TAMPA BAY
Numeric Nutrient Criteria:
Task 3 – Dissolved Oxygen

Letter Memorandum

Prepared for:

Tampa Bay Estuary Program

Prepared by:

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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.

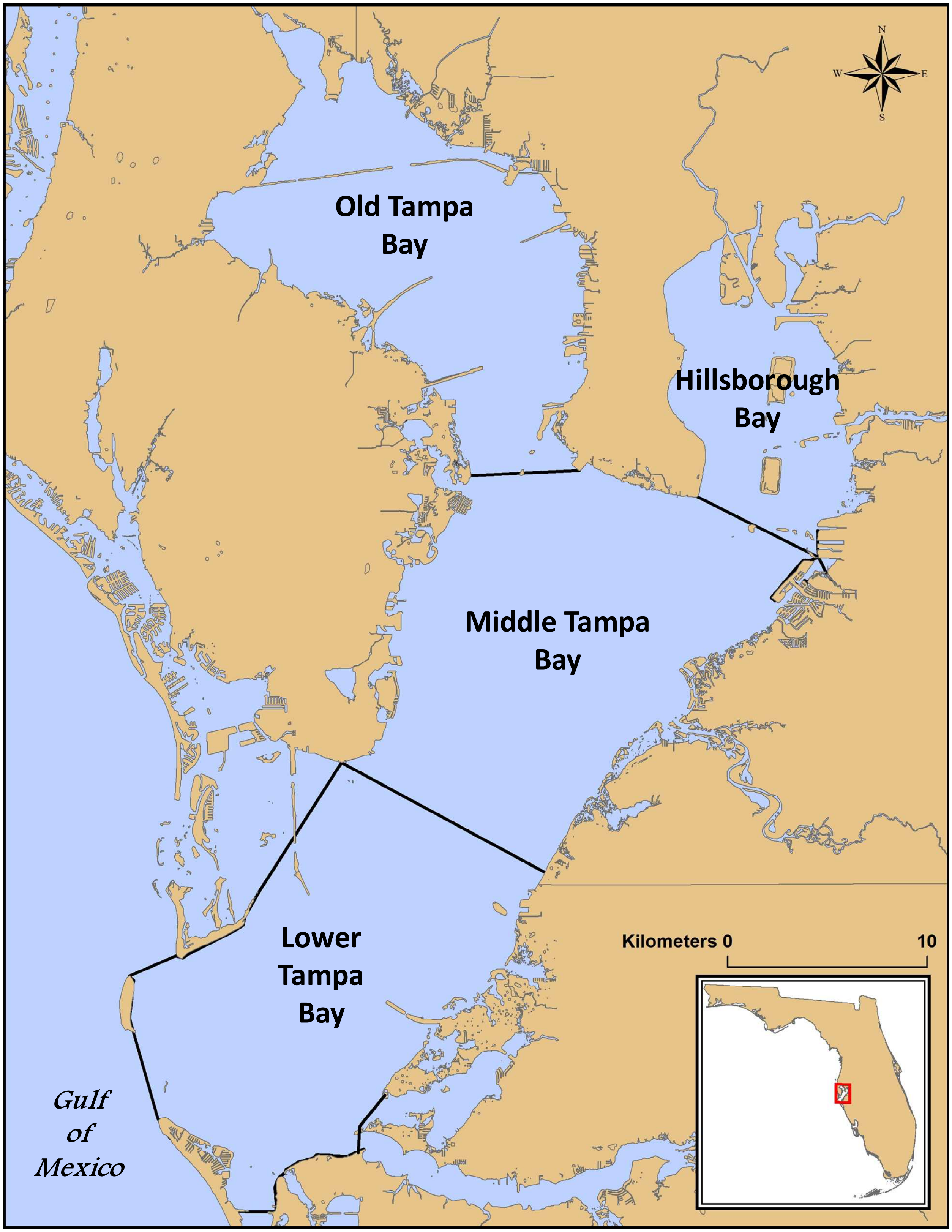

Figure 1. Tampa Bay and its four major bay segments.

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.

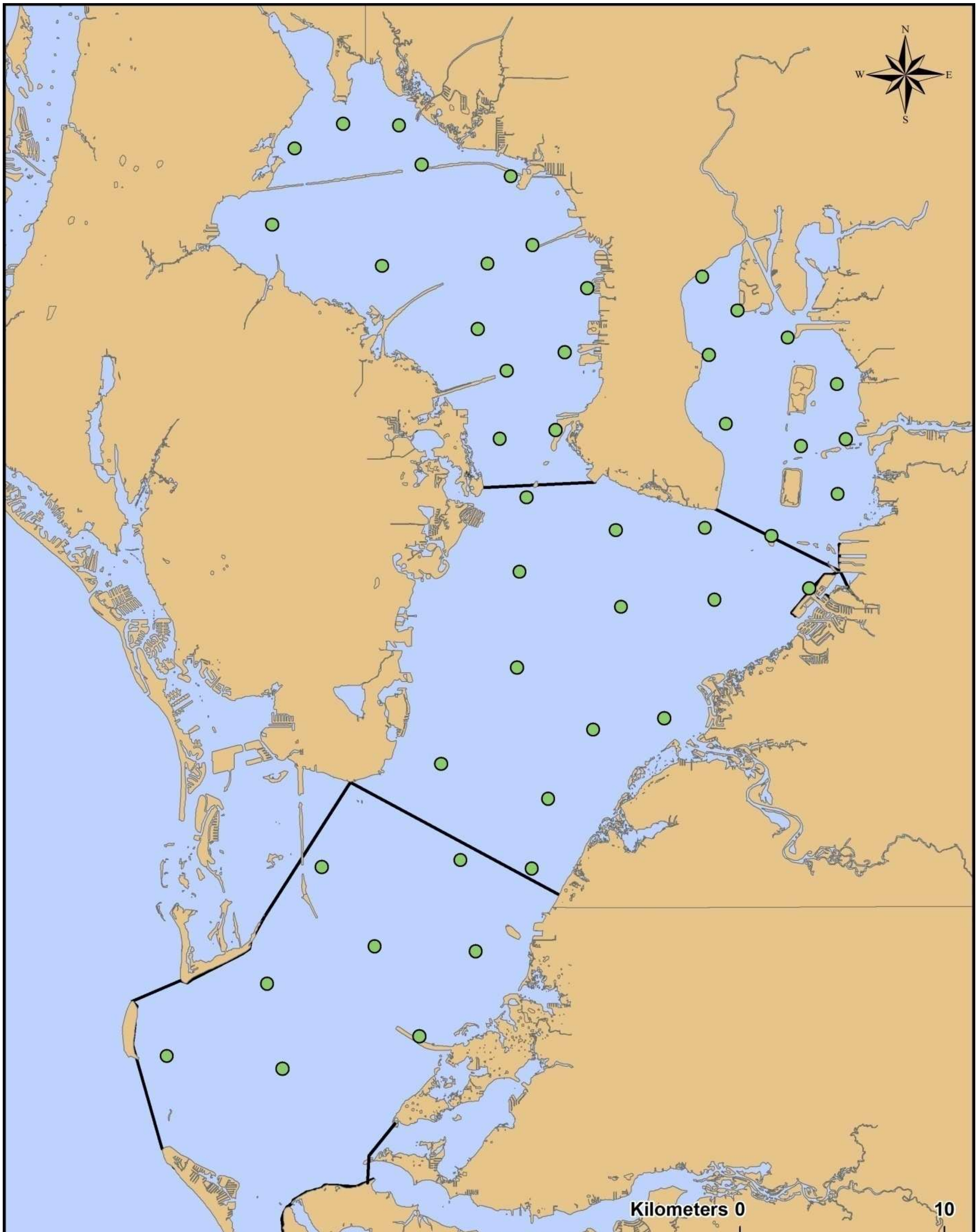

Figure 2. Sampling locations from EPC fixed stations in Tampa Bay sampled since 1974.

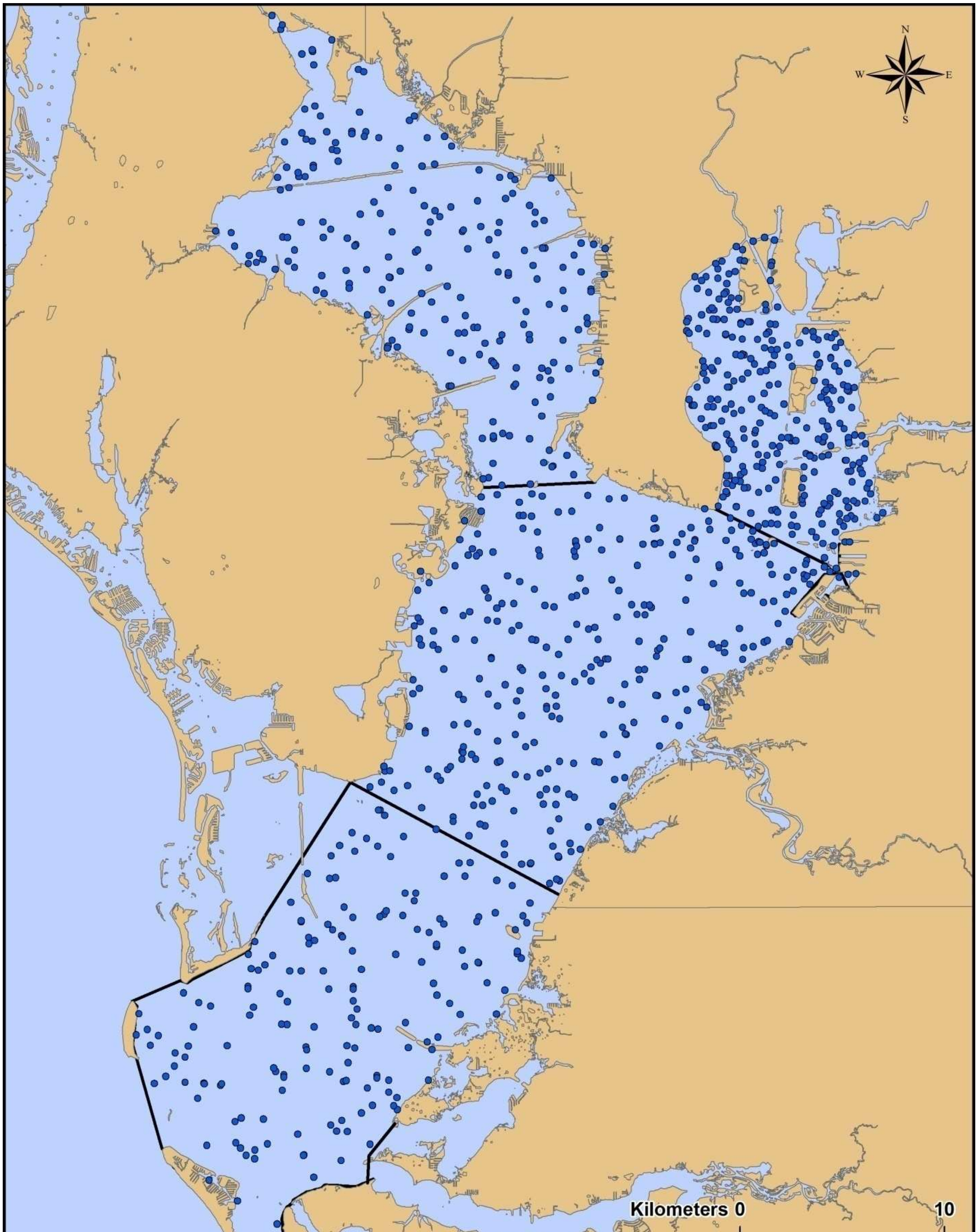

Figure 3. Sampling locations from EPC benthic collections between 1993-2008.

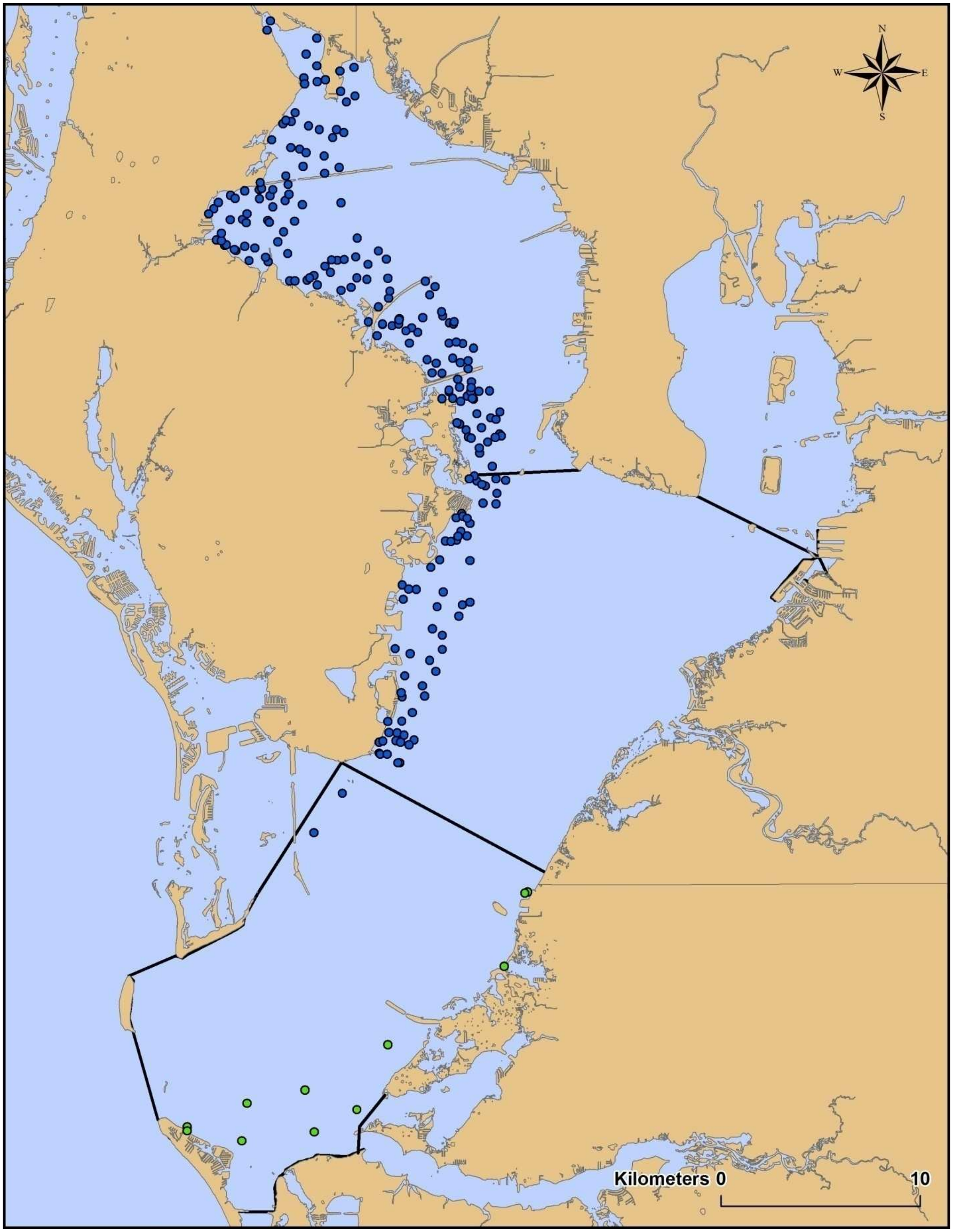

Figure 4. Sampling locations from Pinellas County DEM (blue circles) and Manatee County DEM (green circles).

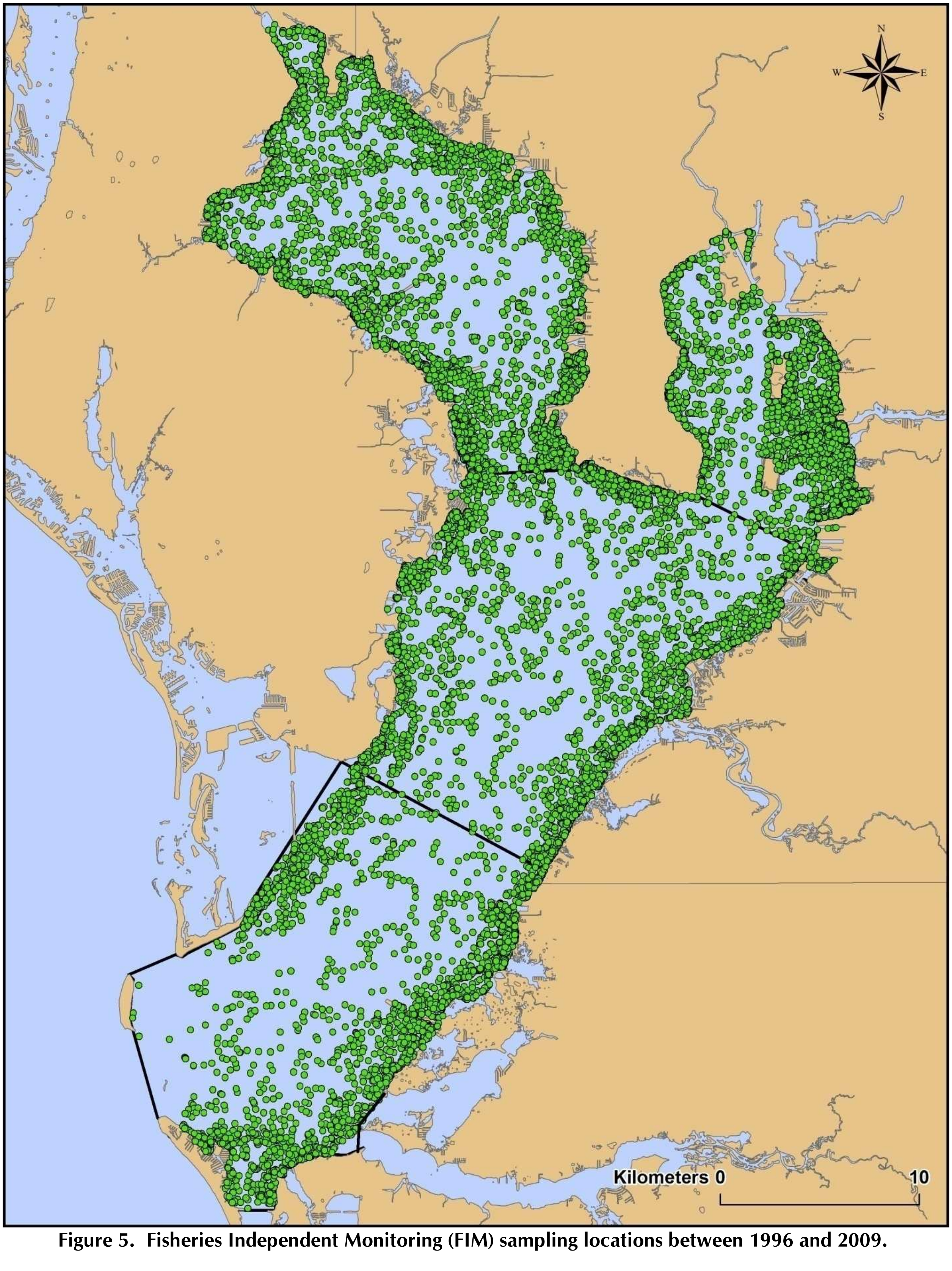

Figure 5. Fisheries Independent Monitoring (FIM) sampling locations between 1996 and 2009.

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

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%.

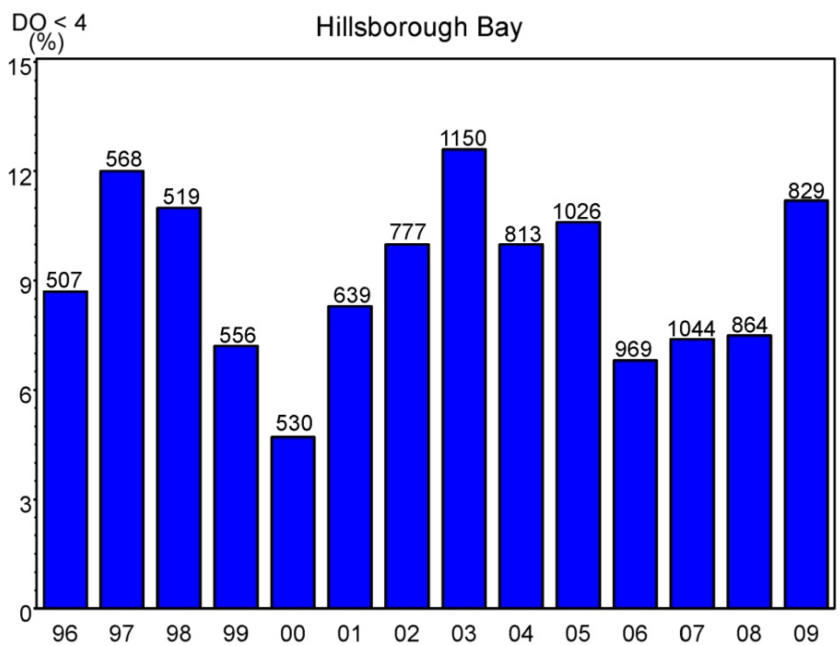

Figure 6. Annual percentage of DO values less than 4 mg/L in Hillsborough Bay. The number of samples shown above each bar.

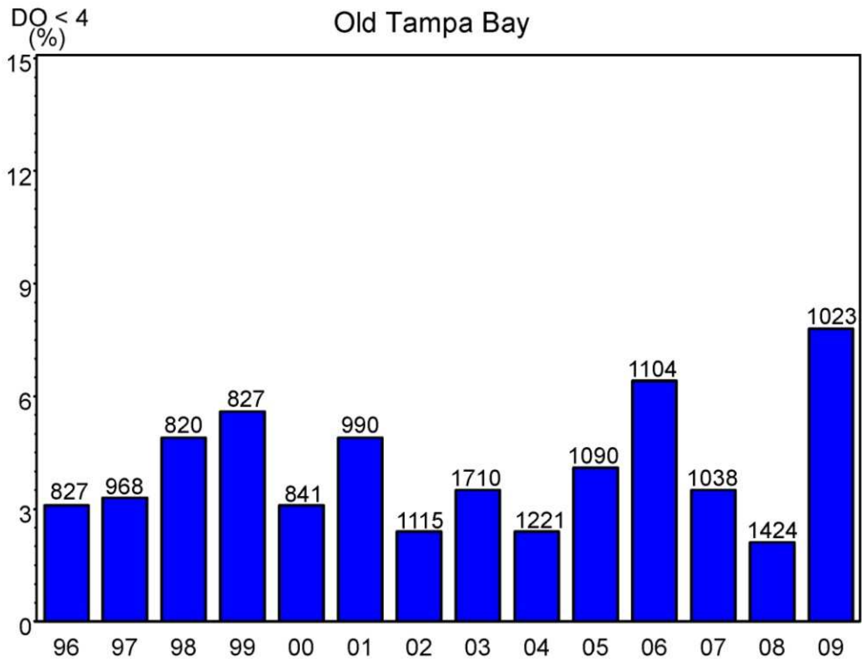

Figure 7. Annual percentage of DO values less than 4 mg/L in Old Tampa Bay. The number of samples shown above each bar.

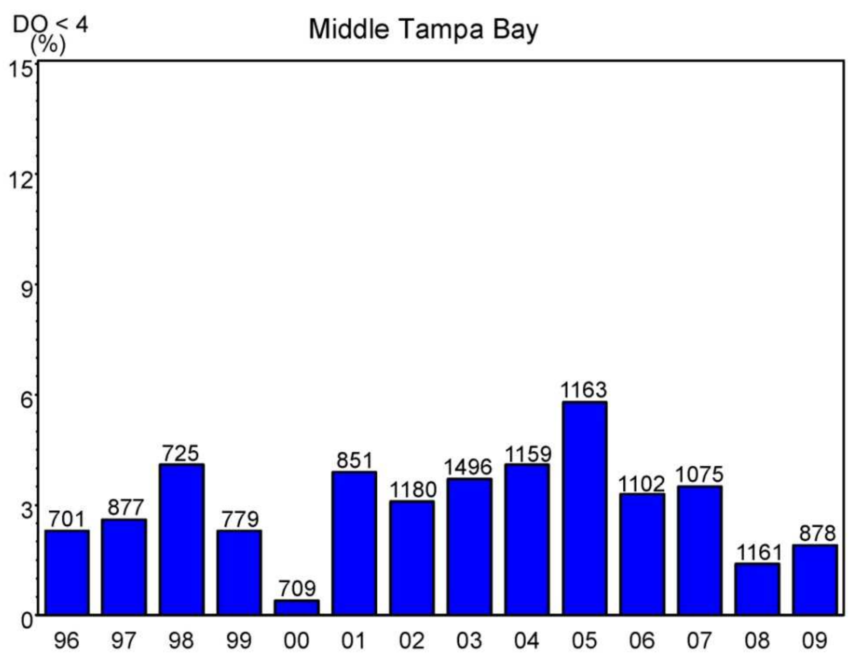

Figure 8. Annual percentage of DO values less than 4 mg/L in Middle Tampa Bay. The number of samples shown above each bar.

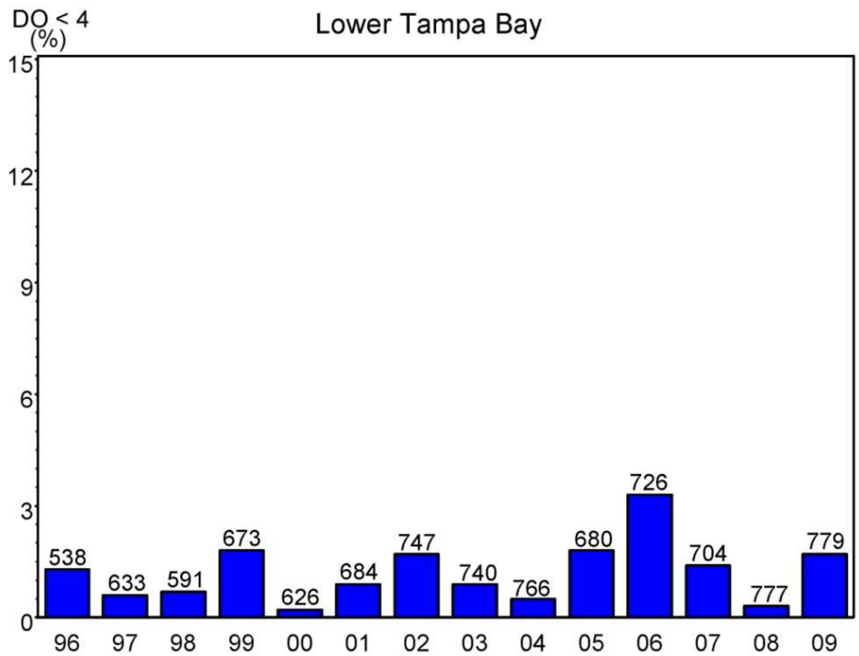

Figure 9. Annual percentage of DO values less than 4 mg/L in Lower Tampa Bay. The number of samples shown above each bar.

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.

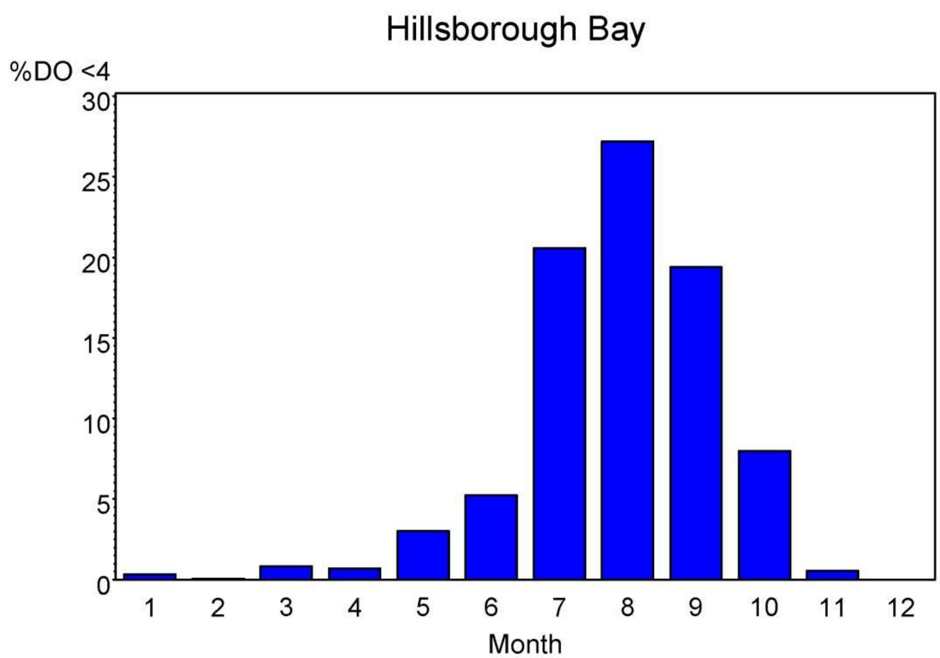

Figure 10. Seasonal distribution of DO exceedances across all years in Hillsborough Bay.

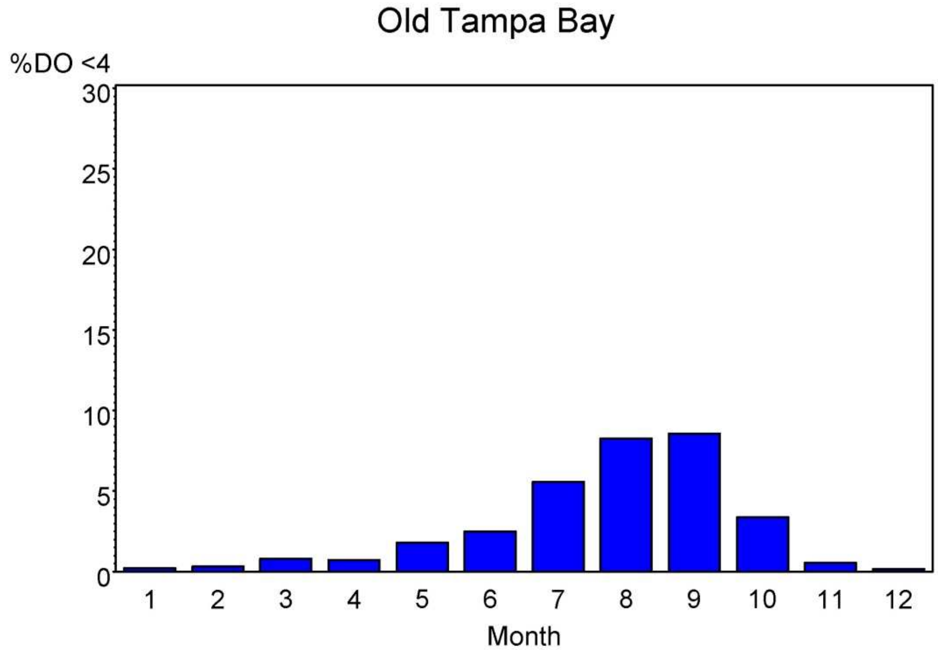

Figure 11. Seasonal distribution of DO exceedances across all years in Old Tampa Bay.

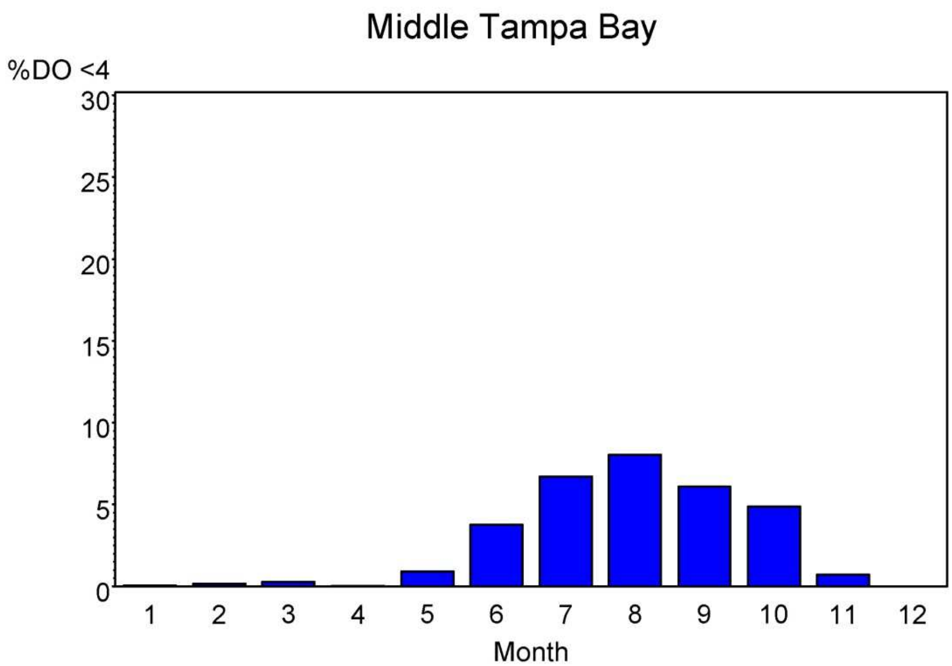

Figure 12. Seasonal distribution of DO exceedances across all years in Middle Tampa Bay.

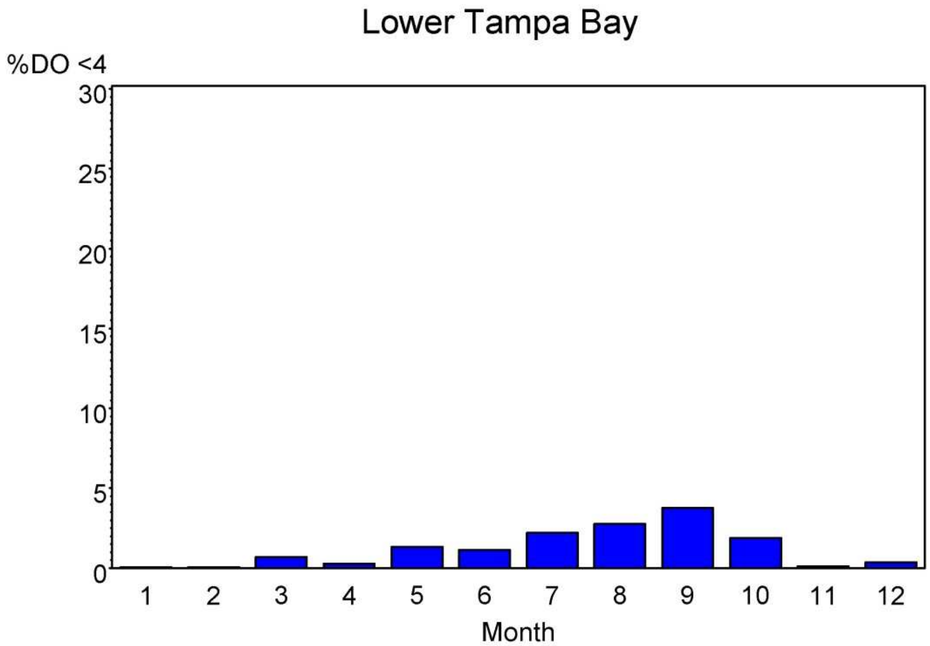

Figure 13. Seasonal distribution of DO exceedances across all years in Lower Tampa Bay.

