THE RELATIVE ROLES OF SALINITY STRATIFICATION
AND NUTRIENT LOADING IN
SEASONAL HYPOXIA IN CORPUS CHRISTI BAY, TX

A Dissertation

by

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Abstract

Hypoxia (low dissolved oxygen concentration) is known to occur in the southeast corner of Corpus Christi Bay, Texas, USA each summer since its discovery in 1988. In 2006, ongoing field research discovered that the hypoxia area has a greater extent spatially and temporally than previously thought. Although it was known that hypoxia was associated with salinity stratification, it was not until 2007 that it was discovered that salty water from both Oso Bay and Laguna Madre were contributing to this stratification. This is interesting because there are three wastewater treatment plants that empty into Oso Creek and Oso Bay, so there is a source of nutrients as well as salt.

The purpose of the current study was to determine the spatial and temporal extent of hypoxia, to explore the role of nutrients and bay currents in the formation and frequency of hypoxia, determine what role small rain events play in the formation of hypoxia, and test the feasibility of disseminating the data collected in this study and others to the public via the use of a standardized database schema and web services. Hypoxia was found to begin as early as the first week of June, and occur as late as the last week of August, i.e. stops when wind stops.

Hypoxic conditions can extend from Ward Island to Shamrock Island, an area estimated to cover 80 km^2. Nutrient concentrations are not at high levels however, ammonium levels are higher in the hypoxic zone, likely due to anaerobic remineralization of organic matter. Even small-scale rain events appear to flush nutrients from Oso Bay;

however, this does not appear to affect hypoxia in Corpus Christi Bay. Differences in acoustic opacity, current velocity, and current direction, and salinity between the bottom waters and those above may all be contributing to stratification, known to cause hypoxia. Hypoxia also appears to be influenced by the fortnightly lunar cycle, bathymetry, and bottom composition. Attempts to transform data from this project into a standard database schema were successful. However, not all of the complexities of biological nomenclature, multivariate data structures, and laboratory information requirements could be met with the system under study.

Dedication

To Shelly:

"If I have seen further, it is by standing on the shoulders of giants." Sir Isaac Newton.

I have only succeeded in this effort because *giants have stood by me*. I dedicate this work to Shelly, my wife and partner in life. She suffered with me through long nights, and tiring days; through times of doubt and of jubilation; through good times and through bad. I do not have the words to express how much her love and devotion mean to me.

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PART I. INTRODUCTION

1.1 Background

Hypoxia is one of many environmental responses caused by multiple stressors including: nutrient enrichment, hydrologic alterations, and climate change. These stressors are influenced by tidal energy, horizontal transport, and optical properties of water resulting in environmental responses that may alter primary production and respiration rates, chlorophyll-*a* (Chl-*a*) concentrations, nutrient ratios, and bottom water dissolved oxygen (DO) concentrations. These responses, in turn, impact the earth system resulting in environmental, human health, and socio-economic costs as well as potential climate impacts. Managing these impacts will require tools for acquisition, analyses, modeling, and visualization of environmental observations.

Hypoxia has occurred in the southeast corner of Corpus Christi Bay since its discovery in 1988 (Montagna and Kalke 1992). Hypoxia is a common phenomenon in estuaries. But its occurrence is unique in Corpus Christi Bay because hypoxia most commonly occurs in deep, stratified waters (Officer *et al.* 194; Gunter 1942; Rabalais *et al.* 1991; Livingston 1996). Corpus Christi Bay is a shallow bay of fairly uniform depth with an average around 3.2 m (Orlando *et al.* 1991b). Stratification in shallow bays is not expected where there are sufficient mixing forces. Corpus Christi Bay experiences a consistent wind forcing (monthly average from 17km/hr - 28km/hr), predominately from the southeast during the period from April to September (Port of Corpus Christi Authority 1993).

Hypoxia is usually defined as dissolved oxygen (DO) concentrations at or below 2.0 mg/L, and at this concentration adverse direct and indirect effects have been shown for aquatic animals (Diaz and Rosenberg 1995). There is evidence that Corpus Christi Bay shows effects at 3.0 mg/L (Ritter and Montagna 1999).

Historically, it has been thought that Corpus Christi Bay hypoxia is due to a process whereby salinity stratification in the water column inhibits the re-aeration of oxygen from the upper water column to the bottom water (Ritter and Montagna 1999). Aerobic organisms in the salty bottom waters use the oxygen in respiration resulting in the depletion of oxygen at depth. Stratification does occur in Corpus Christi Bay and is associated with occurrence of hypoxia (Ritter and Montagna 1999). The authors speculated that high salinity water in Corpus Christi Bay is sourced from Laguna Madre; and it is transported north either by southeast winds through the Intra-coastal Waterway, or pumped into Oso Bay after being used as cooling water for the Barney Davis power plant and then north into Corpus Christi Bay. This latter assertion is bolstered by observations of a hyper-saline gravity current originating in Oso Bay and extending into Corpus Christi Bay (Hodges et al. submitted 2008). Hodges also observed hypoxia coincident with stratification and asserts that wind forcing energy and isolation time of bottom water are key elements contributing to the phenomenon.

Freshwater flushing rate can also influence the likelihood of the occurrence of hypoxia. Turner and Rabalais (1999) found that in estuaries with long turnover times, oxygen concentrations were more susceptible to change with fluctuations in nutrient loading than estuaries with shorter turnover times. Corpus Christi Bay has a fairly long replacement time of ~350 days (Solis and Powel 1999). The southeast corner in particular displays some of the most sluggish circulation in the entire bay (Ward 1997). Detailed bathymetry of Corpus Christi Bay shows depressions that may be constraining the mixing of bottom water. Modeling efforts incorporating this information have shown hypoxia in Corpus Christi Bay is not continuous in spatial extent and is associated with these small-scale bathymetric changes in Corpus Christi Bay (Ernest To 2008, personal communication).

While associated with hypoxia, stratification is not requisite. Hypoxia can occur in well-mixed environments and can be a signal of eutrophication (Verity *et al.* 2006). In addition to hypoxic and anoxic water conditions, coastal eutrophication enhanced by nutrient loadings is responsible for reduced fishery harvests, algal blooms, and reductions in biotic diversity (Howarth *et al.* 2000). Eutrophication also affects the coastal system of the Gulf Mexico. A region of hypoxic/anoxic waters on the continental shelf, called a "Dead Zone" by the media, is directly related to nutrient enhanced coastal eutrophication (Rabalais *et al.* 2002). Nutrient loadings from the Mississippi River promote algal growth in the Gulf of Mexico. Detritus resulting from fecal pellets and organic matter due to dying algae sinks to the bottom where it is consumed by bacteria. The respiratory demands of proliferating bacteria can cause a drawdown in dissolved oxygen below hypoxic levels (Verity *et al.* 2006). Additionally, increased algae can inhibit the penetration of sunlight into the water column. Although the recent discovery of high-salinity water entering Corpus Christi Bay from Oso Bay (Hodges personal communication) confirms a role for stratification in causing hypoxia, there are three wastewater treatment facilities located in the Oso Bay system, so it is possible that there may be a nutrient component to the formation of Corpus Christi Bay Hypoxia.

Oxygen and nutrient concentrations in the water column are due to loadings to the system as well as the interplay between primary productivity and respiration, which are collectively known as metabolism. Production (autotrophy) releases oxygen into the water column, whereas respiration (heterotrophy) removes it. Net ecosystem metabolism (NEM) is the balance between all forms of production (P) and all forms of respiration (R); NEM=P-R. Odum (1956), proposed NEM as a way to remove detail and focus on the system as a whole. NEM into flowing waters, integrates loads, temperature, salinity, cloud cover, day length, wind, stratification and Chlorophyll-*a*. In this capacity, NEM is a measure of the system's ability to export oxygen or carbon dioxide to the atmosphere. Net heterotrophic systems (where R > P) export and regenerate nutrients while net autotrophic systems (where P < R) require input of inorganic nutrients from external sources (Smith *et al.* 1991). NEM has also been shown to be an indicator of the effect of freshwater inflows on estuarine ecosystem metabolism (Russell *et al.* 2006).

Increasing inorganic nutrient (nitrogen and phosphorous) loadings to water bodies affect oxygen concentrations *indirectly* by fueling algal growth (Bricker *et al.* 1999). Detritus, concomitant with this growth provides the organic matter to fuel bacterial respiration, drawing down benthic dissolved oxygen levels. Increasing organic nutrients affect oxygen concentrations directly by providing fuel for respiration. Increases in estuarine nutrient levels are linked to population and land use trends. Changing agricultural processes were also shown to influence increasing nutrient levels (Verity *et al.* 2006).

Oso Creek, the main input of freshwater inflow to Oso Bay, drains agricultural lands, and the fastest growing region of the city of Corpus Christi, TX. Three wastewater treatment facilities located on Oso Creek and Oso Bay could also play a role in nutrient input and allochthonous oxygen demand. Brock (2001) looked at the nutrient loadings into the Nueces River Estuary, including loadings from Oso Bay, and found that wastewater is the dominant source of nutrients in this system. Nitrogen loading in riverine inflow and rainfall runoff combined, measured only half that of the input from wastewater treatment facilities. Another small contribution was due to atmospheric deposition.

Environmental observations of the Corpus Christi Bay system are available from a variety of number of sources. In fulfilling the requirements of the Clean Water Act, the Texas Commission on Environmental Quality (TCEQ) has compiled a large number of environmental observations, including surface water quality monitoring data. This data is available from the TCEQ website for internet download. A large, historical database of observations of the bays of Texas is maintained by the Ecosystem Modeling group at the Harte Research Institute. This data is housed in native SAS format and for the most part, is available only internally. This short list of disparate, heterogeneous data sources, while not comprehensive illustrates the rationale behind work to provide robust collaboration tools and to decentralize data (Minsker *et al.* 2006).

1.2 Purpose and Questions

The research in this dissertation is aimed at furthering understanding of the causes of hypoxia in Corpus Christi Bay, and in particular to determine if there is a contribution from nutrient loading into the bay. Furthermore, it is the goal to determine the relative contributions of nutrient loading and salinity dynamics to hypoxia in Corpus Christi Bay. Is there a nutrient component to Corpus Christi Bay hypoxia? If so, what are the relative roles due to salinity stratification, geological features, and eutrophication in causing hypoxia?

Linear geological features in the bay may be compartmentalizing the bay bottom, constraining highly saline bottom water, leading to hypoxia. Can this compartmentalization be observed in temperature and salinity patterns in the record? If so, can this effect be used to better model hypoxia in the bay? Can it be used to guide the direction of future sampling in the bay? Additional questions to be addressed in this research are: What is the extent in time and space of hypoxia in Corpus Christi Bay? What role do freshwater pulsed inputs play in nutrient loading and bay hypoxia? What role do the wastewater treatment facilities located on Oso Bay play? The purpose of the research proposed in this document is to address these questions posed above.

All data resulting from the research (where allowed by possible copyright restrictions) has been ported to the observations data model (ODM) schema. This was done in order to leverage current efforts in modeling, analysis, and visualization to provide added value to the data publication and to move toward a concept of the digital estuary. The digital estuary conception combines historical data, real-time sensor data, as well as standardized access methods in a geospatially-centered representation of the Nueces-Corpus Christi Bay system. The digital estuary system will be easily accessible by scientists, public, and managers through direct access via a web portal, or programmatically via web services. Additionally, all geo-referenced visualizations resulting from this research will be made available to scientists and the public at-large via a web application based on the Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI) Hydrology Information Server (HIS).

1.3 Hypotheses

To answer the question, the following hypotheses are posed and will be tested:

H_1: There is a contribution to Corpus Christi Bay hypoxia due to nutrient loading:

Is there a nutrient contribution to hypoxia in Corpus Christi Bay? If so, what is the relative contribution of nutrient loadings to the hypoxia phenomenon?

H_2: Freshwater inflow and pulsed inputs to the southeast corner of Corpus Christi Bay affects nutrient dynamics and contributes to increased heterotrophy contributing to bay hypoxia.

What influence does freshwater inflow from Oso Bay have on the hypoxic disturbance in Corpus Christi Bay? What are the natures of the bays' responses to pulsed inflow? Can these responses be related to the hypoxic disturbance?

H_3: Bathymetric features in Corpus Christi Bay affect the nature of circulation in the southeast corner of Corpus Christi Bay contributing to the spatial distribution of hypoxia.

What effects do small bathymetric features in Corpus Christi Bay contribute the hypoxic disturbance in Corpus Christi Bay?

H_4: The spatial and temporal extent of Corpus Christi Bay Hypoxia is greater than previously measured.

What is the extent in space and time of the hypoxic disturbance in Corpus Christi Bay?

These hypotheses are tested in a series of field experiments. Links between nutrient concentrations and hypoxia are tested in a synoptic survey over a five month period. The spatial and temporal extent of the synoptic survey is chosen to determine the extent of hypoxia in space and time. Nutrient sampling during this survey provides the most comprehensive characterization of nutrient distribution in Corpus Christi Bay to date.

The fate of nutrients from pulsed freshwater inflow events into Oso and Corpus Christi Bays are examined by surveying water quality and nutrient concentrations during events on several scales not previously studied.

Acoustic Doppler current profilers and datasondes are used to collect a continuous time series to test for the effect of bottom features, current speed and direction, and acoustic opacity on the occurrence and duration of hypoxia. The length of these series and the locations of the observations make it possible to determine the relationships between the frequency of hypoxia and tidal cycles and bathymetry.

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PART II. Observation Data Model for the Corpus Christi Bay System

2.1 Introduction

Management, stakeholders, and interested members of the public benefit from increased access to tools that make their endeavors easier. These tools come in a number of forms from social media like Facebook to public safety systems like Nixle. From simple notifications to complex digital "dashboards", these tools are desired increasingly in the market and the scientific community.

Spurred by low-cost and the high availability of sensors, groups like researchers in the weather forecasting community (Plale and Gannon 2006), and the Consortium of Universities for the Advancement of Hydrologic Sciences (CUAHSI, http://his.cuahsi.org) (Maidment 2005) have developed the cyber-infrastructure to coordinate data from various sources and provide data-driven tools for forecasting, modeling, and adaptive sampling. CUAHSI has developed a database schema, or observations data model (ODM), for the purpose of providing a standardized repository for historical and continuous observations of hydrological data as well as the accompanying metadata (Tarboton *et al.* 2008). Developed in concert with the ODM, WaterOneFlow, is a set of XML-based web services that provide common Internet-based access methods for online data sources (Valentine and Whitenack, 2008).

The CUAHSI model is designed for hydrologic observations. Is the model generic, and robust enough to encapsulate observations from outside the hydrological paradigm, such as the biological data from Rincon Bayou? Can ODM provide the necessary data and metadata structures to store and maintain biological data and laboratory-derived data?

Ecosystem informatics is the process of blending ecosystem studies, computer science, and mathematics to further contributions in these fields, but also to facilitate ecosystem and/or natural resource management. Various observing agencies, universities, and other organizations collect data from many sources and organize this data using a variety of means. Access to the data is often limited to one desktop. When shared on multiple desktops, complicated schemes are necessary to ensure concurrency of the data. Limited access and varied platforms inhibit the ability to synthesize data, which is necessary to perform analyses and employ visualization techniques.

2.2 Background

The ODM was used in three "experiments", growing in complexity; in support of the development of cyber-infrastructure to support large-scale environmental engineering, to facilitate the synthesis of date for the study of Rincon Bayou, and finally a more complicated, but similar project to support a study of sediment quality status and trends in the coastal bend.

In the first case the goal was to instantiate a CUAHSI Hydrographic Information Server. This server would be part of one of 11 WATERS network testbeds around the country created to implement a large-scale collaborative network of data streams, warehouses, and web servers. In particular, this testbed was set up to create an observation network to study the hypoxic area in Corpus Christi Bay.

The second study used the ODM/webservice construct to synthesize and publish relatively small data sets from HRI, University of Texas Marine Science Center (UTMSI), and the Center for Coastal Studies (CCS). Unlike the previous hypoxia example, this project required the input of more complex environmental and biological data used to study restoration efforts in Rincon Bayou.

Restoration of Rincon Bayou and marsh in the Nueces Delta began in 1994 with construction of a channel to divert fresh water into the marsh (BOR, 2000). The diversion was filled in 2000 but reopened in 2001. In 2007, a pipeline began to deliver water directly into Rincon Bayou from the Calallen Pool. Extensive monitoring of the Rincon Bayou area has taken place, first funded by the U.S. Bureau of Reclamation (Bureau of Reclamation (BOR) 2000), and more recently funded by the City of Corpus Christi. The purpose of the freshwater inflow diversions has been to restore marsh function and is part of an overall strategy to manage environmental flows from the Nueces River water system to increase firm yield of the water supply. The Nueces Delta is one of only three places in Texas where the permit and State orders require environmental flows, making this an important public issue.

To make possible the exploration of these questions, Rincon Bayou data was extracted from historical sources, transforming the environmental data into the ODM schema and instantiating web services for online access to the data.

Finally, the third project was to support a status and trends study coastal bend area sediment and water quality. The original status and trends report for the Coastal Bend area was completed nearly 15 years ago (Ward and Armstrong 1997b; Ward and

Armstrong 1997a), and included analyses of water and sediment data through December 1994, 18 years ago. A status and trends project is actually two projects: one to assemble and organize the data base, and one to perform analyses and write the report. This work encompasses the first of these two projects.

2.3 Materials and Methods

2.3.1 Information System Requirements

The ODM requires a relational data base management system, SQL Server 2005 in this case. To run the CUAHSI web services, MS Internet Information Server and MS Visual Studio 2005 were necessary. All components were installed on a server running MS Windows Server 2003. A blank database ODM schema was downloaded from the CUAHSI website: http://his.cuahsi.org/odmdatabases.html. The blank schema was attached to a workstation running SQL Express using the SQL Server Management Studio. It should be noted that while the Express version of SQL Server was used to create the final synthesis product, tools found only in the Enterprise version of the SQL Server (i.e., SQL Management Studio and SQL Server Integration Services (SSIS)) were used in the process.

2.3.2 Data Sources

Data sources for the hypoxia project came from Harte Research Institute for Gulf of Mexico Studies at Texas A&M University - Corpus Christi (HRI). This data has been collected for over 20 years. first by UTMSI, then HRI. Latitude and longitude for each site was provided using GPS. The source data was all native SAS tables.

Data from the Rincon Bayou and in the Nueces River Delta and Nueces Estuary system in Corpus Christi, Texas came from three sources: The Center for Coastal Studies at Texas A&M University - Corpus Christi (CCS), HRI, and UTMSI. Each observation by every institution was made at a specific location, however latitude and longitude were not provided for all of the points in data collected along transects. Coordinates for these sites were obtained by interpolation. A variety of data management methods were employed by the participating groups, including MS Access databases, MS Excel spreadsheets, and SAS-based data files.

Coastal Bend sediment and water data for the current status and future trends study came from many sources. The data used for this project exists in two forms, electronic and paper records. Paper records were not of sufficient quality to use optical character recognition, so were hand-keyed into Excel spreadsheets prior to import and transformation. For electronic records, a copy of the source database was procured. Many types of source files were represented: Excel spreadsheets, Access databases, native SAS tables, and text-based extracts of proprietary databases such as those from the Texas Commission on Environmental Quality (TCEQ) and the Texas Parks and Wildlife Department (TPWD). In few cases were the data definitions for the data sources similar. This meant that each source file was treated individually with little opportunity to reuse code.

2.3.3 Extraction Transformation, and Loading

The overall process of data extraction, transformation and loading (ETL) is illustrated in Figure 1.

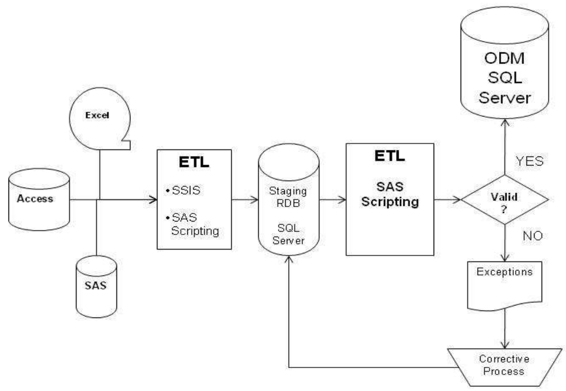

Figure 1 - Extraction, transformation, loading process

Extraction for the SAS-based and Excel-based data files was accomplished mainly through the use of SAS import functions (PROC IMPORT) and scripting using the SAS data language (SAS Institute 1999). The SAS-SQL Server connection was accomplished using open database connectivity (ODBC) facilities in SAS, SQL Server, and Windows XP. Data extracted from original digital sources were staged on the SQL server, with little modification to their original structures or data types. Access database files were imported into the staging database using SSIS. Paper records were "extracted" by hand into Microsoft Excel, then imported into the staging database via SSIS. Once staged, the SQL data language, via SAS PROC SQL, was used to transform, validate, and load the data into the ODM schema. Validation exceptions were routed to the data managers for research and correction and subsequent reloading. Once the ETL process was complete, the ODM instance was detached from the development workstation and reattached to the production server.

2.3.4 Web Services

After the ODM instance was loaded, it was attached to the SQL server, and web services to access the ODM were created by tailoring the generic WaterOneFlow web services downloaded from the CUAHSI website at http://his.cuahsi.org/wofws.html. Installation proceeded as instructed by Valentine and Whitenack (2008). The procedure called for creating the required accounts on the operating system and SQL Server, mapping these accounts to logins and roles on the server, installing the web services application on the server and configuring the web server for access to the application.

2.4 Results

2.4.1 Hypoxia Network

Water quality data was successfully extracted and transformed into the ODM schema. This database was successfully detached and reattached to the production server. CUAHIS web services were attached to the database and all functionality of the HIS server was utilized as designed. All data types were successfully represented in the ODM schema, however while the original records' variables were tied to each other by record structure, in the ODM, the record is decomposed into a record for each variable, in effect losing the connection between them.

2.4.2 Rincon Bayou Reconstruction Project

Transformation of the data resulted in over 600,000 distinct observations in 44 different variable types grouped below into five general categories (

Table 1). The number in parentheses denotes the number of distinct variables of that type. For instance, under biota, the variable

Table 1 - Listing of variables in the ODM by general category. Numbers in parentheses represent the number of variables of a specific type.

Atmosphere	Biota	Water Nutrients	Water	Sediment	Other
Barometric Pressure	Avian Activity	[NH_4]	Dissolved Oxygen	$\delta\ ^{13}C$	Instrumentation (15)
Cloud Cover	%Plant Coverage (18)	[N + N]	DO % Saturation	$\delta\ ^{15}N$	Tidal Statge
Days since precipitation	Species (g/m^2) in core (7)	[NO_3]	Color	%C	
Precipitation	Species (mass) in core (7)	[NO_2]	Redox Potential	%N	
Relative Humidity	Species (#/m^2) in core (7)	[Orthophosphate]	pH	%Sand	
Temperature	Species # in core (7)		Depth	%Rubble	
Wind Direction	Species # indexed (5)		SECCHI Depth	%Clay	
Wind Speed	[Chlorophyll]		Salinity	%Silt	
Weather Conditions			Surface Appearance		
			Specific Conductance		
			Temperature		
			Visual Turbidity		

"%Plant Coverage" denotes the percentage of cover for a specific plant species. In this exercise, there were 18 different species, including wrack represented in the data. Each species was coded as a separate variable. Similar schemes were used in the other biota variables accompanied by a number in parenthesis. For instrumentation, the number represents variables used in procedures used to derive a final observation. For instance, tare weight and rubble mass were used to derive sediment grain size percentages.

The geographical extent of the synthesized data includes observation sites along the entire estuary (Figure 2). A total of 483 different sites are represented in the data. This includes interpolated positions along the plant coverage transects. Observations from Nueces Bay, Nueces River, and hypoxia studies in Corpus Christi Bay and Oso Bay are also included in the synthesis.

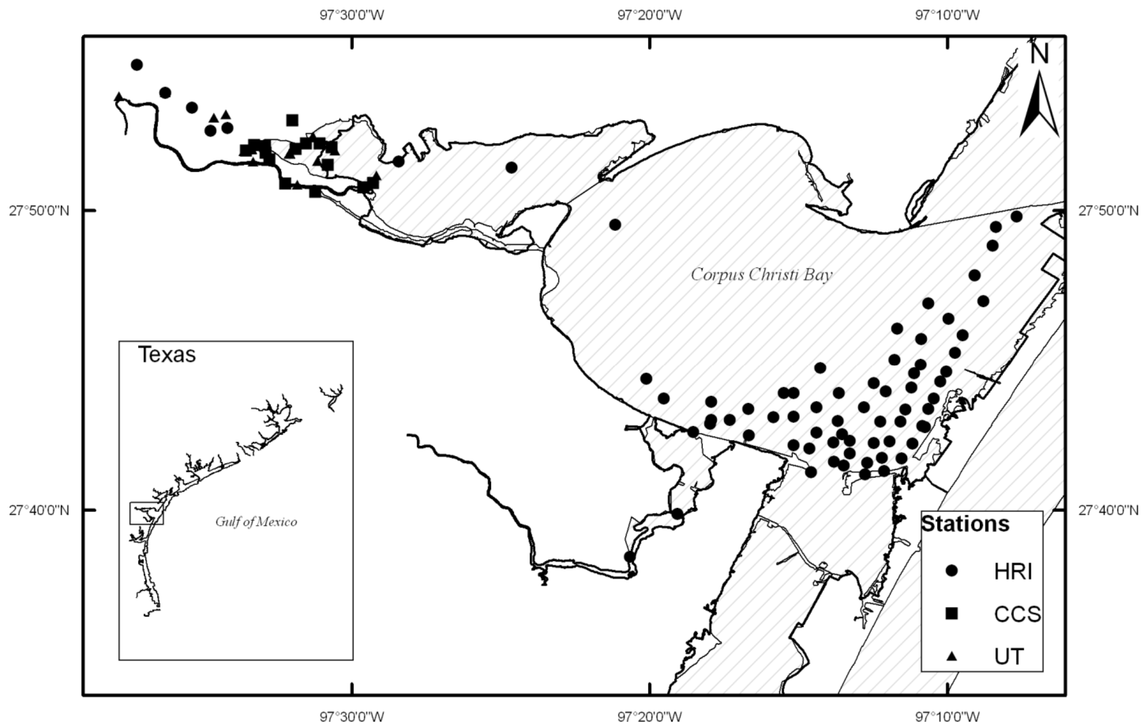

Figure 2 - Geographical extent of synthesized data. Marsh plant transects shown as one point.

The UT Marsh Database sites are unique in the project. These sites are arrays of transects consisting of various numbers of sample sites. (Figure 3) The latitudes and longitudes for the sites indicate the position of the transect array, not the location of the sample. Interpolation was used to determine the coordinates of each point location on the transects.

Figure 3 - Example of UTMSI Marsh Database site showing scale and transects

2.4.3 Status and Trends Project

Sites

The vast majority of these sites are from the TCEQ database. All sites that have observations of the environmental variables of interest were included in the transformation even if they were not from the Corpus Christi Bay system (Figure 4 and

Figure 5). Transformation of the data to date has resulted in 8,938,576 distinct observations, the majority, 7,504,629 from the TCEQ database (Table 2). Observations range in date from 1968 to 2011. In total, there are 8,279 sites in the database.

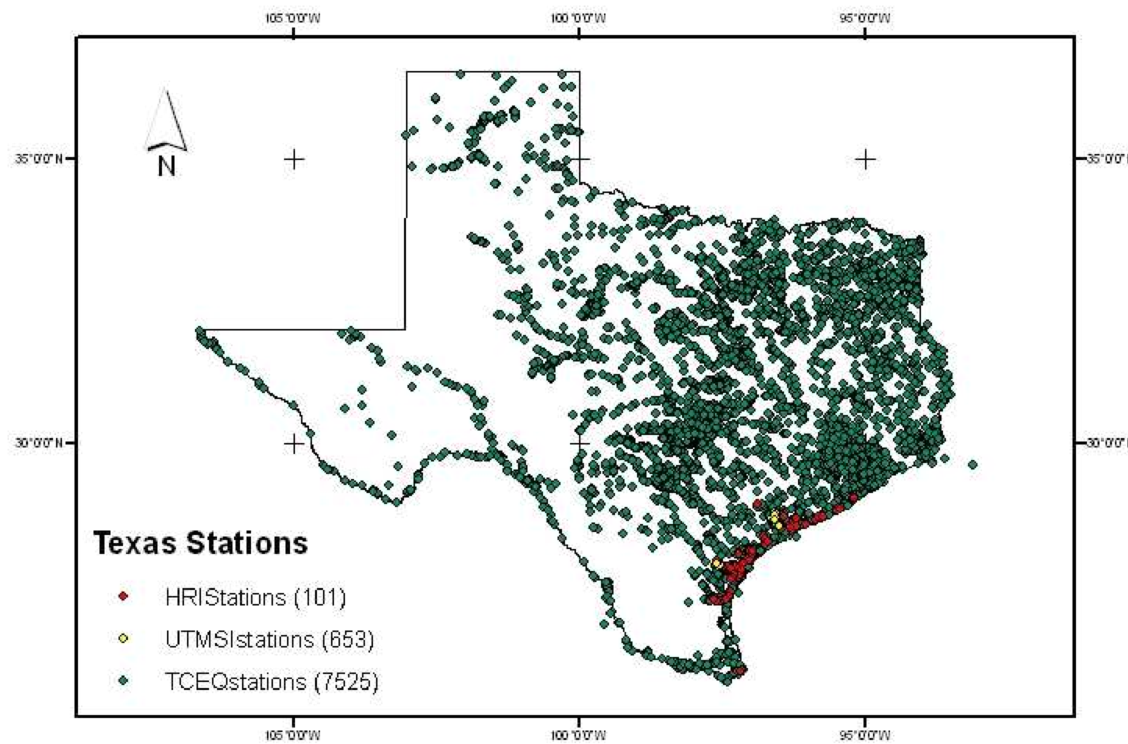

Figure 4 - Sites included in current status and trends project

Table 2 - Listing of observation counts by source description

Source Description	Count
Extraction from TCEQ database	7,504,629
Collection of Continuous sonde observations supporting multiple projects	1,060,998
Extraction from UTMSI Marsh Database	349,318
Collection of nutrient/chlorophyll concentrations for Texas Coastal waters	20,733
Hardcopy text of final report for Texas Water Development Board	2,898

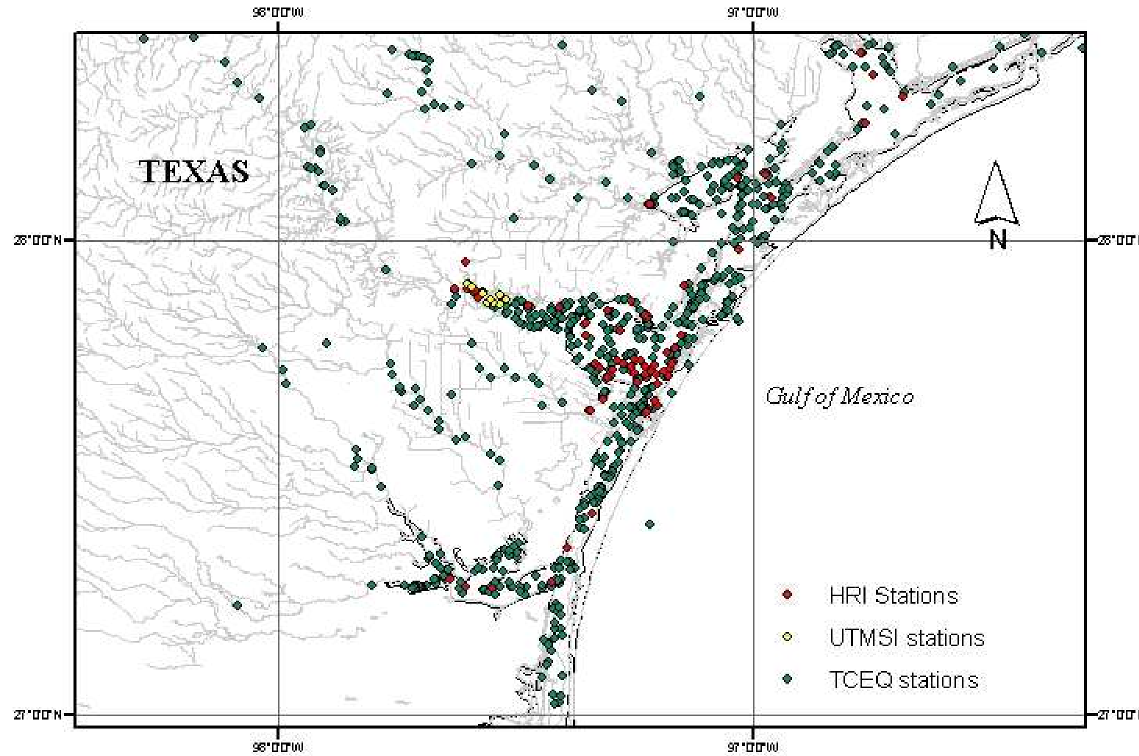

Figure 5 - Coastal Bend Area Stations included in the project

Table 1 shows the top 25 sites by the number of observations collected at each site. The list is dominated (16 of the 25 sites) by continuous observations gathered by Dr. Paul Montagna's research on hypoxia (designated as HY) in Corpus Christi Bay. In these instances, 1 to 5 environmental observations were taken at the same time. Because each variable is treated separately in the ODM, each observation is included in the counts even though logically they are part of a larger, multivariable record.

Table 3 - Listing of top 25 sites by number of observations

Site Name	Count
Site 24 in Bay/Project HY	182,986
Site 19 in Bay/Project HY	100,019
Site 2 in Bay/Project HY	78,931
Site 309 in Bay/Project HY	54,995
Site 41 in Bay/Project HY	53,684
Site 199 in Bay/Project HY	53,679
Lake Travis Near Dam At LCRA Travis County Park	52,881
Site 39 in Bay/Project HY	52,643
Site 310 in Bay/Project HY	51,982
Site 430 in Bay/Project HY	47,362
Site 17781 in Bay/Project HY	40,222
Site 410 in Bay/Project HY	37,592
Site 17787 in Bay/Project HY	36,706
Lake Travis At Arkansas Bend To The West Of Ranch Road 620	36,348
Lake Buchanan Near Buchanan Dam Approx 475 Meters To The West Of Coronado Rd	34,153
Site 17793 In Bay/Project HY	32,716
Site 440 In Bay/Project HY	31,511
Site 18247 In Bay/Project HY	30,944
Site 420 In Bay/Project HY	30,315
Lake Travis Mid Lake Adjacent To Lakeway/To The North Of Corinthian Road	29,257
Lake Lyndon B Johnson Near Alvin Wirtz Dam Approx 658 Meters North Of Fm 2147	26,728
Richland-Chambers Reservoir Chambers Creek Arm Near TCWCID 1 Pump Station 570 M S And 1.16 Km W Of Intersect Of Se 3240 And Se 3250	26,596
Lake Buchanan At Rocky Point Approx 1.3.Km Northwest Of Rocky Ridge	26,254
Lake Travis Mid Lake At Confluence With Cow Creek Arm At Pace Bend Approximately 2.02 Kilometers To The South Of Fm 1431	23,574
Inks Lake Near Inks Dam Approx 161 Meters To The Northeast Of Roy Inks Dam	22,794

Variables

A total of 230 variables have been coded into the database. The vast majority of these are from water quality observations, but variables representing measurements of the biota are also included. While most of the observations in the project so far are from surface water, observations in air, sediment, pore water and tissue are also represented. Table 4 lists the top 25 variables ordered by the number of observations of that variable.

Table 4 - Listing of top 25 sample media variables ordered by number of observations

Variable Name	**Count**
Temperature	1,056,823
pH	852,000
Oxygen, Dissolved	835,054
Specific Conductance	818,926
Oxygen, Dissolved Percent Of Saturation	286,112
Salinity	270,820
Phosphorus, Total	243,781
Chloride	240,724
Sulfate	230,173
Chlorophyll a	228,330
Streamflow	224,602
Solids, Total Suspended	220,505
Nitrogen, NH_3 + NH_4	200,485
Coliform, Fecal	195,633
Phosphorus, Orthophosphate Dissolved	195,466
Turbidity	164,002
Solids, Total Dissolved	155,595
Alkalinity, Total	148,108
Carbon, Total Organic	144,101
Secchi Depth	140,694
Nitrogen, Nitrate (NO_3)	132,405
Water Depth	129,683
Solids, Volatile Suspended	118,458
Nitrogen, Nitrite (NO_2) + Nitrate (NO_3)	116,642
Nitrogen, Total Kjeldahl	112,996

2.4.4 Public Access

Please note that at the time of this writing, the HydroServer system created during these projects is complete and all functionality has been tested. It currently resides behind the Texas A&M University-Corpus Christi firewall and so is not accessible to the public. A request has been made to locate the HydroServer on the DMZ and to impliment the necessary configuration changes required for public access.

As soon as the server is online, access to the data in the project is accomplished via web services. Web services provide a reliable way to discover data, query the database, and display the results. While it is conceivable that researchers will utilize the web service calls in unique ways, a couple of methods have been developed that are fairly easy to use - HydroDesktop, and HydroExcel.

Web Services

Web services were completed as a part of all three studies. All of the data can be accessed at http://ccbay.tamucc.edu/CBBEPDAP_ODWSv11/cuahsi_1_1.asmx. This link can be used by various clients to access the data for this project. Operations provided by the web services are shown in Table 5. Object forms of the operations have a more complicated, but more powerful return. Non-object forms return data streams in WaterML a superset of XML or Extended Markup Language. This list, as well as more information and a service description can be found going to the CBBEP Data Access Project web service address above in any web browser.

Table 5 - CBBEP Web Service Operations

Operation	Returns
GetSiteInfo	Site metadata
GetSiteInfoMultipleObjects	Metadata from multiple sites
GetSiteInfoObject	Site metadata (object form)
GetSites	Sites
GetSitesByBoxObject	Sites in a geographical box
GetSitesObject	Sites (object form)
GetValues	Values given site and variable
GetValuesForASiteObject	Values given site and variable(object form)
GetValuesOb ject	Values (object form)
GetVariableInfo	Variable information based on variable code
GetVariableInfoObject	Variable (object form)
GetVariables	Variable
GetVariablesObject	Variable (object form)

HydroDesktop

Several tools were developed by the CUAHSI community. Currently, HydroDesktop is the most functional and easy to use to download data from CUAHSI web services. HydroDesktop is a desktop-based application designed to integrate with the CUAHSI HIS services for data discovery, download, and display (Figure 6). Users can connect to centralized datasets registered with HIS Central, or they can download the observation catalog from any CUAHSI-compatible web service for use with HydroDesktop. Once connected, users can query a geographical region, select multiples sites and variables, and download the selected data series.

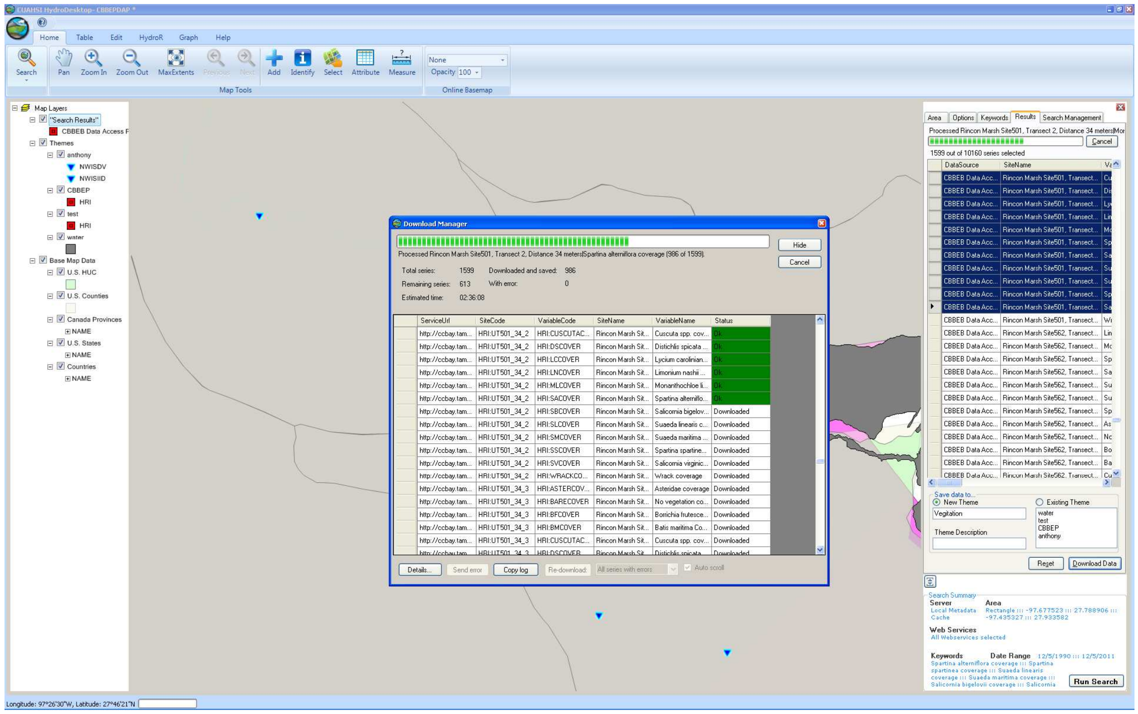

Figure 6 - Screen capture showing selection and download from multiple sites using HydroDesktop

Once data have been selected and downloaded into the user interface, a graphical display of the data can be created. For these screen captures, data from the UT Marsh database were downloaded from the web services. HydroDesktop facilitates the plotting of time series from multiple sources in one graph. For instance, the plot in Figure 7shows the percent coverage of *Batis maritima* at several points along a transect from the UT Marsh database, overlaid with stream flow data from USGS web services supplied via HIS central.

