Galveston Bay: changing land use patterns and nutrient loading. Causal or casual relationship with Water Quality, Quantity, and Patterns?

Prepared by:
Dr. Antonietta Quigg, Dr. Jamie Steichen and Rachel Windham
Department of Marine Biology
Texas A&M University Galveston (TAMUG) campus
200 Seawolf Parkway, Galveston, Texas 77553

Funding Source:
Fiscal Year 15 Clean Water Act Section 320
Prepared in cooperation with the Galveston Bay Estuary Program (GBEP) a program of the Texas Commission on Environmental Quality (TCEQ)
and the U.S. Environmental Protection Agency (EPA)
TCEQ Contract # 582-15-53393
Federal ID #CE-00655005

June 2017

Table of contents

Abbreviations

ASCII – American Standard Code for Information Interchange

BBEST – Basin and Bay Expert Science Team

CAP – Corrective Action Plan

CDOM – Colored Dissolved Organic Matter

DIN – Dissolved Inorganic Nitrogen

DOM – Dissolved Organic Matter

EPA – Environmental Protection Agency

GBEP – Galveston Bay Estuary Program

GBP – Galveston Bay Plan

GERG – Geochemical and Environmental Research Group

GF/F – Glass Fiber Filter

GPS – Global Positioning System

HAB – Harmful Algal Bloom

HGAC – Houston-Galveston Area Council

HPLC – High Performance Liquid Chromatography

HUC – Hydrologic Unit Codes

NLCD – National Land Cover Database

NOAA – National Oceanic and Atmospheric Administration

NPS – Nonpoint Source

QAPP – Quality Assurance Project Plan

SWQM – Surface Water Quality Monitoring

TAMUG – Texas A&M University at Galveston

TCEQ – Texas Commission on Environmental Quality

TPWD – Texas Parks and Wildlife Department

TWCA – Texas Water Conservation Association

TWDB – Texas Water Development Board

USGS – United States Geological Survey

1. Executive Summary

In this study, we used a variety of approaches to address our question of *causal versus casual relationships in influencing water quality, quantity, and patterns with changing land use patterns and nutrient loading to Galveston Bay.* We monitored the bay at monthly intervals using the Dataflow system to measure water quality parameters (objective 1). 2016 and 2017 were particularly windy years, reducing our capacity to sample effectively each month. Nonetheless, we were able to show the spatial and temporal variations in water temperature, pH, salinity, water clarity (beam transmittance), chlorophyll *a* (*in situ* fluorescence), and dissolved organic matter (DOM; *in situ* fluorescence). Along with wind, freshwater inflows had the greatest influence on these variables, both from the Trinity River and the San Jacinto River (objective 2). Nutrient (dissolved, total) and chlorophyll concentrations in the bay are variable but do not reflect the presence of eutrophication (associated with high nutrients) nor algal blooms (associated with high chlorophyll) during the study period (objective 3). This finding was consistent with observations of phytoplankton productivity, community composition, and the absence of harmful algal blooms (objective 4). Historical and current nutrient inputs into Galveston Bay, specifically nitrate, nitrite and ammonia, showed no direct correlation between nutrient loading to the bay versus riverine flows when considering all sources including domestic and industrial wastewater sources (objective 5). We examined land use land cover in relation to water quality in the bay (objective 6). An examination of the counties surrounding this watershed revealed that forest land cover experienced the greatest loss, primarily due to development (urbanization) from 1992 to 2014. Forests were also lost to grasslands and more shrubs. In addition, agricultural (cultivated) lands and wetlands also were lost in the region. Wetlands were converted into developed lands, to shrubs and grasslands associated with urban community centers connected to waterways. We found, whether looking at bay-wide averages or at specific locations, annual averages or seasonal variations, that there were no discernible trends in water quality parameters typically associated with eutrophication or water degradation in other regions (e.g., nutrient loading, hypoxia). We propose that until now, Galveston Bay is resilient to the upstream changes in land use and land cover. This may in part, be facilitated by the relatively high freshwater inflows and short turnover time in the bay, but this would require additional study to verify. This may also be due to vast majority of developed lands (as urbanization) flushing into the river which contributes to only a quarter of the bays freshwater inflows (San Jacinto Rivers); the other important river (Trinity) contributes ~55% but has had fewer alterations to its landscape which is primarily forest and wetlands areas. As regional planning bodies and natural resource managers endeavor to determine the appropriate amount of freshwater inflows for Galveston Bay, understanding the balance between land use land change and water quality will be key to maintaining ecosystem services and functions for future generations. This is very challenging as linear responses to land-use change are unlikely given the complex and dynamic nature of estuarine systems.

2. Introduction

The conversion of land to support growing populations is a major component of human modification of the environment. This has been most dramatically observed in recent years in Southeast Asia, South America, and Africa. Rates of intensification of agriculture, expansion of urban areas (development), extraction of timber and other natural resources, as well as development of freshwater resources will likely continue in decades to come (DeFries et al., 2004). The impact of urbanization on nutrients in watersheds has been examined worldwide (Alberti, 2005; Alberti et al., 2007; Allan, 2004; Carpenter et al., 1998; Halstead et al., 2014; Hogan et al., 2014; Lenat and Crawford, 1994; Paul and Meyer, 2001; Zampella et al., 2007). Increased urban land cover (development) is increasing impervious surface area and subsequently increasing water pollution (Chang, 2008; Chang et al., 2014; Hogan et al., 2014; Paul and Meyer, 2001), most often as a result of increased runoff which exports fertilizers and pollutants (Dietz and Clausen, 2008; King et al., 2012; Lehman et al., 2011). Urban-related runoff/stormwater is one of the largest contributors to the impairment of river and stream water quality in most states (Kemp et al., 2005). High levels of eutrophication were reported in 45% of the estuaries surrounding the Gulf of Mexico (Clement et al., 2001).

The Chesapeake Bay watershed is degraded as a result of urban development and population growth over the last 200 years, specifically the increase in fertilizer usage has been linked to algal blooms, decreased water clarity, hypoxia, loss of biodiversity, etc. (e.g., Dauer et al., 2000; Kemp et al., 2005; Smith et al., 2003). San Francisco Bay is also heavily impacted with recent studies showing that nutrient loading, particularly from waste water facilities, has altered nutrient loading, nutrient utilization patterns, phytoplankton community composition and the appearance of harmful algal blooms (Glibert et al., 2014 a, b). Galveston Bay (Texas) is located in one of the fastest growing regions in the United States (Census Bureau, 2012), with a 36% increase in the population between 1997 and 2012, such that 6.5 million people live within the lower watershed (Houston-Galveston Area Council (HGAC), 2014). This growth has resulted in demand for industrial, commercial, and housing development. Galveston Bay is home to a large petrochemical and oil refinery complex and also provides many economically and recreationally important resources to local communities (Gonzalez and Lester, 2011). *The goal of this* *investigation is to determine if the increase in development around Galveston Bay caused a corresponding decrease in estuarine water quality*. The spatial scale for performing this kind of study can be local (buffer zone) or basin-wide (watershed); each approach has pros and cons (Chang et al., 2014; Gburek and Folmar, 1999; Gove, 2001; Bruno et al., 2014; Tong and Chen, 2002; Alberti et al., 2007; Tran et al., 2010).

3. Project Significance and Background

<u>The Galveston Bay Plan (GBP)</u> - The Galveston Bay Estuary Program (GBEP) identified an “examination of the impacts of freshwater inflow and bay circulation” as a priority area in its comprehensive conservation and management plan (the GBP). Specifically, *to ensure beneficial freshwater inflows necessary for a salinity, nutrient and sediment loading regime adequate to maintain productivity of economically important and ecologically characteristic species in Galveston Bay* (GBEP, 1994). More than two decades later, the major gap in our knowledge base to address present and future concerns is a clear understanding of the downstream ecological impacts of changes to freshwater inflows and modes of nutrient loading on the estuary.

Through work performed by the GBEP, the Texas Water Development Board (TWDB), the U.S. Environmental Protection Agency (EPA), the TCEQ, and the Texas Water Conservation Association (TWCA), a common understanding of Galveston Bay (Texas) has evolved. Key elements of that understanding include:

1. Galveston Bay has been modified extensively from its natural condition. The watershed has changed, flood events have been greatly reduced by reservoir construction, a steady and increased base flow has been added from water imported to the basin as a result of a large population increase, and the bay’s exchange with the Gulf of Mexico has been greatly increased.
2. Our (entities stated above) data gathering and analytical capacity has increased substantially in the recent decades.

3. As a result of improvements in data gathering, more detailed information on spatial and temporal patterns associated with the significant decline in a key measure of the bay's productivity, chlorophyll *a,* is available.
4. But with so many changes taking place during the last four decades, it is not known at this time how specific system changes have produced the decline.
5. Perhaps equally important, in a system that is so heavily modified, it is not known what natural levels were and we do not have a common understanding of what a desirable level of primary productivity (chlorophyll *a*) should be in today's system.

The approach used addresses this situation and builds on key elements that now exist including:

1. greatly improved monitoring of chlorophyll *a* and nutrients,
2. an improved understanding of what nutrient will most likely be limiting, and
3. substantial improvements in our (entities stated above) ability to understand and model key elements of the system including reservoirs, watershed runoff, and bay hydraulics.

<u>Texas Coastal Nonpoint Source (NPS) pollution control program</u> - Texas proposes to implement its Coastal NPS Pollution Control Program through a group of networked programs that would combine geographical and categorical approaches to addressing NPS pollution. The geographical approach is addressed through Texas' basin management cycle, which provides a framework for coordinating, developing, and implementing water quality management programs throughout the state. Key water quality activities such as monitoring, assessment, data management, permitting and reporting are coordinated on a basin-wide scale. *This project directly supports this mission*.

This project adds to the scientific information needed to protect, sustain, and restore the health of critical natural habitats and ecosystems, specifically areas identified by the hydrologic unit codes (HUC) and Segment IDs in the Galveston Bay Watershed (Texas) in Table 1 below.

Table 1. Hydrologic unit codes and Segment IDs in the Galveston Bay Watershed.

Watershed or Aquifer Name	*Hydrologic Unit Code*	*Segment ID*
Houston Ship Channel/San Jacinto River Tidal		1005
Houston Ship Channel Tidal		1006
Upper Galveston Bay		2421
Trinity Bay		2422
East Bay	12040202	2423
West Bay	12040204	2424
San Jacinto Bay		2427
Texas City Ship Channel		2437
Lower Galveston Bay		2439
Lower Trinity	12030203	
Buffalo-San Jacinto	12040104	
North Galveston Bay	12040203	

In Charting the Course to 2015: Galveston Bay Strategic Action Plan (GBEP, 2009), Galveston Bay stakeholders identified future demands for freshwater and alterations to circulation seriously affecting productivity and overall ecosystem health as the number four priority for the bay. The major gap in our knowledge base to address present and future concerns is a clear understanding of the downstream ecological impacts of changes to freshwater inflows and the effects nutrient loading have on the estuary. Concurrently the 80th legislative session, Senate Bill 3, mandated defining freshwater inflow needs for our estuaries in Texas.

Project objectives:

***Objective 1:* Monitor the bay at monthly intervals using the Dataflow system to measure water quality parameters.**

High spatial and temporal resolution mapping of water quality in Galveston Bay was performed monthly with a Dataflow, a high-speed, flow-through measurement apparatus developed for mapping physico-chemical parameters in shallow aquatic systems (Madden and Day, 1992;

Quigg et al., 2007) from a boat, running tight transects across the estuary (Figure 2) Water quality measurements were taken at 4-sec intervals (every 2–8 m depending on boat speed) from about 10 cm below the surface (Figure 1). An integrated Global Positioning System (GPS) was used to simultaneously plot sample positions, allowing geo-referencing of all measurements for each variable.

This integrated instrument system was used to concurrently measure water temperature, pH, salinity, water clarity (beam transmittance), chlorophyll *a* (*in situ* fluorescence), and dissolved organic matter (DOM; *in situ* fluorescence). This process took two eight hour days to complete given the size of the bay and desire to map at high resolution. Each map consisted of between 2000 and 3000 data points which can be geo-referenced both spatially and temporally.