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).

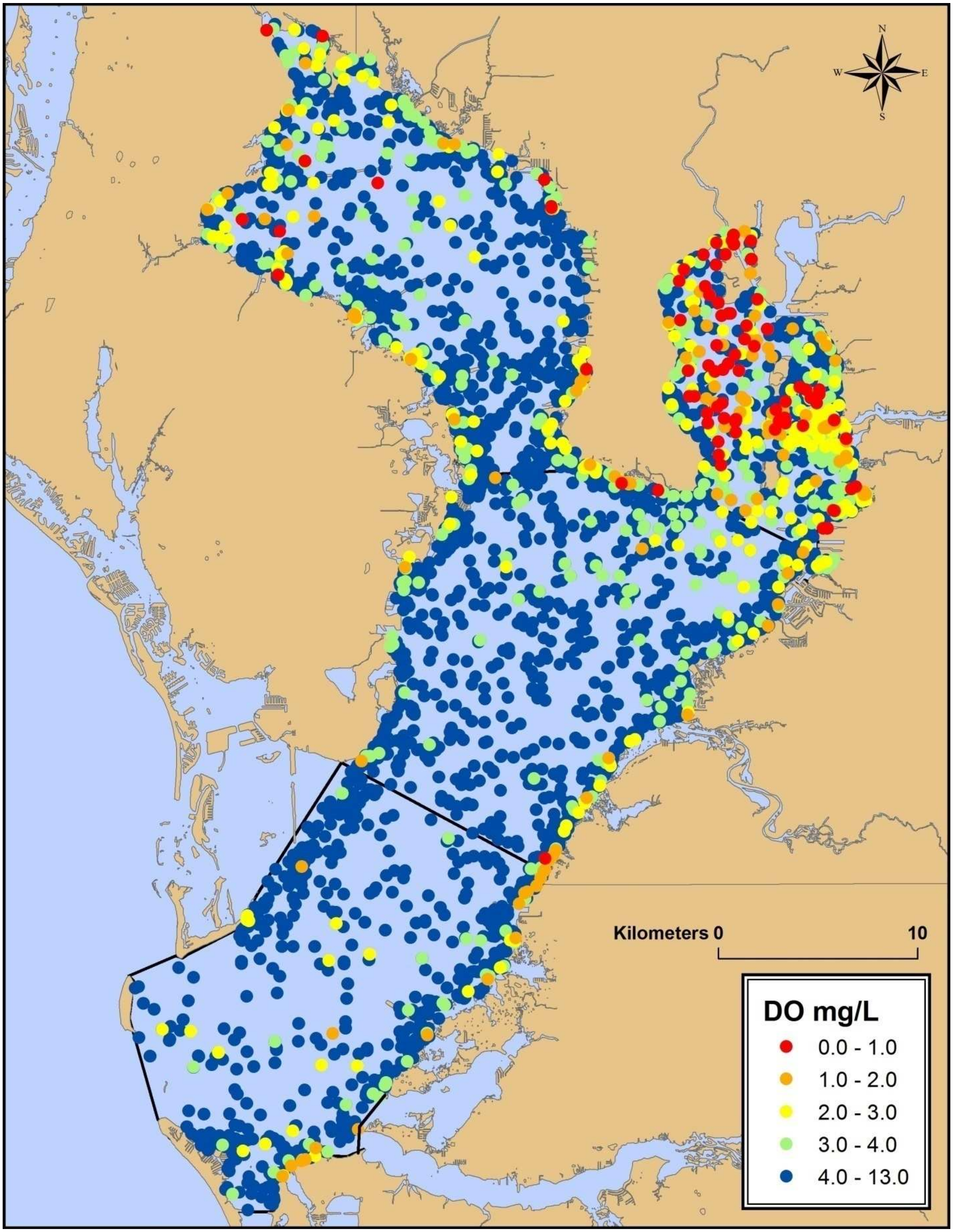

Figure 14. Spatial distribution of DO showing spatial susceptibility during summer months (July-August) by highlighting the lowest DO value recorded in a particular area.

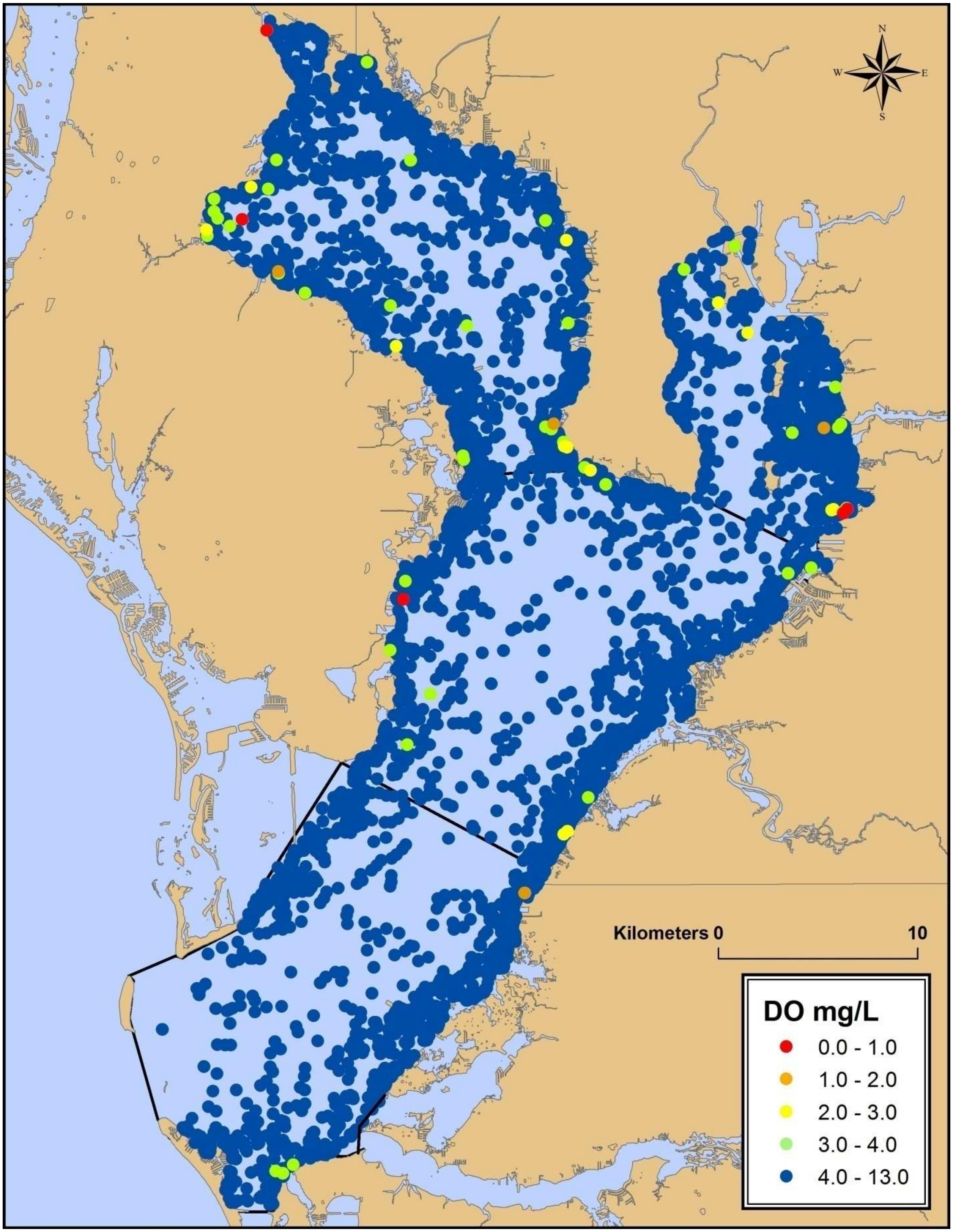

Figure 15. Spatial distribution of DO showing spatial susceptibility during winter months (November-March) by highlighting the lowest DO value recorded in a particular area.

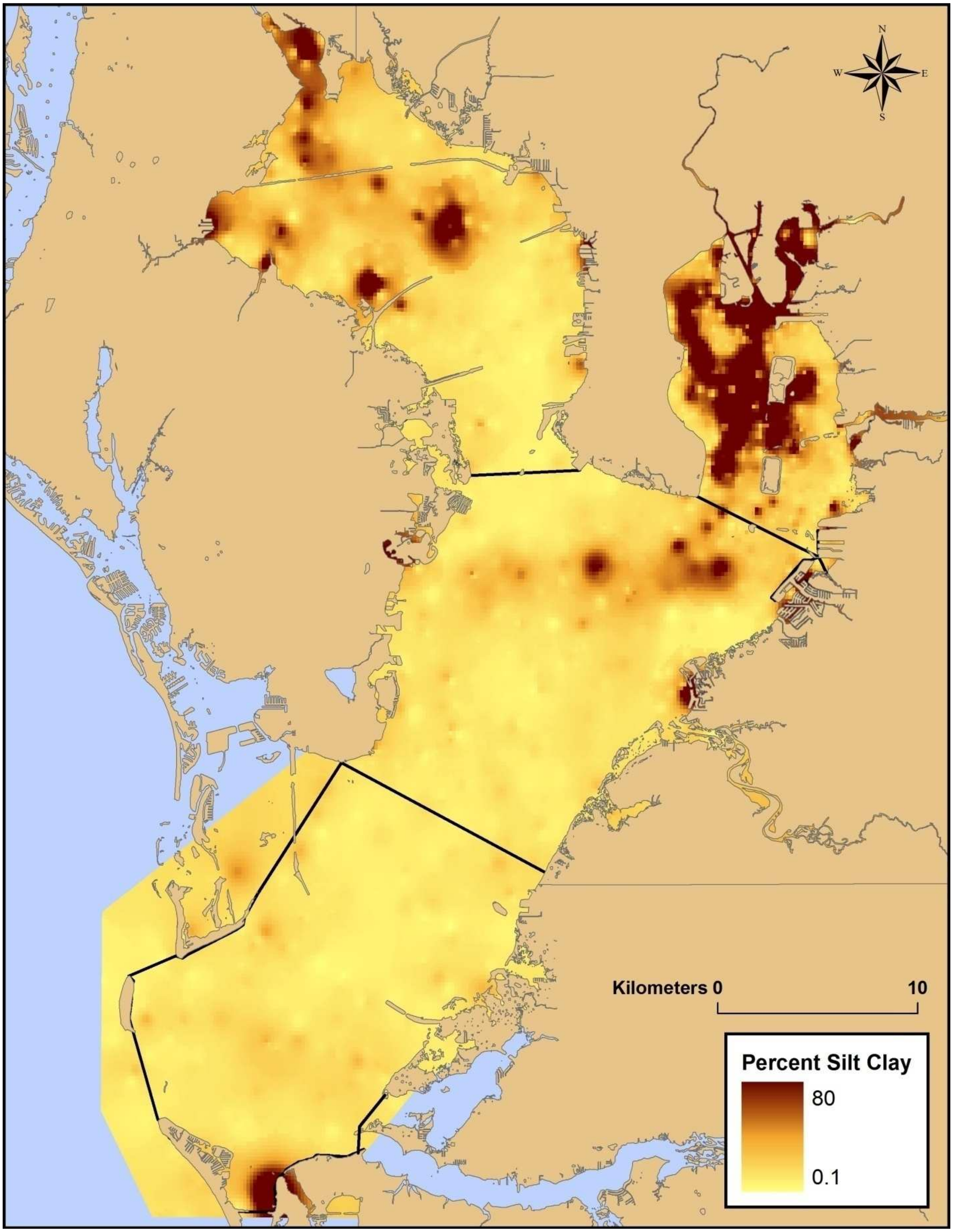

Figure 16. Contour plot of silt-clay content from data collected by the EPC benthic program.

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.

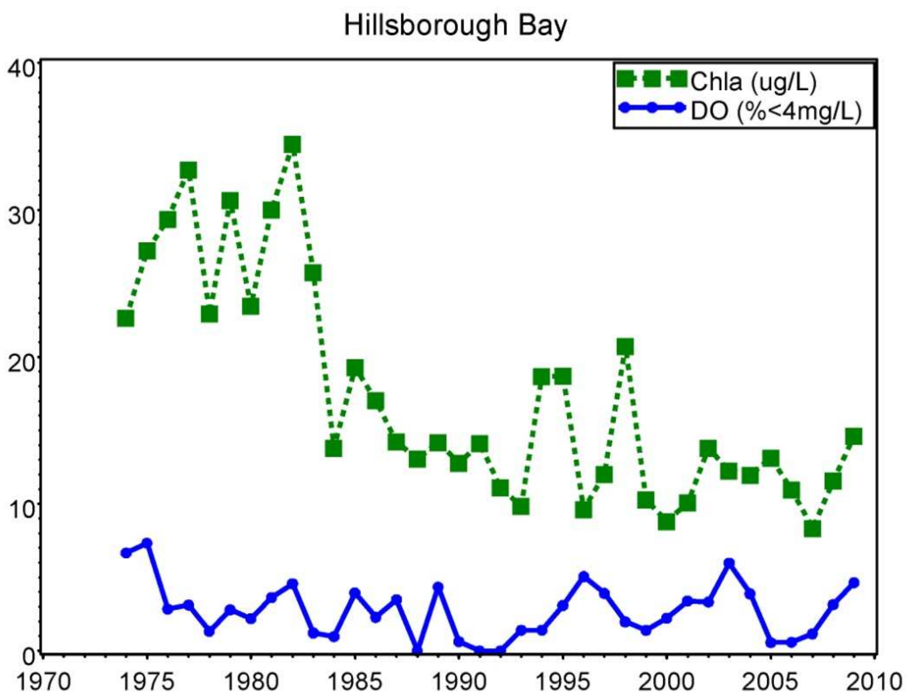

Figure 17. Time series of annual segment average chlorophyll *a* concentrations (µg/l) (broken green line) and annual segment percentage of DO values below 4 (mg/L) (solid blue line) in Hillsborough Bay between 1974 and 2009, as collected at EPCHC fixed stations.

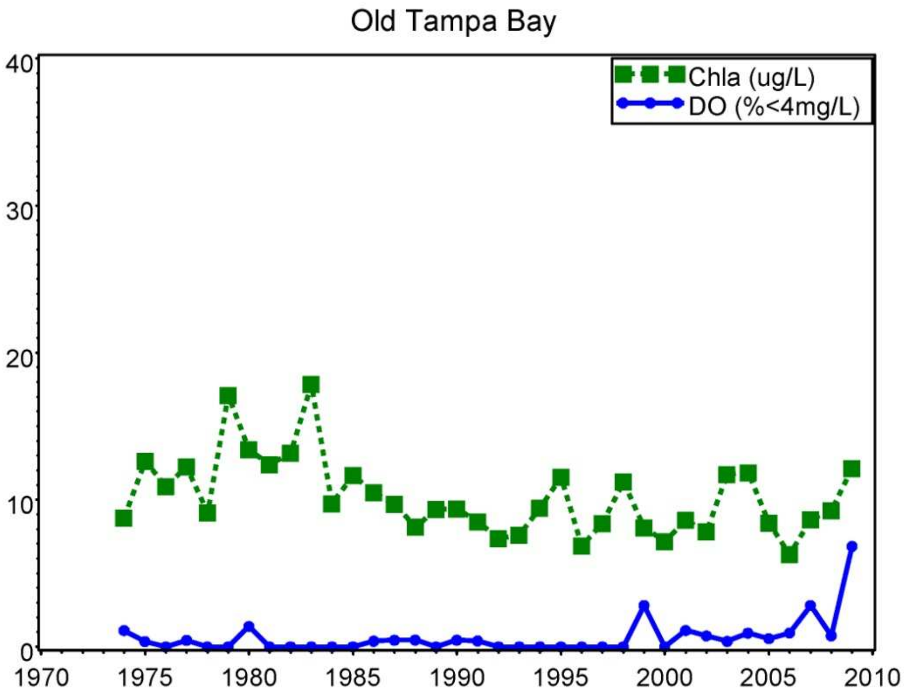

Figure 18. Time series of annual segment average chlorophyll *a* concentrations (μg/l) (broken green line) and annual segment percentage of DO values below 4 (mg/L) (solid blue line) in Old Tampa Bay between 1974 and 2009, as collected at EPCHC fixed stations.

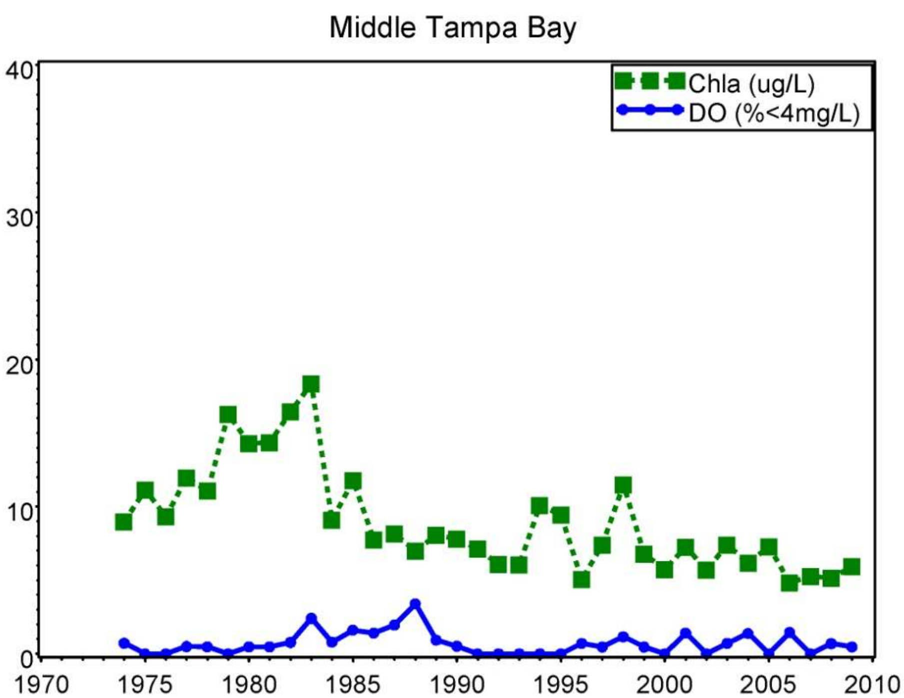

Figure 19. Time series of annual segment average chlorophyll *a* concentrations (μg/l) (broken green line) and annual segment percentage of DO values below 4 (mg/L) (solid blue line) in Middle Tampa Bay between 1974 and 2009, as collected at EPCHC fixed stations.

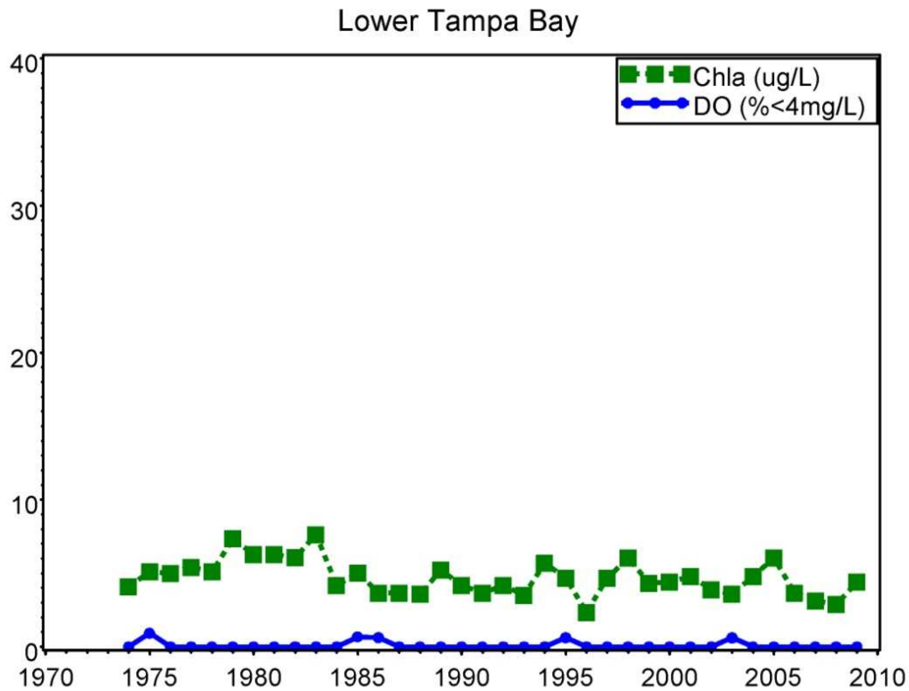

Figure 20. Time series of annual segment average chlorophyll *a* concentrations (μg/l) (broken green line) and annual segment percentage of DO values below 4 (mg/L) (solid blue line) in Lower Tampa Bay between 1974 and 2009, as collected at EPCHC fixed stations.

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.

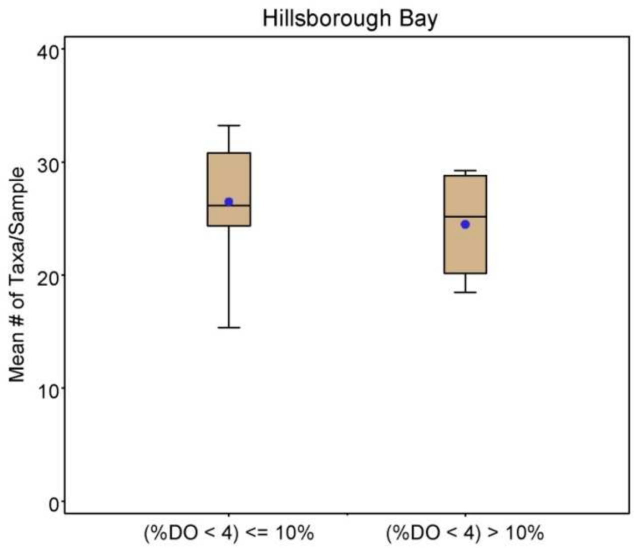

Figure 21. Comparison of the mean number of benthic taxa/sample in Hillsborough Bay for those years in which the percentage of DO samples < 4 mg/L exceeds 10% and those years when the percentage of DO samples < 4 mg/L is less than 10%. The DO classification was based on all available DO data.

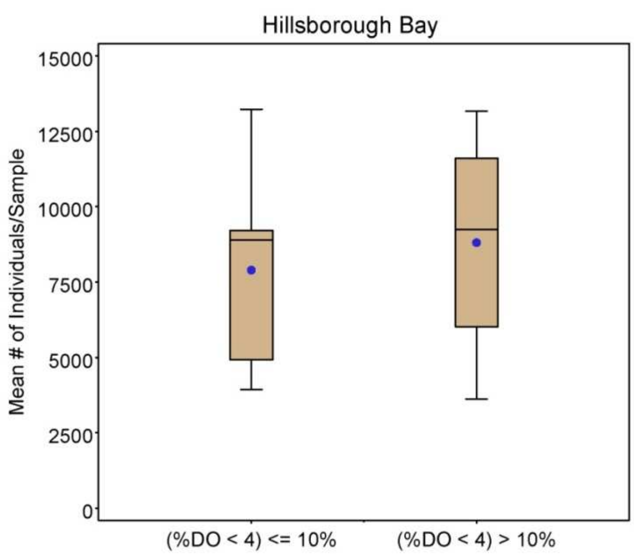

Figure 22. Comparison of the mean number of benthic individuals/sample in Hillsborough Bay for those years in which the percentage of DO samples < 4 mg/L exceeds 10% and those years when the percentage of DO samples < 4 mg/L is less than 10%. The DO classification was based on all available DO data.

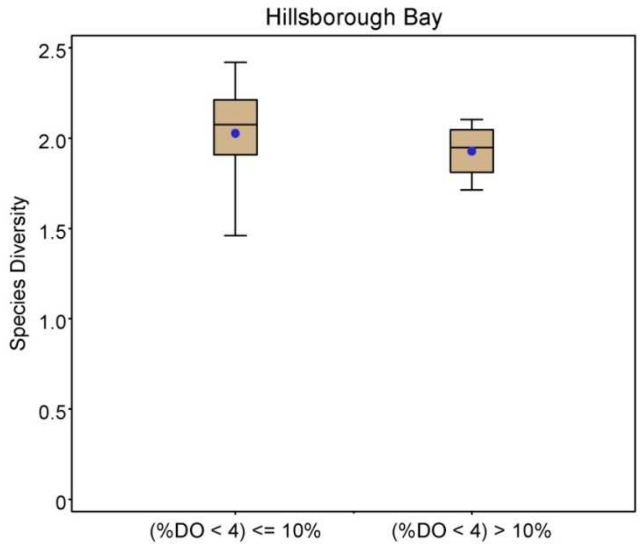

Figure 23. Comparison of the mean benthic species diversity/sample in Hillsborough Bay for those years in which the percentage of DO samples < 4 mg/L exceeds 10% and those years when the percentage of DO samples < 4 mg/L is less than 10%. The DO classification was based on all available DO data.

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%.

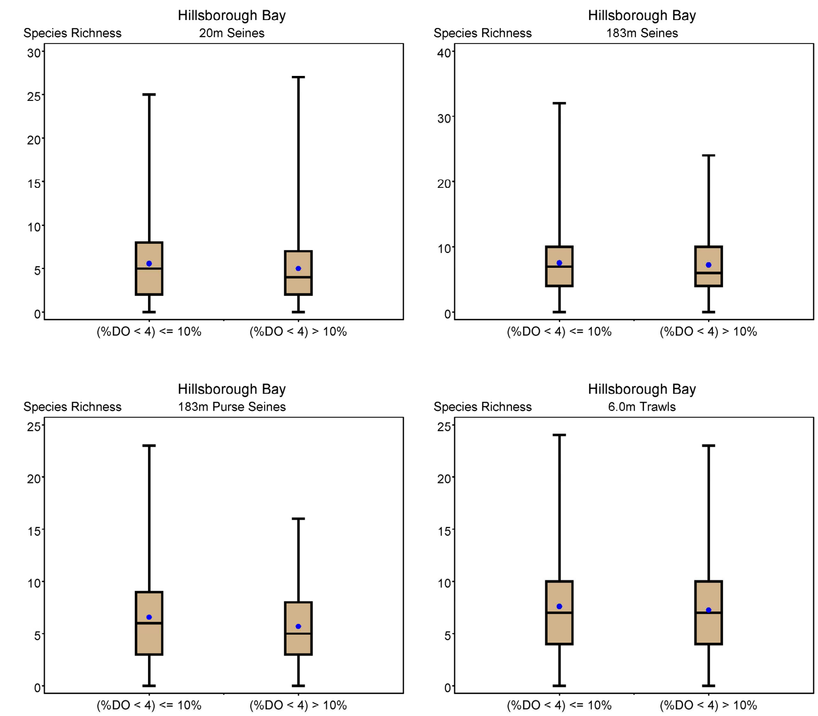

Figure 24. Comparison of the mean fish species richness in Hillsborough Bay for those years in which the percentage of DO samples < 4 mg/L exceeds 10% and those years when the percentage of DO samples < 4 mg/L is less than 10%. DO data are from samples taken concurrently with fish collections.

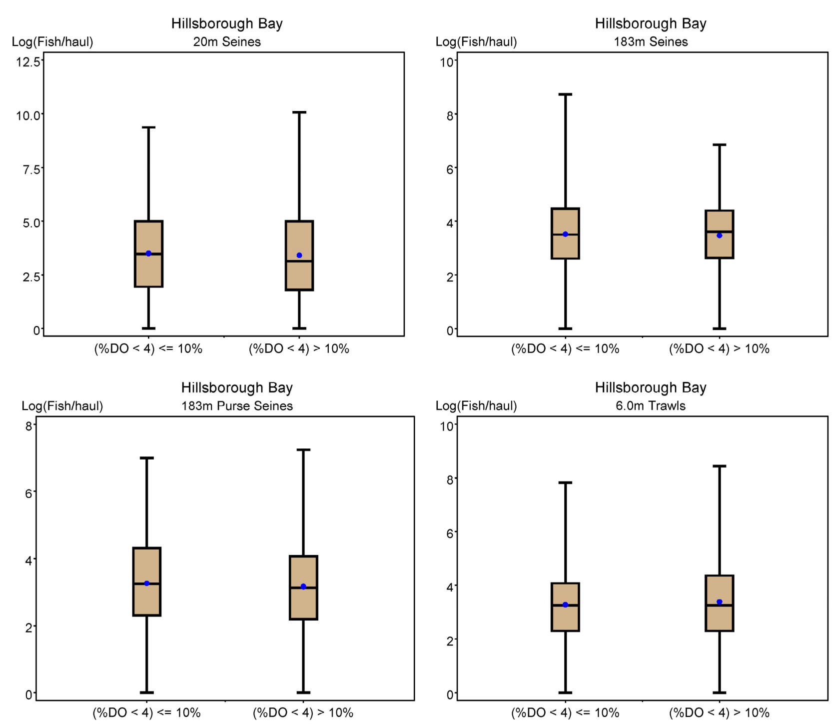

Figure 25. Comparison of the mean number of fish/haul in Hillsborough Bay for those years in which the percentage of DO samples < 4 mg/L exceeds 10% and those years when the percentage of DO samples < 4 mg/L is less than 10%. DO data are from samples taken concurrently with fish collections.

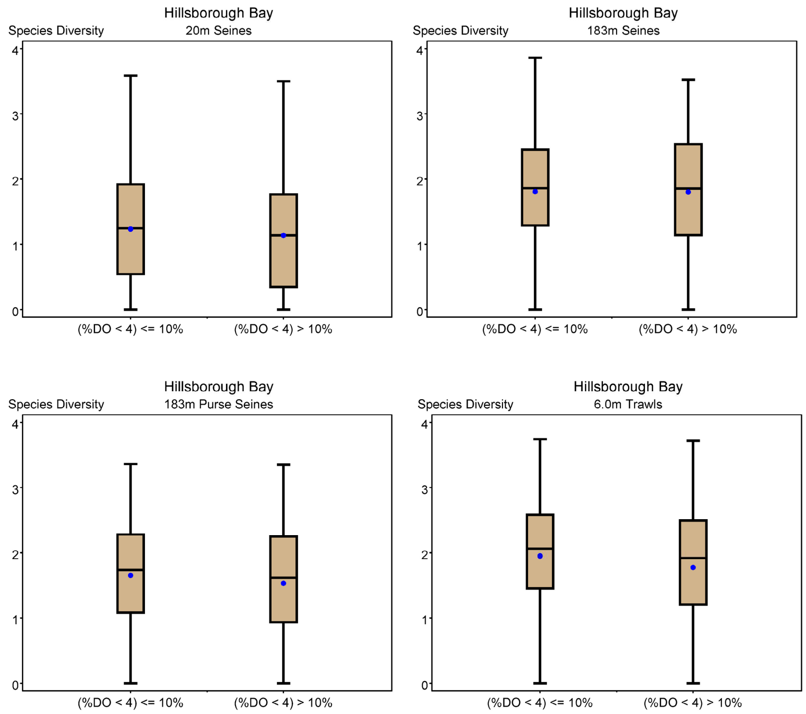

Figure 26. Comparison of the mean fish species diversity in Hillsborough Bay for those years in which the percentage of DO samples < 4 mg/L exceeds 10% and those years when the percentage of DO samples < 4 mg/L is less than 10%. DO data are from samples taken concurrently with fish collections.