HydroDesktop can be downloaded free of charge from the CUAHSI website at http://hydrodesktop.codeplex.com/wikipage?title=Getting%20HydroDesktop&referringTitle=Documentation. Thorough documentation for HydroDesktop can be downloaded at http://hydrodesktop.codeplex.com/documentation. Included on this documentation page is a link to a document outlining how to connect unpublished web services to HydroDesktop - Unpublished Web Services Tutorial.pdf. This tutorial outlines the procedure for connecting unpublished services, like the new CBBEP Data Access Project webservices to HydroDesktop. This is a slightly more complicated procedure than for HIS Central-published web services, but it enables HydroExcel to connect to any CUAHSI-compliant web services.

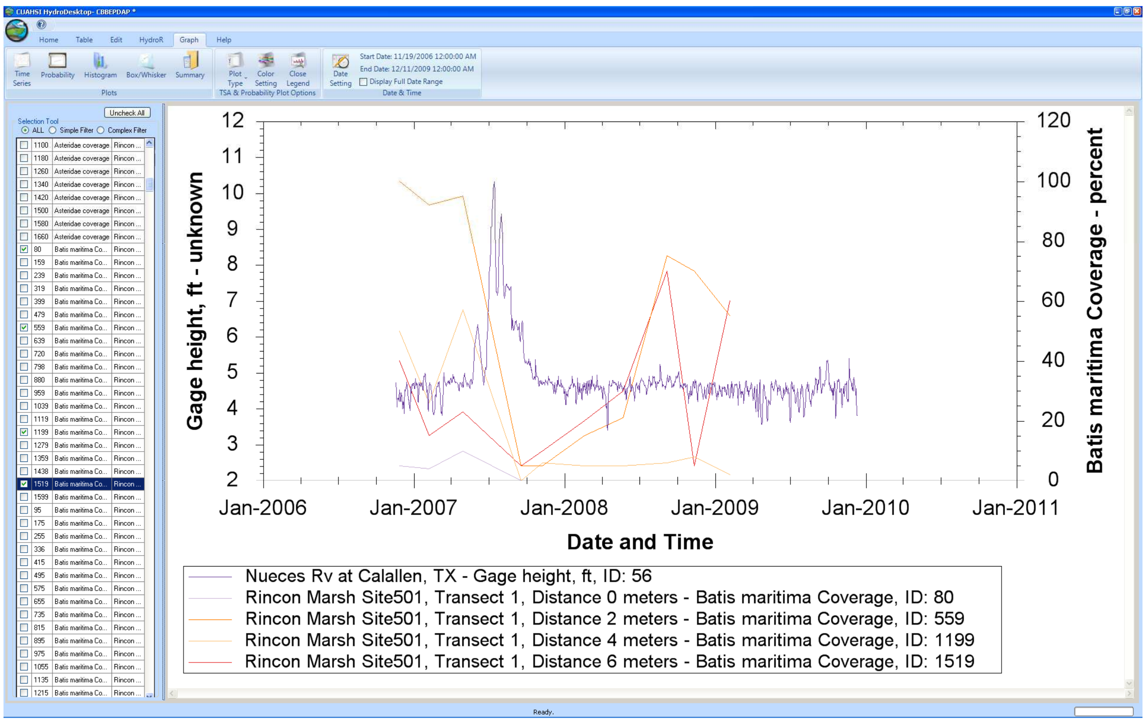

Figure 7 - HydroDesktop screen capture of multiple data sources data plot

HRI HydroServer Web Application

The HRI HydroServer resulting from these three case studies also serves a CUAHSI-created web application. This application removes the requirement of any desktop software except a browser and provide a description of the capabilities of the HydroServer including data regions, and observation and geographic data services

(Horsburgh 2011b). Once open to the public, access to query the map application, information about the services, access the time series analysis tool, and data query functions are located at the default website: http://ccbay.tamucc.edu.

Selecting a region and launching the map application brings up a web page showing the region and all of the sites available for selection. The base map and site information is delivered by an ArcGIS map service running on the HydroServer and a connection to the ODM database (Horsburgh 2011a). A screen shot of the HydroServer map application displaying Corpus Christi Bay is shown inFigure 8.

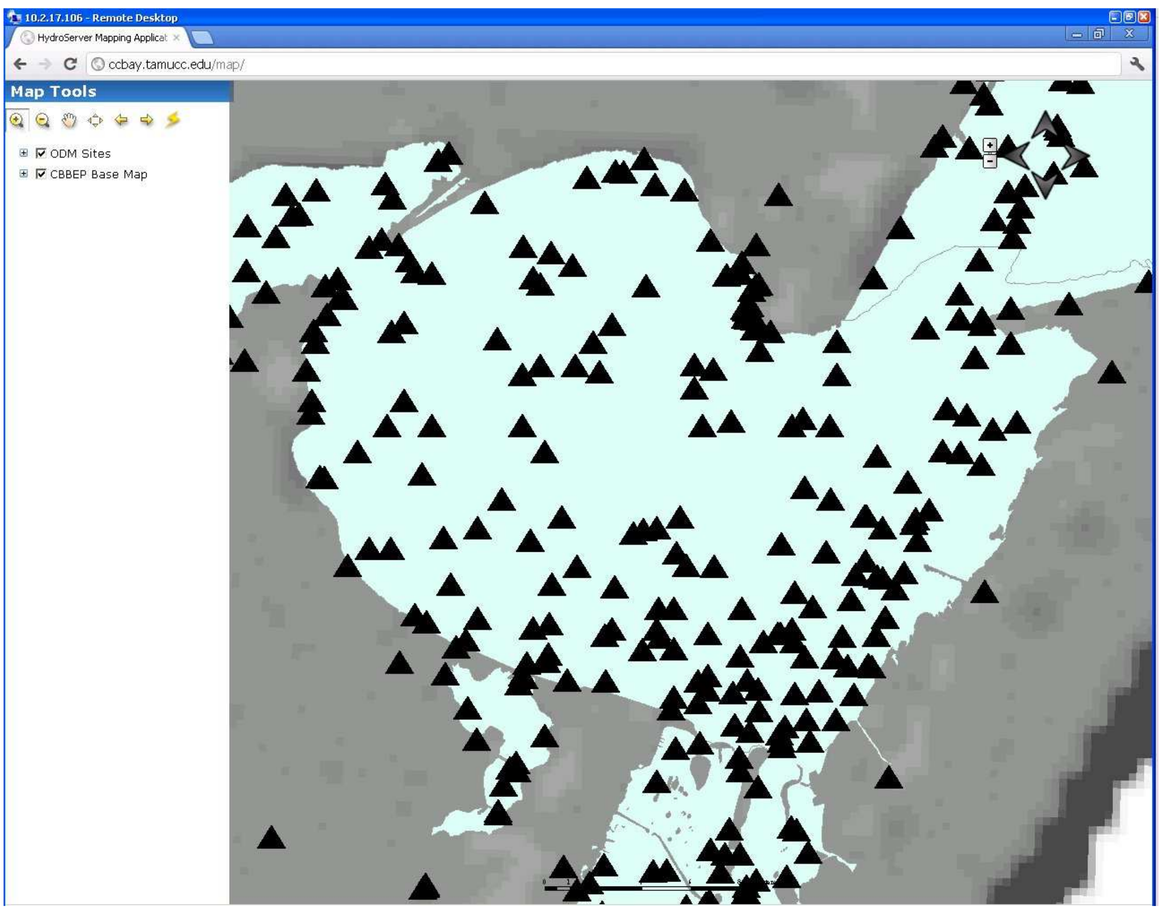

Figure 8 - Zoom-in of Corpus Christi Bay using the HydroServer map application

The application is fully-functional and allows panning the geographical area and zooming in or out on a region. Once a region of interest has been identified, the user can activate the time series analysis (TSA) tool by clicking the lightning bolt in the top left corner and then selecting a site (Figure 9).

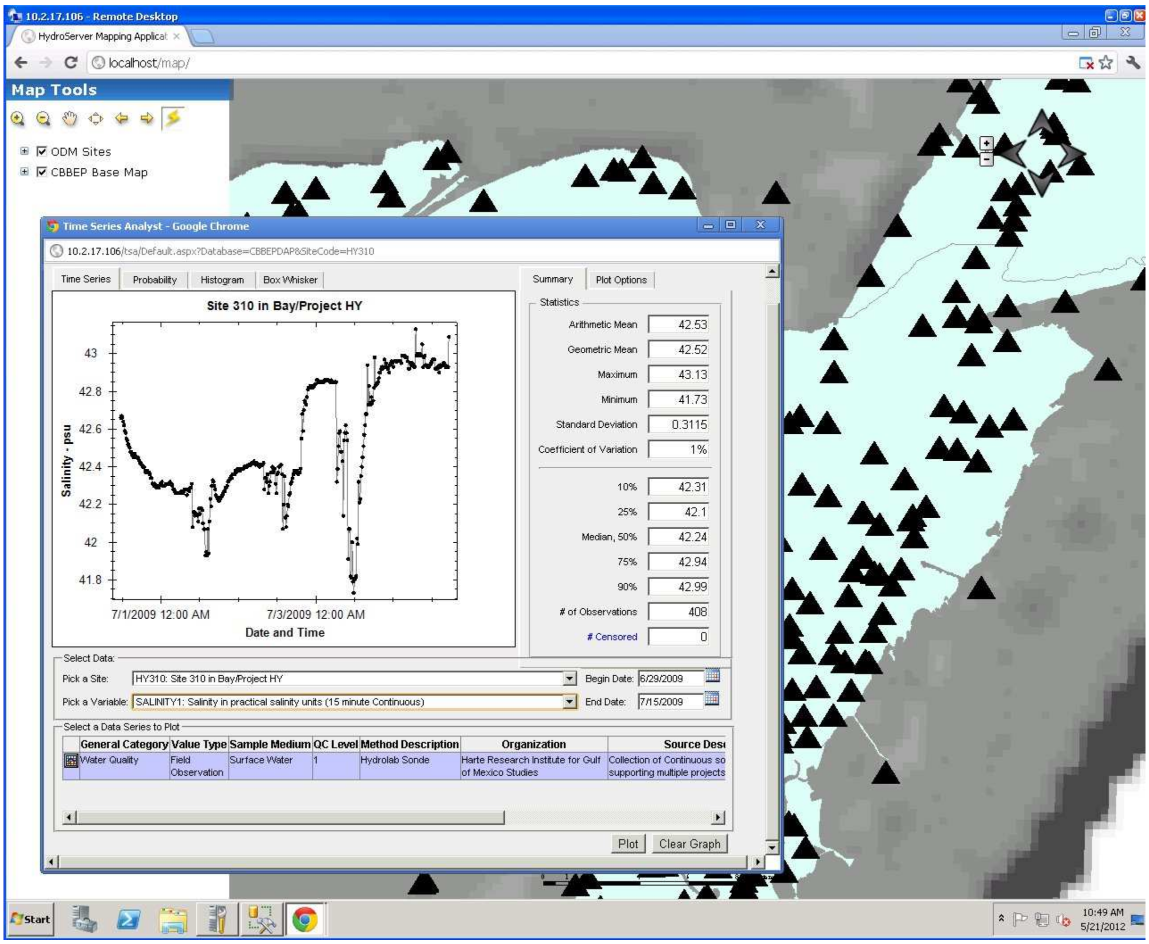

Figure 9 - Time Series Analyst Application showing salinity data from site HY310 in Corpus Christi Bay

The TSA will launch with a display of user controls providing site information and a list of variables available at the site.

Once a variable has been selected, clicking <Plot> will create a time series chart of the selected variable as well as summary statistical data. In the example in Figure 9, a chart of continuous values for salinity at HRI site 310 in Corpus Christi Bay are shown. Probability plots, histograms, and box-whisker plots are also available. In the TSA, the user can also view the data series in text form, export it to a local database, or download the metadata for the series into a local spreadsheet. While the TSA is integrated into the map application, it is also a standalone application that can connect to multiple web services on the HydroServer (Horsburgh 2011c).

The infrastructure utilized for this project also allows for the published web services to be included in CUAHSI's Hydrology Information System (HIS) Central (Figure 10). HIS Central is a data discovery and integration platform where services, like those created for this project, as well as others using this framework can be registered in a centralized catalog. Once registered with HIS Central, the data included in the project would be available in queries by the larger scientific community as part of the entire collection.

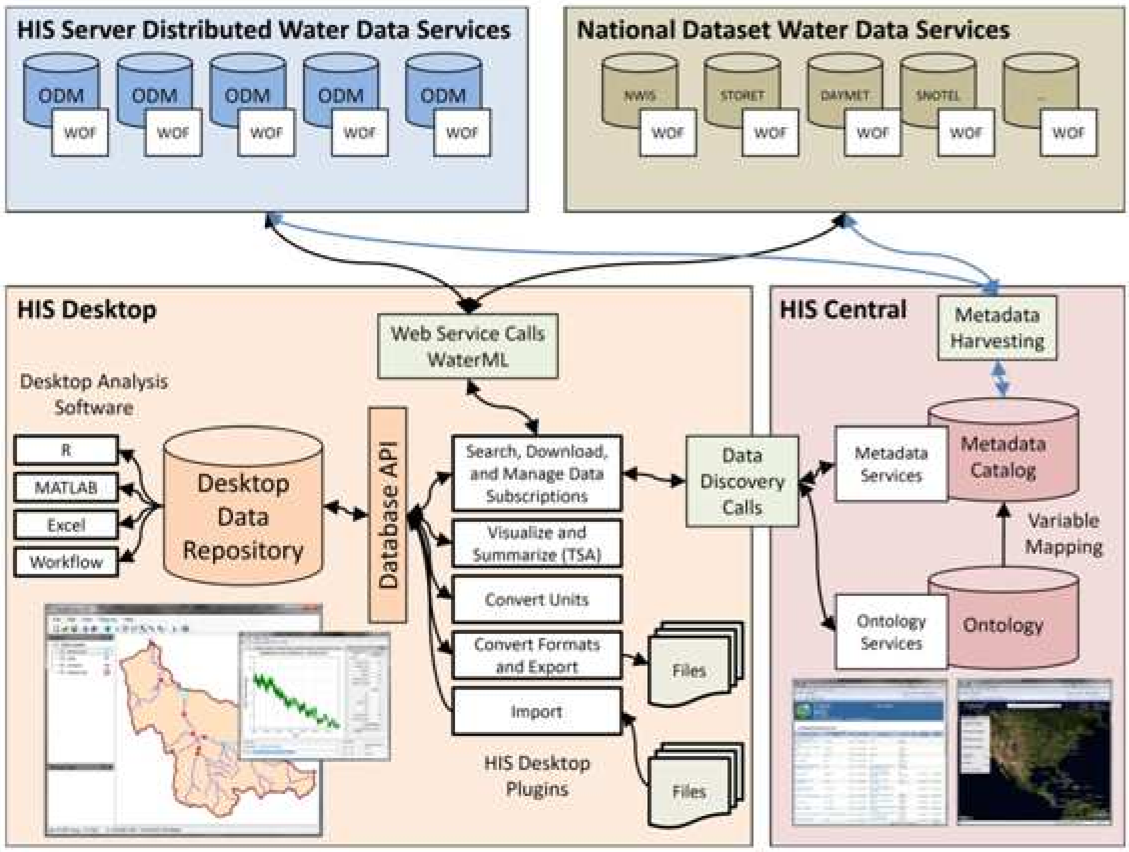

Figure 10 - Development approach for HydroDesktop (http://hydrodesctip.codeplex.com)

2.5 Discussion

To examine the robustness of the ODM, a self-imposed restriction on ad hoc augmentation of the schema was used, meaning the ODM was not modified. However, some trivial modifications to the schema were made to facilitate loading of the data. For example, removing the restriction on the index field insertions in order to use externally created key field values. Some of the variable and method names from the Rincon Bayou data sources were not included in the original ODM controlled vocabularies. In these instances, variable and method names were inserted into the controlled vocabularies.

Overall, these changes from the standard ODM structure are considered trivial because no new entities (i.e., tables) or relationships were defined.

The ODM was originally designed for hydrological data, such as simple time series observations from a single stream gauge. Series of this type in the synthesis, such as water temperature, were readily ported to the ODM and the metadata facilities were ample. However, more complicated samples were not straightforward. For instance, nutrient concentration data values result from multiple analyses performed on sample splits. Each analysis results in one data value, but all from the same sample. Logically, there is a one-to-many relationship between sample and data value. Constraints in ODM do not allow this relationship. In this synthesis, laboratory method metadata was loaded into the Methods table; a table more properly used for sample collection methods.

Each data value in ODM represents a measurement at some point in time and space. Date, time, latitude and longitude are each required fields. If the measurement is taken above or below the surface, then an additional offset value is required. Depth below the surface would be an example. ODM provides the flexibility to define this offset for other uses. For example, in this synthesis, the offset was used as key into a master species table. The variable “Species # indexed” is an example of this use of the offset. The count of a particular species is contained in the data value and a code for the species is contained in the offset. The master species table was not included in the synthesis as it would require the augmentation of the schema, therefore prior knowledge of the code is required. The alternative to this method would be to create a variable for each species. This solution could result in a proliferation of variables depending on the nature of the data. Where there is a small number of species represented in the data, a variable for each species might be more practical and in fact was used for the vegetation coverage in this synthesis. In some cases, both species and depth are needed to describe an observation. This situation occurs in species-based measurements in sediment cores. The offset denotes the section of the core. In this scenario, there is no place for the species code resulting in the need for a variable for each species. Fortunately in this synthesis, species were few, or represented at a taxonomic level high enough to result in few variables.

The nature of the transformation process removes some relationships implicit in the record-level collection of data. Transformation into ODM requires transposition and decomposition of the original record, (Figure 11). Typically, when hydrographic measurements are taken, values for water temperature, salinity, pH, and others are taken at the same time and depth.

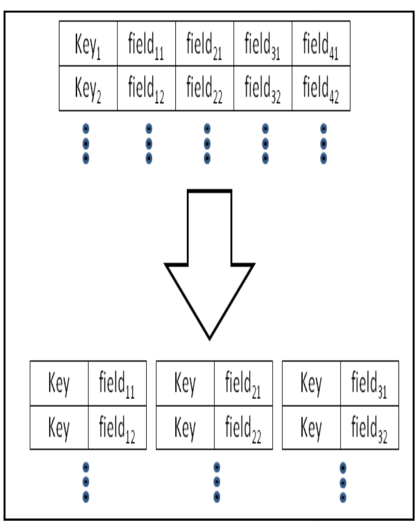

Figure 11 - Decomposition of records resulting from transformation into ODM.

Logically, and practically, they are represented in a single record for each site, date, and depth. Indeed, all of the native data sources used in this synthesis employed this structure. Therefore, two records, each containing values taken at the same site, date, and depth can be considered replicates. Values in one replicate can be distinguished from those in another by their placement in the file. This is not a problem in most cases. After transformation into the ODM, the original record can be reconstructed by grouping the values by date, site, and depth. However, when there are replicate measurements this reconstruction is not possible without something denoting which replicate a data value belongs to. Facilities for easily denoting replicate associations are lacking. To differentiate replicates in ODM requires creating groups representing replicate numbers, REP1 for example, and keying each data value to the proper group.

In conclusion, the ETL was successfully used to load data into the ODM, and CUASHI web services were successfully used to provide public access to data. While the ODM is reasonably robust, there are some limitations in the ability to store laboratory method metadata and replicate sample numbers. One shortcoming of the ODM is the inability to store the hierarchy of biological names.

2.6 References

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PART III. Nutrient Concentrations and Water Quality in Oso Bay Related to an Inflow Event

3.1 Introduction

Nutrient enrichment in estuaries is on the rise worldwide particularly in urban areas where it is linked to anthropogenic inputs (Cloern 2001; Boesch 2002; Bricker *et al.* 2007; Diaz and Rosenberg 2008) and global climate change (Scavia *et al.* 2002; Rabalais *et al.* 2009). Estuaries are the interface where fresh water inflow mixes with sea water, and by their nature are productive ecosystems with naturally occurring nutrient loading from watersheds. Inflow causes gradients of salinity, nutrients, and sediments in estuaries, and coupled with tidal effects provide ample niches for aquatic life to thrive.

Input of nitrogen and phosphorous provide the necessary required nutrients that fuel primary production in these diverse areas. However, increased input of nutrients such as nitrogen and phosphorous can lead to over-enriched estuaries and this can lead to eutrophication. As the population migrates to the coast (Culliton *et al.* 2010), pressure due to development is increasing the amount of nutrients entering the estuaries (Peierls *et al.* 1991; Nixon *et al.* 1996). Water quality degradation, which is manifested by increased frequency of algal blooms and/or hypoxia, are common effects associated with eutrophication in the coastal zone (Cloern 2001; Boesch 2002; Bricker *et al.* 2007; Diaz and Rosenberg 2008).

Pulsed inputs of freshwater are known to deliver a spike of nutrients into estuaries, particularly when the pulse is large such as during and after tropical storms and hurricanes (Mallin *et al.* 1999; Paerl *et al.* 2001; Peierls *et al.* 2003; Arismendez 2010).

Smaller storm events are much more common and are likely the main source of nutrient loading. Small events however, are less well studied. The purpose of the current study was to examine the dynamics of nutrient loading from a small tributary to a larger bay during a dry period. Several wastewater treatment plants empty into the tributary, and the bay suffers from seasonal hypoxia. The main question addressed in this study is: do small rain events change the loading of nutrients in the bay?

3.2 Methods

3.2.1 Study Location

Oso Bay, Texas is a secondary bay between Oso Creek and Corpus Christi Bay proximal to Corpus Christi, TX (Figure 12). The bay is shallow, ~0.5 m with an area of 20.52 km^2 at mean low tide and maximum volume of 15.6×10^6 m^3 at mean high water (Diener 1975). Freshwater input to Oso Bay is provided by Oso Creek. Oso Creek is an effluent-dominated system (Watson 1991) with three wastewater treatment facilities discharging into the 637 km^2 Oso catchment. The Maximum Permitted Daily Average Flow (MPDAF) into Oso watershed is 570.2715 millions of gallons per day (MGD) (Arismendez 2010). The watershed is predominately comprised of agricultural land (64%) and urban area (21%) (MRLC 2008).

Another feature that alters hydrology of Oso Bay is the American Electric and Power, Barney Davis Power Station (AEP-BDPS). Cooling water for electrical generation is drawn into the plant from Laguna Madre near Pita Island and discharged into Oso Bay. The average monthly plant discharge over the five year period from 1988 to 1992 was about 40 thousand ac-ft or 660 cfs (Powell *et al.* 1997). The discharge rates have decreased in recent years because of less electrical demand. Because Laguna Madre is hypersaline and evaporation in the cooling ponds, the water discharged can be very high in salinity.

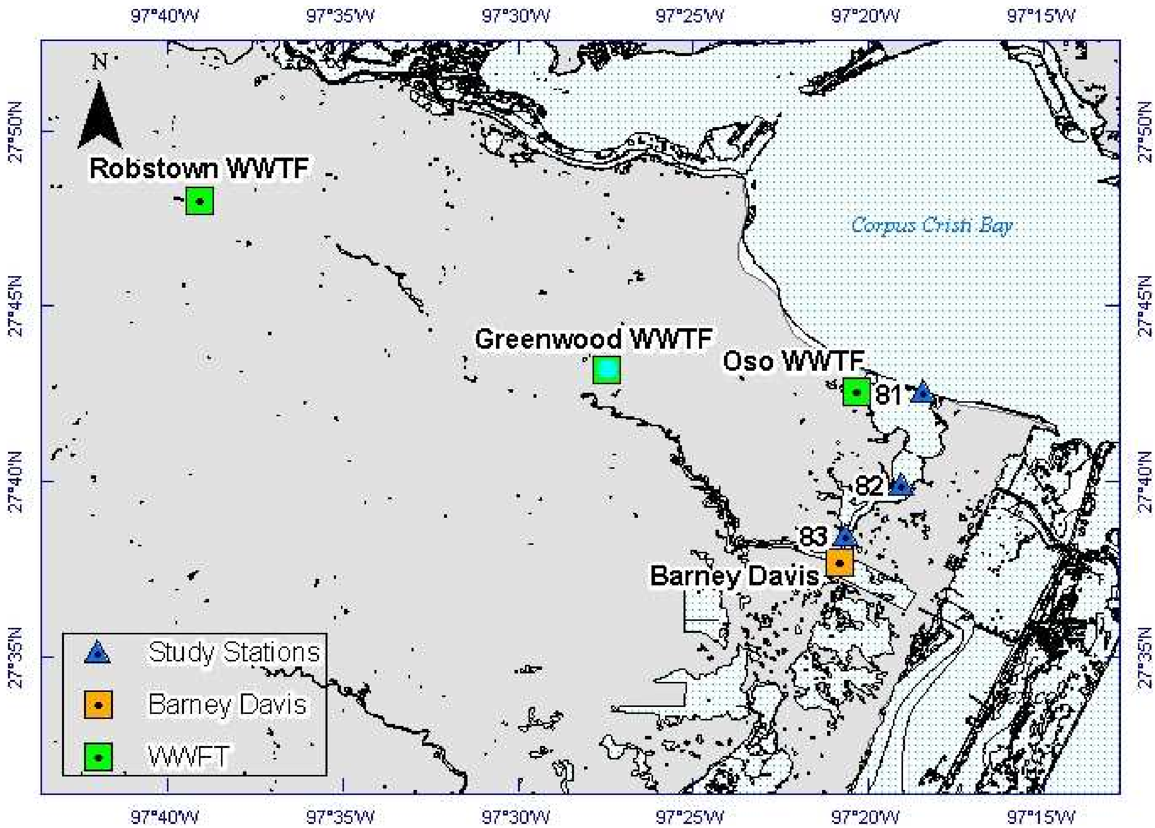

Figure 12- Oso Bay Study Area

The focus of the current study is on discharge from Oso Creek. During the period of the current study inflow from Oso Creek was less than the long-term average (Figure 13). During this period. May through October 2008, the area's short-term drought classification ranged from mid-range to severe using the Palmer Z index (NOAA 2008d; NOAA 2008c; NOAA 2008b; NOAA 2008a; NOAA 2008e) and preceded a more extensive period of drought.

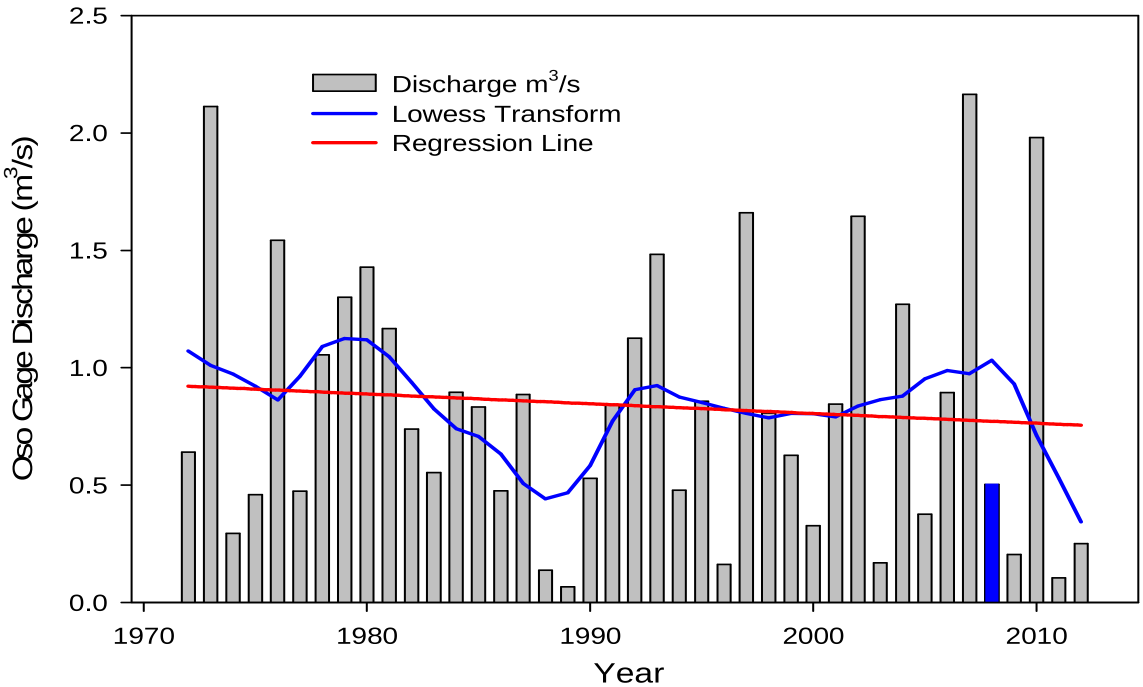

Figure 13 - Yearly long-term Oso Gauged Discharge. Blue bar denotes year of current study.

3.2.2 Study Design

Three locations were sampled (Figure 14), on at the nexus of Oso Bay and Corpus Christi Bays (station 81), the second, 5 km from Corpus Christi Bay (station 82), and the third, 10 km from Corpus Christi Bay, (station 83), see Table 6. Station 81 is located below the bridge on Ocean Dr, between Ward Island and Corpus Christi Naval Air Station and is the deepest of the sampled locations. For the continuous study, it was not possible to moor at the exact location of the grab sampling station instead, an existing mooring from a previous deployment by the Texas Coastal Ocean Observation Network (TCOON) was used.

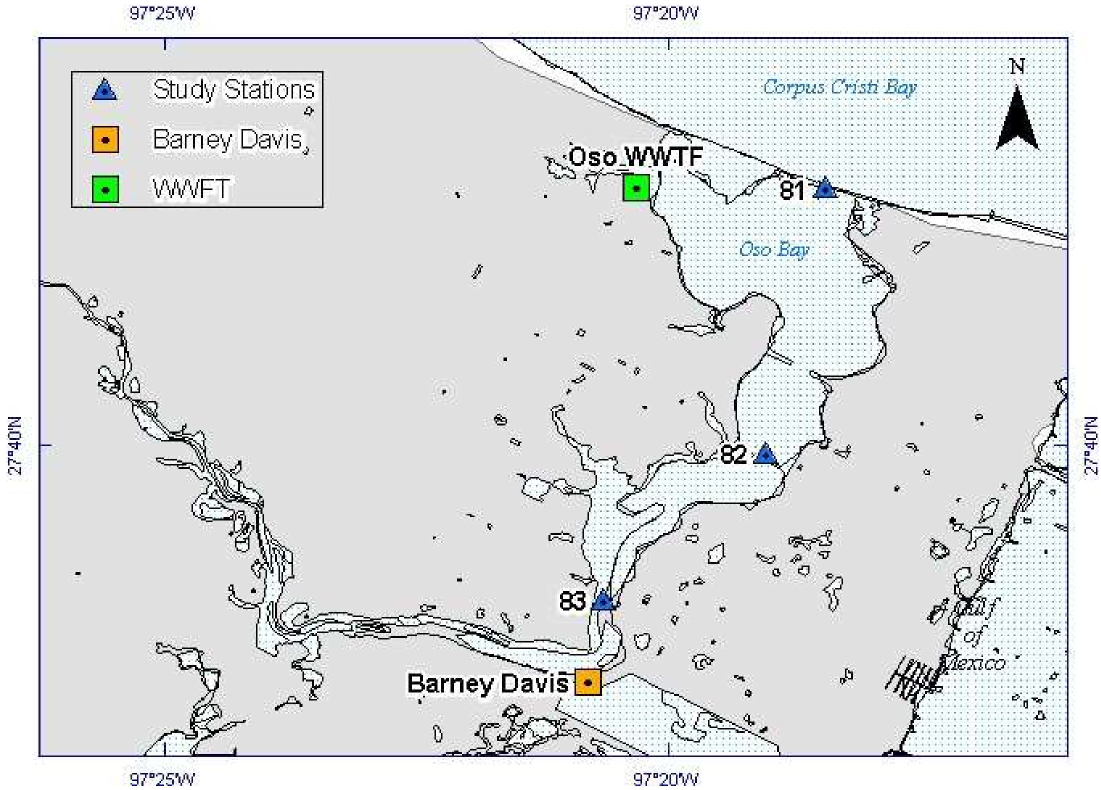

Figure 14 - Oso Bay Study Area Detail

Table 6 - Station desinator, location and brief descriptions

Station No.	Short description	Latitude (N)	Longitude (W)
81	Under bridge at Ocean Drive and Oso Bay	27.70959	97.30831
82	Middle of derelict Railroad trestle at south end of Holly Road 5 Km from Corpus Christi Bay	27.66480	97.31809
83	Under bridge at Yorktown Road and Oso Bay. 10 Km from Corpus Christi Bay	27.64059	97.34413

This mooring is located approximately 100 m upstream from the grab sampling location. Station 82 is located in the middle of Oso Bay on a derelict railroad trestle at the south end of Holly Road. This station is the shallowest of the three sampled locations. The final station is located 10 km from Corpus Christi Bay under the bridge on Yorktown Road, north of the American Electric and Power, Barney Davis Power Station (AEP-BDPS). Cooling water from this plant is discharged into Oso Bay south across the bay from this location.

Sampling was conducted on three time scales: a daily sampling regime during a small rain event, a weeklong continuous period in late September, and at a bi-monthly schedule during the summer months). Figure 15 shows the gauged discharge from the Oso Creek gage during the sampling period. The rain event studied is denoted in red, the summer study period for grab samples are denoted in blue. The highest discharge rates were during hurricane *Dolly*. The sampling dates were scheduled in support of ongoing nutrient and hypoxia studies in Corpus Christi Bay (Table 7).

Table 7 - Study sampling schedules

Sampling Dates			
	Rain Event	Summer Study	Continuous
Frequency	Daily	Bi-monthly	15-minute
Duration	8-days	5-months	1-week
Parameters	*hydrographic, **nutrients, [Chl-*a*]	*hydrographic, **nutrients, [Chl-*a*]	*hydrographic
Dates (2008)	5-Jul	19-May	19-Sep
	6-Jul	27-May	20-Sep
	7-Jul	18-Jun	21-Sep
	8-Jul	25-Jun	22-Sep
	9-Jul	18-Jul	23-Sep
	10-Jul	1-Aug	24-Sep
	11-Jul	6-Aug	25-Sep
	12-Jul	18-Sep	
		24-Sep	
* Hydrographic parameters - [DO], temperature, salinity, pH, depth			
* Nutrient parameters - [NH_4], [NO_{2+3}], [PO_4], [SiO_4]			

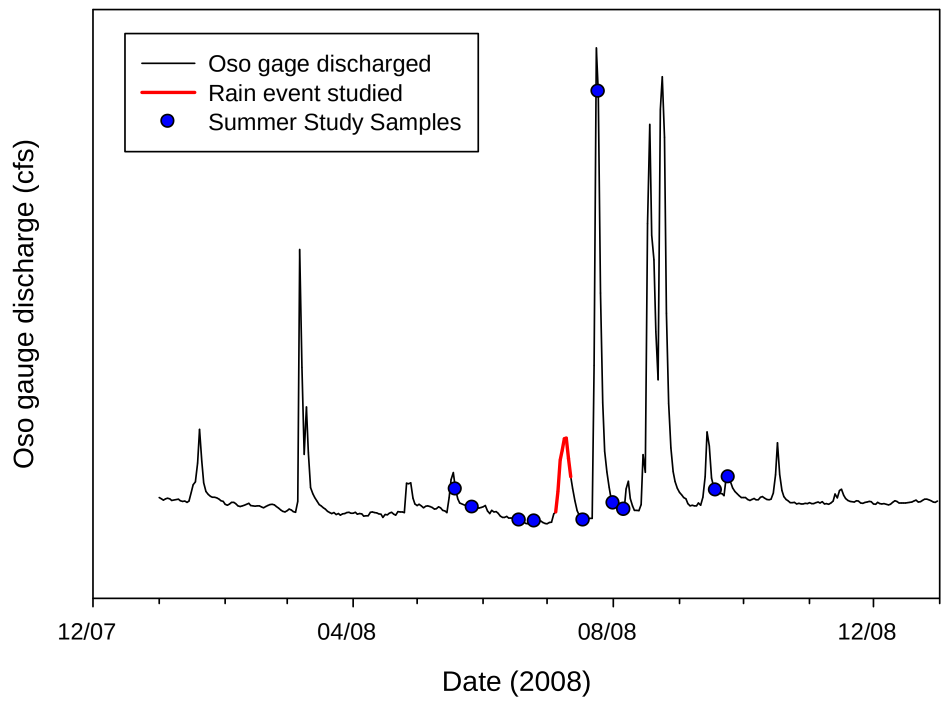

Figure 15 Oso discharge for year 2008 shown with sampling dates.

3.2.3 Equipment

YSI multi-parameter water quality sondes, models 6920-S, 6920 v2, and 600XLM were used to measure water quality during the surveys of Corpus Christi Bay. The YSI sondes have the following accuracy and units: temperature (±0.15 ºC), ph (± 0.2 units), dissolved oxygen (mg l^{-1} ± 0.2), dissolved oxygen saturation (± 2%), specific conductivity (± 0.5% of reading depending on range), depth (± 0.2m), and salinity (± 1% of reading or 0.1 ppt, whichever is greater, automatically corrected to 25 ºC) (YSI Incorporated 1999).

3.2.4 Nutrients

Water column samples for nutrient analysis were collected at each site from the surface and from about 10 cm above the sediment surface using a Van Dorn bottle. Two replicate samples were taken from each depth and decanted into 125 mL opaque brown Nalgene bottles that had been rinsed with sample water. Each bottle was placed immediately into ice for transport to the lab for preparation and analysis. At the lab, 12 ml of sample was filtered using 0.45 micron glass fiber filters and a hand syringe. Filtrate was stored in a pre-cleaned, non-glass 15 ml capped tube. Information about the sample was recorded on the tube. Samples were frozen at ≤ -20 ºC until analysis, typically less than two weeks.

Analysis was performed on a Lachat Quikchem 8000 using EPA-equivalent methods. NO_X analysis was performed using a cadmium reduction method, (Lachat method 31-107-04-1-A for brackish or seawater matrix) equivalent to EPA method 353.2 (USEPA 1993b). Ortho-phosphate concentrations were determined using EPA method 365.1 (USEPA 1993c) (Lachat method 31-115-01-1-J for brackish or seawater matrix). Silicate concentrations were determined using a method equivalent to EPA 366.0 (Zhang and Berberian 1997) for brackish or seawater (Lachat method 31-114-27-1-B) and Ammonium concentration was determined using EPA method 350.1 equivalent method (USEPA 1993a) (Lachat method 31-107-06-1-B for brackish or sea water matrix). The detectible concentration limit for all chemistries was 0.03 μM

3.2.5 Chlorophyll-a

After collection, 25 mL - 50 mL of sample water, depending upon the water column clarity as measured by Secchi disk at the sample site, was filtered using a 0.45 micron glass fiber filter and a hand syringe. In general, a volume, in mL of half the numerical value of the Secchi depth was used up to a maximum of 50 mL and a to a minimum of 25 mL. The filter containing the sample to be analyzed for chlorophyll-*a* concentration was frozen at ≤20 ºC until analysis, typically less than two weeks. For analysis, 5.0 mL of methanol was added to each sample and allowed to rest over night at ≤-20 ºC to extract the chlorophyll-*a*. The concentration was then measured fluorometrically on a Turner fluorometer using a non-acidification technique - EPA method 445.0 (Welchmeyer 1994).