The sampling crew stopped briefly at 41 stations (Figure 1) to measure discrete water samples to further calibrate the Dataflow unit. Some samples were tested *in situ* (on the boat) while others were returned to the laboratory for further processing. All environmental data was archived in a database housed at the TAMUG and will be available upon request.

***Objective 2:* Monitor freshwater inflows.**

Real-time flow data from a USGS monitoring station (Trinity River at Romayor; 08066500) near the Trinity River mouth was used to determine the freshwater discharge rates into Galveston Bay. The influence of the San Jacinto River was determined by combining flows at both the East Fork (USGS 08070000) and West Fork (USGS 08067650) in the analysis.

***Objective 3:* Collect nutrient and other data at fixed stations in the bay which can then be used to explain patterns in water quality such as the chlorophyll data.**

At fixed stations shown on Figure 1 (circled numbers), discrete water samples were collected to measure the following parameters.

- Dissolved nutrients (NO_3^-, NO_2^-, NH_4^+, PO_4^{3-} and SiO_3),
- Total nitrogen (TN) and total phosphorus (TP), and
- Phytoplankton biomass (chlorophyll and phaeophytin).

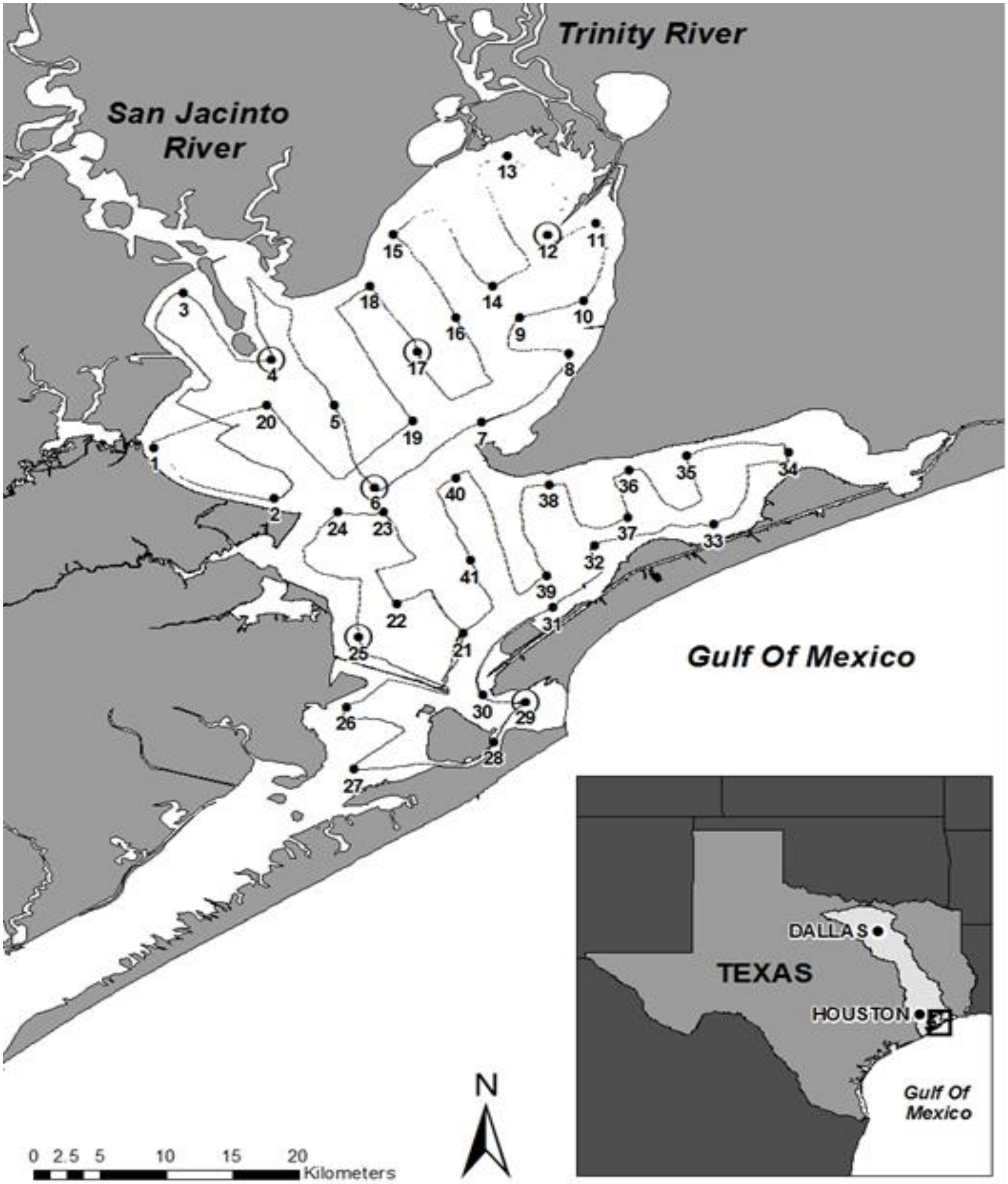


Figure 1. Area map depicting Galveston Bay and detailed transect (dataflow lines) and discrete sampling sites (numbered).

***Objective 4:* Measure phytoplankton productivity, community composition, and the presence of harmful algal blooms (HABs), if present.**

Primary productivity was measured at fixed stations shown on the map in Figure 1 (circled numbers) using the traditional light/dark bottle method. Water samples were taken at the same stations to determine phytoplankton community composition using High Performance Liquid Chromatography (HPLC) to measure a range of marker pigments which were then analyzed with the algorithm ChemTax to determine the major phytoplankton group. Given the TAMUG now has an Imaging FlowCytobot, a subsample was collected at each of the fixed stations to examine the individual cells, and to determine if HABs may be present.

***Objective 5:* Build a quantitative understanding of the current and historical nutrient inputs from domestic and industrial wastewater sources from the large number of discharges in the bay.**

The TAMUG will use data from the various state agencies in Texas to determine nutrient inputs into the bay since records have been collected. Specifically, we will determined if there have been changes in ammonia and nitrate inputs into the bay.

***Objective 6:* Use the long term data set being established (since 2008) to understand how the inter-annual variability and extreme events (e.g., 2011 drought) need to be factored into an understanding of freshwater inflows effects on the bay. Long term data sets are key to understanding how much freshwater is going to be required for maintaining an ecologically sound bay.**

This objective was designed to help resolve issues that arose as part of the Basin and Bay Expert Science Teams (BBEST) deliberations to develop recommendations for freshwater inflows into Galveston Bay (see Espey et al., 2009). The BBEST found that “flows incorporated within the proposed recommendation are necessary for a sound ecological environment and would be limited to only those organisms studied, and not suggested as representing a healthy Galveston Bay ecosystem in its entirety.” Given the scope of the current program, the TAMUG endeavored to address these issues.

4. Methods

Dataflow

Spatial patterns of water quality in Galveston Bay were measured at least 12 times per year (i.e. monthly) with Dataflow, a high-speed, flow-through measurement apparatus developed for mapping physico-chemical parameters in shallow aquatic systems (Madden and Day, 1992). This integrated instrument system was used to concurrently measure water temperature (Signet Conductivity/Temperature Sensor), conductivity (Signet Conductivity/Temperature Sensor), water clarity (WET Labs C-Star Transmissometer), chlorophyll *a* (WET Labs WET Star), and dissolved organic matter (WET Labs CDOM WET Star), from a boat, running transects across the estuary.

It took two 8 hour days to physically map Galveston Bay along transect lines shown in the map in Figure 1. Preparation for the Dataflow included calibration and readiness of the items detailed in the project Quality Assurance Project Plan (QAPP). Water quality measurements were taken at four-second intervals (every two - eight meters depending on boat speed) from about 10 cm below the surface. An integrated GPS was used to simultaneously plot sample positions, allowing geo-referencing of all measurements for each variable. The Dataflow work was conducted using standard procedures for estuarine systems according to Madden and Day (1992). Comprehensive details are provided in the Standard Operating Procedure found in the project QAPP.

Dataflow data were tied to GPS and fed into an Omnidata Polycorder Datalogger and stored in American Standard Code for Information Interchange (ASCII) file format. GPS and Dataflow information were used to create highly detailed GIS-based contour maps of water quality parameters in relation to physiographic features. Discrete grab samples from the flow-through system during continuous sampling were collected for laboratory calibration of Dataflow unit. In addition to these samples, profiles of salinity, dissolved oxygen, and temperature were measured to determine the degree of stratification of the water column in this shallow estuary according to Hansen and Rattray (1966).

After each sampling campaign, the Dataflow and sensors were rinsed by continuously pumping deionized water through the unit for no less than 20 minutes. The unit was stored dry and clean in the laboratory between sampling events.

The calibration prior to each sampling campaign was used to determine, by measurement or comparison with a standard, the correct value of each scale reading on a meter, instrument, or other device. The levels of the applied calibration standard were used to bracket the range of expected sample measurements. The blank was used to confirm that there is no contamination of instruments. If there was a need to decontaminate, the team proceeded according to the manufacturer's directions. If due to a contamination event, there was an issue with previously collected data, we identified the data and corrected any instrument related issues. This included rechecking instrument calibrations and running blanks.

Fixed station samples

Samples were collected into a single, one liter bottle which was previously acid washed and rinsed three times with sample water before being filled. These were kept on ice whilst sampling the rest of the bay. Immediately upon return to the lab from the field, a portion of each water sample was homogenized, and used to measure the parameters detailed below. Sample holding times were less than four hours, that is, upon returning to the laboratory each evening, samples were processed immediately.

Nutrient analysis

A sub-sample (no less than 100 ml) was vacuum-filtered through a pre-ashed, pre-rinsed, 4.7 cm Glass Fiber Filter (GF/F). The filtrate was frozen immediately and then analyzed for dissolved inorganic nitrogen (NO_2^-, NO_3^-, and NH_4^+), dissolved inorganic phosphorus (HPO_4^{2-}) and silicate. The remaining "whole" water samples (i.e., unfiltered) were analyzed for total nitrogen and total phosphorus. The samples were shipped to the Geochemical and Environmental Research Group (GERG) at Texas A&M University.

The autoanalyzer method was modeled after those developed and commonly used for seawater analyses (Valderrama, 1981). Nitrate and nitrite analyses were based on the methodology of

Armstrong et. al (1967) and utilize a ground Cd column for reduction of NO_3^- to NO_2^-. Orthophosphate was measured using chemistry based on the investigations of Bernhardt and Wilhelms (1967) with the modification of hydrazine as reductant. Silicate determination was accomplished using the methods of Armstrong et al. (1967) incorporating stannous chloride. Ammonium analysis was based on the method of Harwood (Harwood and Kuhn, 1970).

Samples designated for total nitrogen and phosphorus determination were not filtered. Sample volumes were transferred gravimetrically after vigorously shaking and resuspending any settled material. Quantitative decomposition of particulate nitrogen and phosphorus in alkaline solution has been observed (Valderrama, 1981) and is mediated by pH shift from 9.7 in the initial oxidation to a value of three to five during and after heating. This shift and oxidation occurs due to the Boric acid-NaOH system in which the persulfate is dissolved. In addition, spike controls of known quantities were run in the form of Certified Reference Materials (CRMs as particulate, SPEX Certi-prep Corporation) with sample runs. At least one spike recovery was run per 15 sample batch. From these spiked samples recovery analysis is performed and reported.

The process of persulfate oxidation in a salt water matrix unfortunately involves the formation of halide radicals (i.e chloride radicals). These radicals interfere with the phosphate chemistry utilizing alkaline phenol operating on the Technicon II AA. Hydrazine elimination through radical interaction has been suggested as contributing to methodology error. For this reason, Ascorbic acid (12 grams NaAscorbate/L) was introduced near the sample input to the continuous flow system. These particular problems justify the careful consideration of spike recoveries during each analysis.

Chlorophyll

Water (no less than 100 ml) from each station was filtered (GF/F; Whatman) onto a filter under low vacuum (< 130 kPa) pressure for chlorophyll analysis (Arar and Collins, 1997). Filters were folded and frozen at -20°C for chlorophyll analysis. Chlorophyll *a* and phaeophytin concentrations will be measured using a Turner 10-AU fluorometer.

