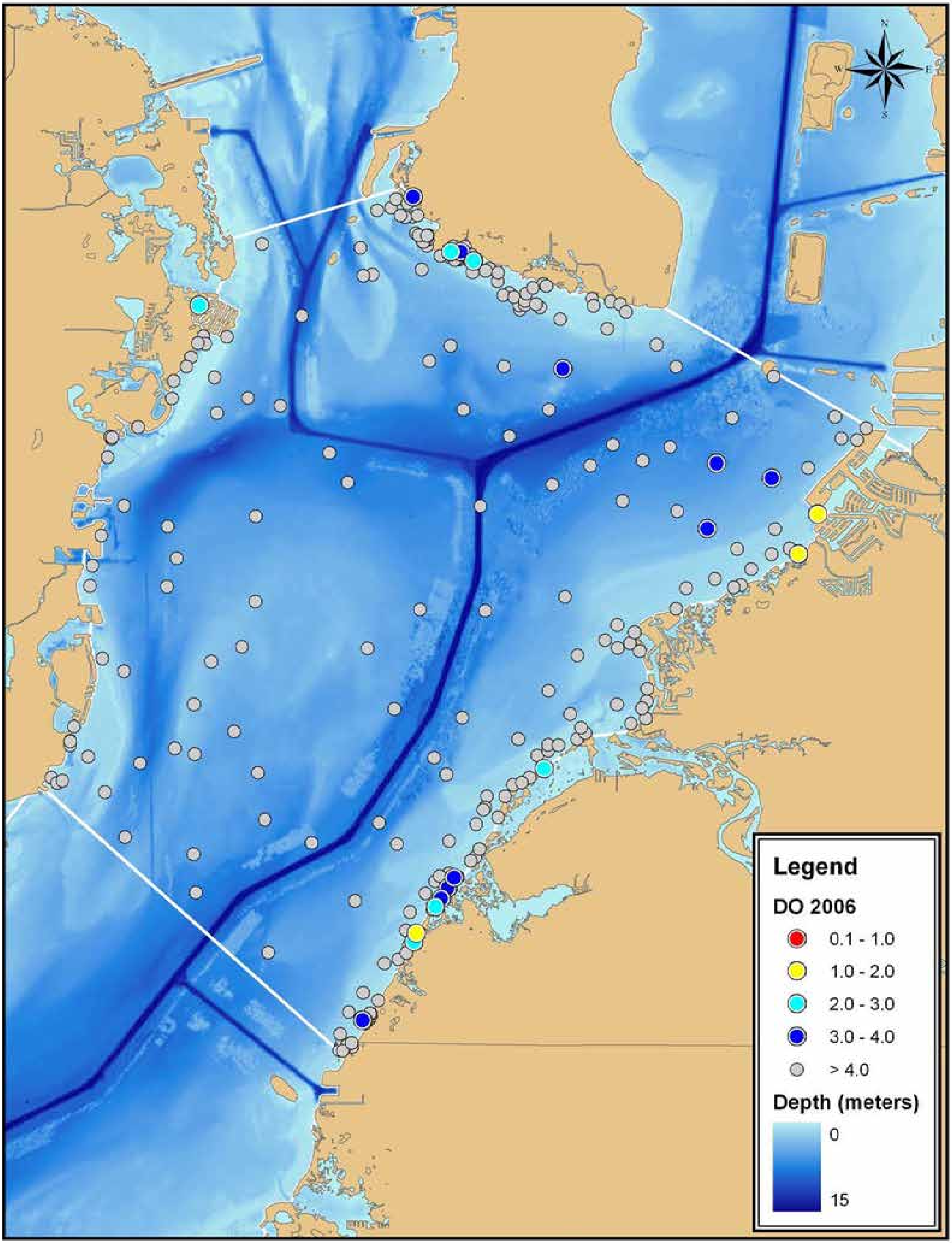

N
S
E
W
Legend
DO 2002
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

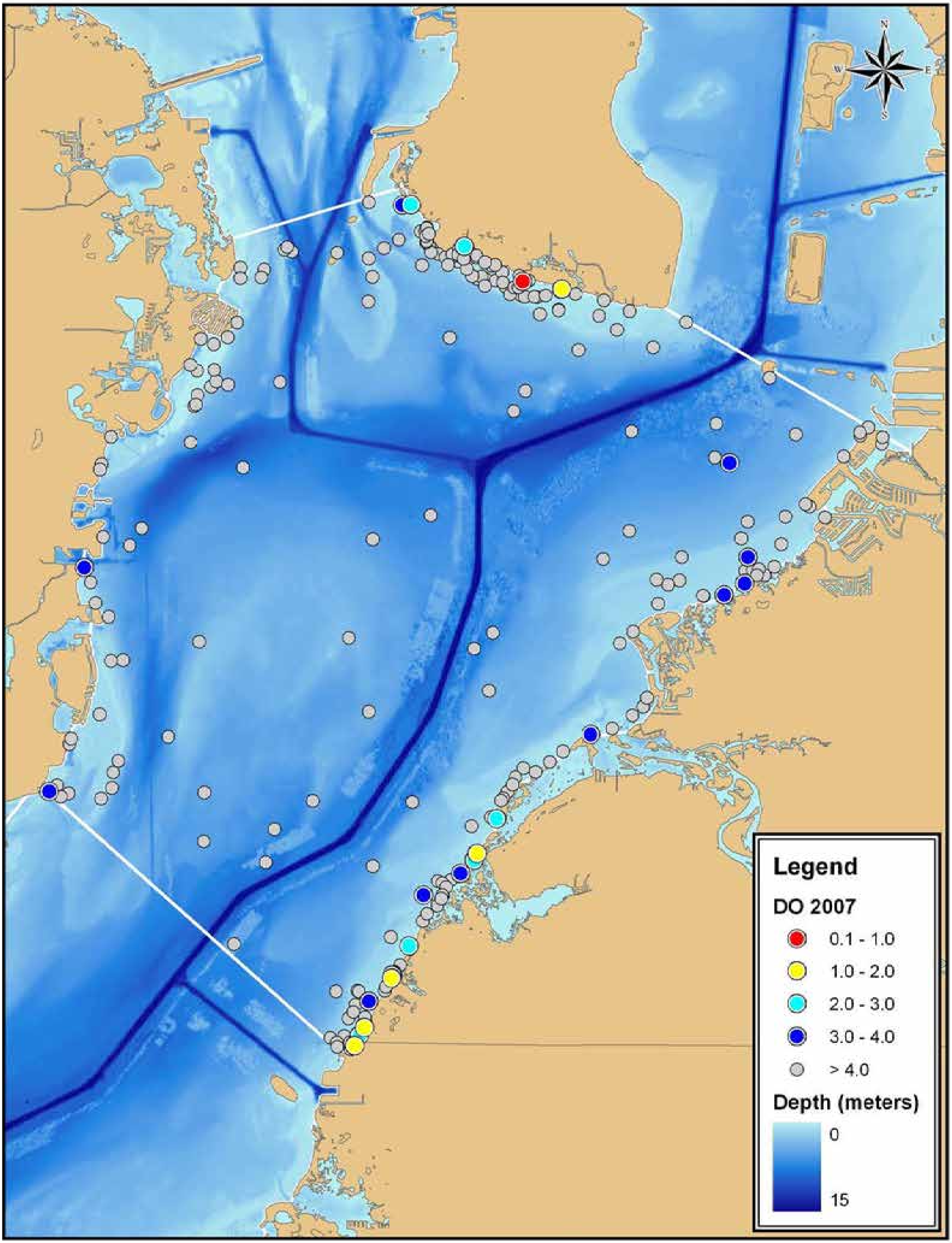


N
S
W
E
Legend
DO 2003
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

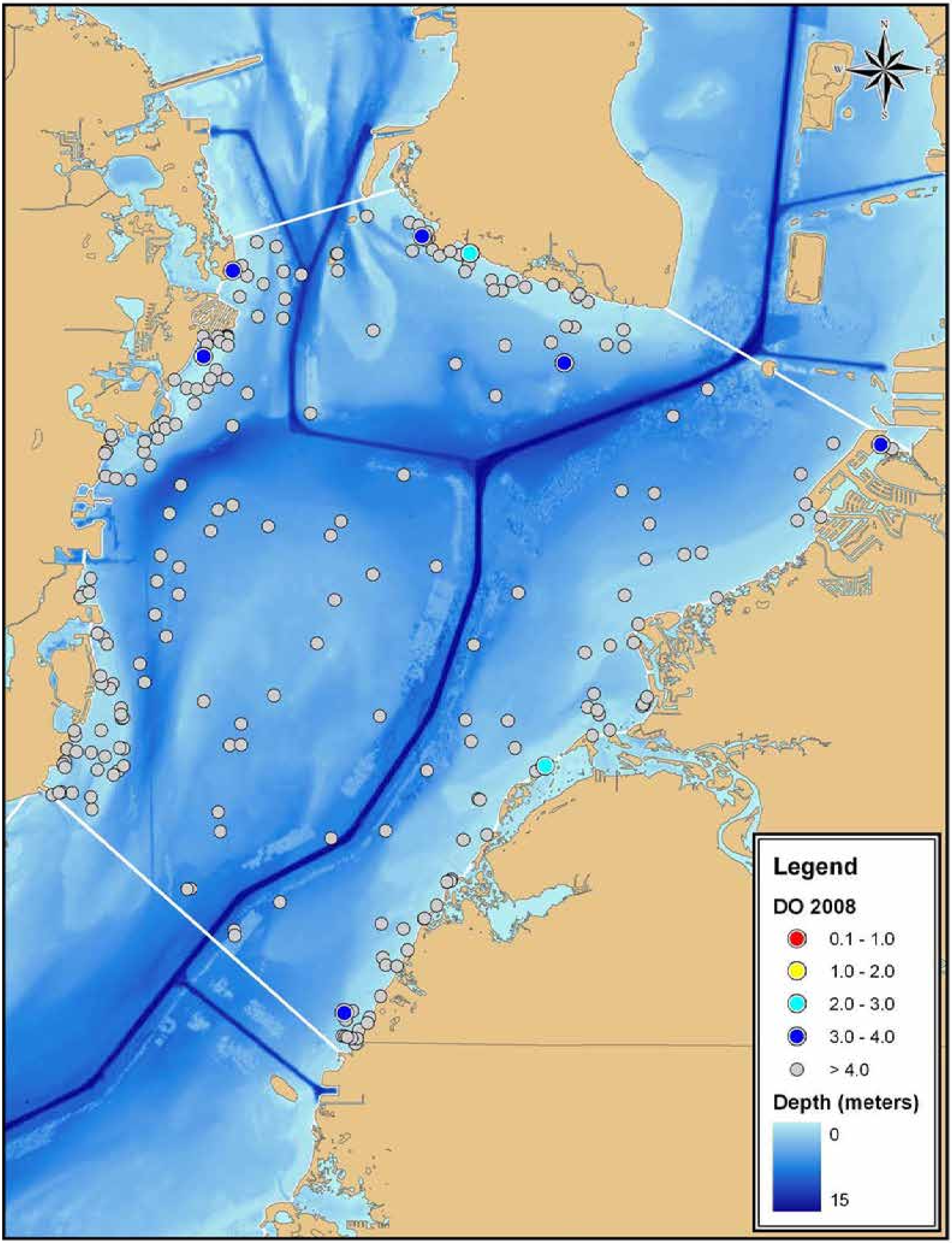

N
S
E
W
Legend
DO 2004
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

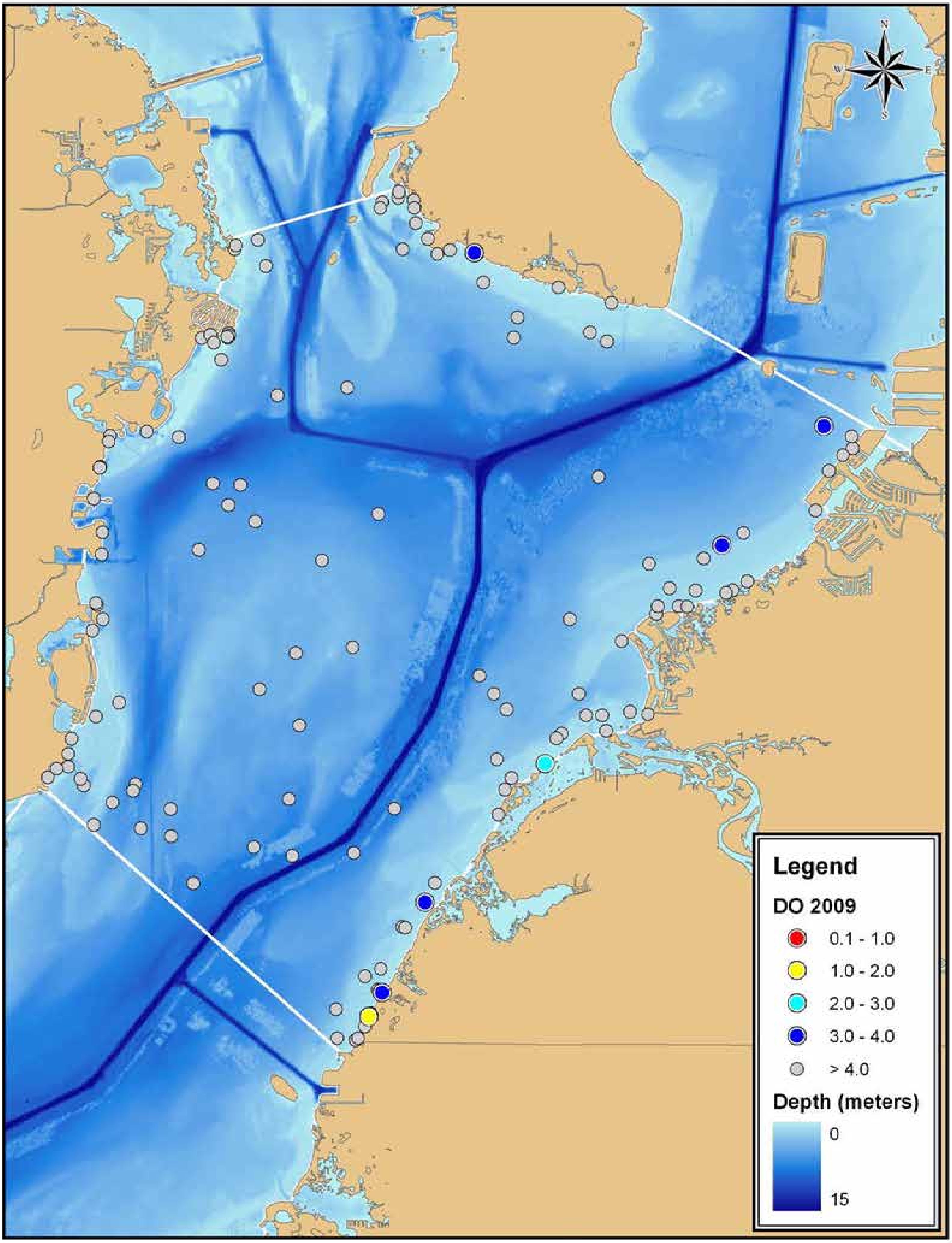

N
S
E
W
Legend
DO 2005
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

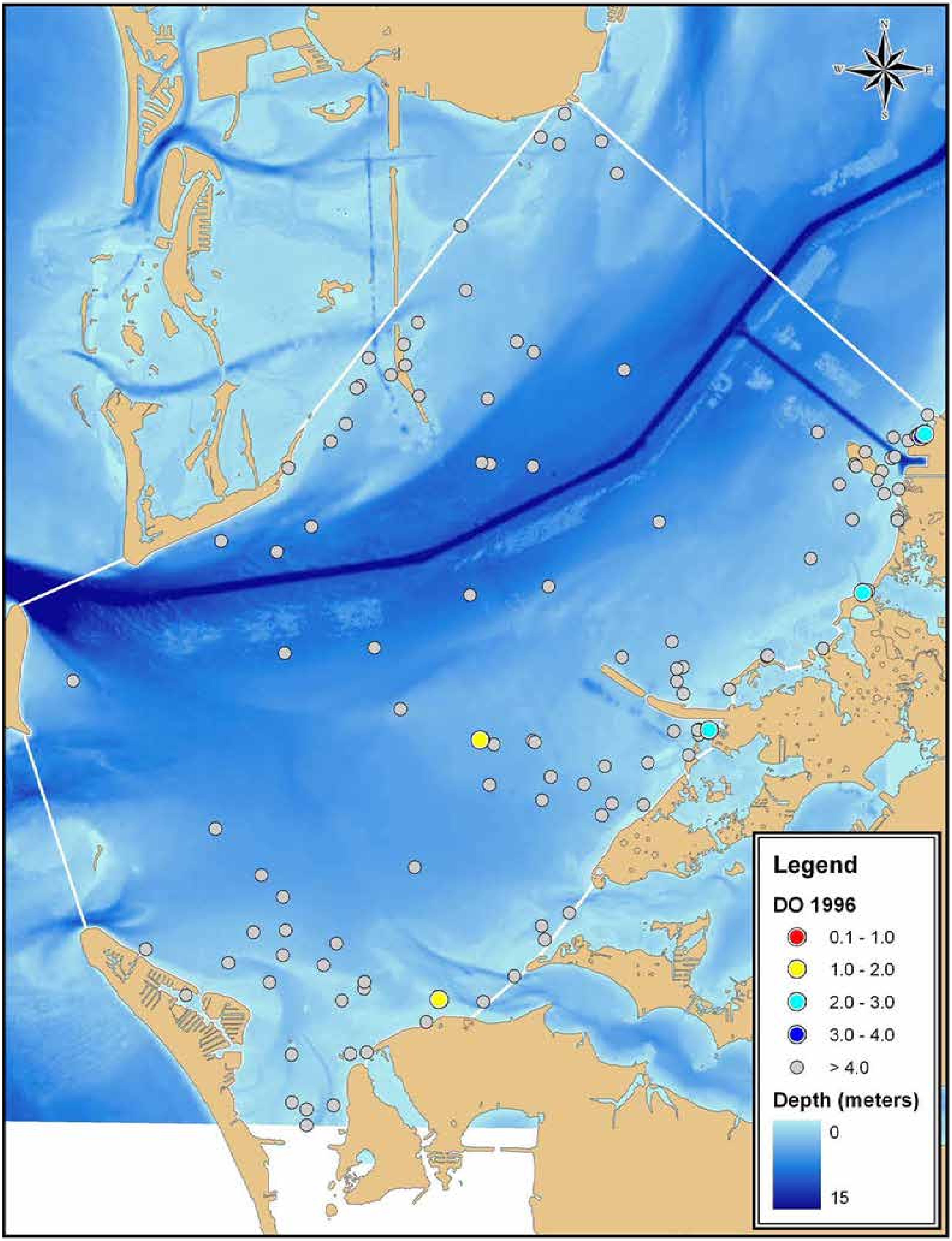

N
S
E
W
Legend
DO 2006
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

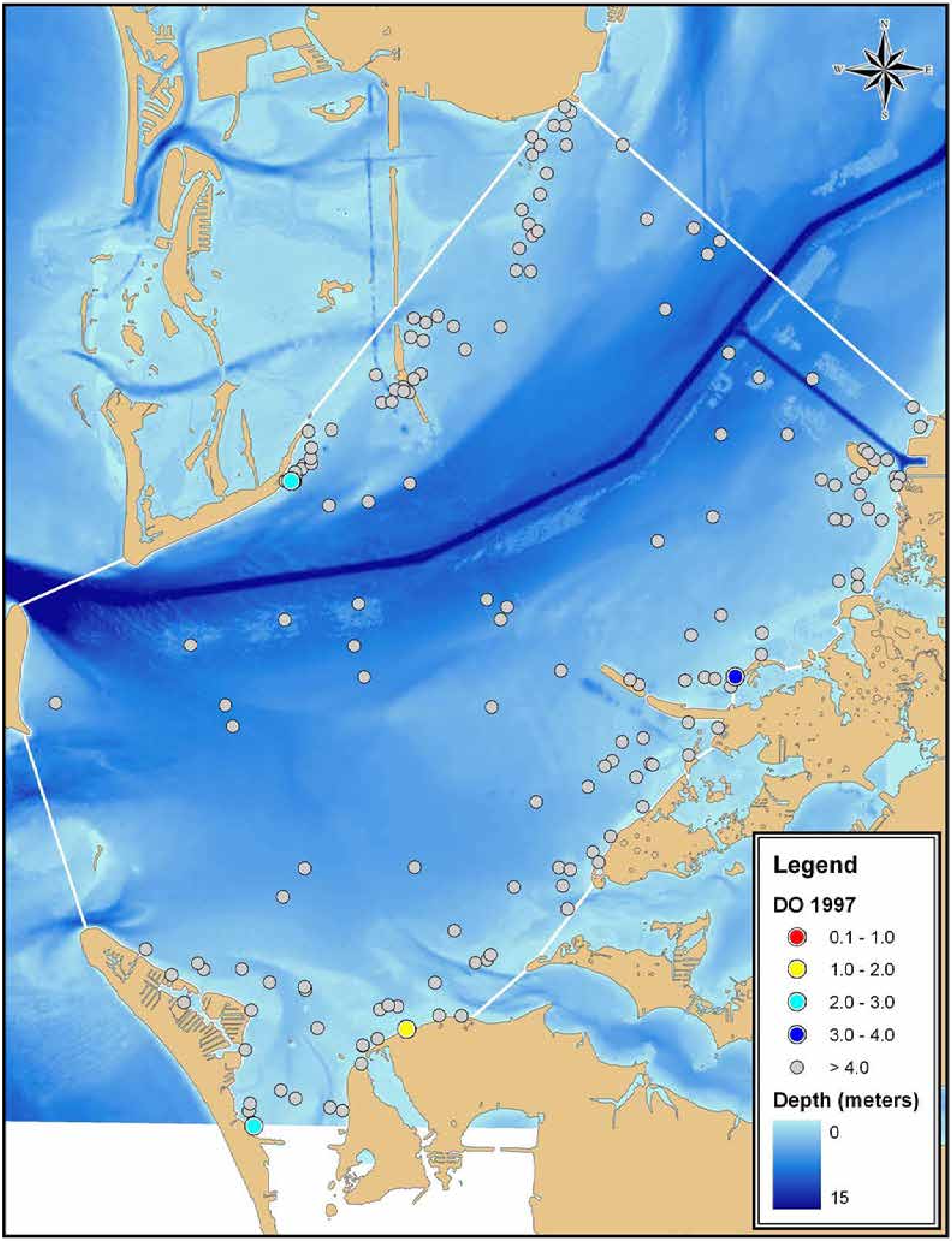


N
S
E
W
Legend
DO 2007
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

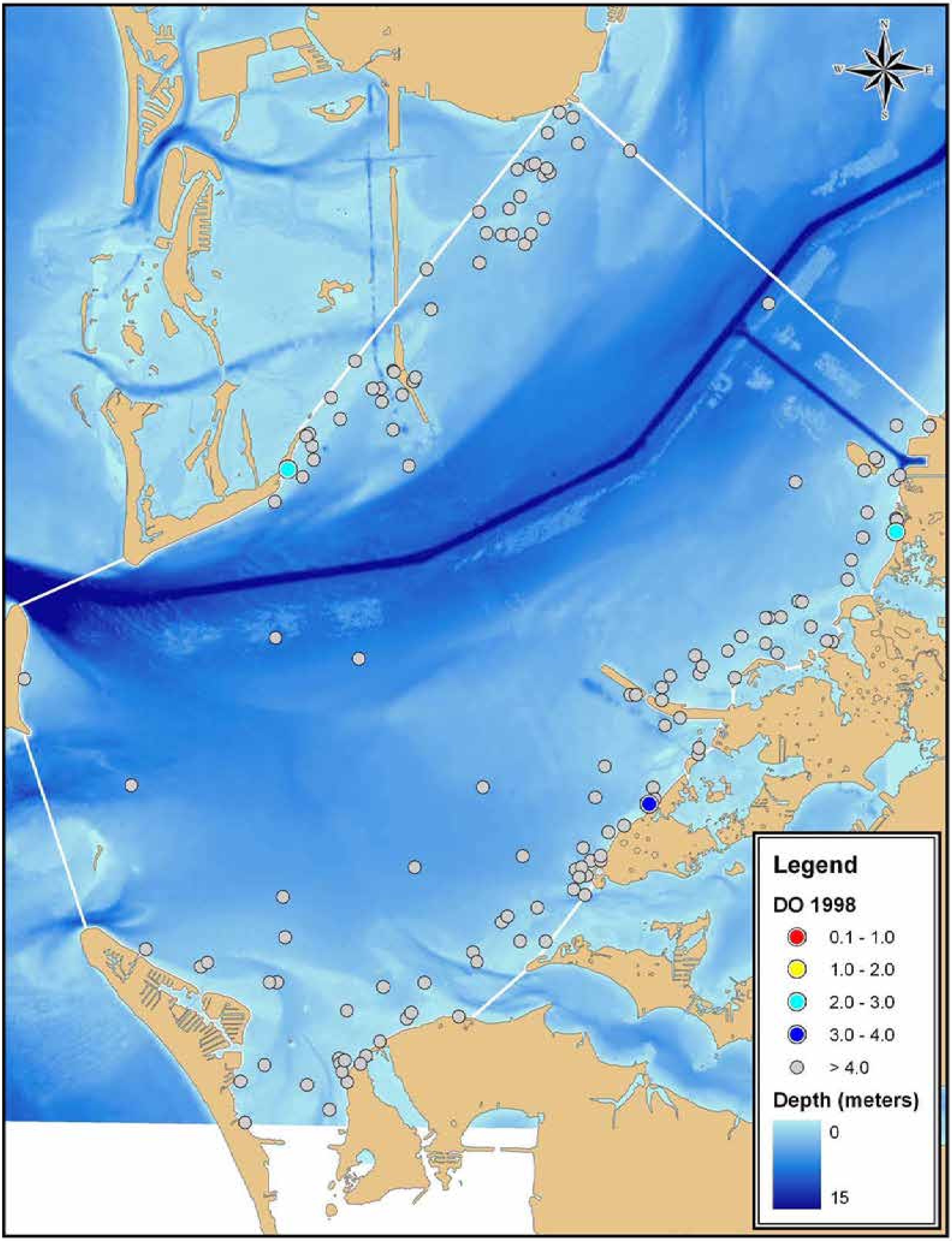