3.3 Results

3.3.1 Rain Event

In the first study, a weeklong daily survey of Oso Bay was conducted during a small rain event beginning July 5th, and ending July 12. During this period, approximately 2.644×10^5 m^3 of gauged discharge flowed into Oso Bay. Mean temperature was consistent across locations at just above 30 °C (Table 8).

The largest change in the Oso system during the rain event was an increase in discharge rate, temperature, dissolved oxygen, and pH; all which was inversely correlated to ammonium and silicate (Figure 16). Principal components analysis (PCA) resulted in 53% of the variability being explained by the first two components. PC-1, explained

34% (eigenvalue = 3.39) and PC-2 explained 19% (eigenvalue = 1.86). A decrease in salinity was associated with an increase in nitrite+nitrate and phosphate.

There was a cyclicity of the change in water quality (Figure 17). Salinity was highest and nutrients were lowest on July 5, nutrients increased to peak on July 8, and decreased afterwards. By July 9 and 10, temperatures were highest. By July 12, conditions were returning to those prior to the rain event.

There was also a gradient in the stations during the rain event (Figure 18). Stations 82 and 83 were similar with high salinities and low nutrients. In contrast, Station 81 was different from these two with high nutrients and low salinity.

Table 8 - Hydrographic values and nutrient and chlorophyll-a concentrations by station during rain event

	Station	Mean	S.D.	Min.	Max.
Temp.	81	30.06	2.10	27.41	32.67
	82	30.01	2.16	26.03	32.26
	83	30.21	2.19	27.07	32.65
Salinity (psu)	81	37.02	1.35	35.46	39.20
	82	42.47	3.54	36.68	45.76
	83	43.31	1.58	40.18	44.69
[DO] mg/L	81	7.97	1.73	6.03	10.78
	82	6.64	0.79	5.33	8.00
	83	7.04	0.55	6.09	7.63
pH	81	8.21	0.17	6.03	10.78
	82	8.24	0.16	7.98	8.39
	83	8.25	0.06	8.16	8.30
[Chl-*a*] (ug/L)	81	4.06	1.71	6.03	10.78
	82	5.73	2.52	2.69	10.44
	83	8.71	0.06	8.16	8.30
[NH_4] (mg/L)	81	0.66	1.36	N.D.	3.97
	82	1.03	3.57	N.D.	6.67
	83	1.38	1.61	N.D.	4.12
[NO_{2+3}] (mg/L)	81	1.74	4.81	N.D.	13.64
	82	1.32	3.57	N.D.	10.14
	83	0.75	1.20	N.D.	2.73
[PO_4] (mg/L)	81	0.34	0.57	N.D.	1.70
	82	0.04	0.09	N.D.	0.26
	83	0.04	0.06	N.D.	0.17
SiO_4 (mg/L)	81	62.64	22.46	26.95	107.54
	82	78.79	24.80	52.55	121.35
	83	88.16	28.87	53.11	122.15
Discharge (cfs)	Oso	13.51	6.72	2.61	21.42

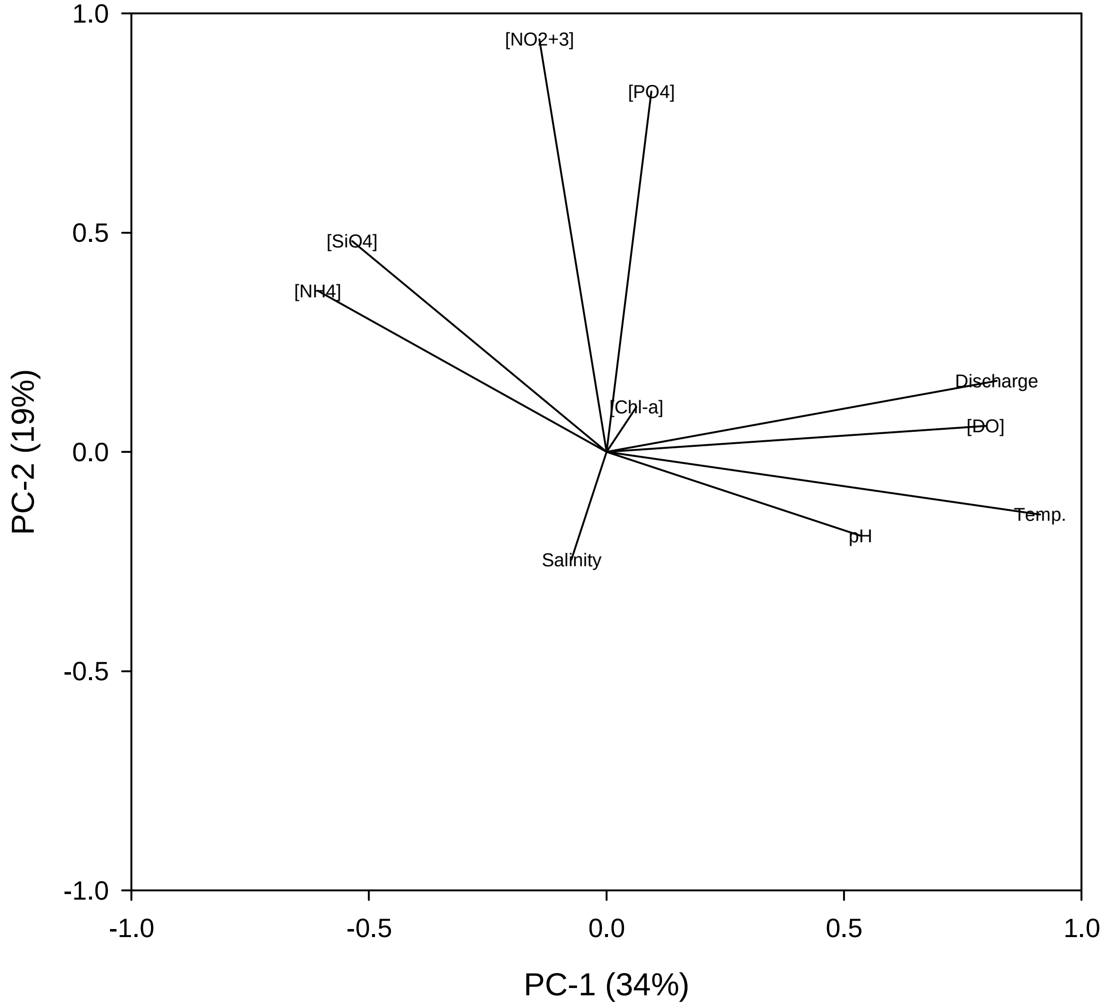

Figure 16 - Vector plot of PC1-PC2 space for samples collected during rain event.

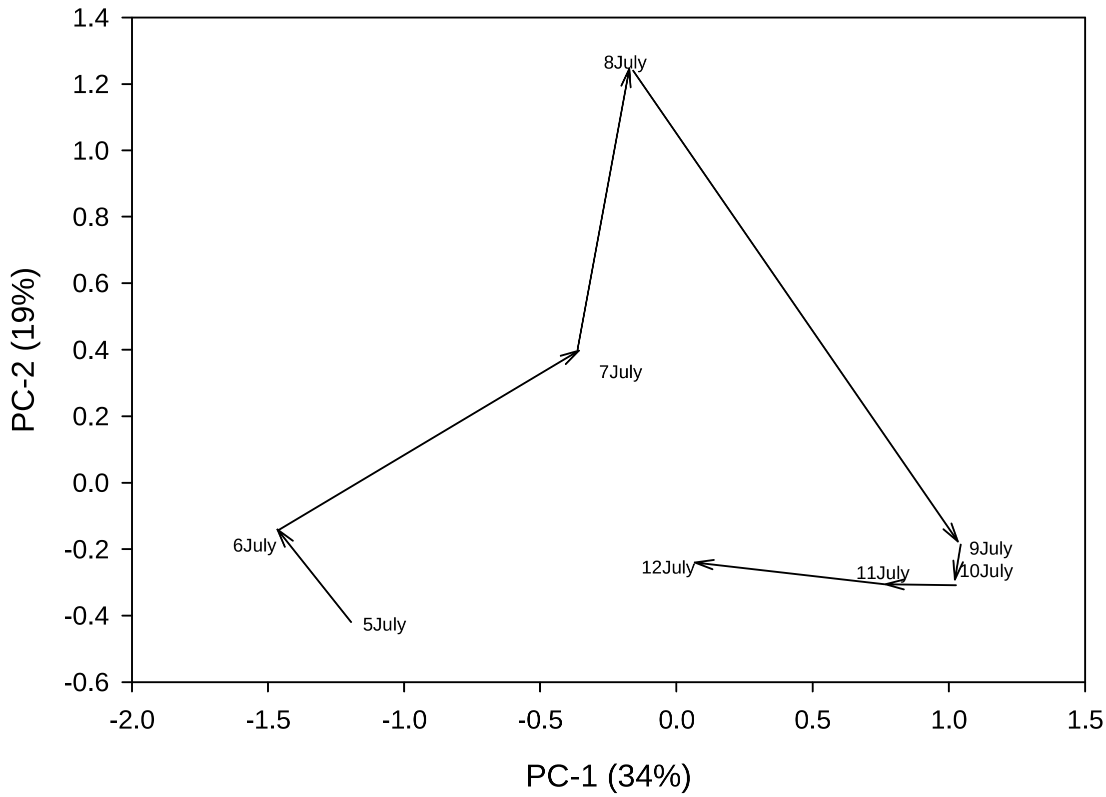

Figure 17 - Sampling dates in PC1-PC2 space for samples collected during the rain event.

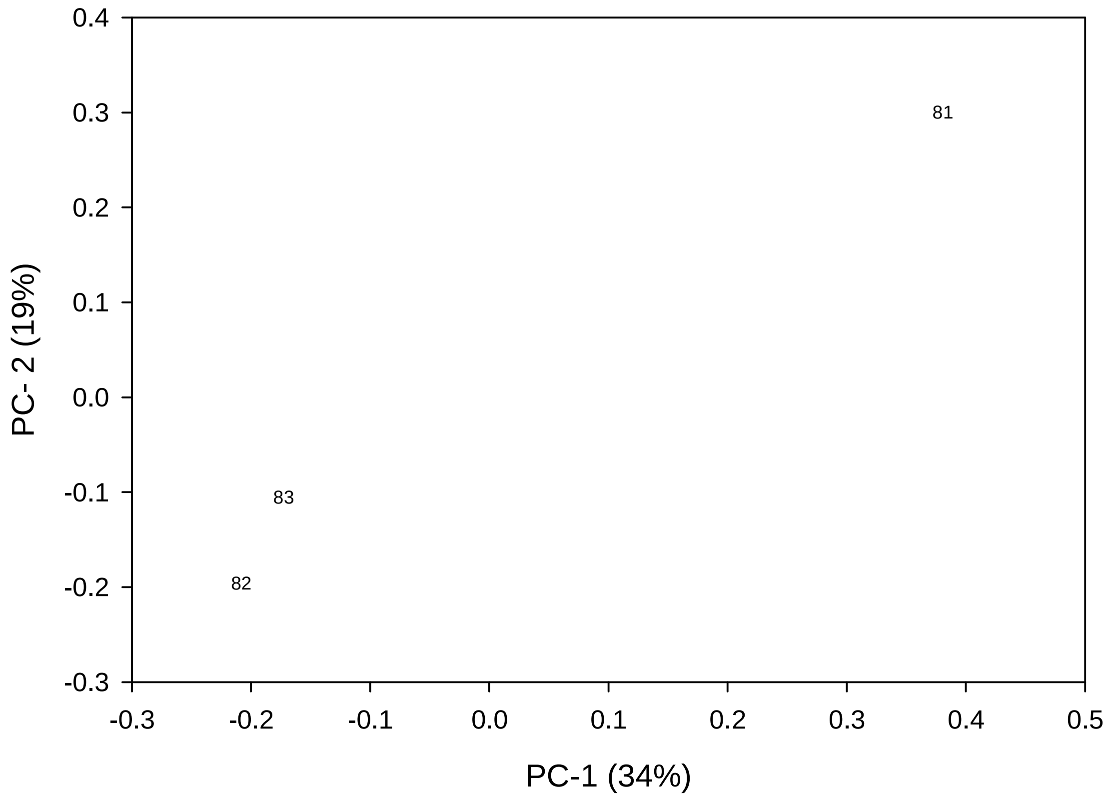

Figure 18 - Oso Bay stations in PC1-PC2 space for samples collected during the rain event.

The highest recorded temperature, 32.67 °C was recorded at the Ocean Drive location (station 81) and the lowest, 26.03 °C in mid-bay (station 82). Temperature initially drops with the beginning of the event, but then generally increases until the peak of the event when it declines at every station (Figure 19). The increase in temperature from July 5 to July 8 was not monotonic. It is possible that local rainfall contributed to the variation as well as water flowing from Oso Creek.

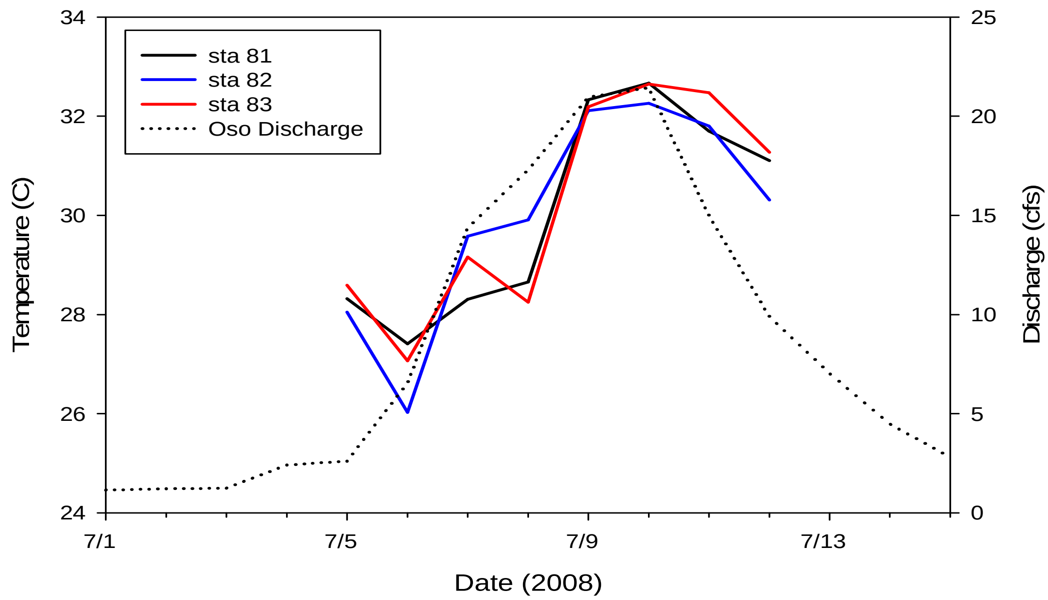

Figure 19 - Temperature by station for samples collected during rain event

The mean salinity gradient in Oso Bay was inverted with an increase in salinity from Corpus Christi Bay to Yorktown road (i.e., from stations 81 to 83), ranging from 37.02 psu to 43.31 respectively. This pattern was also seen for minimum salinities, but maximum salinity was observed mid-bay (Table 8). Both the mid-bay and the Yorktown stations (stations 82 and 83 respectively) initially respond to the event with a drop in salinity (Figure 20), however while salinity in mid-bay continues to drop over the next 2 days, it climbs at the Yorktown station. Clearly the water mid-bay is mixing with fresh water.

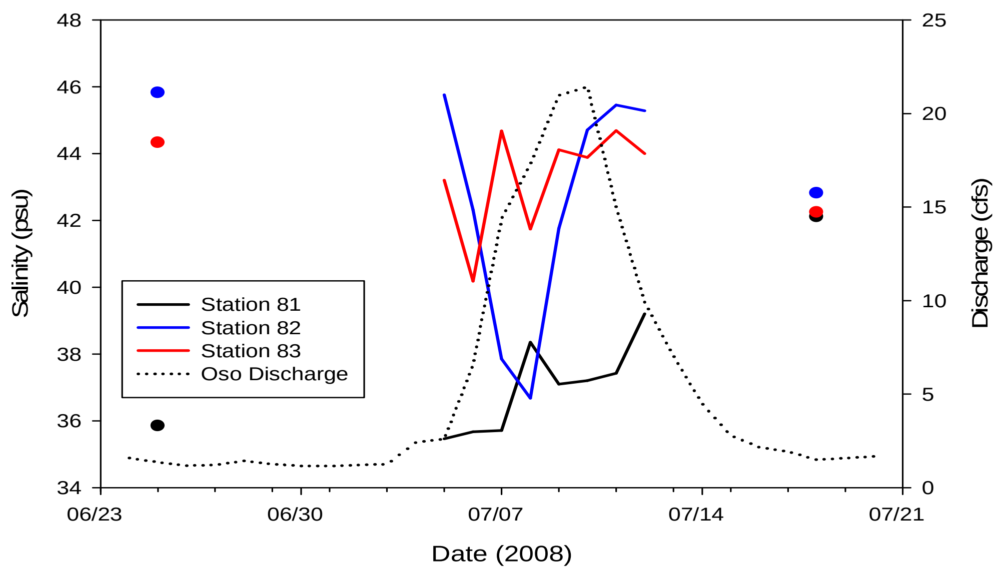

Figure 20 - Salinity by station for samples collected during the rain event

The Yorktown site shows a general trend upward as the event continues. This could indicate that the station is not capturing what is happening in nearby waters. This could be due to channelized flow or pooling at the location. It is also possible that water is entering the system between the uppermost stations from sources other than Oso Creek. The Ocean Drive site showed a general increase in as the event progressed. This could be due to more saline water from the upper reaches of Oso Bay being pushed toward Corpus Christi Bay by inflow from the event.

Mean dissolved oxygen during the event was highest at Ocean Drive (station 81). This occurred at the discharge apex of the event. The lowest mean do concentration occurred at the mid-bay site shortly after the beginning of the event on July 7 (Figure 22). All stations appear to trend with discharge, however unlike the discharge, they did not behave monotonically during the rise or the fall of the discharge.

At both the Ocean Drive site and the Yorktown Road site, there was a positive relationship with dissolved oxygen and discharge (Figure 21) as inflow provided nutrients to the bay.

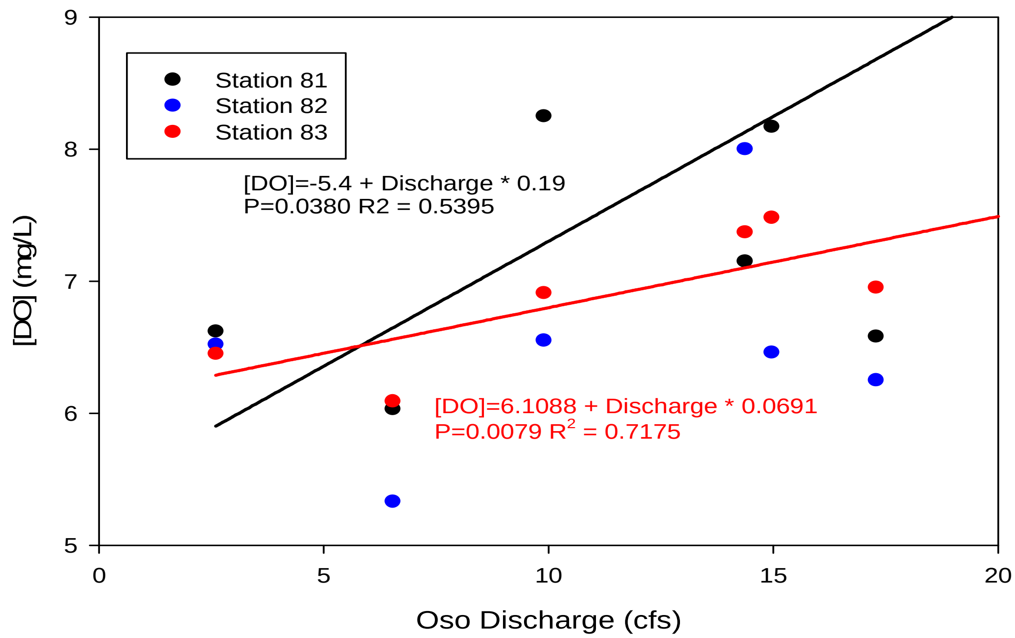

Figure 21 - Dissolved oxygen concentration [DO] vs. Oso discharge during the rain event

However regression analysis showed that there was significant autocorrelation of residuals at the Yorktown Road site and the power of this regression was slightly below the desired value. Dissolved oxygen was most highly correlated with temperature at the Ocean Drive Site and the Yorktown sites (Figure 23).

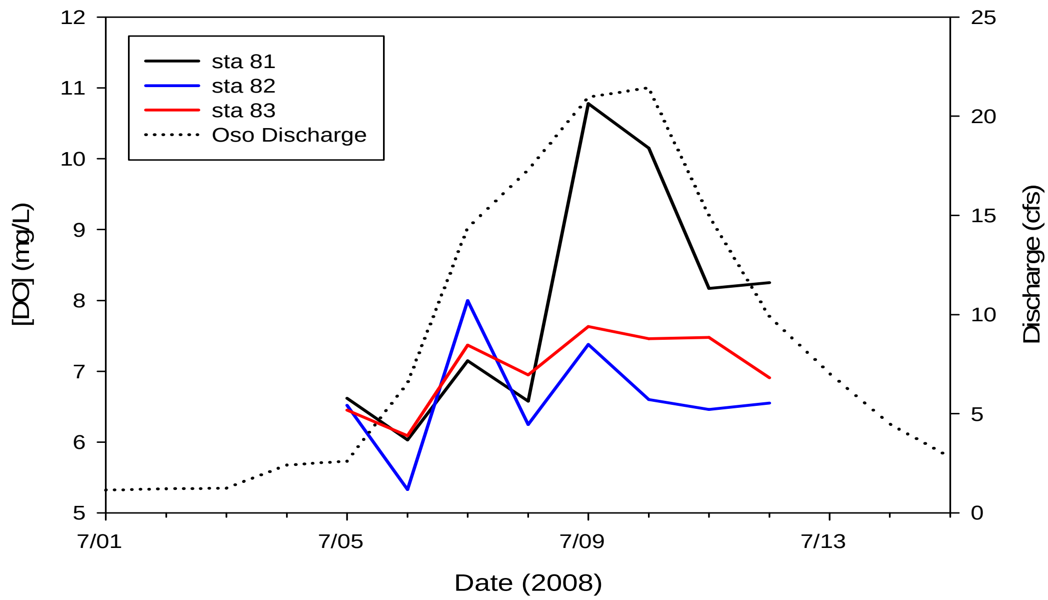

Figure 22 - Dissolved oxygen concentration [DO] by station for samples collected during the rain event.

Mean pH was consistent across locations near 8.21.

Ammonium concentrations decreased from the Yorktown site (station 83) to the Ocean Drive site (station 81). The highest value, 6.67 mg/L was observed at the mid-bay site on July 6 at the beginning of the event (Table 8). This was followed by a sharp decline as the nutrient was utilized, it then it trended with discharge (Figure 24).

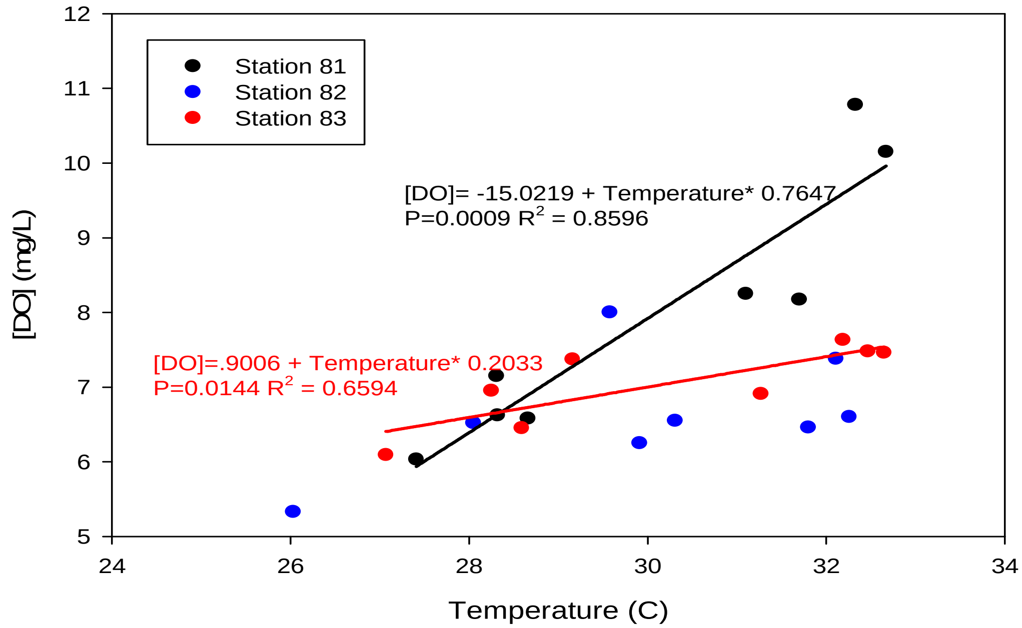

Figure 23 - Relationship between temperature and dissolved oxygen by site

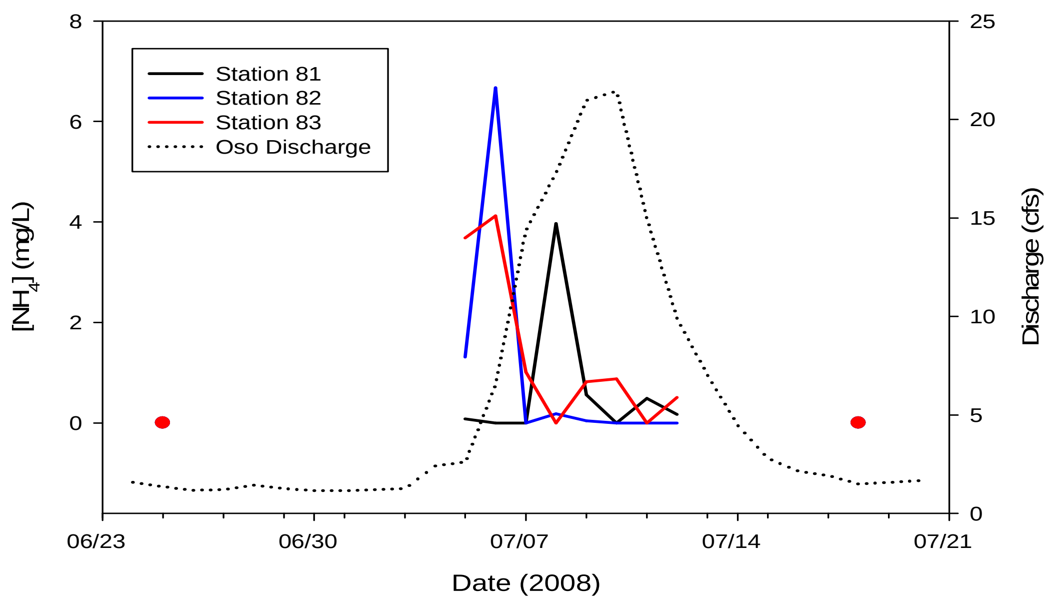

Figure 24 - Ammonium concentration [NH_4] by station from samples collected during the rain event

Regression analysis of the data from this station, however, showed an unacceptable level of autocorrelation of the errors and the power of the regression was substantially below the acceptable level (Figure 25).

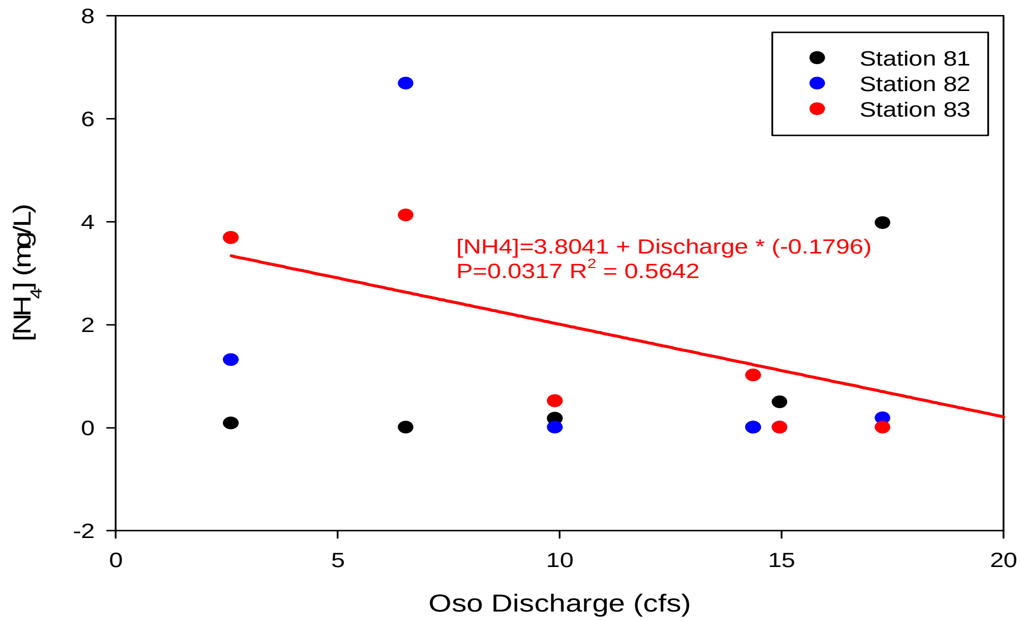

Figure 25 - Ammonium concentration [NH_4] vs Oso discharge during rain event

A peak in ammonium was also seen on July 6 at the Yorktown Road site and unlike the mid-bay site, dropped off markedly the next day and remained near the detection limit for the duration of the event. The Ocean Drive site ammonium concentration peak lagged a day later at 3.97 mg/L as inflow progressed toward Corpus Christi Bay. All stations had minimum concentrations below the limits of delectability at some point in the event. Ammonium concentrations the week before, and the week after the event also were below detection limits.

Nitrite/nitrate (NO_{2+3}) nitrogen displayed a somewhat similar pattern in response to the freshwater flow during the inflow event (). All stations showed a peak in [NO_{2+3}]. The upper site responded initially, and followed by the middle site and lower site in the following days. The Yorktown Road site showed a smaller response in the initial stages of the rain event than the others.

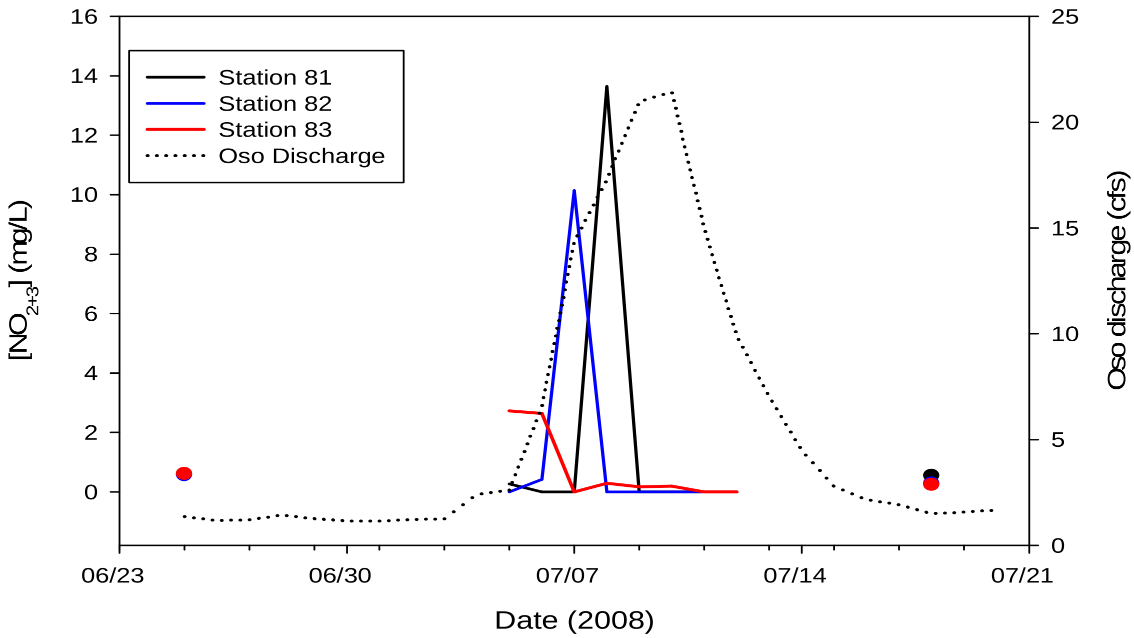

Figure 26 - Nitrite plus nitrate concentration [NO_{2+3}] by station for samples collected during rain event

It is possible that sampling efforts missed the peak, or that peaks in the lower bay stations are influenced heavily by non-point source inflow. Unlike ammonia-nitrogen, there was no subsequent smaller peaks as the rain event progressed possibly due the rapid utilization rate of NO_{2+3}. After the peak, each station's [NO_{2+3}] dropped below the limits of detection and remained there in all subsequent samples. In the week before, and the week after the rain event, nitrite/nitrate ammonia concentrations were low, near the limit of delectability. Yorktown site ammonia concentrations correlated negatively with discharge and like previous regression analyses, there was unacceptable levels of autocorrelation and low power (Figure 27).

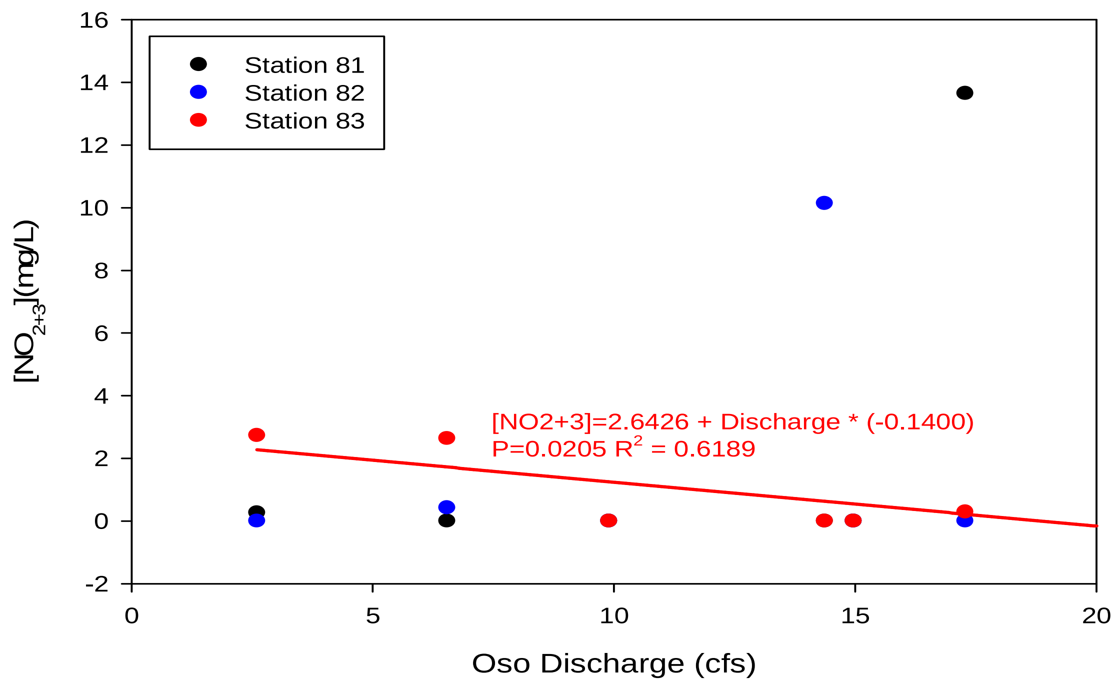

Figure 27 - Nitrite plus nitrate concentration $[NO_{2+3}]$ vs Oso discharge during rain event

Silicate concentrations during the rain event were considerably lower at all three stations than those the week before and the week after (Table 8). The highest concentration of silicates, 122.14 mg/L, was observed at the Yorktown Road Station (Station 83). The lowest silicate concentration was observed at station 81, the Ocean Drive station. This pattern was also present in the mean where $[SiO_4]$ ranged from 62.64 mg/L to 88.16

mg/L. The lower two stations' silicate concentrations behaved similarly during the event - a small rise, then a peak, followed by declining concentrations (Figure 28). However, the Ocean Drive station lagged behind the mid-bay station. At the upper bay station, there was a negative correlation between silicate concentrations and gauged flow in Oso Creek, (r=-0.84165, P=0.0088). At station 83, the upper bay station, silicates exhibited a pattern inverse of Oso gauged discharge. As flow increased silicate concentrations decreased. A significant linear relationship, [SiO_4]=137.0298+(-3.6173*Discharge), R^2=0.7084, P=.0088, passed all tests for normality, autocorrelation of the errors, and constant variance (Figure 29). This is likely due to dilution by fresh water from Oso Creek.

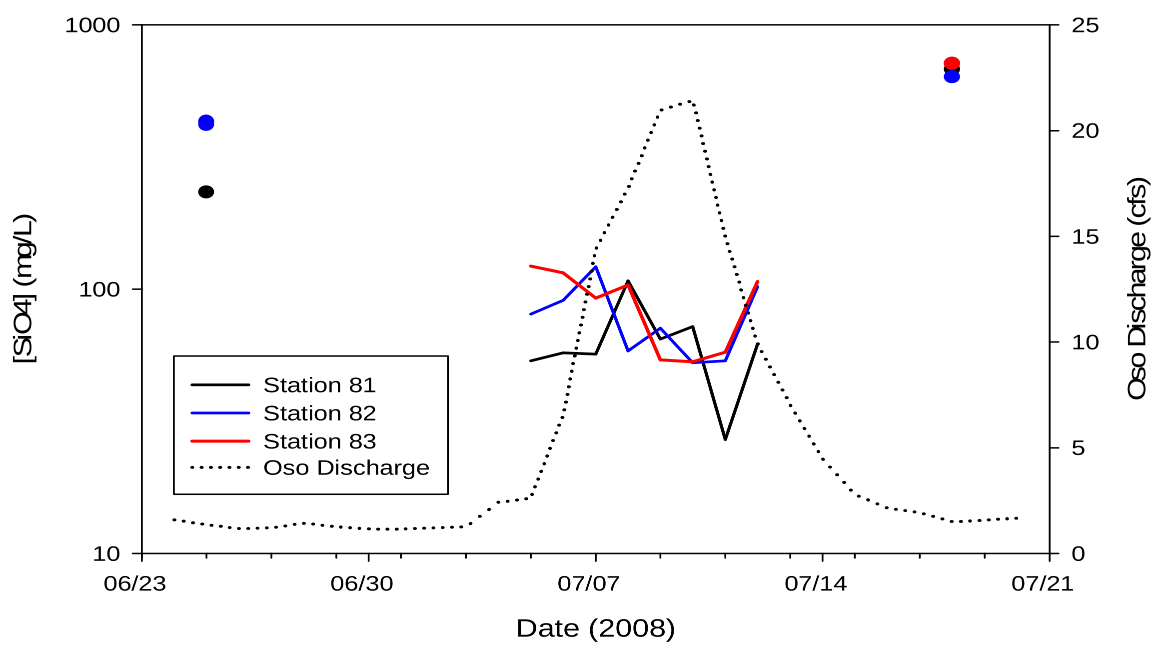

Figure 28 - Silicate concentration [SiO_4] by station from samples collected during rain event

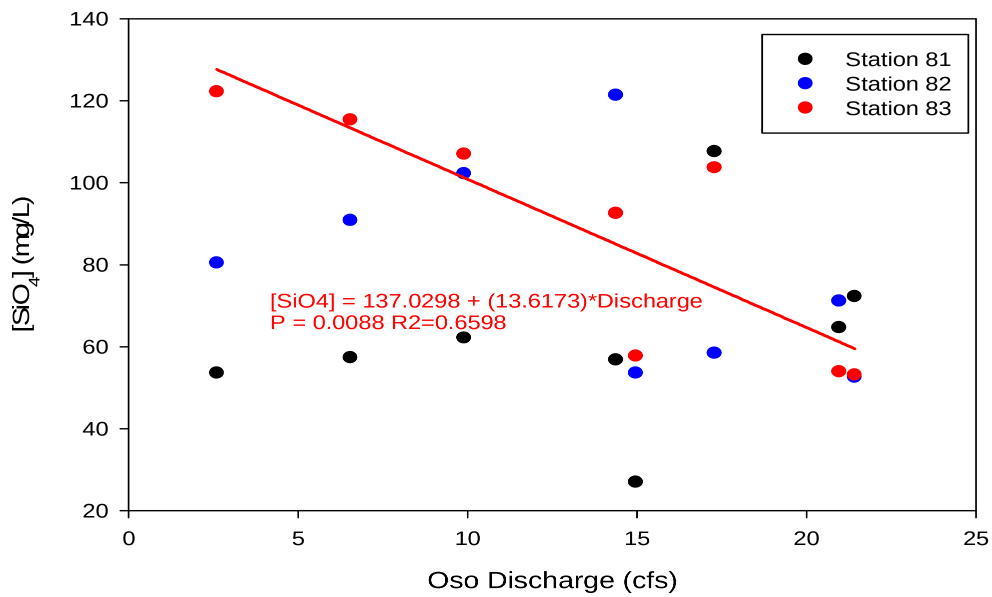

Figure 29 - Silicate concentration {SiO_4] vs. Oso discharge during rain event

3.3.2 Summer study

Data used for this study was obtained from grab samples taken on the same days as sonde deployments for a study of hypoxia on Corpus Christi Bay. Because they were taken in support of another study, they are not timed in any way to control for tide or other conditions. The sparse sample over the 5-month period resulted in ten samples at each of the three stations. For the following analysis, one point was removed as an outlier. This point was during a very-high flow event, hurricane Dolly. Also, the decision was made not to include the samples from the rain event in this section as the higher sample frequency relative to the summer study would likely skew the results.