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

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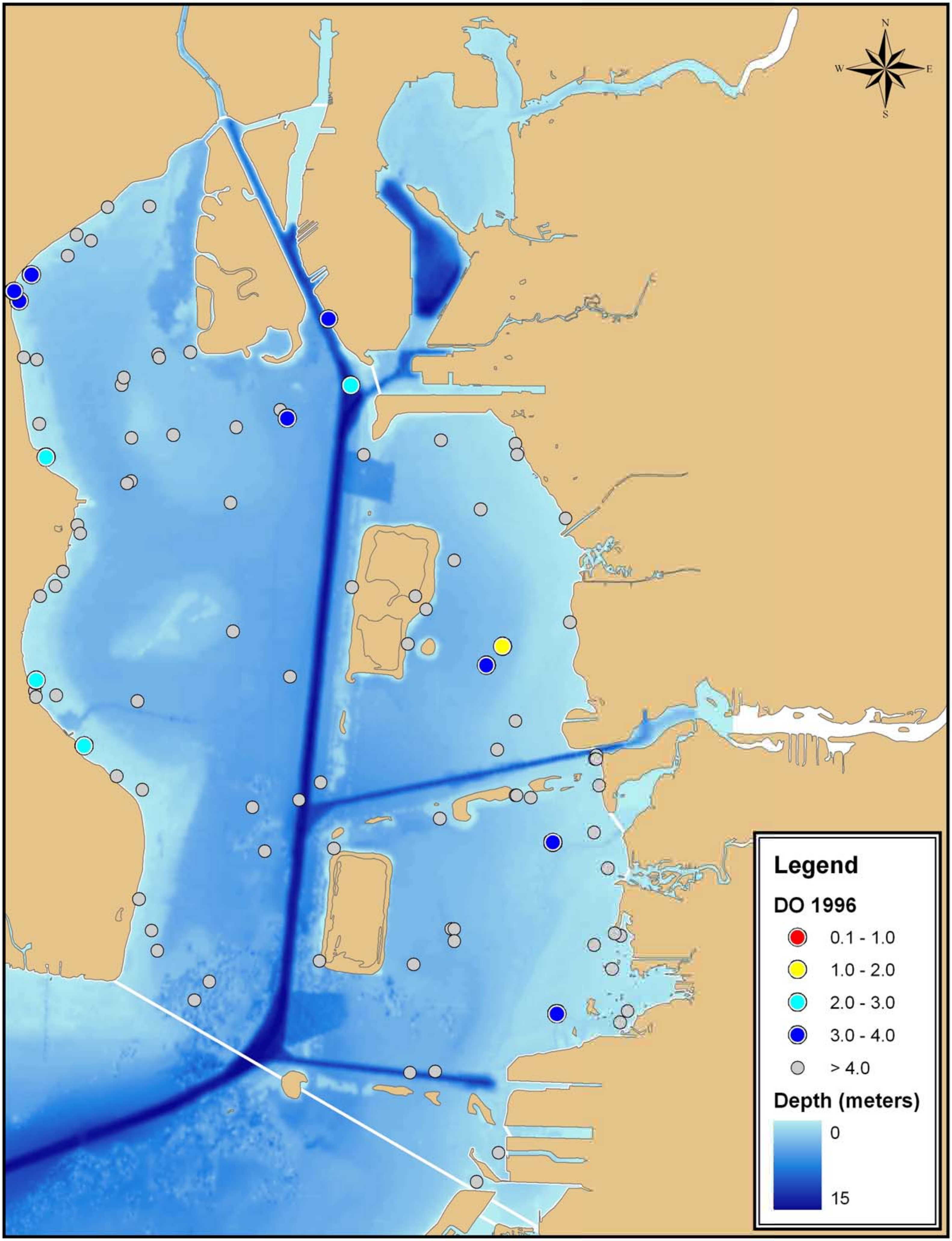
Attachment 1

Annual Spatial Distribution of DO Data for Each Major Bay Segment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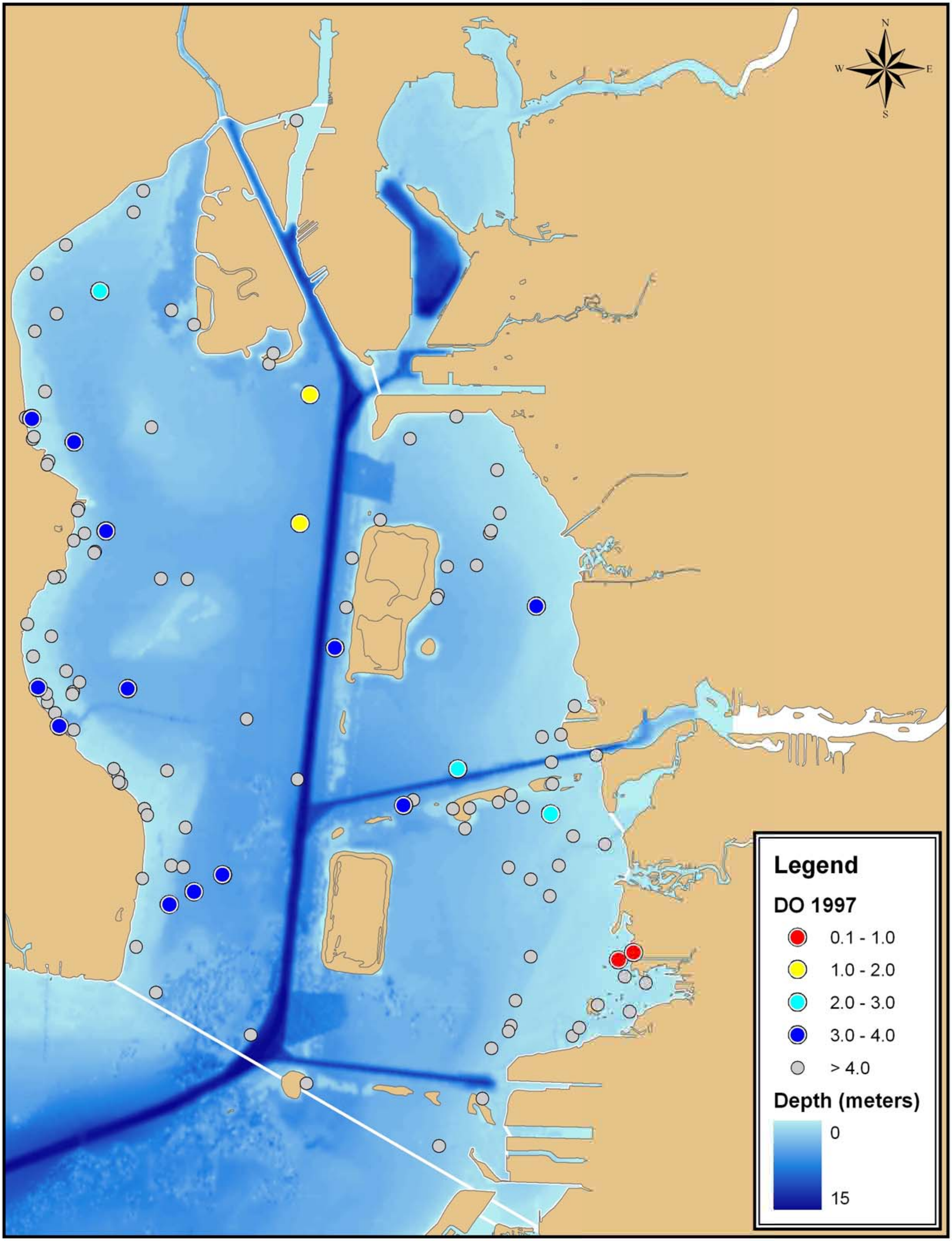
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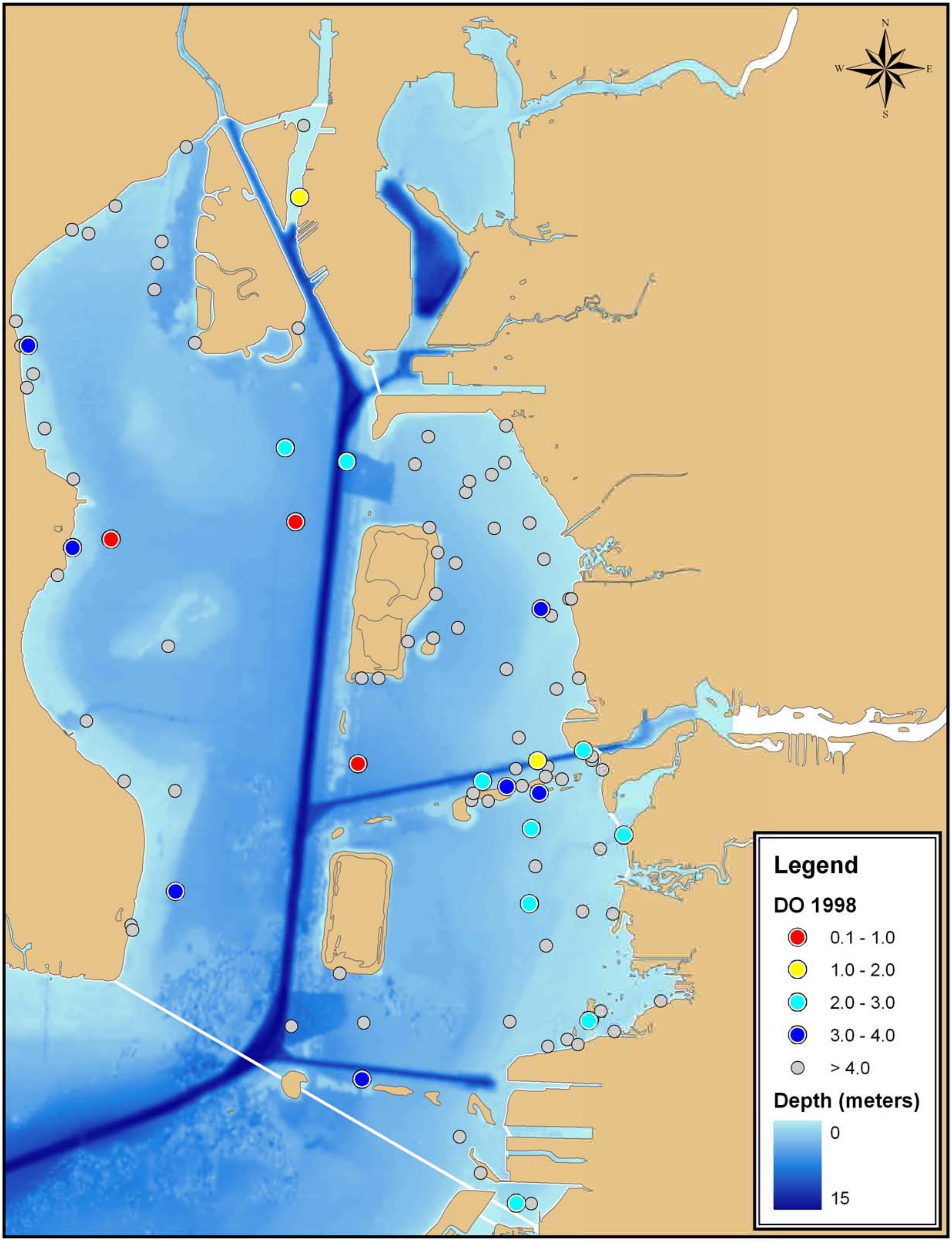

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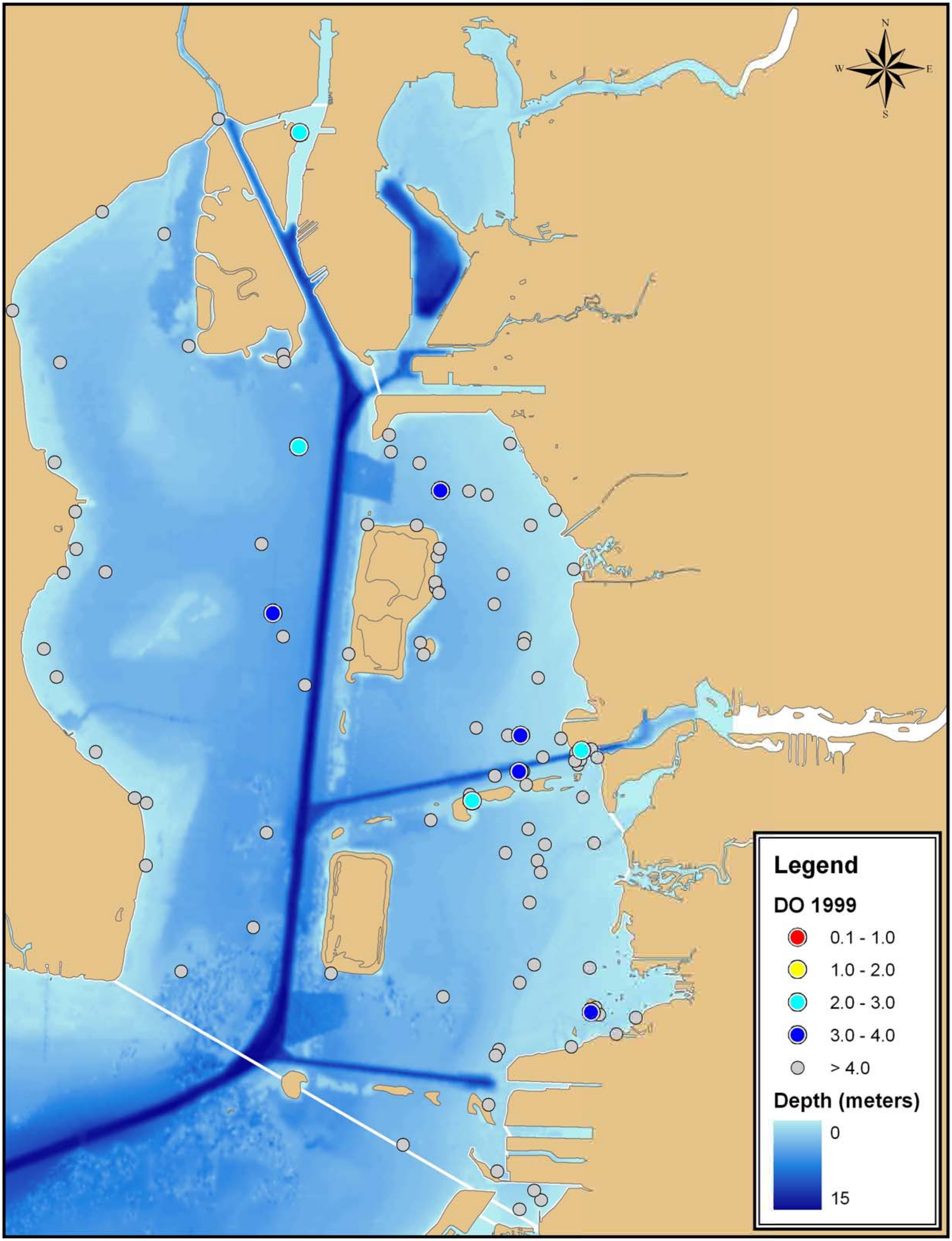
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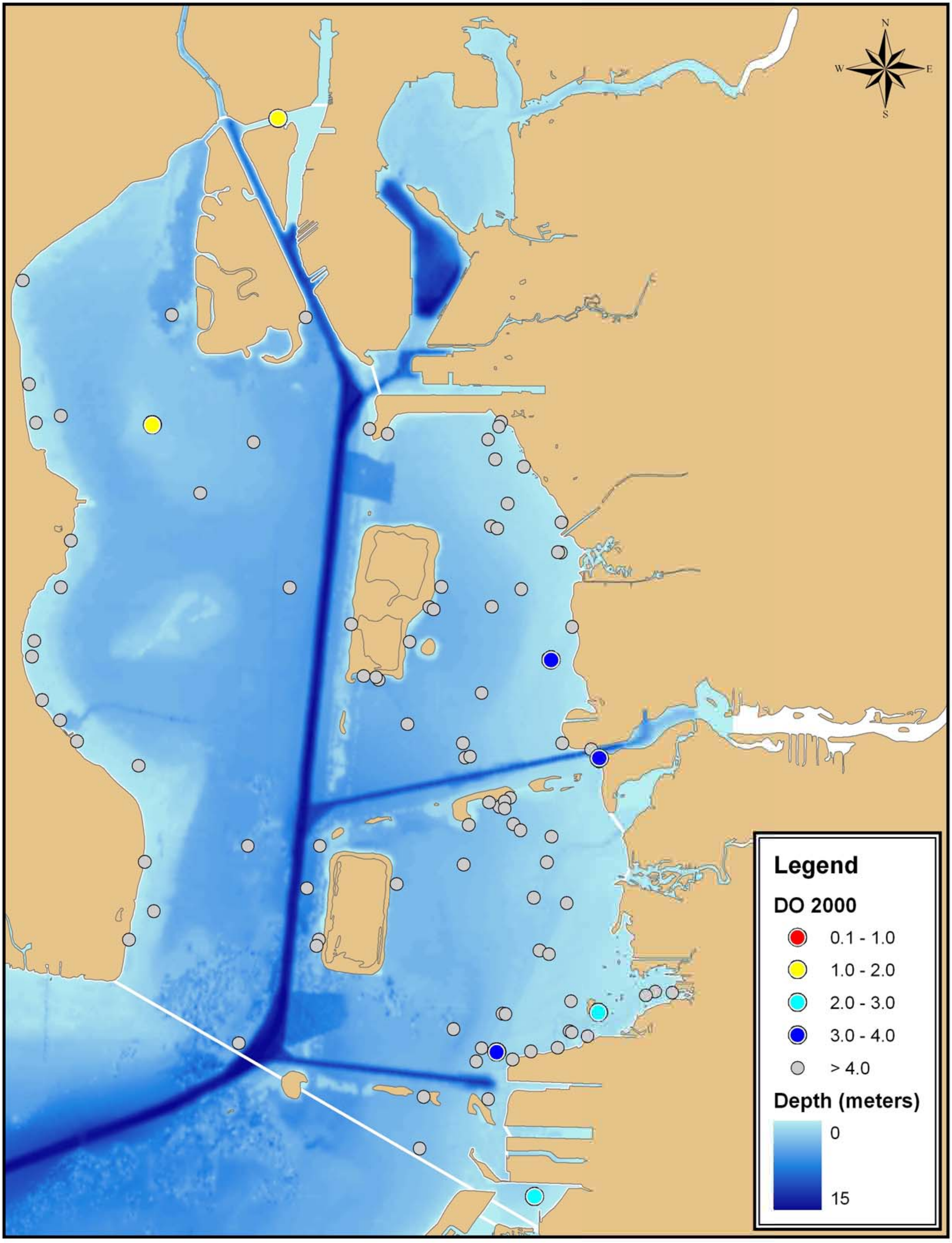
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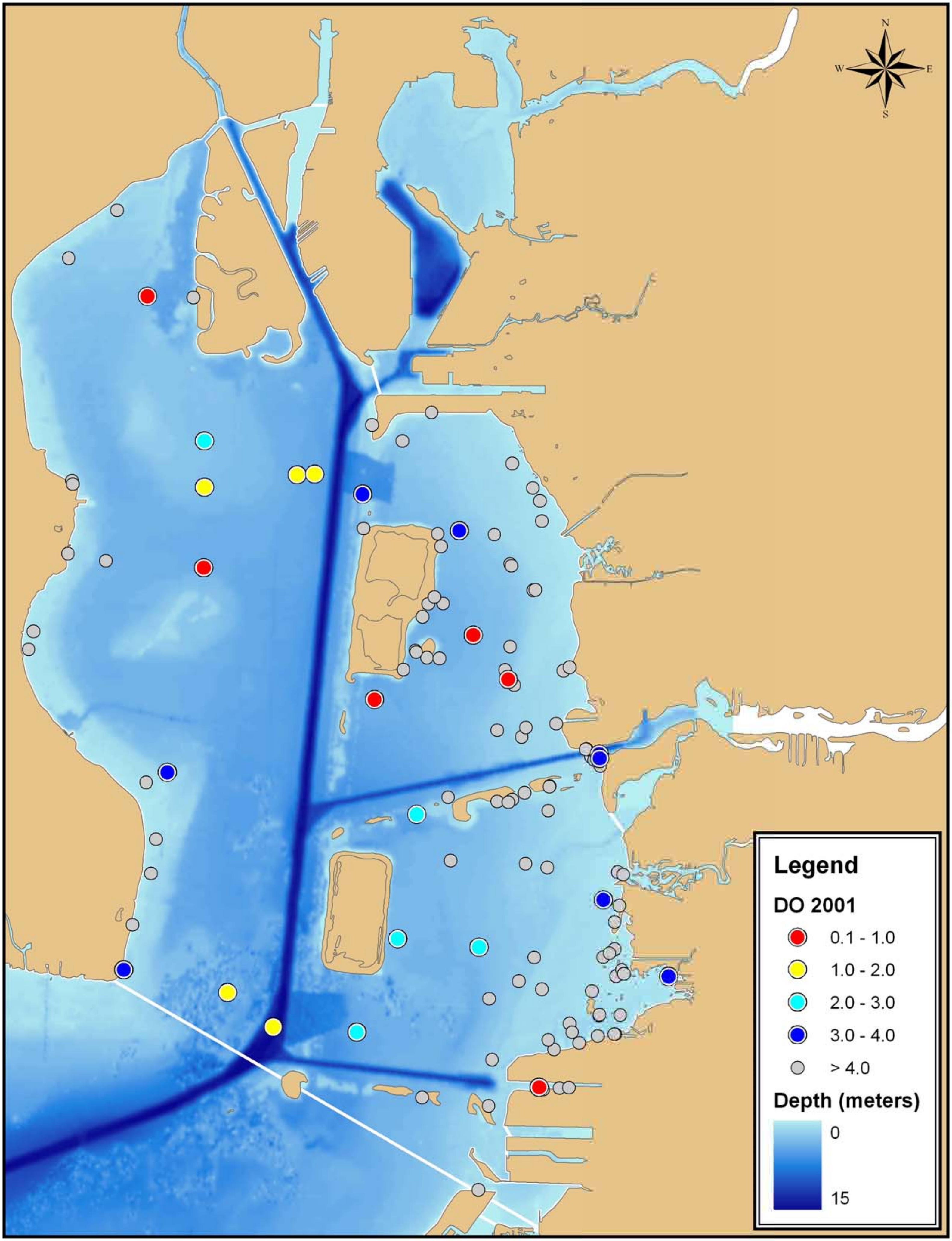
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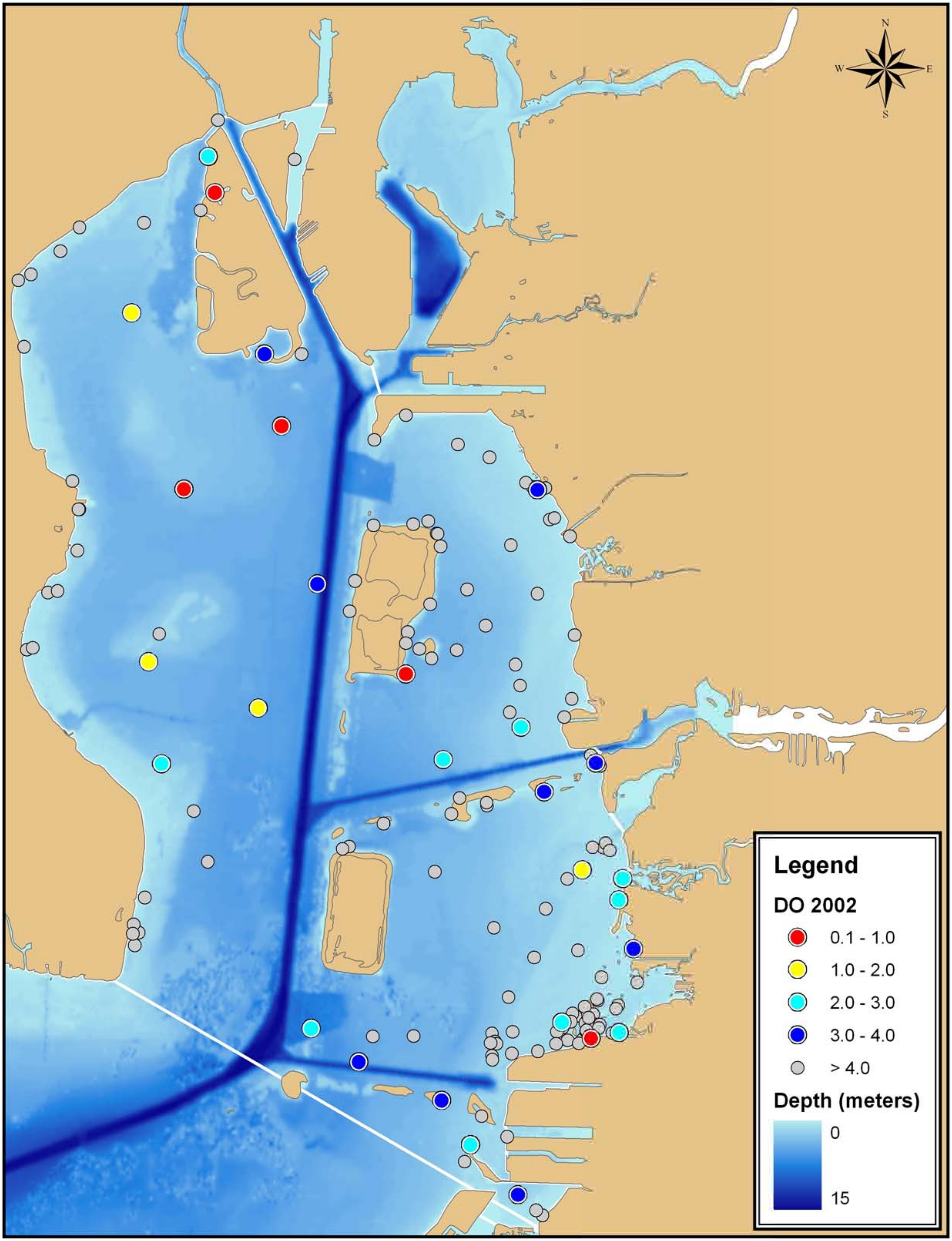
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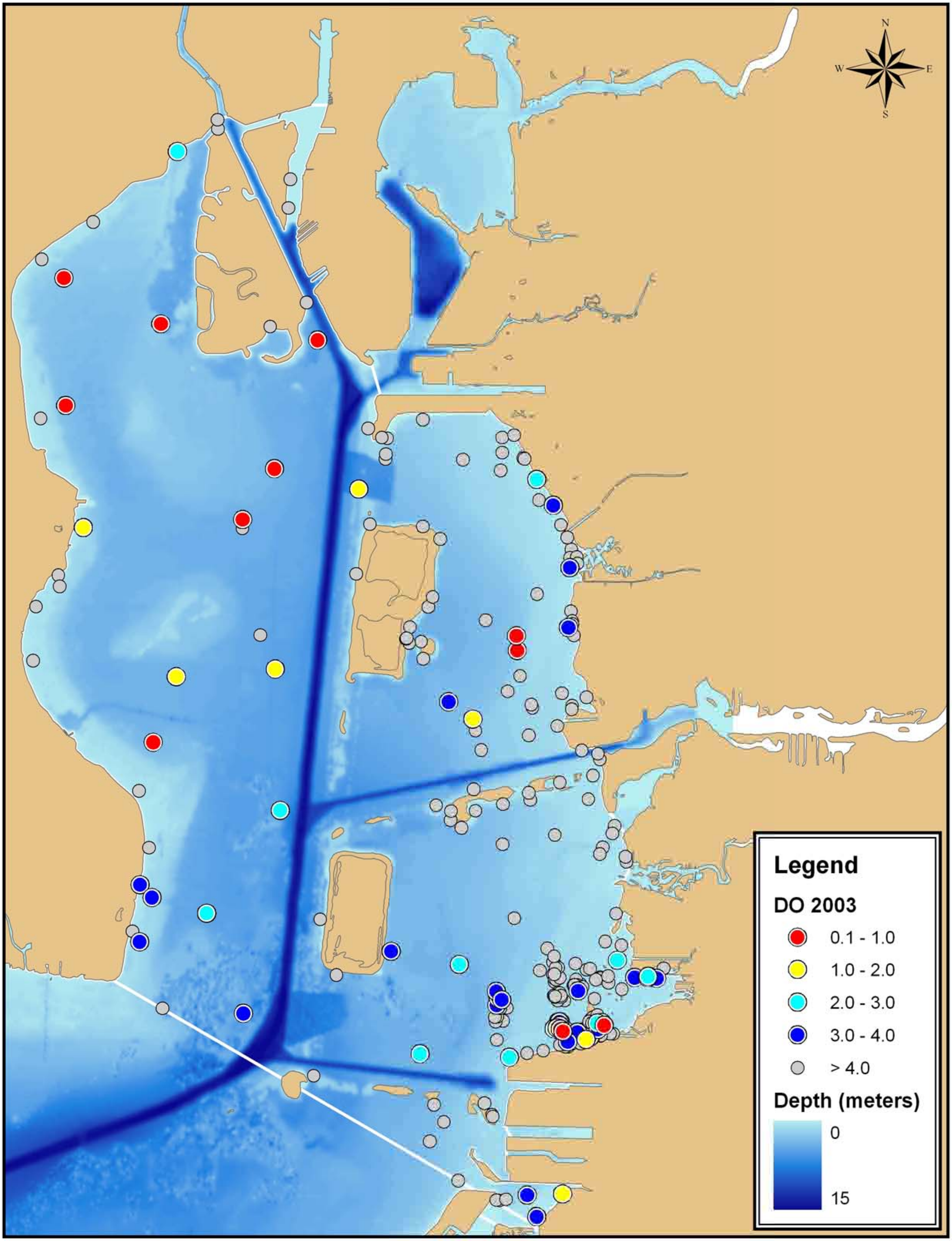

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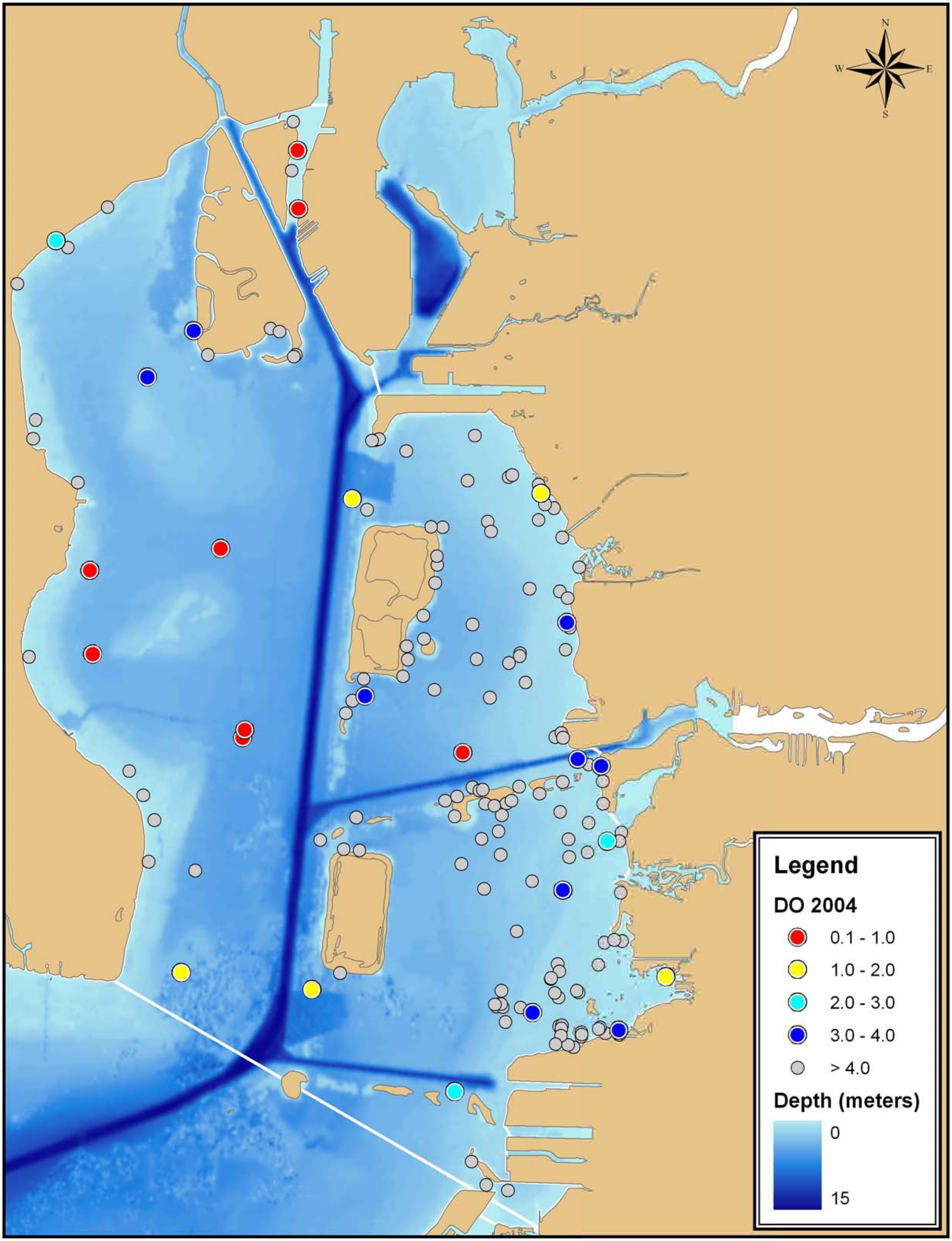