Water Column Productivity

The in-field plankton response to inflow events and nutrient loadings was investigated by measuring water column productivity at locations, shown in the sampling map (see Figure 1), using widely-accepted *in situ* light and dark bottle techniques (Wetzel and Liken, 2000). Productivity measurements were made during each of the Dataflow samplings (at least 12 y^{-1}).

Pigment Analysis

HPLC was used for photopigment-based chemosystematic characterization of microalgae (Millie et al. 1993, Jeffrey et al. 1997, Pinckney et al. 1998). Aliquots (0.3 to 1.0 L) of water were filtered under a gentle vacuum (<50 kPa) onto 2.5 cm diameter glass fiber filters (Whatman GF/F), immediately frozen, and stored at -80 C. Frozen filters were placed in 100% acetone (3 mL), sonicated, and extracted at -20 C for 12 - 20 h. Filtered extracts (200 µL) were injected into a Spectra-Physics HPLC equipped with a single monomeric (Rainin Microsorb-MV, 0.46 x 10 cm, 3 µm) and two polymeric (Vydac 201TP, 0.46 x 25 cm, 5 µm) reverse-phase C_{18} columns in series. This column configuration was devised to enhance the separation of structurally similar photopigments and degradation products. Monomeric columns provide strong retention and high efficiency, while polymeric columns select for similar compounds with minor differences in molecular structure and shape (Van Heukelem et al., 1994, Jeffrey et al., 1997). A nonlinear binary gradient, adapted from Van Heukelem et al., (1994), was used for pigment separations (for details, see Pinckney et al., 1996). Solvent A consists of 80% methanol: 20% ammonium acetate (0.5 M adjusted to pH 7.2) and solvent B is 80% methanol: 20% acetone. Absorption spectra and chromatograms (440 nm) were acquired using a Shimadzu SPD-M10av photodiode array detector. Pigment peaks were identified by comparison of retention times and absorption spectra with pure crystalline standards, including chlorophylls *a* and *b*, carotene (Sigma Chemical Company), fucoxanthin, and zeaxanthin (Hoffman-LaRoche and Company). Other pigments were identified by comparison to extracts from phytoplankton cultures and quantified using the appropriate extinction coefficients (Jeffrey et al., 1997). The HPLC was calibrated prior to each sample batch being processed. Blanks were run first to confirm that therewas no contamination of the instrument. More details of the protocol, pigments and appropriate quality assurance/quality control methods can be found in the project QAPP.

Imaging FlowCytobot

Samples were collected at six of the discrete stations for analysis in the Imaging FlowCytobot (Olson and Sosik, 2007). This instrument used a combination of flow cytometric and video technology to capture high resolution (one micrometer) images of suspended particles in the size range <10 to 100 µm (such as diatoms and dinoflagellates). Laser-induced fluorescence and light scattering from individual particleswere measured and used to trigger targeted image acquisition; the optical and image data were then uploaded to the electronic database. This allowed monitoring with an automated image classification (often to genus or even species level) with accuracy comparable to that of human experts (Sosik and Olson, 2007).

The Imaging FlowCytobot was intended to be used to investigate harmful algal blooms in Galveston Bay and to understand how the phytoplankton community evolves and responds to the immediate environment by using *insitu* observations. Given this is a relatively new instrument we are still developing protocols and procedures towards a "standard operating procedure". Since there was no identification library, we started one from scratch. We worked towards developing the categories within a training set that would sort the images based on the lowest possible taxonomic level using several different reference texts including Tomas et al. (1997).

A "Dashboard" is a website where the Imaging FlowCytobot data are shared with the state and federal agency personnel and the public (http://ifcb-data.whoi.edu). The dashboard for the Galveston Bay Imaging FlowCytobot can be found at: http://dq-cytobot-pc.tamug.edu/TAMUG.

5. Results and Observations

***Objective 1:* Monthly water quality.**

Using a deck-mounted Dataflow, we captured continuous surface water quality data during each monthly sampling campaign. These values were interpolated to visualize the spatial variance in surface water quality in Galveston Bay each month. In some months we were not able to perform sampling campaigns (see statement 'no data' in Figures 2-7). In all of these cases, wind or other inclement weather conditions were such that we could not complete one or both days of sampling. While only anecdotal, we are finding that each year, the spring months are getting windier in Texas.

Below, we have presented temperature (°C), salinity (no units, practical salinity scale), transmittance as proxy for water clarity (volts), chlorophyll *a* (volts) and dissolved organic matter (volts) from January 2016 to March 2017. No stratification was observed at the fixed stations during the course of this study (data not shown) as calculated according to Hansen and Rattray (1966). This is consistent with wind driven mixing observed in this shallow estuary throughout the study period (which also prevented more frequent sampling campaigns). In Figure 2, high temperatures are represented with the color red while cooler temperatures are shown in pale blue. During the study period, surface water temperatures increased in summer months and peaked at 32.2°C in July 2016. Temperatures were lowest in winter with a minimum of 11.6°C observed in February 2016. While water temperatures typically are homogenous in the summer and fall, in the spring (see February 2016 and 2017), we capture the heterogeneity as water masses switch from cooler to warmer waters.

Surface water salinity varied throughout the study period both spatially within months and temporally across the study period. In Figure 3, light colors represent fresher waters whereas dark blues are representative of more saline waters. A gradient of salinities ranging from <1 to 30 from the mouth of the Trinity River to the Gulf of Mexico respectively was observed early in 2016 (February).

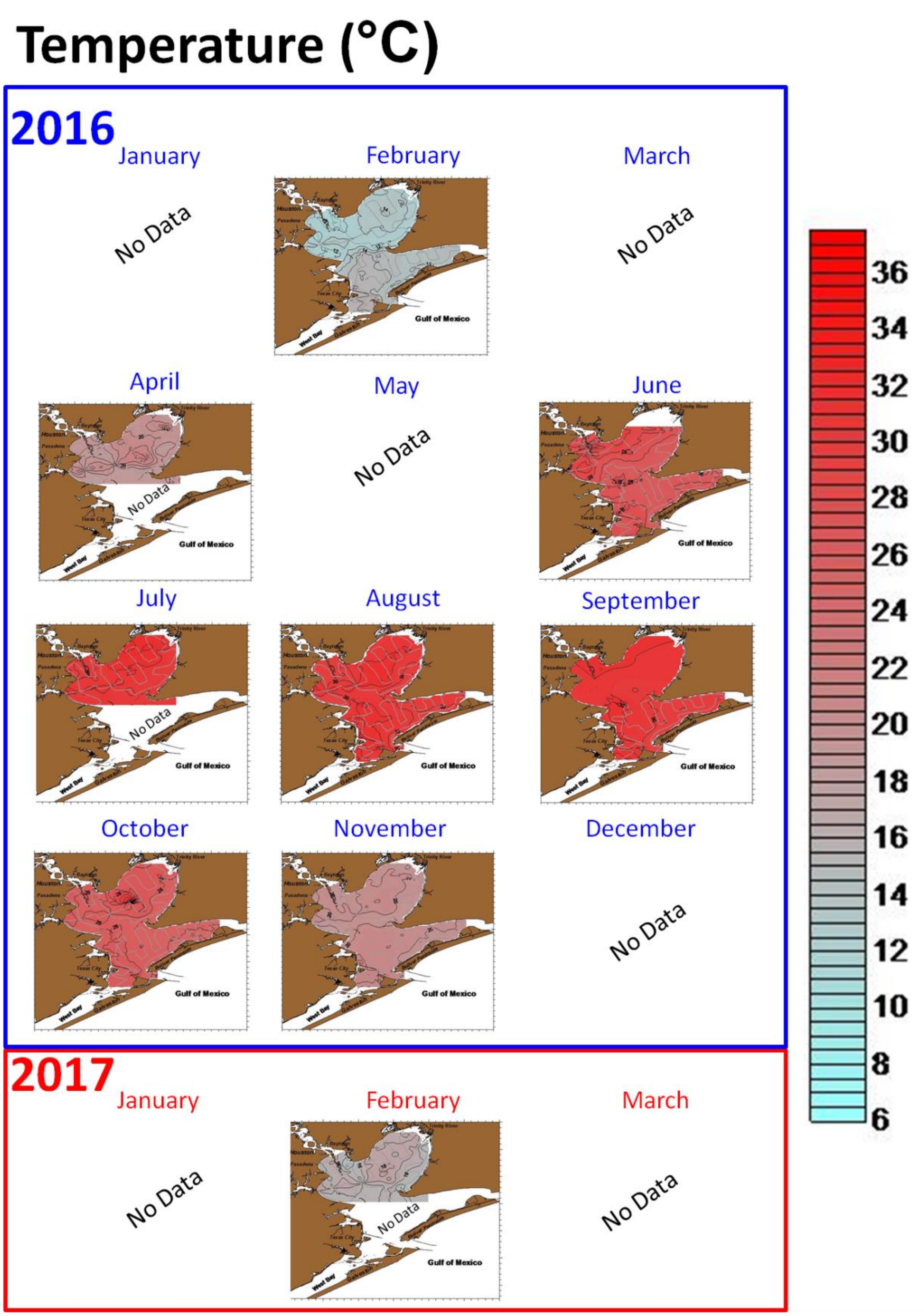


Figure 2. Temperature (°C) of surface water in Galveston Bay from January 2016 – March 2017.

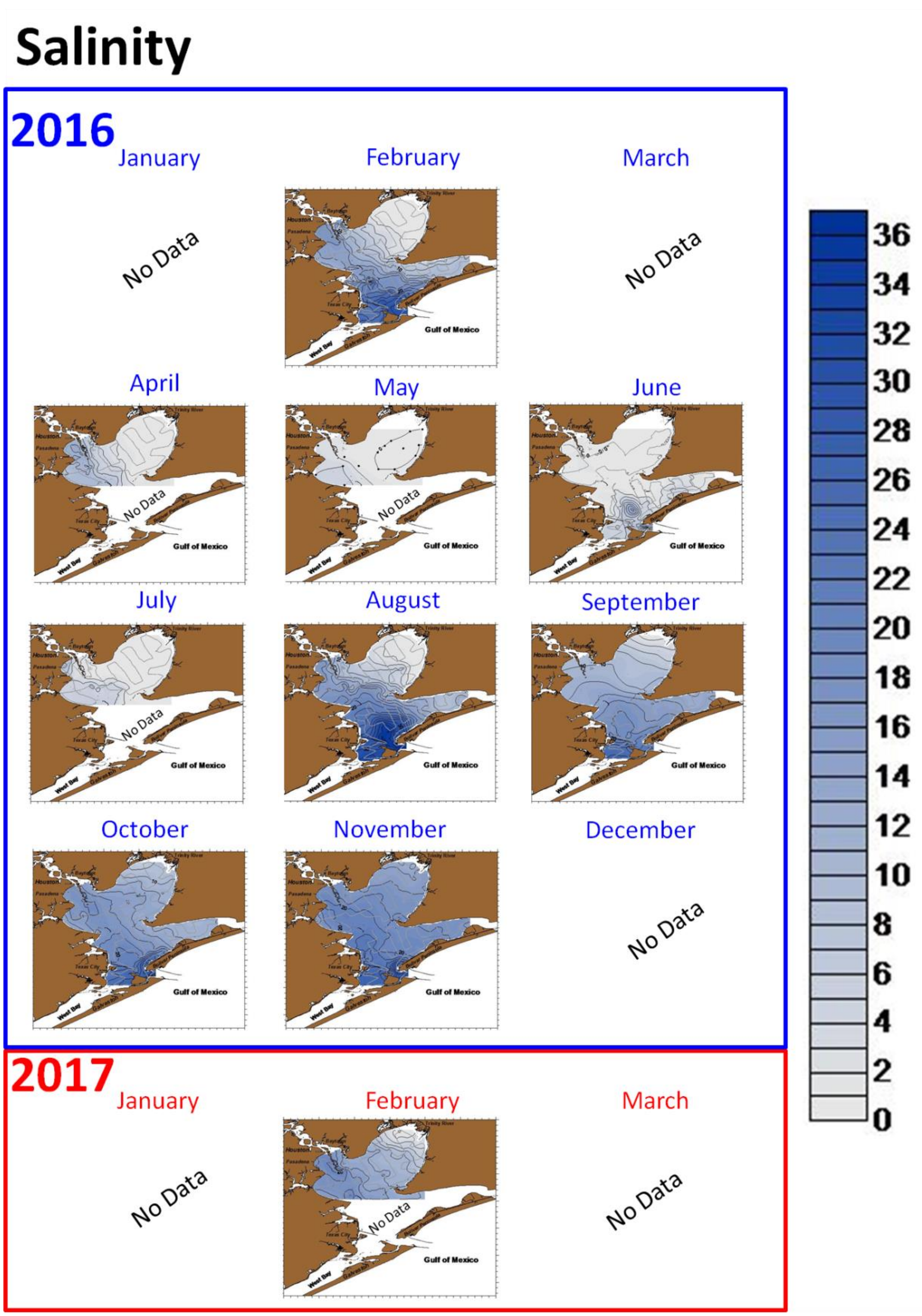


Figure 3. Salinity of surface water in Galveston Bay from January 2016 – March 2017.