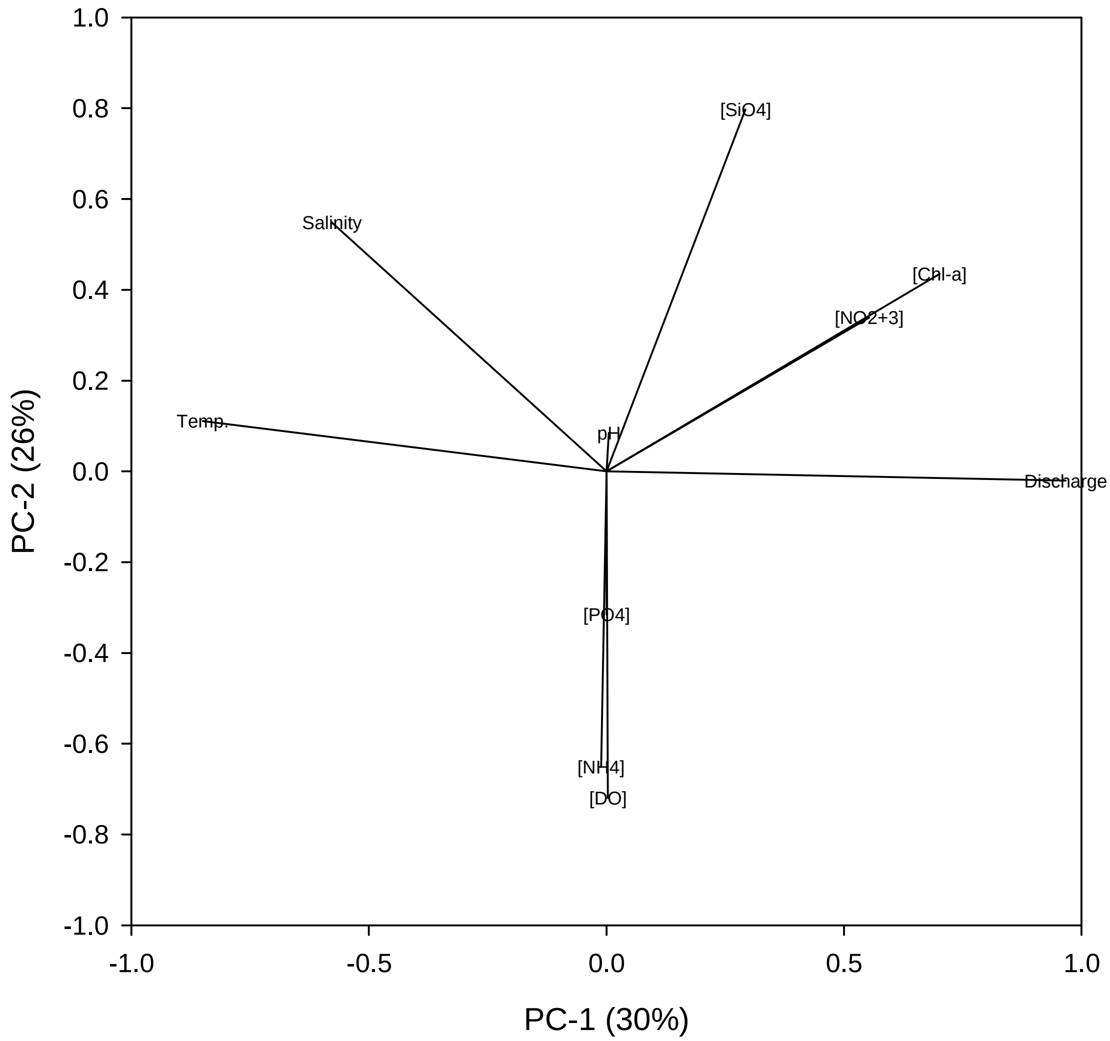

Figure 30 - PCA vector plot of PC1-PC2 space for samples collected during summer study

Principle components analysis of the samples taken during the summer study resulted in 56% percent of the variation accounted for in the first two components (Figure 30). PC-1 explained 30% (eigenvalue = 3.0) and PC-2 explained 26% (eigenvalue = 2.58). Most of the variation was due to higher discharge with decreasing salinity and temperature. Dissolved oxygen, ammonium, and phosphates varied negatively with salinity, silicates, nitrite-nitrate nitrogen and silicates. This is markedly different from the rain event where increasing discharge resulted in increasing temperature. Changes in temperature during the summer study show no influence on dissolved oxygen, also very different from the rain event.

A plot of sample dates in PC1-PC2 space, (Figure 31), shows a general increase in the discharge axis in time, with one outstanding point, May 19th, the earliest sample. This date was also just after another small rain event. The sample dates tend towards increasing [DO], [NH_4], and [PO_4] with time while salinity decreased.

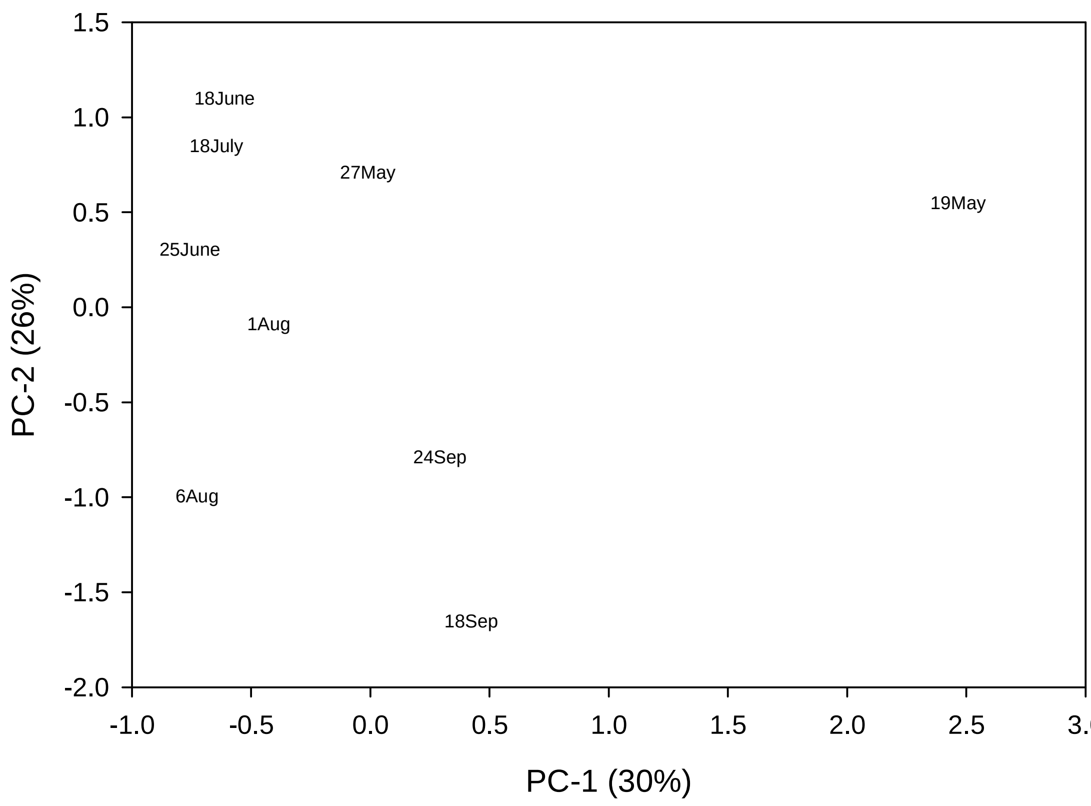

Figure 31 - Sampling dates in PCI-PC2 space for samples collected during summer study

There was a gradient in the bay during the summer study (Figure 32). Salinity at the upper two stations was high and nutrients were low, while the Ocean Drive station had lower salinity and high nutrients. This pattern was also seen during the rain event Temperature at all of the stations is related to discharge (Figure 33).

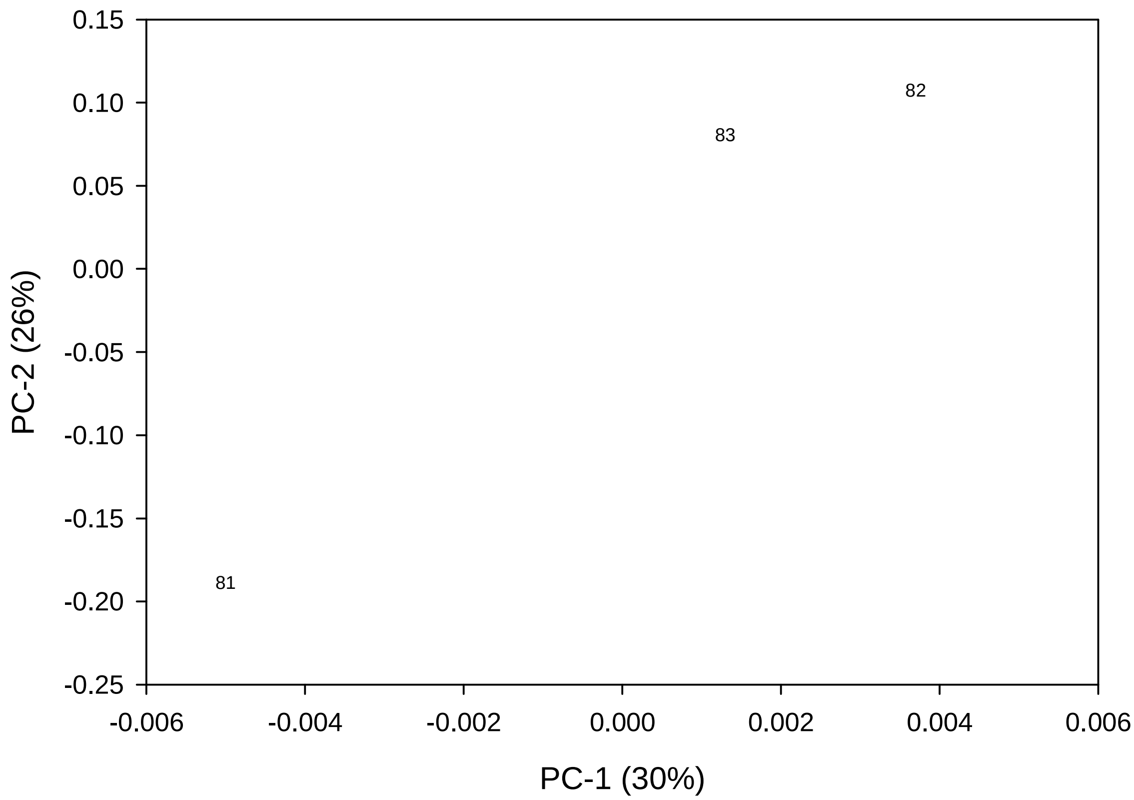

Figure 32 - Stations plotted in PC1-PC2 space for samples collected during the summer study

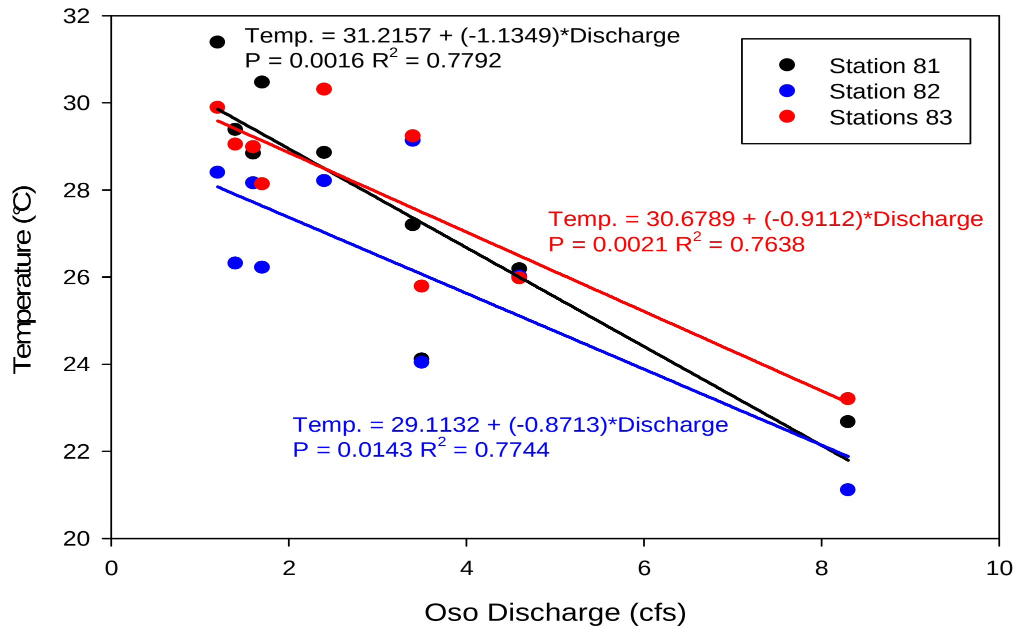

Figure 33 - Temperature vs. Oso discharge for summer study

Taken as a whole, the stations show a linear relationship between discharge and temperature: Temp.=30.3359 + -0.9725*Discharge, R2=0.6627, P<0.0001. However, when considered separately there are indications of autocorrelation in the errors. It is questionable if the bay canbe considered a unit based on the different hydrologic and geomorphologic characteristics of the stations.

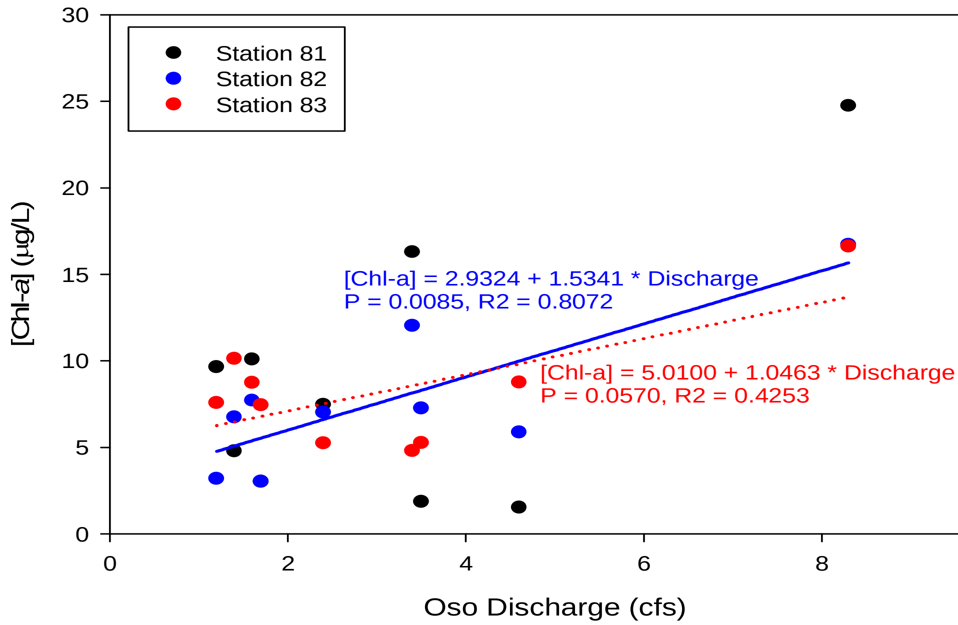

Figure 34 - Chlorophyll a concentration [Chl-*a*] vs. Oso gage discharge during the summer study. The Yorktown station relationship (dotted red line) significance was just below the .95 threshold.

Discharge was also related to chlorophyll-*a* concentrations at the two upper bay sites (Figure 34). Linear analysis showed that there was autocorrelation in the errors and regression power less than desired. Still, it seems likely that this relationship is real and that it shows a system response of increased production with increased freshwater inflow, even at small levels of flow.

Temperature was correlated negatively with [PO_4] at Yorktown Road, and negatively with [DO] at the mid-bay station. Temperature also was positively correlated with pH at the Ocean drive station. It is unclear what these relationships mean. The nutrient and DO relationships are represented on PCA axis two, and the pH relationship is represented in PCA axis 3, neither of which is related to discharge from Oso Creek.

3.3.3 Continuous Observations

Sondes were deployed at each site at a depth that would insure that they were not exposed to the atmosphere during low tide. They were set to record every 15 minutes during the period from September 19, 2008 to September 25, 2008.

Table 9 - Hydrographic values for continuous sond deployment. 9/19/2008 - 9/25/2008

	Station	Mean	S.D.	Min.	Max.
Temp.	81	27.67	2.9	22.67	31.38
	82	26.39	2.54	21.10	29.13
	83	27.83	2.35	23.20	20.30
Salinity(psu)	81	36.92	4.30	30.13	42.30
	82	38.93	5.53	30.28	45.82
	83	36.85	5.85	25.11	44.32
[DO] mg/L	81	5.43	1.33	3.86	7.20
	82	5.04	1.08	3.50	7.00
	83	4.89	0.79	3.48	6.41
pH	81	8.14	0.09	7.94	8.28
	82	8.26	0.08	8.10	8.38
	83	8.22	0.12	8.05	8.49

They recorded depth, temperature, salinity, conductivity, pH, dissolved oxygen, and percent oxygen saturation (Table 9). During this time flow ranged from 2.0 cfs to 6.1 cfs. The maximum was at the peak of a very small, short-duration event that began on 9/22/2008 and peaked the next day then declined over the next two days.

Temperature at the stations exhibited similar patterns (Figure 35). There was a general decline in temperature at all stations. The Yorktown station, (83), temperature became more variable around the diel cycle, and appears level off as the inflow mixes with the bay water. There were no significant temperature differences in the mean. (Figure 36).

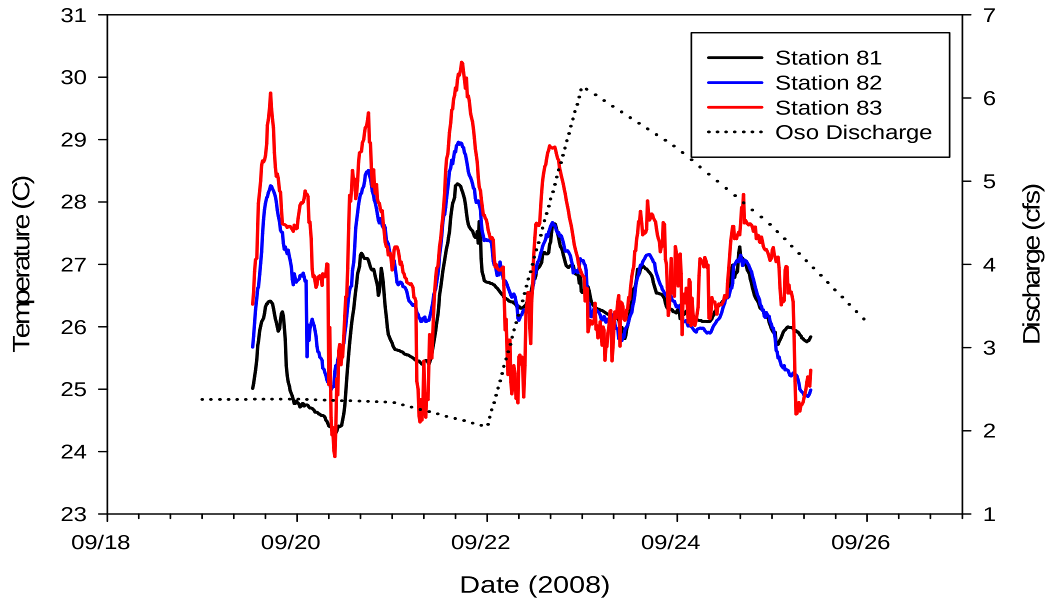

Figure 35 - Temperature traces by station for continuous sonde deployment

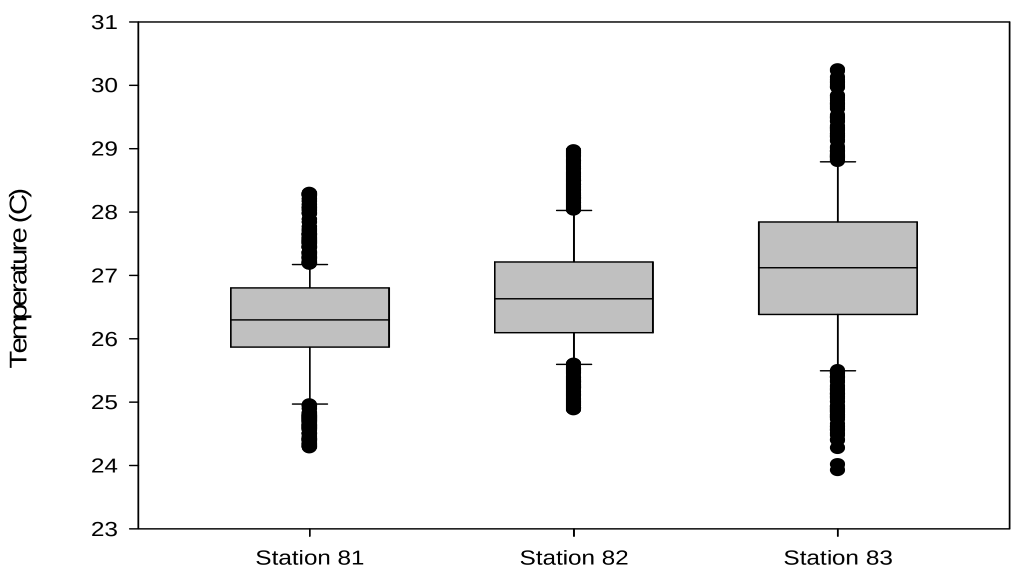

Figure 36 - Temperature by station for continuous observations

Salinity behaved differently during the continuous deployment (Figure 37). The Ocean Drive station (blue in Figure 37) was dominated by Corpus Christi Bay and the tidal cycle. Salinity became more volatile at the onset of the small inflow event but maintained its normal tidal variation. As expected, salinity dropped the greatest with inflow at the Yorktown station, (red in Figure 37), dropping from 37-38 psu to a low around 16psu. Most interesting was the mid bay station (blue in Figure 37). As water flowed into the Oso and made its way toward Corpus Christi Bay, it pushed more saline water into the mid bay driving salinities slightly higher showing that mixing continues at least to the mid-bay. In the mean, there was a salinity gradient during the event with decreasing salinity away from Corpus Christi Bay (Figure 38).

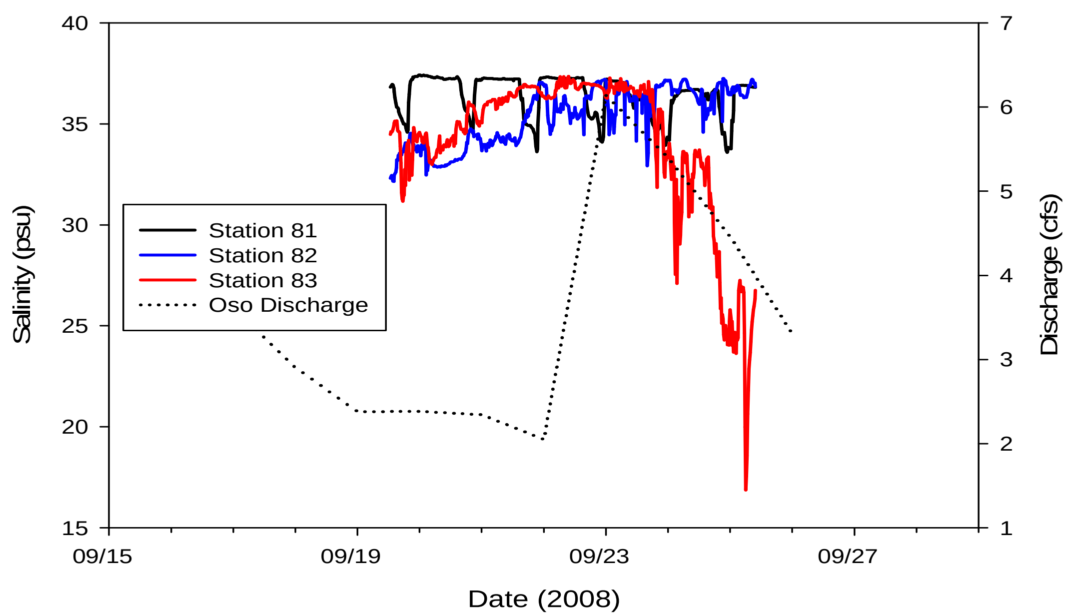

Figure 37 - Salinity traces from continuous sonde study deployment

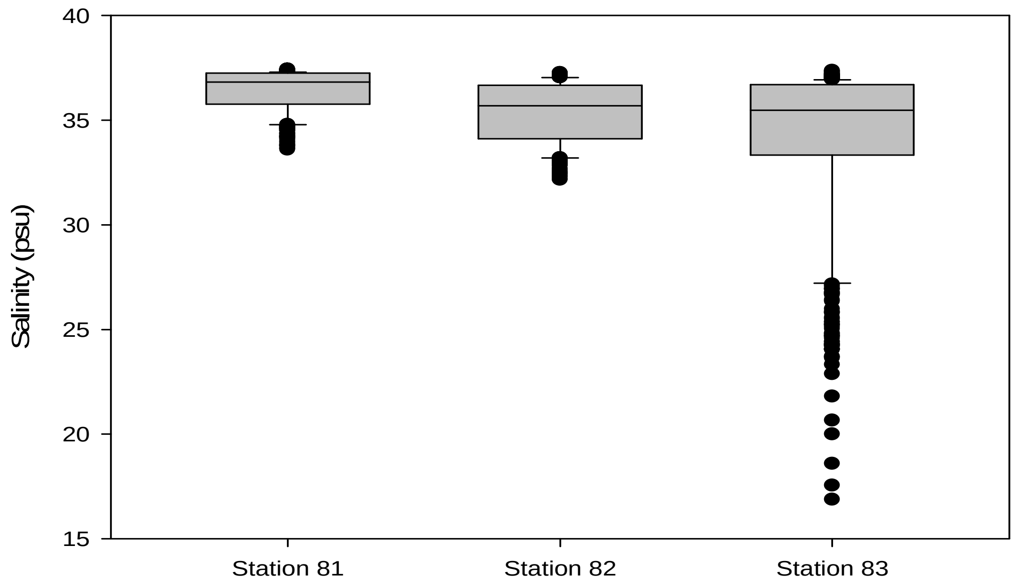

Figure 38 - Salinity during continuous sonde deployment

Dissolved oxygen declined around a diel cycle during the first part of the deployment, prior to the inflow of fresh water (Figure 39). All stations show this pattern. The upstream station (red in Figure 39) saw an increase in variability around the mean that was not as pronounced as at the other stations. No evidence of a [DO] gradient was observed.

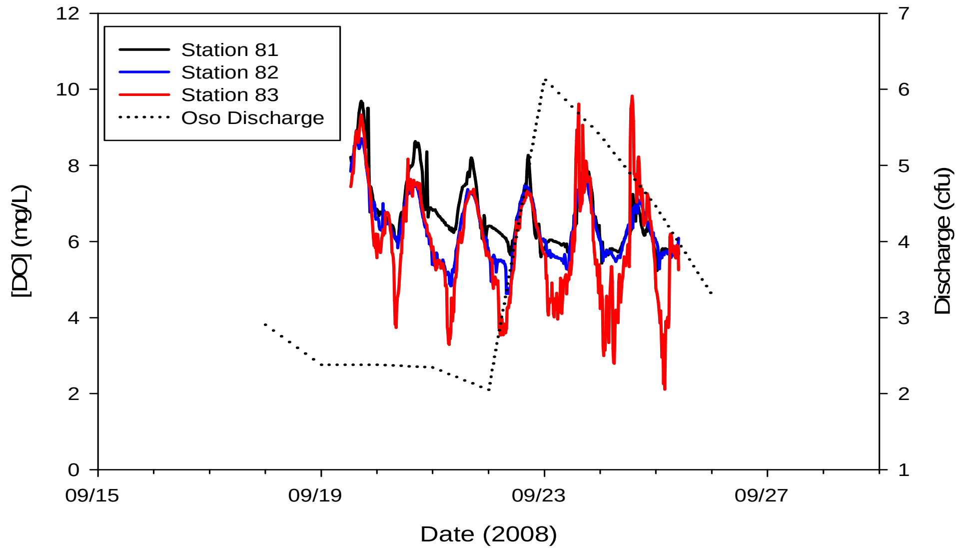

Figure 39 - Dissolved oxygen traces from continuous sonde deployment

The pH was highly variable during the continuous deployment. The Ocean drive site, (black in Figure 40) was dominated by Corpus Christi Bay and varied on a diel cycle. There may have been some of this diel influence seen at the mid-bay station, but at the upstream station, there was no diel signal. However, pH does appear to rise in the mean with the inflow from the small event.

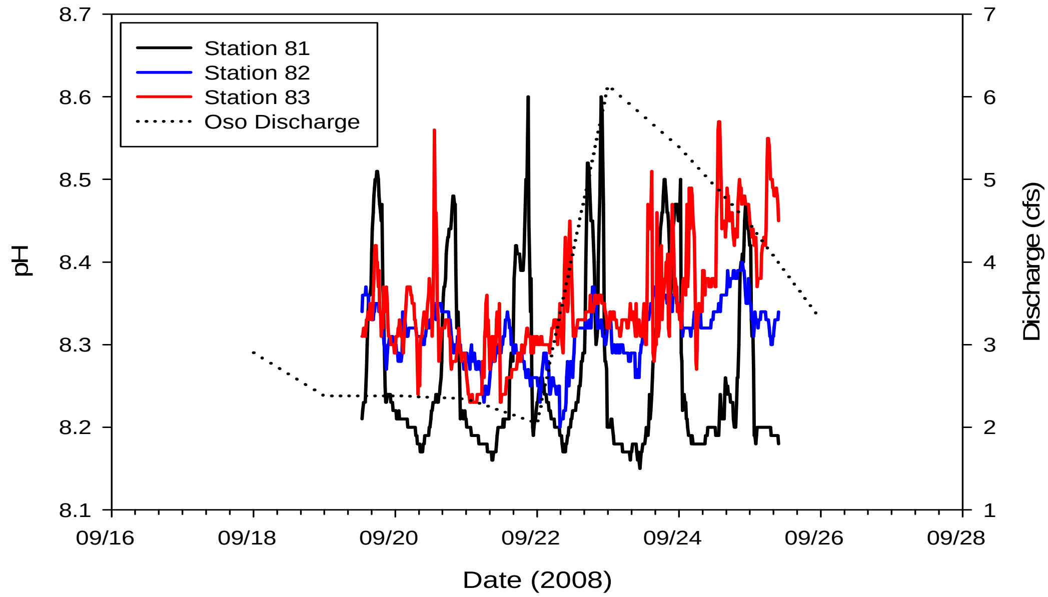

Figure 40 - pH traces for continuous sonde deployment

3.3.4 Discussion

Small rain events have surprising results in Oso Bay. In other regions of the world it is common for temperatures to decrease and nutrients and sediments to increase. And this appears to be the pattern for small changes during minimal flow periods. But during small pulses from normal rainfall in the watershed of Oso Bay, higher levels of discharges are associated with higher temperatures, dissolved oxygen, and pH. In contrast, silicate and ammonium decrease. This is likely due to the unique nature of Oso Bay in that it is fed by wastewater treatment plants and cooling water from a power plant. The warm water from the power plant explains the increased temperatures, and the urban nature of the water shed explains the lack of sediment (i..e., silicate increases). Nutrients (nitrite+nitrate and phosphate) were higher prior to and early in the rain event and then decreased. Evidently, the nutrients were transported out of Oso Bay by these low levels of discharge, rather than being loaded.

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PART IV Nutrient Concentrations and Their Relationships to Hypoxia in Corpus Christi Bay

4.1 Introduction

Estuarine hypoxia (low dissolved oxygen concentration) occurs world-wide and up to 245,000 km^2 of the marine environment experiences hypoxia and the occurrence of the phenomenon is likely increasing (Diaz and Rosenberg 2008). Anthropogenic changes to coastal systems and climate change are predicted to facilitate an increase in extent of hypoxia (Rabalais *et al.* 2010). It is estimated that 6% of the estuaries of the northern Gulf of Mexico experience hypoxia (Engle *et al.* 1999). Hypoxia is known to have occurred in the southeast corner of Corpus Christi Bay each summer since its discovery in 1988 (Ritter and Montagna 1999). Hypoxia is commonly defined as dissolved concentrations less than 2.0 mg/L (Dauer *et al.* 1992). At this level, and perhaps at levels below 3.0 mg/L, physical intolerance to low oxygen can cause reduction of benthic biomass, abundance , diversity, species richness and species evenness (Ritter and Montagna 1999; Montagna and Ritter 2006).

Over the long term, the Corpus Christi Bay hypoxic area has a decrease in diversity among the epibenthic community of fish and mobile invertebrates (Montagna and Froeschke 2009). On shorter time scales, hypoxia has been shown to affect mortality and egg production in harpacticoid copepods, especially when accompanied by elevated concentrations of ammonium (Ryckman 2010).

It is now certain that the hypoxia in Corpus Christi Bay has a greater extent spatially and temporally than previously thought and that it is in part caused by saline stratification due to hyper-saline water moving into the southeastern corner of the bay from Laguna Madre and/or Oso Bay (To 2009) coupled with sediment BOD (Sell and Morse 2006).

From 1988 to 1993 monitoring was confined to July, and August was added in 1994. This was expanded to June in 2005 and 2006 and it is now apparent that hypoxia is just as prevalent in early June and late August as in July, thus we do not know when it starts or when it stops. Since 1999, the areal extent was thought to be limited; extending only as far west as the entrance to Laguna Madre over an area of about 57 km^2 (Applebaum *et al.* 2005).

While it has been confirmed that stratification plays an important role in the onset of hypoxia in Corpus Christi Bay, the role of nutrients from ground water sources or Oso Bay has not been explored as a causal mechanism of hypoxia in Corpus Christi Bay. In contrast, opening Packery Channel in 2005 (Palmer *et al.* 2008) may alleviate the occurrence of hypoxia by introducing cooler and less salty water from the Gulf of Mexico to Corpus Christi Bay or by increasing circulation and mixing in the southeastern corner of the bay. However, no information existed on water quality exported from Oso Bay or Laguna Madre.

The Corpus Christi Bay hypoxic area is located in the lower-bay zone far from the largest source of freshwater inflow, the Nueces River (Ritter and Montagna 1999). Generally, turbidity decreases farther from the source of fresh water resulting in more efficient nutrient uptake, resulting in lower nutrient concentrations. However, Oso Creek delivers fresh water to Oso Bay, and subsequently into Corpus Christi Bay near the hypoxic area. There are three municipal waste water treatment facilities that discharge into Oso Bay waters, two into Oso Creek, and one directly into Oso Bay. This raises the possibility that nutrient flux into this region of Corpus Christi Bay is contributing to hypoxia via eutrophication. Eutrophication, excess production due to increased nitrogen and phosphorous from anthropogenic sources is an increasing worldwide phenomenon in coastal systems (Nixon 1995).

4.2 Methods

4.2.1 Study Location

Corpus Christi Bay is a shallow, ~3.2 m. (Orlando *et al.* 1991a), almost enclosed bay with a level bottom (Figure 41). Corpus Christi Bay has a total open water surface area of 432.9 km^2 and is microtidal, which makes it sensitive to meteorological forcing. Average monthly wind speeds range from 17 $km\ h^{-1}$ to 28 $km\ h^{-1}$.

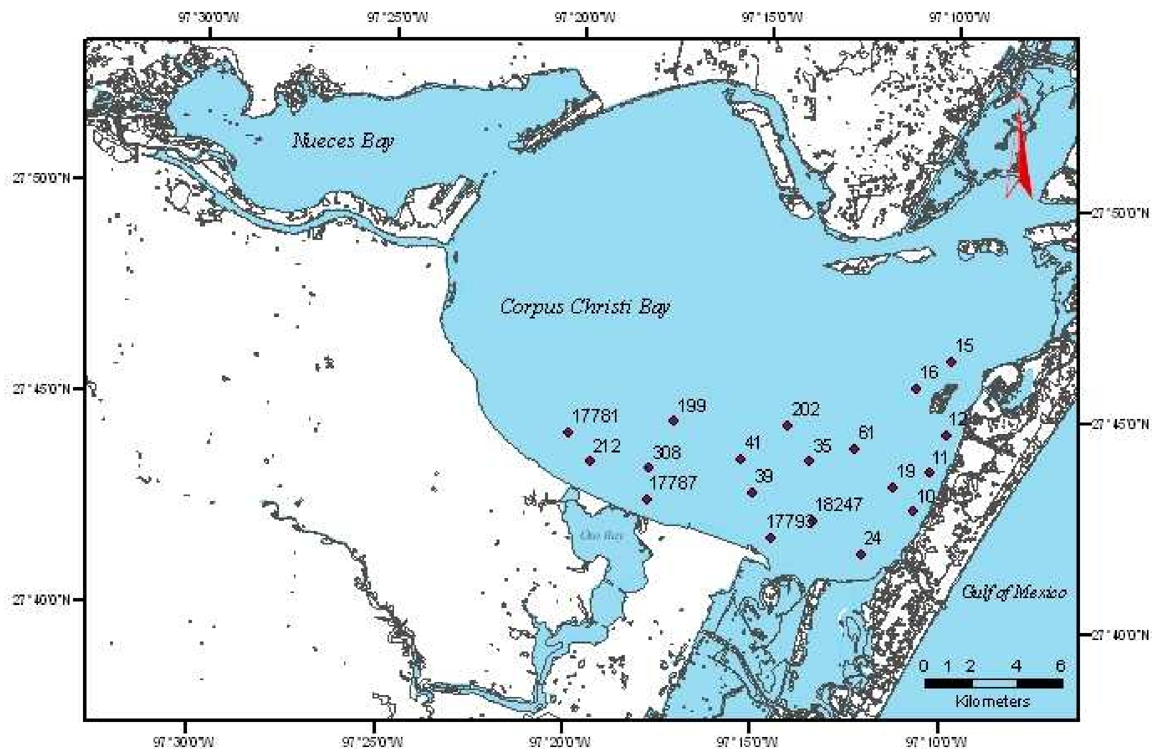


Figure 41 - Map of station locations in Corpus Christi Bay, Texas, USA. Nueces River discharges into eastern Nueces Bay. Oso Creek discharges into Oso Bay which connects to southeastern Corpus Christi Bay. Corpus Christi Bay is located western Gulf of Mexico

Two principle wind regimes dominate in the Corpus Christi Bay area: persistent, southeasterly winds from March through September and episodic north-northeasterly winds from October through March (Behrens and Watson 1977; Brown and Militello 1997). Corpus Christi Bay receives an average of 74 cm yr^{-1} of rainfall and 25 m^3 s^{-1} inflow (Orlando *et al.* 1991a). The average evaporation rate is high at 150 cm yr^{-1}. The combination of low rainfall and high evaporation causes high salinities, and the average salinity between 1977 and 2007 for the Nueces Estuary (which includes Nueces and Corpus Christi Bays) is 29 (Montagna et al. 2010)

4.2.2 Study Design

Hypoxia in Corpus Christi Bay has been monitored since 1988 (Ritter and Montagna 1999; Applebaum *et al.* 2005; Montagna and Ritter 2006; Montagna and Froeschke 2009), It was discovered in 2006 that the hypoxic area is likely much larger than previously thought and it could occur in spring and fall as well (Nelson and Montagna 2009). There are two types of sampling: grab sampling where DO is measured at specific points in space and time by placing the sonde in the water and taking readings; and continuous sampling where DO is measured at short time intervals over a long period of time in one place by mooring the sonde. The current project expanded the scale of the past grab sample monitoring in both space and time. Sampling began in May, 2008 and continued into late September, 2008. Nineteen stations were selected in the southern half of Corpus Christi Bay (Table 10) for a synoptic survey. To determine if hypoxia is intermittent, four stations were established; in the historic epicenter, as well as stations near Oso Bay, and Laguna Madre, and one western site, outside the known extent of the hypoxic region. Continuous sampling was conducted at these locations for 5, 7-day time periods between May 19, and September 24.