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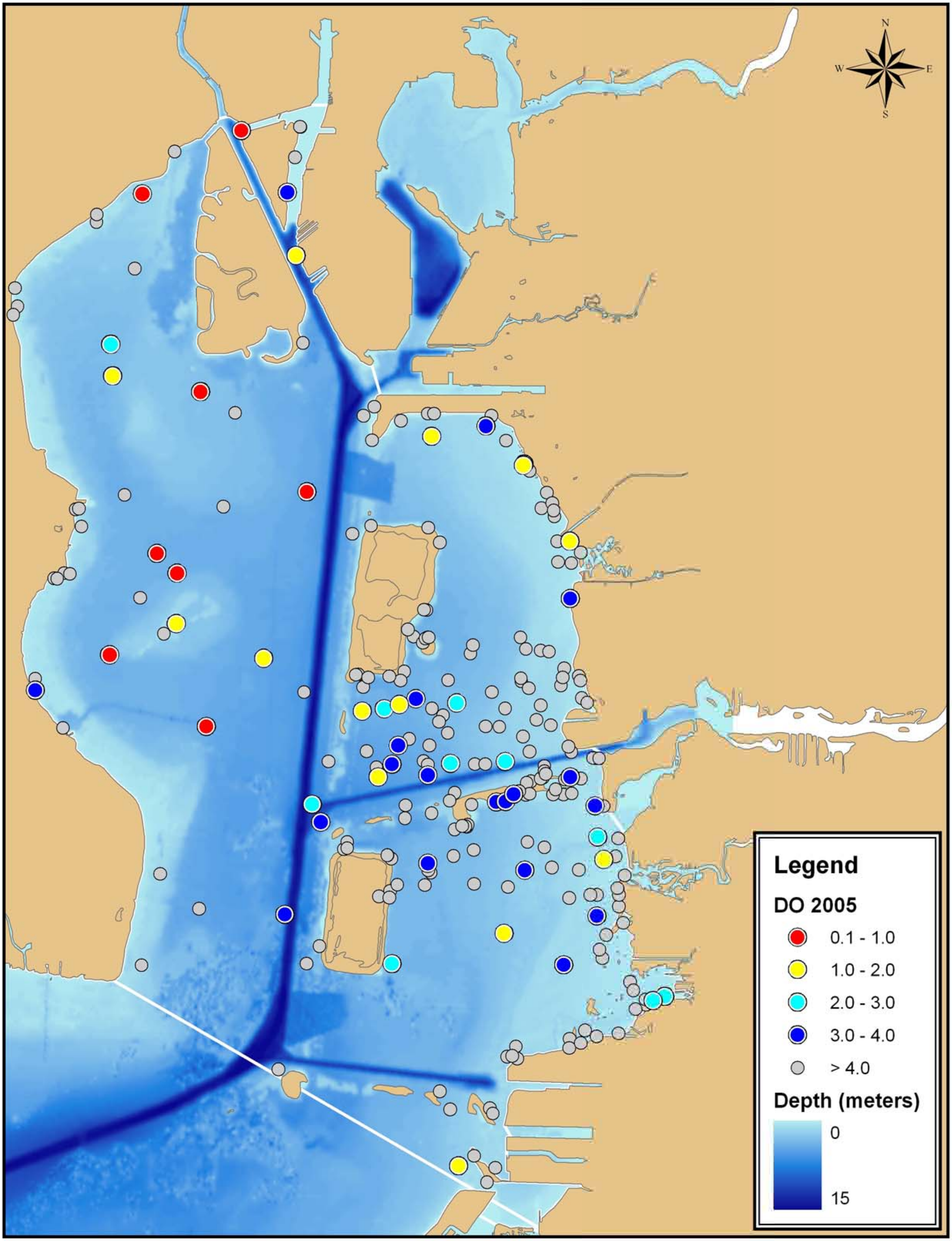
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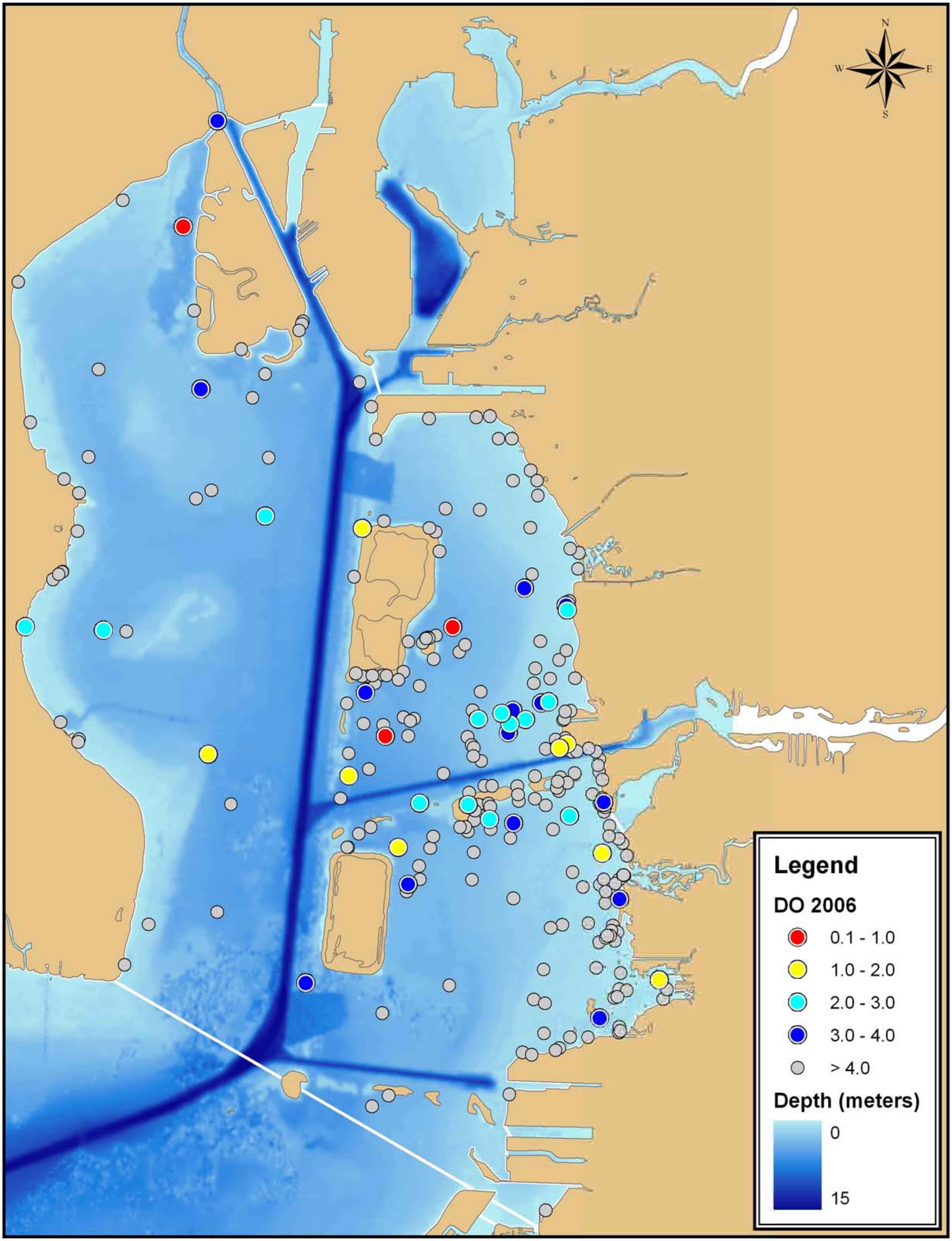

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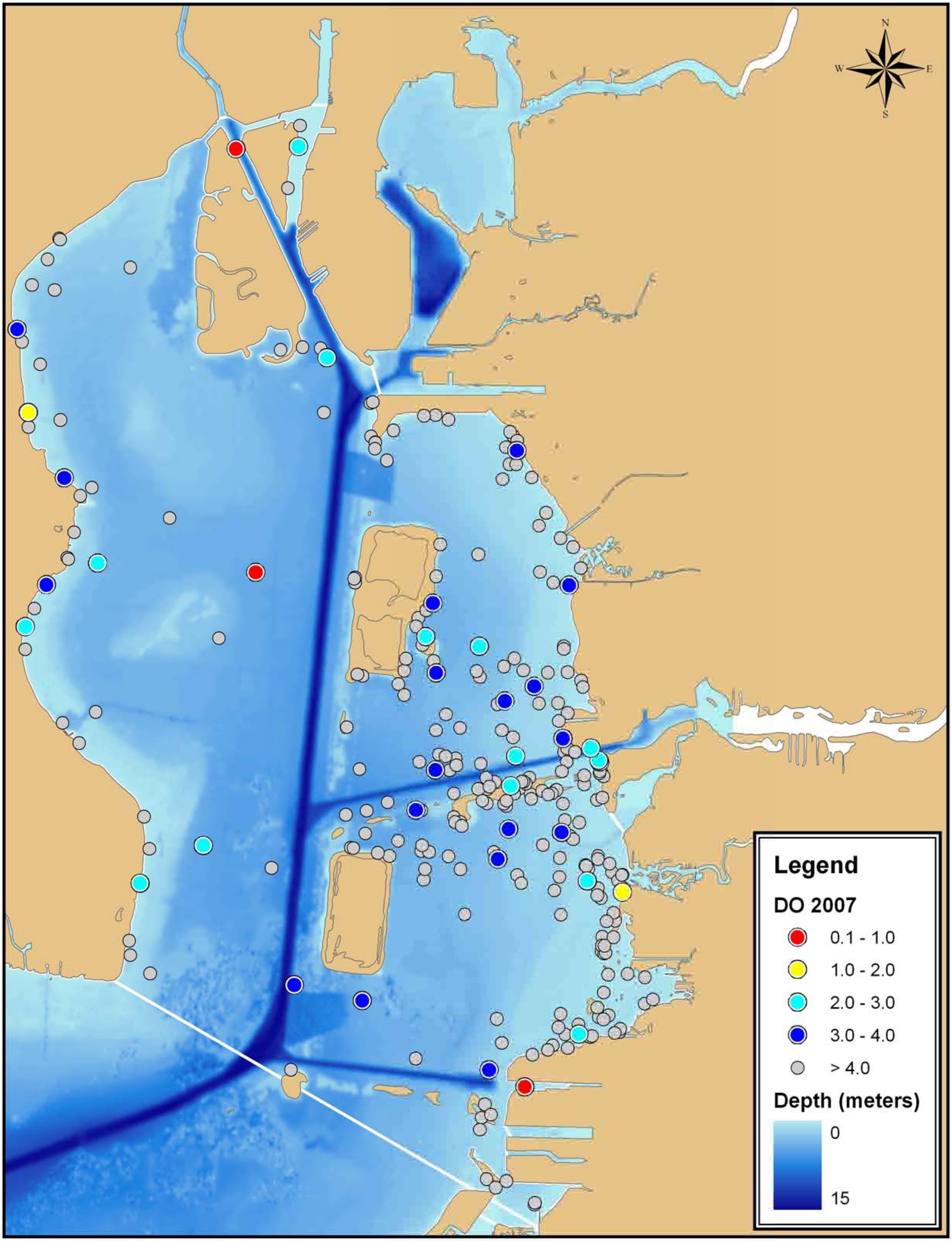
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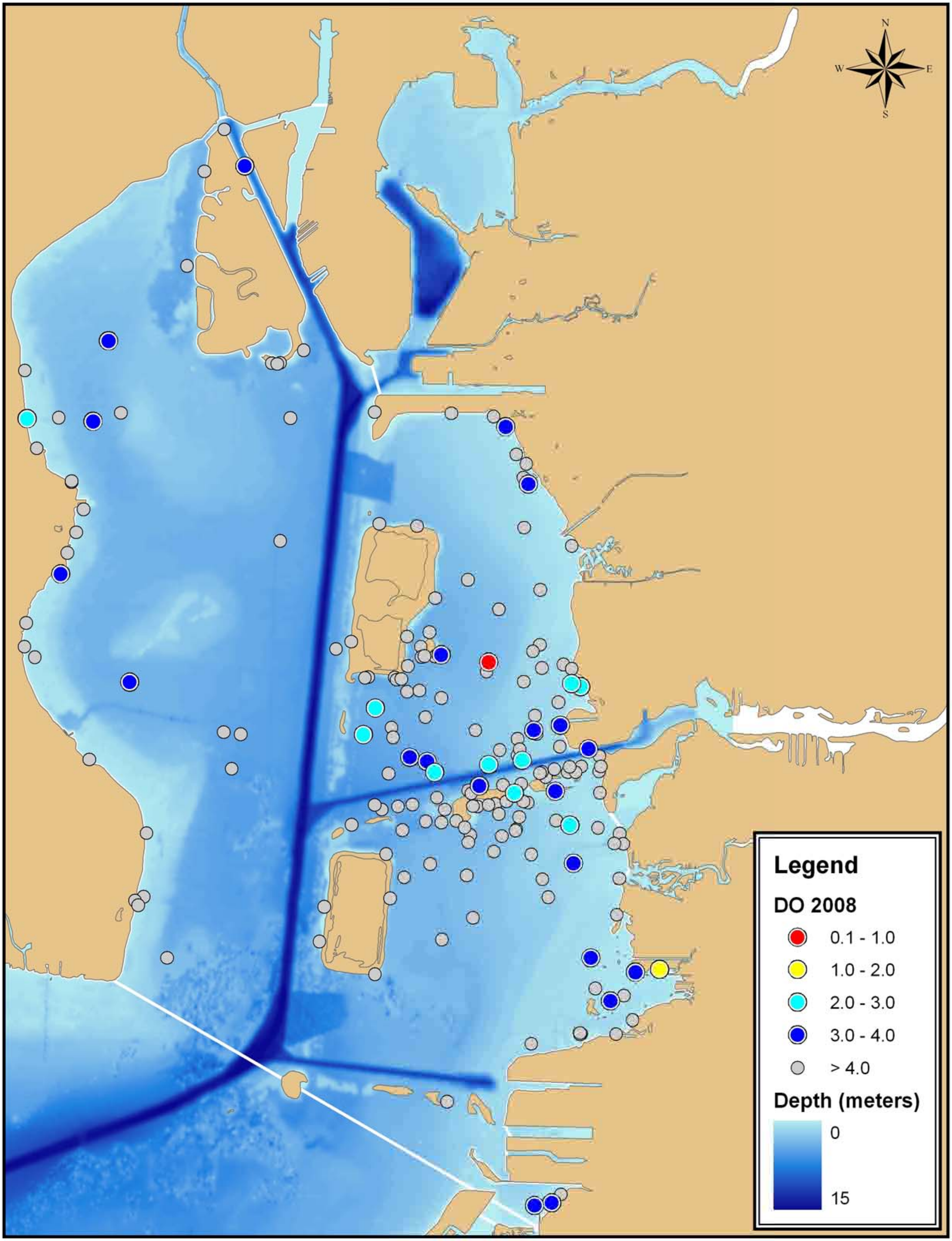
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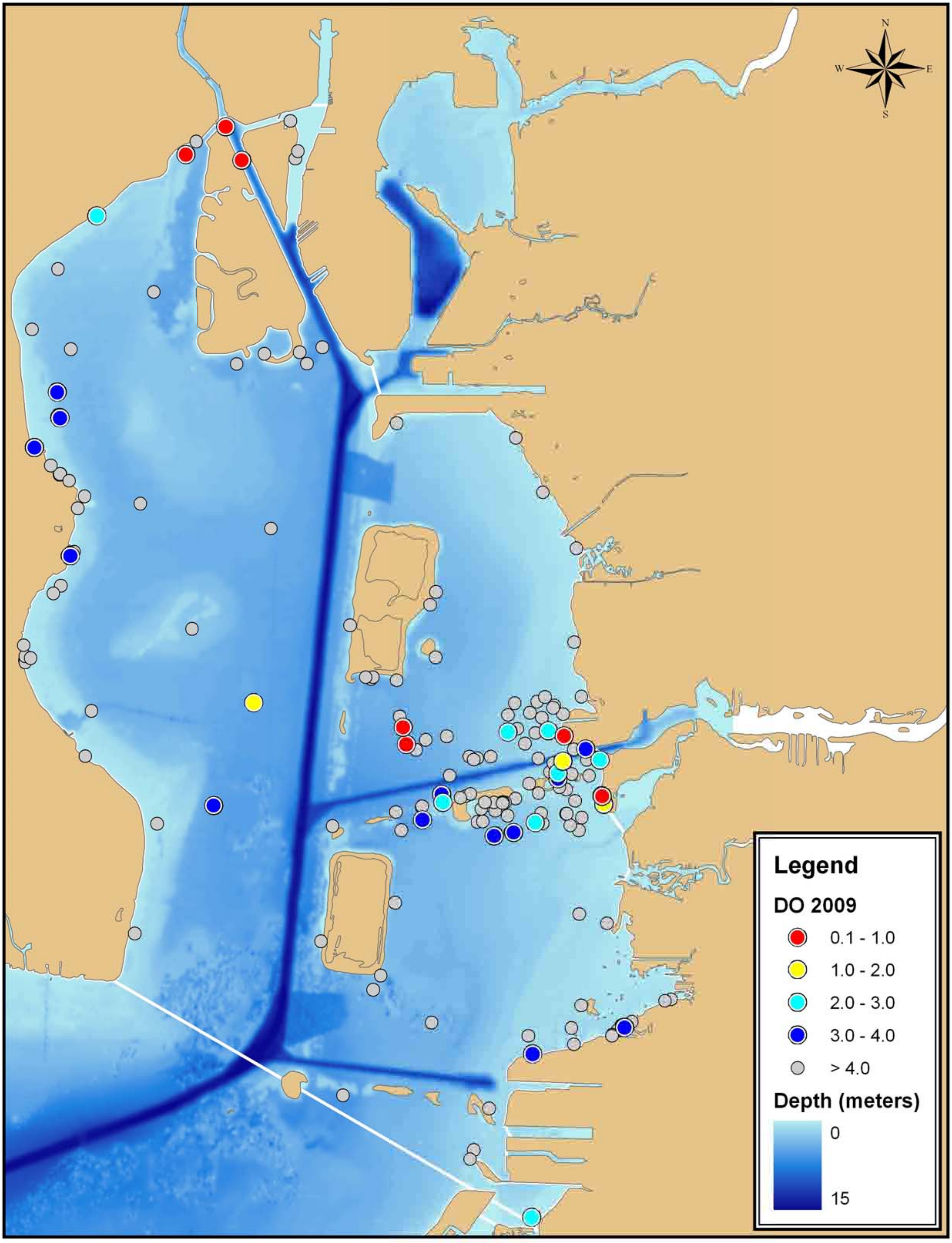

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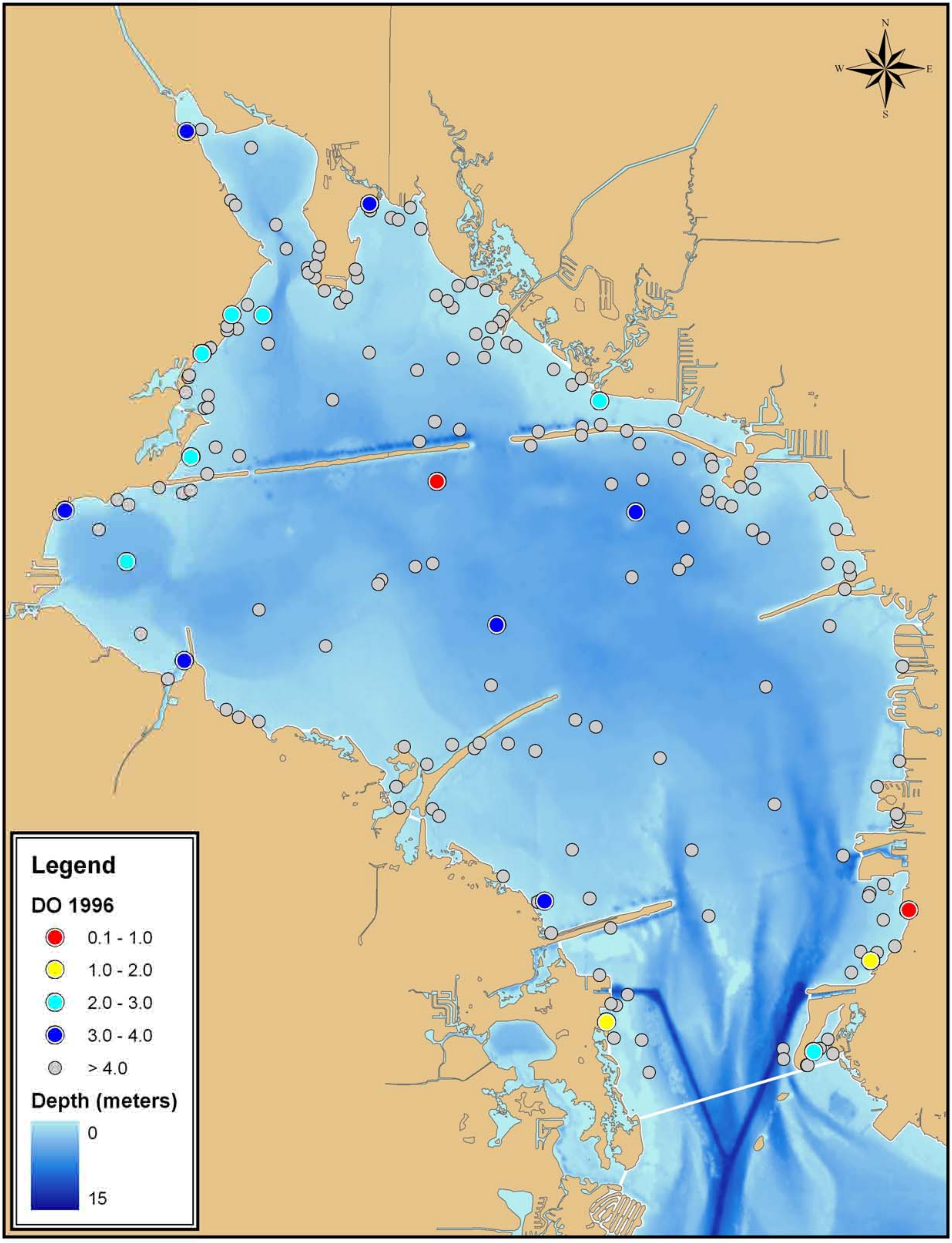
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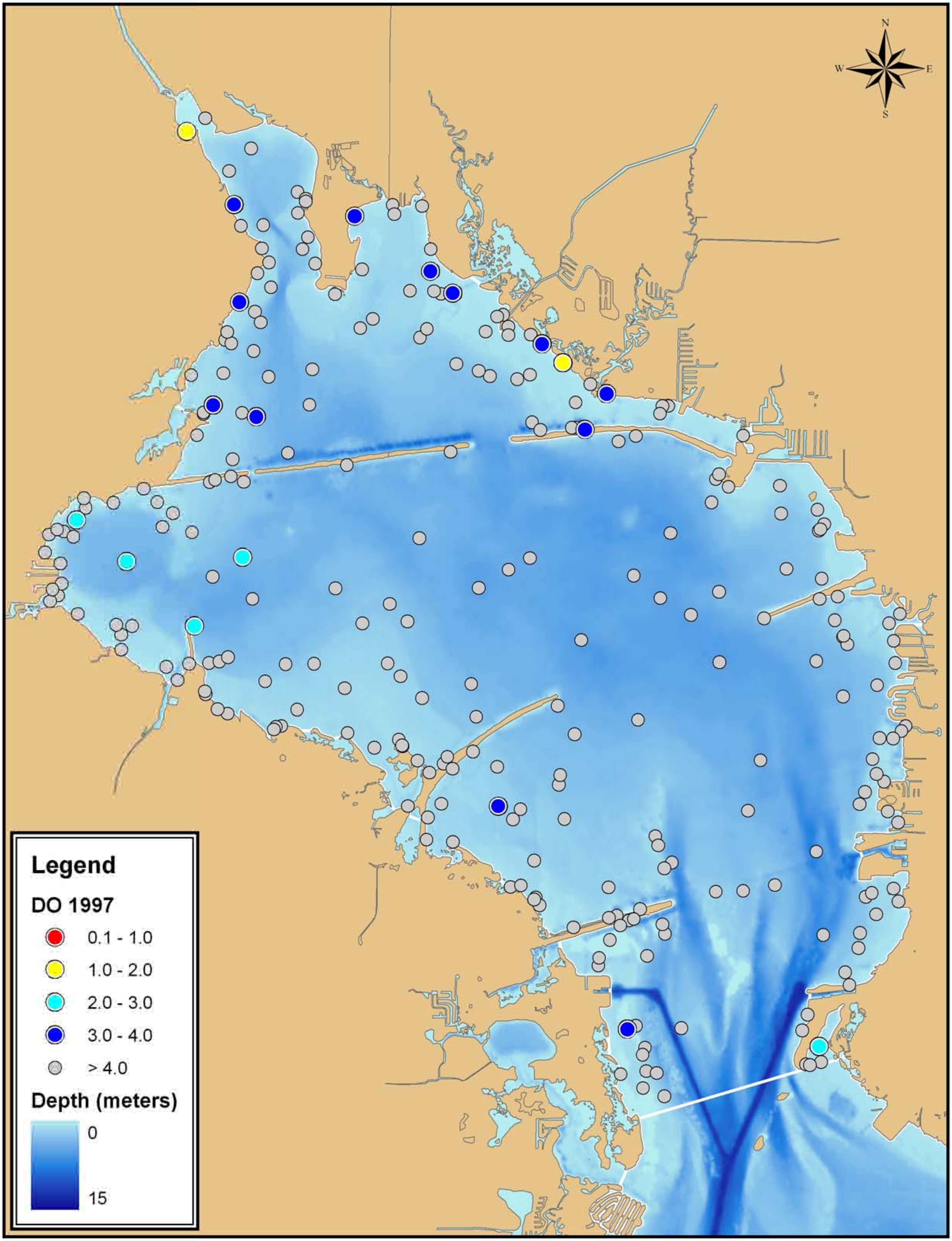

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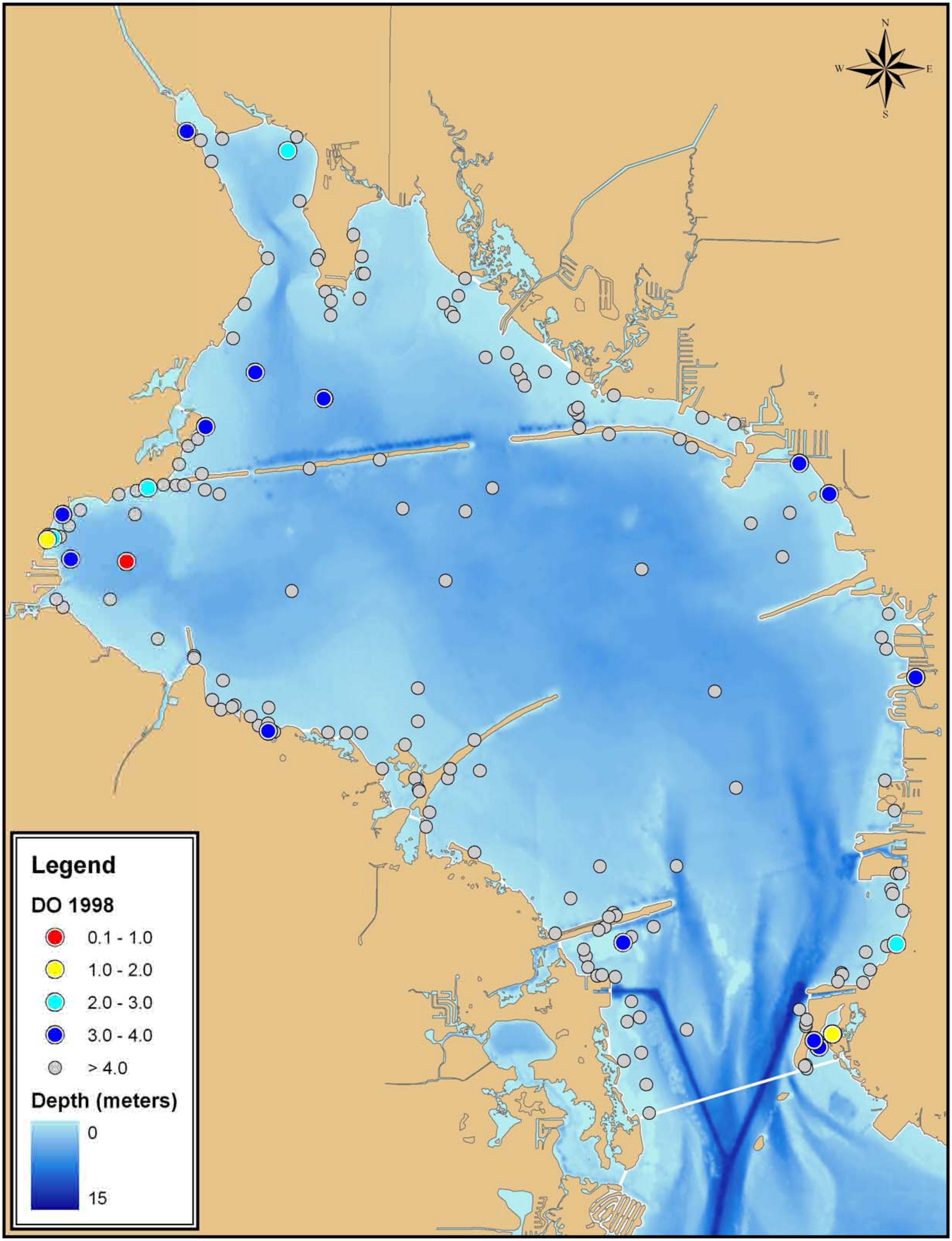
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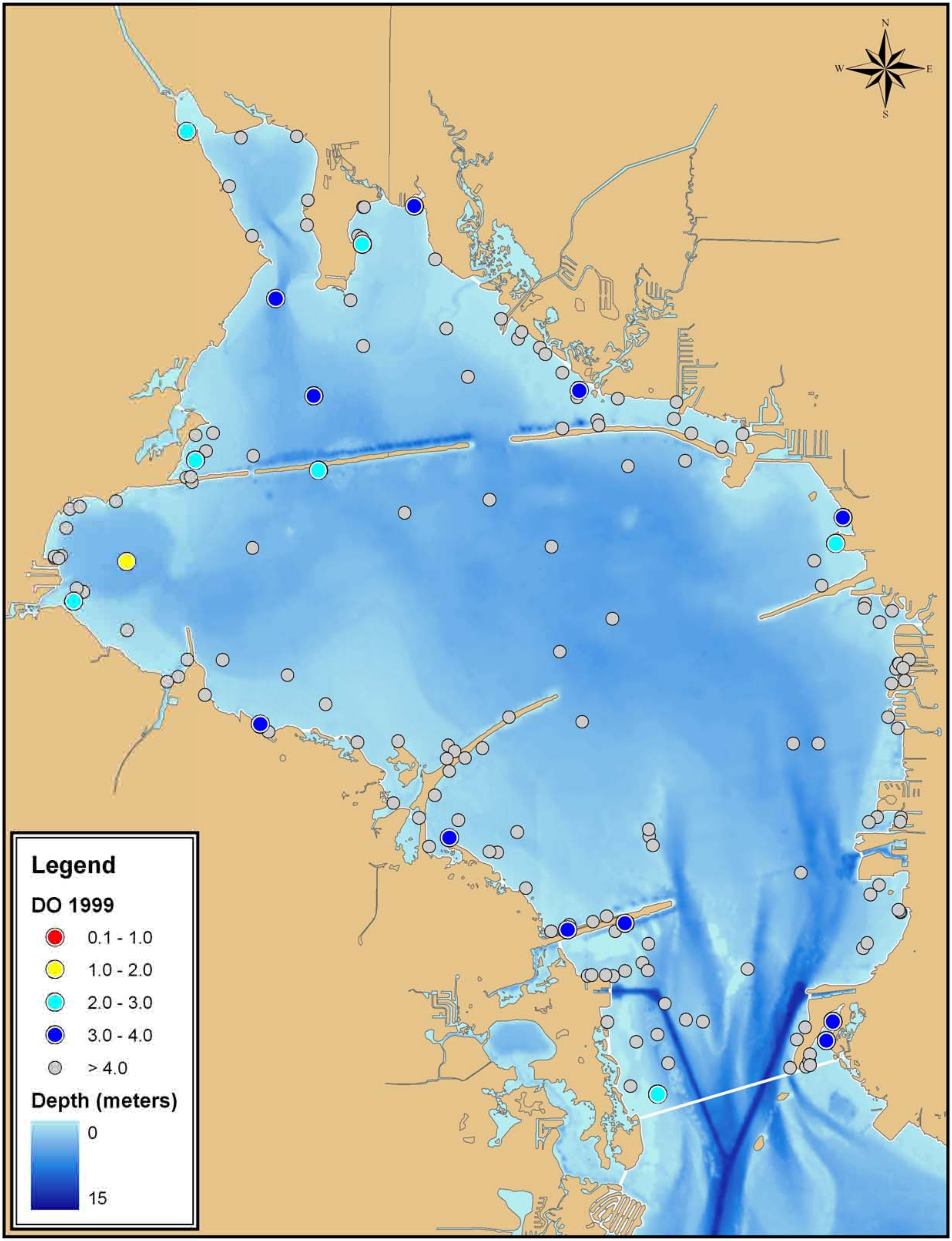
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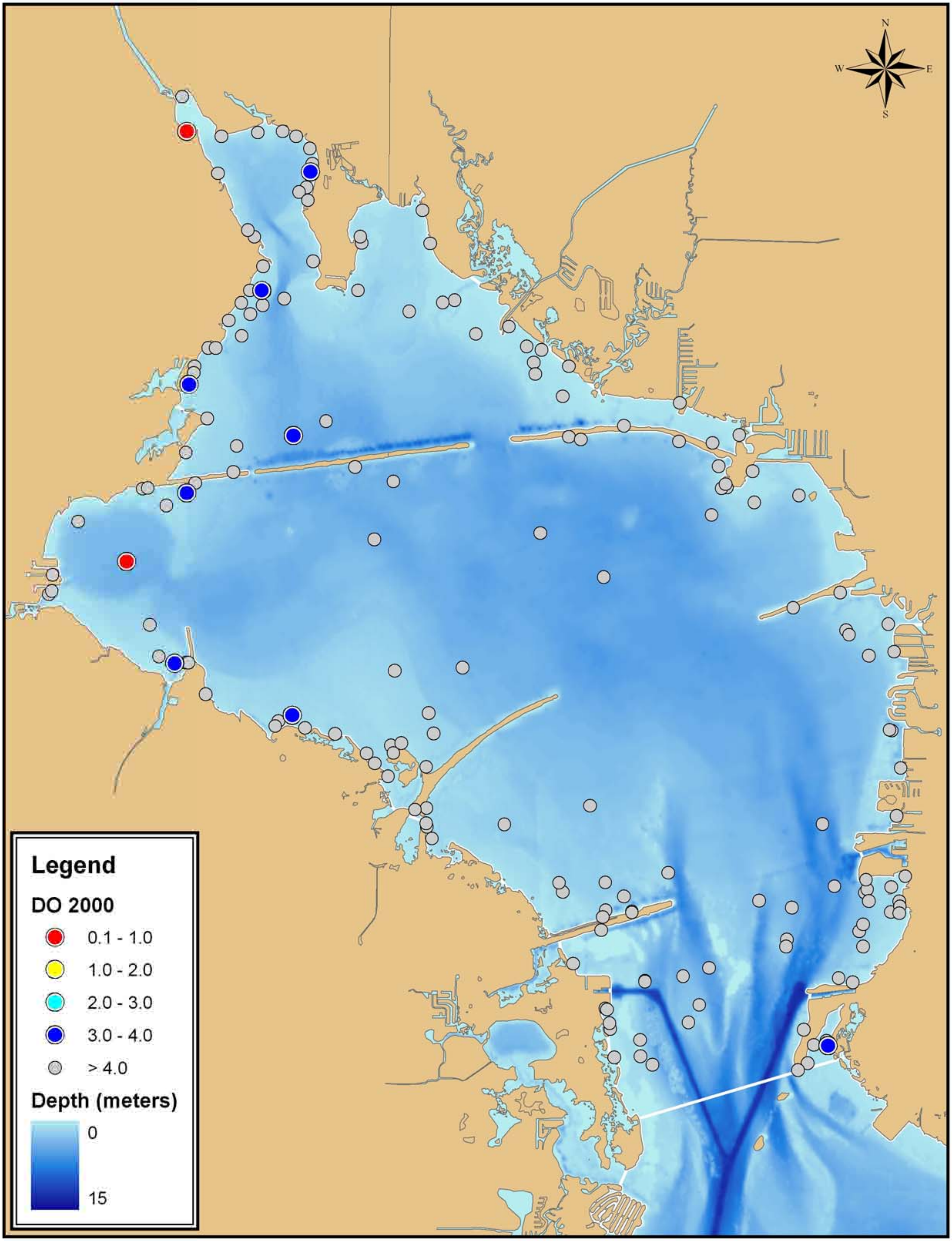
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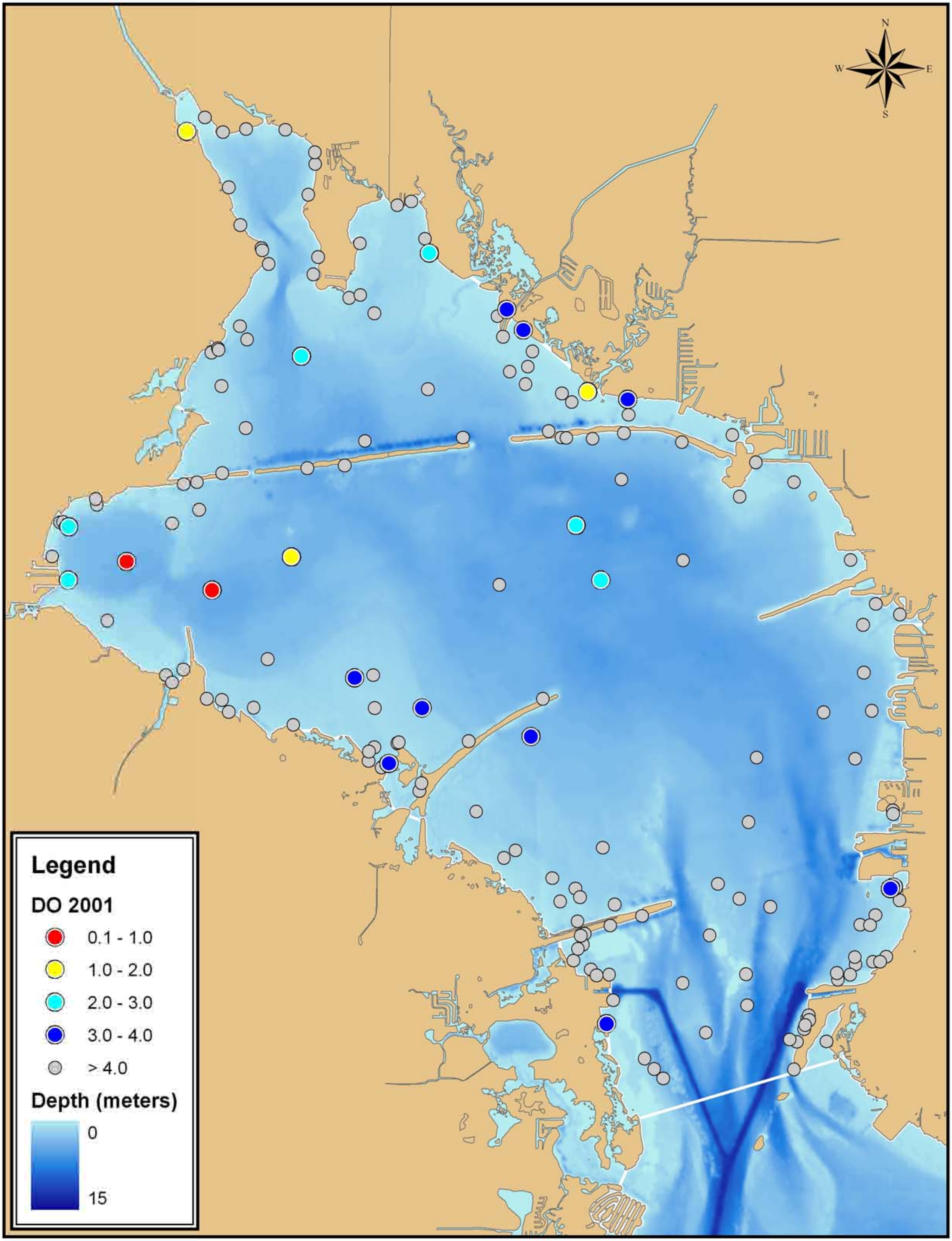
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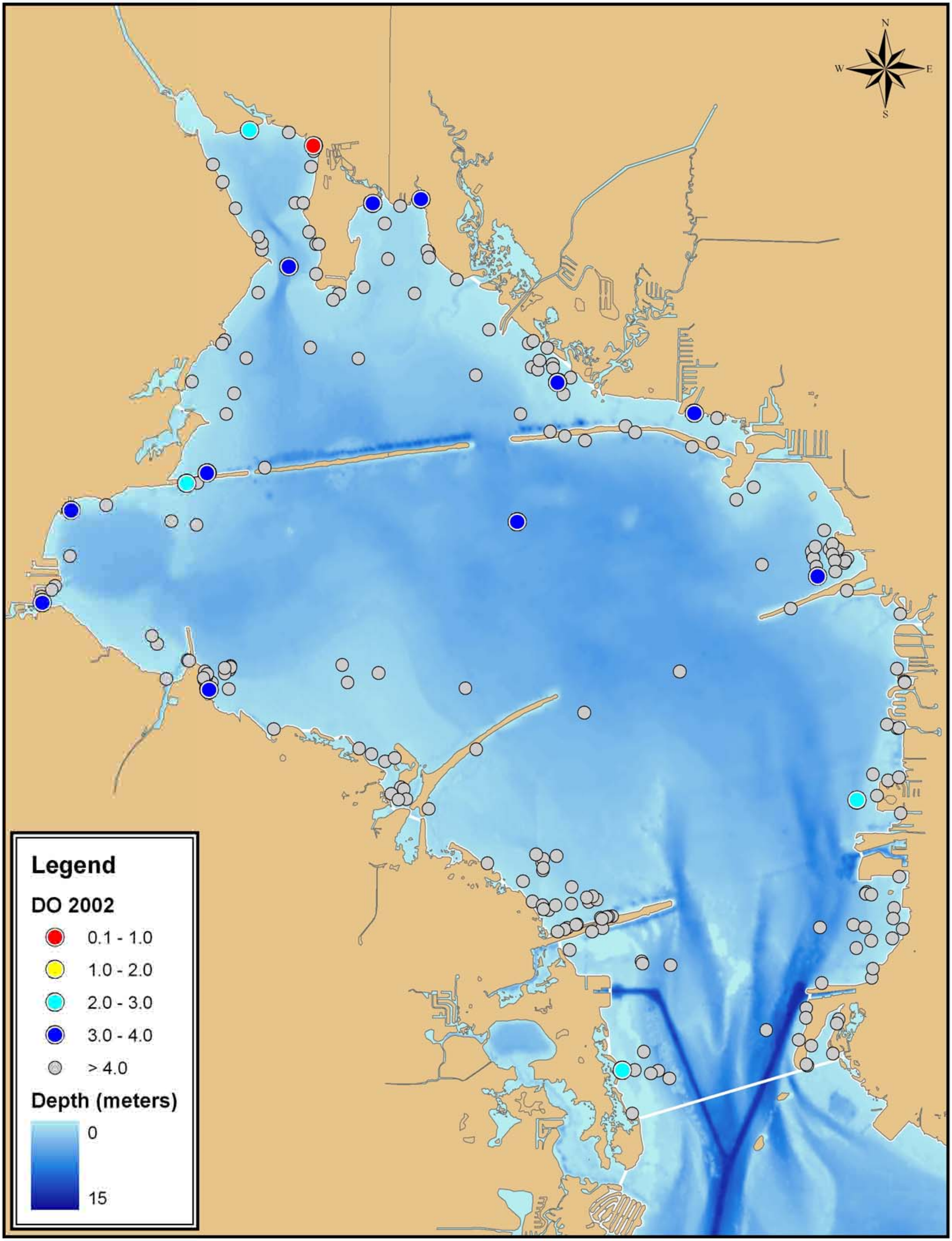
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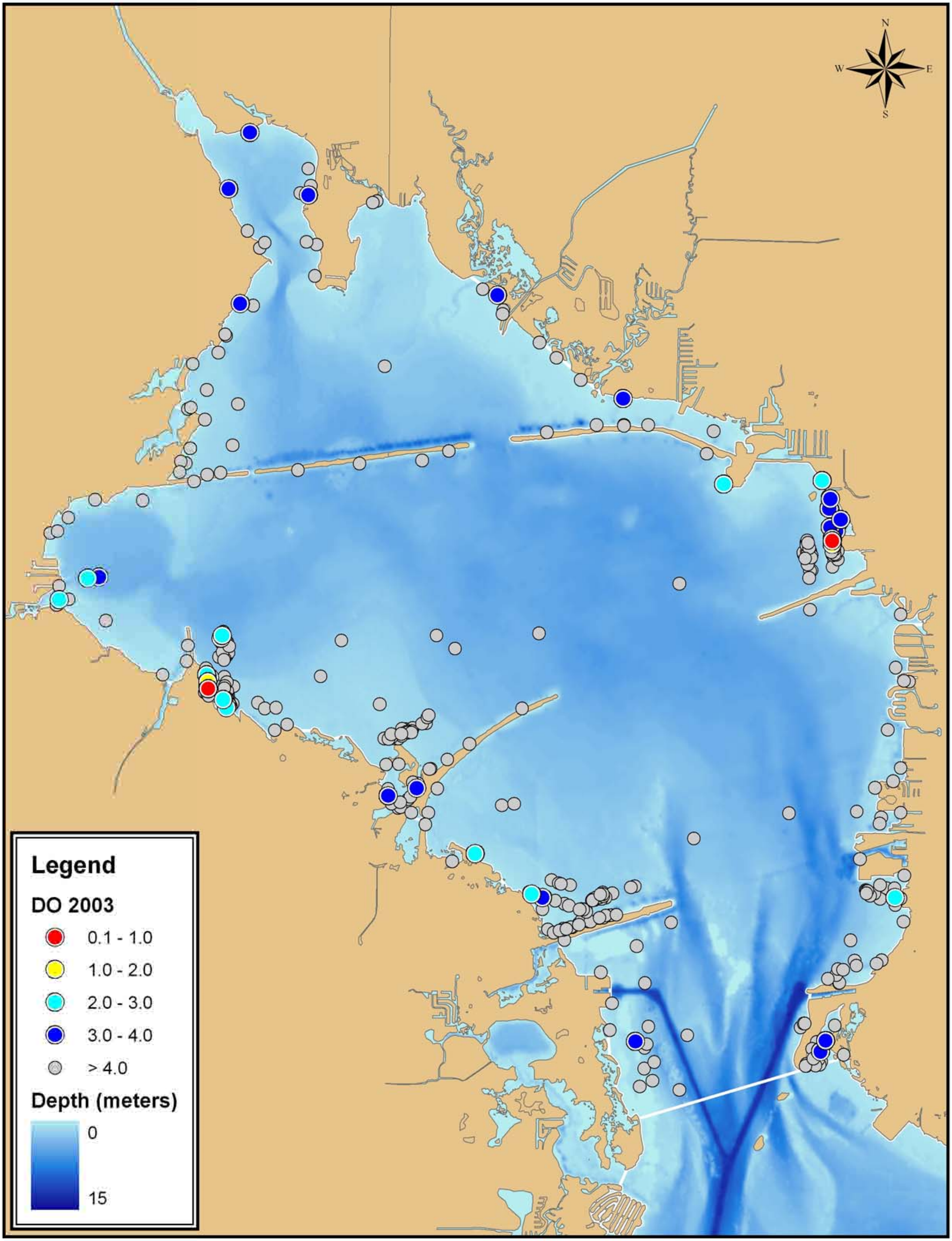