N
S
E
W
Legend
DO 2008
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

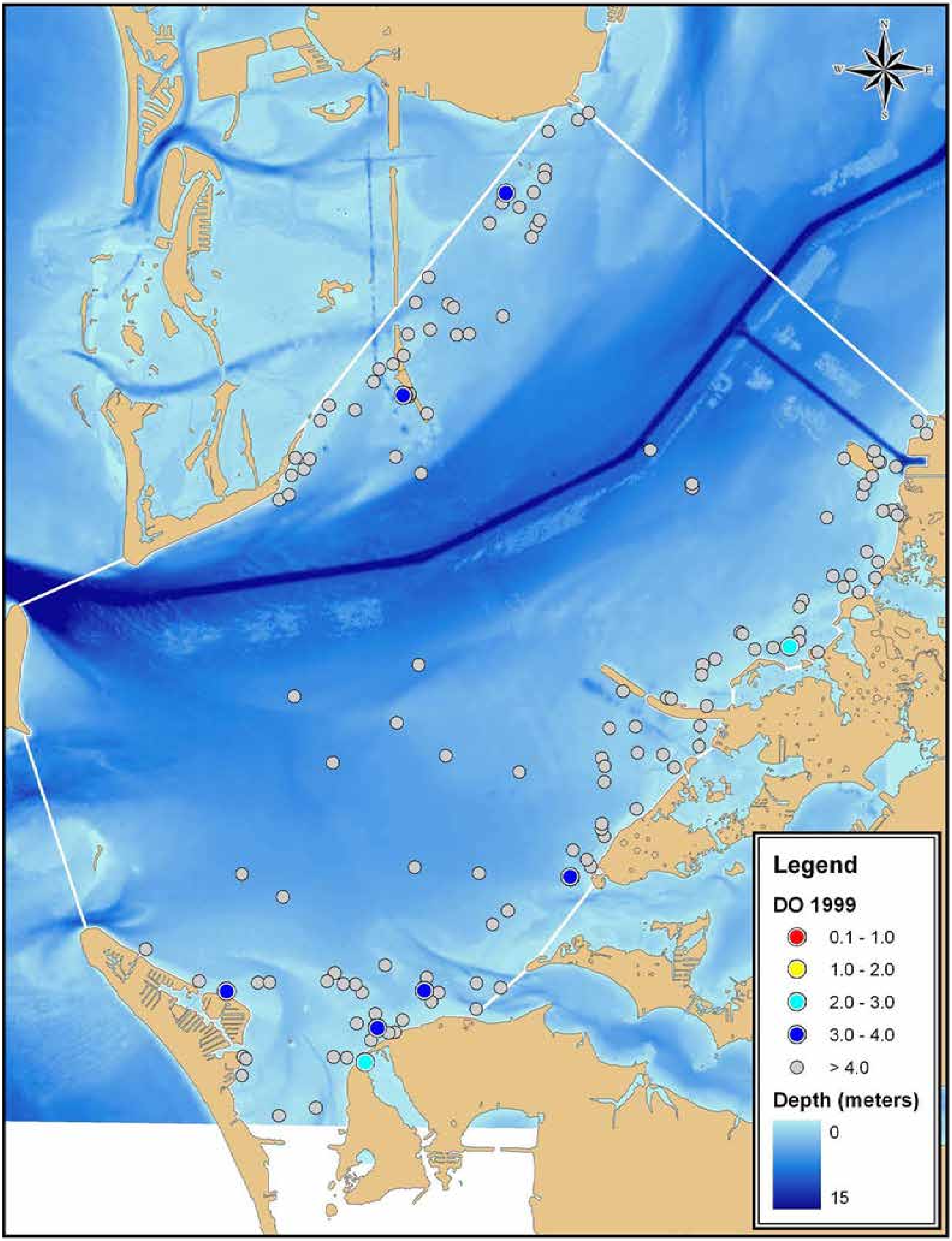

N
S
E
W
Legend
DO 2009
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15


N
W
E
S
Legend
DO 1996
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

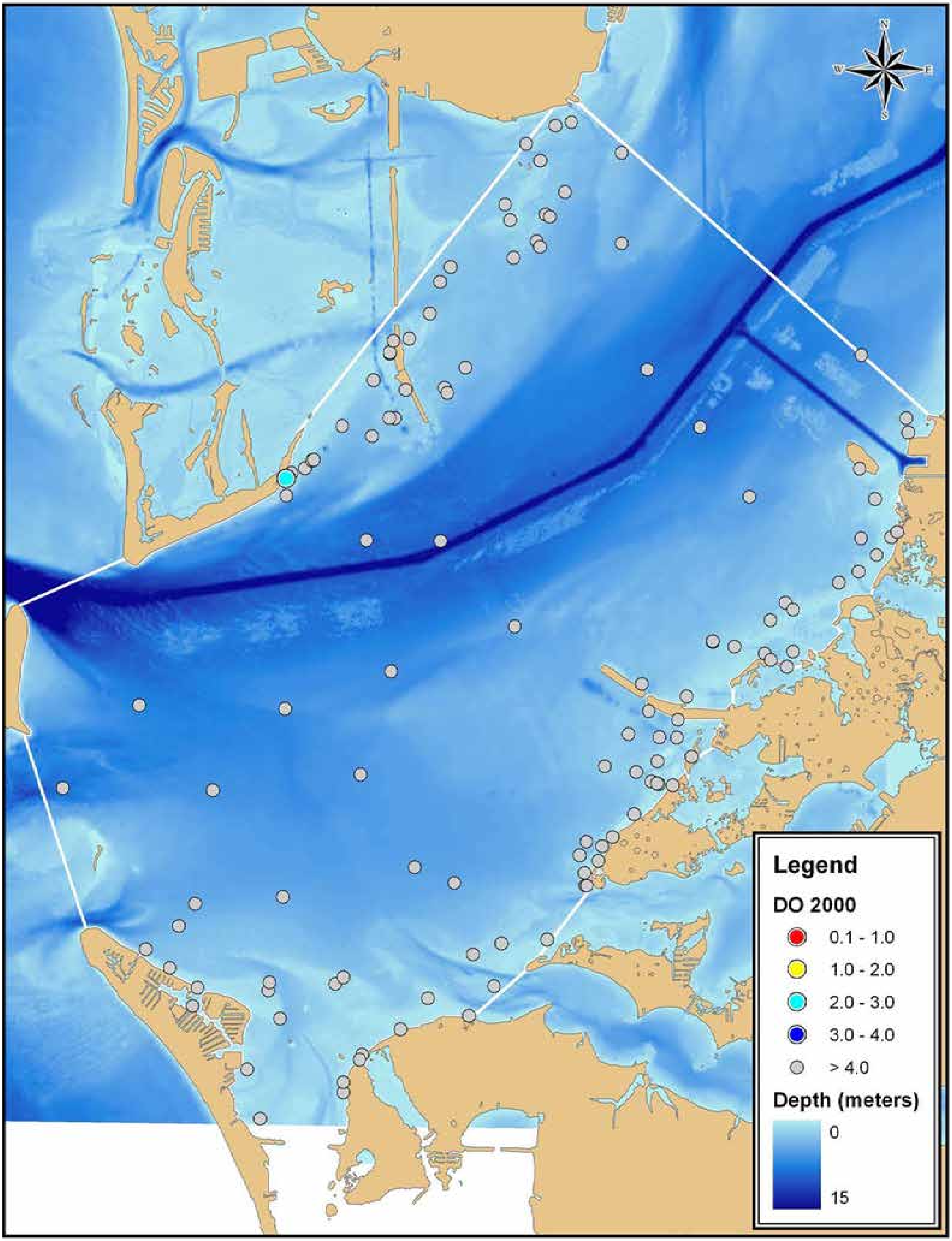


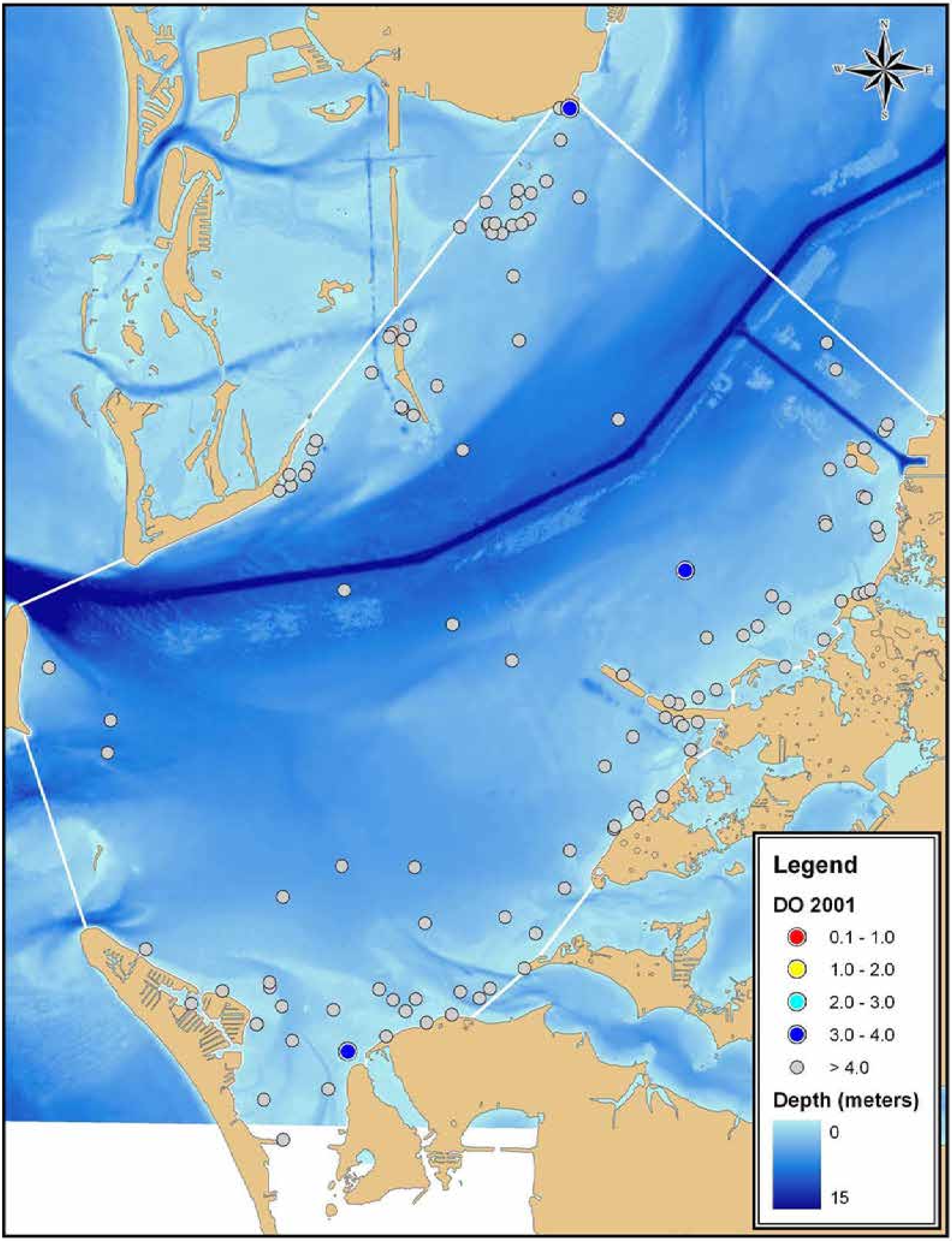
N
W
E
S
Legend
DO 1997
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

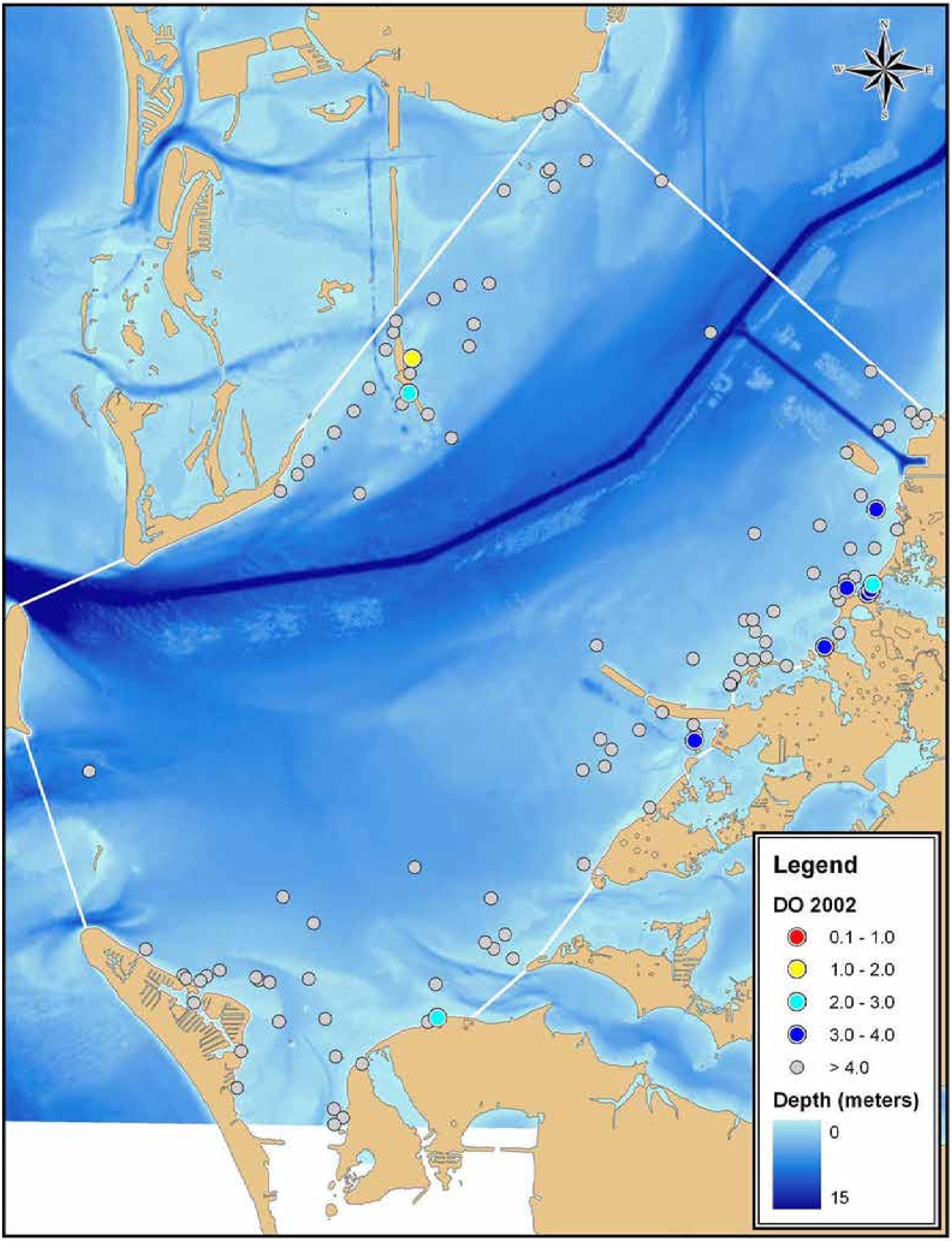

N
S
W
E
Legend
DO 1998
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

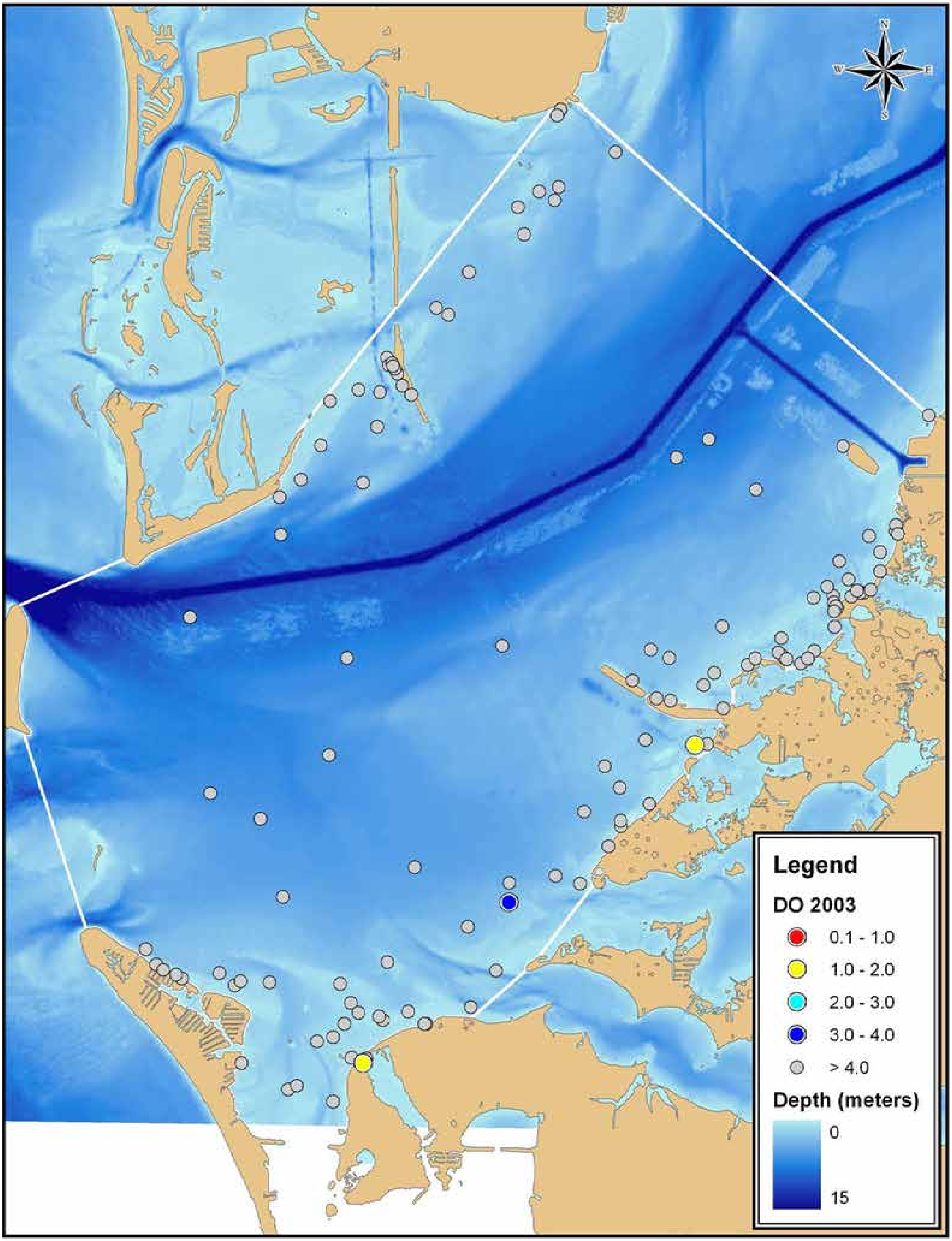


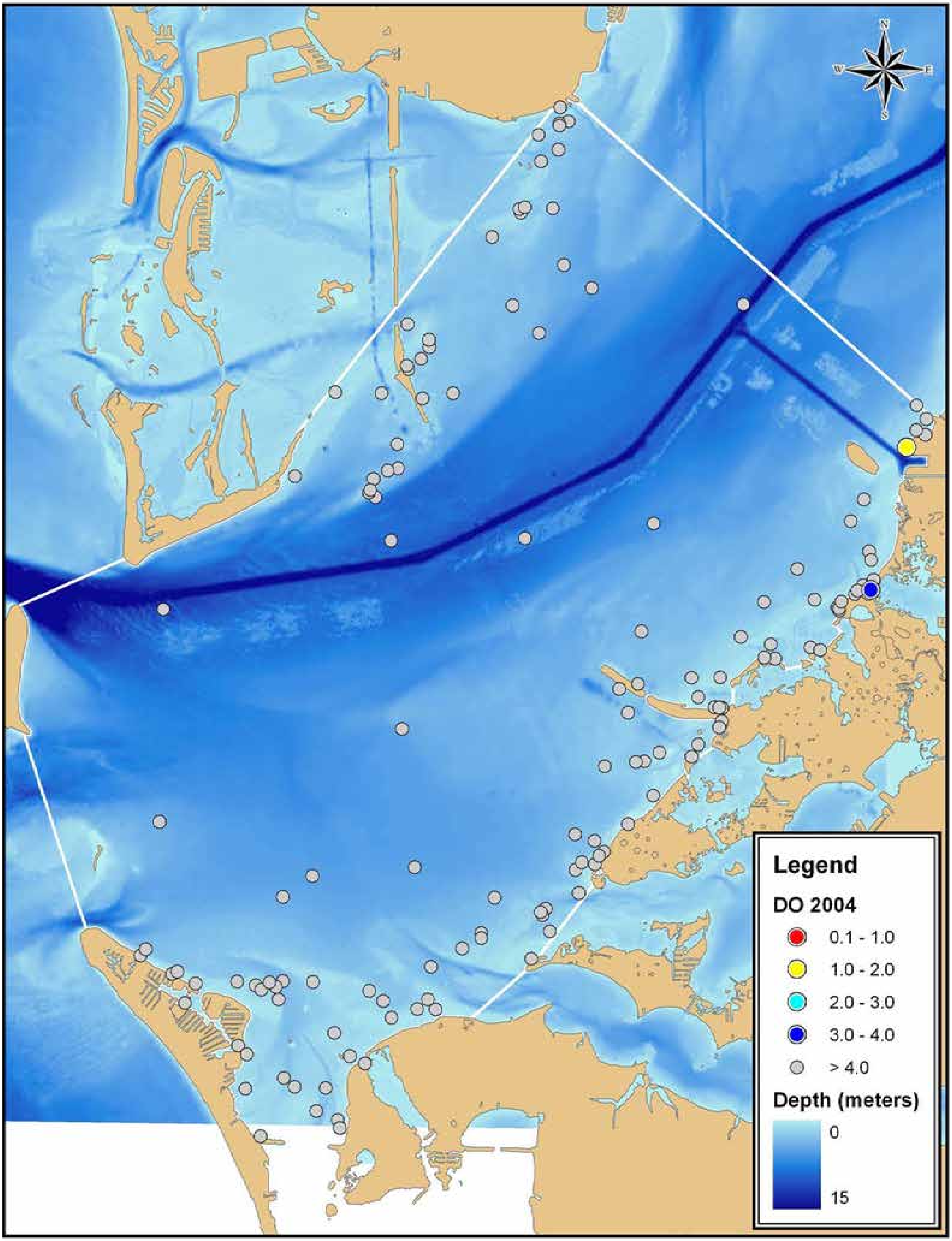
N
W
E
S
Legend
DO 1999
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15