Table 10 - Station designator, location and brief location descriptions. Sediment mean diameter from (Shideler 1984)

Station No.	Short description	Latitude (N)	Longitude (W)	Mean Diameter (non-gravel fraction)
17781	4.3 Km NW of Oso	27.73972	97.33472	6.0 φ - 7.0 φ
212	2.7 Km NW of Oso	27.72861	97.32489	6.0 φ - 7.0 φ
17787	1.0 Km N of Oso	27.71445	97.29916	4.0 φ - 5.0 φ
308	2.2 Km N of Oso	27.74556	97.23722	8.0 φ - 9.0 φ
199	4.5 Km N of Oso	27.74556	97.28806	7.0 φ - 8.0 φ
41	Between Oso and Laguna Madre 3.5 Km from S shore	27.73167	97.25777	7.0 φ - 8.0 φ
39	Between Oso and Laguna Madre 2.4 Km from S shore	27.71862	97.25222	7.0 φ - 8.0 φ
202	Between Oso and Laguna Madre 5.5 Km from S shore	27.74556	97.23722	8.0 φ - 9.0 φ
17793	West of CC Bay/Laguna Madre nexus 0.85 Km from S shore	27.70083	97.24333	5.0 φ - 6.0 φ
35	4.6 Km N of Laguna Madre	27.73167	97.22695	7.0 φ - 8.0 φ
18247	2.2 Km N of Laguna Madre	27.70833	97.22500	6.0 φ - 7.0 φ
61	5.7 Km N of Laguna Madre	27.73713	97.20745	8.0 φ - 9.0 φ
16	0.7 Km E of Shamrock Is.	27.76205	97.18070	7.0 φ - 8.0 φ
15	1.0 Km N of Shamrock Is.	27.77310	97.16552	4.0 φ - 5.0 φ
24	1.0 Km from SE corner of CC Bay	27.69552	97.20298	3.0 φ - 4.0 φ
19	Near SE shoreline of CC Bay	27.72267	97.18978	5.0 φ - 6.0 φ
10	Near SE shoreline of CC Bay	27.71375	97.18012	3.0 φ - 4.0 φ
11	Near shoreline of CC Bay 2.7 Km from Shamrock Is.	27.72873	97.17373	4.0 φ - 5.0 φ
12	Near shoreline of CC Bay 1.1 Km S. of Shamrock Is.	27.72861	97.32489	3.0 φ - 4.0 φ

4.2.3 Equipment

YSI multi-parameter water quality sondes, models 6920-S, 6920 v2, and 600XLM were used to measure water quality during the surveys of Corpus Christi Bay. The YSI sondes have the following accuracy and units: temperature (±0.15 ºC), ph (± 0.2 units), dissolved oxygen (mg l^{-1} ± 0.2), dissolved oxygen saturation (± 2%), specific conductivity (± 0.5% of reading depending on range), depth (± 0.2m), and salinity (± 1% of reading or 0.1 ppt, whichever is greater, automatically corrected to 25 ºC) (YSI 2012).

4.2.4 Nutrients

Water column samples for nutrient analysis were collected at each site from the surface and from the bottom at about 10 cm above the sediment surface using a Van Dorn bottle. Two replicate samples were taken from each depth and decanted into 125 mL opaque brown Nalgene bottles that had been rinsed with sample water. Each bottle was placed immediately into ice for transport to the lab for preparation and analysis. At the laboratory, 12 ml of sample was filtered using 0.45 micron glass fiber filters and a hand syringe. Filtrate was stored in a pre-cleaned, non-glass 15 ml capped tube. Information about the sample was recorded on the tube. Samples were frozen at ≤ -20 ºC until analysis, typically less than two weeks.

Analysis was performed on a Lachat Quikchem 8000 using EPA-equivalent methods. NO_X analysis was performed using a cadmium reduction method, (Lachat method 31-107-04-1-A for brackish or seawater matrix) equivalent to EPA method 353.2 (USEPA 1993b). Ortho-phosphate concentrations were determined using EPA method 365.1 (USEPA 1993c) (Lachat method 31-115-01-1-J for brackish or seawater matrix). Silicate concentrations were determined using a method equivalent to EPA 366.0 (Zhang and Berberian 1997) for brackish or seawater (Lachat method 31-114-27-1-B) and Ammonium concentration was determined using EPA method 350.1 equivalent method (USEPA 1993a) (Lachat method 31-107-06-1-B for brackish or sea water matrix). The detectible concentration limit for all chemistries was 0.03 mg/L

4.2.5 Chlorophyll-a

After collection, 25 mL - 50 mL of sample water, depending upon the water column clarity as measured by Secchi disk at the sample site, was filtered using a 0.45 micron glass fiber filter and a hand syringe. In general, a volume, in mL of half the numerical value of the Secchi depth was used up to a maximum of 50 mL and a to a minimum of 25 mL. The filter containing the sample to be analyzed for chlorophyll-*a* concentration was frozen at ≤20 ºC until analysis, typically less than two weeks. For analysis, 5.0 mL of methanol was added to each sample and allowed to rest over night at ≤-20 ºC to extract the chlorophyll-*a*. The concentration was then measured fluorometrically on a Turner fluorometer using a non-acidification technique - EPA method 445.0 (Welchmeyer 1994).

4.2.6 Spatial and Temporal Extent

Continuous measurements for dissolved oxygen (DO) concentration, DO saturation, salinity, conductivity, sonde depth, pH, and temperature data were collected at stations 17781, 17787, 17793, and 18247 (Figure 41). These stations were chosen both for their proximity to Oso Bay, Laguna Madre, and the historic epicenter of the hypoxic zone, as well as to collect data beyond the known historical spatial extent. Five roughly week-long sampling missions were conducted during the period from May 19, 2008 through September 24, 2008. Sampling in May and September were conducted in order to determine whether or not hypoxia occurred before or after the known temporal extent.

For continuous measurements using the YSI 6920-S and 600XLM model sondes fitted with a Clark cell DO probe, quality control was assured by changing the DO membrane prior to deployment. The YSI 6920 V2 instruments employ an optical DO sensor that does not require a probe membrane. Once DO membranes have been changed, they are left set to run continuously to allow time for the new membranes to become stable. The sondes are then calibrated to 100% saturation in oxygen-saturated water. During calibration, only fresh standards were used and each probe was rinsed with the proper standard prior to calibration. The pH probes are calibrated using a two-point calibration - pH 7 and pH 10. The sonde salinity probes were also calibrated using a two-point calibration - 0.0 mS and 50 mS.

Each sonde was then covered in plastic wrap and duct tape to prevent fouling and ease cleaning. The probe end of each sonde was wrapped with a damp towel for transport. The sondes were deployed at each site approximately 1.0 m below the water surface and another approximately 25 cm above the sediment surface on semi-permanent, low-relief moorings using SCUBA (Figure 42). Measurements were taken every 15 minutes for the duration of the deployment. Once the deployment period was complete, the sondes were retrieved, wrapped in damp towels, returned to the lab and again placed in an oxygen-saturated environment for a few logging cycles. Logging was then stopped and the data downloaded. Data was acceptable if the pre- and post-deployment periods in a saturated environment returned to the same levels and the pre- and post-calibration values were within acceptable values.

During deployment runs, and retrieval events, grab samples were taken at the surface and at the bottom at each site using a YSI multi-parameter data sonde. At each depth, dissolved oxygen concentration, dissolved oxygen saturation, salinity, conductivity, depth, pH, and temperature were recorded.

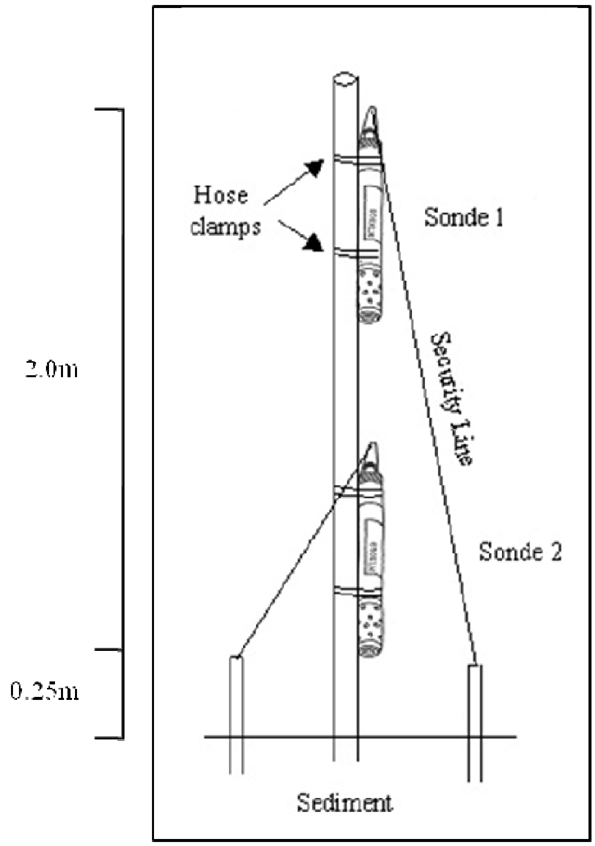


Figure 42 - Mooring for YSI sondes used in continuous monitoring

4.3 Results

4.3.1 Spatial and Temporal Extent

The earliest sonde deployment, from May19, 2008 to May 27, 2008 observed no hypoxic conditions at any sampled locations. The lowest DO measurement from the May deployment was 3.08 mg/L on May 24, 2008. Mean station bottom water DO during this period ranged from a low of 3.05 mg/L at station 17793 to a high of 6.82 mg/L at station 17781 (Table 11).

Table 11 - Mean continuous hydrographic values by station

	Station	Month	Depth (m)		Temp. (°C)		Salinity (ppt)		[DO] mg/L		pH	
			Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD
Bottom	17781	5	0.69	0.16	27.68	0.95	32.25	0.88	5.34	1.09	8.10	0.11
	17787	5	.	.	.	.	.	.	.	.	.	.
	17793	5	1.01	0.13	28.21	0.77	32.75	0.97	.	.	8.34	0.15
	18247	5	0.52	0.14	28.07	0.76	32.12	0.60	6.37	0.51	**8.09**	0.09
	17781	6	0.55	0.08	30.21	0.42	33.89	0.30	6.04	0.34	8.15	0.04
	17787	6	0.56	0.07	29.84	0.49	**31.72**	0.47	.	.	8.14	0.02
	17793	6	0.84	0.08	29.68	0.52	35.51	1.50	.	.	8.25	0.10
	18247	6	0.97	0.08	29.90	0.64	35.79	1.17	6.19	0.93	8.29	0.05
	17781	7	0.74	0.23	29.71	0.89	36.33	0.58	5.85	0.26	8.19	0.02
	17787	7	0.46	0.23	29.53	0.85	36.54	0.68	6.17	0.36	8.17	0.05
	17793	7	0.57	0.21	29.48	1.10	38.27	1.44	**5.10**	0.67	**8.55**	0.13
	18247	7	0.72	0.16	29.65	1.00	**39.09**	1.20	5.62	0.7	8.25	0.07
	17781	8	0.60	0.07	**30.48**	0.45	35.15	0.10	.	.	8.17	0.02
	17787	8	0.41	0.07	30.05	0.57	35.45	0.32	5.90	0.73	8.10	0.03
	17793	8	0.53	0.07	30.34	0.51	37.75	0.88	5.93	0.47	8.40	0.12
	18247	8	0.81	0.06	30.29	0.54	36.48	0.22	6.04	0.44	8.38	0.04
	17781	9	0.88	0.11	25.98	0.61	36.43	0.13	6.93	0.46	8.22	0.04
	17787	9	0.92	0.11	**25.91**	0.78	36.56	0.25	**7.16**	0.5	8.24	0.03
	17793	9	0.82	0.11	25.93	0.71	37.32	0.13	6.86	0.72	8.25	0.07
	18247	9	0.82	0.10	26.03	0.54	36.69	0.08	6.96	0.36	8.21	0.02
Top	17781	5	3.96	0.14	27.79	1.04	**31.52**	1.07	5.91	0.56	8.14	0.07
	17787	5	3.27	0.14	27.92	1.05	33.77	1.48	5.13	1.11	8.26	0.07
	17793	5	3.43	0.14	28.26	0.74	34.51	1.83	6.06	0.73	8.14	0.15
	18247	5	3.91	0.14	27.84	0.74	33.04	0.87	.	.	8.41	0.17
	17781	6	4.01	0.08	29.69	0.27	33.82	0.91	5.52	0.37	8.11	0.03
	17787	6	3.32	0.08	29.62	0.47	37.12	2.33	3.94	1.03	8.22	0.09
	17793	6	3.43	0.08	29.50	0.29	39.88	2.27	**3.05**	1.15	8.35	0.20
	18247	6	3.90	0.08	29.54	0.20	40.34	2.04	2.65	1.34	8.35	0.14
	17781	7	4.27	0.20	29.36	0.77	36.32	0.51	5.70	0.41	8.19	0.05
	17787	7	3.49	0.18	29.37	0.74	38.10	1.21	4.42	1.42	8.16	0.11
	17793	7	3.99	0.17	29.23	1.03	39.11	1.72	5.00	0.85	8.30	0.12
	18247	7	4.11	0.16	29.39	0.85	**40.61**	2.71	.	.	8.29	0.10
	17781	8	3.99	0.07	29.9	0.26	35.04	1.48	5.34	0.63	**8.06**	0.03
	17787	8	3.23	0.07	29.96	0.34	35.56	1.44	4.05	1.24	8.25	0.08
	17793	8	3.34	0.06	**30.47**	0.52	38.23	0.77	5.11	1.14	**8.59**	0.09
	18247	8	3.86	0.06	30.21	0.29	36.89	0.84	4.03	1.28	8.54	0.08
	17781	9	4.20	0.11	**25.69**	0.61	36.47	0.13	**6.82**	0.45	8.28	0.04
	17787	9	3.36	0.11	25.83	0.82	36.94	0.18	6.81	0.44	8.27	0.03
	17793	9	3.40	0.11	25.98	0.73	40.06	0.13	6.67	0.56	8.31	0.08
	18247	9	4.10	0.10	25.83	0.64	39.4	0.09	6.47	0.25	8.32	0.02

Bottom water dissolved oxygen concentration readings from this deployment do not include station 18247. The sonde deployed at site 18247 failed QAQC upon return to the laboratory, so this data is not reported. The first hypoxia occurrence in the 2008 season was on June 18th with a measurement of 1.87 mg/L.

The last sonde deployment, from September 18, 2008 to September 25, 2008, recorded no hypoxia. The lowest dissolved oxygen concentration observed in the September deployment was 5.8mg/L at site 17781on September 24, 2008. The latest-in-the-year hypoxic observation for the 2008 sampling was a value of 1.86mg/L on August 6, 2008. Mean station bottom water DO during this period ranged from a low of 6.46 mg/L at station 18247 to a high of 6.82 mg/L at station 17781 ().

Station 17781 was established approximately 1.0 km offshore, 2.2 Km northwest of the mouth of Oso Bay. This station was established beyond the western extent of previous study locations in an effort to determine a maximum position of the western boundary of the hypoxic area (Figure 41). Hydrographic measurements and sonde deployments at site 17781 found no hypoxia at any time during the five-month period. The lowest dissolved oxygen concentration found at site 17781 during the 2008 deployments was 3.61 mg/L on August 4, 2008. The other three continuous stations observed hypoxic conditions during the study period. Station 17787 experienced 10.25 hours of hypoxia during the 792 hours of continuous measurements (Table 12).

Table 12 - Bottom-water hypoxia at station 17787

Date Time		Duration of Hypoxia		
Begin	End	≤3 mg/L	≤2 mg/L	≤1 mg/L
6/18/08 15:16	6/18/08 22:46	7.50	0.00	0.00
6/19/08 17:31	6/18/08 23:01	5.75	1.75	0.00
6/20/08 03:46	6/20/08 06:46	3.75	0.00	0.00
6/20/08 07:16	6/20/08 07:31	0.50	0.00	0.00
6/20/08 21:01	6/20/08 23:01	2.25	0.00	0.00
6/21/08 21:01	6/21/08 21:31	0.75	0.00	0.00
6/22/08 21:16	6/22/08 23:01	2.00	0.00	0.00
6/23/08 19:31	6/23/08 23:46	4.50	2.00	0.00
6/24/08 00:16	6/24/08 00:16	0.25	0.00	0.00
6/24/08 02:00	6/24/08 02:00	0.25	0.00	0.00
6/24/08 06:15	6/24/08 06:15	0.25	0.00	0.00
6/24/08 07:01	6/24/08 07:16	0.50	0.00	0.00
6/24/08 07:46	6/24/08 09:31	2.00	0.00	0.00
6/24/08 15:31	6/24/08 17:16	2.00	0.00	0.00
6/25/08 04:16	6/25/08 05:31	1.50	0.00	0.00
6/25/08 06:31	6/25/08 06:45	0.25	0.00	0.00
6/25/08 07:01	6/25/08 07:31	0.75	0.00	0.00
7/18/08 11:31	7/19/08 00:01	12.75	4.50	1.50
7/19/08 08:31	7/19/08 19:31	11.25	0.00	0.00
7/19/08 20:01	7/20/08 00:01	4.25	0.00	0.00
7/20/08 07:31	7/20/08 08:01	0.75	0.00	0.00
7/20/08 09:01	7/20/08 09:01	0.25	0.00	0.00
7/20/08 11:01	7/20/08 14:31	3.75	0.00	0.00
7/20/08 17:16	7/20/08 19:31	2.50	0.00	0.00
7/20/08 23:01	7/20/08 23:01	0.25	0.00	0.00
7/21/08 20:16	7/21/08 20:16	0.25	0.00	0.00
7/21/08 21:16	7/21/08 21:16	0.25	0.00	0.00
7/21/08 21:46	7/21/08 22:46	1.25	0.00	0.00
7/21/08 23:16	7/21/08 23:16	0.25	0.00	0.00
7/22/08 00:01	7/22/08 00:01	0.25	0.00	0.00
7/22/08 00:31	7/22/08 00:46	0.50	0.00	0.50
8/03/08 02:31	8/03/08 03:31	1.25	0.00	0.00
8/03/08 15:01	8/03/08 15:01	0.25	0.00	0.00
8/03/01 15:31	8/03/01 15:31	0.25	0.00	0.00
8/03/08 16:01	8/03/08 16:01	0.25	0.00	0.00
8/04/08 13:46	8/04/08 14:31	1.0	0.00	0.00
8/05/08 03:31	8/05/08 06:01	2.75	0.00	0.00
8/05/08 09:16	8/05/08 19:01	10.00	0.00	0.00
Sum		89.00	8.25	2.00
Percent of time hypoxia occurred at night		40.45	63.64	0.00

Two hours were below 1.0 mg/L. Hypoxia occurred mostly at night (67%). Station 17793 experienced 37.5 of hypoxia during 789 hours of continuous monitoring (Table 13). When hypoxia was measured, it occurred at night 76% of the time. Station 18247, the highest salinity station observed the most frequent hypoxia, 88.75 hours out of 767 hours continuous observations. Like the other stations, when station 18247 experienced hypoxia, it was most frequent at night (63.6%).darkness (Table 14).

Table 13 - Bottom-water hypoxia at station 17793

Date Time		Duration of Hypoxia		
Begin	End	≤3 mg/l	≤2 mg/l	≤1 mg/l
6/18/08 13:01	6/18/08 14:31	1.75	0.00	0.00
6/18/08 15:01	6/18/08 15:16	0.50	0.00	0.00
6/18/08 17:16	6/18/08 19:16	2.25	0.00	0.00
6/18/08 19:46	6/18/08 21:16	1.75	0.00	0.00
6/18/08 21:46	6/19/08 00:01	2.50	0.25	0.00
6/19/08 11:01	6/19/08 12:16	1.50	0.00	0.00
6/19/08 14:16	6/19/08 14:31	0.50	0.00	0.00
6/19/08 16:01	6/19/08 16:01	0.25	0.00	0.00
6/19/08 16:31	6/19/08 21:46	5.50	0.00	0.00
6/20/08 10:16	6/20/08 14:01	4.00	1.00	0.00
6/20/08 16:31	6/21/08 05:31	13.25	6.50	0.00
6/21/08 06:01	6/21/08 06:16	0.50	0.25	0.00
6/21/08 12:01	6/21/08 12:01	0.25	0.00	0.00
6/21/08 13:16	6/21/08 13:31	0.50	0.00	0.00
6/21/08 16:46	6/22/08 00:46	8.25	7.25	0.00
6/22/08 10:16	6/22/08 10:16	0.25	0.00	0.00
6/22/08 11:01	6/22/08 12:16	1.50	0.00	0.00
6/22/08 16:01	6/22/08 16:31	0.75	0.00	0.00
6/22/08 18:16	6/23/08 12:31	18.50	12.25	0.00
6/23/08 15:16	6/24/08 01:16	10.25	9.75	0.00
6/24/08 11:46	6/24/08 13:31	2.00	0.25	0.00
6/24/08 15:16	6/24/08 16:01	1.00	0.00	0.00
6/25/08 08:16	6/24/08 09:46	1.75	0.00	0.00
6/25/08 10:16	6/24/08 11:16	1.25	0.00	0.00
7/18/08 18:01	7/18/08 19:01	1.25	0.00	0.00
7/18/08 21:46	7/18/08 21:46	0.25	0.00	0.00
7/18/08 22:16	7/18/08 22:16	0.25	0.00	0.00
7/21/08 19:01	7/21/08 19:01	0.25	0.00	0.00
7/21/08 19:46	7/21/08 19:46	0.25	0.00	0.00
7/21/08 23:46	7/22/08 02:46	3.25	0.00	0.00
8/04/08 21:01	8/05/08 00:30	3.75	0.00	0.00
8/05/08 01:31	8/05/08 02:00	0.75	0.00	0.00
8/05/08 02:46	8/05/08 02:46	0.25	0.00	0.00
8/05/08 03:16	8/05/08 08:31	5.50	0.00	0.00
8/05/08 13:31	8/05/08 14:01	0.75	0.00	0.00
8/05/08 14:31	8/05/08 15:01	0.75	0.00	0.00
8/05/08 15:31	8/05/08 16:46	1.50	0.00	0.00
Sum		99.25	37.50	0.00
Percent of time hypoxia occurred at night		53.27	76.00	N.D.

Table 14 - Bottom-water hypoxia at station 18247

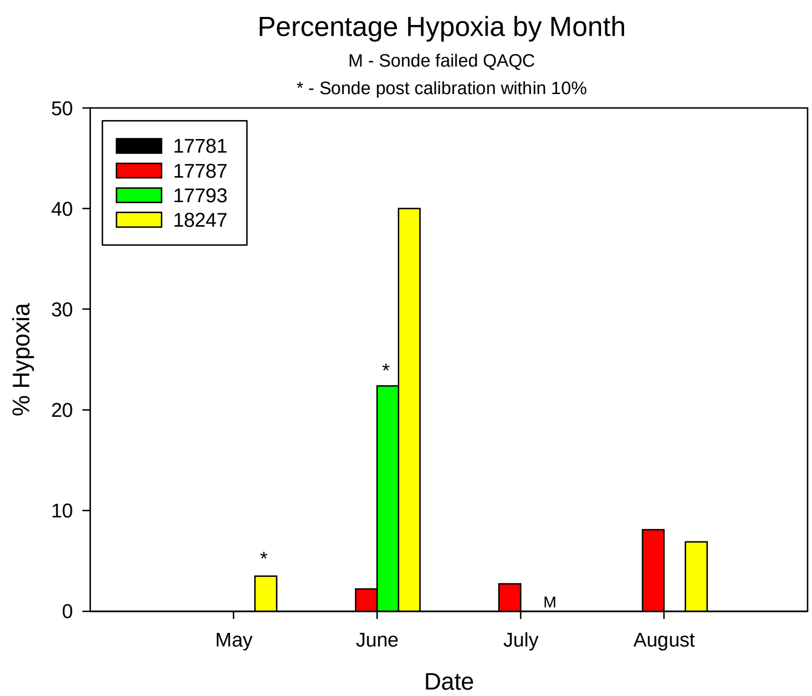
Date Time		Duration of Hypoxia		
Begin	End	≤3 mg/l	≤2 mg/l	≤1 mg/l
6/18/08 18:46	6/19/08 06:31	12.00	6.25	0.75
6/19/08 07:46	6/19/08 11:31	4.00	1.00	0.00
6/19/08 15:01	6/19/08 17:31	2.75	0.75	0.00
6/19/08 18:01	6/19/08 18:31	0.75	0.00	0.00
6/19/08 19:01	6/19/08 19:01	0.25	0.00	0.00
6/19/08 21:01	6/20/08 00:46	4.00	0.00	0.00
6/20/08 01:31	6/20/08 01:31	0.25	0.00	0.00
6/20/08 02:01	6/20/08 04:16	2.50	1.25	0.00
6/20/08 05:16	6/20/08 10:46	5.75	3.75	0.00
6/20/08 15:16	6/21/08 10:16	19.25	9.75	0.00
6/21/08 18:16	6/21/08 18:16	0.25	0.00	0.00
6/21/08 18:46	6/22/08 10:31	15.75	14.25	0.00
6/22/08 17:46	6/22/08 17:46	0.25	0.00	0.00
6/22/08 18:31	6/23/08 11:16	17.00	15.75	9.50
6/23/08 15:31	6/24/08 06:31	15.25	14.25	3.00
6/24/08 07:31	6/24/08 07:31	0.25	0.00	0.00
6/25/08 07:31	6/25/08 07:46	0.50	0.00	0.00
8/03/08 09:01	8/03/08 09:46	1.00	0.00	0.00
8/04/08 04:46	8/04/08 04:46	0.25	0.00	0.00
8/04/08 05:16	8/04/08 07:16	2.25	0.00	0.00
8/04/08 08:31	8/04/08 08:31	0.25	0.00	0.00
8/04/08 09:31	8/04/08 11:01	1.75	0.00	0.00
8/05/08 03:46	8/05/08 03:46	0.25	0.00	0.00
8/05/08 04:16	8/05/08 18:46	14.75	6.25	0.00
8/05/08 19:16	8/06/08 05:16	10.25	2.00	0.00
8/06/08 09:46	8/06/08 11:01	1.50	0.25	0.00
8/06/08 11:31	8/06/08 11:46	0.50	0.00	0.00
Sum		133.50	75.50	13.25
Percent of time hypoxia occurred at night		47.94	61.25	98.11

Hypoxia was observed in a grab sample at station 199, the northern-most station in the survey on June 18, 2008, leaving the possibility open for the existence of hypoxia further north into the central bay.

Table 15summarizes hypoxia occurrences during the study period in 2008. As expected, hypoxia occurred only in the bottom waters and mostly during the night. The total time that hypoxia was recorded increased by station from Ward Island to Shamrock Island.

Table 15 - Summary of hypoxia events

Station	≤3 mg/L		≤2 mg/L		≤1 mg/L	
	Total (hrs)	% at night	Total (hrs)	% at night	Total (hrs)	% at night
17781	0.00	N.D.	0.00	N.D.	0.00	N.D.
17787	89.00	40.45	8.25	63.64	2.00	0.00
17793	99.25	53.27	37.50	76.00	0.00	N.D.
18247	133.50	47.94	75.50	61.25	13.25	98.11



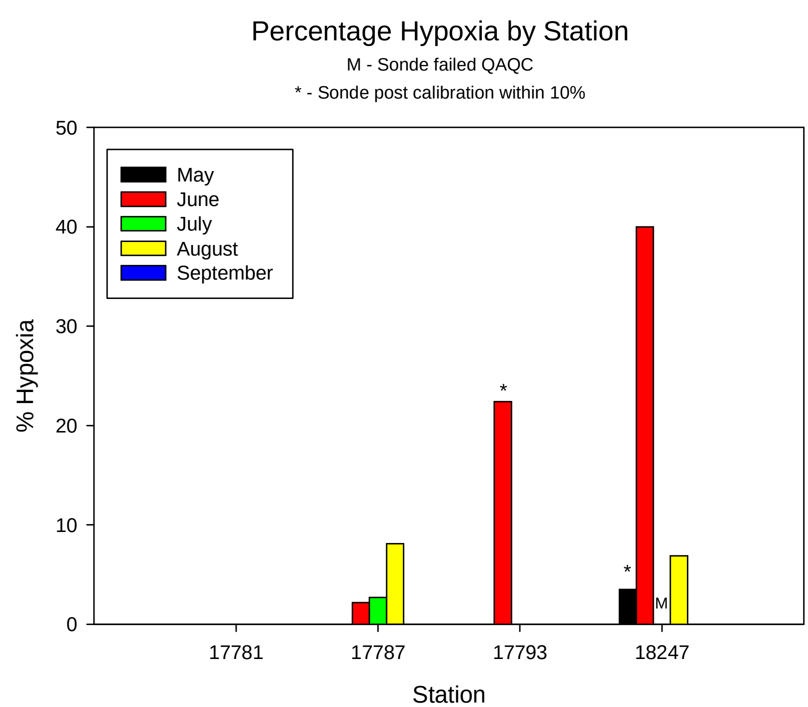


Figure 43 - Percentage Hypoxia by Station and Month

The highest percentage of hypoxic observations occurred in June (Figure 43) and during this deployment there was a spatial pattern with the percentage of hypoxic observations increasing along the salinity gradient (Figure 44).

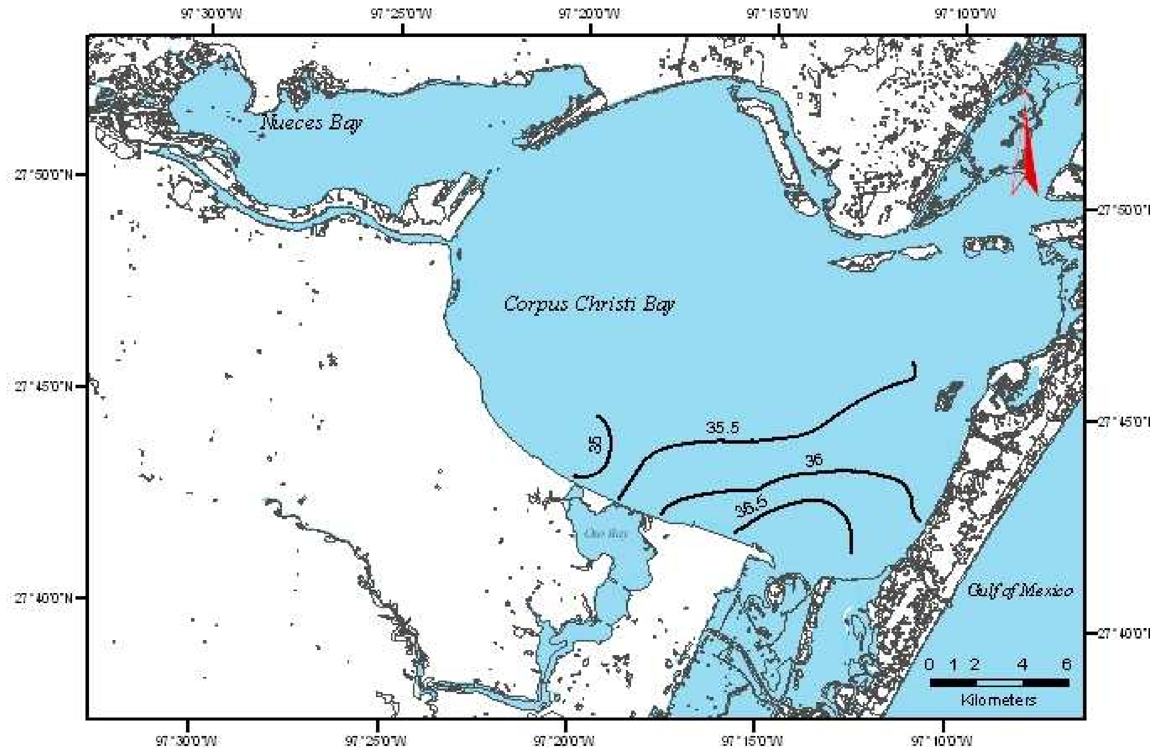


Figure 44 - Average bottom salinity gradient in southeast Corpus Christi Bay during period 5/19/2008 - 9/24/2008. Based on 10 twice-monthly samples at all 19 current study locations.

This pattern was not repeated in July, likely because the bay was mixed due to the winds and inflow from hurricane Dolly.

4.3.2 Temporal Extent

The earliest-in-the-year hypoxic measurement in Corpus Christi Bay occurred in 2007 on June 5 (Table 16). Hypoxic measurements were recorded on this day of the year in various years at stations in the southeast region of the bay. In 2008, there was no hypoxia between May19, 2008 to May 25, 2008. The lowest DO measurement from the May deployment was 3.08 mg/L on May 24, 2008. This value is near the 3.0mg/L shown to have effects on the benthos in Corpus Christi Bay (Ritter and Montagna 1999). The earliest hypoxic event observed in 2008 was June 18th, with a measurement of 1.87mg/L. Based on historical data and data from this project, the earliest onset of hypoxia is sometime between the last week of May and the middle of June.

Table 16 - Earliest Hypoxic Observation by Year

Year	Start Date	Month	Day	[DO] mg/L	Station
1996	7/24	7	24	1.41	8
1997	7/24	7	24	1.60	15
1998	7/16	7	16	0.49	17
1999	6/30	8	3	1.71	18
2000	6/12	8	24	1.99	7
2001	6/05	6	5	0.62	12
2002	7/06	7	6	1.35	12
2003	6/26				
2004	6/14	6	28	1.94	8
2005	6/14	6	21	0.60	7
2006	6/05	6	5	1.99	19
2007	6/5	6	5	1.14	11
2008	5/19	7	18	1.48	17787

The latest-in-the-year hypoxic measurement in Corpus Christi Bay occurred in 2006 on August 31st (Table 17). There was no hypoxia from September 18, 2008 to September 25, 2008. The lowest dissolved oxygen concentration observed in the September deployment was 5.8mg/L at site 17781on September 24, 2008. The latest hypoxic event observation for the summer of 2008 was a value of 1.86mg/L on August 6,

2008. Based on historical data and the data from this project, the latest occurrence of hypoxia is sometime between the last week of August and the third week of September.

Table 17 - Latest Hypoxia Observation by Year

Year	End Date	Month	Day	[DO] mg/L	Station
1996	7/30	7	30	1.03	14
1997	7/24	7	24	1.83	10
1998	7/16	7	16	0.49	17
1999	8/03	8	3	1.24	30
2000	8/31	8	24	1.99	7
2001	8/21	8	21	1.08	7
2002	8/08	8	8	1.26	18
2003	8/08				
2004	8/09	8	2	1.58	39
2005	8/30	8	23	1.81	39
2006	8/31	8	31	1.75	39
2007	9/13	8	28	1.48	202
2008	9/24	8	6	1.86	18247

Historical data collected by UTMSI, and continued by HRI was used to calculate the percentage of hypoxia at all sites for which data existed Figure 45. For this study, data extends back to 1994 through 2008. All measurements were taken specifically to search for hypoxia. All were taken in the early morning from the 20 cm of water just above the sediment surface. Probability was calculated as the number of hypoxic measurements divided by the total number of measurements. Light blue dots indicate that there were at least 10 observations used in the calculation. The highest percentage of hypoxia is at the nexus of Corpus Christi Bay and Laguna Madre. High percentages of hypoxia are also seen at the mouth of Oso bay. These percentages as well as the spatial limits from the current study were used to estimate the extent of the hypoxic area (Figure 46). The total area of the hypoxic zone is estimated to be 80 km^2. One grab sample taken ate site 202 was hypoxic. This could indicate that the area that experiences summer hypoxia is greater in extent to the north.

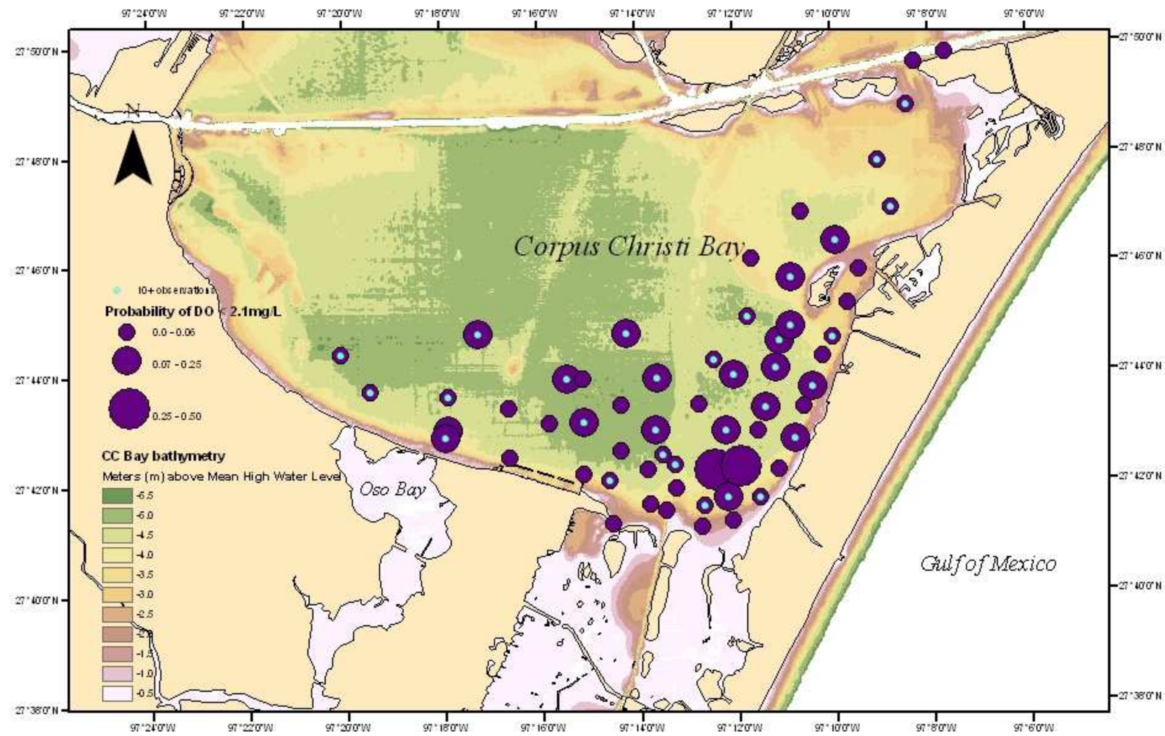


Figure 45 - Percentage of measurements exhibiting hypoxia in bottom water based on all grab observations overlayed on bathymetry. Bathymetry from NOAA (Department of Commerce (DOC) *et al.* 1998)

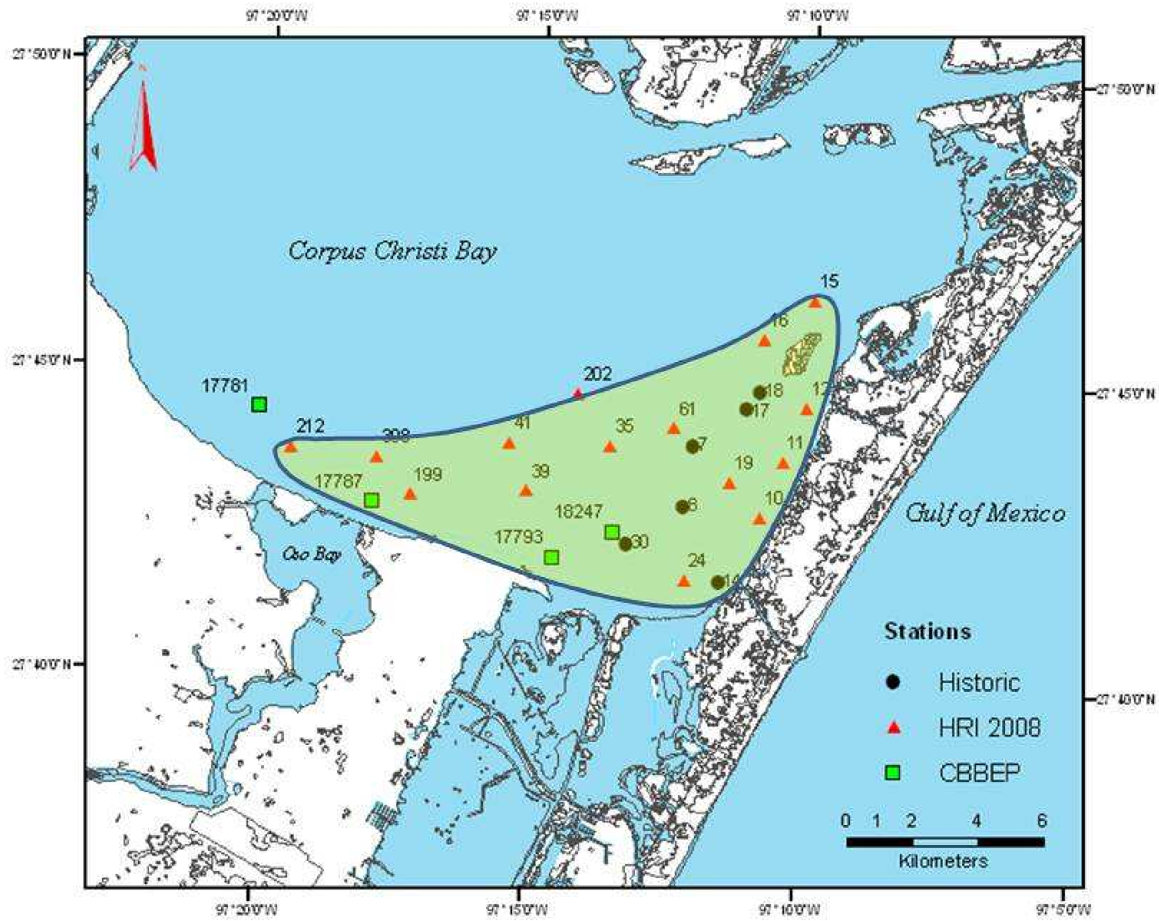


Figure 46 - Estimated extent of hypoxic area

4.3.3 Nutrient and Chlorophyll-*a* Concentrations

Grab samples were collected from surface and bottom waters at all sites on all sample dates in 2008. Mean surface and bottom water nutrient and chlorophyll-*a* concentrations by station are shown in (Table 18).