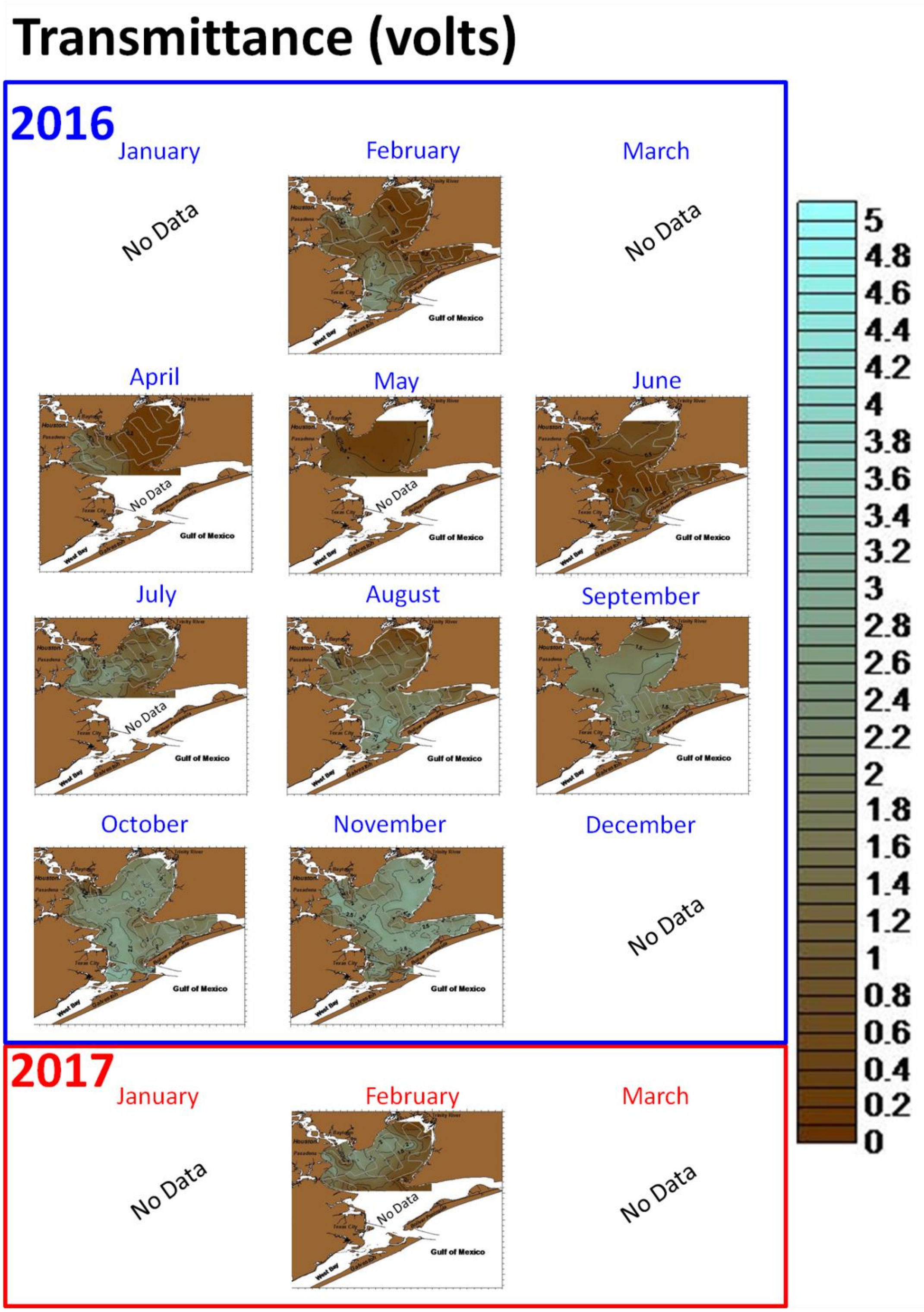


Figure 4. Transmittance (volts) of surface water in Galveston Bay from January 2016 – March 2017.

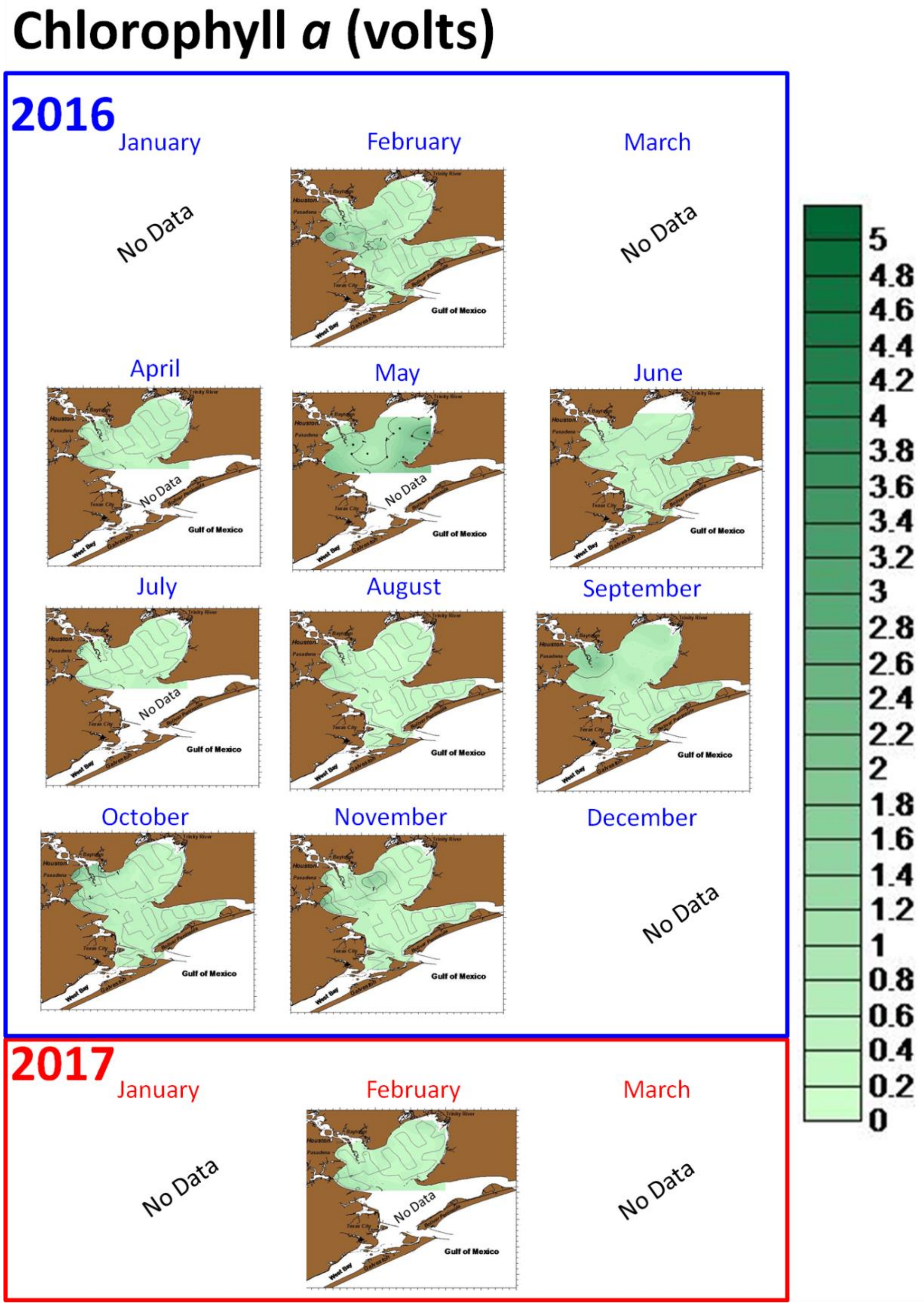


Figure 5. Chlorophyll *a* (volts) of surface water in Galveston Bay from January 2016 – March 2017.

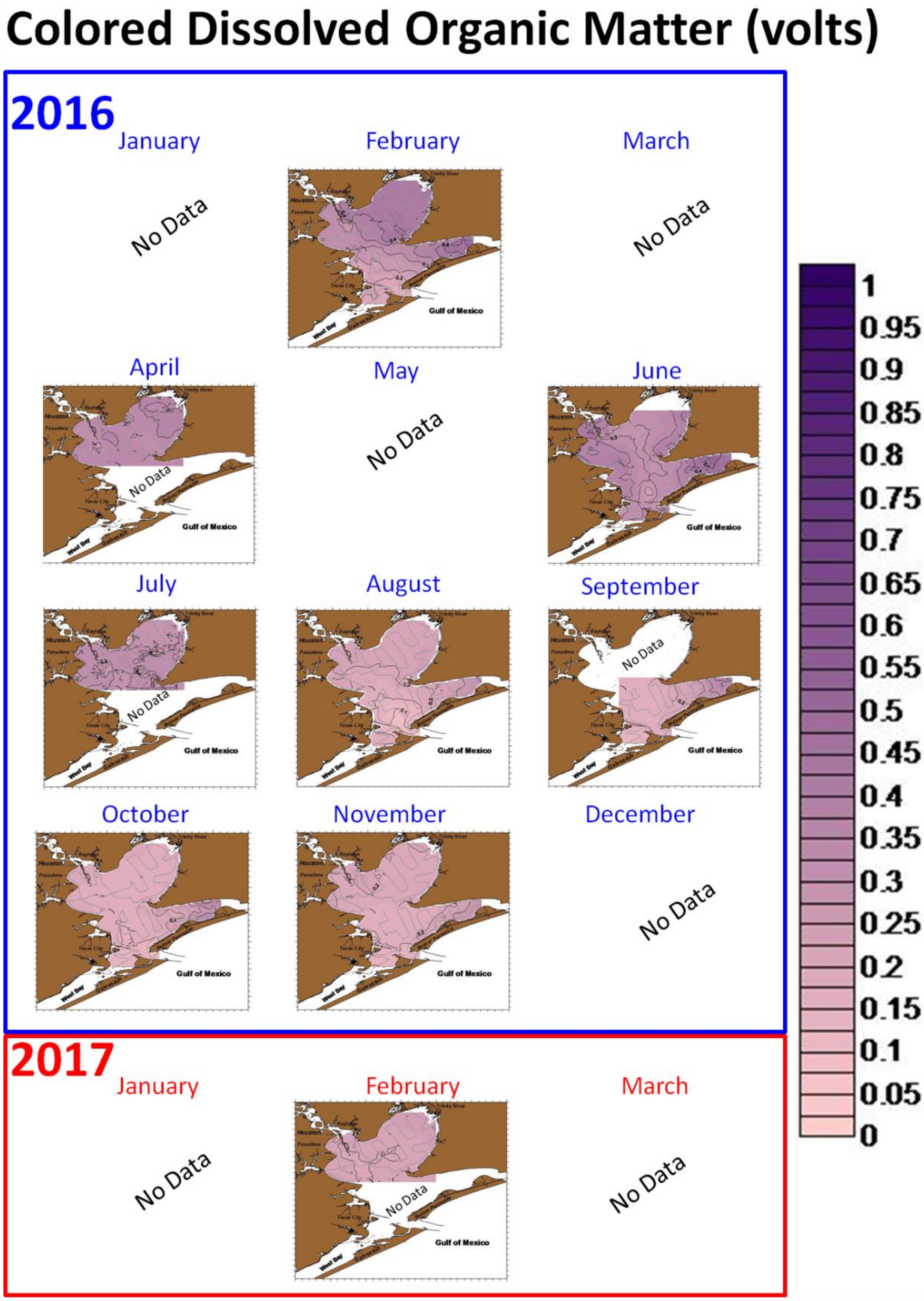


Figure 6. Dissolved organic matter (volts) of surface water in Galveston Bay from January 2016 – March 2017.