N
S
E
W
Legend
DO 2000
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

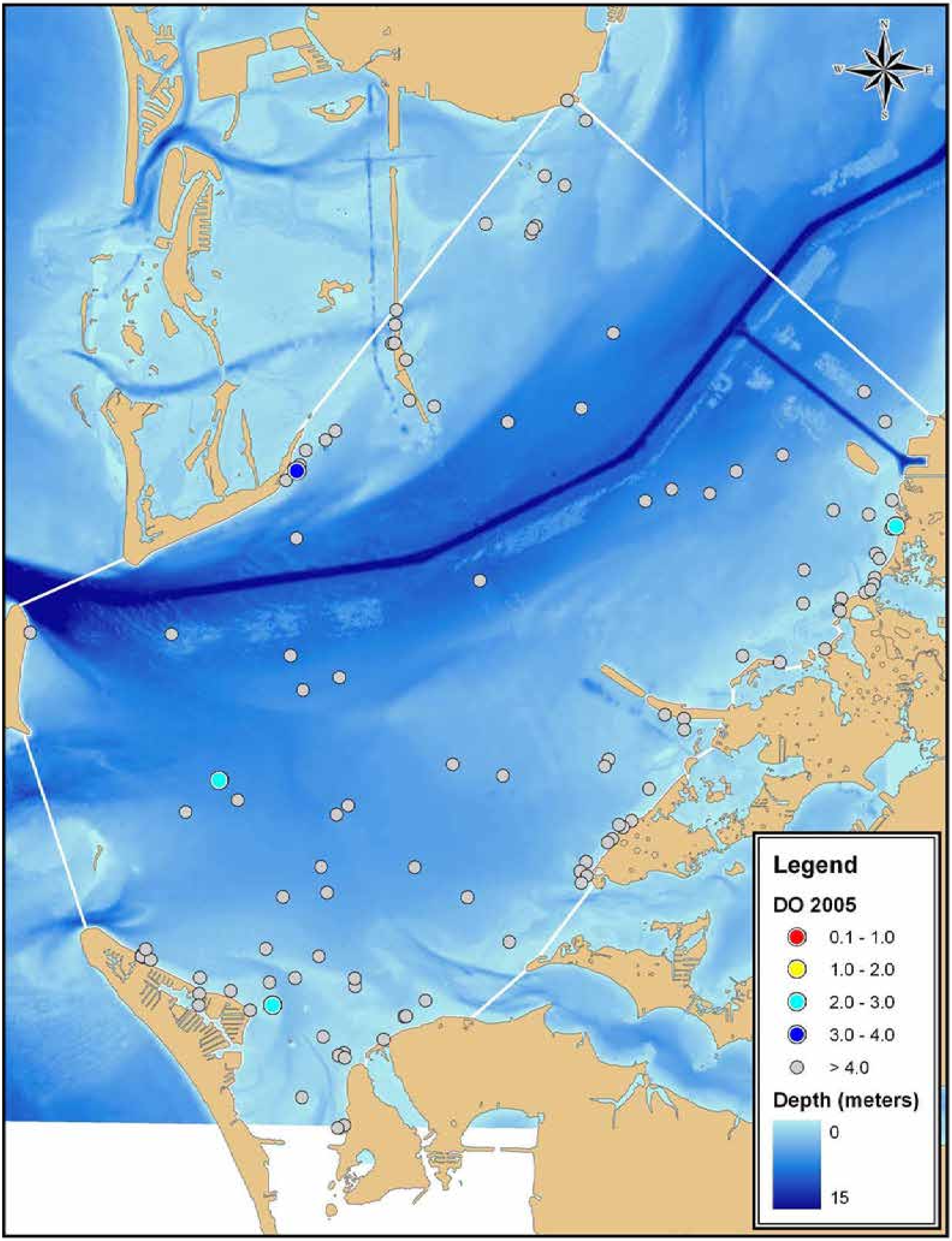

N
W
E
S
Legend
DO 2001
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

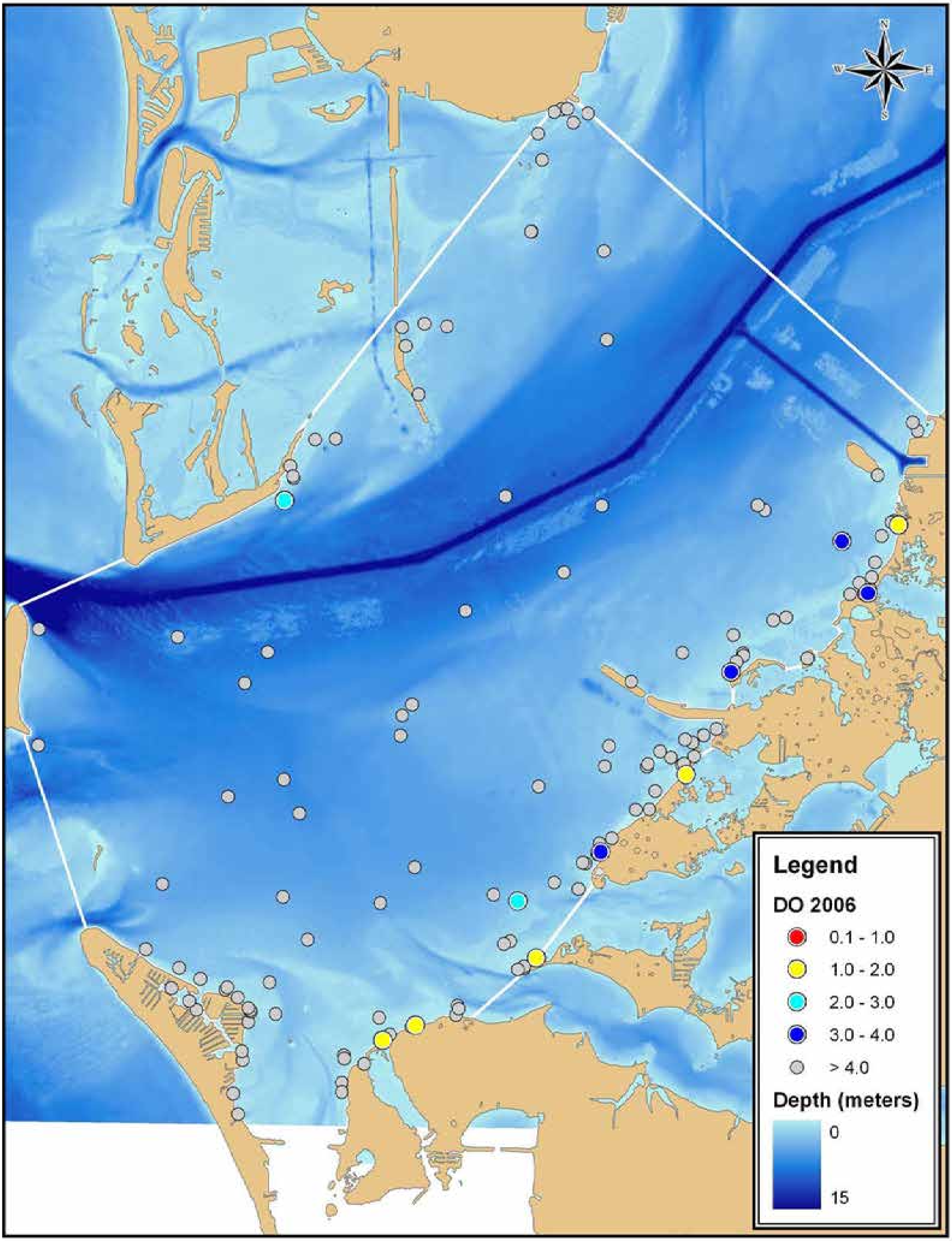

N
W
E
S
Legend
DO 2002
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

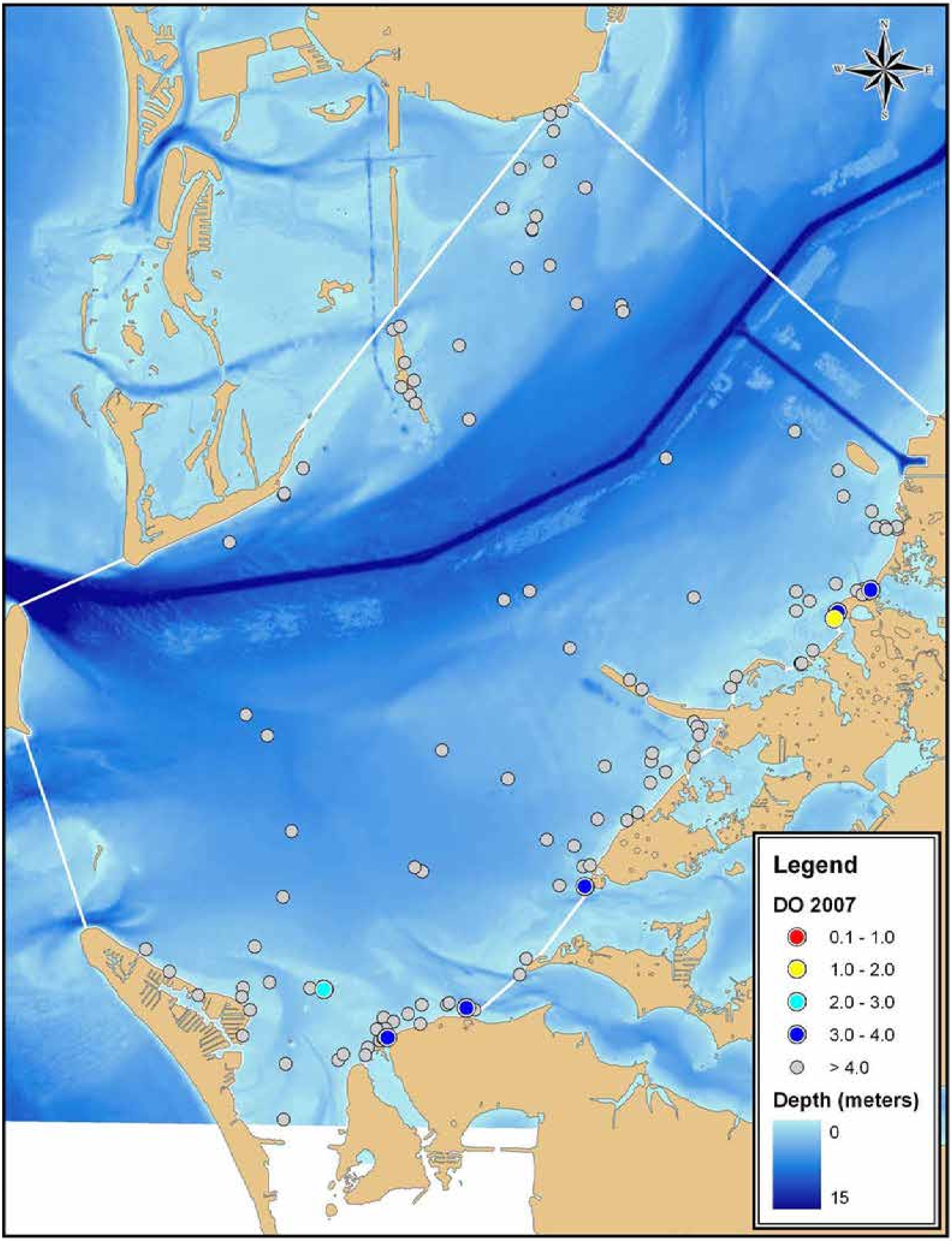

N
S
E
W
Legend
DO 2003
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

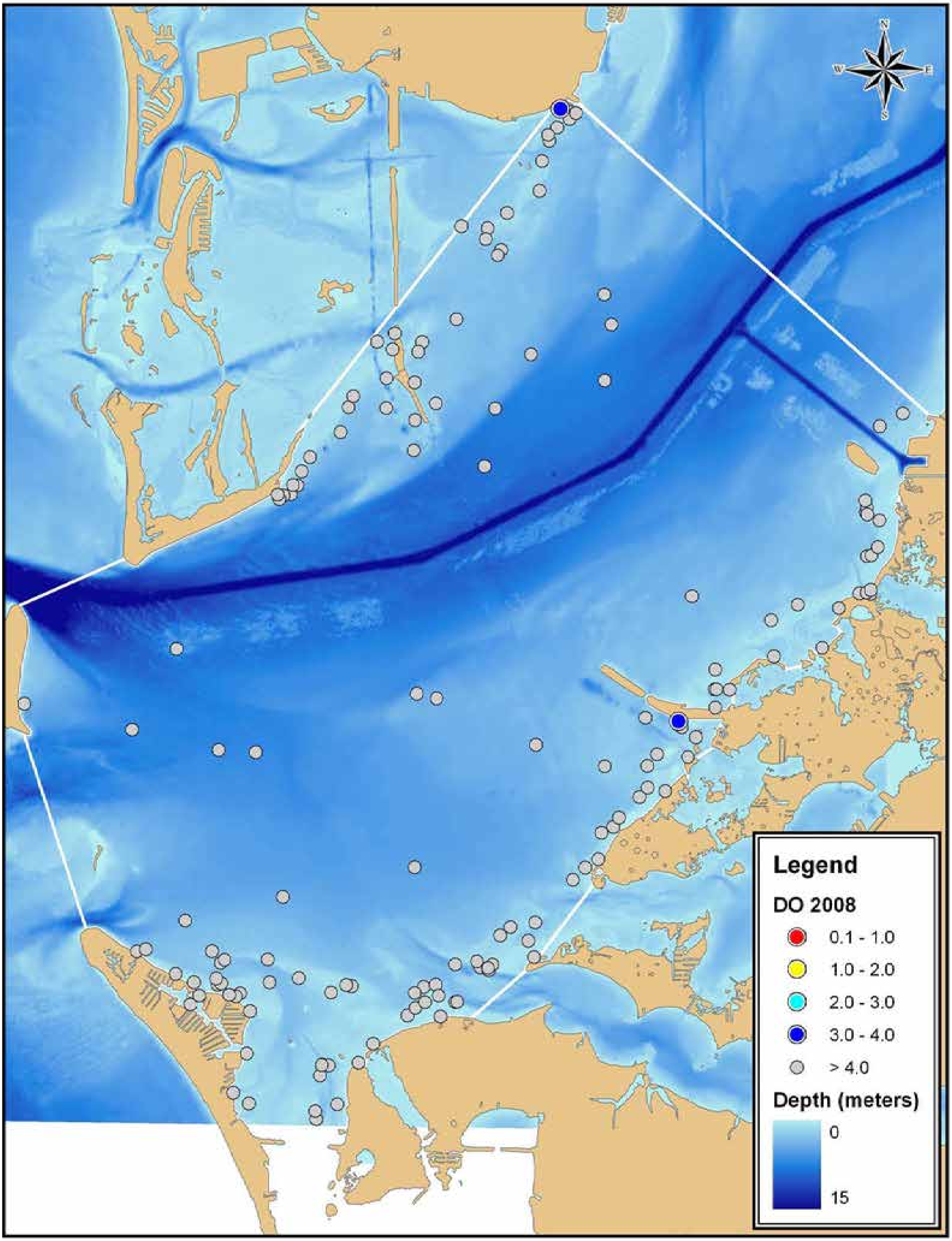


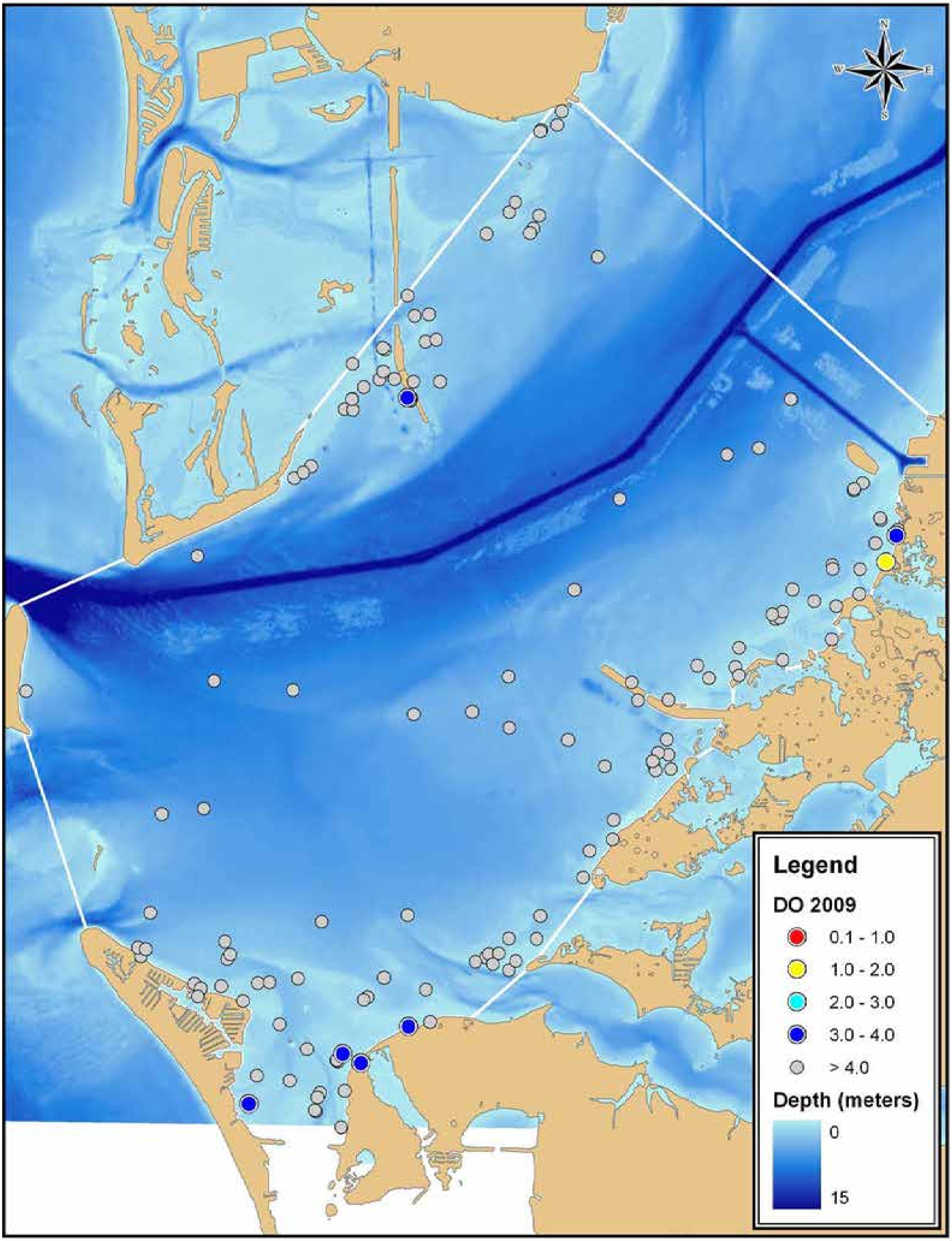
N
S
E
W
Legend
DO 2004
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15


N
S
W
E
Legend
DO 2005
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15


N
W
E
S
Legend
DO 2006
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15


N
W
E
S
Legend
DO 2007
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15


N
W
E
S
Legend
DO 2008
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15



N
S
W
E
Legend
DO 2009
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15

TAMPA BAY
Numeric Nutrient Criteria:
Tidal Creeks

Letter Memorandum

Prepared for:

Tampa Bay Estuary Program

Prepared by:

Janicki Environmental, Inc.

16 February 2011

Foreword

This letter memo was produced in partial fulfillment of Purchase Order #6584, TBEP Contract T-07-01 - Development of Numeric Nutrient Criteria for Tampa Bay.

Acknowledgements

We wish to thank the Partners of the Tampa Bay Estuary Program and members of the Tampa Bay Nitrogen Management Consortium for the numerous conversations providing direction and insight into concerns regarding numeric nutrient criteria establishment and appropriate methodology for developing the proposed criteria. Ms. Holly Greening and Mr. Ed Sherwood were particularly helpful in their insights to this issue.

EXECUTIVE SUMMARY

Tidal creeks are relatively small coastal tributaries (<1-20 km in length) that lie at the transition zone between terrestrial uplands, freshwater streams, and the open estuary, and serve as a link between terrestrial and estuarine systems. Despite their close connection to these systems, tidal creeks play a unique and integral role in the ecological function of coastal estuaries as:

- a source of high primary and secondary production,
- a site of nutrient cycling, and
- a source of food for small-bodied fishes and crustaceans, as well as a foraging area for larger piscivorous fishes, wading birds, snakes, and alligators, and nursery habitat for juvenile fishes and crustaceans of economic value, including the common snook (*Centropomus undecimalis*).

Tidal creeks possess water quality characteristics that differ from freshwater systems and from the open estuary. As a result of their direct connection and close proximity to watershed sources of nutrient inputs and their smaller volumes and shallower depths relative to the open estuary, tidal creeks have relatively high nutrient and chlorophyll concentrations and low dissolved oxygen (DO) levels compared to downstream waterbodies. DO levels from 2-4 mg/L are commonly observed in tidal creeks in the southeastern United States, including creeks from undeveloped watersheds. Higher nutrient concentrations and lower DO levels in tidal creeks relative to the greater estuary may be required to support the higher levels of primary and secondary production in these systems. Nutrient inputs from the surrounding watershed supply much of the fuel that drives primary production in tidal creeks, in the form of benthic microalgal communities and phytoplankton. The algal stocks, in turn, support upper trophic levels and drive secondary production by benthic macroinvertebrates, fishes, and decapod crustaceans. Despite possessing water quality conditions that would otherwise be considered impaired in freshwater and estuarine systems, tidal creeks have been shown to support higher densities of many species of small-bodied fishes compared to the adjacent estuary and tidal rivers. Many of these species have acquired physiological and behavioral adaptations, including aquatic surface respiration (ASR) and air-gulping, which allow them to persist under the low-DO conditions that often occur in tidal creeks and to take advantage of the forage and refuge value of these systems.

In the Tampa Bay estuary, there are approximately sixty tidal creeks that are terminal tributaries to the bay or to smaller embayments within the bay. Most tidal creeks in Tampa Bay are relatively small (<10 km in length) and narrow (spanning only 25-50 m from bank to bank) in contrast to the tidal rivers which range from 40-100 km in length and 100-300 m wide on average. Many of Tampa Bay's tidal creeks have been developed for urban, industrial, or agricultural land uses, though some tidal creeks remain relatively undeveloped and are predominantly found in mangrove wetlands. Unlike the open estuary of Tampa Bay which possesses expansive seagrass beds, tidal creeks are typically devoid of seagrass. For this reason, the development of nutrient criteria based on water clarity and seagrass persistence is not appropriate.

Given the current state of knowledge for tidal creeks, four approaches to develop numeric nutrient criteria in tidal creeks are available. Each of these approaches has previously been considered for development of nutrient criteria for the Tampa Bay estuary. These include: 1) stressor-response models which examine quantitative relationships between nutrient concentrations and either chlorophyll *a* or DO concentrations within a specific waterbody of concern (i.e., tidal creek); 2) reference condition methods which use available data for selected reference periods in creeks to derive numeric nutrient criteria for the creeks; and 3) downstream protective values which are based on the relationship between water quality in the creek and that of the downstream receiving estuary such that the water quality in the tidal creek does not result in water-quality exceedances in the downstream estuary.