Table 18 - Summary of Chl-*a* and Nutrient concentrations

	Site	[Chl-*a*]		$[NH_4]$		PO_4		SiO_4		$[N0_{2+3}]$	
		Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD
Surface	10	1.88	0.94	0.40	1.08	0.33	0.24	152.34	130.42	**0.54**	0.49
	11	1.54	0.86	0.67	1.55	0.42	0.63	158.94	132.84	0.45	0.39
	12	2.18	1.21	0.48	1.07	0.29	0.22	155.29	128.14	0.41	0.37
	15	2.15	1.23	0.44	1.25	0.31	0.22	141.49	118.12	0.28	0.23
	16	1.82	0.70	**0.23**	0.56	0.30	0.18	149.53	123.35	0.25	0.20
	19	2.17	1.97	0.65	1.67	0.36	0.29	158.92	126.20	0.43	0.30
	24	1.83	1.25	0.53	1.36	0.38	0.27	166.30	139.10	0.33	0.28
	35	1.92	1.24	0.52	1.49	0.34	0.27	139.13	97.58	0.25	0.22
	39	1.87	0.76	0.60	1.18	0.36	0.24	131.53	94.72	0.31	0.29
	41	**1.41**	0.64	0.62	1.37	0.37	0.27	**116.32**	85.13	0.28	0.28
	61	1.66	0.75	0.60	1.55	0.31	0.21	144.74	116.41	0.30	0.38
	199	1.85	0.99	0.55	1.31	0.43	0.38	137.01	99.19	0.34	0.39
	202	1.62	0.78	0.29	0.78	0.37	0.28	132.76	94.17	0.24	0.22
	212	2.07	0.88	**0.98**	2.85	0.46	0.39	147.57	109.89	0.28	0.25
	308	2.01	1.25	0.92	2.44	**0.52**	0.81	145.81	107.55	0.56	1.08
	17781	2.06	1.03	0.59	1.38	0.39	0.26	152.98	114.93	**0.19**	0.18
	17787	2.77	1.31	0.84	2.04	0.40	0.38	**167.76**	129.58	**0.19**	0.16
	17793	**2.89**	1.53	0.42	1.18	**0.18**	0.09	153.03	106.33	0.24	0.22
	18247	2.47	1.32	0.61	1.48	0.33	0.20	152.81	117.03	0.29	0.24
Bottom	10	1.97	1.31	1.32	2.97	0.48	0.44	166.05	148.56	0.42	0.35
	11	2.01	1.14	1.27	2.49	0.44	0.38	174.60	155.65	0.38	0.32
	12	1.62	0.67	0.55	1.08	0.26	0.22	154.17	133.10	0.26	0.18
	15	1.59	0.67	0.54	1.42	0.35	0.24	150.48	121.59	0.30	0.21
	16	1.71	0.68	**0.20**	0.59	0.29	0.19	149.21	122.20	0.24	0.16
	19	1.71	1.15	1.69	2.39	**0.60**	0.40	174.33	161.00	**0.64**	0.39
	24	2.06	1.52	0.51	1.48	0.46	0.29	172.82	148.65	0.44	0.25
	35	1.85	1.21	0.69	1.54	0.39	0.27	**134.46**	96.69	0.26	0.22
	39	1.98	1.24	0.61	1.18	0.35	0.22	149.24	111.85	0.34	0.28
	41	1.48	0.74	0.77	1.46	0.43	0.31	139.99	102.79	0.36	0.35
	61	1.67	0.85	0.78	1.72	0.40	0.24	160.75	129.65	0.31	0.26
	199	1.91	1.44	0.96	1.43	0.50	0.27	147.90	111.62	0.37	0.24
	202	1.91	0.81	0.26	0.50	0.40	0.20	141.83	106.94	0.34	7.54
	212	**1.46**	0.92	0.64	1.38	0.48	0.27	149.49	121.33	0.34	0.25
	308	**3.68**	3.90	1.00	1.54	0.41	0.29	259.77	370.66	0.33	0.30
	17781	2.02	1.31	0.76	1.87	0.44	0.31	164.99	123.63	0.29	0.36
	17787	3.18	1.93	**2.02**	3.19	0.43	0.38	**345.47**	614.41	**0.25**	0.29
	17793	2.82	1.29	0.38	0.62	**0.16**	0.13	187.96	152.79	**0.25**	0.24
	18247	3.04	1.98	1.00	1.71	0.35	0.25	177.87	141.03	**0.25**	0.22

Chlorophyll-*a* concentrations were low, X = 2.05 μg/L, σ = 1.5 μg/L. Nutrient concentrations during the study period were also low. Ammonium concentration ranged from below the threshold of detection, to 9.32 μM, X = 0.71 μM, σ = 1.61 μM. The highest values in the study period occurred just after hurricane Dolly when higher concentrations were observed bay-wide. Phosphate concentrations also were highest just after hurricane Dolly bay-wide. Phosphate concentrations ranged from below the threshold of detection, to 2.87 μM, X = 0.38 μM, σ = 0.31 μM during the study period. There were also higher concentrations of NO_X measured just after hurricane Dolly, however it was only at two stations. [NO_X] ranged from the limits of detection to 3.69 μM, X = 0.33 μM, σ = 0.32. Silicate concentrations for the entire study period were high compared to other nutrient concentrations, ranging from 15.0 μM to 1783.8 μM, X = 160.7 μM, σ = 155.4 μM. Silicate concentrations were lower after hurricane Dolly and remained lower for the duration of the study period.

4.3.4 Nutrient Distributions

Nutrient concentrations during the sampling periods were not at high levels. There was however, a pattern to the distribution of nutrients. Ammonium and phosphorous concentrations were higher in areas with low mean dissolved oxygen concentrations (Figure 47 and Figure 48). While concentrations were higher than in other regions of the sampling area with higher dissolved oxygen concentrations, the levels can be explained by microbial remineralization. Thus, it was the hypoxia that caused the high nutrient concentrations, because dissolved oxygen is consumed by microbial respiration, and ammonium is produced. The high phosphate is likely due to release from sediments because of the high salinity.

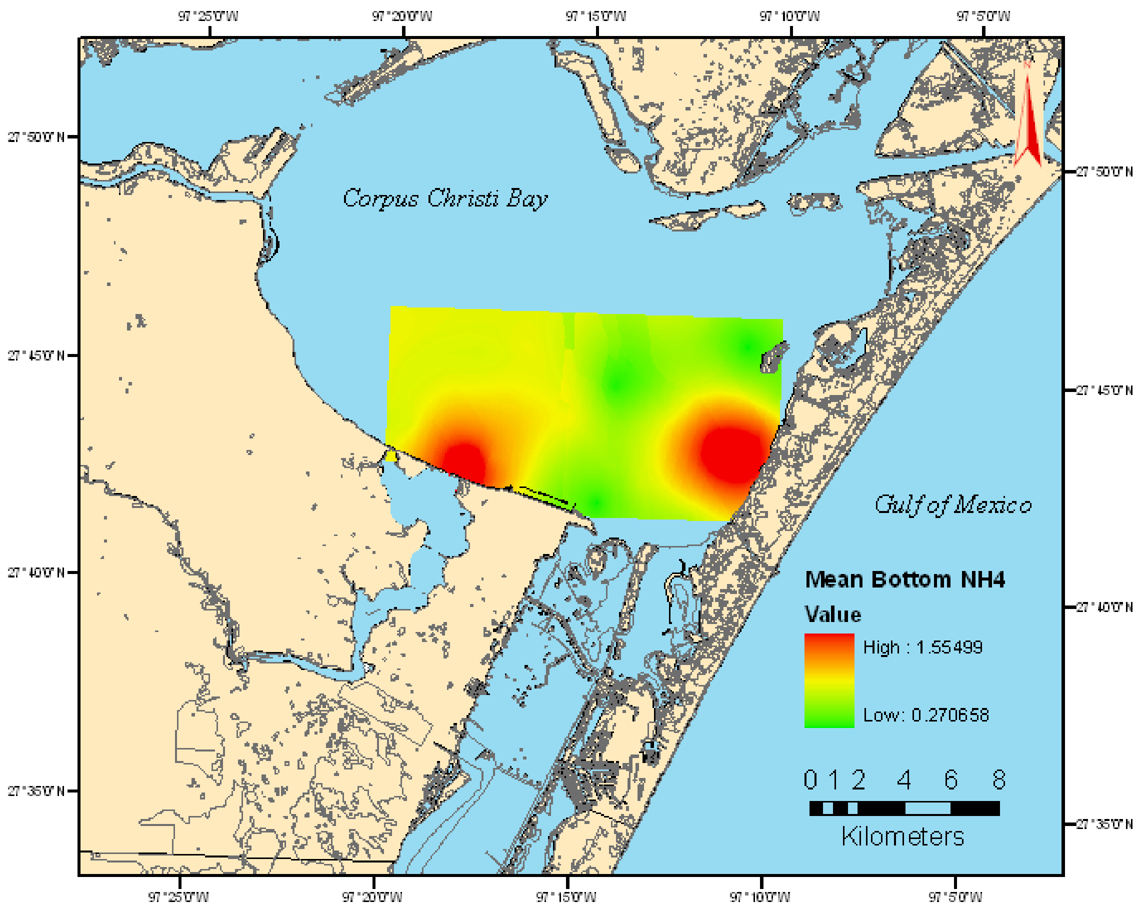


Figure 47 - Interpolation of mean bottom ammonium concentrations in the southeast region of Corpus Chrsiti Bay using all data collected in the study. Interpolation used 10 bottom water samples from all 19 stations.

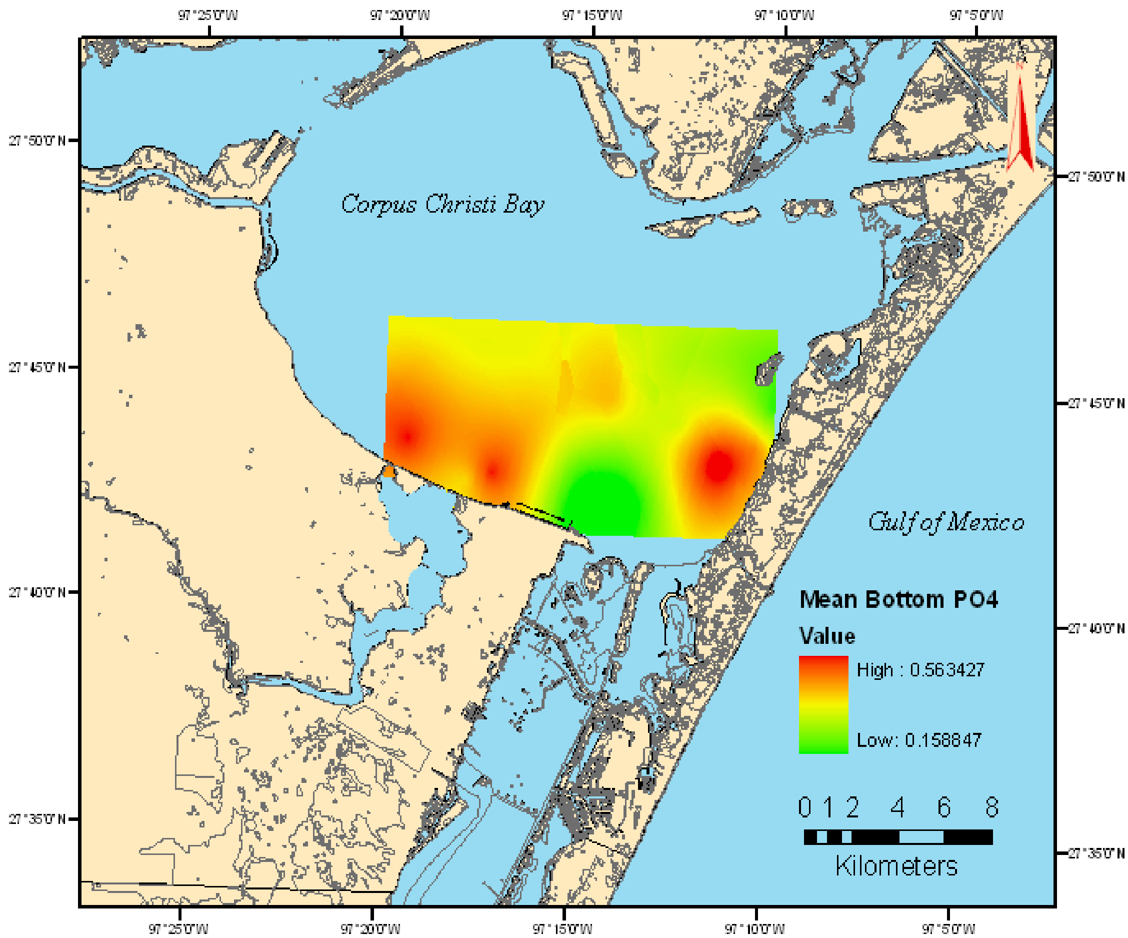


Figure 48 - Interpolation of mean bottom orthophosphate concentrations in the southeast region of Corpus Christi Bay. Interpolation used 10 bottom water samples from all 19 stations.

4.3.5 Possible Indications of Groundwater Flow

Several instances of low salinity spikes occurred during the study period. These are summarized in Table 19. These spikes are typically less than thirty minutes in duration and range from 0.5 ppt to 12.0 ppt less than ambient salinity. The majority of these events, 87%, occur in the bottom observations. One possible explanation for these occurrences is the percolation of groundwater into the bay. While there is no indication of sondes malfunctioning, only further study incorporating replicate sonde measurements can rule out the possibility.

Table 19 - Observed Bottom-water low-salinity spikes.

Station	Date	Depth	δ (ppt)
17781	20-May	bottom	-12.0
17793	22-May	bottom	-2.0
17793	22-May	bottom	-4.0
18247	26-May	bottom	-1.5
18247	27-May	bottom	-1.0
17781	21-Jun	surface	-1.0
17781	21-Jun	surface	-1.5
17781	18-Jun	bottom	-9.0
17787	20-Jun	surface	-0.8
17793	18-Jun	bottom	-12.0
18247	19-Jun	bottom	-3.0
17781	1-Aug	bottom	-5.0
17781	2-Aug	bottom	-10.0
17787	5-Aug	bottom	-11.0
17781	21-Sep	bottom	-9.0

4.3.6 Environmental Conditions

Hourly wind speed and directions were obtained from the Texas Coastal Ocean Observation Network (TCOON) for the study period. Data was downloaded from the TCOON station at Packery Channel. As expected, the wind was predominately from the southeast where forty percent of the time the wind direction was between 290° and 330° (Figure 49)

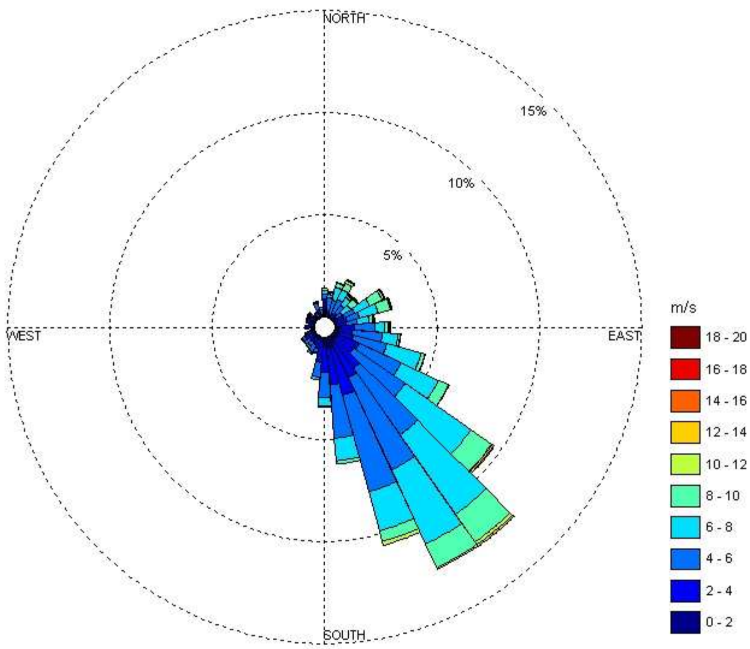


Figure 49 - Distribution of hourly wind speed (m/s) and direction measured at Packerey Channel, TX for May through September 2008

Wind speed and direction followed a dial pattern generally like those in Figure 50, tending southerly during the night, and picking up speed and shifting north during the day.

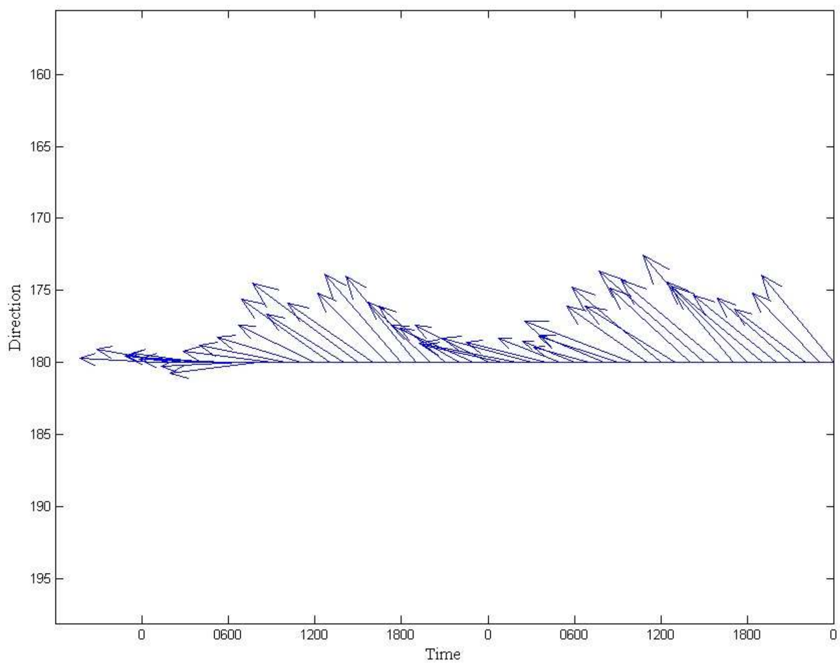


Figure 50 - Hourly wind speed and direction measured at Packery Channel, TX for May 20 - 21

Peak speeds occurred between noon to 3:00 PM. Hurricane Dolly made landfall south of the study area bringing the highest winds observed (Figure 51a).

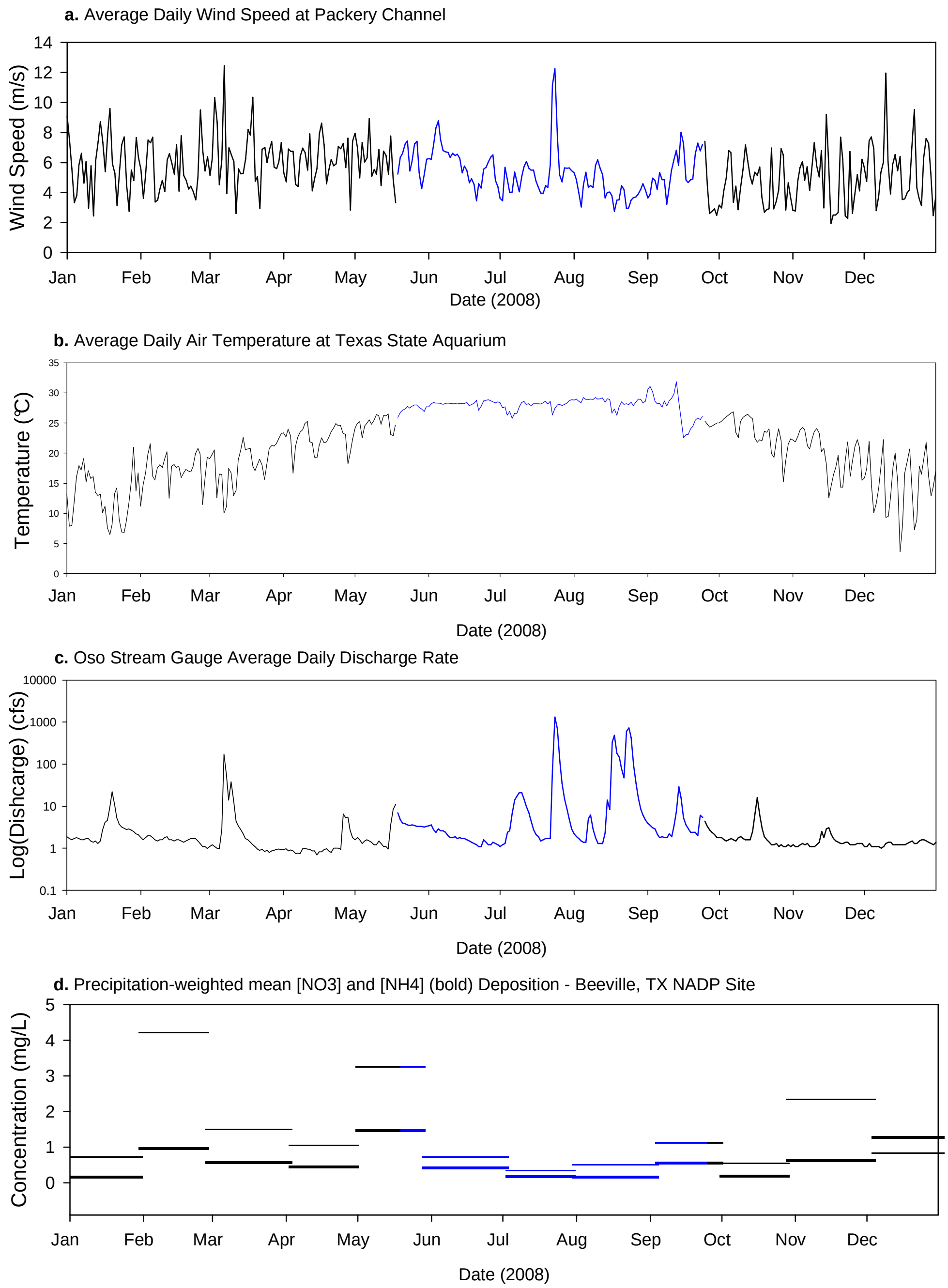


Figure 51 - Conditions in the study area for 2008. The portion of the trace highlighted in blue represents the duration of the study period 5/19/2008 - 9/24/2008

During the study period, most of the freshwater inflow, as measured by average daily discharge rate from the from the USGS stream gauge on Oso Creek, can also be attributed to hurricane Dolly (Figure 51c). During Dolly, rates reached 1300 ft^3/s (36.81m/s) compared to a mean of 45.3ft^3/s (1.28m/s)and a minimum of 1.1 ft^3/s (0.03m/s). Monthly, precipitation-weighted atmospheric nutrient deposition, measured at the National Atmospheric Deposition Program's permanent station at Beeville, TX showed the highest levels of deposition during the study period to be in May: 1.46 mg/L NH_4 and 3.25 mg/L NO_{2+3}. The lowest values during the period were measured in late July/early August: 0.15 mg/L NH_4 and 0.51 mg/L NO_{2+3} (Figure 51d). These are precipitation-weighted means and lower values likely are due to lower rainfall in the during the summer period.

The study period encompassed the hottest time of the year, (Figure 51d). During this period, variability in atmospheric temperature decreases compared to the rest of the year resulting in consistent high temperatures. Seasonal peak temperatures began just after the start of the study and continued throughout the period with the seasonal drop in temperature beginning at the end of the five month study period.

Spot hydrographic observations, nutrient and chlorophyll-*a* concentrations, and environmental data were joined by date and station for principal component analysis (PCA). Secchi depth was used to estimate the light attenuation coefficient, k, using the formula $k = 2.00 \times SECCHI^{-0.76}$ (Padial and Thomaz 2008). This estimate was included in the analysis instead of the raw Secchi value and resulted in an increase in the percentage of total variability explained. The first three components in the PCA explained 64% percent of the variability in the data. PC-1, explaining 26% of the variability (eigenvalue = 3.25), represents environmental flow (Figure 52).

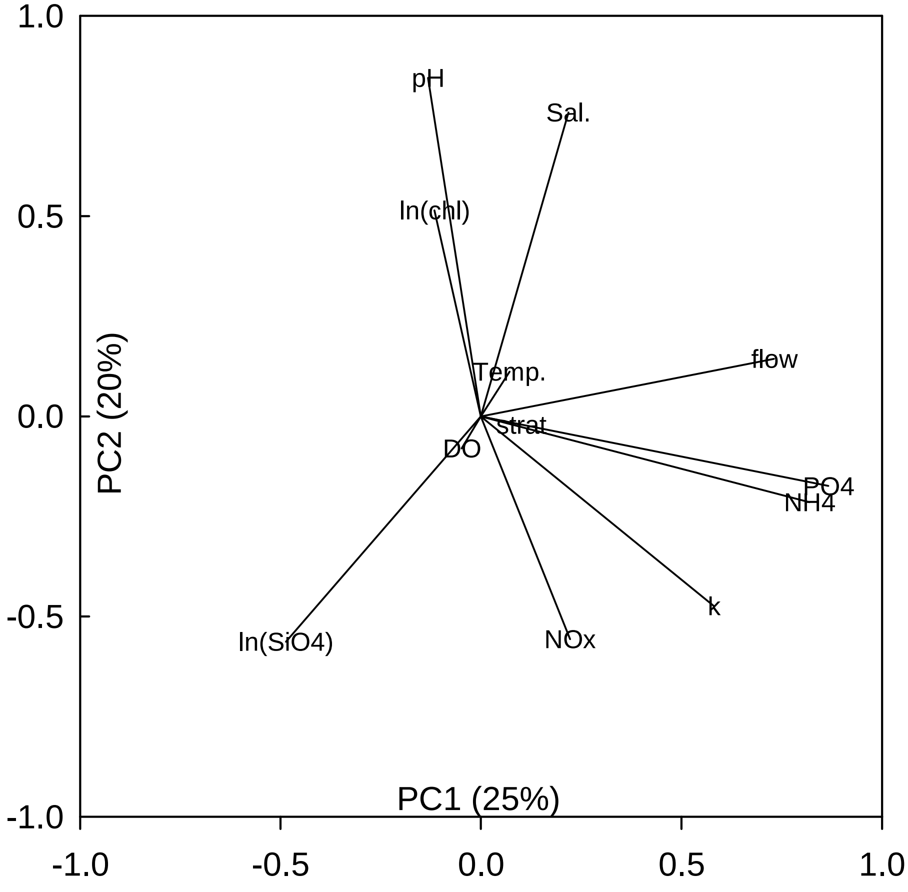


Figure 52 - Vector plot of PC1 vs. PC2 from principle component analysis of environmental conditions

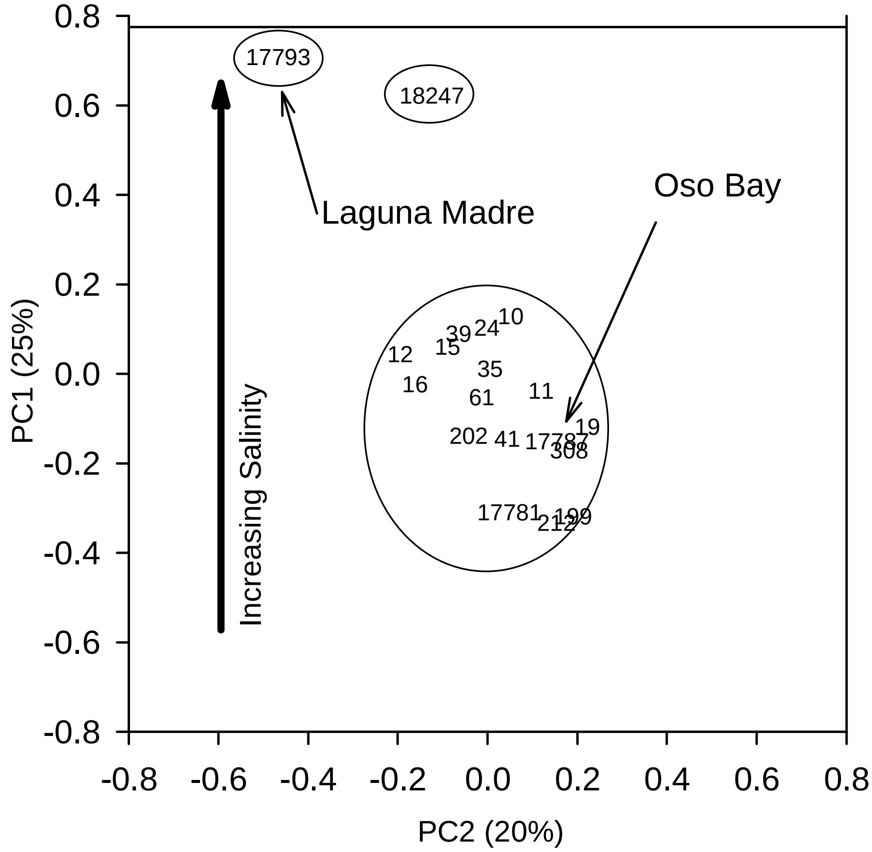


Figure 53 - Study stations depicted in PC1-PC2 space

Phosphate, ammonium, and NO_{2+3} concentrations varied with flow on this axis. DO concentration and water clarity opposed flow on this component a. PC-2, representing 20% of the variability, aligned with the salinity gradient (eigenvalue = 2.6). The pH varied with salinity and nutrient concentrations, and DO concentration varied opposite salinity on this component. A spatial pattern emerges on PC-2 with stations increasing on PC-2, increasing salinity, as station location varies from west to east, (Figure 53). PC-3 represented 19% of the total variability (eigenvalue = 2.47) . Water temperature and DO concentration are opposed on this component and likely represents relationships due to higher summer temperatures and hurricane *Dolly*. A temporal pattern emerges on PC-3 where in general, PC-3 increased with date during the study period (Figure 54).

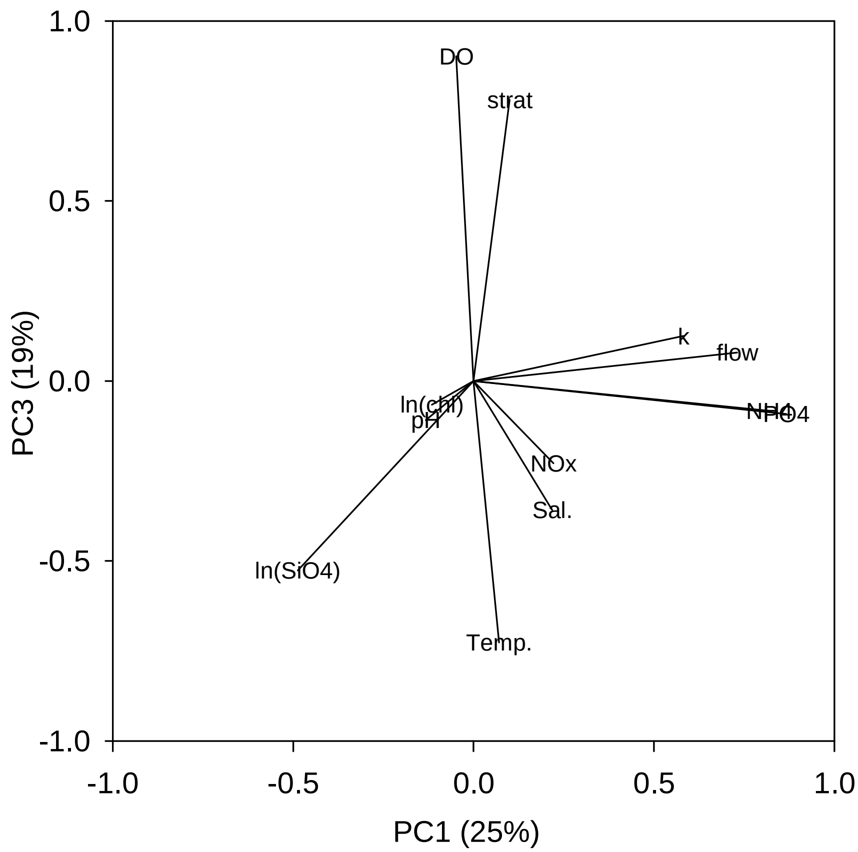


Figure 54 - Vector plot of PC1 vs. PC3 from principle component analysis of environmental conditions

4.4 Discussion

During the study period, two regimes were evident: a summer "default" regime, and an "inflow-influenced" regime. Each regime was characterized by salinity and the nutrient relationships to environmental conditions. Both regimes exhibit salinity gradients with salinity increasing from west of Oso Bay east to Laguna Madre.

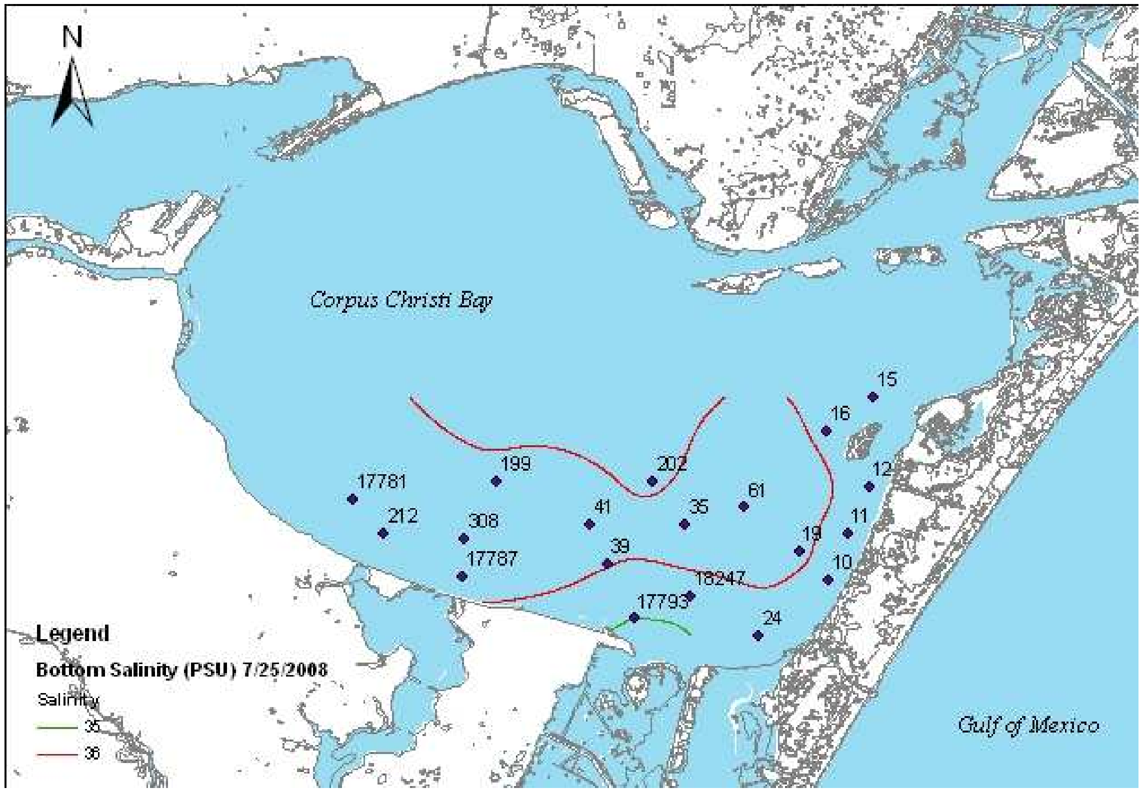


Figure 55 - Bottom salinity gradient in Corpus Christi Bay during inflow salinity regime

During the inflow regime the salinity difference across the gradient is about 2 psu. The best example during the study period was during landfall of hurricane Dolly (Figure 55). These periods are characterized by increased freshwater inflow, reduced water clarity, lower measurements of salinity stratification, and a lack of relationships between DO and nutrient concentrations. However, NH_4 and PO_4 concentrations increase with the root-1/3, 10-day cumulative flow measured at the USGS stream gauge on Oso Creek, $\rho = 0.43$, $\rho = 0.41$ respectively, $p < 0.0001$. NO_{2+3} concentrations during this regime also increase with increasing freshwater inflow, however the correlation is not as strong, $\rho =$

0.17, $p = 0.0322$. This could be due to the microbial depletion of the more easily utilized form of nitrogen. DO concentration during this regime is correlated with water temperature and salinity stratification, $\rho = -0.75$, $\rho = 0.46$ respectively, $p < 0.0001$.

In contrast, the default regime (Figure 56) displayed during the study period was characterized by lower freshwater inflow, increased water clarity, and positive relationships between DO and nutrient concentrations. In this regime, the salinity gradient exhibited a steeper range of on average, about 6 psu and more intense salinity stratification.