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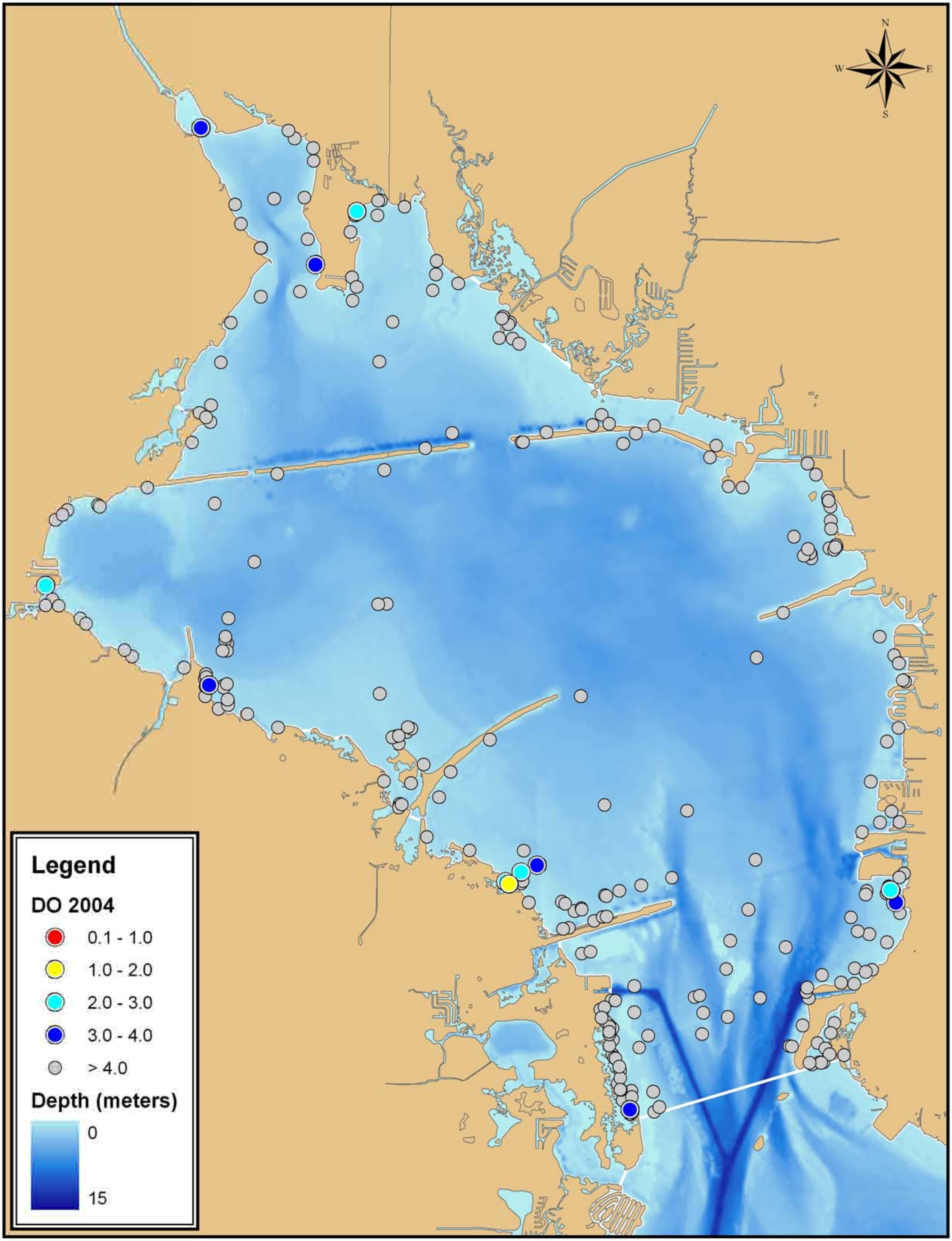
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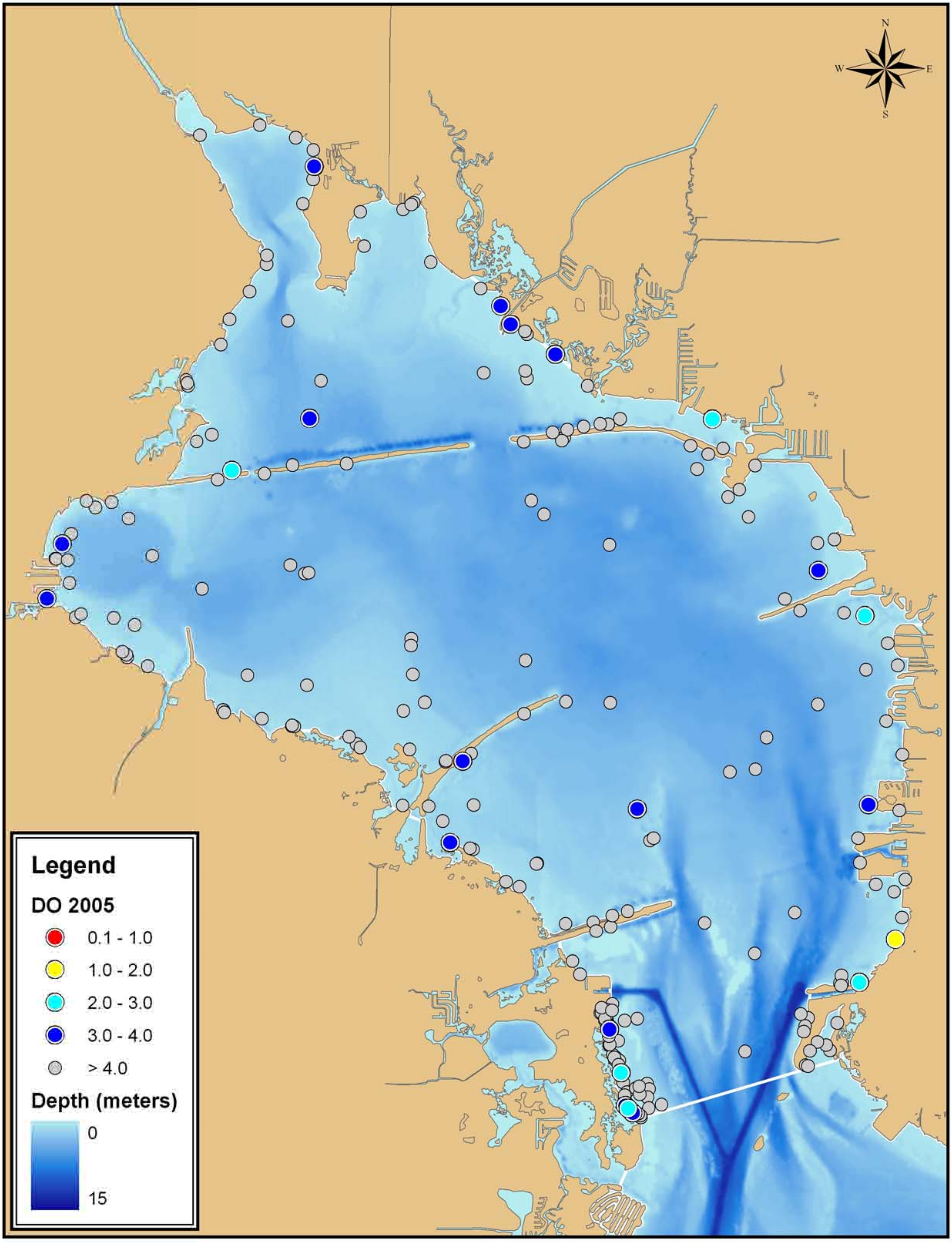
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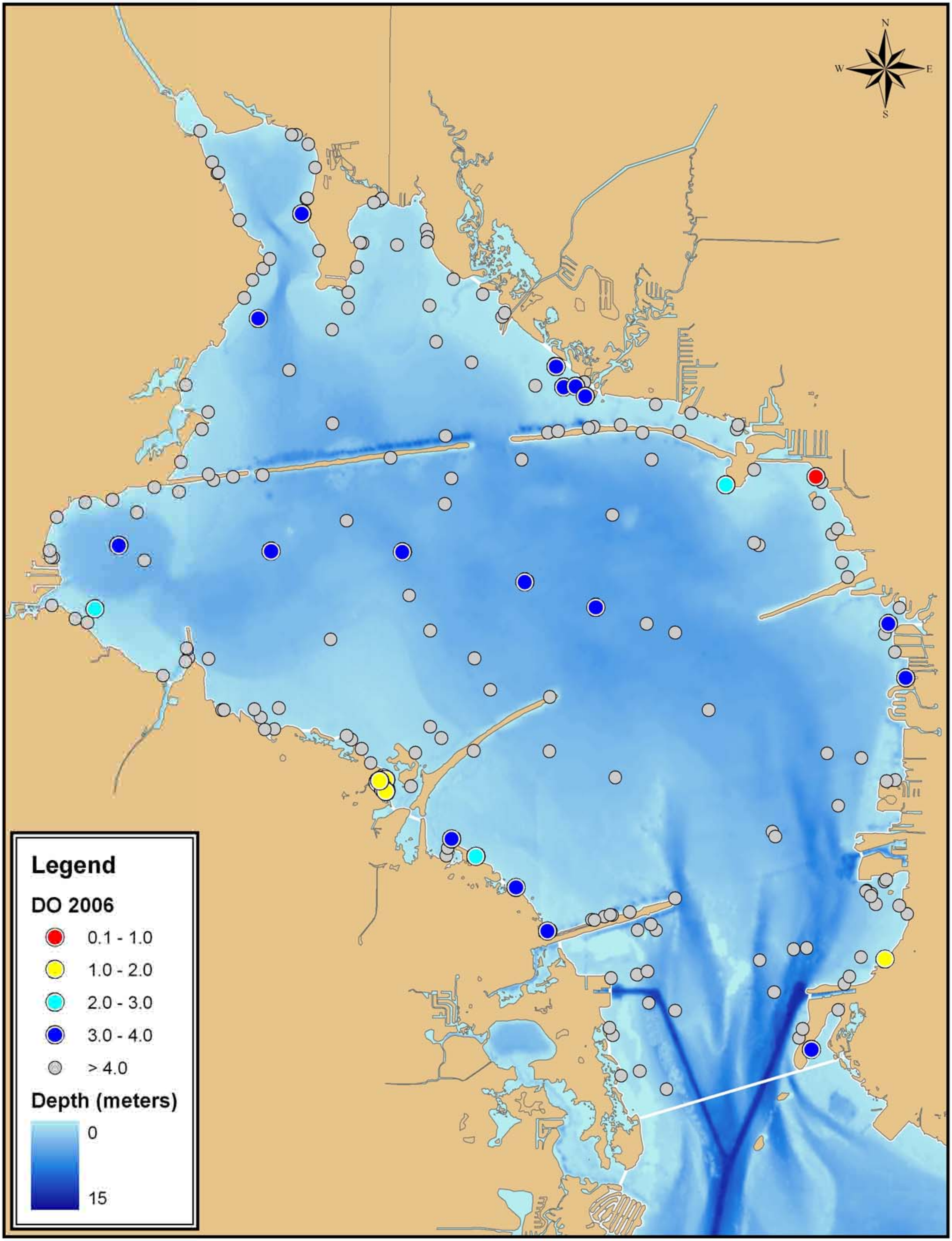

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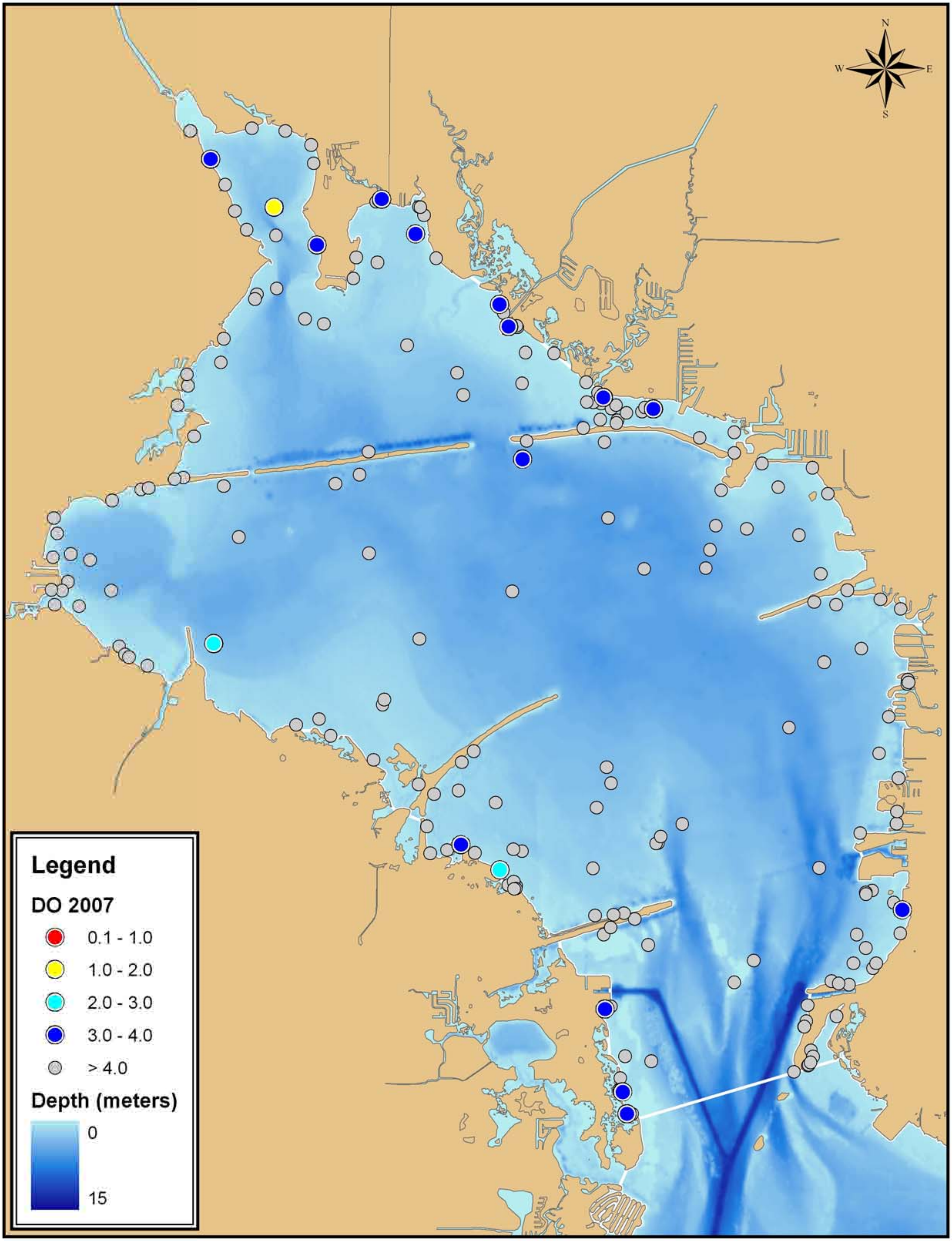
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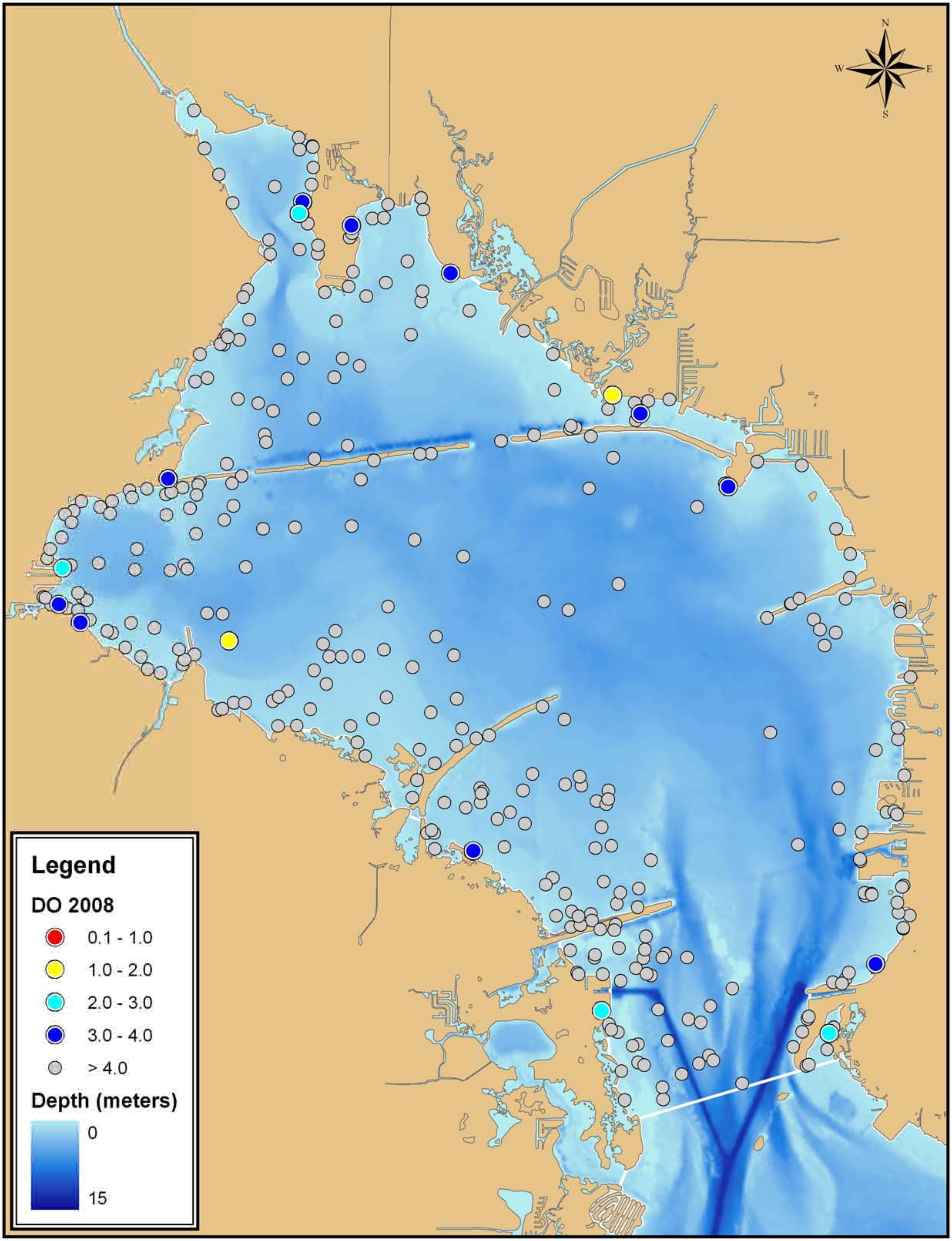