The most desirable approach to establish numeric nutrient criteria would be to develop stressor-response models. Stressor-response models require the identification of an indicator variable that can be used to evaluate the condition of the tidal creek. Moreover, stressor-response models require identification of a threshold value above (or below) which the system would no longer fully support its designated use. Due to a current lack of data with which to develop stressor-response models for Tampa Bay's tidal creeks, numeric nutrient criteria for these systems are currently not recommended.

Numeric nutrient criteria established for tidal creeks must consider the different ecological processes and functions that distinguish them from both the freshwater systems upstream and the open estuary downstream. It is important that the established criteria for tidal creeks also account for the fact that these systems by nature are more variable than their upstream or downstream counterparts. This variability is in part what makes these systems so productive and also so difficult to generalize. Implementation of criteria for tidal creeks should also rely heavily on quantifying the uncertainties in both the derivation of criteria and in the evaluation of potential remediation efforts associated with failure of the criteria. Only with careful consideration of these factors can criteria be developed that will maintain the function of tidal creeks in support of the greater estuarine ecosystem.

Based on the recognized need to define distinct biological endpoints for tidal tributaries and water quality criteria to support them, TBEP staff recommends the following:

- Recognize tidal tributaries as a separate waterbody class; and
- Consider setting a schedule (i.e., within 3 years) by which time endpoints and criteria will be proposed, but do not attempt to set interim or final criteria with insufficient data.

TBEP has dedicated funds to continue work in tidal tributaries in Tampa Bay and will commit to work with EPA to develop recommendations by September 2014.

1.0 Background

The Florida Department of Environmental Protection (FDEP) began development of numeric nutrient standards in December 2001. The FDEP formed a technical advisory committee and an agency work group to assist in identifying appropriate nutrient standards. FDEP conducted a number of workshops and meetings as well as several studies that were conducted since 2002.

In 2008, several environmental groups filed suit against the U. S. Environmental Protection Agency (EPA) in Federal Court alleging that EPA had determined in 1998 that Florida's current narrative nutrient standard did not comply with the Clean Water Act and that EPA had not established numeric nutrient standards pursuant to Section 303(c)(4)(B) of the Clean Water Act. As a consequence of this lawsuit, EPA sent FDEP a letter on January 14, 2009 finding that FDEP's narrative nutrient standard did not comply with the Clean Water Act and directing the State of Florida to develop its own numeric nutrient standards for rivers and lakes by January 2010 and estuarine and coastal waters by January 2011 or EPA would adopt its own nutrient standards. In August 2009, these groups and EPA agreed to a Consent Decree formally establishing these deadlines and EPA will be responsible for establishing these criteria.

Currently, EPA is developing numeric nutrient criteria for four water body types in Florida (EPA, 2010):

- Estuaries,
- South Florida flowing waters,
- South Florida coastal waters, and
- Other coastal waters.

The definition used by EPA for estuaries is similar to that of Pritchard (1967) and incorporates the State of Florida definition of a "predominantly marine water" and is as presented by Hagy (2010):

> "An estuary is a semi-enclosed body of water, connected to the open sea, defined at the upstream limit by average salinity equal to 2.7 and at the seaward margin by the natural limits of the semi-enclosed basin."

Questions have been raised as to whether the criteria to be proposed for the estuary proper should apply to tidal creeks that drain to the estuary. The objective of this document is to provide support for the recommendation that unique numeric nutrient criteria be developed for tidal creeks.

Tidal creeks play an integral role in the ecological function of coastal estuaries. The treatment of tidal creeks in the implementation of the estuarine numeric nutrient criteria is, therefore, a significant issue. A thorough understanding of the ecological elements (e.g., faunal and floral species and communities), processes (e.g., primary productivity, nutrient cycling, secondary production), dynamics of tidal creeks (e.g., temporal fluctuations in dissolved oxygen) and function in exporting energy to estuarine and coastal ecotones is paramount to the establishment of ecologically appropriate nutrient criteria. Numeric nutrient criteria established for tidal creeks must consider the different ecological processes and functions that distinguish them from both the freshwater systems upstream and the open estuary downstream. Only with careful consideration of these attributes can criteria be developed that will maintain the function of tidal creeks in support of the greater estuarine ecosystem. The objective of this task is to:

- Provide a definition of tidal creeks,
- Provide a generalized overview of the ecological function of tidal creeks in relation to the estuary,
- Identify factors to be considered when establishing criteria for tidal creeks, and
- Discuss potential methods for data evaluation directed at establishing nutrient criteria for these systems.

1.1 Definition of a Tidal Creek

Located at the transition zone between terrestrial uplands and the open estuary, tidal tributaries deliver freshwater and nutrients from the surrounding watershed to the estuary. Tidal tributaries can be classified based on size, with larger tidal rivers often a prominent feature in the estuarine landscape. Smaller tidal tributaries (herein referred to as "tidal creeks") include natural and manmade creeks, canals, navigational channels, and ditches created for stormwater drainage or mosquito control. The geomorphological and physicochemical features of the tidal creeks distinguish them from the non-tidal, freshwater tributaries, springs, and lacustrine systems that are found elsewhere in the watershed and determine zonation patterns for the flora and fauna that inhabit these systems. Tidal creeks in peninsular Florida may reach well upstream of the mouth and may be distinguished on the basis of elevation; tidal creeks extending above sea-level are often greater in length and drain larger watershed areas than creeks restricted to elevations below sea-level. Those tidal creeks draining only intertidal areas are likely dominated by tidal fluctuations and are less influenced by stormwater runoff than creeks originating above sea-level which often have well-developed freshwater reaches and are more sensitive to stormwater inputs.

The differences in physiographic and water quality attributes observed along the gradient from headwater streams to larger rivers are the result of processes related to the flow of water and have been termed the "River Continuum Concept" by Vannote et al. (1980). This concept is based on the idea that first-order tributaries are more strongly linked to terrestrial processes and inputs and, as a result, are inherently different from downstream reaches. Flow-related changes to the geomorphology of the tributary (e.g., stream width, bank slope, channel depth) along the river continuum translate to differences in the composition of floral and faunal communities, trophic structure and ecological processes. There is evidence that this concept can be applied to coastal systems, as well, from freshwater tributaries to tidal tributaries to the estuary (Greathouse and Pringle, 2006).

1.2 Hydrological and Water Quality Processes in Tidal Creeks

Tidal creeks are expected to possess water quality characteristics that differ from freshwater systems and from the open estuary; this should be a key consideration when developing numeric nutrient criteria for transitional systems like tidal creeks. As a result of their direct connection and close proximity to watershed sources of nutrient inputs and their smaller volumes relative to the open estuary, tidal creeks have relatively high nutrient and chlorophyll *a* concentrations and low dissolved oxygen (DO) levels (Holland et al., 2004; Sherwood, 2008) in comparison to downstream waterbodies where nutrient loads are rapidly diluted by the greater water volumes. Flushing time in unmodified tidal creeks is relatively rapid (Buzzelli et al., 2007), but retention time and concentration of nutrient inputs from the watershed increases in developed watersheds as the hydrology is impaired by sediment deposition, water-control structures, etc. Tidal creeks with extended flushing times or high nutrient inputs, in particular, have the potential to become hypoxic as nutrients are metabolized by the system and oxygen is consumed. For this reason, it is necessary that land use considerations be included when developing water-quality criteria for these systems. Even then, the complexity of the landscape, extent of directly connected impervious areas and the spatial arrangement of land use types within the watershed may limit the ability to use the same criteria for different tidal creeks.

DO levels and biochemical oxygen demand in tidal creeks are tightly coupled to nutrient inputs via algal biomass which responds quickly to increased nutrients, often consuming oxygen in the process (Mallin et al., 2004). A graphical interpretation of the linkages among factors influencing dissolved oxygen levels is provided in Figure 1. Linkages among these factors are consistent across aquatic systems, though the nature of the relationships varies as a result of multiple factors. The relative importance of allochthonous carbon (i.e., detritus from vascular plants, such as mangrove leaf litter, saltmarsh grasses, terrestrial vegetation) versus autochthonous carbon (i.e., phytoplankton and benthic algae produced within the system) has a large influence on the rate of nutrient cycling and fluctuations in DO in tidal creeks. In the open estuary, autochthonous carbon is more important to nutrient, chlorophyll *a*. and DO dynamics, but in the transitional waters of the tidal creeks, the contribution of allochthonous inputs may be more important. For any system, including tidal creeks, it is necessary to have sufficient knowledge to relate these factors to the DO response prior to establishing appropriate carbon-supply rates commensurate with desired DO conditions. Typically, information on freshwater inflows, nutrient supplies, the associated autochthonous carbon response (i.e., via phytoplankton), and the biotic integrity of the system are more readily available than the supply rate of allocthonous organic carbon, re-aeration rates, and sediment oxygen demand that influence DO concentrations. Uncertainties related to the effects of these less-defined impacts act as confounding factors in the development of relationships between nutrients, phytoplankton responses, and DO.

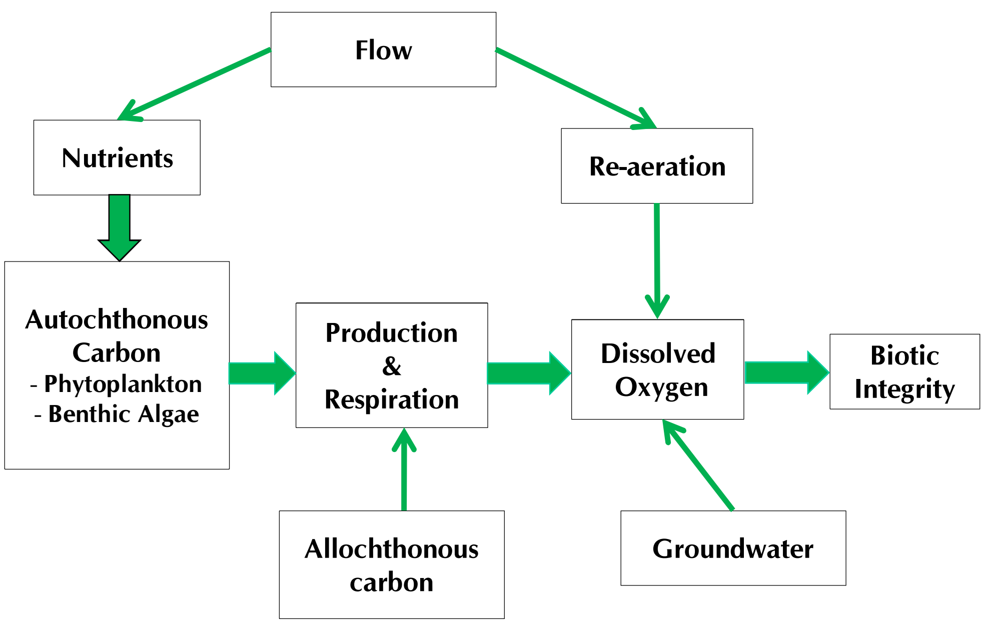


Figure 1. Conceptual diagram depicting the relationships among water-quality parameters and physical factors that influence the biotic integrity of aquatic systems. Large arrows identify the key relationships that can be used to develop numeric nutrient criteria for estuaries and tidal creeks.

Low DO is not uncommon in tidal creeks in the southeastern US, particularly during the warmer spring and summer months and at night when primary producers switch from oxygen production to oxygen consumption (MacPherson et al., 2007). Several tidal creeks from watersheds with varying land use characteristics in North Carolina all experienced low DO (2.0-4.0 mg/L) during the warmer, wetter months between May and September, in contrast to cooler, drier months when considerably higher (4.0-8.0 mg/L) DO levels were observed (MacPherson, et al., 2007). Groundwater inflows, common in coastal areas where the surficial aquifer is in close contact with surface waters, can also be a significant driver of DO conditions in tidal creeks and may need to be accounted for when developing water-quality relationships. As anoxic groundwater infiltrates the tidal creek, greater oxygen demand results (MacPherson, et al., 2007).

1.3 Value of Tidal Creeks as Habitat for Estuarine Benthos and Nekton

Though the ecological role of tidal creeks in the coastal ecosystem is not yet fully understood, their value as a source of primary and secondary production and their contribution as habitat for juveniles of many species of marine, estuarine and freshwater fishes and crustaceans is becoming clear (Mallin and Lewitus, 2004; Holland et al., 2004; Krebs et al., 2007; Greenwood et al., 2008a; Sherwood et al., 2008). Nutrient inputs from the surrounding watershed supply much of the fuel that drives primary production in tidal creeks, in the form of benthic microalgal communities and phytoplankton. The algal stocks, in turn, support small-bodied fishes such as killifishes, sailfin mollies, and mosquitofish that reside permanently in the shallow waters of the tidal creeks (Nordlie, 2000) as well as schooling species like silversides and anchovies that feed on planktonic blooms.

The gently sloping banks of unmodified tidal creeks allow large expanses of intertidal habitat to be inundated by rising tides and provide access to resident fishes which use the intertidal areas adjacent to tidal creeks for spawning, feeding, and refuge from predators. These conditions allow many of the populations of resident fishes and crustaceans to reach densities that exceed those observed in the open estuary (Tukey and DeHaven, 2006; Sherwood, 2008; Stevens et al., 2010a) and provide an abundant food source which is consumed by upper trophic levels including large-bodied fishes, wading birds, mangrove-saltmarsh snakes, alligators, and raccoons that forage in tidal creeks. In addition to resident taxa, relatively high abundances of juvenile transient fishes and blue crabs are found in tidal creeks (Krebs et al., 2007; Yeager et al., 2007; Greenwood et al., 2008a,b; Brame, 2010) compared to adjacent habitats, suggesting that tidal creeks serve as nursery habitat for some estuarine and coastal marine species during their early life history.

Tidal creeks along the mid-Atlantic coast of the U.S. support a large number of nekton species. At least 100 taxa have been identified in tidal creeks from New Jersey to Georgia many of which also occur in Florida's tidal creeks. Schooling species, including Atlantic silversides (*Menidia menidia*), bay anchovy (*Anchoa mitchilli*) and several species of herring and shad, mullet (*Mugil* spp.), *Fundulus* killifishes and palaemonid grass shrimp are the numerically dominant taxa in many of these systems. Penaeid and crangonid (sand) shrimp, spot (*Leiostomus xanthurus*), summer flounder (*Paralichthys dentatus*) and blue crab (*Callinectes sapidus*) are among the dominant economically important taxa found in tidal creeks(Cain and Dean. 1976; Hackney et al., 1976; Rozas and Hackney, 1984; Rountree and Able, 1992; Holland et al., 2004).

In temperate New Jersey estuaries, greater nekton densities have been documented for saltmarsh tidal creeks compared to adjacent seagrass and macroalgae habitats demonstrating the importance of tidal creeks as habitat for fish and crustaceans and suggesting relatively high secondary production of small-bodied forage fishes in tidal creeks compared to adjacent habitats (Sogard and

Able, 1991). The value of tidal creeks in terms of their aquatic-life support function is exemplified by higher growth rates and lower mortality of some juvenile fishes relative to downstream habitats in North Carolina (Ross, 2001).

Macrobenthic invertebrates serve as an important component of the faunal community in tidal creeks, particularly as a food source for higher trophic levels. In South Carolina, 97 macroinvertebrate taxa were collected from tidal creeks, though nearly half of these were rarely collected (Lerberg et al., 2000). Annelid worms, specifically oligochaetes and polychaetes were the dominant taxa with nine species representing 90% of the community in terms of abundance, though nemertean worms were also more abundant than most taxa. In Tampa Bay tidal creeks, at least 44 taxa have been documented (Sherwood et al., 2007) with annelid worms, amphipods and mysid crustaceans among the dominant macrobenthos. The latter two taxa may be particularly important as trophic intermediates between primary production and upper-level consumers (Sherwood, 2008).

In terms of habitat value for macrobenthos, tidal creeks in South Carolina have relatively low Shannon diversity (1.6-3.0) compared to adjacent estuarine habitats (1.9-4.0, Chesapeake Bay; Lerberg et al., 2000). The range of macrobenthic diversity in Tampa Bay tidal creeks (1.5-3.0) was very similar to that observed for creeks in South Carolina for many of the tidal creeks, but very low diversity (0.5-1.0) was observed for several Tampa Bay creeks (Sherwood et al., 2007). Compared to the adjacent estuary, median diversity in Tampa Bay tidal creeks was generally lower (<2.0 vs. approximately 2.5; Karlen et al., 2008).

1.4 Southwest Florida Tidal Creeks

Tidal creeks in Florida are known to support a diverse fish community by providing habitat for numerous species and by maintaining high abundances of forage fish. Approximately 150 taxa of fishes and decapods crustaceans have been collected from almost 80 tidal creeks from Cedar Key to Naples (Adams, 2005; Krebs et al., 2007; Greenwood et al., 2008a,b; Stevens et al., 2008; Stevens et al., 2010a,b). Among these taxa are at least twenty-four species of economic value including spot, mullet, red drum, penaeid shrimp, blue crabs (Yeager et al., 2006) and common snook, many of which use tidal creeks as a nursery during their juvenile stage. In comparison, approximately 200 taxa were collected from the Tampa Bay estuary (including the tidal rivers) during 2008 fisheries-monitoring efforts (FWC, 2008). Similar species numbers were recorded for the Charlotte Harbor and Cedar Key estuaries (FWC, 2008).

Relative to adjacent bay and tidal river habitats, equivalent or higher fish densities have been documented in tidal creeks from Cedar Key to Charlotte Harbor (Tukey and DeHaven, 2006; Krebs et al., 2007; Greenwood et al., 2008a; Stevens et al., 2010a,b). One species in particular, common snook, were observed as juveniles in tidal creeks at densities 2-36 times greater than shoreline habitat just outside the mouth of the creeks in Tampa Bay (Greenwood et al., 2008a) and 6.5 times greater in tidal tributaries of the Caloosahatchee River compared to the mainstem river (Stevens et al., 2010a). Fish densities in Gulf coast tidal creeks typically range from several hundred to several thousand fish/100 m^2 (Adams, 2005; Tuckey and DeHaven, 2006; Krebs et al., 2007; Greenwood et al., 2008a, b; Dixon and Adams, 2010) though fish densities in some of these study creeks were <100 fish/100 m^2. Some of the most diverse fish assemblages in Tampa Bay tidal creeks were observed to have densities of 1,000-2,000 fish/100 m^2 and >30 taxa (Krebs, unpubl. ms). In comparison, average nekton densities from adjacent estuarine habitats, including tidal rivers, seagrass and mangrove shorelines, are typically <1,000 fish/100 m^2 (Tuckey and DeHaven, 2006), but have been shown to reach 2,500 fish/100 m^2 just outside the mouth of Tampa Bay tidal creeks (Greenwood et al., 2008a).

1.5 Dissolved Oxygen and Tidal Creek Fishes

Dissolved oxygen levels in tidal creeks are often lower than those observed in the receiving waters. For example, a study by Stevens et al. (2010a) reported average DO levels for the Caloosahatchee River to range from 7.0-7.9 mg/L in contrast to smaller tidal creeks which ranged from 6.4-6.8 mg/L and were 1.3 mg/L less than DO levels in the first 30 km of the mainstem river. Despite lower DO levels in the tidal creeks, total fish densities did not differ between the tidal creeks and mainstem Caloosahatchee River and were, in fact, slightly greater in the tidal creeks (mean 502 vs. 554 fish/100 m^2). Species-level differences in abundance between river and creeks were observed, with higher densities of many resident taxa in the tidal creeks. As has been documented in several previous studies (Greenwood et al., 2008; Sherwood et al., 2008; Brame, 2010), higher densities of juvenile common snook were observed in tidal creeks, reinforcing the idea that tidal creeks serve as a nursery for this economically important species. The species composition of the fish assemblage was distinctly different between tidal creeks and adjacent areas, as well. Of the 33 taxa collected during the Stevens et al. (2010a) study, nearly half ($n = 14$ taxa) were collected in greater abundance in the tidal creeks, while only 9 taxa were collected in greater abundance in the mainstem river. The remaining taxa were equally abundant in both habitats.

Seasonally, fish abundances in Tampa Bay tidal creeks are highest near the end of the summer months when water temperatures are highest and dissolved oxygen levels are lowest. The trend is reversed during the cooler winter months when DO levels are highest and fish densities are lowest (Adams, 2005; Greenwood et al., 2008b). Although no relationship was found between land use and the community structure of macrobenthos in Tampa Bay tidal creeks (Sherwood et al., 2007), there was a clear pattern for tidal creek benthos in coastal South Carolina where pollution-tolerant taxa dominated the assemblage in urban watersheds (Lerberg et al., 2000). Lack of a relationship in Tampa Bay tidal creeks may have been related to very low rainfalls (i.e., low connectivity) during the study year and less runoff from the watershed.

Nekton species that commonly occur in tidal creeks have adapted to the physiologically stressful conditions of these systems. The often low DO conditions in tidal creeks have been suggested to provide a physiological refuge from predation for small fishes and crustaceans. For example, juvenile snook have been shown to have a much greater tolerance to low DO levels than adult snook, which has been proposed as a way to segregate smaller from larger individuals and reduce cannibalism (Peterson and Gilmore, 1991). Atlantic tarpon and Mayan cichlids are also able to persist at low DO levels by gulping air and storing it until oxygen is absorbed into the bloodstream (Geiger et al., 2000; Schofield et al., 2009). Similar physiological and behavioral adaptations have been observed for highly abundant prey species such as the poeciliid, cyprinodontid and fundulid fishes which include sailfin mollies, gulf killifish, and sheepshead minnows, all of which are capable of aquatic surface respiration (Nordlie, 2006), an adaptation that allows these species to utilize dissolved oxygen at the air-water interface when DO levels are otherwise low in the tidal creek. Abundances of palaemonid grass shrimp and juvenile striped mullet, also very common prey for many species including juvenile snook and tarpon, were negatively correlated with DO, with the highest abundances observed between 3-6 mg/L and very low abundances at $DO > 6$ mg/L (Greenwood et al. 2008a).

2.0 Establishing a Foundation for the Development of Numeric Nutrient Criteria in Tampa Bay Tidal Creeks

The following sections provide a summary of information that should serve as the foundation for developing meaningful and relevant numeric nutrient criteria that will preserve the ecological function and habitat value of Tampa Bay tidal creeks. Further summary of recent and historical studies on the ecology of tidal creeks in the Tampa Bay area is provided by Krebs et al. (2010), MacDonald et al. (2010), and Sherwood (2010).

2.1 Tampa Bay Tidal Creeks

There are approximately sixty tidal creeks that are terminal tributaries to Tampa Bay or to smaller embayments within the bay (Figure 2). Tampa Bay tidal creeks differ substantially in scale from the larger tidal rivers and these differences in relative channel geomorphology result in disparate hydrological and physicochemical characteristics from Tampa Bay's tidal rivers. Some of the larger tidal creeks extend far enough into the watershed that they have lower order, freshwater tributaries that feed into them (e.g., Bullfrog Creek, Double Branch Creek, Frog Creek). Tidal creeks also differ from freshwater tributaries of the same size primarily due to their connection to the estuary. Small freshwater tributaries do not experience the semidiurnal tides which cause the daily and even hourly fluctuations in water level, flow direction, salinity, water temperature and dissolved oxygen (DO) often recorded in tidal creeks (Buzzelli et al., 2007). Delineation of estuarine and freshwater tributaries to Tampa Bay is provided in Figure 3.

Unmodified tidal creeks are characterized by sinuous, meandering channels with average water depths <1.0 m, while those creeks modified for drainage, mosquito control, or navigation often have straightened channels with steeper, more uniform banks than unmodified creeks. Tidal creeks altered for navigation are typically deeper than other creeks (>2.0 m in depth) and often have hardened shorelines that have been cleared of vegetation. Most tidal creeks in Tampa Bay are relatively narrow, spanning only 25-50 m from bank to bank, in contrast to the tidal rivers which are 100-300 m wide on average, although some of the larger tidal creeks reach 100 m or more in width near the mouth. The bathymetry of tidal creeks consists of alternating areas of deep, erosional and shallow, depositional bottom, unless the creek has been channelized, in which case, it is often uniformly deep.