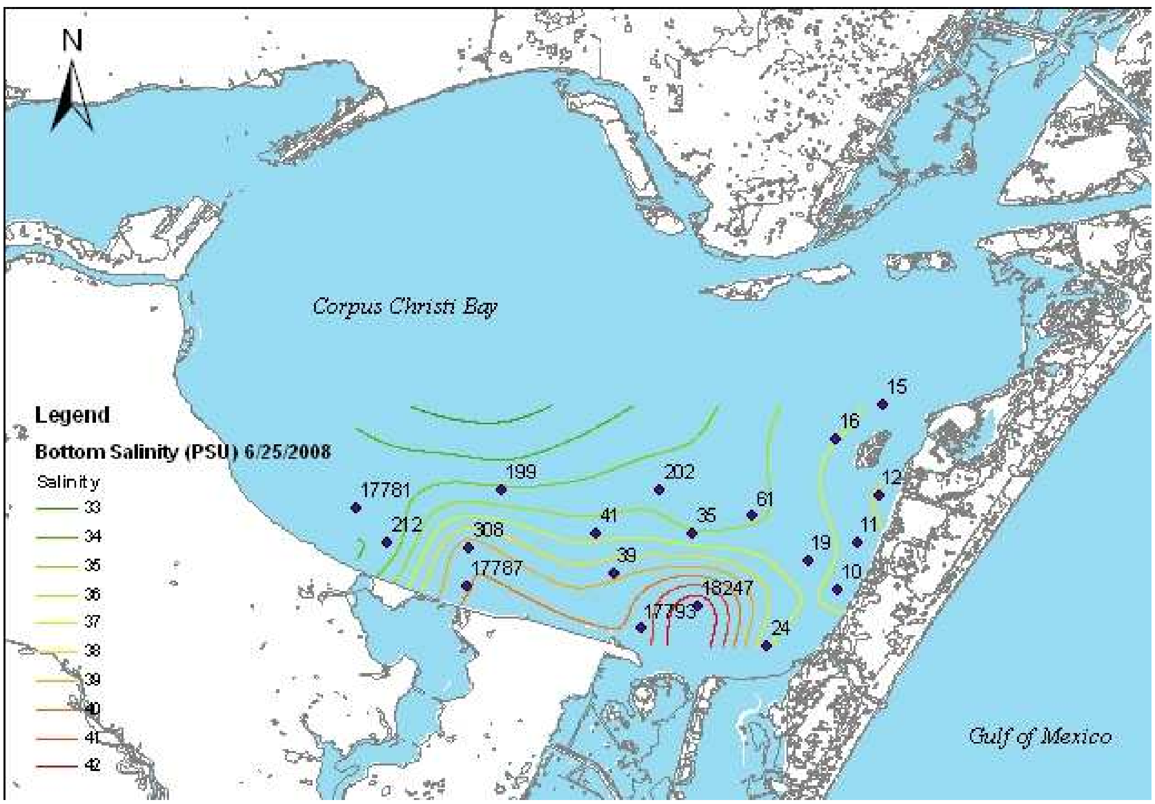


Figure 56 - Bottom salinity gradient in Corpus Christi Bay during summer default salinity

The highest salinities were observed at the nexus of Corpus Christi Bay and Laguna Madre and decreased fairly uniformly into Corpus Christi Bay. This is likely the result of tidal and wind-driven exchange of water between the two bodies of water. Freshwater inflow is reduced compared to the inflow regime and unlike the inflow regime, there is no correlation between inflow and nutrient concentrations. However, NH_4 and PO_4 concentrations do show a correlation with dissolved oxygen, $\rho = -0.78$, $\rho = -0.62$ respectively, $p < 0.0001$. During the default regime, the highest nutrient concentrations are associated with the lowest [DO]. Twenty-two days elapsed between the observation of this regime and the previous sampling, putting an upper limit on the setup time for hypoxic conditions. While all of the samples were taken in the early morning, the large number of sites precluded taking samples at the same time, making it possible that the relationships have a diel component not resolvable at the scale of the grab sampling effort.

Low levels of Chl-*a* throughout the study period can imply either that hypoxia is apparently not caused chiefly by oxygen demand due to oxidation of autocthonous phytoplanktonic detritus, or that if it is, that the blooms occurred before the study period and had already exited the system or been sequestered in the sediments. Oxidation of allocthonous nutrients and organic matter also contributes to oxygen demand. While this study did not include measures of organic matter; that hypoxia occurred more frequently during periods associated with lower freshwater inflow is evidence that precludes this as the chief mechanism for hypoxia. Sediment resuspension is another source of oxygen demand. It has been shown that in Corpus Christi Bay, turbidity is related to wind speed in the short term (Shideler 1984). Contributions to oxygen demand from resuspended material are two-fold: demand due to oxidation of nutrient and organic matter; and inhibition of photosynthesis. Hypoxia was most frequent during times of higher water clarity so it remains unclear what sediment resuspension contributes to the likelihood of hypoxia. From this study, and previous studies, the salinity stratification plays an important role in the forming of hypoxia. During the study period, when the water column is stratified, there is increased likelihood of hypoxia. And with this hypoxia is a positive correlation with nutrient levels. It has been shown that hypoxia at the sediment surface results in higher ammonium and phosphorous levels released into the water column from the sediments (Cowan and Boynton 1996; Heggie *et al.* 1999) and so possible that higher observed nutrient levels are a result, not a cause of hypoxia.

Nitrogen is delivered to the estuary as ammonia, nitrate, nitrite, in dissolved organic matter (DOM) and as a constituent of detritus. Ammonia is reduced in the sediments and the water column by nitrifying bacteria into the more easily utilized nitrate and nitrite. These ions are in turn fixed by denitrifying bacteria and converted into nitrogen gas. Nitrogen gas is released into the water column and atmosphere and to some extent incorporated into organic compounds. This organic matter, as well as terrestrial-sourced organic matter decomposes in the sediments producing ammonium, completing the nitrogen cycle. An interruption in the nitrification rate, therefore could cause an increase in ammonia concentrations. Reduced DO levels have been shown to inhibit denitrification rates (Kemp *et al.* 1990). One possible explanation for the link between low DO and inhibited nitrification could be that as DO concentrations drop, HS^- production is stimulated. It is the elevated HS^- concentrations that are hypothesized to inhibit nitrification (Hansen *et al.* 1981; Joye and Hollibaugh 1995) Elevated concentrations of sediment HS^- have been observed under hypoxic bottom waters in Corpus Christi Bay (Sell and Morse 2006), possibly inhibiting nitrification and perhaps explaining the increased ammonium concentrations seen in conjunction with low DO during the default regime.

In a synoptic study of the Nueces estuary, Whitledge (1989) found that the highest levels phytoplankton activity is just upstream from the mouth of the Nueces River and that there is little influence from Oso Bay. However, results from the current study show that during the inflow regime, nitrogen and phosphorous both correlate with inflow in the southeast region of Corpus Christi Bay. Due to the remoteness of the area from the other sources of inflow, these relationships could represent an Oso Bay influence. Brock used data from the years 1988, 1989, 1991, and 1992 to determine a nitrogen budget for the Nueces estuary (Brock 2001). In all years in the study, the budget calculated a net transport out of the estuary. Brock notes one possible explanation is that some nitrogen sources might be under-represented. He reports a 1.6×10^9 g N/yr flux into Corpus Christi Bay from Oso Bay during the year of highest inflow, 1992. Using a steady-state model in the style of the Land-Ocean Interactions in the Coastal Zone (Gordon *et al.* 1996) (Figure 57), budgets for salt and water flux between Corpus Christi and Oso Bays were calculated.

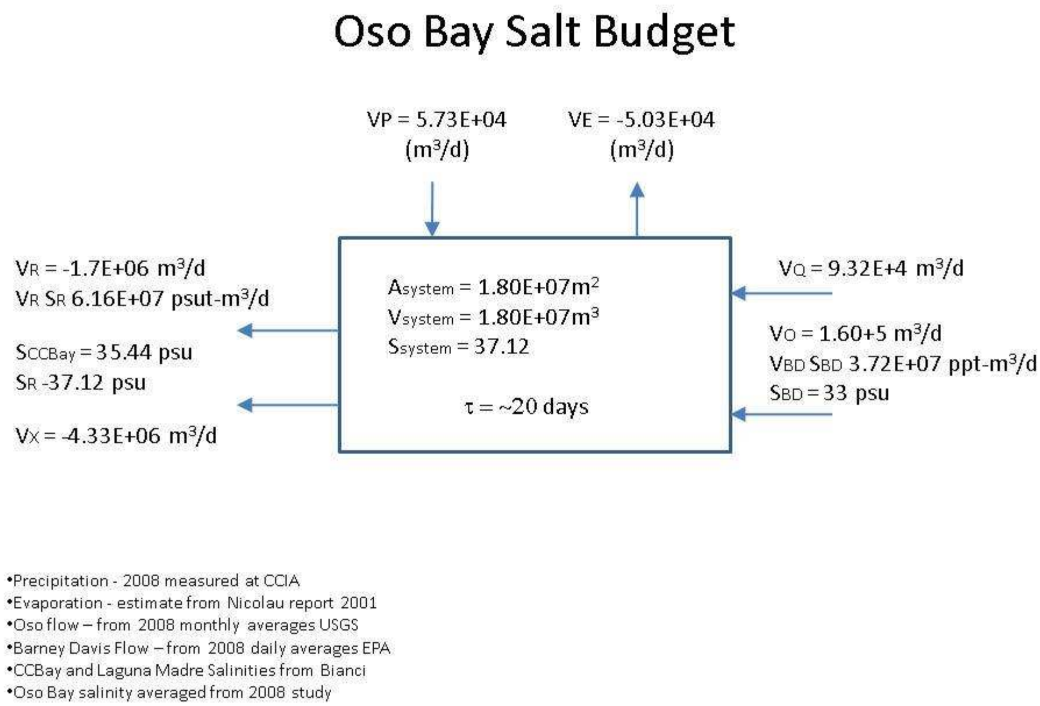


Figure 57 - Salt and water budget for Oso Bay using data from the 5-month study period May-September, 2008. Precipitation and evaporation and area estimates from Nicolau and Albert (2001). Oso Bay volume calculated based on average depth of 1.0m.

The residual water flux from Oso into Corpus Christi Bay was estimated to be 1.7 X 10^6 m^3/day. This value and mean nutrient concentrations from the nexus of Corpus Christi Bay and Oso Bay yielded an estimate of dissolved nitrogen ($NH_4 + NO_{2+3}$) at (3.10 X 10^7 g N/yr). The short time frame, and the episodic nature of inflow challenge the steady-state assumption of the LOICZ model and likely contribute to a lower estimate of nutrient from Oso Bay into Corpus Christi Bay.

Similarly, phosphorous flux from Oso Bay into Corpus Christi bay was calculated to be 3.15 X 10^7 g P /yr using the LOICZ model. Phosphorous enters an estuary mainly via runoff and is typically cycled rapidly by bacteria and plankton (Emsley 1980). Estuarine phosphorous levels are usually low due to this uptake as well as to precipitation of compounds with iron, calcium, and aluminum. These compounds are utilized by macrophytes, or eventually sequestered in undisturbed sediments (Emsley 1980). In the presence of oxygen, phosphorous will bind to metals in the sediment rapidly, but phosphorous can be released from the sediments under low oxygen conditions. Hypoxic conditions, like those seen in Corpus Christi Bay may facilitate the release of phosphorous into the water column (Bulleid 1983). Phosphorous contributes to sediment oxygen demand mostly in the labile form, but detrital phosphorous also contributes to sediment oxygen demand (Bulleid 1984), possibly entering into self-reinforcing feedback where phosphorous utilization reduces oxygen concentrations, further increasing the amount of phosphorous flux from the sediments. This mechanism could facilitate the development of hypoxia, but it is contingent on a stratified water column.

From the continuous measurements, it was found that there is an apparent relationship between the occurrence of hypoxia and the tidal cycle (Figure 58).

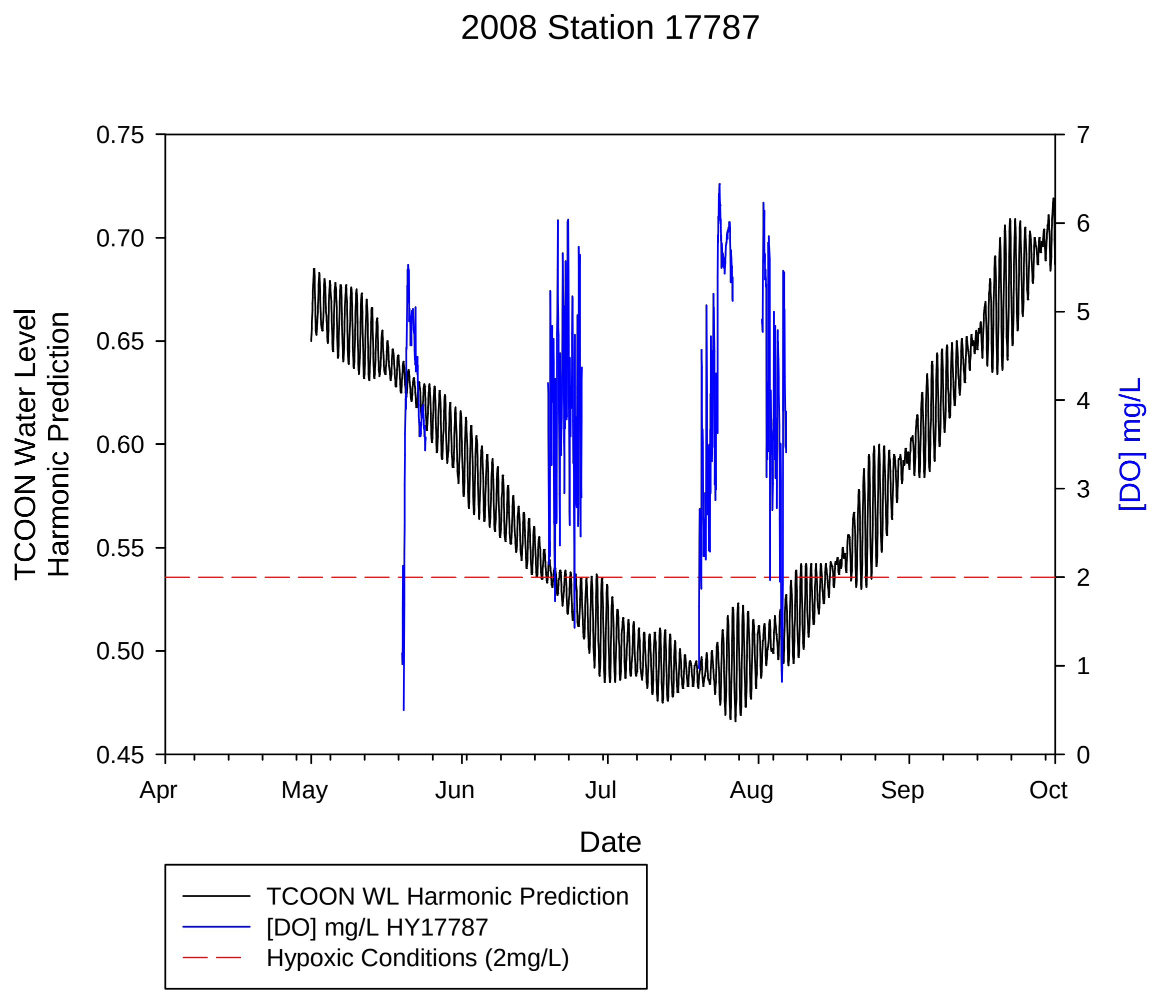


Figure 58 - Continuous dissolved oxygen observations (in blue) shown with the TCOON harmonic prediction for water level (in black).

Hypoxia appears to occur near the fortnightly amplitude minima of the harmonic water level prediction provided by the Texas Coastal Ocean Observation Network (TCOON). This is illustrated best at station 17787, but all continuous stations seem to exhibit this pattern. Continued study of archival data should be able to discern if this pattern is significant.

4.5 Summary

The purpose of the current study was to gain more information on the spatial and temporal extent of hypoxia and begin to explore the potential role of nutrients. Hypoxia in Corpus Christi Bay can begin as early as the first week of June, and occurs as late as the last week of August. Hypoxic conditions can extend from Ward Island to at least Shamrock Island covering an area of at least 80 km^2. Nutrient concentrations are not at high levels. Although ammonium and phosphate levels are higher in both hypoxic zones. During periods of low inflow, there is a significant increase in nutrient concentrations with a decrease in dissolved oxygen. This is more likely due to microbial remineralization than loading from Oso Bay. During periods of higher inflow, there is a significant relationship between flow from Oso Bay with higher nutrient concentrations in Corpus Christi Bay. Further study of possible groundwater inputs is needed. There is not hydraulic head for such input. Additionally, the likelihood of placing a sonde at the exact location of a groundwater source in the bay seems highly unlikely. However, discovery of groundwater inputs to the hypoxic zone is troubling and may be an important route for nutrient loading to the bay. The hypoxic area has two centers of hypoxia, one at the nexus of Corpus Christi Bay and Laguna Madre, and one at the nexus of Corpus Christi Bay and Oso Bay. It does not appear that nutrient-loading is not the chief contributor to hypoxia in the region. At the current time, it appears that salty water driven by tides and prevailing winds into Corpus Christi Bay are the main causes of stratification, and that this stratification isolates bottom water, leading to respiration-driven hypoxia, but further study is necessary to determine the nature of the contributions from each of these salt water sources.

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Part V. A Study of Continuous Currents and Dissolved Oxygen Levels in Corpus Christi Bay

5.1 Introduction

Low dissolved oxygen concentrations occur in estuaries around the globe. An estimated 245,000 km^2 of the marine environment experiences hypoxia and the occurrence of hypoxia is likely increasing (Dauer *et al.* 1992). Due to global climate change and anthropogenic changes to coastal systems, the extent of hypoxia around the globe is predicted to increase (Rabalais *et al.* 2010). An estimated 6% of the estuaries of the northern Gulf of Mexico experience hypoxia (Engle *et al.* 1999) and has been known to occur in the southeast corner of Corpus Christi Bay each summer since discovered in 1988 (Ritter and Montagna 1999). Hypoxia is commonly defined as dissolved oxygen concentrations less than 2.0 mg/L (Dauer *et al.* 1992). At this level, and perhaps at levels below 3.0 mg/L, physical intolerance to low oxygen can cause reduction of benthic biomass, abundance , diversity, species richness and species evenness (Ritter and Montagna 1999; Montagna and Ritter 2006). Studies have shown that the hypoxic area in Corpus Christi Bay has caused a decrease in diversity amount the epibenthic community of fish and mobile invertebrates in the long term (Montagna and Froeschke 2009), and that hypoxia affects mortality and egg production in harpacticoid copepods on shorter time scales (Ryckman et al., submitted).

It is estimated that hypoxia in Corpus Christi Bay occurs in an area of at least 80 km^2 and can begin as early as the first week of June, and end as late as the last week of August (Nelson and Montagna 2009; Nelson 2012 unpublished). While there are three wastewater treatment facilities on Oso Creek, nutrient levels in Corpus Christi Bay are low. Hypoxia occurs most frequently during periods of low freshwater inflow when the bay becomes salinity-stratified. During these periods, DO concentrations decrease significantly with increasing NH_4 and PO_4 concentrations (Nelson 2012 unpublished). The higher nutrient concentrations are possibly due to remineralization. Salinity stratification during these times is likely due to hyper-saline water driven by the prevailing winds into the hypoxic area from Laguna Madre and/or Oso Bay (To 2009) coupled with sediment BOD (Sell and Morse 2006).

To (2009) modeled hypoxia and determined that there could be two separate regions that make up the hypoxic zone defined by the bathymetry of the bay and wind conditions. How do these two areas differ? Are the mechanisms for the onset and persistence for hypoxia different in the proposed regions? Recent research, (Nelson 2012 unpublished) showed evidence that low oxygen levels could be related to the tidal cycle. If there is a link to the tidal cycle, when in the cycle are low dissolved oxygen levels more frequent? Do different locations in the bay display dissolved oxygen concentrations that behave differently as related to the tidal cycle?

5.2 Methods

5.2.1 Study Location

Corpus Christi Bay is a shallow, ~3.2 m. (Orlando *et al.* 1991a), almost enclosed bay with a level bottom (Figure 59).

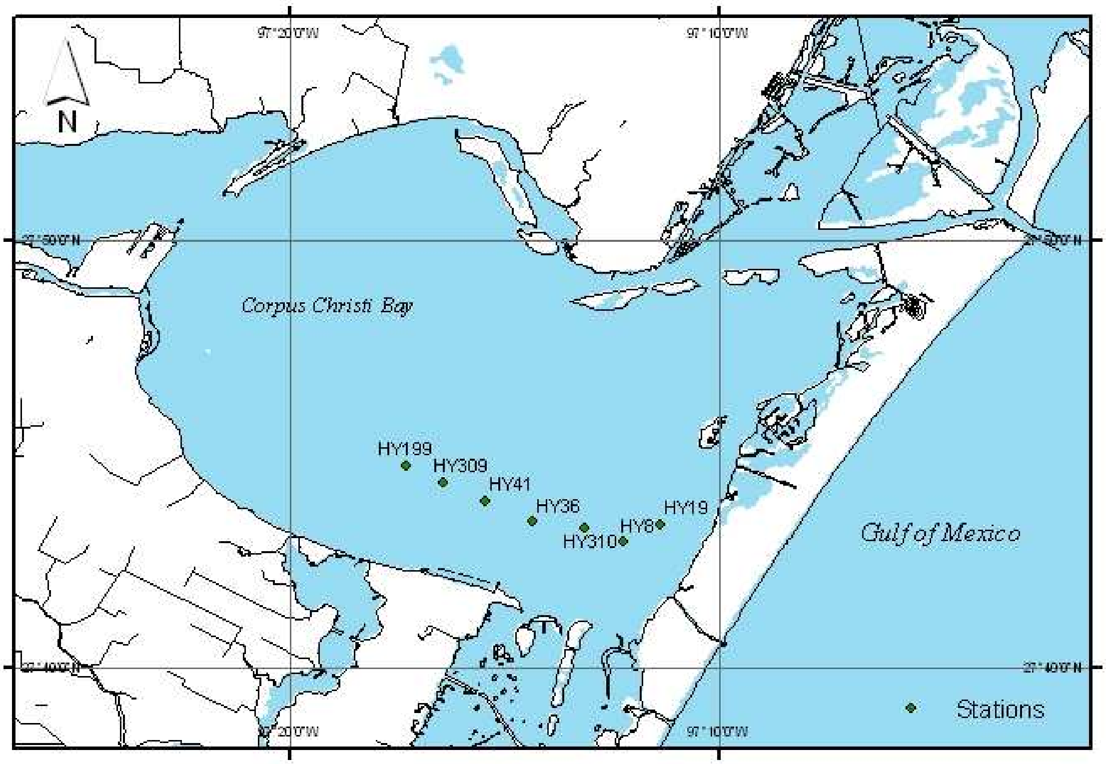

Figure 59 - Map of station locations in Corpus Christi Bay, Texas, USA. Nueces River discharges into eastern Nueces Bay. Oso Creek discharges into Oso Bay which connects to southeastern Corpus Christi Bay. Corpus Christi Bay is located on the western Gulf of Mexico

The total open-water surface area of Corpus Christi Bay is 432.9 km^2 and is microtidal, which makes it sensitive to meteorological forcing. Average monthly wind speeds range from 17 km h^{-1} to 28 km h^{-1}. Two principle wind regimes dominate in the Corpus Christi Bay area: persistent, southeasterly winds from March through September and episodic north-northeasterly winds from October through March (Behrens and Watson 1977; Brown and Militello 1997). Corpus Christi Bay receives an average of 74 cm yr^{-1} of rainfall and 25 m^3 s^{-1} inflow (Orlando *et al.* 1991a) and an average evaporation rate of 150 cm yr^{-1}.

5.2.2 Study Design

The location of the hypoxic area in Corpus Christi Bay is an ideal area for study. The prevailing winds are from the southeast over the barrier island. Thus, there is a difference in fetch across the hypoxic zone. Additionally, during times of low freshwater inflow, there is a salinity gradient generally parallel with the wind increasing from the northwest to the southeast across the hypoxic area. Sites were chosen along a transect to exploit these two natural gradients, (Figure 60).

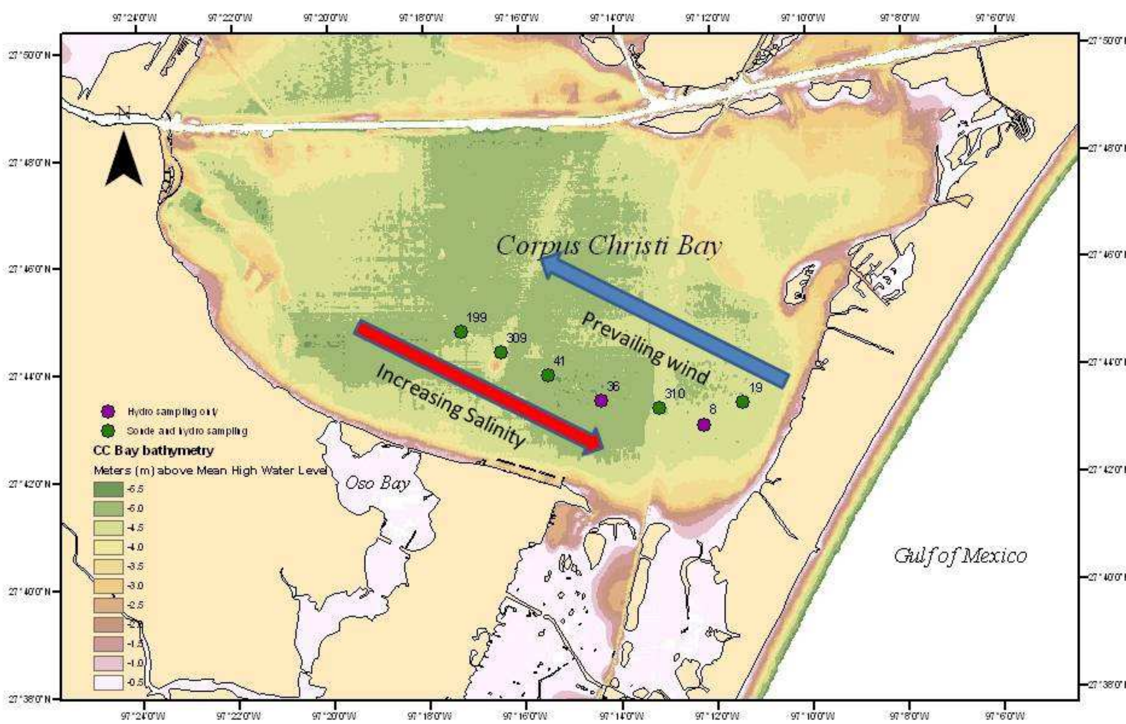

Figure 60 - Map of study area showing study sites and bathymetry. Bathymetry from (Department of Commerce (DOC) et al. 1998)

Also from Figure 60, channels and spoil dredge can be seen in the otherwise flat bay floor. Study sites were chosen on and between these features to determine if these differences might play a role in oxygen levels.

5.2.3 Equipment

In this study, Nortek Aquadopp® ADCPs were used to record current and backscatter. Each of the profilers are capable of measuring at an acoustic frequency of 1.0MHz with a maximum profiling range of 12m - 20m depending on configuration and acoustic scattering conditions. They utilize three beams with a beam angle of 3.4°. Each ADCP has a current velocity range of ±10 m/s with an accuracy of 1% of measured value (±.5cm/s). The echo intensity of each instrument is 0.45dB with a dynamic range of 90dB. (Nortek-AS 2012). ADCPs at each site were set to record average current velocity, direction, and backscatter amplitude during 30-second bursts in half-meter bins. Data was recorded in East-North-Up (ENU) coordinate system. Echo level (EL) for the ADCPs was determined using the formula:

$$EL = Amp*0.43 + 20\log10(R) + 2\alpha_w*R$$

(Nortek-AS 2001b) where Amp is the amplitude measured and recorded by the instrument, R is the range along the beam, and α_w is the water absorption in dB/m. A value of 1.0dB/m was used for α_w per (Nortek-AS 2001a). No correction for particle attenuation was used in calculating the echo level. This is common practice when particle size is not known and when particle concentrations are low. This is a best estimate for echo level. The echo level value is not a proxy for suspended sediment or turbidity, but does provide a relative measure amongst the stations of the amount of acoustically opaque particles in the water column. Current speed s_c for each observation was calculated from the Pythagorean relationship using the formula:

$$s_c = (s_x^2 + s_y^2 + s_z^2)^{-2}$$

where s_x is the east-component, s_y is the north component, and s_z is the up component. The horizontal direction of the current for each observation was calculated using the formula:

$$\theta = \tan^{-1}(s_y / s_x).$$

The ADCPs were utilized in two deployments, the first from 6/2/2009 to 6/30/2009, and the second from 7/14/2009 to 8/20/2009.

Continuous water quality measurements were taken using Hydrolab Series DS-5X datasondes. Each datasonde is capable of measuring dissolved oxygen concentrations from 0.0mg/L to 60mg/L with an accuracy of ± 0.1 mg/L. Salinity can be measured in a range from 0 to 70 ppt with an accuracy of ± 0.2ppt. The pH measurements are accurate to ± 0.2 pH units in a range of 0 - 14 pH units. Each unit was equipped with a self-cleaning turbidity sensor with a documented capability of measuring values from 0 to 3000 NTU and an accuracy 1% to 5% depending on the turbidity of the sample water. The datasondes have a documented capability to measure Chlorophyll-*a* concentrations 0.03 to 500ug/L depending on the Chl-*a* concentration of the sample water with an accuracy of ± 3%. (Hach-Company 2008). It should be noted that both the self-cleaning turbidity sensor and the Chl-*a* sensors experienced periods of out-of-range observations and were found on several occasions to be inhabited by small blue crabs.

Prior to deployment, the sondes are calibrated to 100% saturation in oxygen-saturated water. During calibration, only fresh standards were used and each probe was rinsed with the proper standard prior to calibration. The pH probes are calibrated using a two-point calibration - pH 7 and pH 10. The sonde salinity probes were also calibrated using a two-point calibration - 0.0 mS and 50 mS. Each sonde was then covered in plastic wrap and duct tape to prevent fouling and ease cleaning. The probe end of each sonde was wrapped with a damp towel for transport.

At each of the sites denoted in green in Figure 60, a downward-facing acoustic Doppler current profiler (ADCP) was placed on low-profile moorings 3.2 meters above the sediment surface and a datasonde was placed approximately 25cm above the sediment surface on the same mooring using SCUBA (Figure 61).

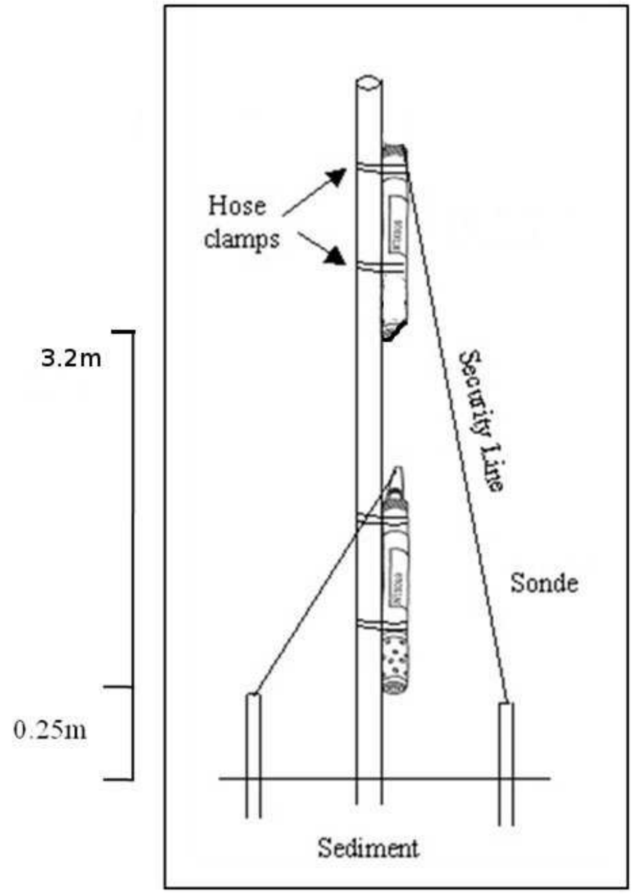

Figure 61 - ADCP/sonde mooring

Measurements were taken every 15 minutes for the duration of the deployments. Once the deployment period was complete, the sondes were retrieved, wrapped in damp towels, returned to the lab and again placed in an oxygen-saturated environment for a few logging cycles. Logging was then stopped and the data downloaded. Data was acceptable if the pre- and post-deployment periods in a saturated environment returned to the same levels and the pre- and post-calibration values were within acceptable values.

The sondes were deployed during the entire period from 6/2/2009 to 8/20/2009. To minimize the effects of bio-fouling of the sondes, they were swapped out with clean, calibrated sondes on average every 5 to 10 days. On each sonde deployment, grab samples using a YSI series 6 V2 sonde were taken at the surface and just above the sediment at each site, including the sites denoted in purple on Figure 60. These grab samples included dissolved oxygen, temperature, pH and salinity. The YSI sonde has the following accuracy and units: temperature (±0.15 ºC), ph (± 0.2 units), dissolved oxygen (mg l^{-1} ± 0.2), dissolved oxygen saturation (± 2%), specific conductivity (± 0.5% of reading depending on range), and salinity (± 1% of reading or 0.1 ppt, whichever is greater, automatically corrected to 25 ºC) (YSI 2010).

5.2.4 Nutrients

Water column samples for nutrient analysis were collected at each site from the surface and the from about 10 cm above the sediment surface using a Van Dorn bottle. Two replicate samples were taken from each depth and decanted into 125 mL opaque brown Nalgene bottles that had been rinsed with sample water. Each bottle was placed immediately into ice for transport to the lab for preparation and analysis. At the lab, 12 ml of sample was filtered using 0.45 micron glass fiber filters and a hand syringe. Filtrate was stored in a pre-cleaned, non-glass 15 ml capped tube. Information about the sample was recorded on the tube. Samples were frozen at ≤ -20 ºC until analysis, typically less than two weeks.

Analysis was performed on a O.I. Analytical Flow Solution IV using EPA-equivalent methods. NO_{2+3} analysis was performed using a cadmium reduction method, (O.I. method 15040908) adapted from EPA method 353.2 (OIA 2008) Ortho-phosphate concentrations were determined using EPA method 365.1 (OIA 2001a). Silicate concentrations were determined using a method equivalent to EPA 366.0 for brackish or seawater (O.I. method 15061001) (OIA 2001b) and Ammonium concentration was determined using EPA method 350.1 equivalent (OIA 2007). The detectible concentration limit for all chemistries was 0.03 μM

5.2.5 Chlorophyll-a

After collection, 25 mL - 50 mL of sample water, depending upon the water column clarity as measured by Secchi disk at the sample site, was filtered using a 0.45 micron glass fiber filter and a hand syringe. In general, a volume, in mL of half the numerical value of the Secchi depth was used up to a maximum of 50 mL and a to a minimum of 25 mL. The filter containing the sample to be analyzed for chlorophyll-*a* concentration was frozen at ≤20 ºC until analysis, typically less than two weeks. For analysis, 5.0 mL of methanol was added to each sample and allowed to rest over night at ≤-20 ºC to extract the chlorophyll-*a*. The concentration was then measured fluorometrically on a Turner fluorometer using a non-acidification technique - EPA method 445.0 (Welchmeyer 1994).

5.3 Results

5.3.1 Acoustic Doppler Current Profiler

Average current speed was low, ranging from 0.06 m/s at station 199 in the bin centered 1 meter above the sediment to 0.6m/s along the bottom at station 19. In profile, the stations behaved similarly with a fairly consistent speed around 0.1m/s from centered at 3.0m above the surface down to the bin centered 1.5m above the surface (Figure 62). In the deepest meter of the water column, current speed generally increased, with station

19 exhibiting the fastest currents. This current was noticed on several occasions by the diver.

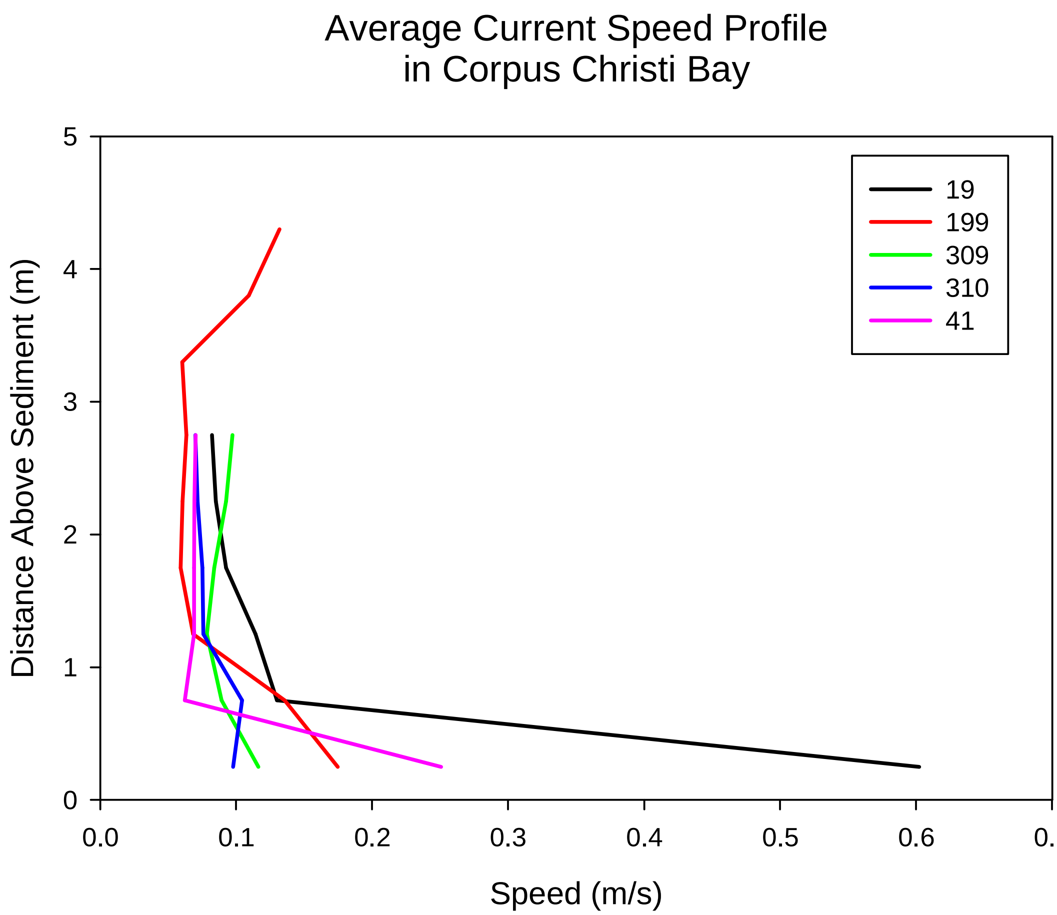

Figure 62- Average current speed profile by site

Average echo location profiles for the stations showed similarities (Figure 63). At each station, the echo level increased with depth until just above the surface. Station 199, the easternmost station, had the highest echo levels and echo levels generally decreased to the west, possibly due to the decreasing fetch to the west behind the barrier island.

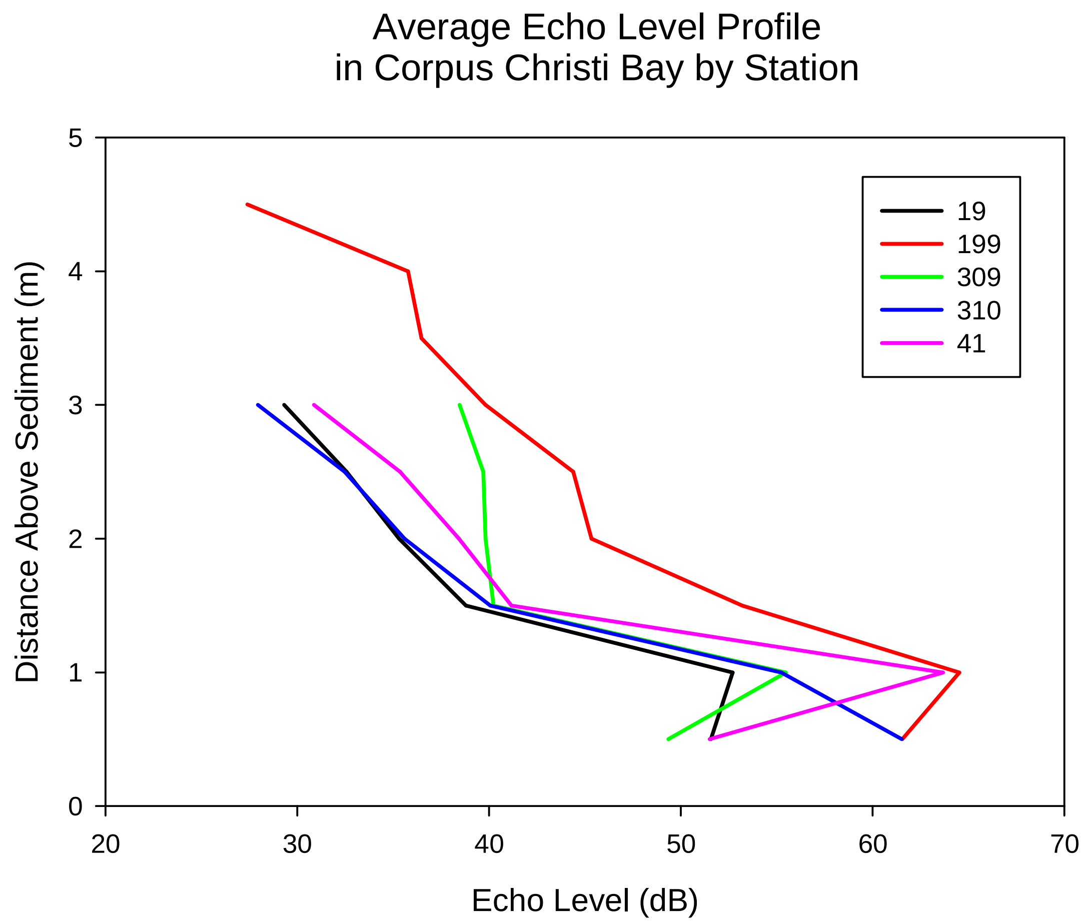

Figure 63 - Average Echo Level Profile in Corpus Christi Bay by Station

During one deployment, the ADCP at station 19 did not pass QAQC for all three beams in the bottom bin for every observation. These measurements were not used in the current velocity calculations. The remainder of the stations show an oscillating current generally aligned with the southeast shore of the bay (Figure 64). Station 310, positioned along the Intra-coastal waterway (ICWW), shows a bimodal current pattern with the additionally mode generally aligned in an onshore direction with the southeast shore of the bay. This second mode could be due to the proximity to the ICWW channel.