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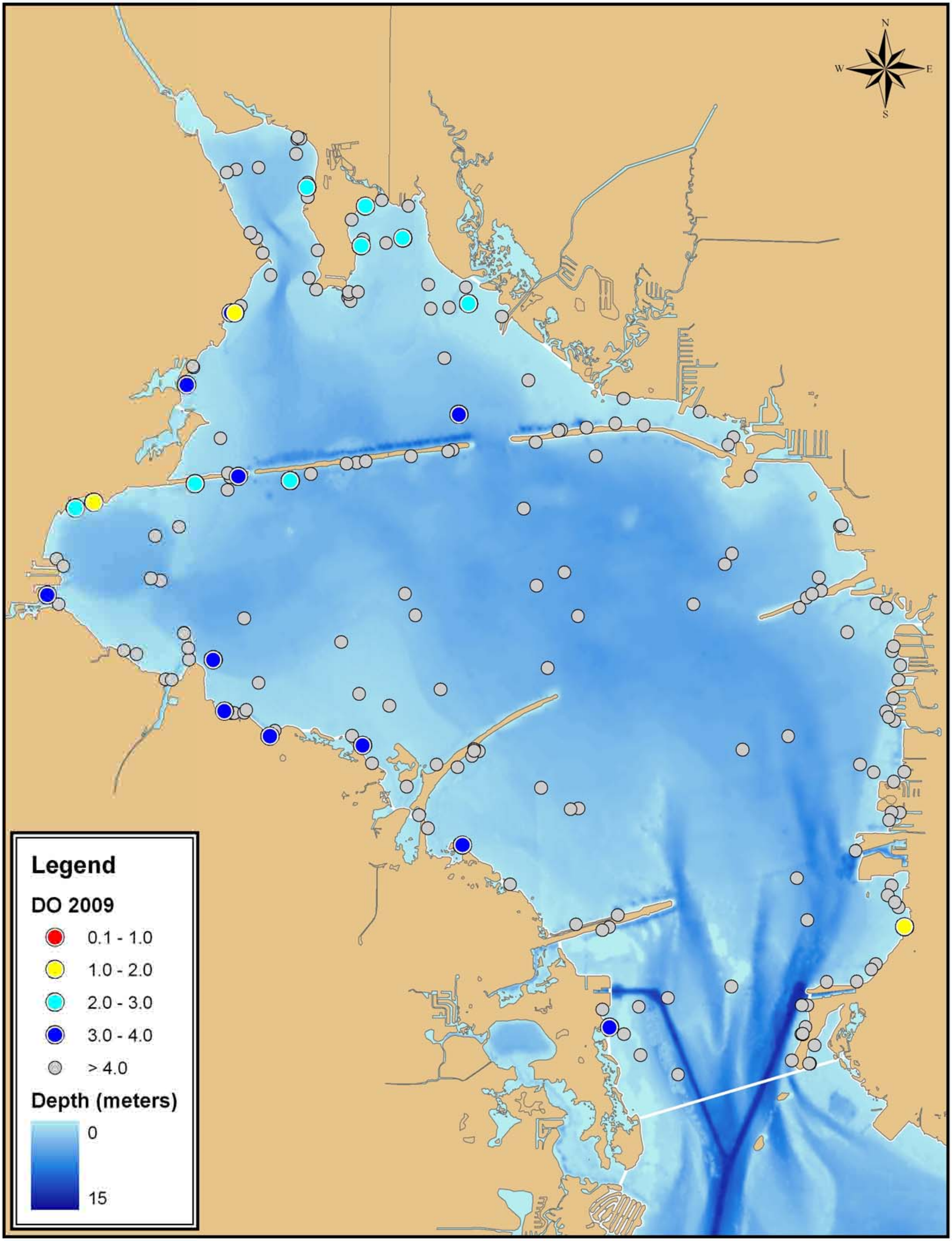
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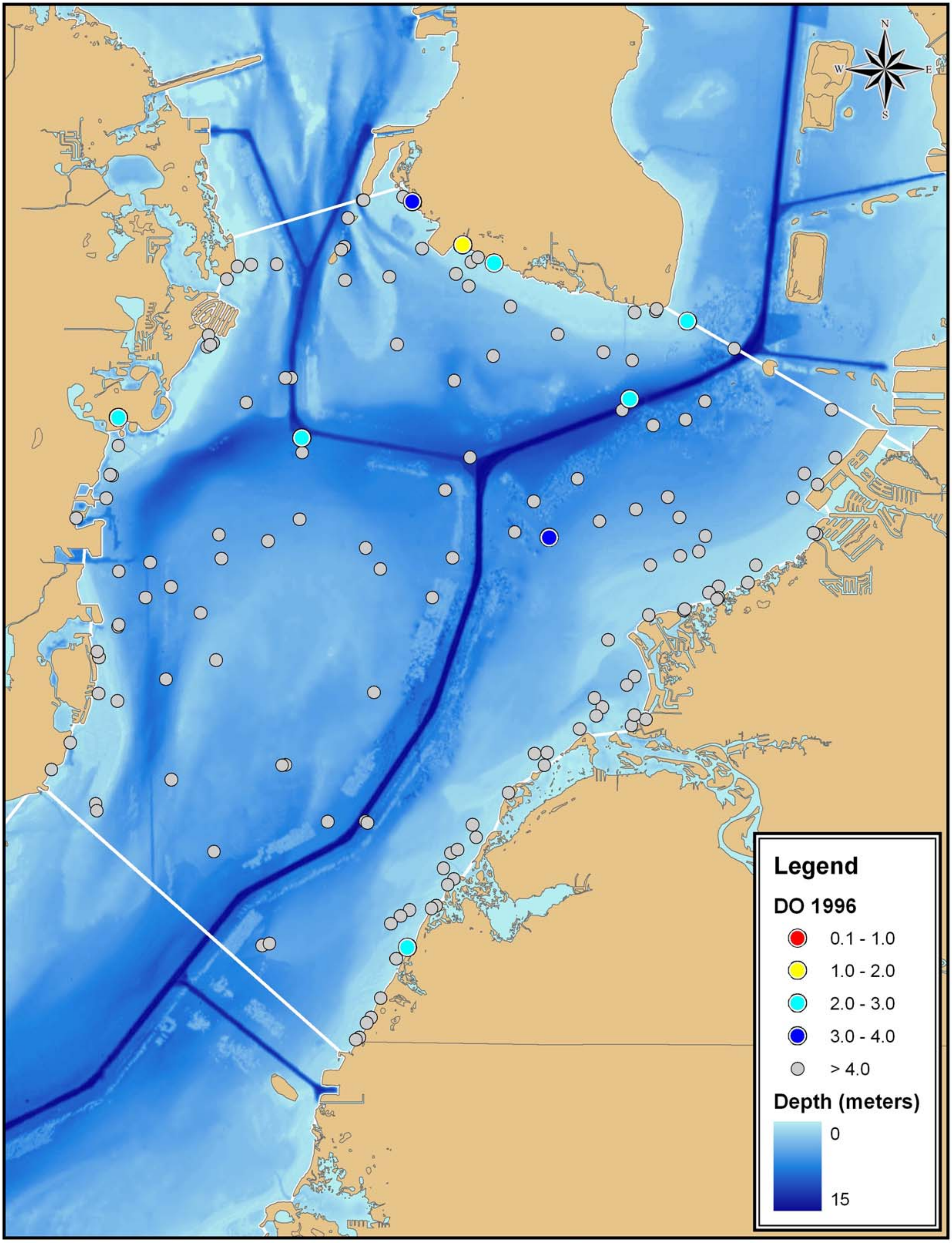
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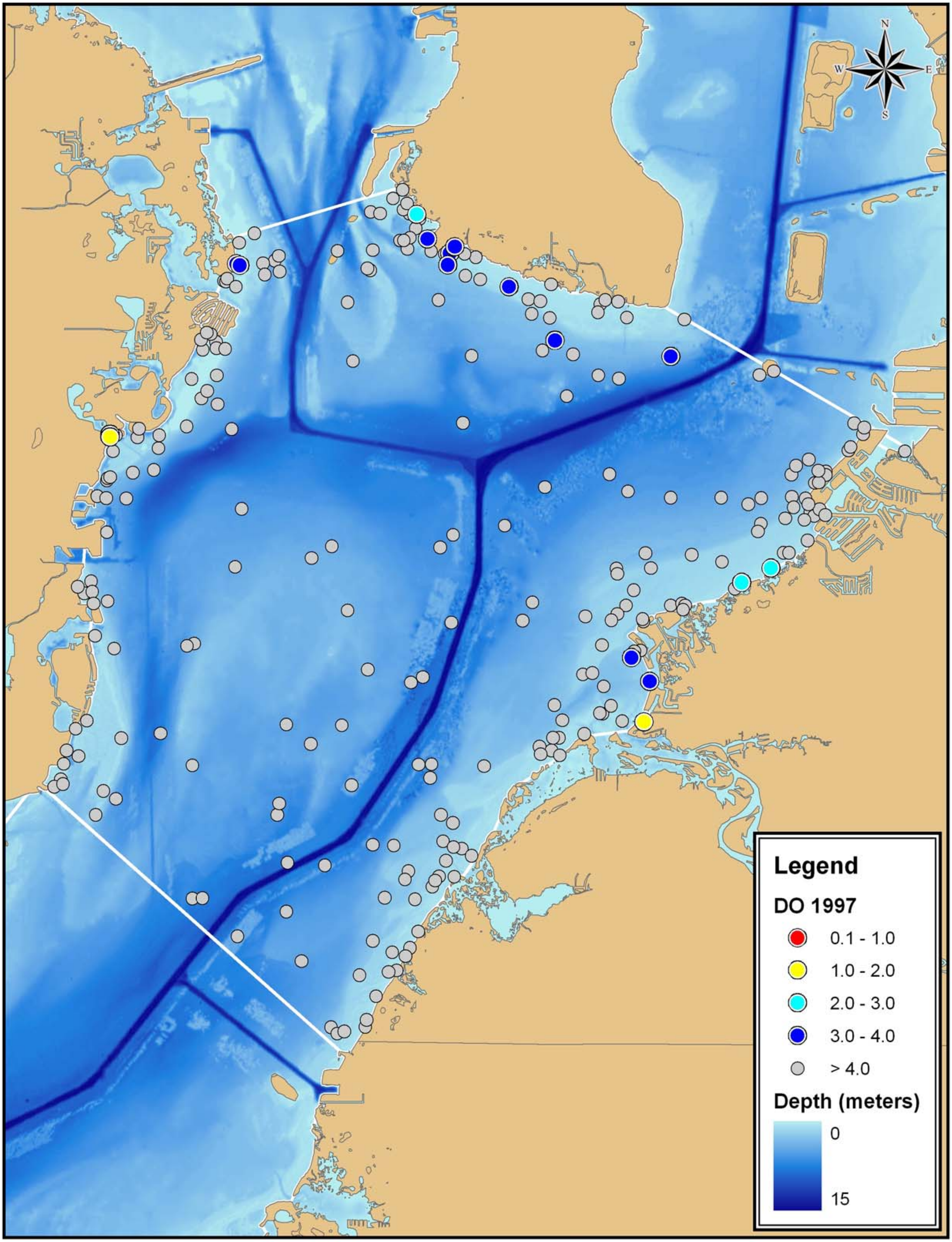

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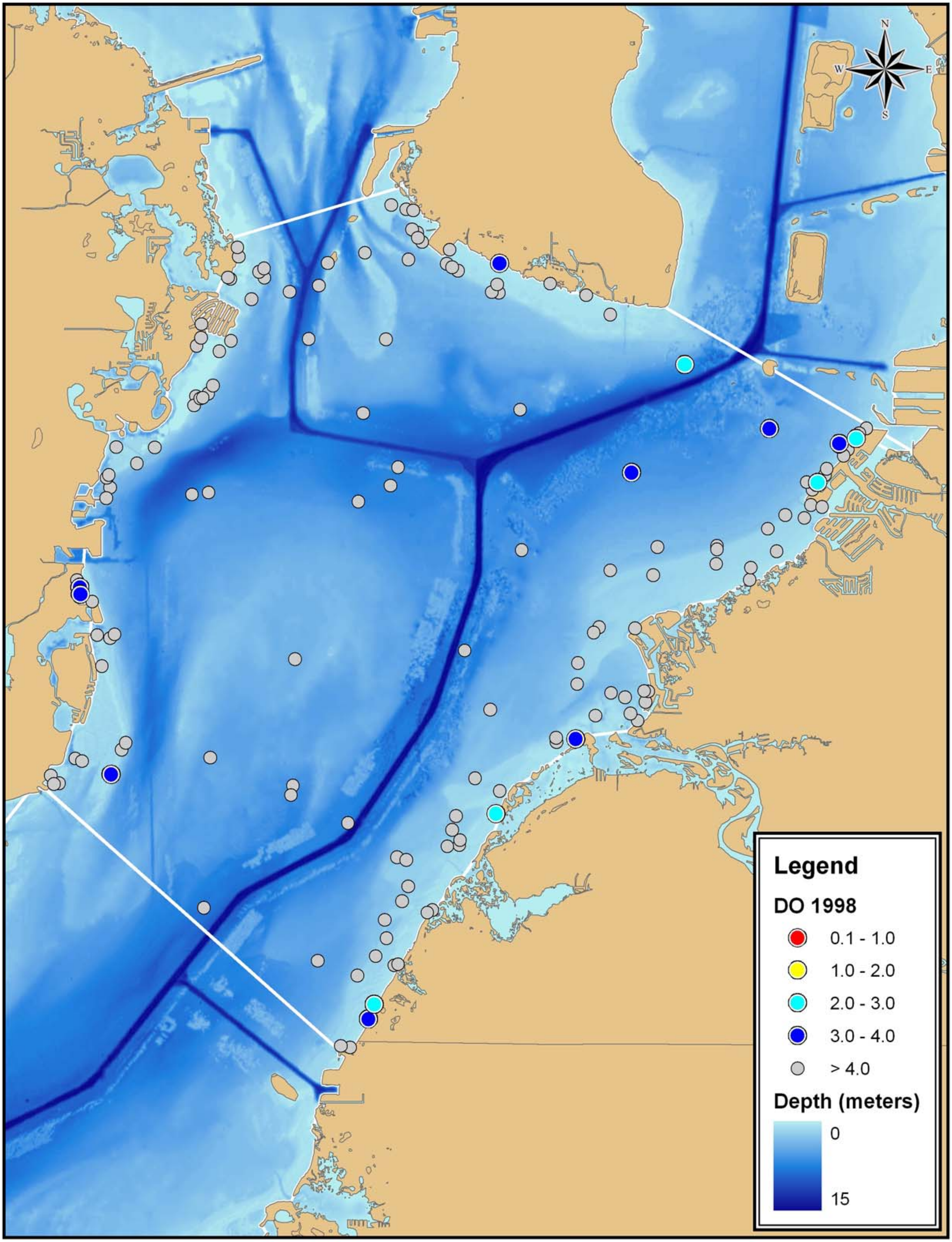
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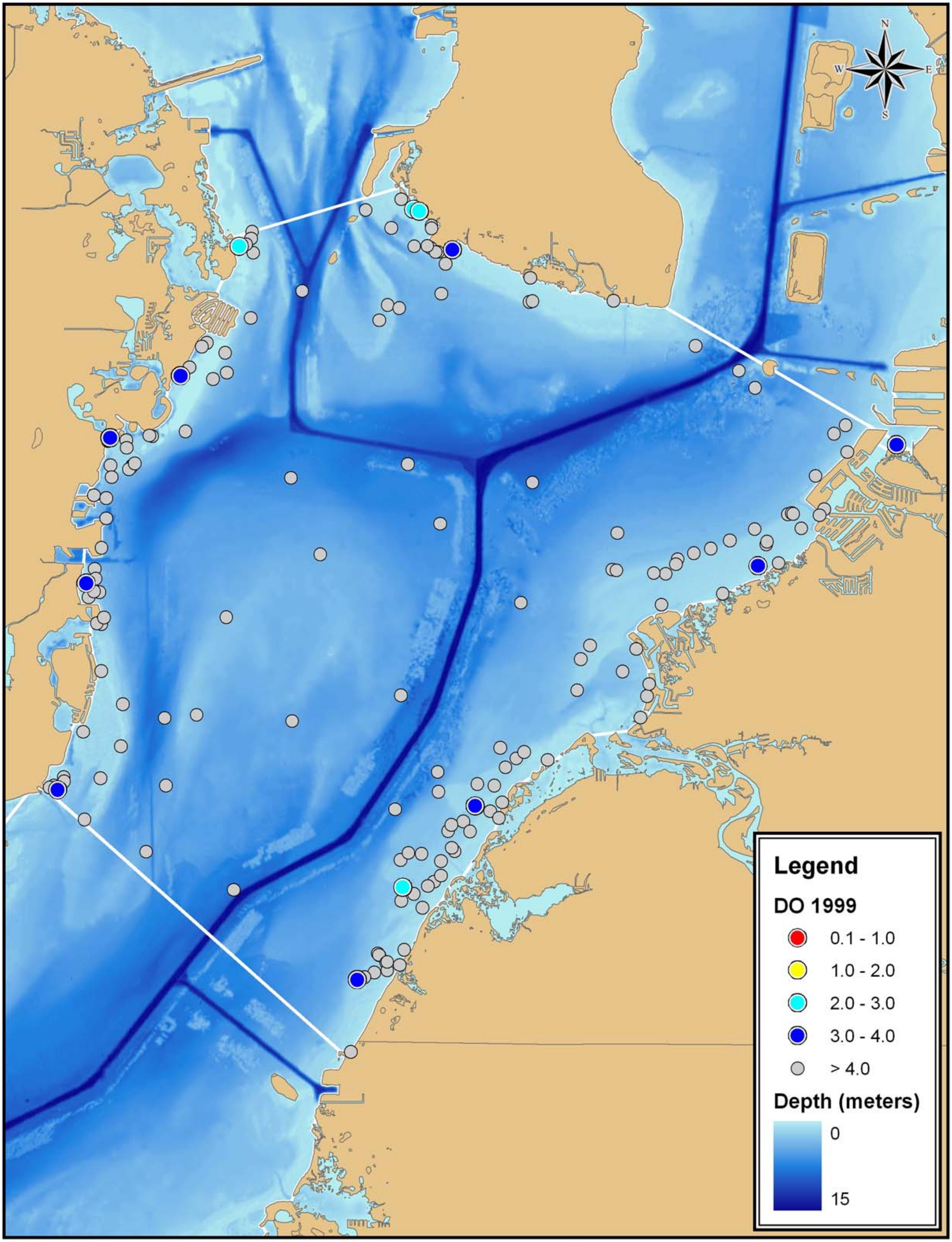
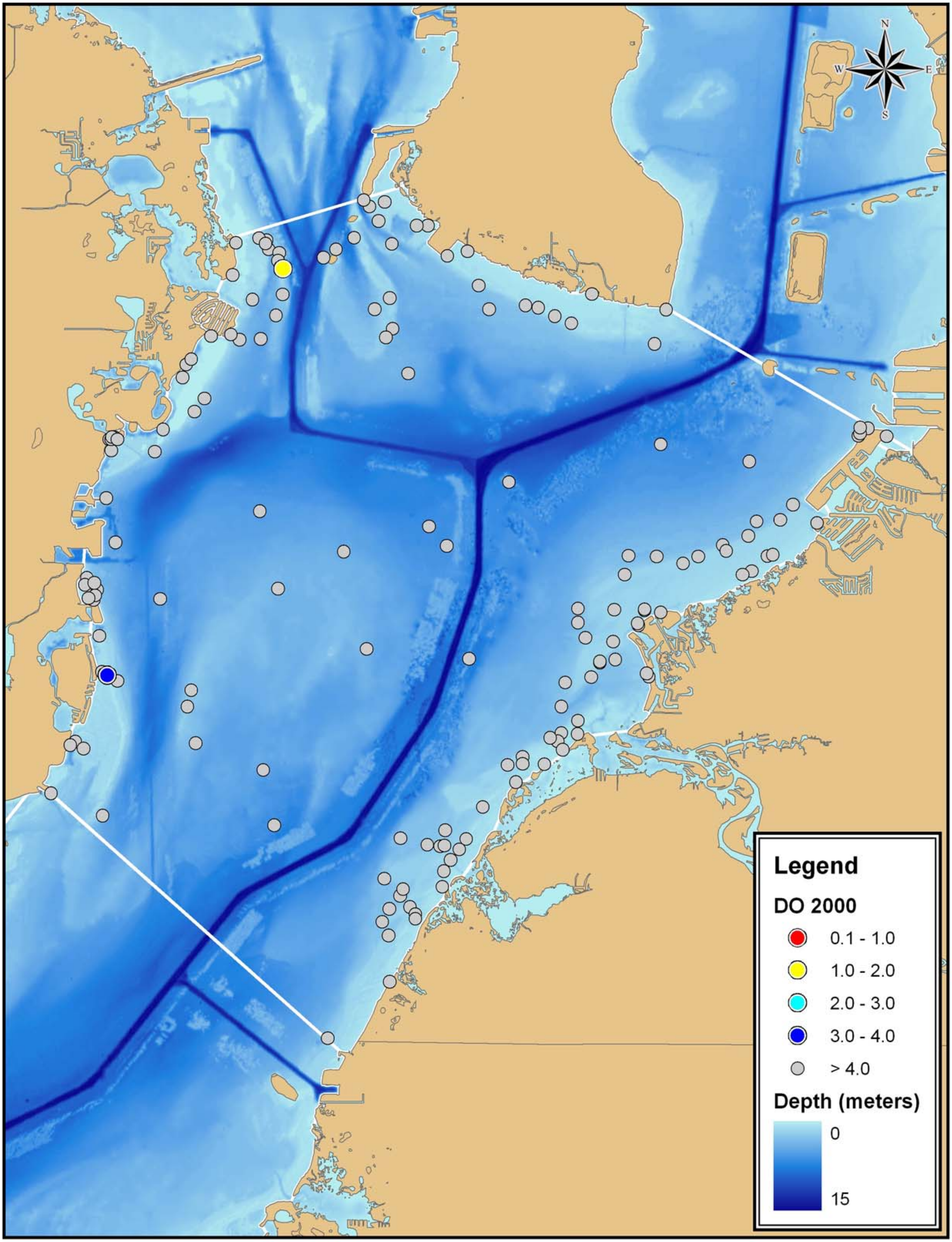

N
S
E
W
Legend
DO 1999
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15


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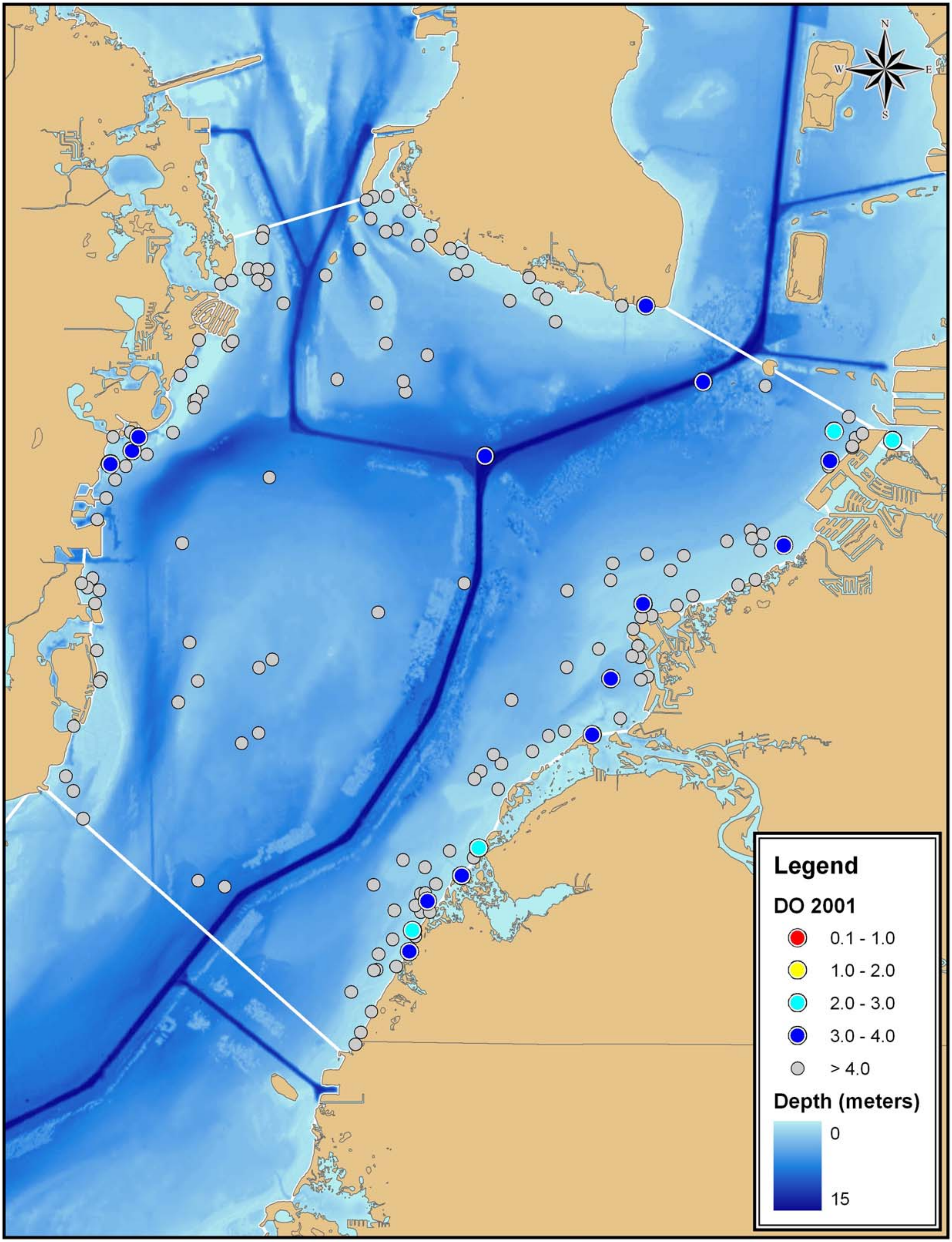
N
W
E
S
Legend
DO 2001
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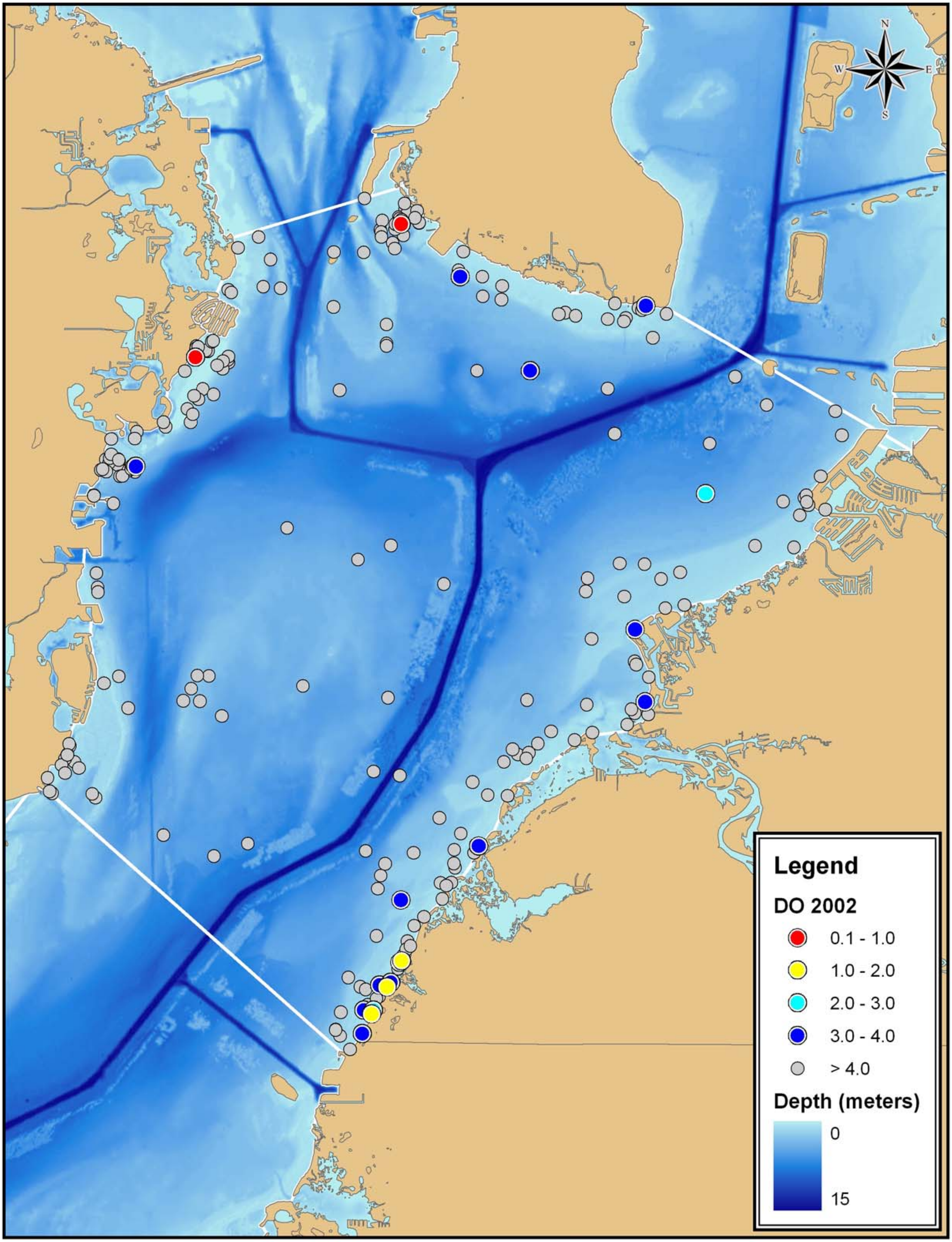
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15


N
S
E
W
Legend
DO 2002
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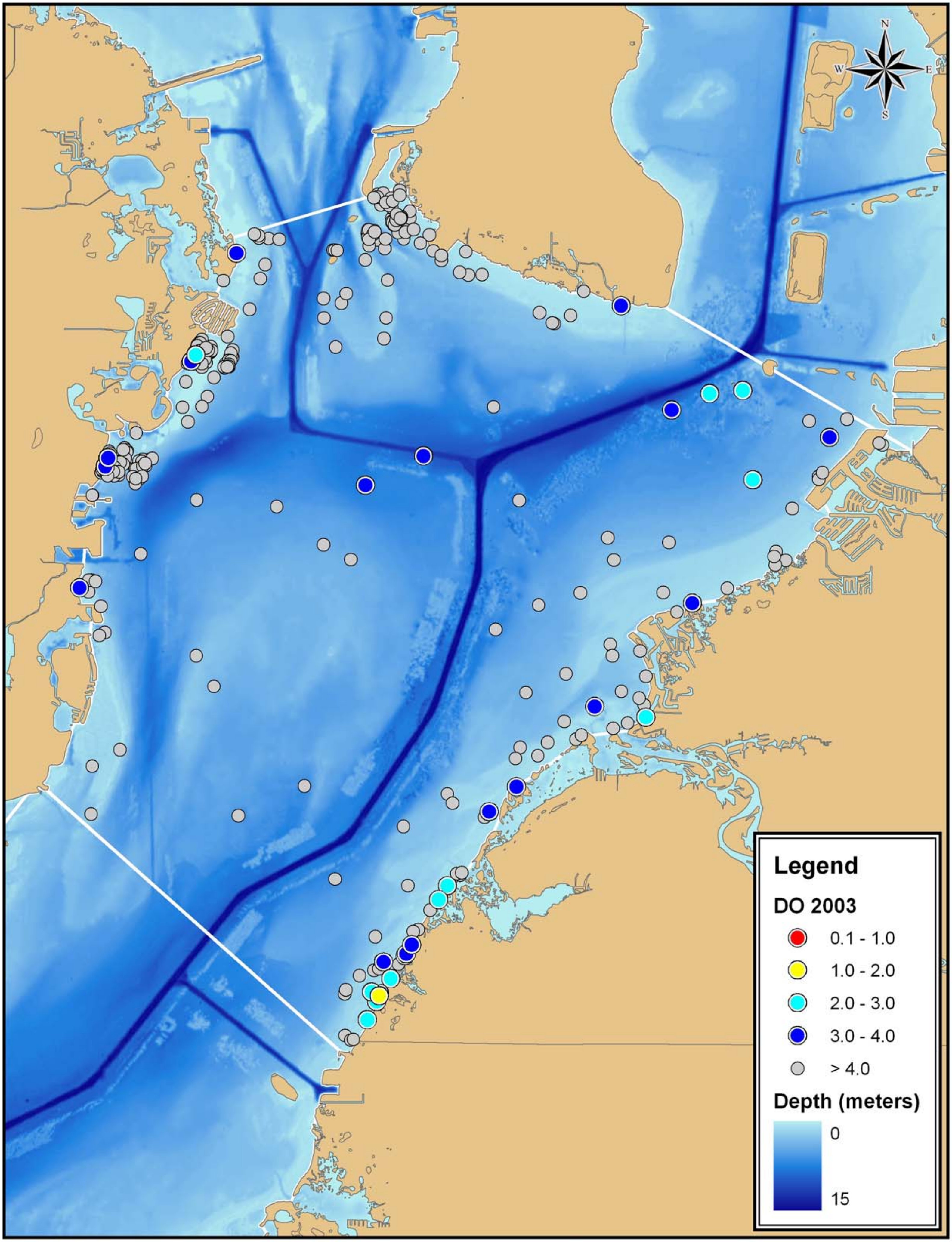
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15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E
S
Legend
DO 2003
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1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
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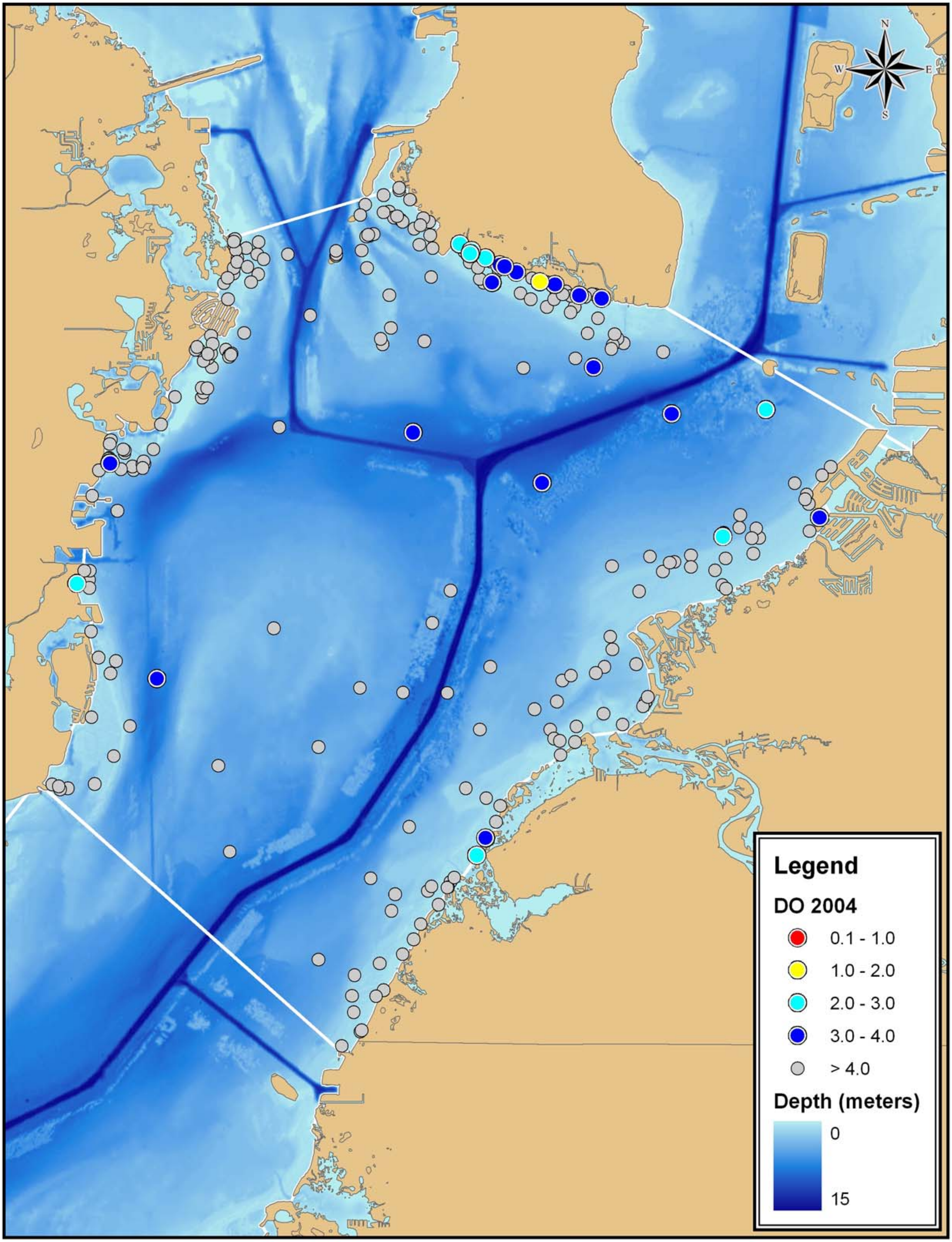
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S
E
W
Legend
DO 2004
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
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Depth (meters)
0
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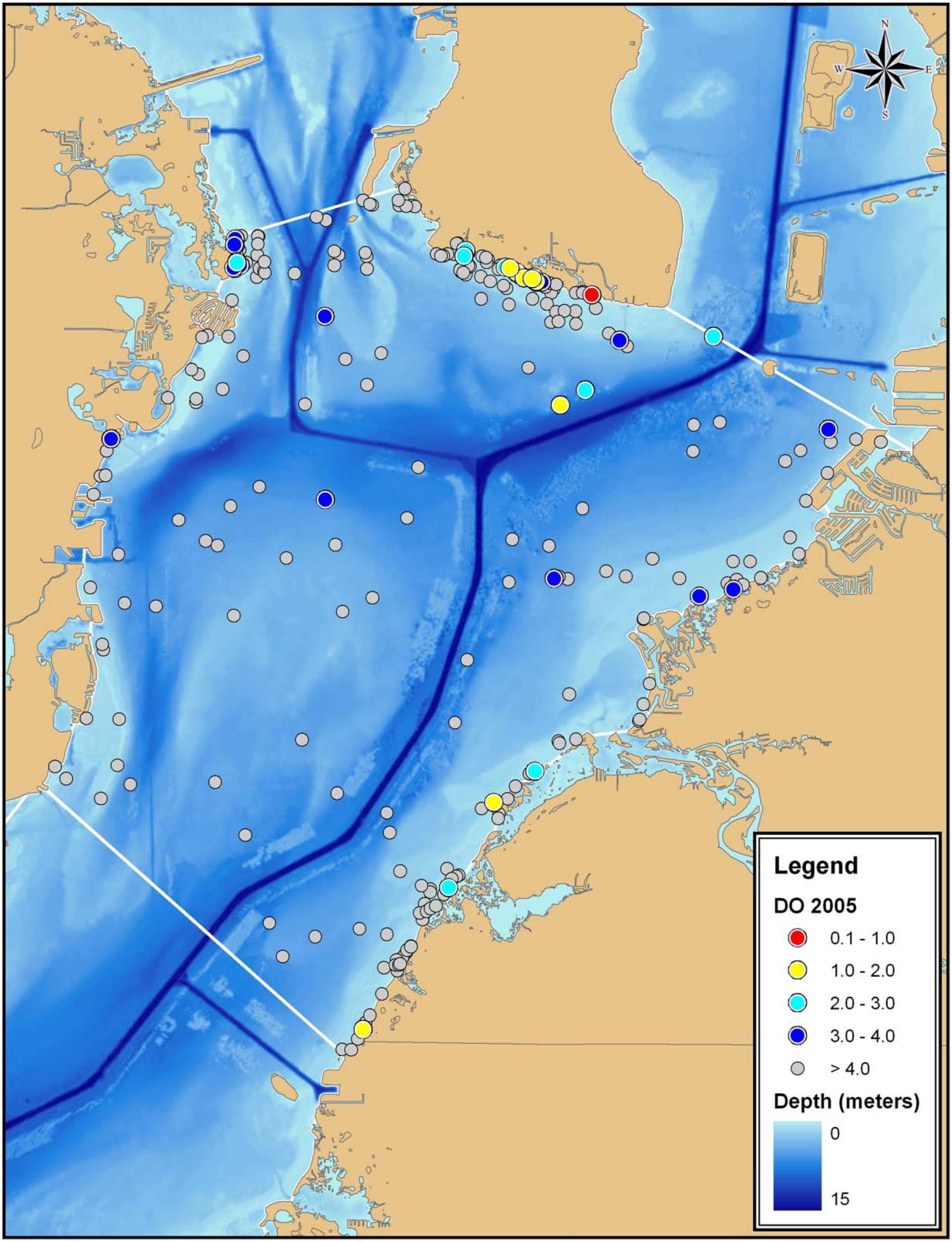