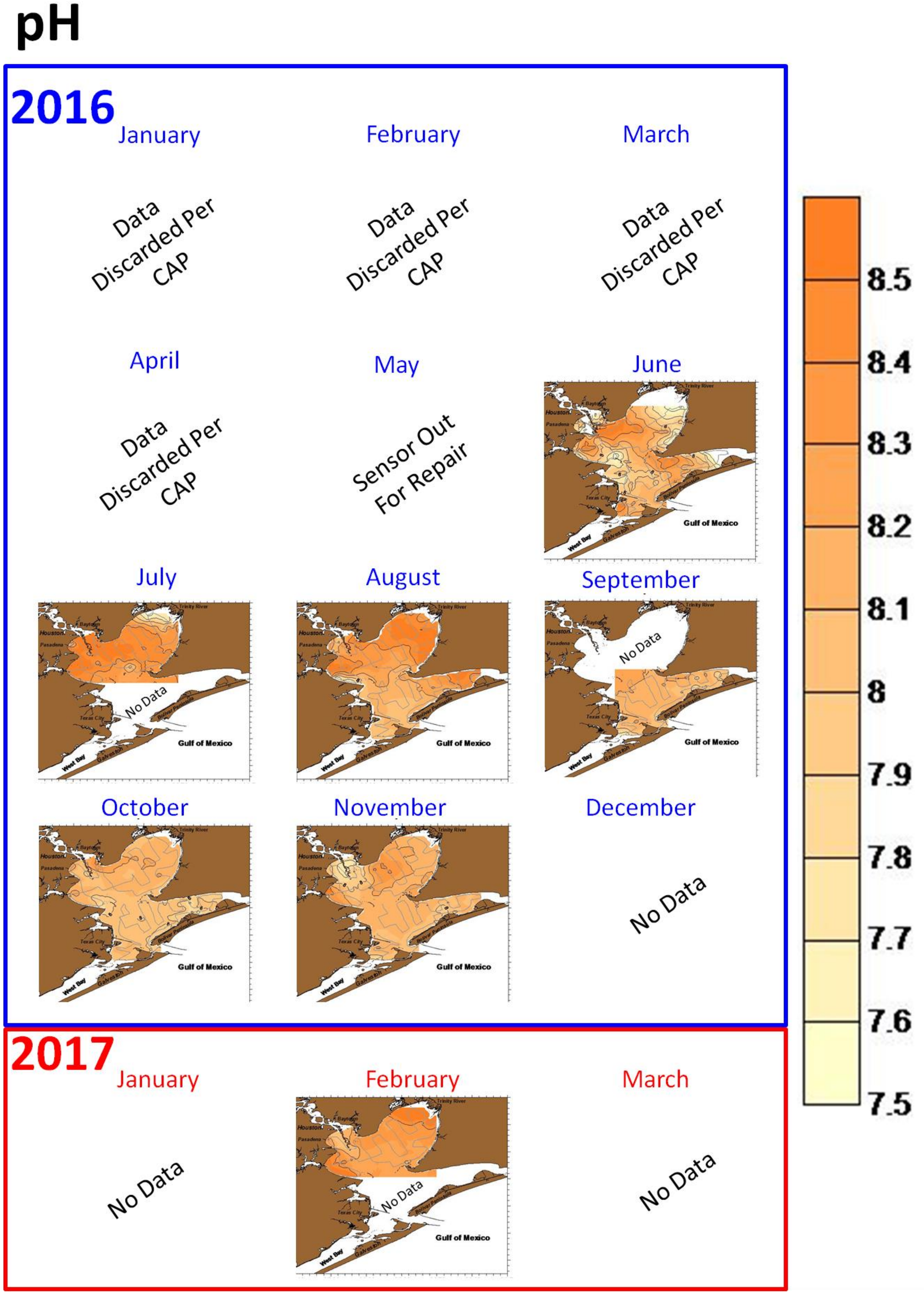


Figure 7. pH (unit less) of surface water in Galveston Bay from January 2016 – March 2017. Note: January – April 2016 data is not shown.

However, following a series of freshwater pulses from both the Trinity and San Jacinto Rivers throughout the spring, surface waters in Galveston Bay were almost uniformly fresh in May, June and July of 2016. The return of salt water intrusion from the Gulf of Mexico was observed beginning in August 2016 and a more classically estuarine salinity gradient was maintained for the remainder of the study period.

Transmittance, a measure of water clarity, was recorded during each monthly sampling campaign. In the Figure 4, dark brown colors represent water obscured by high concentrations of suspended sediments whereas pale blue represents relatively clear water. The increased hydraulic flushing associated with the freshwater pulses observed in the spring of 2016 is well represented with this visual cue in the spatial interpolations above.

The relative concentrations of surface water chlorophyll *a* for each month during the period of study are represented in Figure 5 on a green scale. While chlorophyll *a* concentrations initially appeared to increase in May 2016 near the mouth of the Trinity River, concentrations in subsequent months were much lower and remained fairly low into 2017. This could be indicative of an early positive response of primary producers in the bay to increased freshwater resources accompanying the high volume spring flows which was ultimately unable to sustain itself spatially in the face of continued hydraulic flushing. Further, the freshwater inflows lowered transmittance to much of the bay (Figure 4) acting as a foil to the increased nutrient inputs which may have been introduced.

Colored dissolved organic matter (CDOM) is indicative of the introduction of runoff and river discharge. Higher concentrations of CDOM (dark pink on the pink scale) were observed during months of high flow in 2016 and lower concentrations were seen throughout the remainder of the study period (Figure 6) which was associated with smaller and shorter freshets.

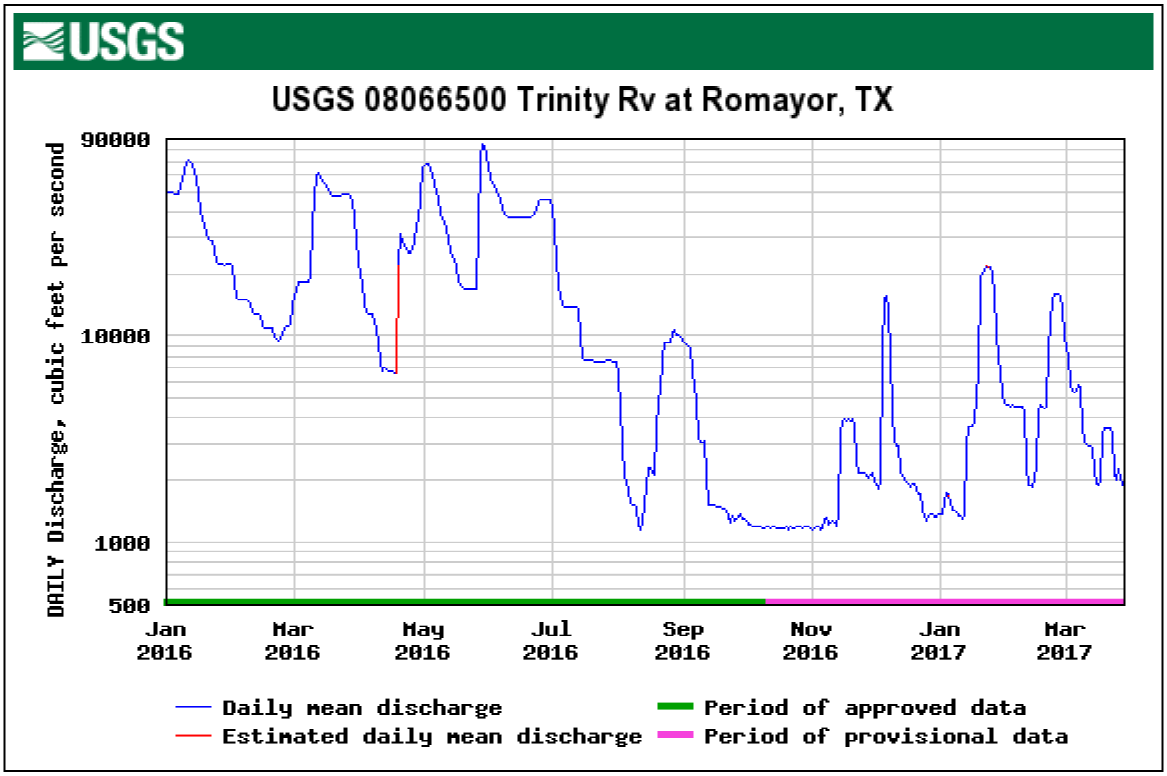
In early 2016, it was determined that the flow-through pH sensor in the deck-mounted Dataflow was not accurately assessing the pH of surface water in Galveston Bay. The unit was sent to the manufacturer for repair in May of 2016 and was delivered back after repairs in June 2016. To account for the lapse in analysis, a corrective action plan (CAP) was submitted to the TCEQ.

Since the repair, values for pH of surface water in Galveston Bay assessed via Dataflow remained fairly uniform throughout the study period as shown in Figure 7.

Objective 2: **Monitor freshwater inflows.**

Major riverine flows to Galveston Bay are the Trinity River (55%) and the San Jacinto River (16%) according to a recent study by Guthrie et al. (2012). Below we show river flows during 2016 and early 2017. Flows along the Trinity River (Figure 8) were very high throughout winter and spring of 2016, including most of the summer. This includes four freshets which were greater than 50,000 cfs. Further, these high flows did not drop below 10,000 cfs until the end of summer. Flows in the fall of 2016 through early spring were marked by 3 freshets greater than 10,000 cfs. The high freshwater inflows had correspondingly relatively high river flows, with gage heights frequently above 20 feet. For the San Jacinto River, flows from the east and west forks are used to provide a snapshot of patterns (Figures 9 and 10 respectively). While the general trends were similar, the magnitude of the flows was significantly lower at both these gages compared to that on the Trinity River. Seven freshets were observed in the first six months of 2016 with corresponding river flows exceeding five feet. Collectively these rivers are the most important sources of freshwater inflows into Galveston Bay.

Examining freshwater inflows, we found that 2016 was a relatively high flow or 'wet' year compared to many since 1990 (Figure 11). By comparison, flows in 2011 certainly reflect the well documented recent drought of that year. Previous drought or 'dry' years include 1996, 2000, 2006, 2013 and 2014. Previous wet years include 1992, 1995 and perhaps even 2015. These designations of wet versus dry are relative terms which are used to describe the significant inter-annual oscillations.