2.1.1 Riparian vegetation

Shoreline vegetation in many of Tampa Bay's tidal creeks consists largely of red mangrove (*Rhizophora mangle*) or white mangrove (*Laguncularia racemosa*), especially in the more mesohaline to polyhaline reaches and transitions. Black needlerush (*Juncus roemerianus*) and cordgrass (*Spartina* spp.) are also found along the banks in the higher salinity reaches, but are not nearly as common as mangroves. In the larger tidal tributaries with large watersheds, freshwater-tolerant and upland vegetation such as cattails (*Typha* spp.), leather fern (*Acrostichum danaeifolium*), buttonwood (*Conocarpus erectus*) and oak (*Quercus* spp.) occur as the tributary moves further into the upland areas.

2.1.2 Submerged aquatic vegetation

Unlike shallow embayments and open estuarine areas, submerged aquatic vegetation is typically absent from tidal creeks, perhaps due to the proximity to freshwater pulses and the resulting lower salinities found in tidal creeks. Occasionally, ephemeral beds of widgeon grass (*Ruppia maritima*) have been observed in Tampa Bay's tidal creeks but seagrass beds consisting of turtle grass (*Thalassia testudinum*), manatee grass (*Syringodium filiforme*) and shoal grass (*Halodule wrightii*) are not typically found in Tampa Bay tidal creeks.

Figure 2. Named tidal creeks within the Tampa Bay watershed.

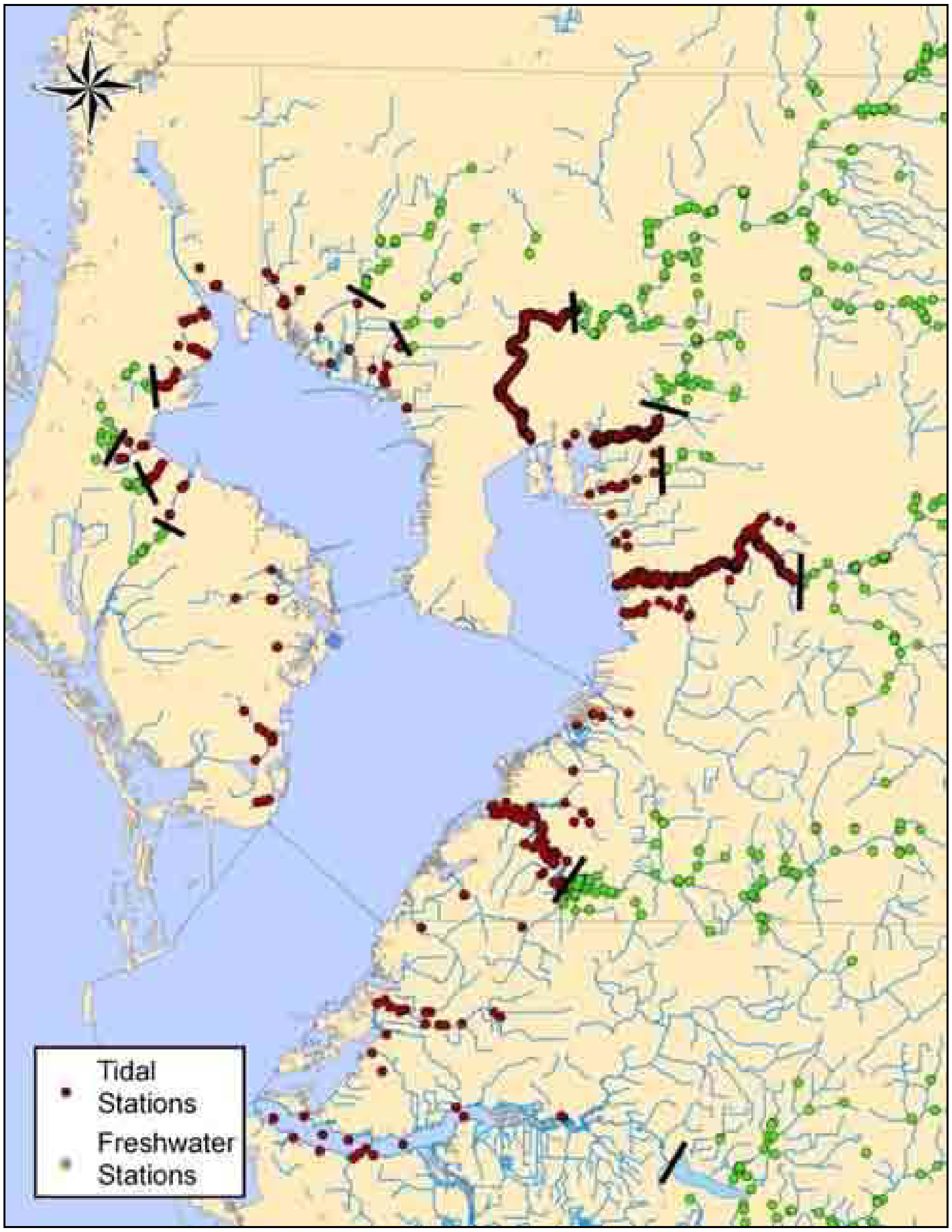


Figure 3. Approximate location of the upstream limit of tidal creeks and rivers as defined by empirical salinity data analysis of data from tributaries within the Tampa Bay watershed.

2.1.3 Dissolved oxygen and fishes

The relationship between fish abundance and species richness with DO has been examined from a number of Tampa Bay tidal creeks (Figures 4 and 5; Krebs et al., 2007; Greenwood et al., 2008a, 2008b). Both fish abundance and species richness in a number of tidal creeks have been shown to be similar at DO levels between 2-10 mg/L. Below 1 mg/L, however, abundance and richness were much lower than observed at levels >2 mg/L. Fish abundance alone may not be a clear indicator of the DO in tidal creeks, as many taxa from these systems are eurytolerant to DO conditions and have adapted to persist at lower DO levels. This is exemplified by the high abundance and low richness between 1-2 mg/L (Figures 4 and 5). Species richness of the fish and decapods crustaceans is probably a more sensitive indicator of the aquatic-life support function of tidal creeks as less tolerant taxa are more likely to occur at higher dissolved oxygen levels, thus increasing species richness. As DO levels decline, less tolerant taxa are less likely to be found and species richness declines. These results emphasize the unique nature of tidal creeks and deserve consideration when the eventual nutrient criteria are proposed.

2.1.4 Phytoplankton as measured by chlorophyll *a*

There is currently a paucity of data on in-stream chlorophyll *a* concentrations for Tampa Bay tidal creeks. The majority of creeks in Tampa Bay are not routinely monitored and therefore there is little information from which to build stressor-response models. Yet, the available information does suggest that these creeks are highly productive systems and that benthic algae are an extremely important indicator of overall productivity in tidal creeks (Sherwood et. al., 2007). While benthic algae are not unique to tidal creeks, their relative contribution to system productivity is greater in tidal creeks than in most other estuarine environments. Further research is needed to understand characteristics of in-stream chlorophyll *a* concentrations and to establish benthic algae as an indicator for developing nutrient criteria for tidal creeks.

2.1.5 Nutrients

Tidal creeks are ecologically distinct in many ways: both from the freshwater streams that drain into them and from the downstream estuarine waters to which they drain. Of particular note, the expectations for water quality in tidal creeks differ from both upstream and downstream waters. Specifically, chlorophyll a concentrations (including planktonic and benthic forms) needed to provide full aquatic-life support in tidal creeks are higher than in the upstream or downstream waters. Similarly, the DO concentrations needed to provide full aquatic-life support in tidal creeks are lower than those required in the upstream or downstream waters. As such, the endpoints used to establish numeric nutrient criteria should be unique to these tidal creeks. Therefore, it is recommended that the eventual numeric nutrient criteria for tidal creeks be based on:

- stressor-response relationships between TN and TP and either chlorophyll a or DO concentrations, and
- chlorophyll *a* thresholds and DO standards that reflect the unique nature of these systems.

The potential options for developing numeric nutrient criteria, including the stressor-response approach are detailed below.

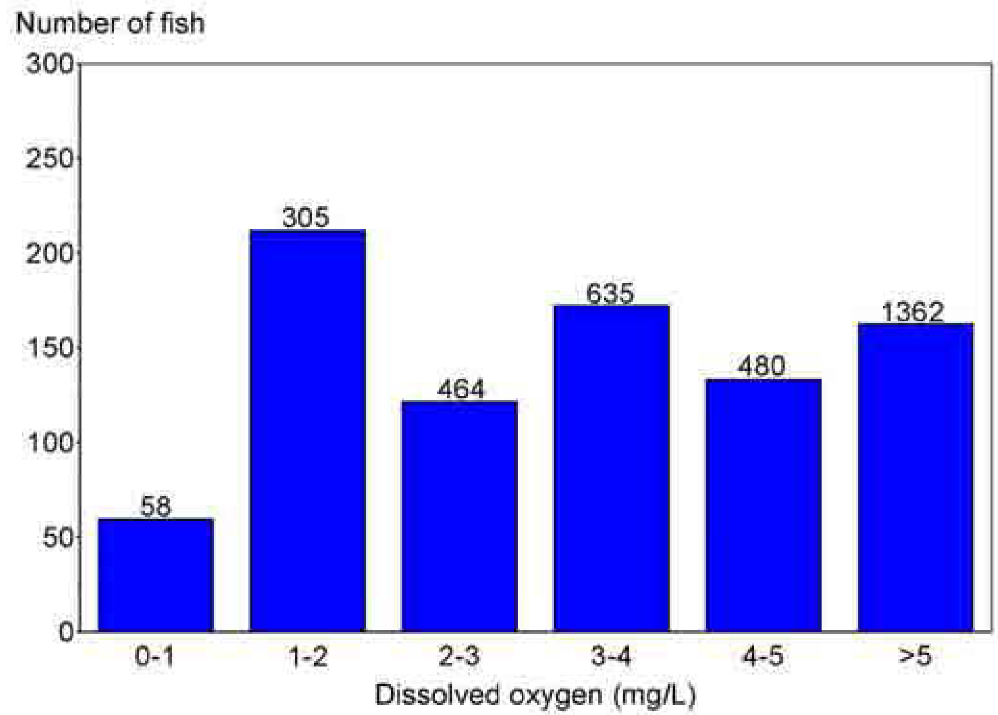


Figure 4. Relationship between mean nekton abundance and DO in Tampa Bay tidal creeks. The numbers above each bar is the number of samples.

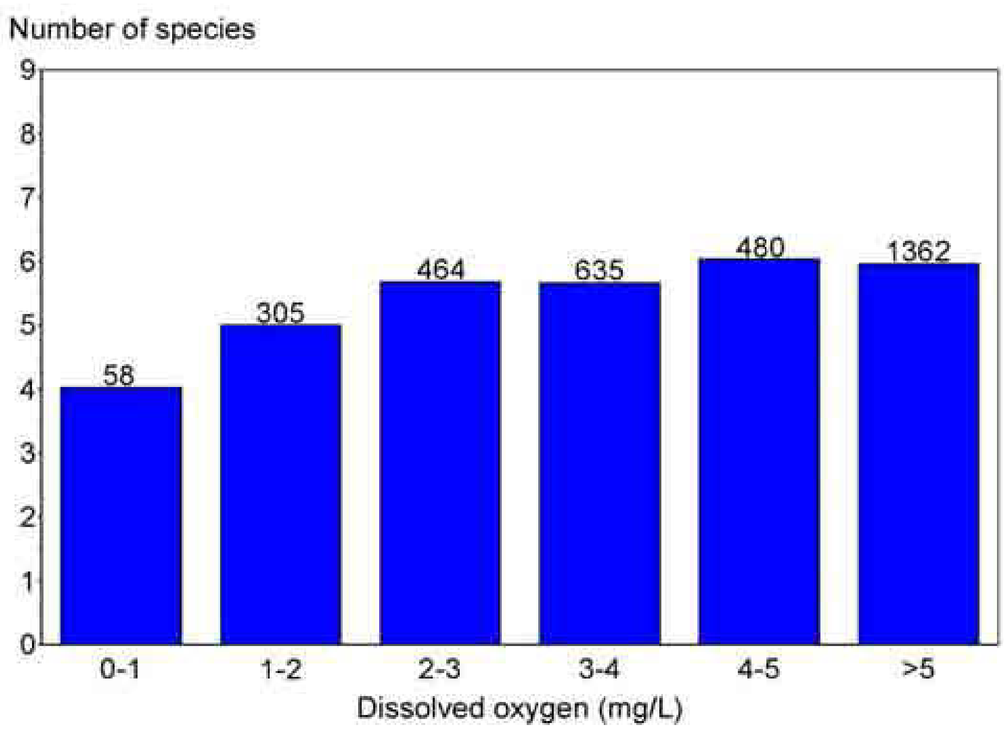


Figure 5. Relationship between mean species richness and DO for nekton in Tampa Bay tidal creeks. The numbers above each bar is the number of samples.

3.0 Potential Approaches for the Development of Nutrient Criteria for Tidal Creeks

Given the current state of knowledge on tidal creeks, three approaches to develop numeric nutrient criteria in tidal creeks are available. Each of these approaches has previously been considered for development of nutrient criteria for the Tampa Bay estuary (Janicki Environmental, Inc. 2011a,b).

- Stressor-response models – Examining quantitative relationships between nutrient concentrations and either chlorophyll *a* or DO concentrations within a specific waterbody of concern (i.e., tidal creek);
- Reference condition methods - Using available data from selected reference periods in creeks to derive numeric nutrient criteria for the creeks;
- Downstream protective values - Based on the relationship between the water quality in the creek and that of the downstream receiving estuary such that the water quality in the tidal creek does not result in water-quality exceedances in the downstream estuary.

3.1 Stressor-Response Method

The stressor-response modeling approach to establish numeric nutrient criteria in tidal creeks relies on the development of a quantitative relationship between known indicators of system health (e.g. chlorophyll *a* concentrations and DO) and anthropogenic stressor variables (e.g., TN or TP). Using these relationships, the goal is to first identify the threshold response beyond which adverse conditions are observed. Once this threshold value is determined, the relationship between stressors and response can be used to set limits on the magnitude of the stressor variable that is expected to maintain adequate water quality and avoid adverse conditions.

3.2 Reference Condition Method

The reference condition method uses available data for the system of interest to establish numeric nutrient criteria. The process involves the identification of ambient water-quality conditions during periods when the system was meeting full aquatic-life support and establishing the criterion values for stressors and response indicators based on these conditions. Often it is advantageous to establish both target values and threshold values using this approach. Target values are those that represent a desired management endpoint for the system while threshold values are those beyond which the system is likely to exhibit adverse effects.

3.3 Downstream Protective Value Method

The goal of the downstream protection method would be to use the estuarine nutrient criteria as a target to establish criteria for the tidal creek that is protective of downstream water quality. For example, relationships between total nitrogen concentration in the tidal creek compared to that in the adjacent bay segment could be used to determine how increases or decreases in nitrogen in the tidal creek might be related to nitrogen concentrations in the bay segment, and to identify the nitrogen concentration in the tidal creek that would be commensurate with the downstream estuarine nitrogen criterion. Using this approach is less desirable, however, as it is not based on maintaining the ecological function within the tidal creek and may result in nutrient criteria for the tidal creek that are insufficient to protect the biological integrity of the waterbody, including the high levels of primary production that are characteristic of these systems.

4.0 Recommendations

Studies of Tampa Bay tidal creeks have revealed compelling evidence that these systems represent unique ecotones within the greater Tampa Bay estuary. Tidal creeks play an integral role in the ecological function of coastal estuaries as sites of high primary and secondary production, nursery and refuge habitat for several species of economically important fish and decapods crustaceans, and foraging areas for large-bodied fishes, wading birds, and other piscivorous species. Higher nutrient concentrations in tidal creeks relative to the greater estuary may be required to support the higher levels of primary and secondary production in these systems.

Analysis of fish collections in tidal creeks suggests that fishes inhabiting tidal creeks appear to be very tolerant to the typical DO conditions found in these systems. Both fish abundance and species richness data indicate that fish communities are relatively invariant to DO levels between 2-10 mg/L. There are indications that at DO concentrations below 2 mg/L, both fish abundance and species richness decline. Species richness of fish and decapods crustaceans may be a more sensitive indicator of the aquatic-life support function of tidal creeks; however, these need further quantification to eliminate the possibility that seasonal recruitment patterns of estuarine-dependent fishes are not correlated with seasonal variation in dissolved oxygen concentrations due to temperature.

This report has provided a foundation from which further research can be conducted to establish scientifically sound and ecologically meaningful numeric nutrient criteria for Tampa Bay tidal creeks. Future research into developing criteria for these systems should recognize that:

- Tidal creeks represent a unique habitat in Tampa Bay, one that serves a different ecological function than both freshwater tributaries, tidal rivers and downstream estuarine environments
- Tidal creeks are generally highly colored systems with reduced water clarity and generally are devoid of seagrass
- Tidal creek productivity (measured as chlorophyll a concentration) is linked to both benthic algal production and water-column phytoplankton
- Dissolved oxygen concentrations are routinely below the current state standard of 4 mg/L for marine waters and evidence from analysis of fish collections suggests that DO does not appear to limit fish abundance or richness until DO concentrations reach levels <2 mg/L
- There is currently a paucity of empirical data from which to establish stressor-response relationships or reference condition approaches for Tampa Bay tidal creeks

The most desirable approach to establish numeric nutrient criteria would be to develop stressor-response models. Stressor-response models require the identification of an indicator variable that can be used to evaluate the condition of the tidal creek. Moreover, stressor-response models require identification of a threshold value above (or below) which the system would no longer fully support its designated use.

Based on current available data it will be difficult to select a reference condition for many of Tampa Bay's tidal creeks due to the paucity of empirical data in these systems. Much of the available data were generated from short duration studies that were intended as investigational and to serve as baseline information. More effort is needed to identify a representative period of time when the systems were fully supporting aquatic uses to confidently establish reference condition criteria.

Because of these constraints, numeric nutrient criteria for these systems are currently not recommended. However, the following recommendations can be made for future efforts to define criteria for these systems.

It is important that any established criteria for tidal creeks also account for the fact that these systems by nature are more variable than their upstream or downstream counterparts. This variability is in part what makes these systems so productive and also so difficult to generalize. The timing and volume of freshwater inflows are physical drivers that exert a great deal of control on tidal creeks. Inflows are deterministic of salinity regimes, nutrient delivery, water depths, temperatures and the potential for salinity stratification in these systems. Inflows also may control access to these systems for both small recruit species looking for refuge and for large-bodied predators. Therefore, the quantification of the effects on inflows on these systems will be necessary both to determine appropriate criteria and in the evaluation process.

Implementation of criteria for tidal creeks should rely heavily on quantifying the uncertainties in both the derivation of the criteria and in the evaluation of potential remediation effort associated with failure of the criteria. Only if the criteria are actually relevant to the ecological function of the system will the criteria be meaningful in protecting full aquatic-life support in these systems. As such, there are many considerations in the implementation process. These considerations are provided in detail in Janicki Environmental (2011c).

It is recommended that the assessment of compliance with the proposed numeric nutrient criteria be performed in a manner similar to that which has been proposed by TBEP for compliance with both the Tampa Bay Reasonable Assurance and TMDL (TBEP and Janicki Environmental, 2010). The goal of the estuarine numeric nutrient criteria is to provide full aquatic-life support within the estuary. The TBEP has determined that seagrasses are important indicators of desirable conditions in the bay and has defined the water-quality conditions (i.e., chlorophyll *a* concentrations) that allow for the maintenance and growth of seagrass beds in Tampa Bay. Therefore, TBEP bases its compliance assessment on the comparison of both observed chlorophyll *a* concentrations and seagrass extent to the goals that have been established.

The TBEP and TBNMC have been utilizing an annual assessment strategy to track conditions in Tampa Bay with respect to chlorophyll *a* (Janicki et al., 2000). The strategy utilizes data collected by the Environmental Protection Commission of Hillsborough County (EPCHC) at numerous stations within the bay on a monthly basis. Conditions are assessed on an annual basis with respect to the FDEP-approved chlorophyll *a* thresholds in the four mainstem segments of the bay. To maintain consistency with these assessments, it is recommended that a similar approach be undertaken for tidal creeks when criteria are ultimately developed for these systems.

TBEP has dedicated funds to continue work in tidal tributaries in Tampa Bay and will commit to work with EPA to develop recommendations by September 2014.

5.0 References

Adams, A.J. 2005. Evaluating the effects of restoration of subtropical oligohaline marshes on abundance and habitat use by juvenile snook, *Centropomus undecimalis* and associated fish communities. Final Report to the Charlotte Harbor National Estuary Program. Mote Marine Laboratory, Sarasota, FL. 54 pp.

Brame, A.B. 2010. A More Comprehensive Approach for Determining Juvenile Snook Nursery Habitat in a Tampa Bay Wetland. In: S.T. Cooper (ed.). Proceedings, Tampa Bay Area Scientific Information Symposium, BASIS 5: 20-23 October 2009. St. Petersburg, FL. pp. 385.

Buzzelli, C., A. F. Holland, D. M. Sanger, and P. C. Conrads. 2007. Hydrographic Characterization of Two Tidal Creeks with Implications for Watershed Land Use, Flushing Times, and Benthic Production. Estuaries and Coasts. 30:321–330.

Cain, R.L. and J.M. Dean. 1976. Annual occurrence, abundance, and diversity of fish in a South Carolina intertidal creek. Marine Biology 36:369–379.

Dixon, L.K. and A.J. Adams. 2010. Water quality and the fish assemblages of mangrove creeks: A snapshot study shows challenges in assessment of coastal zone management strategies: Draft report to the Charlotte Harbor National Estuary Program. 80 pp.

Florida Fish and Wildlife Conservation Commission. 2008. Fisheries-Independent Monitoring Program 2008 Annual Data Summary Report. 342 pp.

Geiger, S. A., J. J. Torres and R. E. Crabtree. 2000. Air breathing and gill ventilation frequencies in juvenile tarpon, *Megalops atlanticus*: responses to changes in dissolved oxygen, temperature, hydrogen sulfide, and pH. Environmental Biology of Fishes. 59:181–190.

Greathouse, E.A. and C.M. Pringle. 2006. Does the river continuum concept apply on a tropical island? Longitudinal variation in a Puerto Rican stream. Can. J. Fish. Aquat. Sci. 63: 134–152.

Greenwood, M.F.D., D.D. Chagaris, T.C. MacDonald, R.E. Matheson, Jr., R.H. McMichael, Jr., R.F. Heagey, F.X. Courtney, G.V. Onorato and S.D. Stahl. 2008a. Tampa Bay tidal tributaries habitat initiative: Fish and fish habitat technical report. Report to the Tampa Bay Estuary Program. 290 pp.

Greenwood, M.F.D., E. Malkin, E.B. Peebles, S.D. Stahl, and F.X. Courtney. 2008b. Assessment of the value of small tidal streams, creeks, and backwaters as critical habitats for nekton in the Tampa Bay watershed. Report to the Florida State Wildlife Grants Program. 411 pp.

Hackney, C.T., Burbanck, W.D., and O.P Hackney. 1976. Biological and physical dynamics of a Georgia tidal creek. Chesapeake Science 17: 271–280.

Holland, A. F., D. M. Sanger, C. P. Gawle, S. B. Lerberg, M. S. Santiago, G. H. M. Riekerk, L. E. Zimmerman, and G. I. Scott. 2004. Linkages between tidal creek ecosystems and the landscape and demographic attributes of their watersheds. Journal of Experimental Marine Biology and Ecology. 298:151-178.

Janicki, A., D. Wade, and J. R. Pribble. 2000. Developing and Establishing a Process to Track the Status of Chlorophyll-a Concentrations and Light Attenuation to Support Seagrass Restoration Goals in Tampa bay. Technical Report #04-00 of the TBEP. Prepared by Janicki Environmental, Inc.

Janicki Environmental, Inc. 2011a. Tampa Bay Numeric Nutrient Criteria: Task 1 – TN and TP Concentrations. Letter Memorandum. Prepared for Tampa Bay Estuary Program.