N
S
E
W
Legend
DO 2005
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1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
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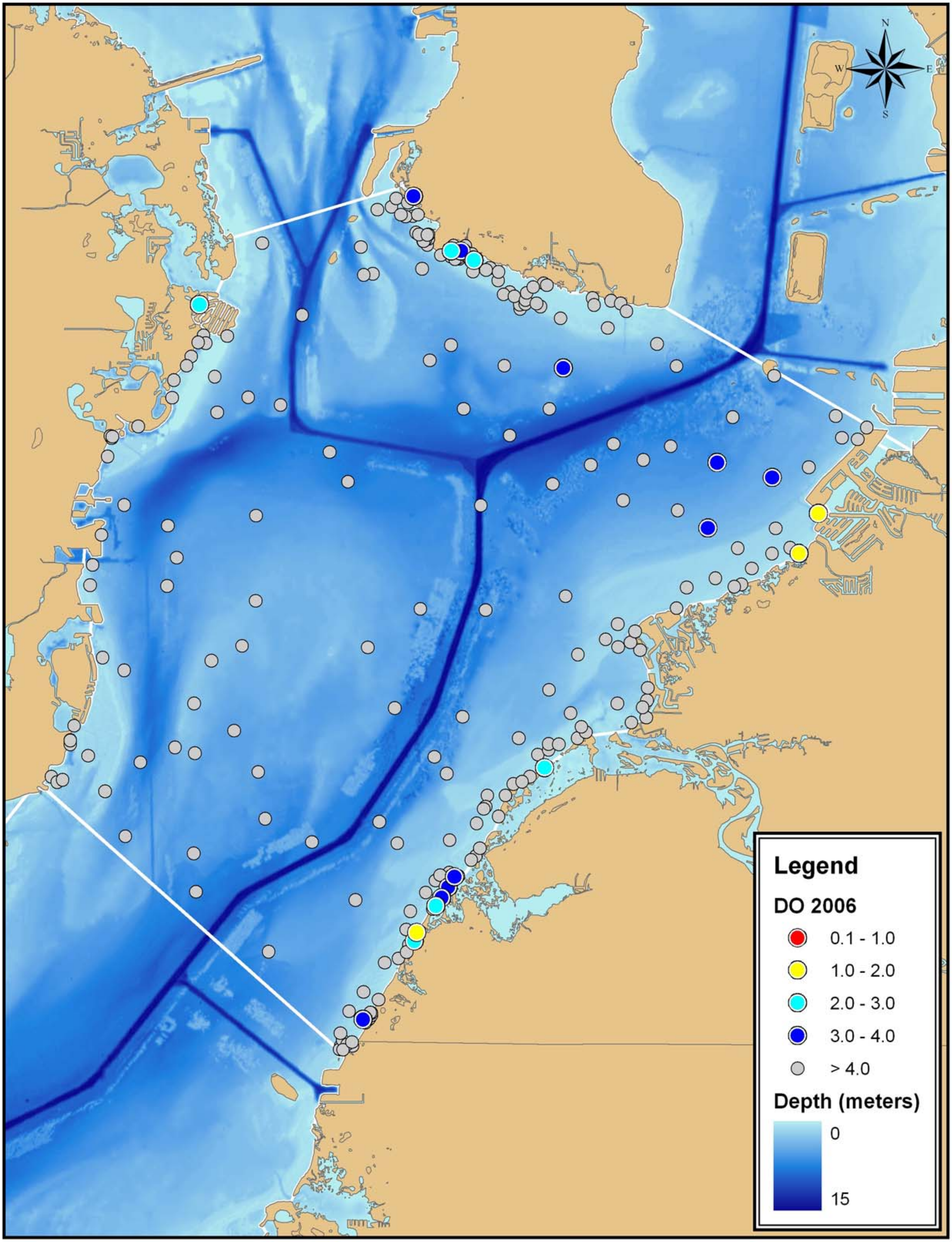
N
S
W
E
Legend
DO 2006
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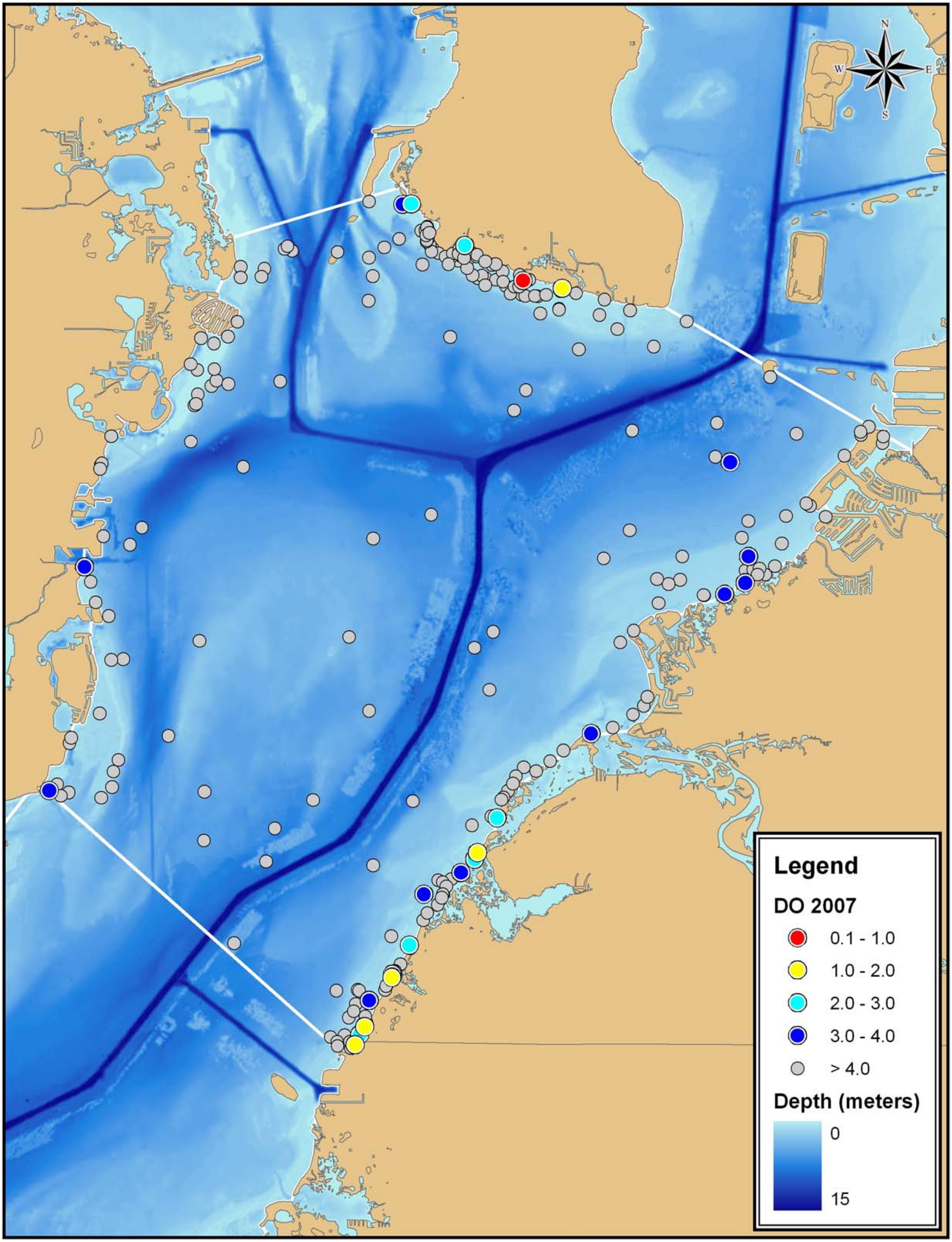
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15


N
S
E
W
Legend
DO 2007
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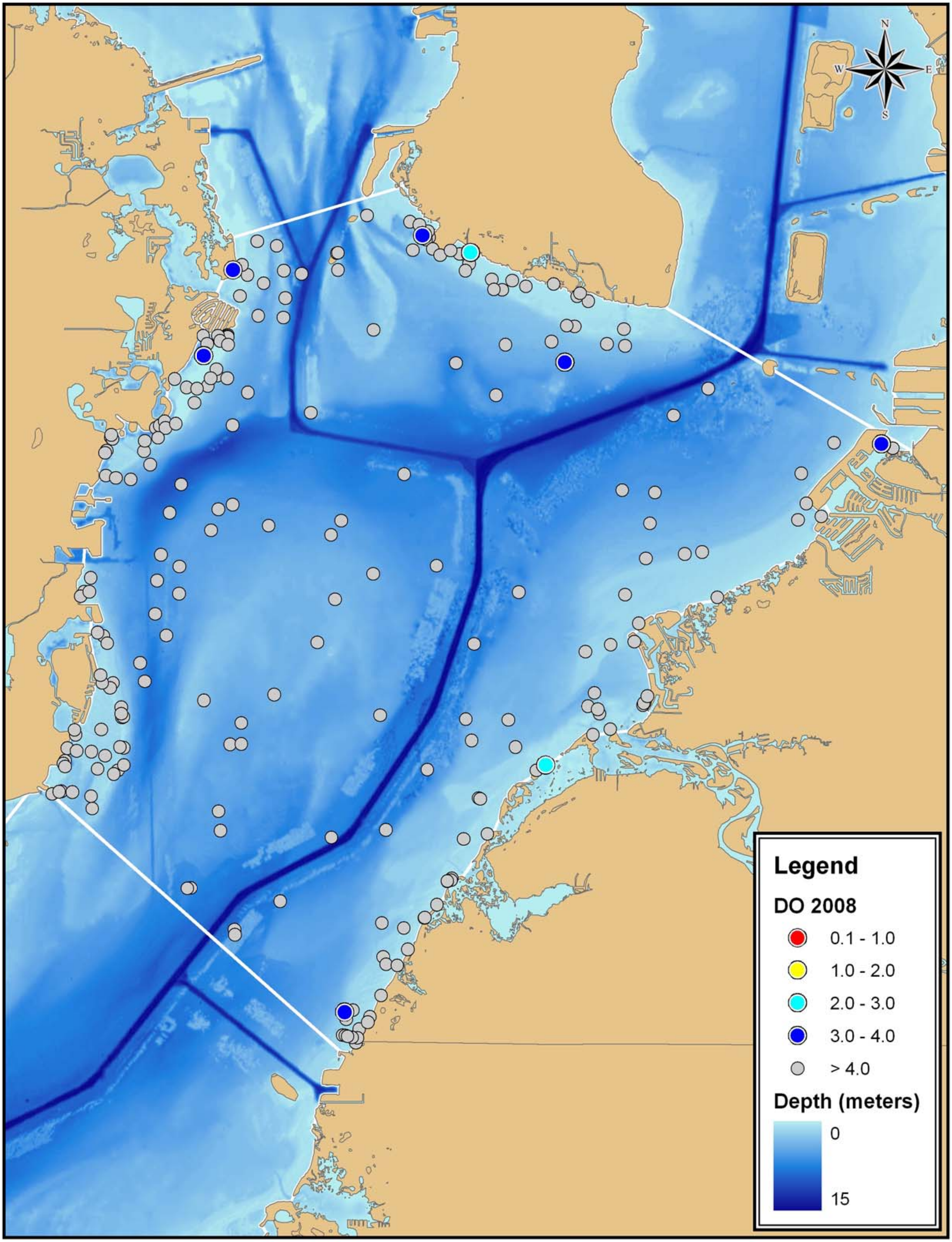
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15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S
E
W
Legend
DO 2008
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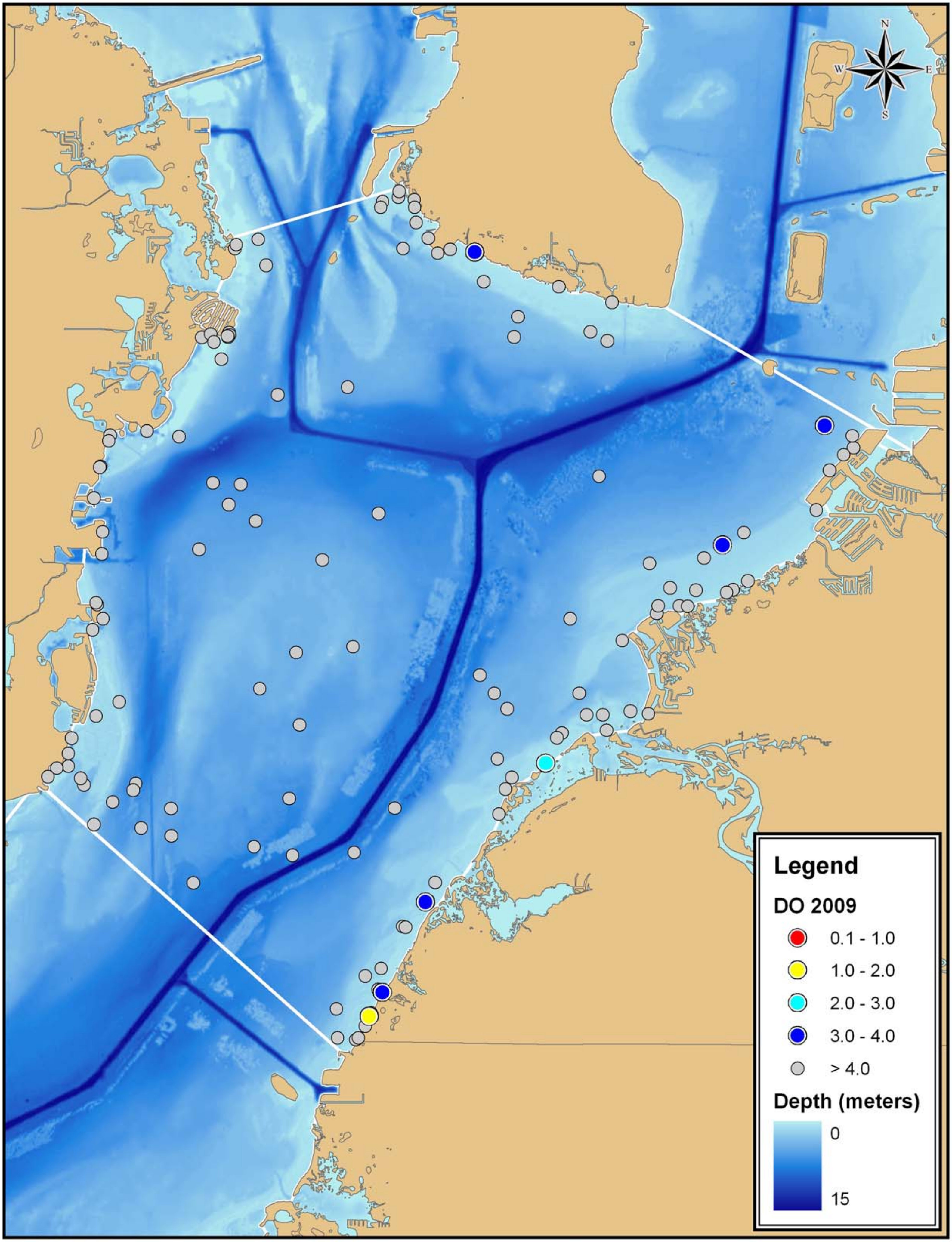
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15


N
S
E
W
Legend
DO 2009
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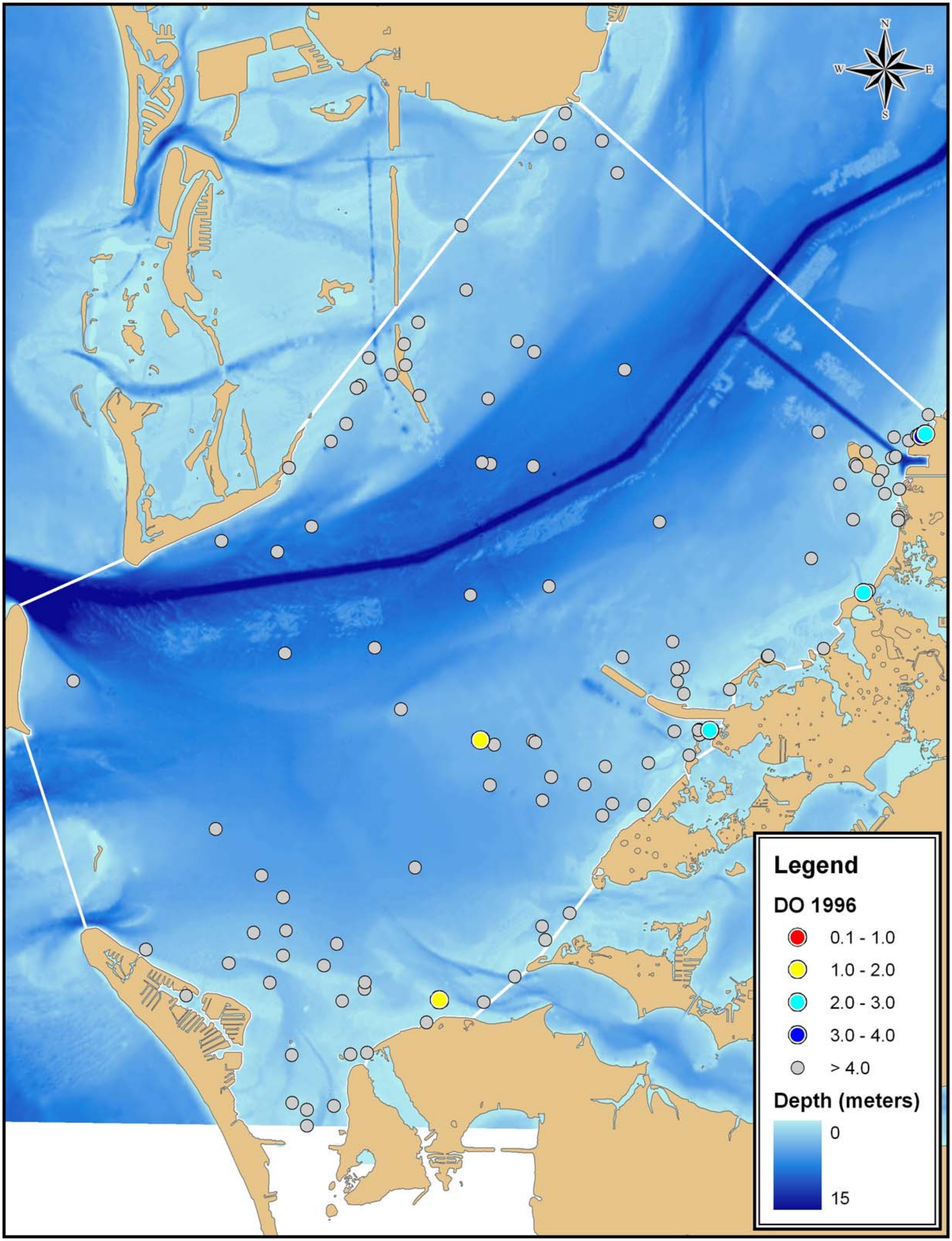
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15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W
E
S
Legend
DO 1996
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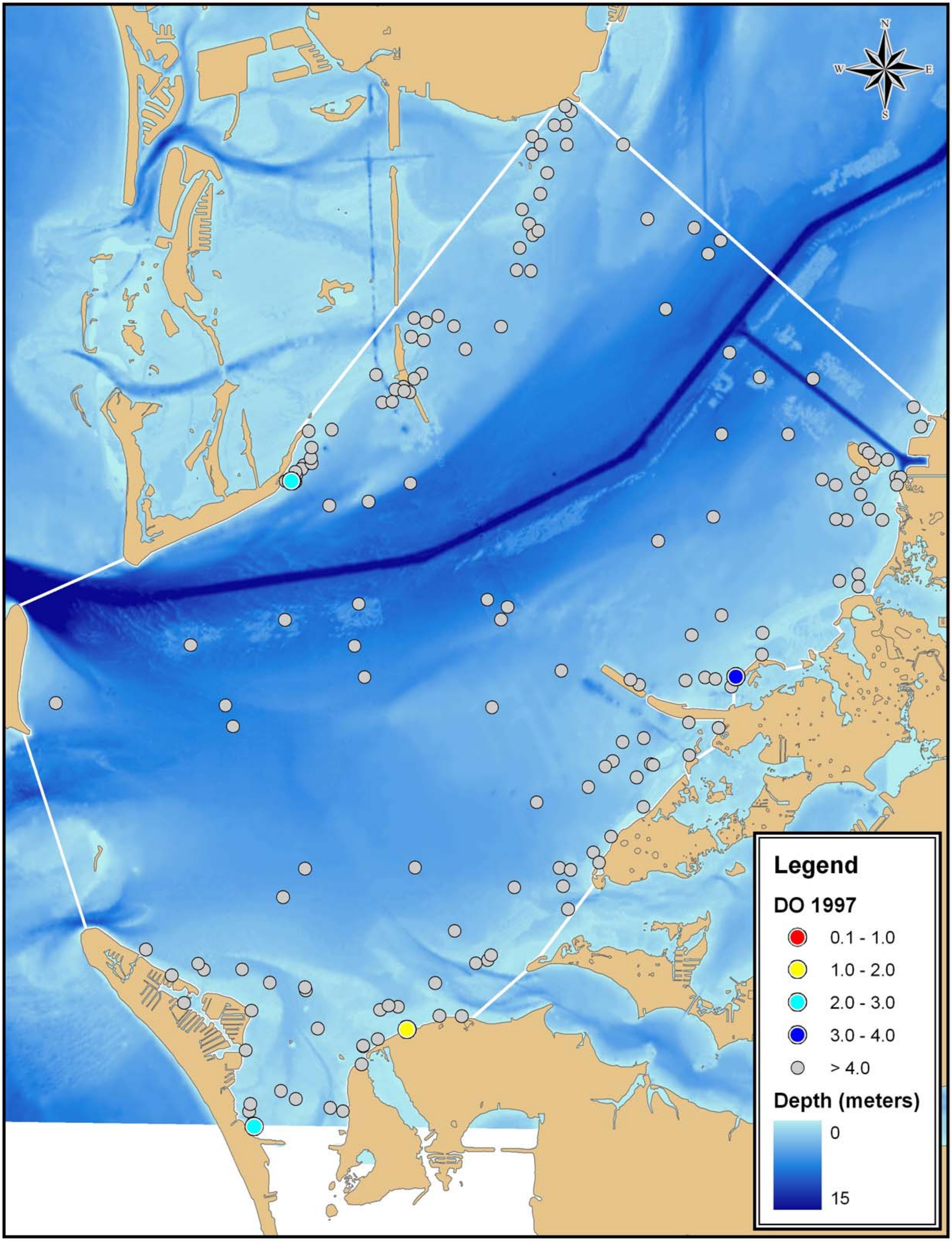
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15



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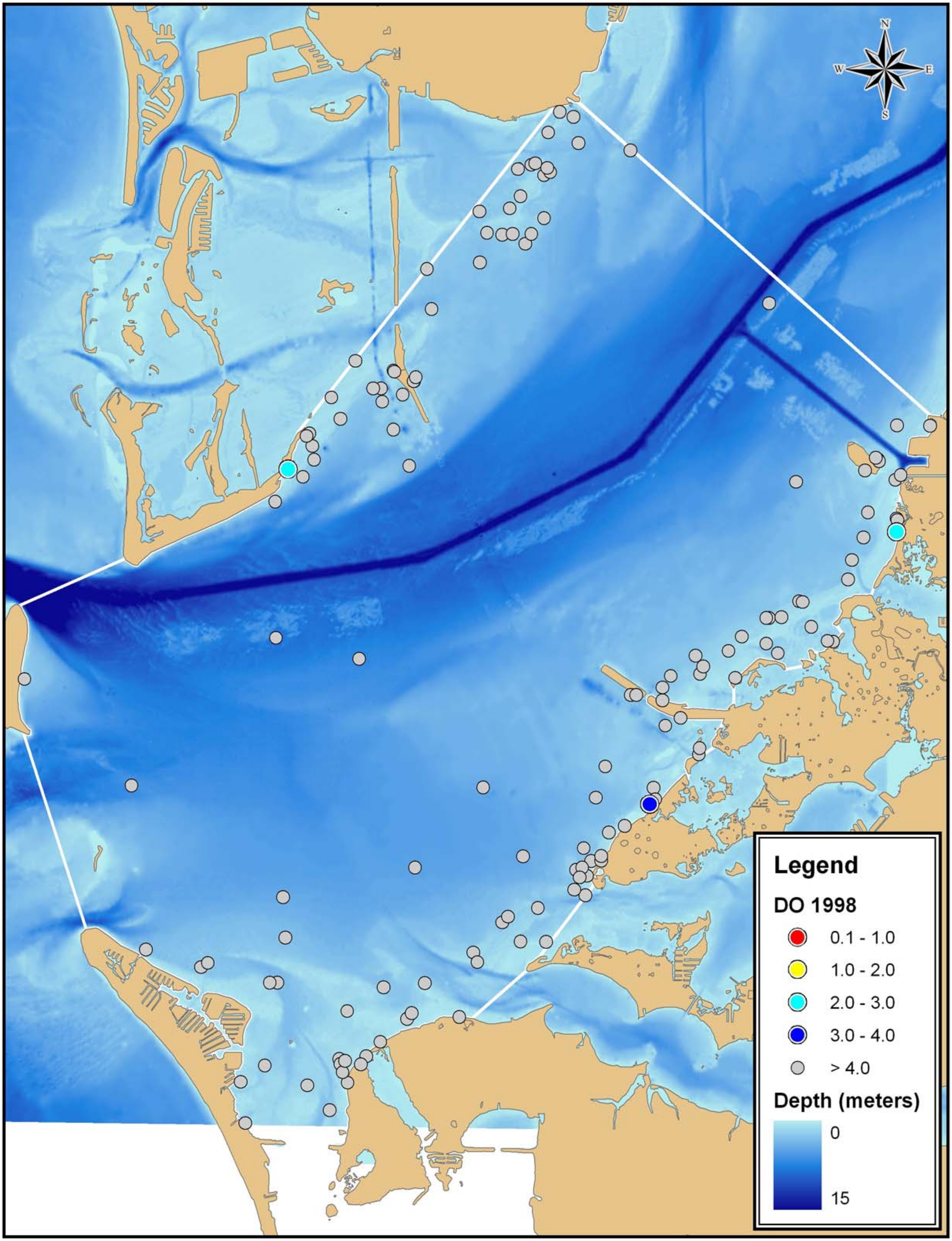
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15


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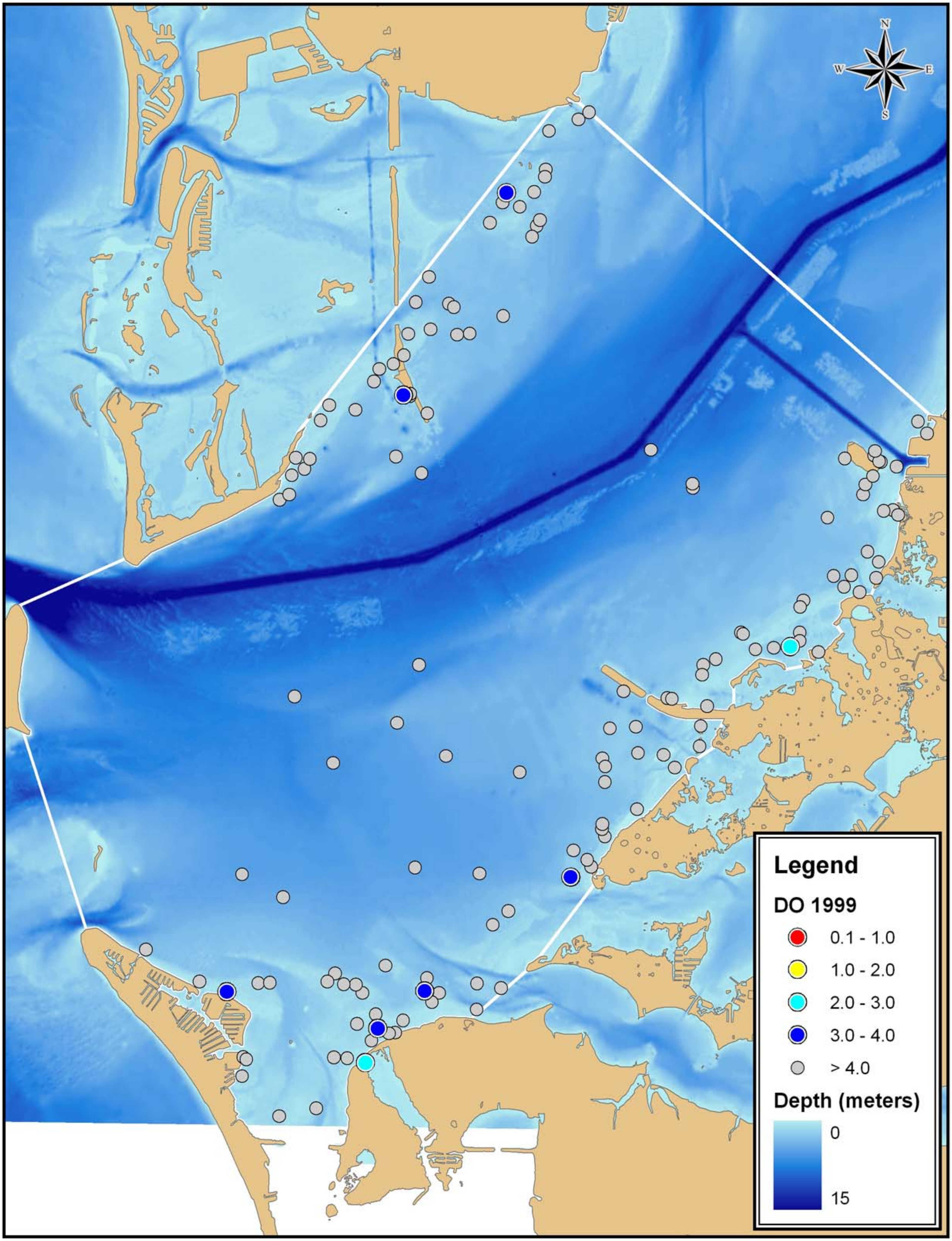
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15