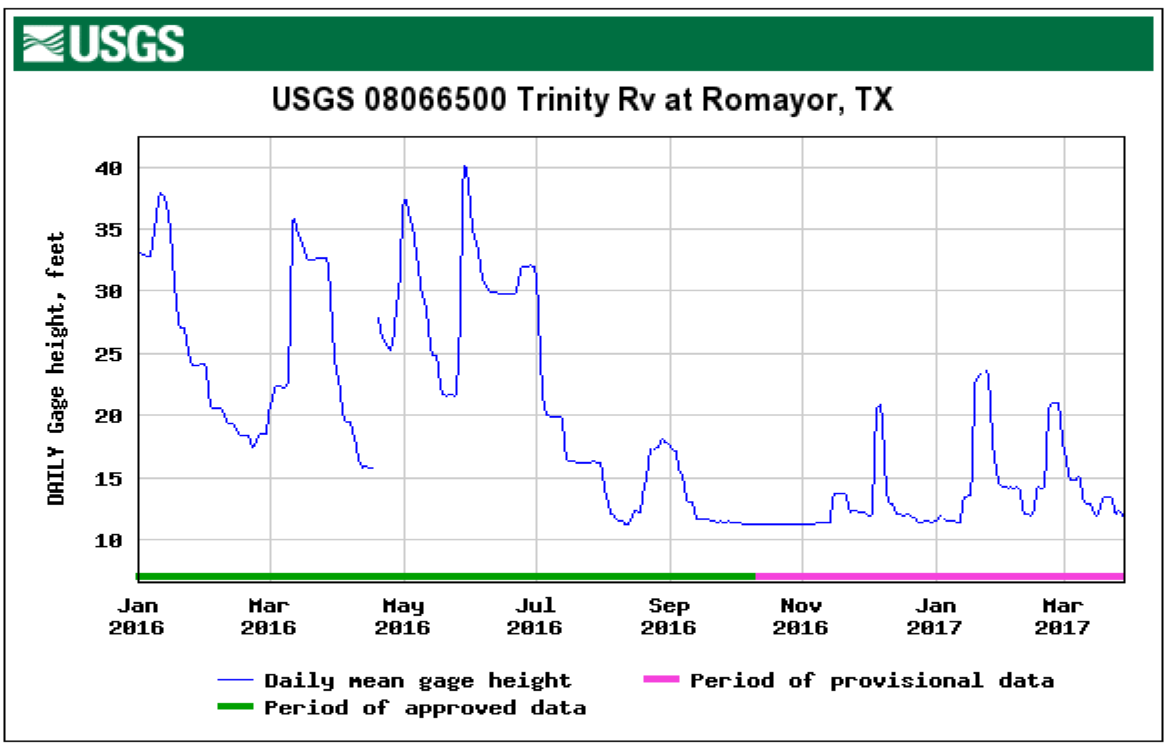
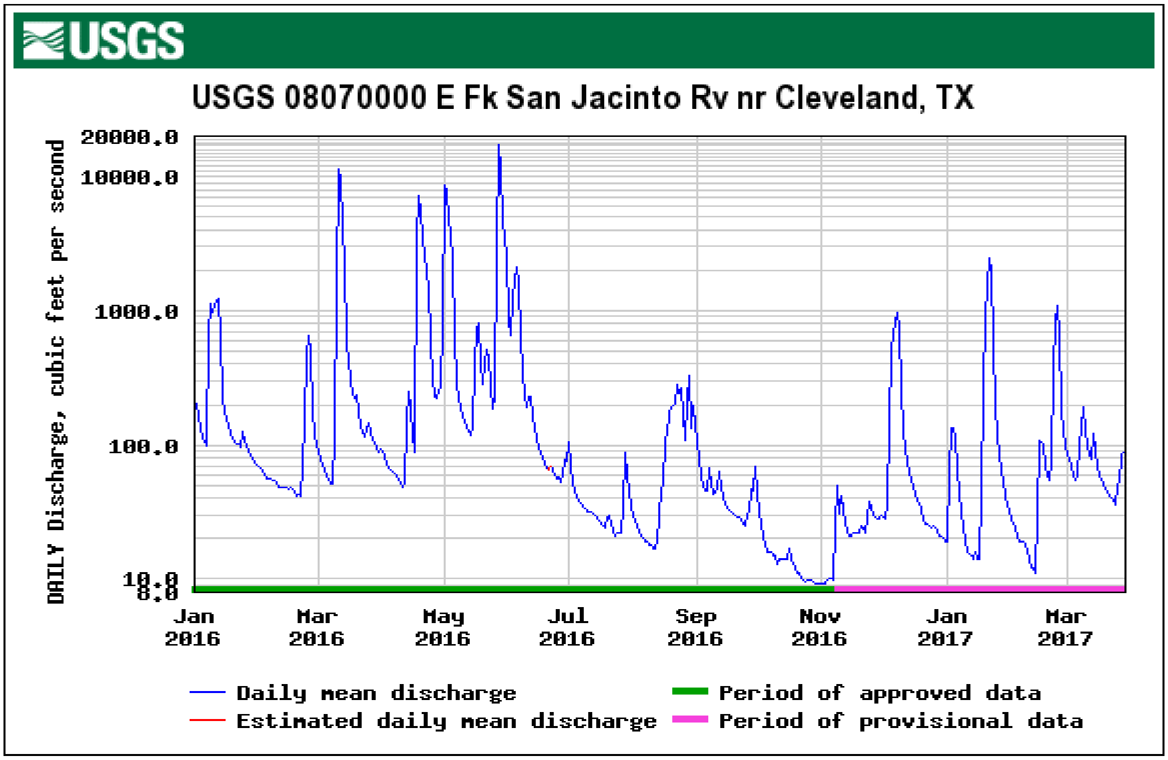


Figure 8. Real-time flow data (above) and gage height (below) from the USGS monitoring station on the **Trinity River (at Romayor 08066500)** are shown from January 2016 to March 2017. (https://waterdata.usgs.gov/nwis/)



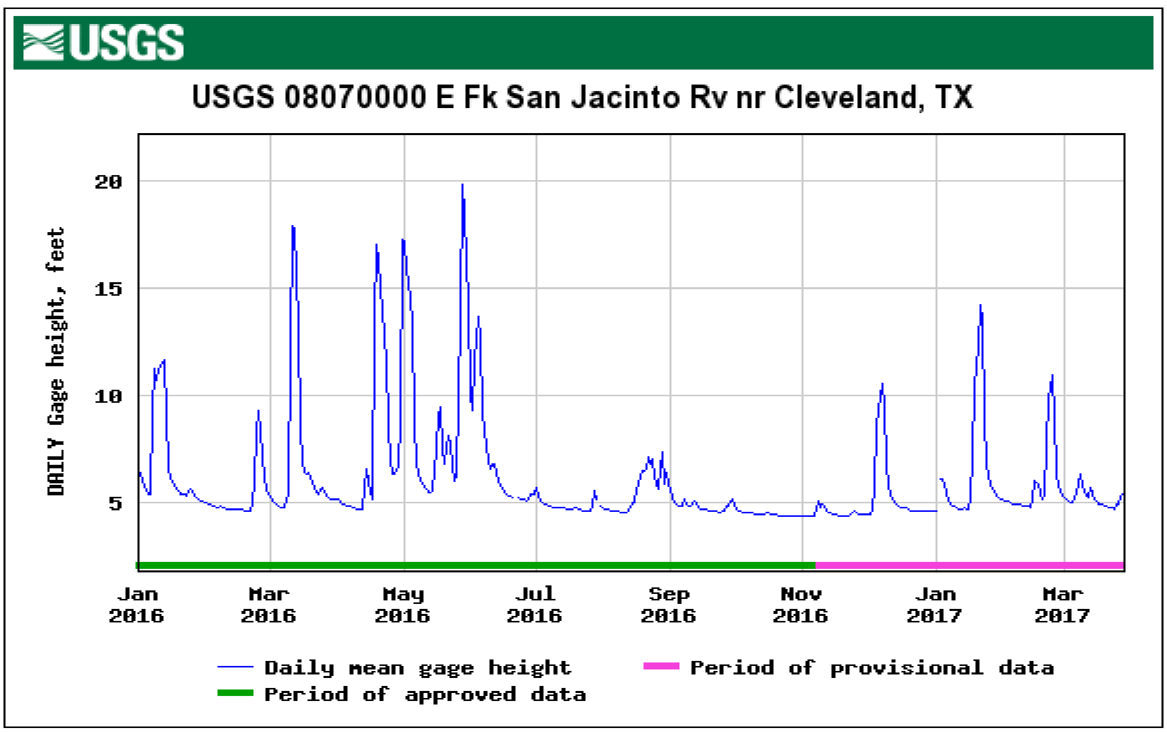
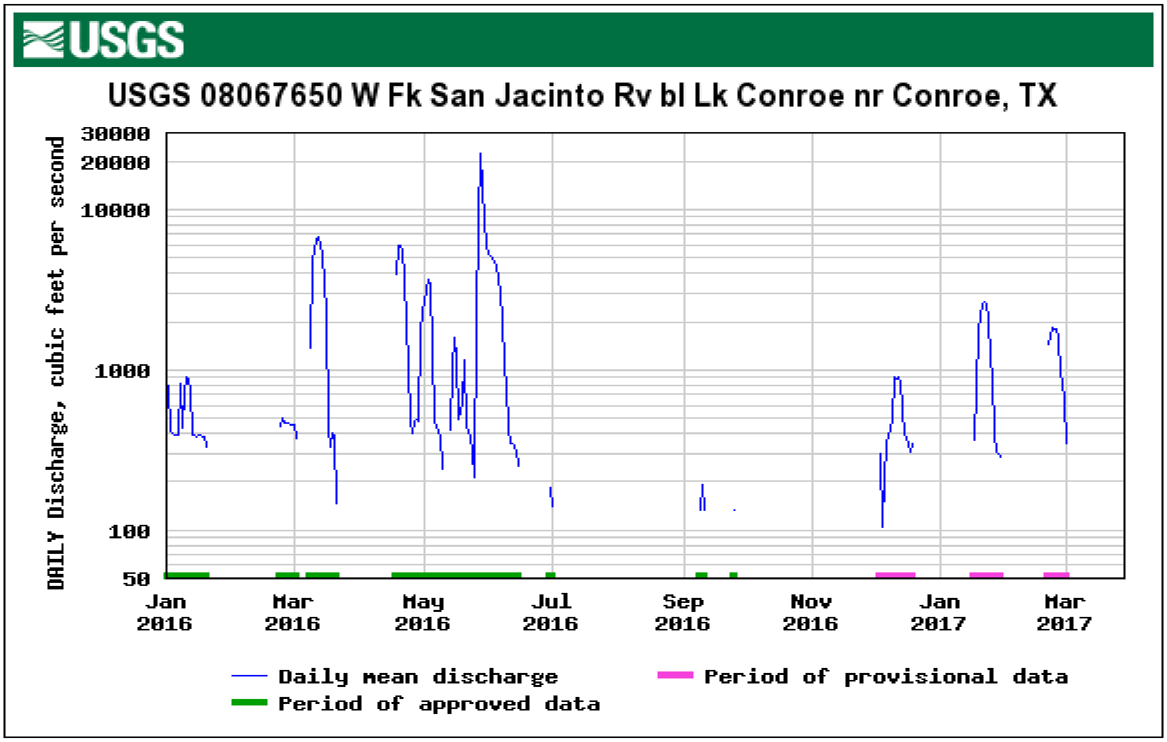


Figure 9. Real-time flow data (above) and gage height (below) from the USGS monitoring station on the **San Jacinto River (at the East Fork 08070000)** are shown from January 2016 to March 2017. (https://waterdata.usgs.gov/nwis/)



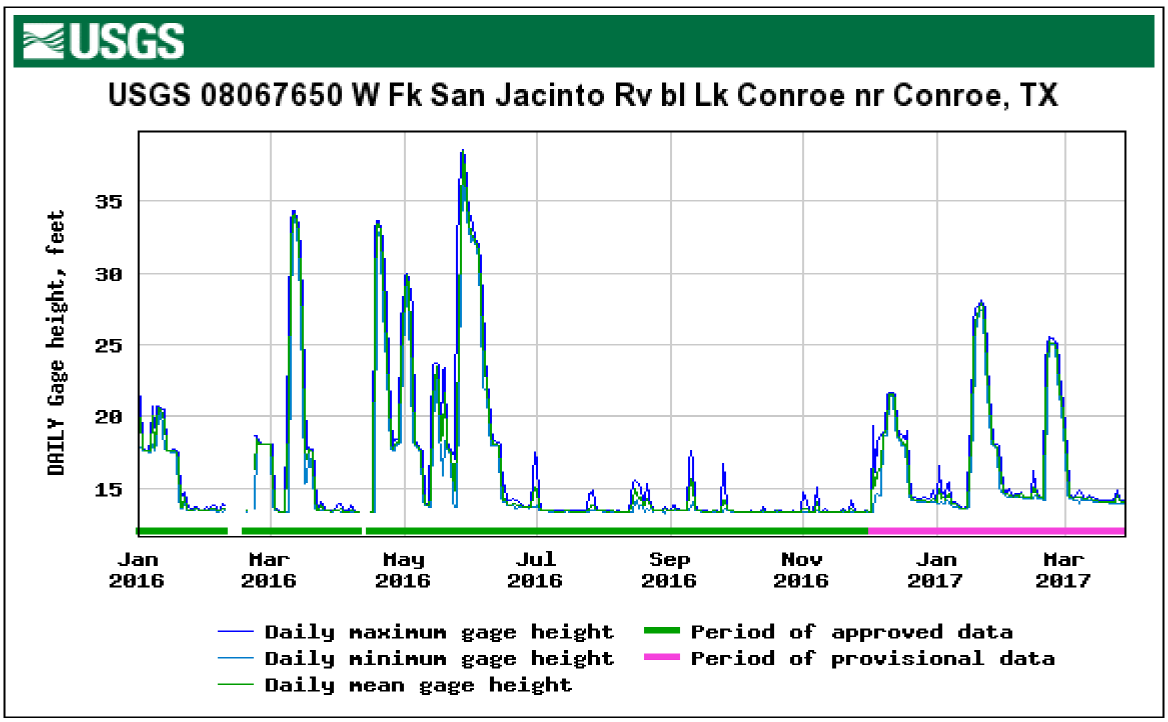


Figure 10. Real-time flow data (above) and gage height (below) from the USGS monitoring station on the **San Jacinto River (at the West Fork 08067650)** are shown from January 2016 to March 2017. (https://waterdata.usgs.gov/nwis/)