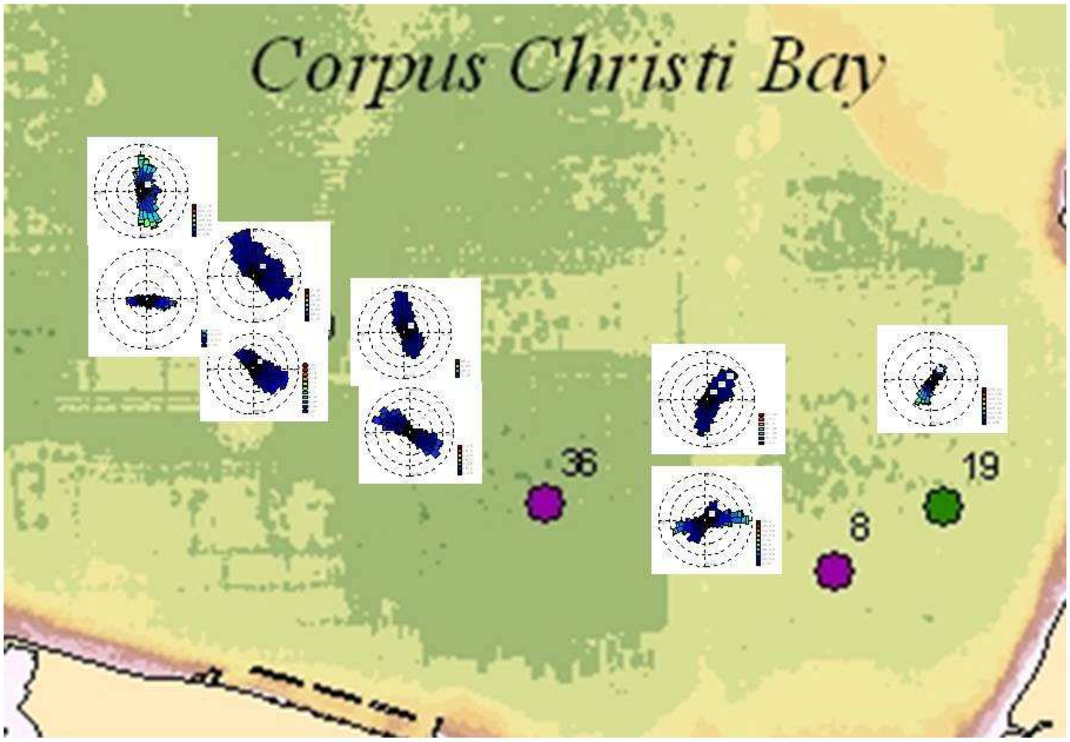

Figure 64 - Current rose graphs for Corpus Christi Bay during first deployment (6/2/2009 - 2/60/2009). Upper figure is in the 3 m bin above the sediment, the lower rose is in the 0.5 m bin above the sediment. Bathymetry from NOAA (Department of Commerce (DOC) *et al.* 1998)

Closer to the surface, in the bin 3 m above the sediment, the stations fall into two groups. Stations 199, 309, and 41, the three westernmost stations, have currents that oscillate in a generally se-nw direction, also the direction of the prevailing winds. The remaining two stations exhibit just the opposite current direction. This suggests that the fetch distance could play a role in the two different circulation patterns.

The highest current speeds were found at the bottom at station 19 in the southeast corner of the bay (Figure 65a). This current was mentioned many times by the divers deploying the moors and sondes. This is interesting because it is well within the hypoxic zone where it was suspected that sluggish water decreased mixing. However the dramatic change in current speed could be causing a barrier to oxygen from the surface. Salinity stratification has long been known to cause the barrier but this is the first time current velocity has been implicated in hypoxia in Corpus Christi Bay.

All of the stations had some degree of shear in the last meter of the water column, they were not as pronounced as at station 19 (Figure 65b,c,d,e).

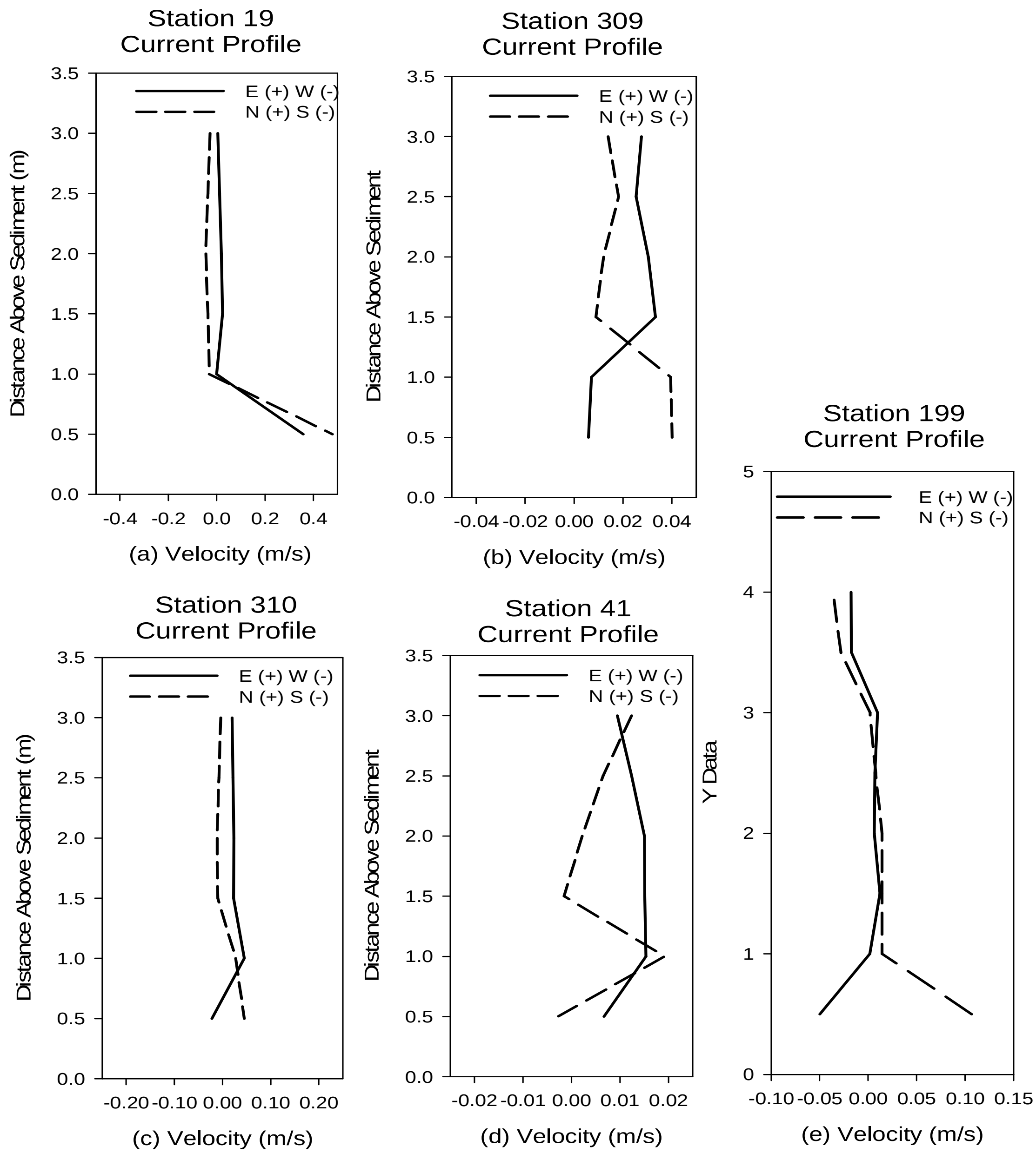

Figure 65 - Current profiles for all stations

Average echo levels for the bin next to the sediment were created by averaging the value for all valid beam values. For the vast majority of values, this was true for all three beams. However, if a beam did not pass QAQC, this value was not included in the average. At least one beam had to pass QAQC for an average to be calculated. This value, as well as the current speed, was joined with wind speed data from the TCOON station at Bird Island and the sonde bottom measurements into one file. Various transforms were utilized on the variables in order to achieve the highest amount of the variance explained in a PCA of the data. Only 41% of the variation is accounted for in first two components. Exponentially transformed salinity varied opposite the current speed and the square of the wind speed. The second principle component may be related to the fetch (Figure 67). Station 310 showed notable differences. This location is shallower, and has more shell hash in the bottom compared to the other stations, which might explain the different behavior.

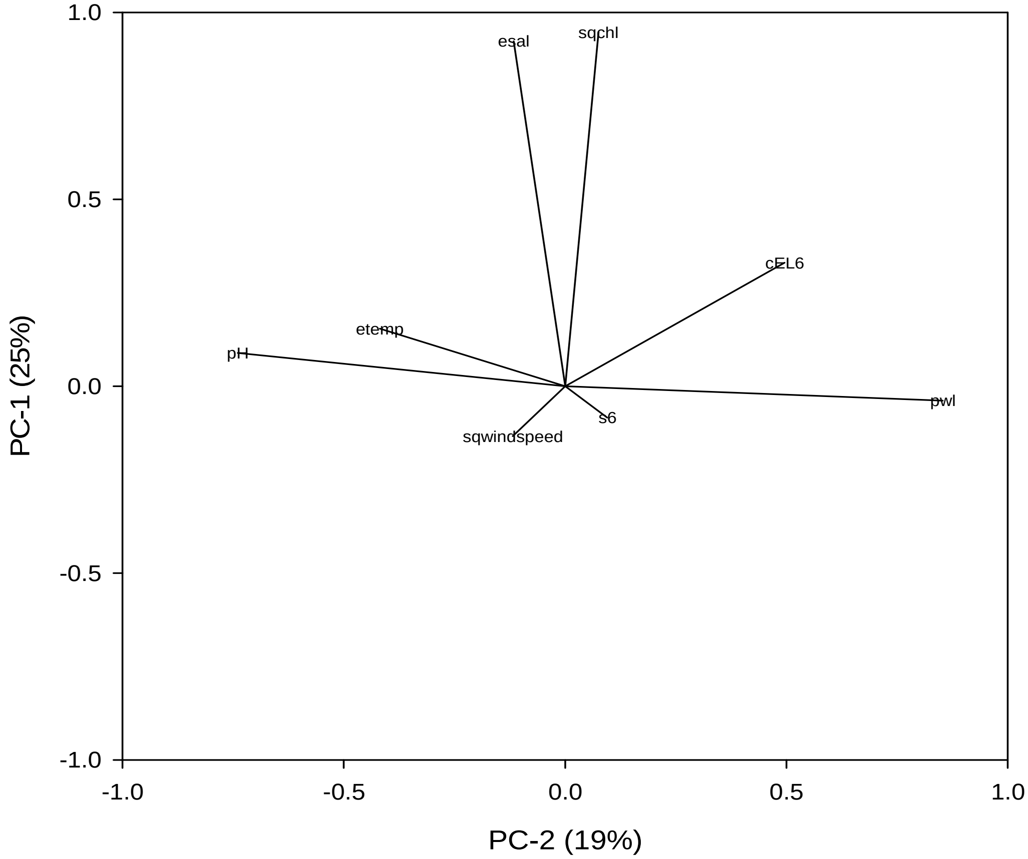

Figure 66 - Vector plot of variables during current study

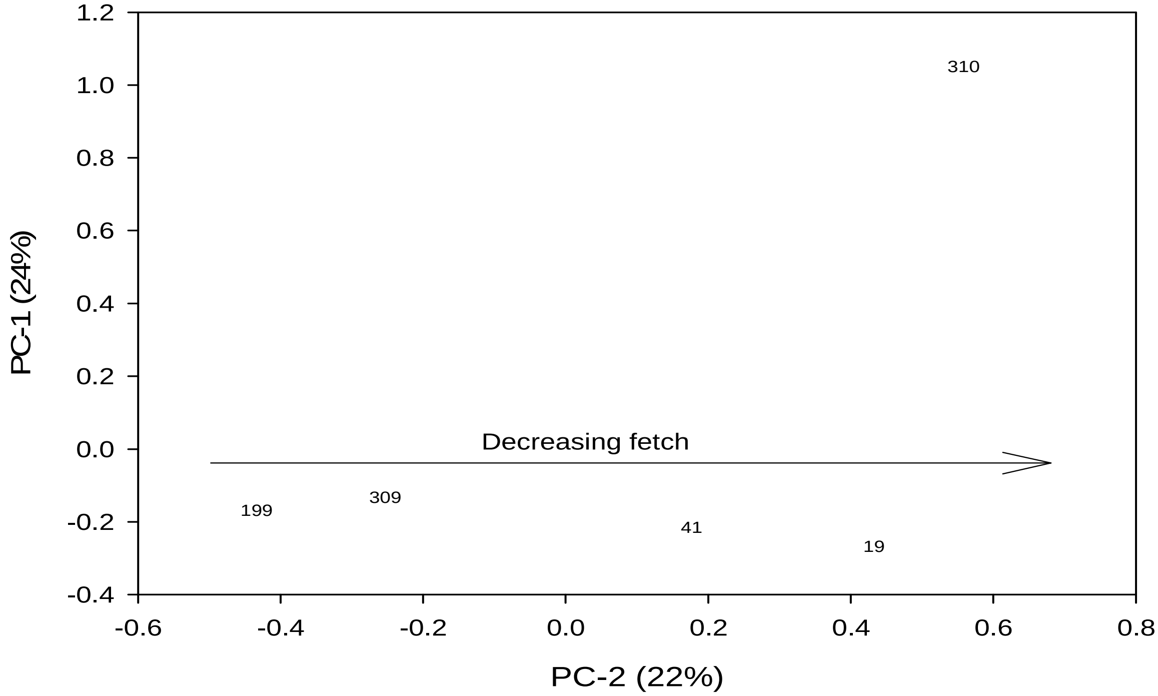

Figure 67 - Stations in PC1-PC2 space. PC-2 decreases with fetch.

5.3.2 Sonde Observations

Salinity ranged from 33 psu at stations 309 to 49 at station 310 (Figure 68). Station means varied from a low 40 psu at at station 309 to a high of 43 psu at station 19 (Figure 69).

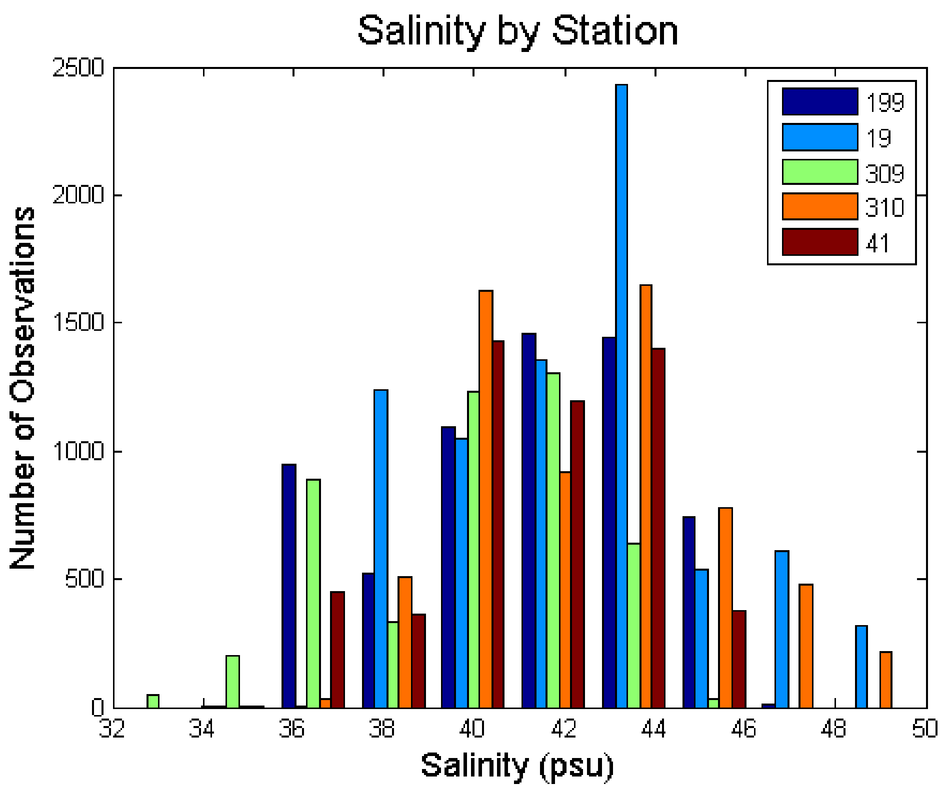

Figure 68 - Histogram by station of salinity

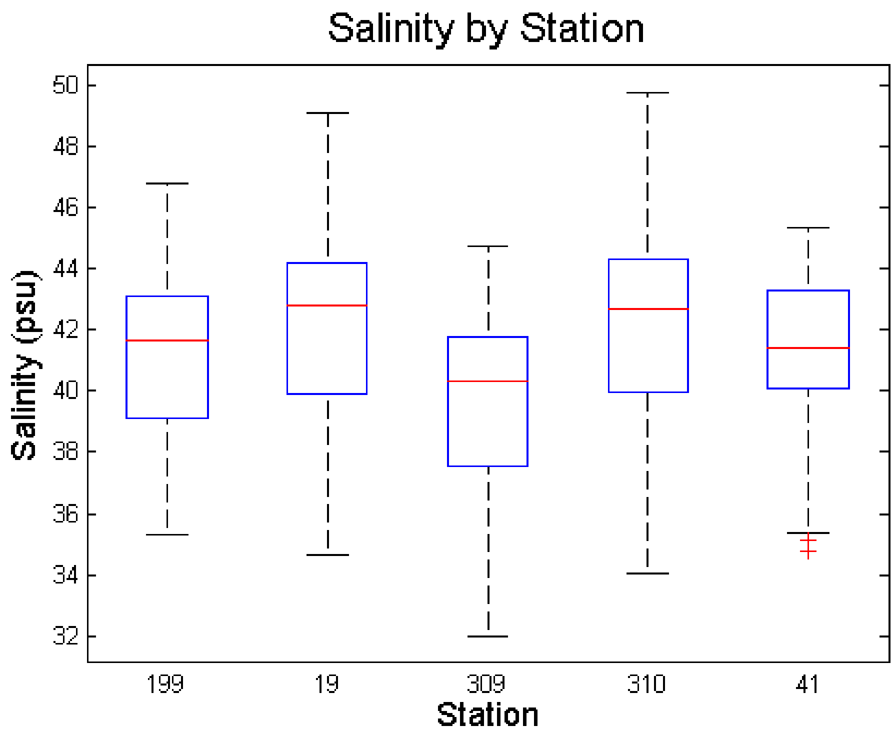

Figure 69 - Salinity during the current study

The bay behaved homogenously regarding temperature where the means and standard deviations were the same. Most observations fell between 30 and 30.5 degrees C (Figure 70) The mean fell at 30.25 degrees (Figure 71)

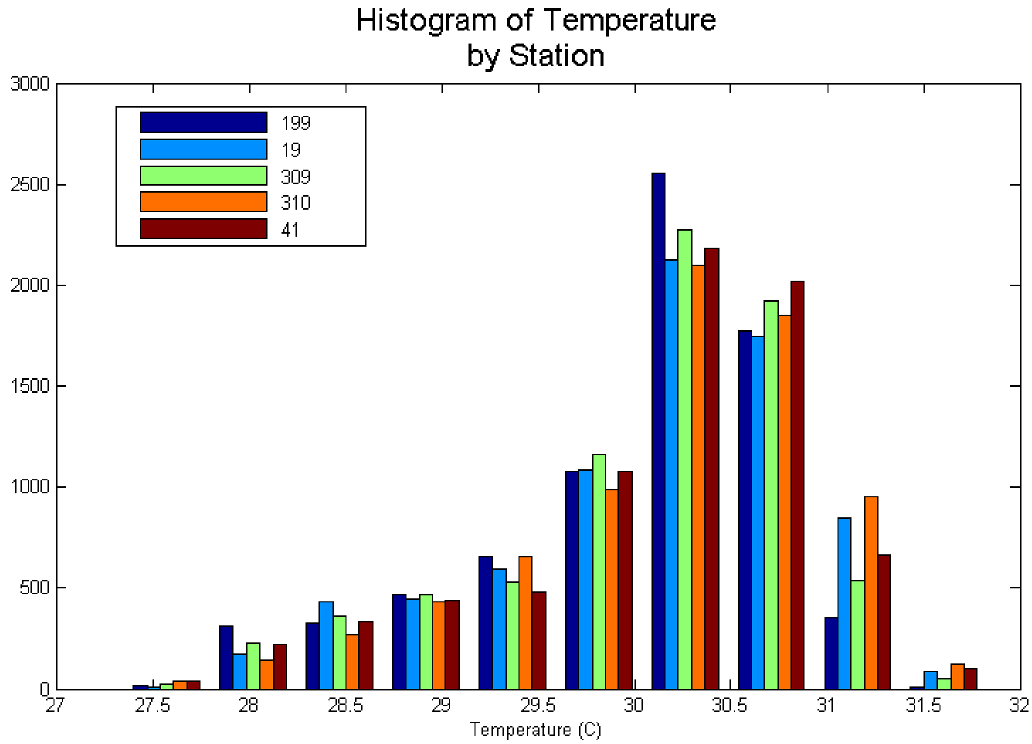

Figure 70 - Histogram of temperature by station during current study

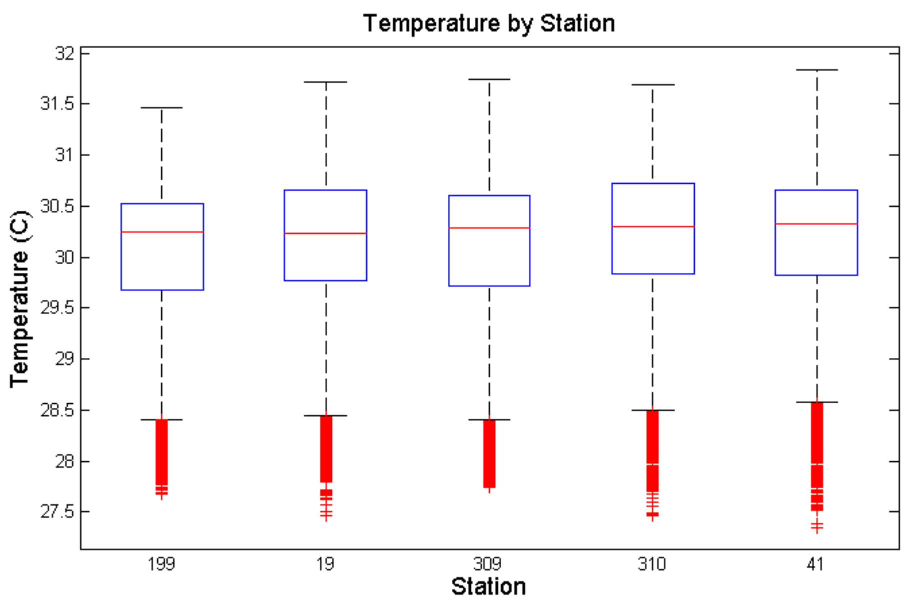

Figure 71 - Temperature during current study

Dissolved oxygen during the study ranged from near anoxic conditions at stations 19 and 310 to normal concentrations (Figure 72). Stations 19 and 310 are located near the nexus of Laguna Madre and Corpus Christi bay, and of the mouth of the Oso, respectively. The highest values, just under 8 were observed at the shallow, rocky-bottomed station, 309. Stations 19 and 310 also showed the lowest average [DO] and more hypoxic observations than the other stations (Figure 73).

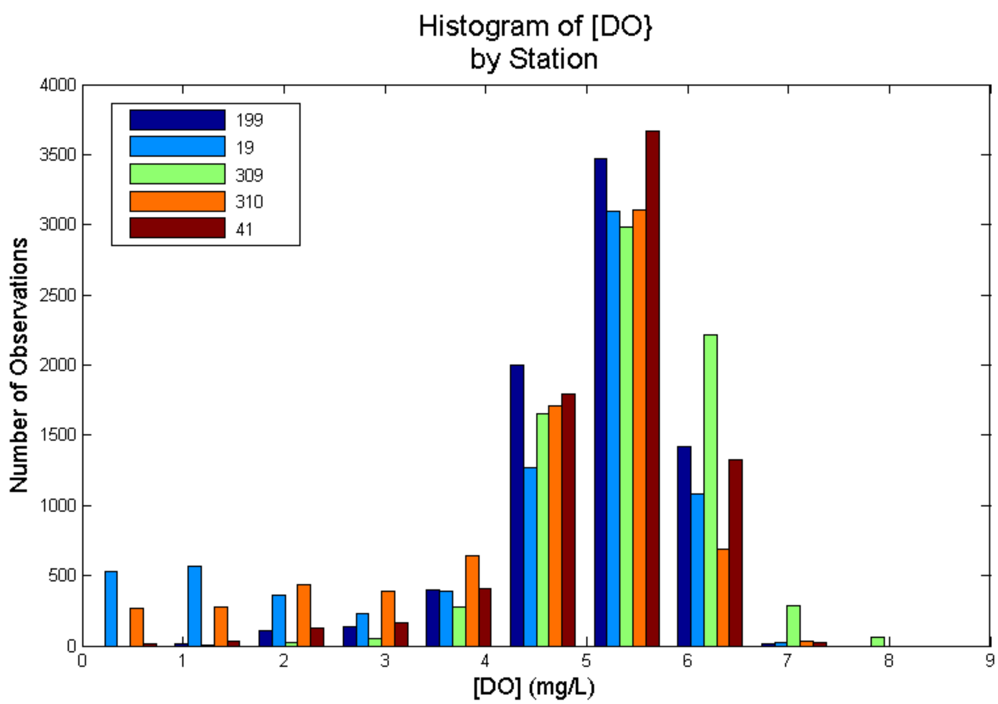

Figure 72 - Histogram of dissolved oxygen by station during the current study

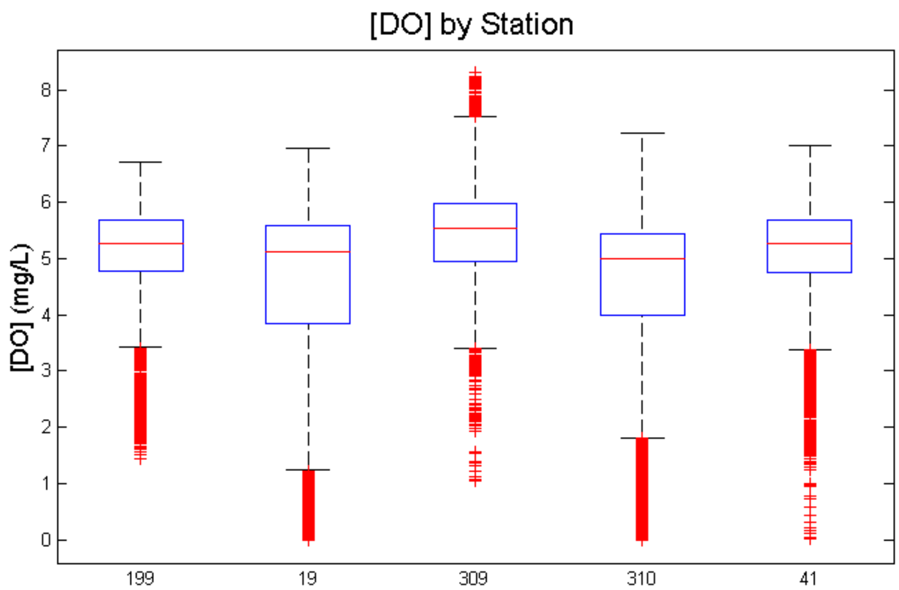

Figure 73 - [DO] during current study

During the study, it was observed that there might be some periodicity in the occurrence of hypoxia (Figure 74). To quantify this relationship, the data was prepped and passed through a fast Fourier analysis. There were few missing data points. Missing values were supplied by linear interpolation of the values on either side. Observations outside three standard deviations from the mean were replaced with an interpolated value. Depending on the analysis, various filters were used to remove noise and higher frequency signals. Long-term trends in the data were removed using a best-fit line. The diel cycle could clearly be seen in this analysis. However when the diel cycle was filtered out, no significant longer-term periodicity was observed. It is possible that the relationship does exist, but was unable to be teased out of this short data series.

To further investigate possible connection to the lunar cycle and dissolved oxygen concentrations, the time of the observation was used to calculate a time-distance from the observation to the nearest of the date and time of the closest phase of the moon. Data for the phases of the moon was downloaded from NASA's Eclipse website: http://eclipse.gsfc.nasa.gov/phase/phasecat.html.

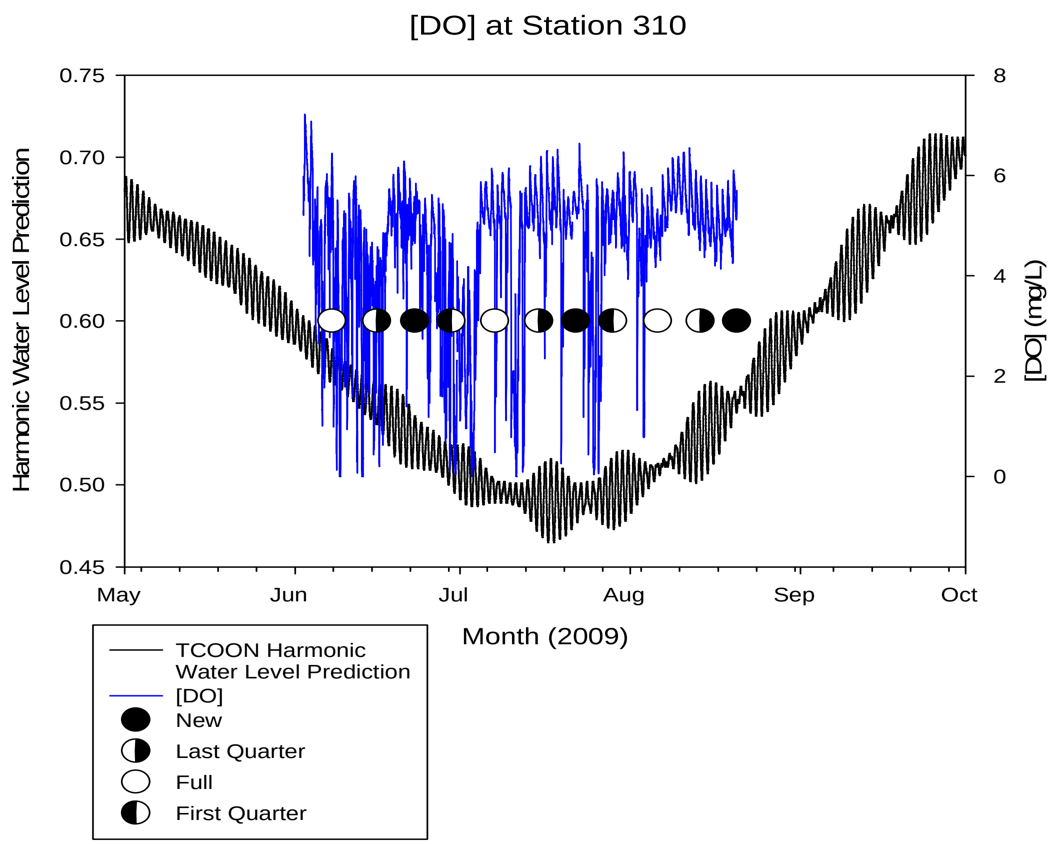

Figure 74 - Dissolved oxygen at station 310 shown with the phase of the moon and the TCOON Harmonic Water Level Prediction (m)

Once binned into the four phases, this phase variable was treated as a class for analysis of variance. This analysis resulted in significant difference in dissolved oxygen concentrations by station and phase of the moon. However, while lower dissolved oxygen was associated with the new and full moon, there was no difference between the two.

Next, a variable was created that was a measure of the time-distance of an observation to the nearest of either the full moon, or the new moon. This time-distance was calculated for all observations and then split into normoxic and hypoxic observations. Figure 74 shows that for all of the stations, the normoxic observations were evenly distributed around the theoretical mean distance. However, the hypoxic observations did not show this pattern. Station 199, the northern-most station experience hypoxic conditions at a time distance below the theoretical mean. Station 309, the shallow rocky station saw very few hypoxic observations, but they were all at a time distance greater than the theoretical. The remaining stations all had mean time-distances above the theoretical mean.

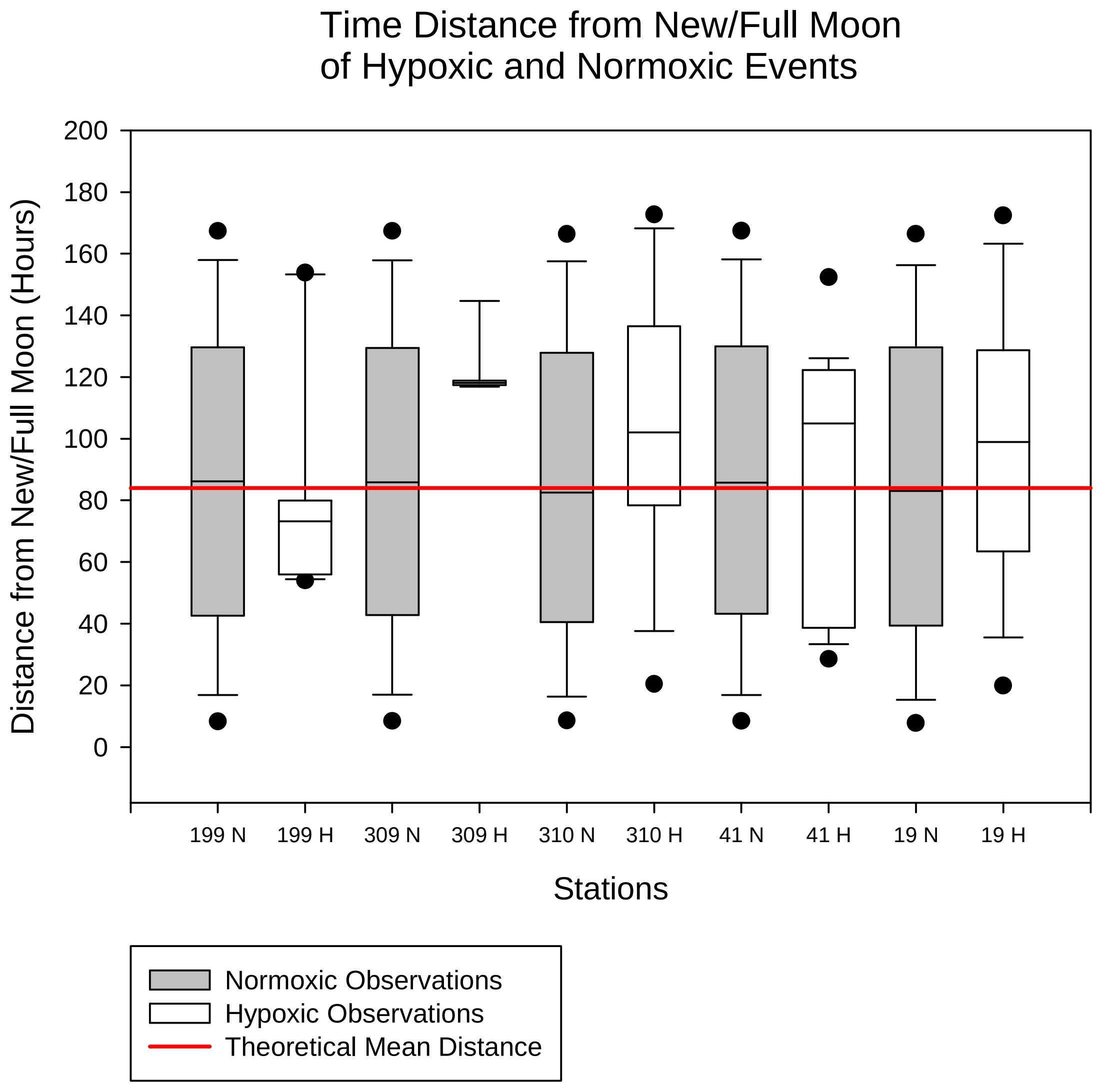

Figure 75 - Time-distance of hypoxic and normal [DO] from the new or full moon by station. For each observation, the time-distance used is the shortest of the amount of time measured from the observation to the closest new or full moon.

5.4 Discussion

Corpus Christi Bay during this study displayed two distinct water layers in current speed, direction and echo level. The bottom layer occurs in the first one meter above the sediment. The bottom layer, where hypoxia is observed has varies across the bay in both echo location values and current speeds. In the average, the bottom layer is acoustically clearer that the water above, except for station 310. This could be explained by the flow of turbid, salty water from Oso Bay. It is possible that stratification due to current speed is a factor in hypoxia particularly at the southeast corner of the bay. Current speed in the bottom layer varied with the wind speed. This is interesting because one would expect to see an increase in acoustic opacity with increasing wind, which was not in general seen. In the top-most layers, this becomes more reflective to acoustically opaque particles with depth. Current speeds in this layer tend to be consistent bay-wide, slightly increasing with depth.

5.5 References

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Part VI. Summary

Hypoxia is known to occur in the southeast corner of Corpus Christi Bay, Texas, USA each summer since its discovery in 1988. In 2006, ongoing field research discovered that the hypoxia area has a greater extent spatially and temporally than previously thought. Although it was known that hypoxia was associated with salinity stratification, it was not until 2007 that it was discovered that salty water from both Oso Bay and Laguna Madre were contributing to this stratification. This is interesting because there are three wastewater treatment plants that empty into Oso Creek and to Oso Bay, so there is a source of nutrients as well as salt.

The purpose of the current study was to determine the spatial and temporal extent of hypoxia, explore the role of nutrients and bay currents in the formation and frequency of hypoxia, determine what role small rain events play in the formation of hypoxia, and test the feasibility of disseminating the data collected in this study and others to the public via the use of a standardized database schema and web services.

Hypoxia in Corpus Christi Bay was found to begin as early as the first week of June, and occur as late as the last week of August. Hypoxic conditions can extend from Ward Island to Shamrock Island, an area estimated to cover 80 km^2. Nutrient concentrations are not at high levels, however, ammonium levels are higher in the hypoxic zone, likely due to remineralization. During small-scale freshwater inflow events, temperature of Oso Bay rises with inflow, likely due to cooling water discharged into the Oso from the nearby power generating facility. Even small-scale rain events appear to wash through Oso bay rather than being loaded. This, however does not appear to affect hypoxia in Corpus Christi Bay.

Differences in acoustic opacity, current velocity, current direction, and salinity between the bottom waters and those above may all be contributing to stratification. Salinity stratification is known to cause hypoxia. In the hypoxic area near Laguna Madre, higher-speed bottom currents may also keep bottom waters isolated. Hypoxia also appears to be influenced by the fortnightly lunar cycle, bathymetry, and bottom composition.

Hypoxia observations are not uniformly distributed during the lunar cycle. They appear to occur closer to neap tide maxima than to spring tide maxima in most cases. One station however had most of its hypoxic events closer to the spring tides.

Attempts to transform data from this project and others into a standard database schema were successful. However, not all of the complexities of biological nomenclature, multivariate data structures, and laboratory information requirements could be met with the system under study. Because every data source was different, extraction and transformation took the majority of the effort. This may always be the case for paper records and other no-longer-used digital formats. Scientific information requirements will continue to expand. Collaboration with other scientists will continue to benefit science as a whole. Significant future effort could be avoided by adopting a standard database for scientific observations, but much work will be needed technologically and socially to get that data from the applications that scientists choose to use.