N
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E
S
Legend
DO 1999
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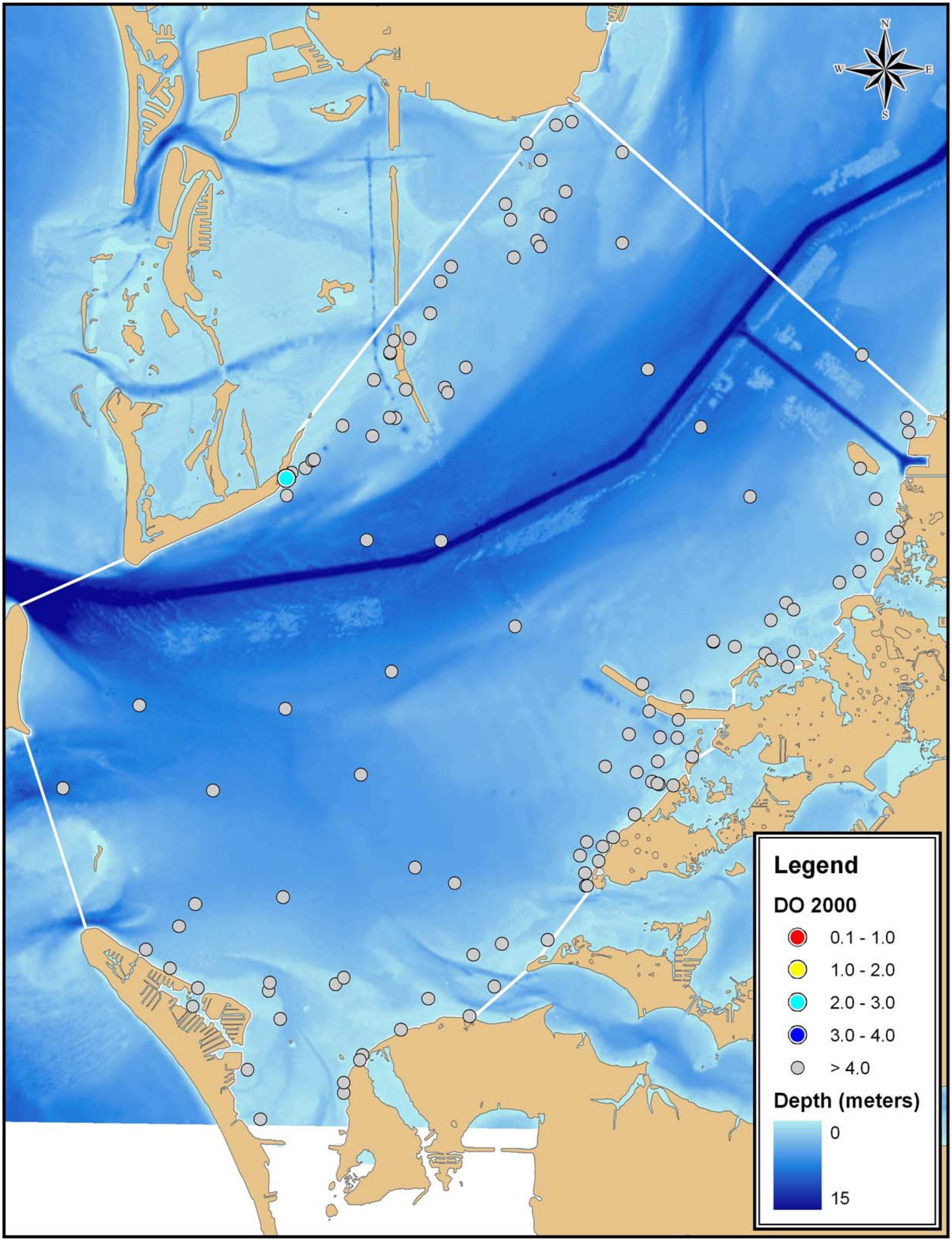
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15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E
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Legend
DO 2000
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1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
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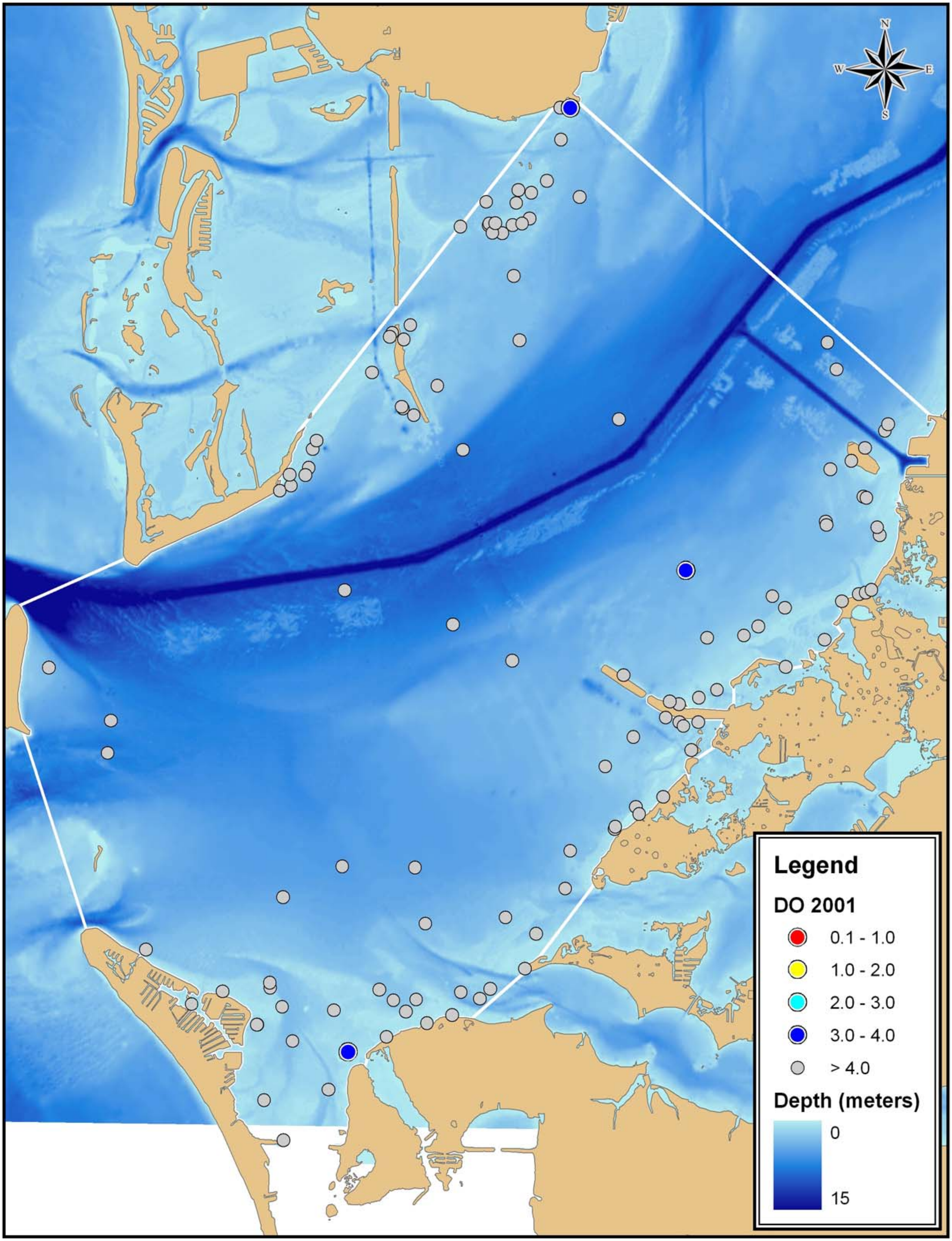
N
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E
S
Legend
DO 2001
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
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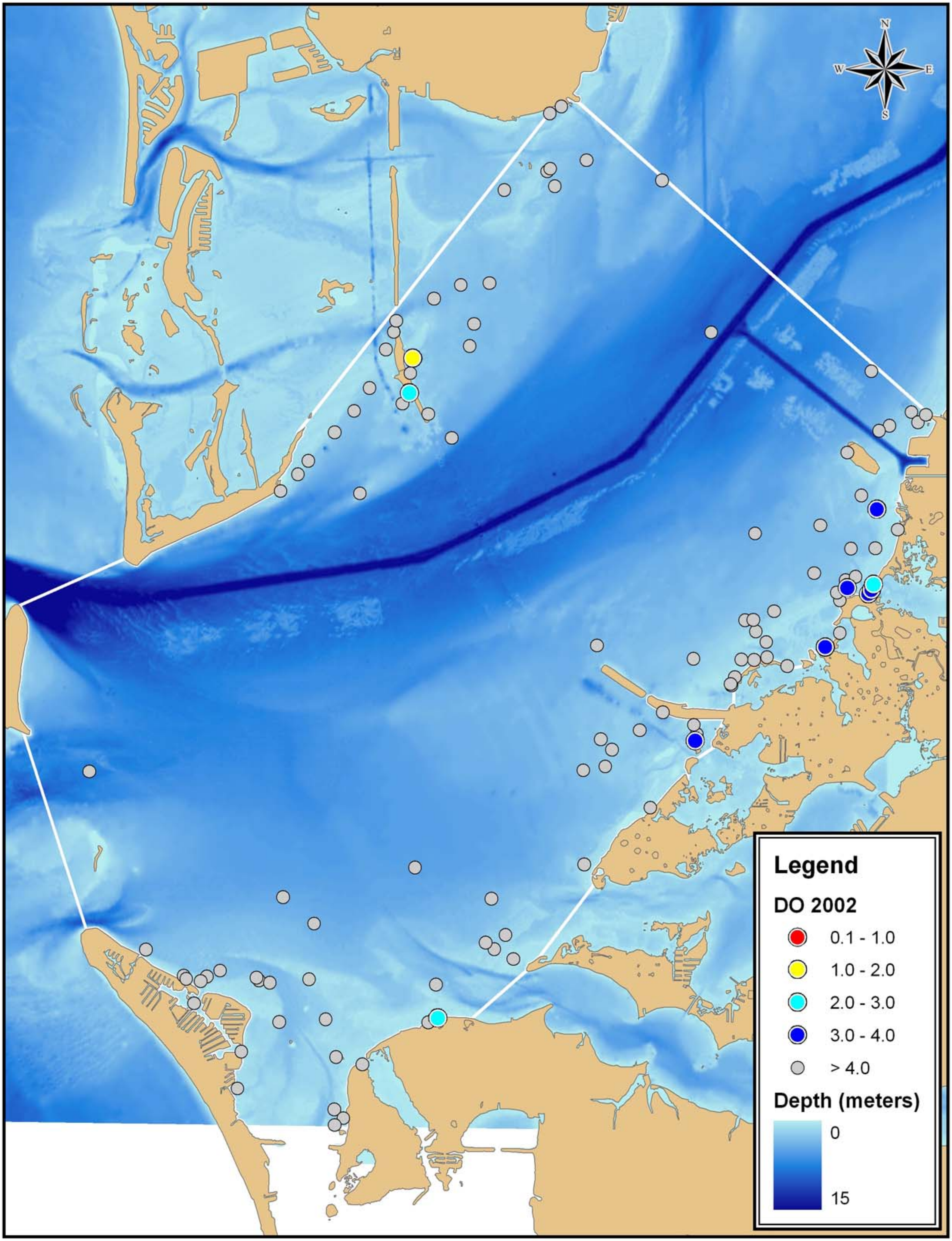
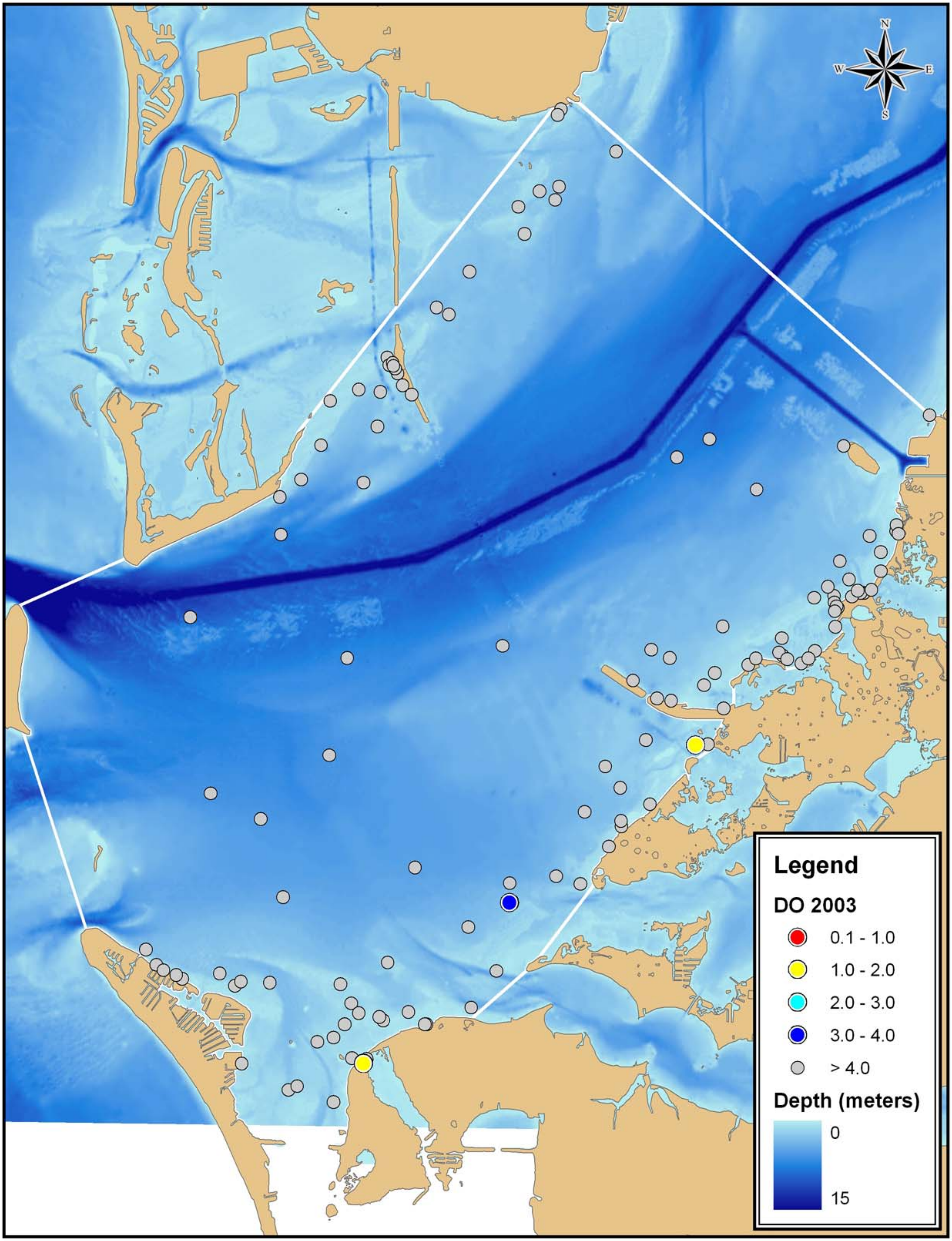

N
S
W
E
Legend
DO 2002
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15


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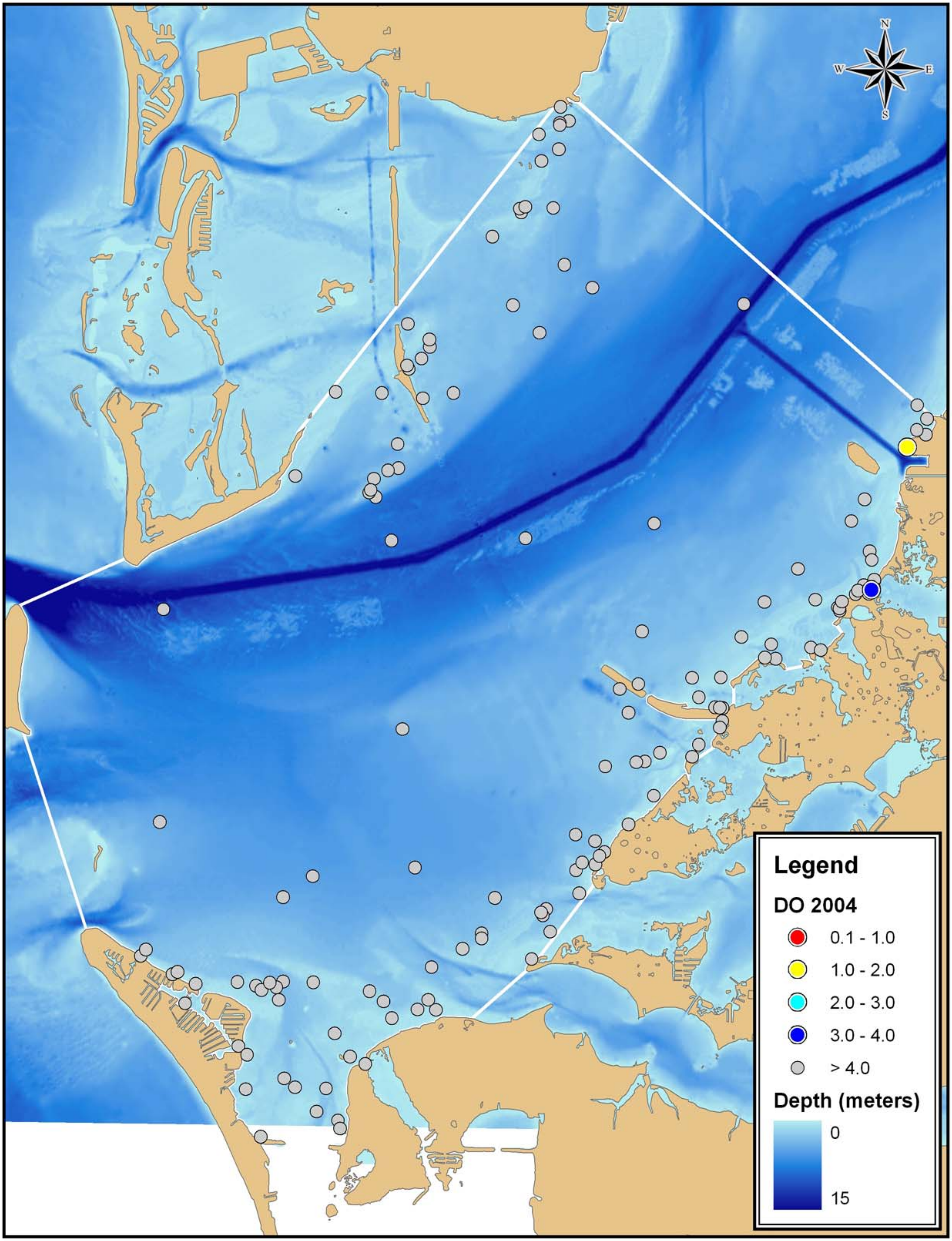
N
W
E
S
Legend
DO 2004
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
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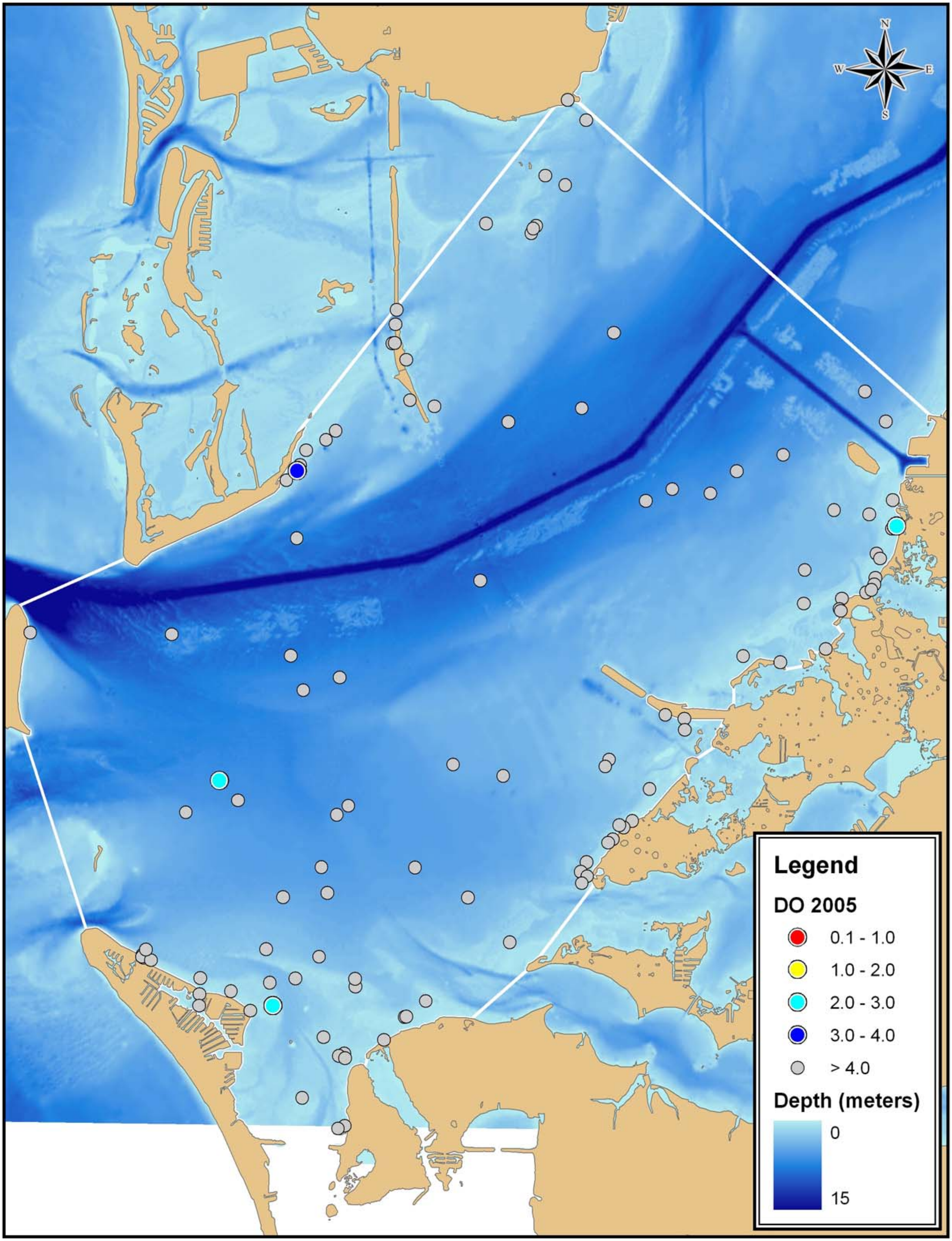

N
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DO 2005
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
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Depth (meters)
0
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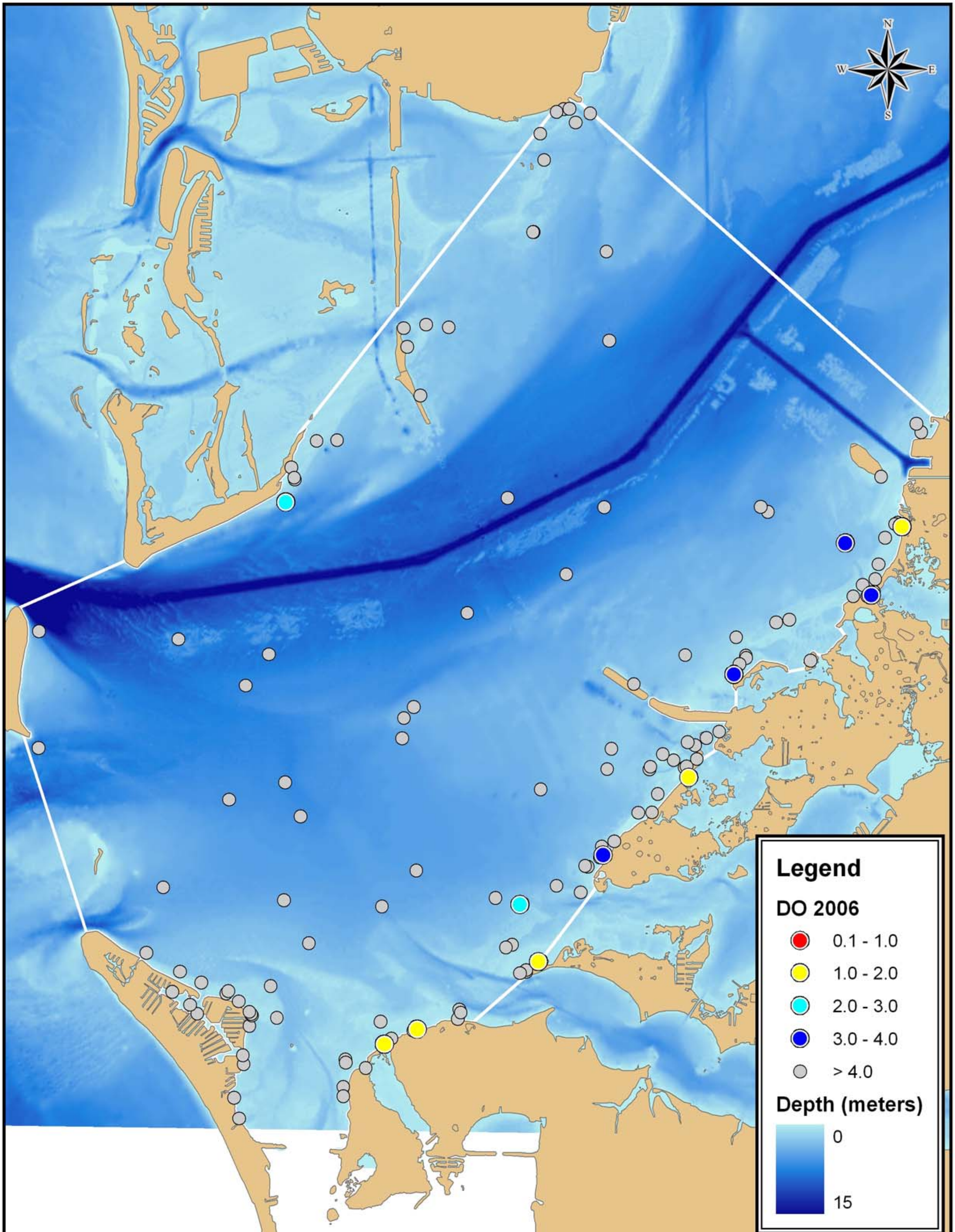
N
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Legend
DO 2006
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
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Depth (meters)
0
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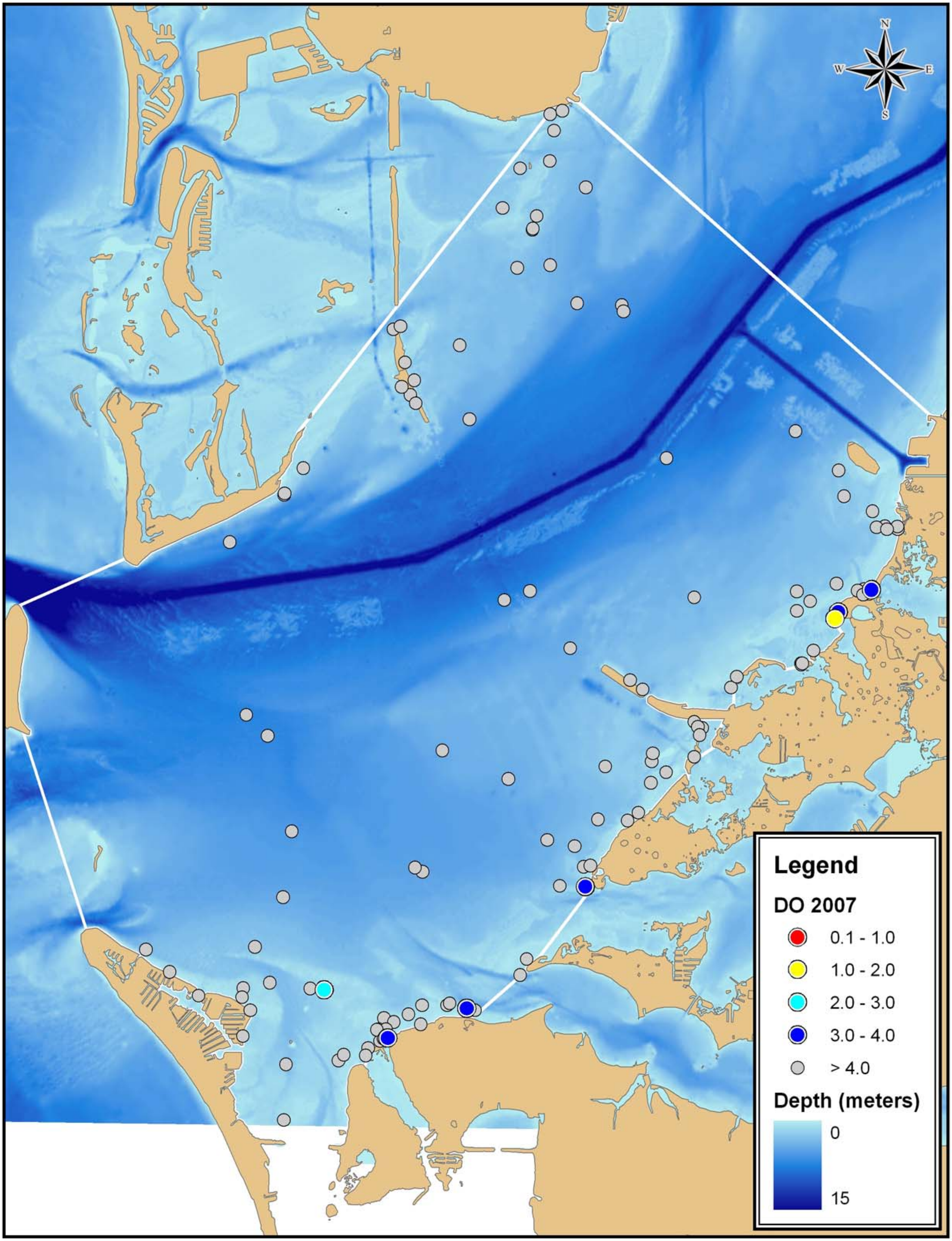
N
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DO 2007
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1.0 - 2.0
2.0 - 3.0
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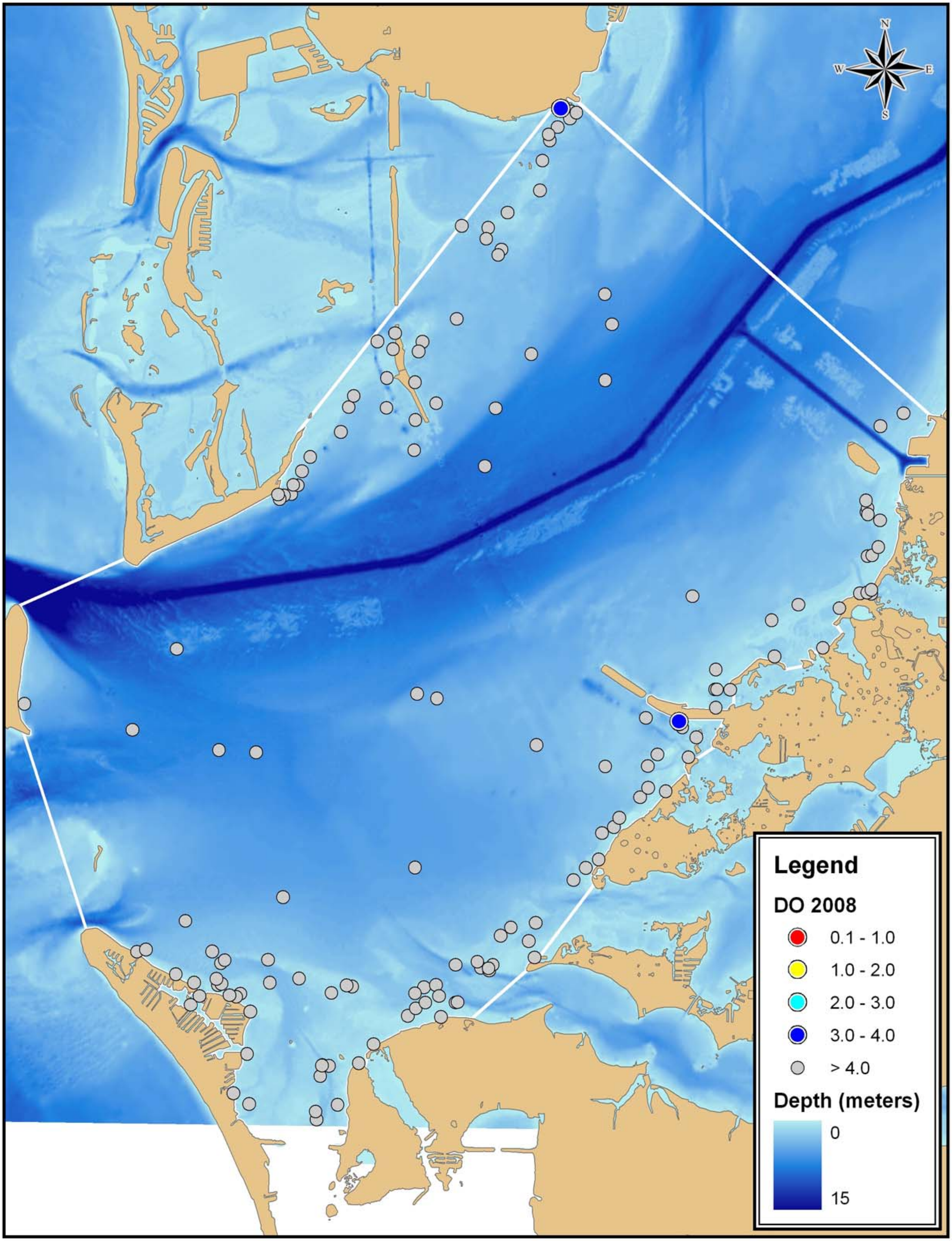
N
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Legend
DO 2008
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
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Depth (meters)
0
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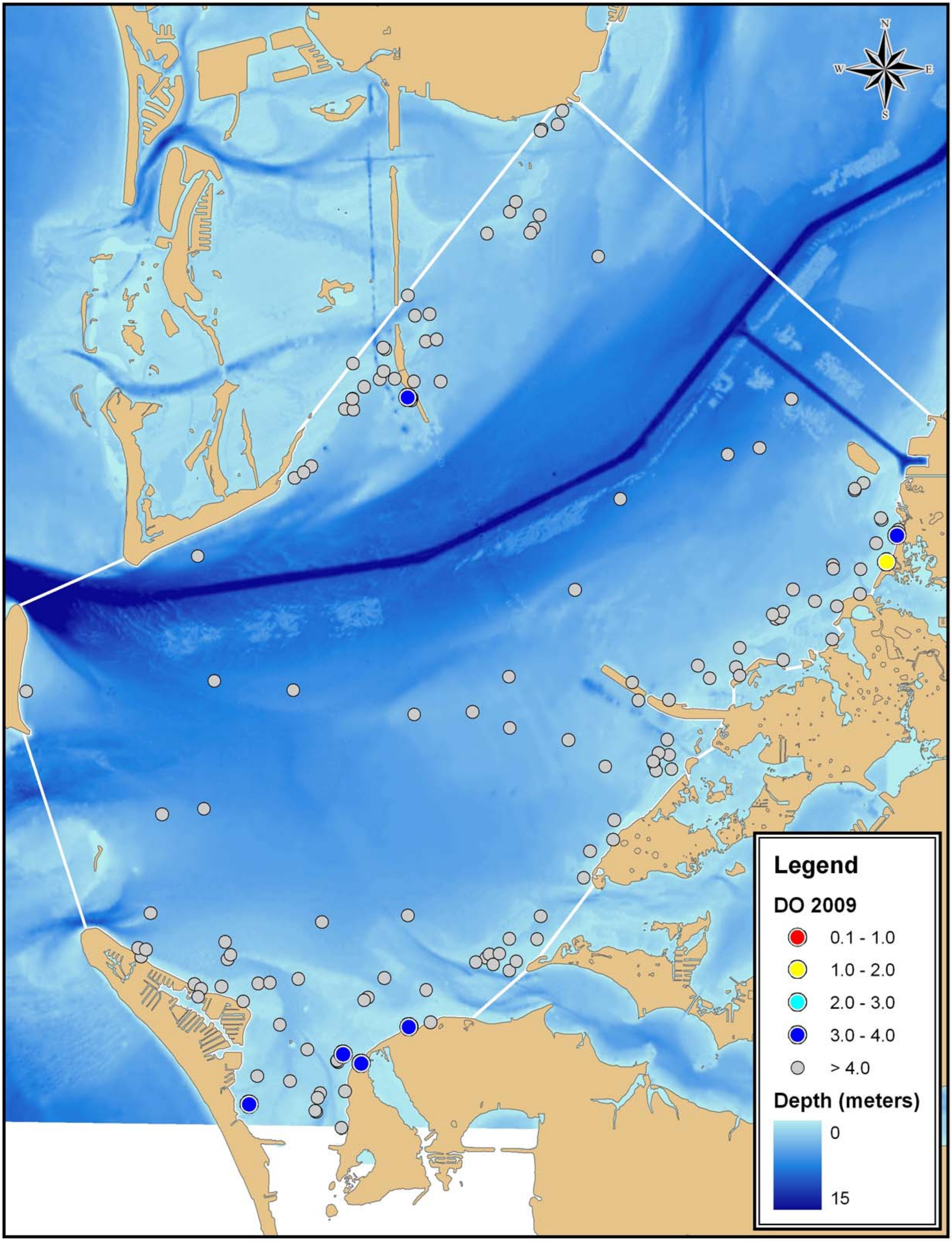

N
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S
W
Legend
DO 2009
0.1 - 1.0
1.0 - 2.0
2.0 - 3.0
3.0 - 4.0
> 4.0
Depth (meters)
0
15