Janicki Environmental, Inc. 2011b. Tampa Bay Numeric Nutrient Criteria: Task 2 – Downstream Protective Values. Letter Memorandum. Prepared for Tampa Bay Estuary Program.

Janicki Environmental, Inc. 2011c. Tampa Bay Numeric Nutrient Criteria: Task 4 – Implementation Issues. Letter Memorandum. Prepared for Tampa Bay Estuary Program.

Krebs, J. M., A. B. Brame, and C. C. McIvor. 2007. Altered mangrove wetlands as habitat for estuarine nekton: are dredged channels and tidal creeks equivalent? Bulletin of Marine Science. 80:839-861.

Krebs, J. M., M. P. Weinstein, E. B. Peebles, and R. G. McConnell. 2010. Revisiting and Updating Our Knowledge of Tampa Bay's Tidal Tributaries: Session Synthesis. In: S.T. Cooper (ed.). Proceedings, Tampa Bay Area Scientific Information Symposium, BASIS 5: 20-23 October 2009. St. Petersburg, FL. pp. 387-395.

Lerberg, S. B., A. F. Holland, and D. M. Sanger. 2000. Responses of tidal creek macrobenthic communities to the effects of watershed development. Estuaries. 23:838–853.

MacDonald, T. C., R. E. Matheson, Jr., E. B. Peebles, R. H. McMichael, Jr. and M.F.D. Greenwood. 2010. Tidal Creeks as Nekton Habitat in the Tampa Bay Estuary. In: S.T. Cooper (ed.). Proceedings, Tampa Bay Area Scientific Information Symposium, BASIS 5: 20-23 October 2009. St. Petersburg, FL. pp. 319-330.

MacPherson, T. A., L. B. Cahoon and M. A. Mallin. 2007. Water column oxygen demand and sediment oxygen flux: patterns of oxygen depletion in tidal creeks. Hydrobiologia. 586:235–248.

Mallin, M. E. and A. J. Lewitus. 2004. Preface: The importance of tidal creek ecosystems. Journal of Experimental Marine Biology and Ecology. 298:145-149.

Mallin et al. 2004. Nutrient limitation and algal blooms in urbanizing tidal creeks. Journal of Experimental Marine Biology and Ecology. 298:211-231.

Nordlie, F. G. 2000. Patterns of reproduction and development of selected resident teleosts of Florida salt marshes. Hydrobiologia. 434:165–182.

Nordlie, F. G. 2006. Physicochemical environments and tolerances of cyprinodontoid fishes found in estuaries and salt marshes of eastern North America. Rev. Fish Biol. Fisheries. 16:51–106.

Peterson, M. S. and R. G. Gilmore, Jr. 1991. Eco-physiology of juvenile snook, Centropomus undecimalis (Bloch): Life-history implications. Bulletin of Marine Science 48:46-57.

Ross, S.W. 2001. The relative value of different estuarine nursery areas in North Carolina for transient juvenile marine fishes. Fishery Bulletin. 101:384–404.

Roundtree, R. A. and K. W. Able. 1992. Fauna of polyhaline sub-tidal marsh creeks in southern New Jersey: Composition, abundance and biomass. Estuaries. 15:171-185.

Schofield, P. J., W. F. Loftus and J. A. Fontaine. 2009. Salinity effects on behavioral response to hypoxia in the non-native Mayan cichlid *Cichlasoma urophthalmus* from Florida Everglades wetlands. J. Fish Biol. 74:1245–1258.

Sherwood, E. T. ed. 2008. Tampa Bay Tidal Tributary Habitat Initiative Project: Final Report and Management Recommendations. Tampa Bay Estuary Program Technical Report 02-08. Report to the Pinellas County Environmental Fund. Tampa Bay Estuary Program, St. Petersburg, FL. 83 pp.

Sherwood, E. T. 2010. Results and Management Recommendations from the 2006 Tampa Bay Tidal Tributaries Habitat Initiative. In: S.T. Cooper (ed.). Proceedings, Tampa Bay Area Scientific Information Symposium, BASIS 5: 20-23 October 2009. St. Petersburg, FL. pp. 355-373.

Sherwood, E. T., D. J. Karlen, T. L. Dix, B. K. Goetting, S. E. Markham, A. Chacour, M. Miller. 2007. Tidal Tributary Study Final Report - Water Quality, Sediment Chemistry, Benthic Macrofauna, and Watershed Characterization. Report to the Tampa Bay Estuary Program. 250pp.

Sogard, S. M. and K. W. Able. 1991. A comparison of eelgrass, sea lettuce macroalgae, and marsh creeks as habitat for epibenthic fishes and decapod crustaceans. Estuarine and Coastal Shelf Science. 33:501-520.

Stevens, P. W., M. F. D. Greenwood, T. C. MacDonald, C. F. Idelberger and R. H. McMichael Jr. 2008. Relationships between freshwater inflows and nekton populations in the Estero Bay estuary. Report to the South Florida Water Management District.

Stevens, P. W., M. F. D. Greenwood, C. F. Idelberger and D. A. Blewett. 2010a. Mainstem and backwater fish assemblages in the tidal Caloosahatchee River: Implications for freshwater inflow studies. Estuaries and Coasts. 33:1216-1224.

Stevens, P. W., T. C. MacDonald, E. Weather and R. H. McMichael, Jr. 2010b. Nekton of the Lemon Bay Estuarine System and a Comparison of Nekton Community Structure in Adjacent Southwest Florida Estuaries. Report to the Charlotte Harbor National Estuary Program.

TBEP and Janicki Environmental, Inc. 2010. 2009 Reasonable Assurance Addendum: Allocation and Assessment Report. Technical Report #03-10 of the TBEP.

Tuckey, T. D. and M. DeHaven. 2006. Fish assemblages found in tidal-creek and seagrass habitats in the Suwannee River estuary. Fishery Bulletin. 104:102-117.

Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell and C.E. Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences. 37:130-137.

Yeager, L.A., J.M. Krebs, A.B. Brame, and C.C. McIvor. 2007. Comparison of juvenile blue crab abundances in three mangrove habitat types in Tampa Bay, Florida USA. Bulletin of Marine Science. 80:555-565.

TAMPA BAY
Numeric Nutrient Criteria:
Task 4 – Implementation Issues

Letter Memorandum

Prepared for:

Tampa Bay Estuary Program

Prepared by:

Janicki Environmental, Inc.

16 February 2011

FOREWORD

This letter memo was produced in partial fulfillment of Purchase Order #6584, TBEP Contract T-07-01 - Development of Numeric Nutrient Criteria for Tampa Bay, Task 4.

ACKNOWLEDGEMENTS

We wish to thank the Partners of the Tampa Bay Estuary Program and members of the Tampa Bay Nitrogen Management Consortium for the numerous conversations providing direction and insight into concerns regarding numeric nutrient criteria establishment and appropriate methodology for developing the proposed criteria.

EXECUTIVE SUMMARY

The objective of this task is to address two key issues identified by the U.S. EPA regarding successful implementation of the proposed numeric nutrient criteria in Tampa Bay, namely the method to account for non-anthropogenic events, such as El Niño and hurricanes, and the allowable exceedance criteria (how often criteria may be exceeded before non-compliance is observed). Analyses were performed to direct input on these subjects, with the following conclusions:

- The annual response time to recover from the maximum monthly chlorophyll *a* concentration during a year is relatively short. Median annual response times are two months or less in all segments, and average annual response times are three months or less in all segments. This indicates that the bay recovers very quickly from normal loading events.

- The typical response times to unusual events, such as El Nino, are longer and, depending upon the timing of such events, can span over parts of two successive years.

- It is important to consider the effects of natural variability in establishing the compliance assessment scheme.

- Comparison of the two temporal assessment schemes (1 in 3 years) vs (2 in 5 years) suggested that the 2 in 5 rule was less likely to result in a violation due solely to natural variability. It is recommended that the assessment of compliance with the proposed numeric nutrient criteria be performed in a manner similar to that which has been proposed by TBEP for compliance with both the Tampa Bay Reasonable Assurance determination and EPA TMDL. The goal of the estuarine numeric nutrient criteria is to provide full aquatic-life support within the estuary. The TBEP has determined that seagrasses are important indicators of desirable conditions in the bay and has defined the water-quality conditions (i.e., chlorophyll a concentrations) that allow for the maintenance and growth of seagrass beds in Tampa Bay. Therefore, TBEP bases its compliance assessment on the comparison of both observed chlorophyll a concentrations and seagrass extent to the goals that have been established. To date, this has proven to be a successful adaptive management approach for abating nutrient eutrophication in the Tampa Bay Estuary.

1.0 Introduction and Objectives

The Tampa Bay Estuary Program (TBEP) and the Tampa Bay Nitrogen Management Consortium (TBNMC) have recommended numeric nutrient criteria to U.S. Environmental Protection Agency (EPA) for Tampa Bay (TBNMC, 2010; Janicki Environmental, 2011). EPA has identified several key issues that must be addressed if the proposed numeric nutrient criteria are to be successfully implemented in Tampa Bay (Figure 1). These issues are as follows:

- Non-anthropogenic events (e.g., El Niño, hurricanes) can significantly affect the nutrient and response conditions in the bay. The effect of these events on the bay's response to nutrient inputs is evaluated, and potential methods to account for these events in the implementation of the proposed numeric nutrient criteria are provided.
- EPA is proposing an allowable exceedance of criteria as no more often that one in three years, while many of the important water quality assessments in Tampa Bay, including the Tampa Bay Reasonable Assurance and WQBEL, are based on a two in five years basis. The effectiveness of these assessment periods are compared.

In addition, TBEP has developed an annual assessment of ambient water quality conditions that would be an appropriate assessment reporting mechanism for estuarine numeric nutrient criteria for Tampa Bay.

2.0 Chlorophyll *a* Concentration Response Times

EPA encouraged input on potential methods to account for non-anthropogenic events that can significantly affect the nutrient and response conditions in Tampa Bay, including the effects of hurricanes or other unusually high rainfall events, such as El Niño. This section provides the results of analyses performed to evaluate the temporal extent of responses in the bay, following both unusual events and the annual maximum monthly chlorophyll *a* concentrations typically observed every wet season.

2.1 Unusual Loading Events

The nutrient conditions and associated chlorophyll *a* responses in Tampa Bay can be affected by unusual loading events. These events may be non-anthropogenic in nature, such as those related to especially high rainfall conditions associated with tropical storms, hurricanes, El Niño events, or other unusually wet periods. Anthropogenic events, such as nutrient-laden spills and accidental releases of wastewater, may also impact the bay.

Consideration of these types of events must be included within the implementation plan of the proposed numeric nutrient criteria. To understand the impacts of these events in the bay, and the temporal extent of these effects, events occurring during the 1985-2009 period were identified, and the responses in the bay were evaluated. Specifically, the duration of the responses as signified by elevated chlorophyll *a* concentrations were estimated for each event.

.

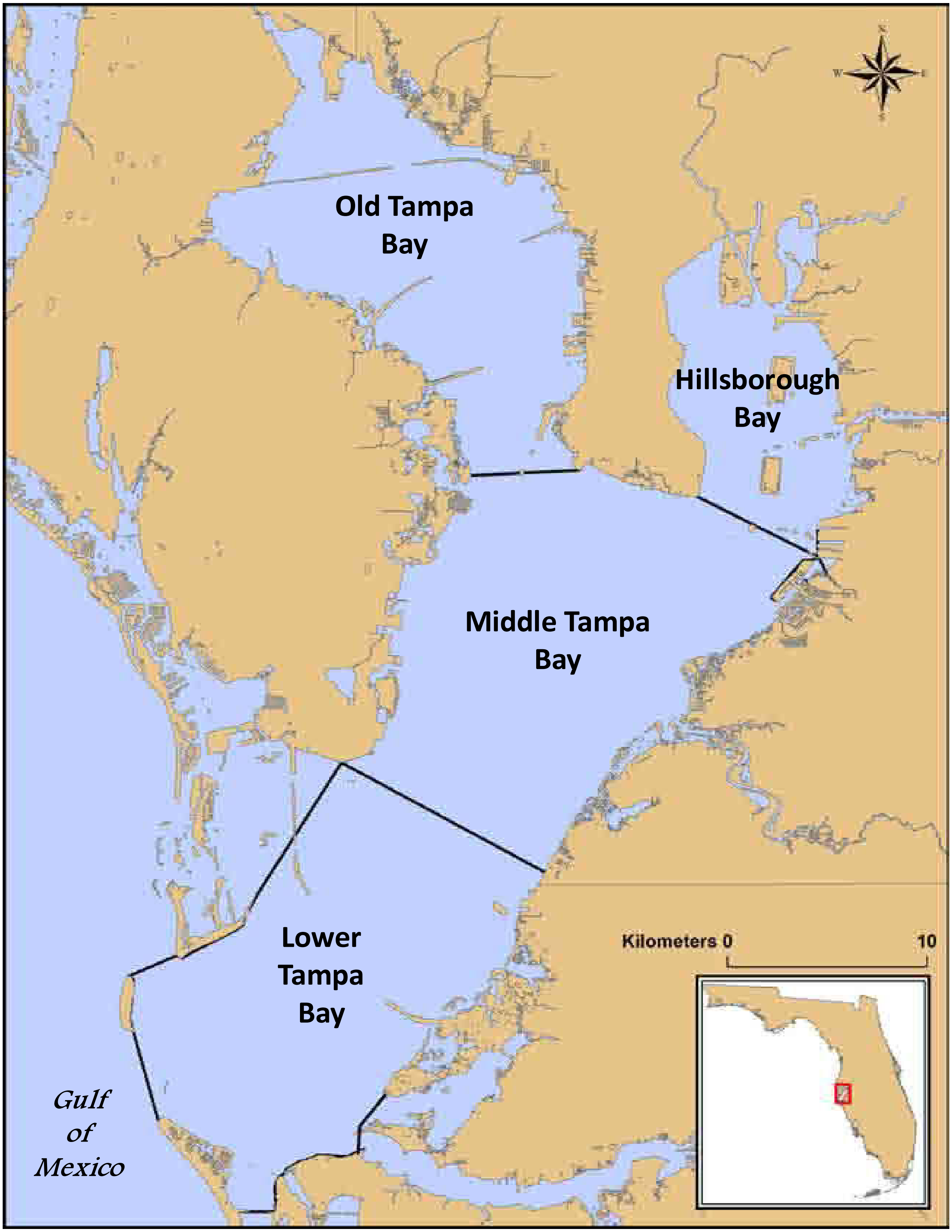


Figure 1. Tampa Bay and its four major bay segments.

Water quality data collected by EPCHC were used to develop the monthly mean chlorophyll *a* and nutrient concentrations for the 1992-2009 period for each of the four mainstem segments of the bay (Figure 1). These data were also used to develop median chlorophyll *a* concentrations for each calendar month within the four segments. The chlorophyll *a* response time within each segment was evaluated for each event, with an unusually high chlorophyll *a* concentration identified as the beginning of the event. Following each event, the number of months until the chlorophyll *a* concentration returned to a level at or below the median calendar month concentration was tallied. This provides a measure of the response time within the bay to an unusual loading event.

Figure 2 presents an example plot that displays how the response time is estimated. In this example the peak chlorophyll *a* concentration occurred in August. The ambient chlorophyll *a* concentrations remain above the monthly median values until January, as indicated by the green arrow. Therefore, the response time for this example is 5 months.

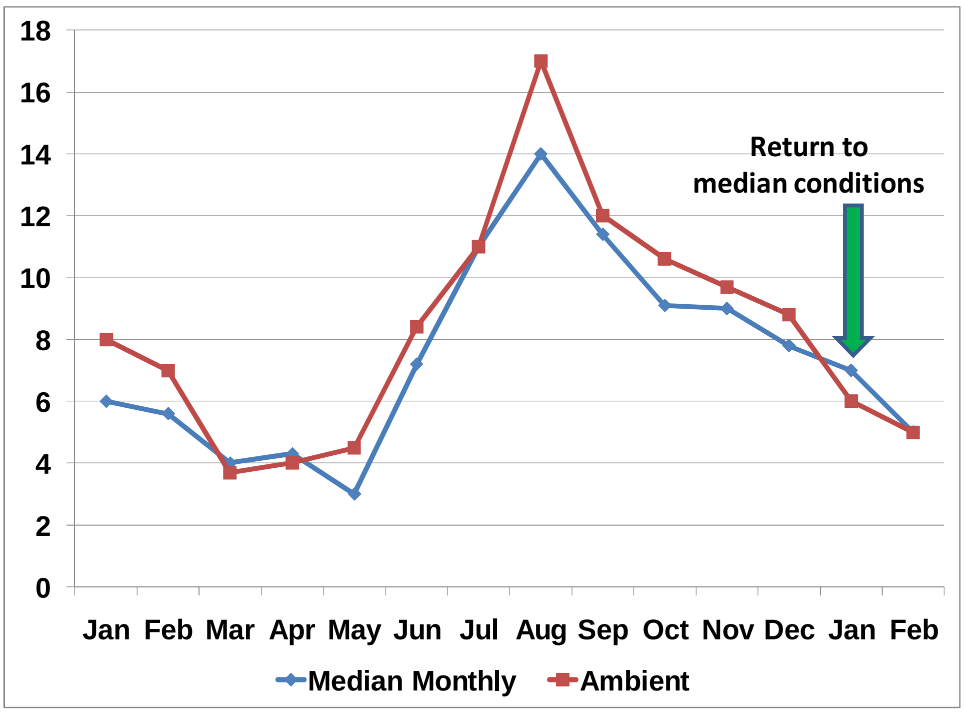


Figure 2. Example of the response time estimation method.

The duration of chlorophyll *a* responses during unusual events represents the serial correlation that exists for that particular event. Understanding how and why values are correlated over time is essential in evaluating the assimilative capacity of the estuary. Correlation across time is termed serial autocorrelation and is a violation of the assumptions associated with many standard statistical testing procedures including some tests used in assessments of the FDEP and EPA water quality standards. This analysis attempts to describe serial autocorrelation in terms of event duration. The assessment is conditional, based on the identification of an event and identified as a deviation from an expected monthly condition (the median value). By comparing observed monthly values to long term monthly medians, the seasonal correlation inherent in chlorophyll *a* responses due to seasonal changes in temperature and photoperiod are accounted for. The expectation is that a value in a given month will vary about its median value as a function of local influences and natural variability. For this assessment, a duration in months of values above their long term monthly median suggests the persistent effects of some influential event. Events examined for this analysis included the following unusual loading events associated with abnormal meteorological conditions:

- Event 1: Unusually high rainfall in 1994-1995 period,
- Event 2: 1997-1998 El Niño, including December 1997 Mulberry spill,
- Event 3: Unusually high rainfall in Autumn 2003,
- Event 4: 2004 hurricane season, including September 2004 Archie Creek spill associated with Hurricane Frances
- Event 5: 2005 hurricane season, and
- Event 6: Unusually high rainfall in May 2009.

A discussion of each bay segment's response to these events is provided below.

2.1.1 Response Times to Unusual Loading Events - Old Tampa Bay

Event 1 - During the unusually wet year of 1995, the chlorophyll *a* concentration in October was 28.9 μg/L, compared to the median value of 14.9 μg/L. Monthly values greater than the median calendar month values were maintained until June 1996, so the response time was 8 months.

Event 2 - The El Niño event of 1997-1998 began in the fall of 1997. The chlorophyll *a* concentration in October 1997 was 19.1 μg/L, compared to the median value of 14.9 μg/L. Monthly values remained greater than the median values until April 1998, giving a response time of 6 months.

Events 3, 4 - Unusually high rainfall occurred during the late autumn/early winter of 2003. The chlorophyll *a* concentration in October 2003 was 41.2 μg/L, compared to the median of 14.9 μg/L. Monthly values remained greater than the median values until November 2004, a period including the very unusually active hurricane season and associated high rainfall of 2004. The response time for the combined effects of both the high 2003 rainfall and the 2004 hurricane-associated rainfall was 13 months

Event 5 – There were no unusually high chlorophyll *a* concentrations following this event.

Event 6 - Unusually high rainfall occurred in the spring of 2009, resulting in unusually high chlorophyll *a* concentrations beginning in July, when concentrations were 30.5 μg/L, compared to the median of 10.9 μg/L. High values also occurred in August (42.7 μg/L), but by September chlorophyll *a* concentrations were below the expected values, giving only a 2-month response time.

2.1.2 Response Times to Unusual Loading Events - Hillsborough Bay

Event 1 - During the unusually wet years of 1994 and 1995, the chlorophyll *a* concentration in September 1994 was 44.3 μg/L, compared to the median September concentration of 18.9 μg/L. Monthly values greater than the median calendar month concentrations were maintained until February 1995, so the response time was 5 months. During September of 1995, the chlorophyll *a* concentration was 57.7 μg/L, and returned to the monthly median or below in April 1996, a period of 7 months.

Event 2 - The El Niño event of 1997-1998 began in the fall of 1997. The chlorophyll *a* concentration in October 1997 was 31.1 μg/L, compared to the median of 13.9 μg/L. Monthly values remained greater than the median concentrations until September 1998, giving a response time of 11 months. This period included the Mulberry spill in December 1997, but the effects on the segment chlorophyll *a* due solely to the loading from the spill cannot be separated from the total loadings to the segment resulting from the El Niño.

Event 3 – The unusually high rainfall during the late fall/early winter of 2003 resulted in an elevated chlorophyll *a* concentration in December 2003 of 16.3 μg/L, compared to the median value of 7.5 μg/L. Within 1 month, however, the chlorophyll *a* concentration returned to a value less than the monthly median.

Event 4 - The effects of the 2004 hurricane season on chlorophyll *a* in Hillsborough Bay were relatively short-term. Rainfall from Hurricane Frances contributed to the spill into Archie Creek in September 2004, and a response in chlorophyll *a* was seen in October 2004, with chlorophyll *a* concentration of 39.9 μg/L, about three times the median value of 13.9 μg/L. By November 2004, however, the chlorophyll *a* concentration (4.7 μg/L) was less than the monthly median, so that the response time to this event was short (2 months).

Event 5 – The effect of the 2005 hurricane season was a maximum chlorophyll *a* concentration of 31.5 μg/L in July 2005, but values returned to normal within 1 month.

Event 6 – The unusually high rainfall in the spring of 2009 resulted in unusually high chlorophyll *a* concentrations beginning in July, when concentrations were 32.4 μg/L, compared to the median value of 16.0 μg/L. High values also occurred in August and September, but by October chlorophyll *a* concentrations were below the expected values, giving only a 3-month response time to the event.

2.1.3 Response Times to Unusual Loading Events - Middle Tampa Bay

Event 1 - During the unusually wet years of 1994 and 1995, the chlorophyll *a* concentration in July 1994 was 11.2 μg/L, compared to the median July value of 9.0 μg/L. Monthly values greater than the median calendar month values were maintained until February 1995, so the response time was 7 months. During August 1995, the chlorophyll *a* concentration was 11.9 μg/L, greater than the median August value of 8.3 μg/L, and returned to the monthly median or below in March 1996, a period 7 months.

Event 2 - The El Niño event of 1997-1998 began in the fall of 1997. The chlorophyll *a* concentration in October 1997 was 15.5 μg/L, compared to the median value of 8.7 μg/L. Monthly values remained greater than the median values until March 1999, giving a response time of 17 months.

Event 3 – The unusually high rainfall during the late fall/early winter of 2003 resulted in an elevated chlorophyll *a* concentration in October 2003 of 12.8 μg/L, compared to the median value of 8.7 μg/L. Within 2 months, however, the chlorophyll *a* concentration returned to a value just slightly greater than the monthly median.

Event 4 - The effects of the 2004-2005 hurricane seasons on chlorophyll *a* in Middle Tampa Bay were relatively short-term. The 2004 maximum chlorophyll *a* concentration (13.6 μg/L) was observed in October. The 2004 response time was only 1 month.

Event 5 - The 2005 maximum chlorophyll *a* concentration (12.9 μg/L) was observed in October. The response time to this event was 3 months.