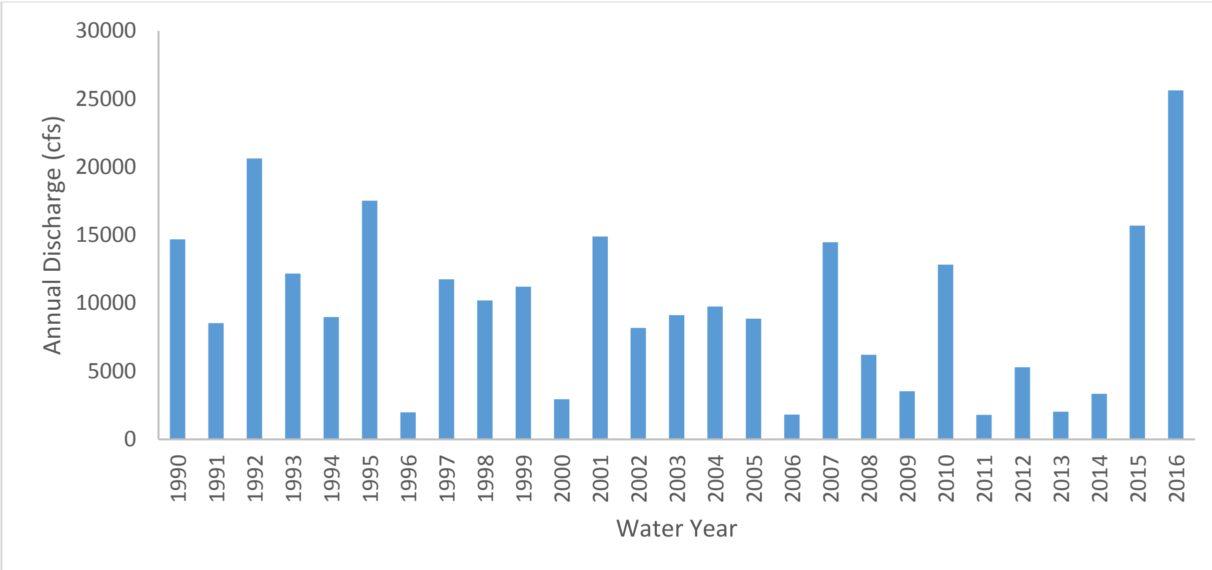


Figure 11. Average annual Trinity River discharge (cfs) from 1990 to presently available records.

***Objective 3:* Fixed station water quality.**

These data will be crucial in understanding seasonal variability in nitrogen and phosphorus loading that will directly impact water column production and respiration and plankton community dynamics throughout the estuary. In Figure 12, mean monthly dissolved inorganic nitrogen (DIN) calculated as the sum of NO_3^- + NO_2^- + NH_4^+ concentrations for Galveston Bay from January to August 2016 are presented. Concentrations ranged from 5.03 (±6.41) to 30.74 (±6.40) µmol/L. Peak DIN was observed in April 2016 and trailed to the lowest observed value in July 2016. DIN data for the fall and winter of 2016 have been collected and processed; however, the results did not meet the specifications of our quality assurance standards and so are not included in the report.

Mean monthly phosphorous concentrations in Galveston Bay from January to August 2016 represented here as HPO_4^- are shown in Figure 13. Throughout the study period, phosphorous concentrations did not vary greatly. The range of phosphorous means was lowest in February at 1.04 (±0.81) µmol/L and highest in May at 1.87 (±1.33) µmol/L. Dissolved phosphorous data for the fall and winter of 2016 have been collected and processed; however, the results did not meet the specifications of our quality assurance standards and so are not included in the report.

Figure 14 plots mean monthly silicate (as $HSiO_3^-$) concentrations in Galveston Bay throughout the study period. Concentrations of this nutrient peaked in May 2016 with a maximum of 104.57 (±6.92) µmol/L following the high-volume freshwater pulses observed in the spring. The lowest observed concentration of 53.58 (±8.42) µmol/L occurred in February 2017 after the high flows that occurred in the previous months.

In Figures 15 and 16, data for mean monthly total nitrogen and phosphorous concentrations are represented respectively. Total nitrogen was lowest in August at 41.86 (±17.09) µmol/L and highest in April at 85.69 (±13.81) µmol/L. For total phosphorous, the low occurred in February at 2.99 (±1.25) µmol/L and peaked in May at 6.12 (±1.35) µmol/L. (These analyses are conducted separately from dissolved nutrient analyses. These results were within the acceptable QA range for the Galveston Bay system.)

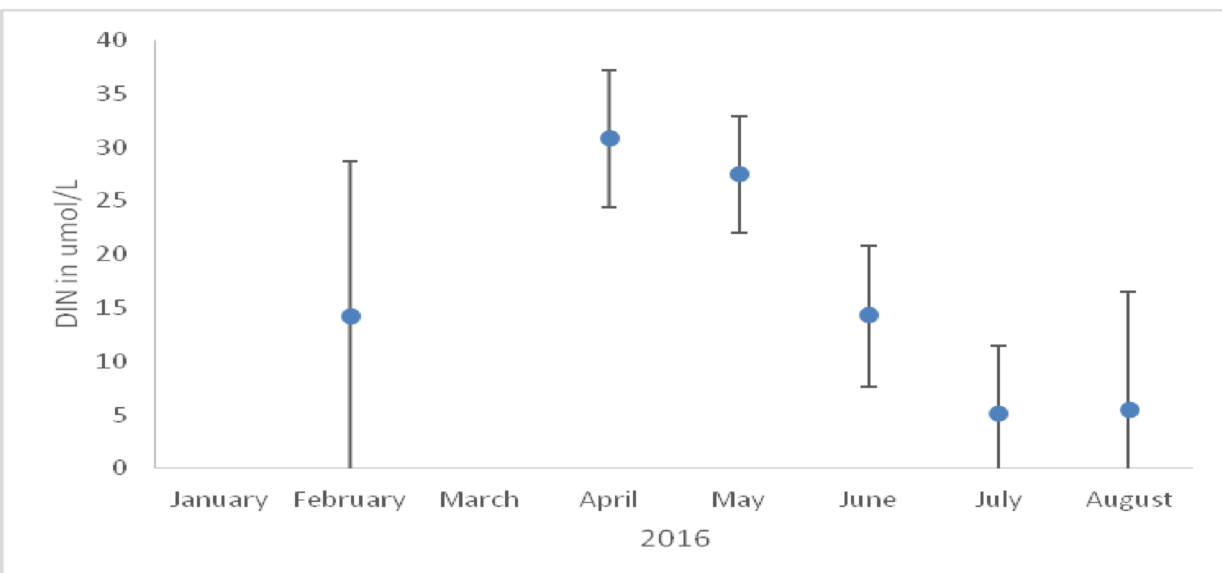


Figure 12. Mean dissolved inorganic nitrogen (NO_3^- + NO_2^- + NH_4^+) concentrations in Galveston Bay, January 2016 – August 2016.

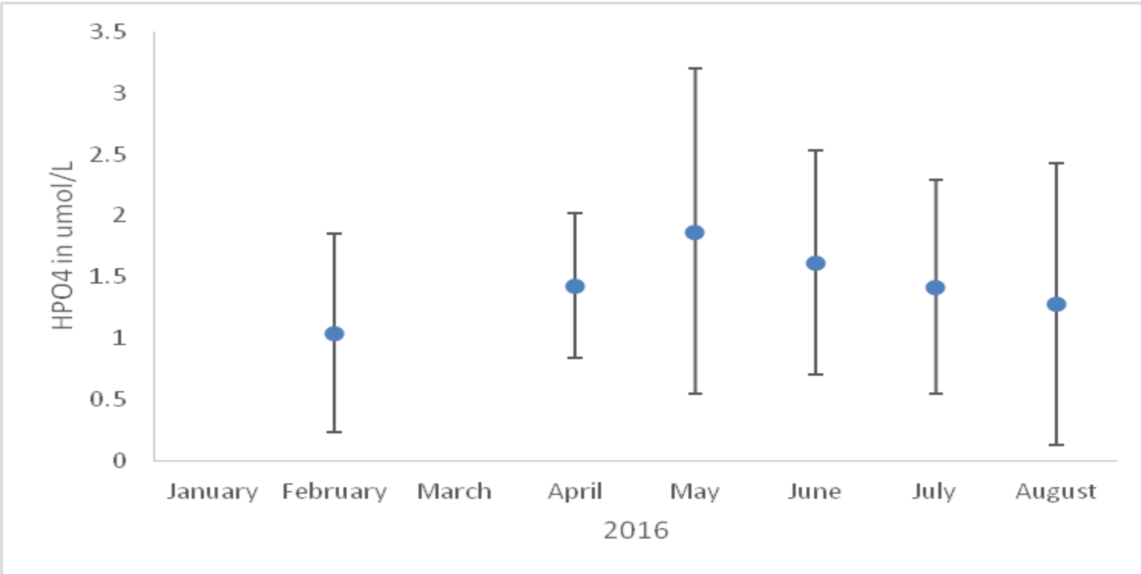


Figure 13. Mean phosphorous (as HPO_4^-) concentrations in Galveston Bay, January 2016 – August 2016.

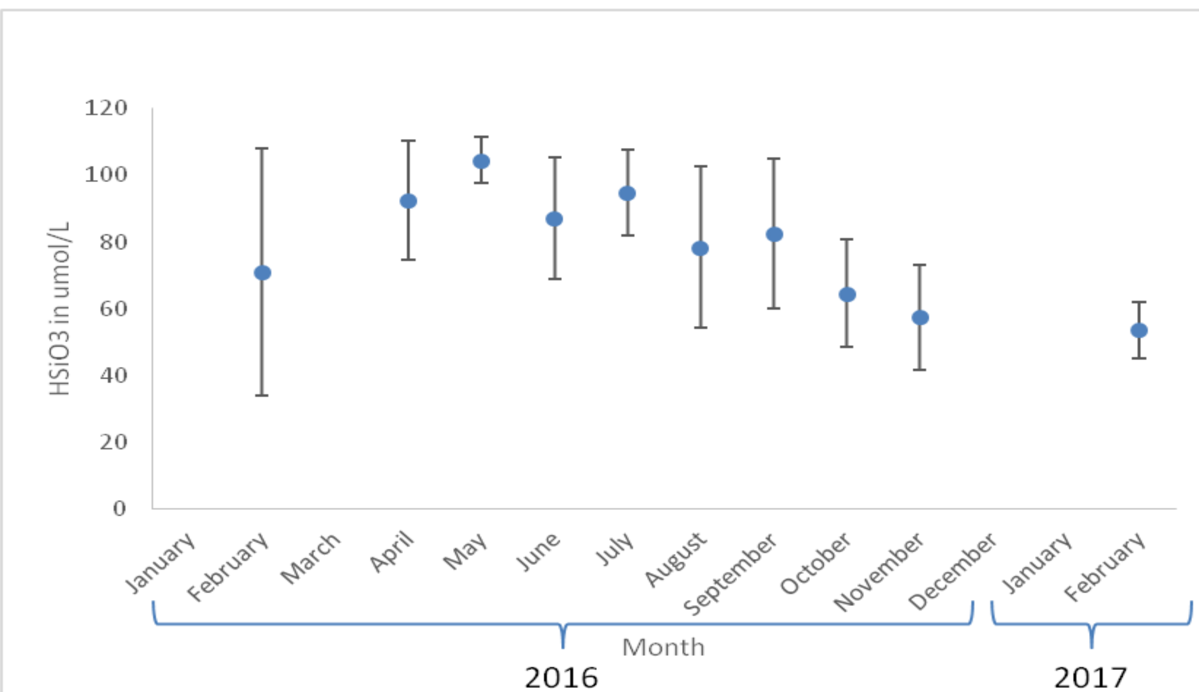


Figure 14. Mean silicate (as $HSiO_3^-$) concentrations in Galveston Bay, January 2016 – February 2017.