Event 6 – The unusually high rainfall in the spring of 2009 resulted in unusually high chlorophyll *a* concentrations beginning in July, when concentrations were 9.7 μg/L, compared to the median value of 5.1 μg/L. High values also occurred in August and September, but by December chlorophyll *a* concentrations were below the expected (median) values, giving only a 5-month response time to the event.

2.1.4 Response Times to Unusual Loading Events - Lower Tampa Bay

Event 1 - During the unusually wet years of 1994 and 1995, the chlorophyll *a* concentration in August 1994 was 6.0 μg/L, compared to the median August value of 5.6 μg/L. Monthly values greater than the median calendar month values were maintained until March 1995, so the temporal extent of this response was 7 months. During September 1995, the chlorophyll *a* concentration was 8.4 μg/L, greater than the median September value of 7.2 μg/L, and returned to the monthly median or below in January 1996, a period 4 months.

Event 2 - The El Niño event of 1997-1998 began in the fall of 1997. The chlorophyll *a* concentration in October 1997 was 7.8 μg/L, compared to the median value of 5.6 μg/L. Monthly values remained greater than the median values until July 1998, giving a response time of 9 months.

Event 3 – The unusually high rainfall during the late autumn/early winter of 2003 resulted in an elevated chlorophyll *a* concentration in October 2003 of 6.7 μg/L, compared to the median of 5.6 μg/L. Within 1 month, however, the chlorophyll *a* concentration returned to a value just slightly greater than the monthly median.

Event 4 - The effects of the 2004 hurricane season on chlorophyll a concentrations in Lower Tampa Bay were relatively short lived. The maximum chlorophyll *a* concentration (13.3 μg/L) was observed in September 2004. The 2004 response time was only 1 month.

Event 5 - The effects of the 2005 hurricane season on chlorophyll *a* concentrations in Lower Tampa Bay were relatively short lived. The 2005 response time was 2 months.

Event 6 – The unusually high rainfall in the spring of 2009 resulted in unusually high chlorophyll *a* concentrations beginning in July, when concentrations were 9.2 μg/L, compared to the median value of 5.1 μg/L. High values also occurred in August, but by September chlorophyll *a* concentrations were below the expected values, giving only a 2-month response time to the event.

2.1.5 Summary of Response Times to Unusual Loading Events

Table 1 provides a summary of the response times in each segment for each event. As provided in the table, longest response times seen in all segments resulted from the El Niño event of 1997-1998. The next longest response times resulted from the unusually wet 1994-1995 period.

Response times to the other events, including the hurricane seasons of 2004-2005, were typically no greater than 3 months. The only exception to this was in Old Tampa Bay, where the response to the wet fall of 2003 continued through the hurricane season of 2004.

Table 1. Chlorophyll *a* response times (months) to unusual loading events in Tampa Bay.

Event	Old Tampa Bay	Hillsborough Bay	Middle Tampa Bay	Lower Tampa Bay
Wet 1994-1995	8	5, 7	7, 7	7, 4
El Niño 1997-1998	6	11	17	9
Autumn 2003	13	1	2	1
Hurricanes 2004	13	2	1	1
Wet 2005	-	1	3	2
Spring 2009	2	3	5	2

The response to most unusual loading events to the bay is typically very rapid, with response times on the order of months, not years. Only the strong El Niño event of 1997-1998 resulted in response times on the order of a year in more than one segment. The bay recovers relatively quickly from most unusual loading events. The annual maxima and the response to each event discussed above did not always occur in the same month. The annual maxima are the maximum annual chlorophyll *a* concentrations observed during each year, while the event response may occur earlier, as during the Spring 2009 event and the late 1997-early 1998 El Niño event.

2.2 Response Times to Annual Chlorophyll *a* Maxima

Chlorophyll *a* concentrations reach annual maxima within each segment of the bay in response to conditions that are conducive to increased productivity. The maxima normally occur in the summer months, as this is typically the time of year when conditions are most conducive to algal growth. The number of months for the monthly segment chlorophyll *a* concentrations to recede to levels below the median monthly concentrations, as estimated from 1985-2009 observations, is defined as the annual response time for this analysis. Therefore, the annual response time provides an indicator of the ability of each segment to recover from typically seasonal increases in loadings associated with the wet season.

The method used in this analysis to estimate the annual response time was the same as that used for examining the response times to unusual events. Following each annual maximum, the number of months until the chlorophyll *a* concentration returned to a level at or below the median calendar month concentration was tallied. This provides a measure of the response time within the bay to the annual chlorophyll *a* maximum.

As shown in Figure 3, the maximum annual response time in Old Tampa Bay was 13 months, following the annual maximum chlorophyll *a* concentration observed in October 2003, resulting from the unusually high rainfall in the Autumn 2003 event described above and extending into the 2004 hurricane season. The maximum annual response time in Hillsborough Bay was 11 months, following the annual maximum chlorophyll *a* concentration observed in October 1997, resulting from the 1997-1998 El Niño event. In Middle Tampa Bay, the maximum annual response time was 17 months following the October 1997 chlorophyll *a* maximum, also resulting from the 1997-1998 El Niño event. Lower Tampa Bay maximum annual response time was 6 months, resulting from both the 1997-1998 El Niño event and from the high rainfall in Autumn 1994.

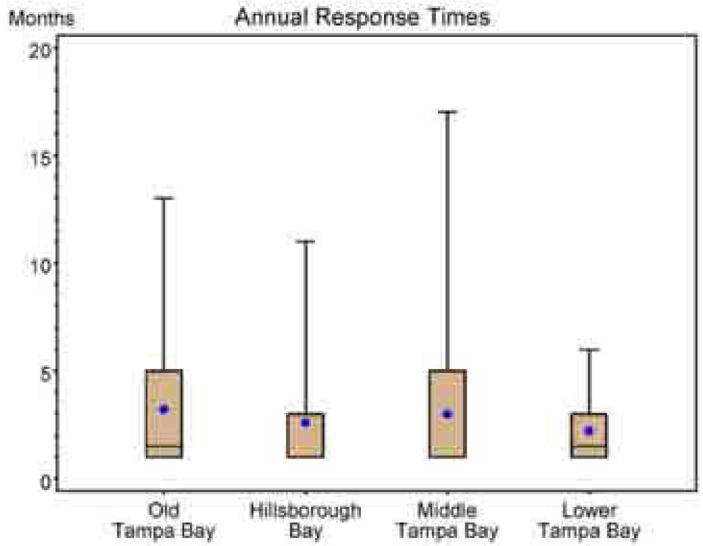


Figure 3. Annual chlorophyll *a* response times (months) for the period 1985-2009.

It should be noted that the maximum chlorophyll *a* during a given year is not always found in the wet season. Maximum chlorophyll *a* concentrations were sometimes found in the winter, as in Old Tampa Bay during two years (both times in January) and Lower Tampa Bay during three years (in December, January, and February). Figure 4 provides histograms for each bay segment of the number of occurrences of chlorophyll maxima within each month over the 1985-2009 period. In Hillsborough Bay, Middle Tampa Bay, and Lower Tampa Bay, the maximum chlorophyll *a* concentration typically occurs in September, while in Old Tampa Bay it typically occurs in November.

A long response time, as indicated by the 75th percentile of annual response times, was 4 months in Old Tampa Bay, Hillsborough Bay, and Middle Tampa Bay, and 3 months in Lower Tampa Bay. Median annual response times were two months in Old Tampa Bay, Hillsborough Bay, and Lower Tampa Bay, and only 1 month in Middle Tampa Bay. Average annual response times were about 3 months in all segments except Lower Tampa Bay, where the average annual response time was just over 2 months (see Table 2 for distribution statistics). These response times are similar to water residence time estimates for Tampa Bay (Burwell et al, 2000; Myers and Luther, 2008).

Table 2. Distribution of response times (months) following annual maximum chlorophyll *a*.

Percentile	Old Tampa Bay	Hillsborough Bay	Middle Tampa Bay	Lower Tampa Bay
100	13	11	17	6
99	13	11	17	6
95	13	11	17	6
90	8	7	6	6
75	5	3	5	3
50	1.5	1	1	1.5
25	1	1	1	1
10	1	1	1	1
5	1	1	1	1
1	1	1	1	1
0	1	1	1	1
Mean	3.2	2.6	3.0	2.2

2.3 Recommendations of Potential Methods to Account for Unusual Loading Events

EPA encouraged input on potential methods to account for non-anthropogenic events that can significantly affect the nutrient and chlorophyll *a* concentrations in Tampa Bay, including the effects of hurricanes or other unusually high rainfall events, such as El Niño. Based on the analyses described above, the bay recovers relatively quickly from most unusual loading events, with only the extreme events resulting in responses of more than one year.

It is recommended that the observed response times to unusual loading events in the future be considered when evaluating compliance with the proposed numeric nutrient criteria. This approach would be consistent with the identification of anomalous events in the assessment process utilized by the TBNMC to report compliance with the FDEP RA determination and the EPA TMDL. The TBEP process initially identifies any chlorophyll *a* concentration and/or water clarity exceedances, then evaluates the severity of these exceedances, and responds accordingly. One example of this process has been the development and completion of several studies investigating the unexplained exceedance of chlorophyll *a* thresholds in Old Tampa Bay in 2004 and 2005, when the rest of the bay has been meeting thresholds. A series of studies examining the potential causes of these exceedances were completed and a nutrient management plan specific to Old Tampa Bay will be developed from these assessments. Similar management responses should be included in the compliance assessment for Tampa Bay numeric nutrient criteria.

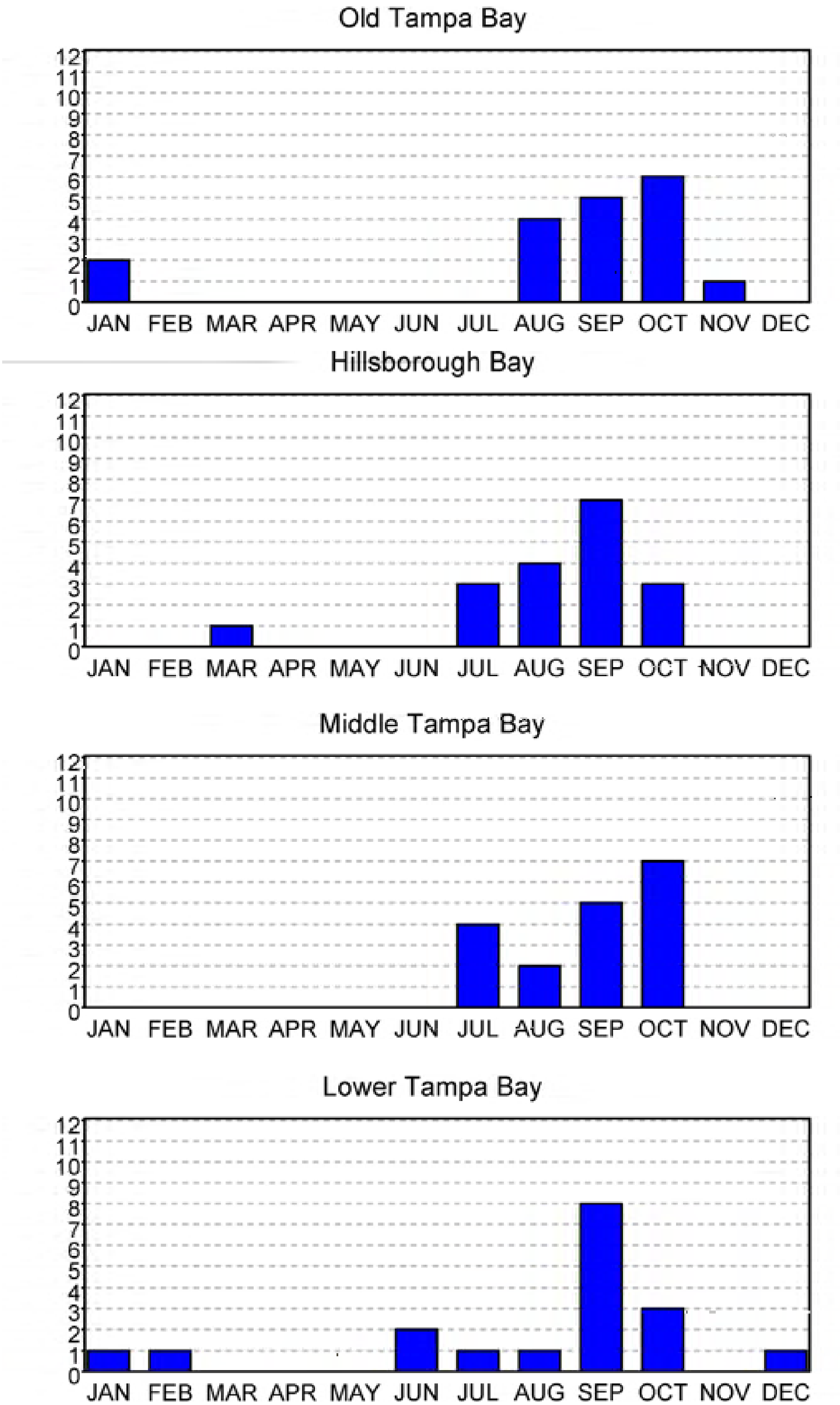


Figure 4. Number of occurrences within each month of maximum chlorophyll *a* for the year, 1992-2009.

3.0 Evaluation of Compliance Assessment Period Length

The implementation of the Florida numeric nutrient criteria proposed by EPA will require the definition of an implementation and assessment cycle. Consideration of the potential ramifications of an assessment that is either too lenient (i.e., does not capture a significant exceedance when one actually occurs) or too strident (i.e., inappropriately identifying a significant exceedance when one has not occurred) is a critical element of the evaluation of alternative assessment cycles.

Both EPA and FDEP are considering allowances of criteria exceedance due to natural variability. The draft freshwater numeric nutrient criteria proposed by EPA (2010) identified a 3-year assessment cycle which incorporates a "1 in 3" rule to allow one exceedance in a three-year assessment cycle to account for natural variability. The Florida Department of Environmental Protection (FDEP) currently uses a 5-year assessment cycle for evaluation of impairment in waterbodies, as well as NPDES, MS4, and other regulatory permitting cycles. FDEP is considering a "2 in 5" rule to allow 2 exceedances in 5 years as an allowance for natural variability (EPA, 2010). Therefore, if based on annual statistics, exceedances would occur when exceedances were at least 2/3 years (67%) or 3/5 years (60%), respectively. The objective of this investigation was to examine the effects of these different temporal assessment schemes on the likelihood of concluding that a waterbody was in exceedance based solely on natural meteorological variability.

Southwest Florida is periodically subjected to meteorological anomalies which result in deviations from expected rainfall and stream flow patterns. The El Niño Southern Oscillation (ENSO) is a strong driver of weather patterns and resulting stream flows in southwest Florida (Kelly and Gore, 2008). The temporal persistence of this oscillation is highly variable (i.e., between 2-7 years) and the magnitude and duration of the effects are dependent in large part on the gradient in atmospheric pressure differences between the eastern equatorial Pacific and Indo–Australian areas (Glantz et al., 1991). El Niño is indicated by a suppression of the upwelling of cold nutrient rich Pacific waters and tends to result in colder, wetter winter temperatures and wetter rainfall patterns in general. Ropelewski and Halpert (1986) studied North American precipitation and temperature patterns associated with ENSO conditions. In the southeastern United States and northern Mexico, above-normal precipitation was recorded for 81% of the cases for the "season" that began in October of the ENSO year and concluded in March of the following year. For temperature anomalies during ENSO, the southeastern United States showed below-normal temperatures around 80% of the time. Clearly these conditions may persist across calendar years.

Hurricane activity is usually minimal during El Niño in the Atlantic Ocean while the La Niña is associated with an increased frequency of hurricanes and tropical systems. La Niña is typically triggered by a reversal of the southern oscillation and tends to result in warmer and drier conditions in southwest Florida. Recent evidence for the correlation of ENSO cycles and weather patterns include the strongest El Niño on record during late 1997 through early 1998 resulting in very wet winter conditions in southwest Florida, followed by severe drought conditions associated with the La Niña of 1999-2001 and a return of wet conditions associated with the El Niño in late 2002-2003. While much is still to learn about the direct correspondence between ENSO and weather patterns in southwest Florida on shorter temporal scales, the resulting natural variability in rainfall and stream flow associated with these events has profound effects on estuarine dynamics, such as influencing residence times, salinities, temperatures, and nutrient delivery.

The objective of this investigation was to examine the effects of these different temporal assessment schemes on the likelihood of concluding that a waterbody was in exceedance based solely on natural meteorological variability. That is, the analysis is designed to characterize natural variability in meteorological conditions, classify "anomalies" as meteorological conditions that deviate substantially in terms of magnitude and duration from long term average conditions, and test which rule is more likely to conclude that and excursion has occurred based solely on these anomalies. It is the duration of these anomalies that will affect the outcomes of this assessment. Anomalies that carry over calendar years will likely result in a violation of the "1 in 3" rule. This same artifact in the data would not trigger an exceedance under the "2 in 5" rule unless another anomaly occurred within the 5 year window. Therefore this assessment examines the correlation that may exist from year to year. This is an assessment of autocorrelation in the annual statistics similar to that described in section 2 for the monthly time scale. In Tampa Bay, studies have demonstrated that water quality conditions are affected by rainfall and streamflow anomalies and that the estuary is resilient in response to these acute anomalies, returning to conditions fully supporting designated uses once meteorological conditions return to more typical conditions (e.g. Morrison et al., 2006, Sherwood, 2010).

3.1 Conceptual Model

This investigation is based on a conceptual model expressed by the EPA that the regulatory compliance assessment cycle should allow for natural disturbance patterns resulting from episodic events in Florida. These events could include hurricanes and ENSO-related droughts and floods that influence water quality independent of anthropogenic effects. Ideally, the natural variability would be absorbed within the assessment cycle while maintaining sensitivity to reporting exceedances due to anthropogenic impacts. Therefore, this investigation is intended to provide insight on the temporal assessment scale that best incorporates natural variability and is less likely to result in an exceedance due simply to natural deviations from expected rainfall and stream flow conditions. There were two components of the analysis for this assessment:

- First, the relationship between variability in stream flow and in-bay chlorophyll *a* concentrations were investigated to support evidence that estuarine responses are related to natural variability in regional hydrology as found in other investigations (e.g., Morrison et al., 2006).

- Second, a method was derived to characterize individual calendar years (i.e., wet, dry, average) based on deviations in stream flow from long term monthly averages and a test was conducted to determine which of the two assessment cycles described above was more likely to report violations due solely on deviations from expected stream flow patterns.

3.2 Methods

Two datasets were chosen for this evaluation. The first dataset was a long-term flow dataset from two USGS stream flow gauges in the Alafia River at Lithia (02301500) and in the Little Manatee River gauge located near Wimauma (02300500). These flow records have consistently recorded river flows since the 1930s to present day. Both the Alafia River and the Little Manatee River are uninterrupted along their main stem although consumptive water use withdrawals do occur in both systems. The second database included chlorophyll *a* concentrations in Hillsborough Bay as described in Janicki Environmental (2008). The period of record for chlorophyll data was 1974 to 2009.

The long-term flow record time series were used to calculate an index representing wet, dry, and normal years. To accomplish this, long-term monthly average flows over the entire period of record were calculated and subtracted from the monthly average flow. This difference was then divided by the standard deviation of the long-term monthly average to derive a flow index representing deviations in monthly averages from the long-term monthly mean.

$$\text{Standardized flow} = \frac{x - \mu_x}{\sigma_x}$$

Where:

X = Monthly flow value

μ_x = Long term monthly average flow

σ_x = Standard deviation of long term monthly average

Cutoff values (events) and exceedance frequencies (durations) were then assigned to classify years as "Wet", "Dry", or "Average" based on these "standardized" flows. Common drought indices, such as the Palmer Drought Severity Index (Palmer, 1965), have been developed in a similar fashion to the approach used in this investigation. The following working definitions are used here:

- Wet years were assigned when there were 5 or more months in a year when flows were greater than 0.5 standard deviations higher than the long-term monthly average.
- Dry years were assigned when there were 5 or more months in a year when the flows were greater than 0.5 standard deviations below the long-term monthly average.

The chlorophyll data were similarly treated to assess annual chlorophyll anomalies and their concordance with variability in stream flow. An annual chlorophyll anomaly was defined as more than 2 consecutive months of chlorophyll levels 0.5 standard deviations above the long-term monthly average between1985-2007. This time period was chosen to eliminate the effects of known point source effects on chlorophyll a concentrations prior to implementation of advanced wastewater treatment. The chlorophyll and stream flow indices were then compared graphically to assess the correspondence between anomalies in stream flow and annual chlorophyll.

The annual stream flow classifications of wet, dry, or average years were then used to compare the assessment outcomes as the number of "exceedances" under the "1 in 3" rule compared to the "2 in 5" rule. Cohen's Kappa statistic (Stokes et al., 2000) was used to measure agreement between the two rules:

$$K = \frac{P(a) - P(e)}{1 - P(e)}$$

where P(a) is the proportion of times the methods agree, and P(e) is the proportion of times the methods are expected to agree by chance alone.

Complete agreement corresponds to K = 1, and lack of agreement corresponds to K = 0. Kappa coefficients less than 0.70 generally signify substantive disagreement between the two methods.

3.3 Results

As expected, stream flows in the Alafia and Little Manatee rivers were variable over the period of record as exemplified in Figure 5. Deviations above and below the horizontal lines indicate monthly anomalies. Cumulative anomalies within a year classify the year as either Wet, Dry, or Average as described above.

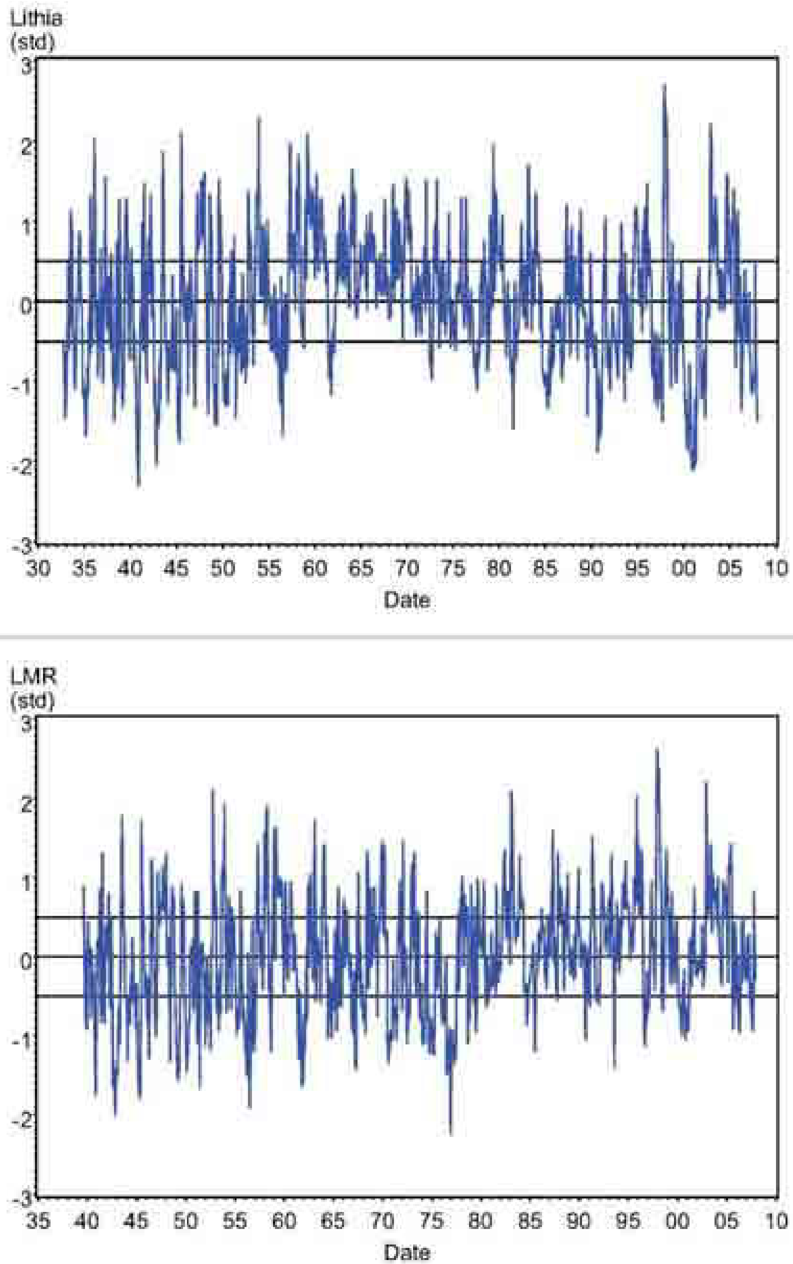


Figure 5. Stream flows for Alafia River at Lithia (top) and Little Manatee River (bottom) expressed as deviations from long-term monthly averages. The period of record was 1933-2007 in Alafia River and 1939-2007 in Little Manatee River.

Greening and Janicki (2006) described several management actions beginning in the late 1970s resulting in nitrogen load reductions to Tampa Bay equivalent to approximately 60% of pre-1985 levels. Since 1985, nitrogen loading to the estuary has remained relatively stable with variability in TN loadings resulting largely from natural variability in rainfall. Chlorophyll *a* concentrations over this time period have responded with substantial declines in biomass corresponding with management actions in the late 1970s and early 1980s and a leveling off of chlorophyll *a* concentrations post-1985. It is easily seen that in Hillsborough Bay, prior to 1985, chlorophyll anomalies occurred frequently and irrespective of deviations in inflow from the Alafia River. However, since 1985 chlorophyll anomalies have only occurred when inflow conditions were above their long-term monthly averages (Figure 6). This suggests that, prior to 1985, anthropogenic impacts were the dominant influence on chlorophyll *a* concentrations and that since that time, natural variability in hydrology and associated nutrient loadings has become a more predictive component of the estuarine response. This analysis correlates well with the results of TBEP's decision matrix and annual scoring of Tampa Bay which has shown that Hillsborough Bay chlorophylls have exceeded their targets only during anomalously wet years (e.g., 1994-5,1998) (Sherwood, 2010).

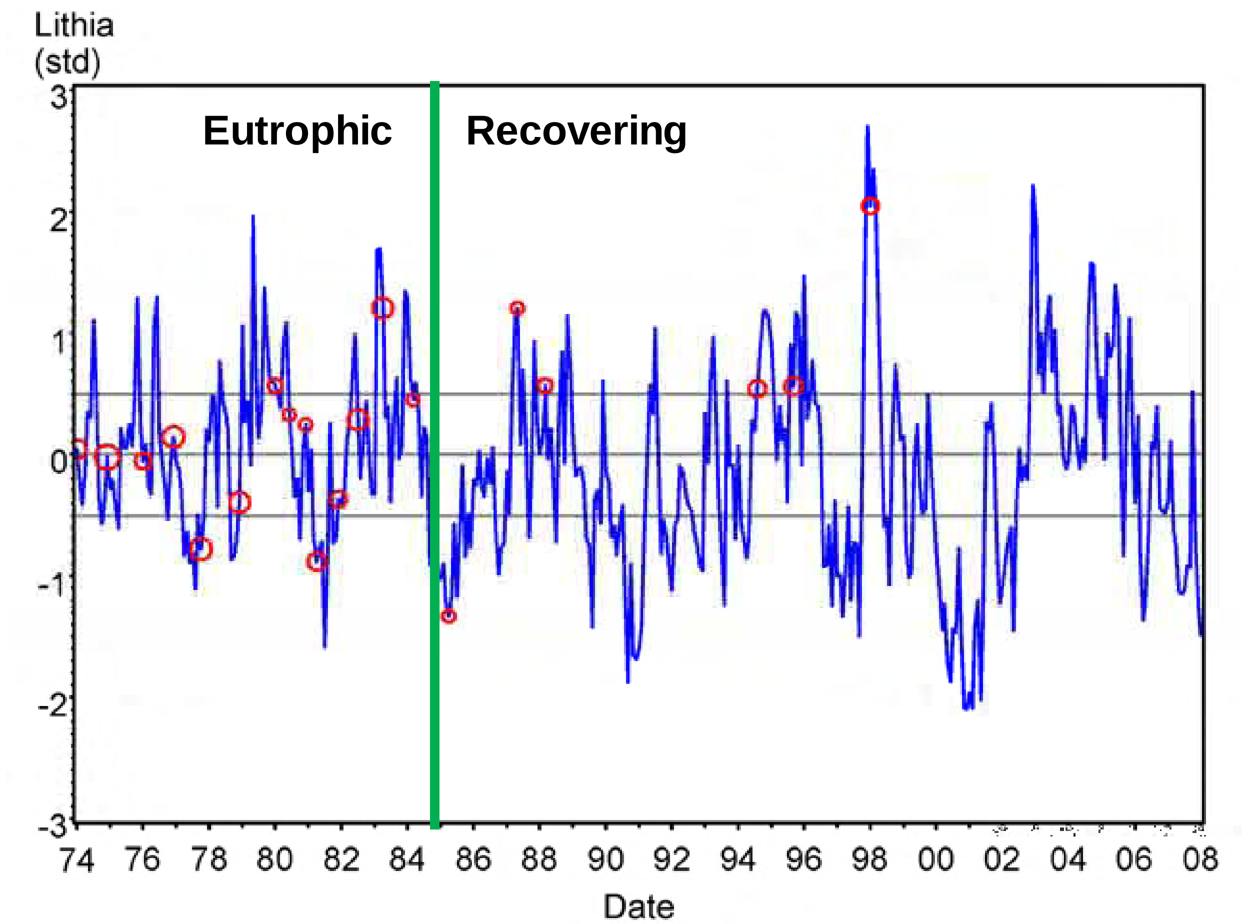


Figure 6. Time series of standardized flows in the Alafia River at Lithia with circles denoting chlorophyll anomalies. The location of the circle represents the month in which the anomaly began and the size of the circle represents the duration of the anomaly.

The analysis above supports evidence by others that annual bay chlorophyll concentrations become elevated when annual stream flows are above long term averages. However, the major objective of this investigation was to assess the two regulatory assessment cycles in allowing for natural variability. Again, it is the duration of these anomalies that will affect the outcomes of this assessment. Anomalies that carry over calendar years will likely result in a violation of the “1 in 3” rule compared to the “2 in 5” rule. Therefore, the second assessment used the time series of annual stream flow classifications (i.e. wet, dry, average; Figure 7) as a proxy to evaluate how the two regulatory assessment cycles would differ with respect to characterizing natural variability as a violation.

Nearly half of the dry years in the Alafia River occurred over a consecutive 2-year period (5 of 13). The remaining dry years were single year events. Wet years tended to be more variable but several multi-year events were also recorded over the period of record.

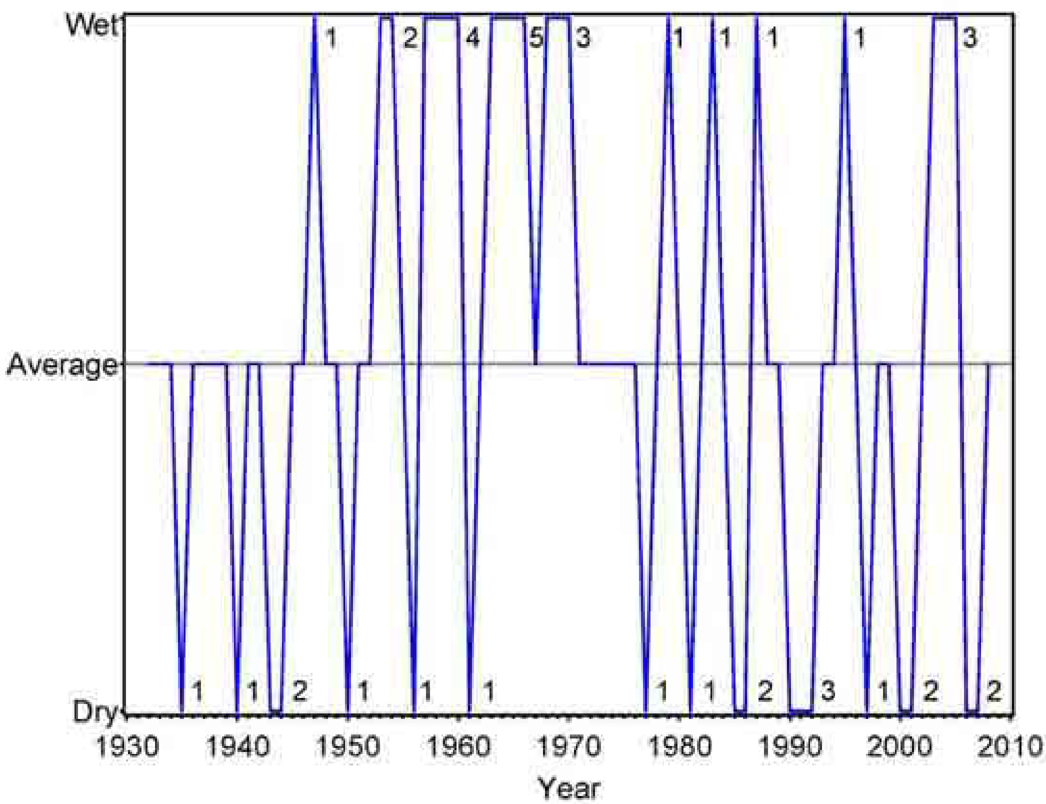


Figure 7. Annual classification of wet, dry and average years for the Alafia at Lithia gauge between 1932 and 2008.

The rule comparison was performed separately for the Dry years and the Wet years. In the Alafia River, the “1 in 3” rule resulted in nearly twice the number of rule exceedances (9 vs. 5) compared to the “2 in 5” rule for the Dry years (Table 3). The Dry years also tended to occur over a two year period in the Alafia while the Wet years tended to be either single year events or more than two year events. The Kappa statistic of 0.53 suggests substantive disagreement between the methods. The comparison of the two rules for Wet years also indicated substantial disagreement with the “1 in 3” rule resulting in more potential exceedances due to natural variability than the “2 in 5” rule (Table 4). Very similar results were obtained for the Little Manatee River (Tables 5 and 6). In both Dry years and Wet years more potential exceedances were found using the “1 in 3” rule compared to the "2 in 5" rule. Therefore, based on this assessment, potential exceedances would more likely be assigned due solely to deviations in expected stream flows using the 1 in 3 rule compared to the 2 in 5 rule.

Table 3. Rule assessment for Dry year evaluation of Alafia River stream flow. Kappa = 0.53.

		5-Year Rule		
		Compliant	Exceedance	Total
3-Year Rule	Compliant	63	1	64
	Exceedance	5	4	9
	Total	68	5	73

Table 4. Rule assessment for Wet year evaluation of Alafia River stream flow. Kappa = 0.54.

		5-Year Rule		
		Compliant	Exceedance	Total
3-Year Rule	Compliant	57	2	59
	Exceedance	7	7	14
	Total	64	9	73

Table 5. Rule assessment for Dry year evaluation of Little Manatee River stream flow. Kappa = 0.49.

		5-Year Rule		
		Compliant	Exceedance	Total
3-Year Rule	Compliant	50	3	53
	Exceedance	6	6	12
	Total	56	9	65

Table 6. Rule assessment for Wet year evaluation of Little Manatee River stream flow. Kappa = 0.41.

		5-Year Rule		
		Compliant	Exceedance	Total
3-Year Rule	Compliant	55	1	56
	Exceedance	6	3	9
	Total	61	4	65

3.4 Recommendation

This investigation used long-term stream flow records to characterize natural variability in the hydrologic conditions in Tampa Bay since the 1930s. This estimate of natural variability was then used to test two potential temporal assessment schemes with respect to their ability to account for natural variability and identify exceedances related to anthropogenic activities.

Implementing a compliance assessment rule to account for exceedances due to natural environmental variability is difficult at best, but this analysis suggests that a "2 in 5" rule is more likely to absorb natural variability than the "1 in 3" rule when considering the effects of inflow variability on observed chlorophyll *a* responses in Tampa Bay. Based on these analyses, the "1 in 3" rule would result in more exceedances due to natural variability alone and, therefore, be overly sensitive to this variability compared to the "2 in 5" rule. Ideally, natural variability would be accounted for within the criterion development process such as was done for TBEP hydrologic normalization procedure documented in the Reasonable Assurance plan (TBEP and Janicki Environmental, 2010). In cases where this variability is not accounted for in the criterion development process, this analysis suggests that the "2 in 5" rule is more robust with respect to minimizing the chances of declaring exceedances due to natural variability.

4.0 Implementation of Tampa Bay Estuarine Numeric Nutrient Criteria: Assessment and Monitoring

It is recommended that the assessment of compliance with the proposed numeric nutrient criteria be performed in a manner similar to that which has been proposed by TBEP for compliance with both the Tampa Bay Reasonable Assurance and TMDL (TBEP and Janicki Environmental, 2010). The goal of the estuarine numeric nutrient criteria is to provide full aquatic life support within the estuary. The TBEP has determined that seagrasses are important indicators of desirable conditions in the bay and has defined the water quality conditions (i.e., chlorophyll *a* concentrations) that allow for the maintenance and growth of seagrass beds in Tampa Bay. Therefore, TBEP bases its compliance assessment on the comparison of both observed chlorophyll *a* concentrations and seagrass extent to the goals that have been established.

The TBEP and TBNMC have been utilizing an annual assessment strategy to track conditions in Tampa Bay with respect to chlorophyll *a* (Janicki et al., 2000). The strategy utilizes data collected by the Environmental Protection Commission of Hillsborough County (EPCHC) at numerous stations within the bay on a monthly basis. Conditions are assessed with respect the FDEP-approved chlorophyll *a* thresholds in the four mainstem segments of the bay, on an annual basis using data from these stations.

The TN and TP concentration-based criteria defined in Janicki Environmental (2011) were developed using data collected from the same series of EPCHC sampling stations (Figure 8). It is recommended that a similar procedure for compliance assessment of TN and TP concentration criteria be developed using the same data source.

Chlorophyll *a* is the primary response variable that is most closely related to variations in nutrient conditions and is a major determinant of the growth and maintenance of seagrasses. Therefore, the recommended initial step in the compliance assessment is evaluation of the annual average chlorophyll *a* concentrations within each segment for a given year, in keeping with the TBEP assessment methodology. Chlorophyll *a* threshold exceedances in two consecutive years do not in themselves indicate non-compliance of numeric nutrient criteria, as nutrient criteria compliance would still be determined by the "2-in-5 year" rule. Recognition of the fact that single anomalous events, such as the 1997-1998 El Niño, have resulted in two consecutive years of chlorophyll *a* exceedances is critical in implementing an appropriate and consistent compliance assessment for the Tampa Bay estuary.

Concurrently, the annual TN and TP concentrations, expressed as geometric means, should be compared to the proposed criteria when chlorophyll *a* thresholds are exceeded within the bay. While exceedances of either or both the TN and TP criteria may occur, an associated chlorophyll *a* response may be absent. These nutrient exceedances should not be ignored, and non-compliance need not be concluded. Rather, if such results are obtained in the future, then the data should continue to be compiles and analyzed to expand on the knowledge of how chlorophyll *a* concentrations respond to changes in nutrient conditions in the bay.

Ultimately the assessment of future seagrass extent with respect to the established seagrass goals is the prime metric for nutrient assessments in Tampa Bay, as the continued growth and expansion of seagrass beds in Tampa Bay is the key management response of concern. Inconsistent results, for example exceedances in either or both of the chlorophyll *a* thresholds or TN or TP criteria while seagrass extent continues to increase would necessarily lead to further analyses of the interrelationships between nutrients, chlorophyll *a* concentrations, and seagrass growth. Thus, continued re-evaluation of the proposed nutrient criteria for Tampa Bay would be recommended in the future.

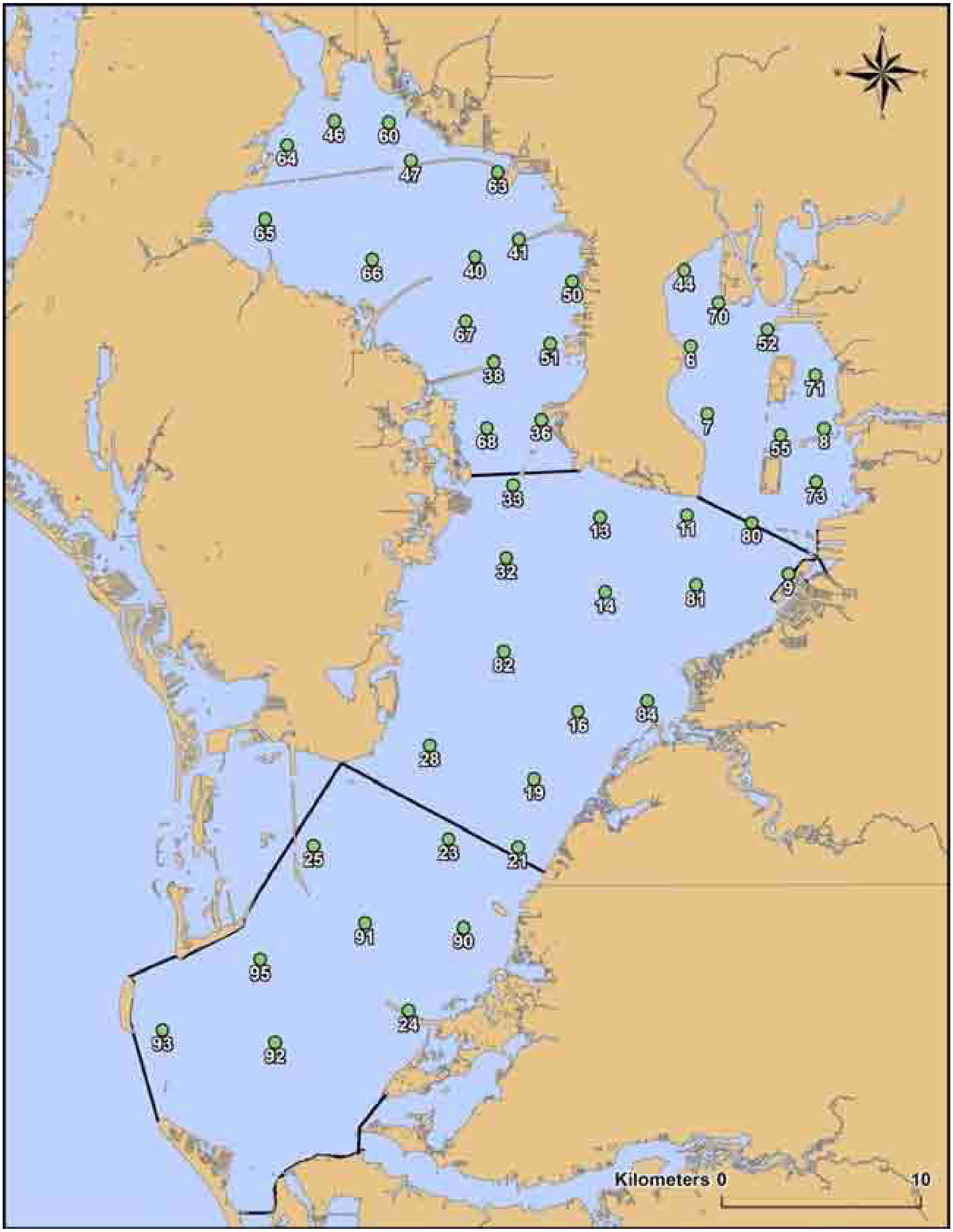


Figure 8. EPCHC sampling stations used to develop the chlorophyll *a* thresholds and nutrient criteria.

5.0 Conclusions

The following conclusions can be drawn from the results discussed above:

- The annual response time to recover from the maximum monthly chlorophyll *a* concentration during a year is relatively short. Median annual response times are two months or less in all segments, and average annual response times are three months or less in all segments. This indicates that the bay recovers very quickly from normal loading events.

- The typical response times to unusual events, such as El Nino, are longer and, depending upon the timing of such events, can span over parts of two successive years.

- It is important to consider the effects of natural variability in establishing the compliance assessment scheme.

- Comparison of the two temporal assessment schemes (1 in 3 years) vs (2 in 5 years) suggested that the 2 in 5 rule was less likely to result in a violation due solely to natural variability. It is recommended that the assessment of compliance with the proposed numeric nutrient criteria be performed in a manner similar to that which has been proposed by TBEP for compliance with both the Tampa Bay Reasonable Assurance determination and EPA TMDL. The goal of the estuarine numeric nutrient criteria is to provide full aquatic-life support within the estuary. The TBEP has determined that seagrasses are important indicators of desirable conditions in the bay and has defined the water-quality conditions (i.e., chlorophyll *a* concentrations) that allow for the maintenance and growth of seagrass beds in Tampa Bay. Therefore, TBEP bases its compliance assessment on the comparison of both observed chlorophyll *a* concentrations and seagrass extent to the goals that have been established. To date, this has proven to be a successful adaptive management approach for abating nutrient eutrophication in the Tampa Bay Estuary.

6.0 References

Burwell, D., M. Vincent, M. Luther, and B. Galperin. 2000. Modeling Residence Times: Eulerian vs Lagrangian. In: Estuarine and Coastal Modeling, M.L. Spaulding and H.L. Butler, eds. ASCE, Reston, VA. pp. 995-1009.

Glantz, M., R. Katz, and N. Nicholls (eds.). 1991. Teleconnections Linking Worldwide Climate Anomalies. Cambridge University Press, Cambridge.

Greening, H. and A. Janicki. 2006. Toward reversal of eutrophic conditions in a subtropical estuary: Water quality and seagrass response to nitrogen loading reductions in Tampa Bay, Florida, USA. Environmental Management. 38:163-178.

Janicki, A., D. Wade, and J.R. Pribble. 2000. Developing and Establishing a Process to Track the Status of Chlorophyll-a Concentrations and Light Attenuation to Support Seagrass Restoration Goals in Tampa Bay. Technical Report #04-00 of the TBEP. Prepared by Janicki Environmental, Inc.

Janicki Environmental, Inc. 2011. Tampa Bay Numeric Nutrient Criteria: Task 1 – TN and TP Concentrations. Letter Memorandum. Prepared for Tampa Bay Estuary Program.

Kelly, M. H., and J. A. Gore. 2008. Florida river flow patterns and the Atlantic multidecadal oscillation. River Res. Applic. 24:598–616.

Meyers, S.D., and M.E. Luther. 2008. A Numerical Simulation of Residual Circulation in Tampa Bay. Part II: Lagrangian Residence Time. Estuaries and Coasts. 31:815-827.

Morrison, G., E.T. Sherwood, R. Boler, and J. Barron. 2006. Variations in water clarity and chlorophyll *a* in Tampa Bay, Florida, in response to annual rainfall, 1985-2004. Estuaries and Coasts. 29:926-931.

Palmer, W. C, 1965. Meteorological Drought. Res. Paper No.45, 58pp., Department of Commerce, Washington, D.C.

Ropelewski, C.F; and M.S. Halpert. 1986. North American precipitation and temperature patterns associated with the El Niño–Southern Oscillation (ENSO). Monthly Weather Review. 114:2352–2362.

Sherwood, E.T. 2010. 2009 Tampa Bay Water Quality Assessment. Technical Report #02-10 of the Tampa Bay Estuary Program, St. Petersburg, FL.

Stokes, M. E. , Davis, C. S., and G.G. Koch. 2000. Categorical Data Analysis Using the SAS System. 2nd. ed. Cary, NC. SAS Institute, Inc.

Tampa Bay Nitrogen Management Consortium (TBNMC). 2010. Letter to Water Docket, U.S. Environmental Protection Agency, March 8, 2010.

TBEP and Janicki Environmental, Inc. 2010. 2009 Reasonable Assurance Addendum: Allocation and Assessment Report. Technical Report #03-10 of the TBEP.

U.S. Environmental Protection Agency (EPA). 2010. Water Quality Standards for the State of Florida's Lakes and Flowing Waters. 40 CFR Part 131. Washington, D.C.