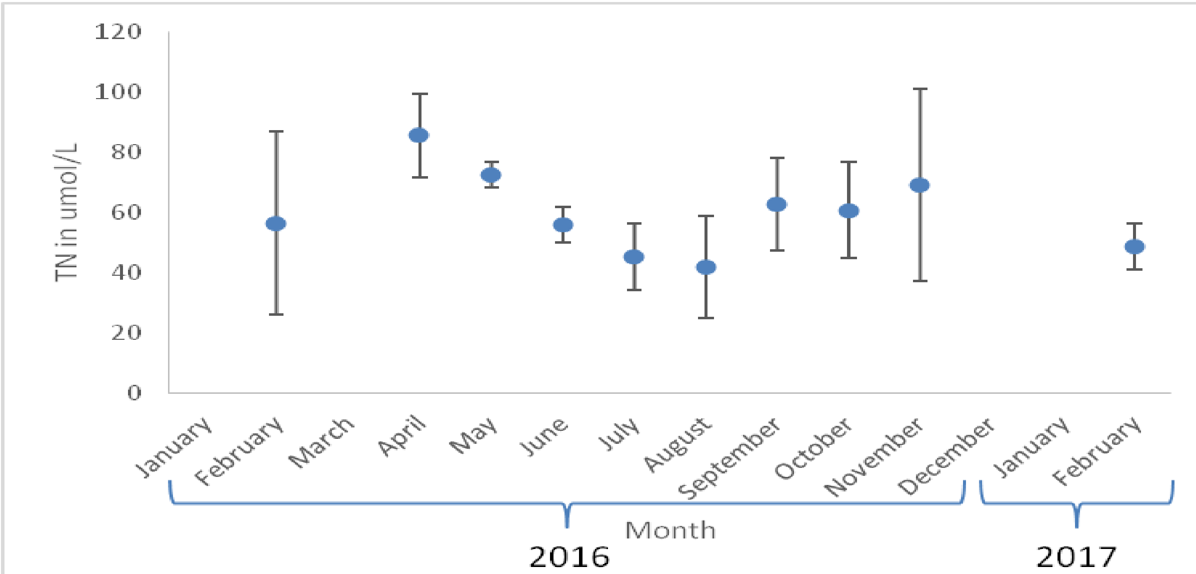


Figure 15. Mean total nitrogen concentrations in Galveston Bay, January 2016 – August 2016.

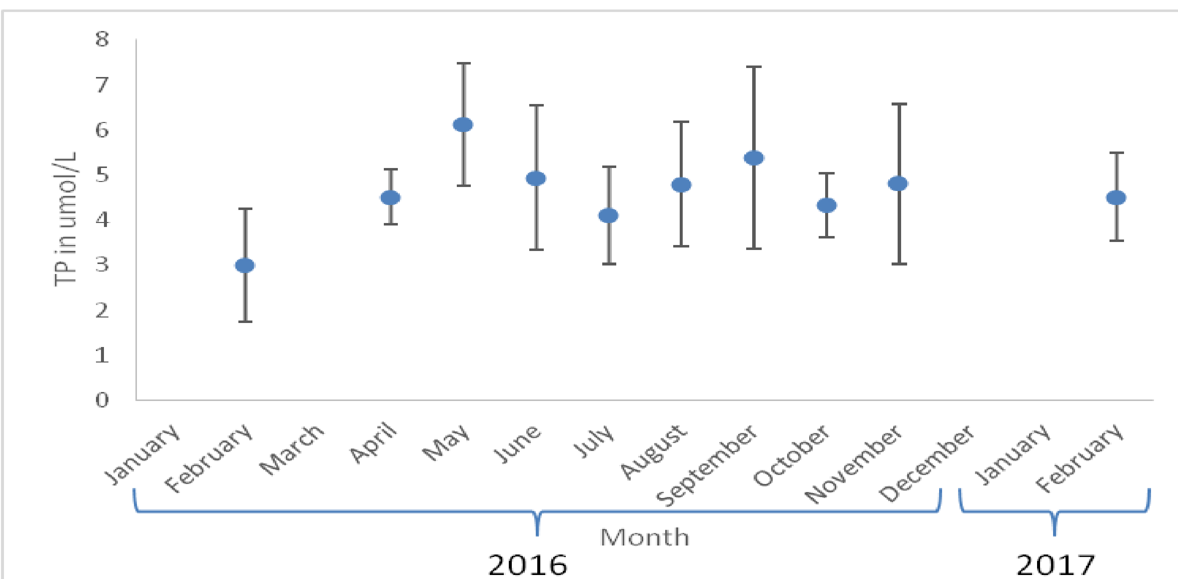


Figure 16. Mean total phosphorous concentrations in Galveston Bay, January 2016 – August 2016.

Mean monthly chlorophyll *a* concentrations in Galveston Bay throughout the study period are presented in Figure 17. As with the interpolation maps of surface water chlorophyll concentrations collected with Dataflow sensor referenced earlier in the document, a peak of chlorophyll was observed from April to June 2016 (~16 µg/L). Concentrations decreased over time during 2016, until reaching the observed low of 7.27 (±4.70) µg/L in November. Phaeophytin concentrations (not shown) remained low or negligible during the study.

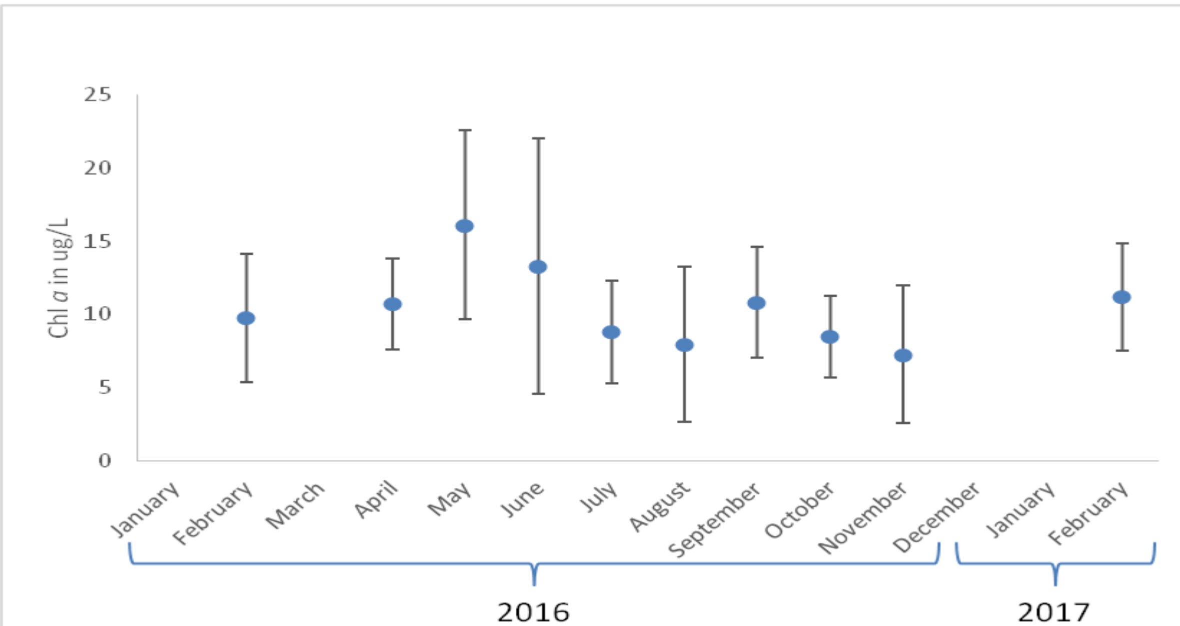


Figure 17. Mean chlorophyll *a* concentrations in Galveston Bay, January 2016 – March 2017.

Objective 4: **Measure phytoplankton productivity, community composition, and the presence of harmful algal blooms (HABs), if present**

Gross primary productivity (Figure 18) is a measure of the performance of the primary producer community in the water column. A community with higher gross productivity is able to perform photosynthesis at a higher rate than those with lower gross productivity values. For our period of study, a range of gross productivity values of 0.17 (±0.11) to 0.94 (±0.66) grams of carbon/square meter/day were observed in February 2016 and February 2017. Gross productivity was high again in May 2016 (0.94 ± 0.18 g-C/m^2/d), potentially as a result of increased availability of resources following freshwater pulse events throughout the spring.

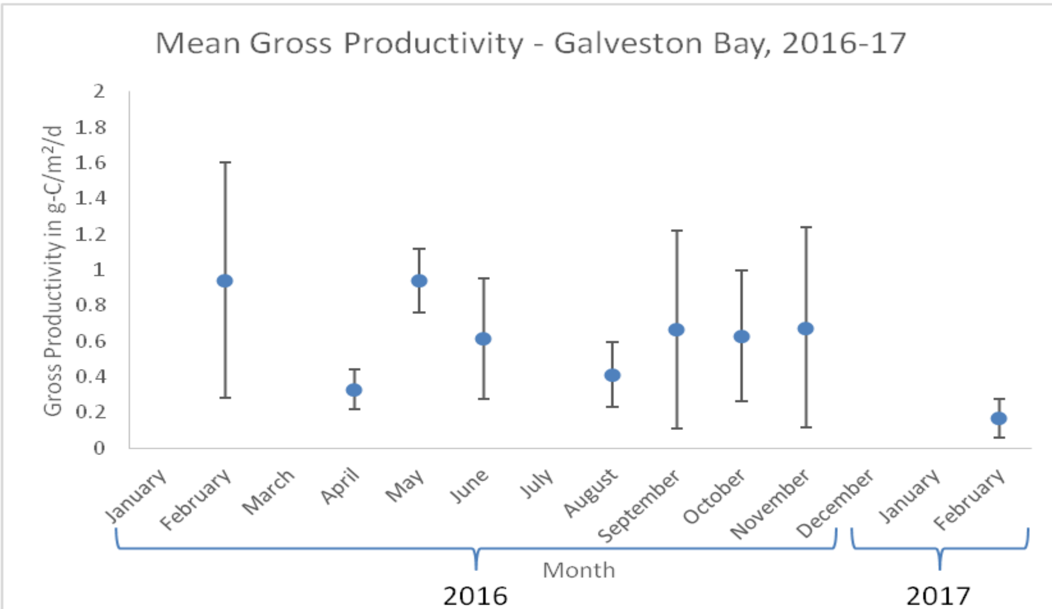


Figure 18. Mean monthly gross productivity in Galveston Bay from January 2016 – March 2017.

The diversity and phylogenetic association of specific photosynthetic accessory pigments (chlorophylls and carotenoids) with different algal groups provides diagnostic biomarker compounds for differentiating the relative abundance of microalgal groups in mixed species assemblages. Protocols for extracting, separating, and identifying photopigments have evolved and improved over the last three decades. The most definitive (and complete) treatment of this topic can be found in the monograph by Jeffrey et al. (1997). Microalgal photopigments provide reliable measures of the relative abundance of characteristic algal groups (Millie et al., 1993, Jeffrey et al., 1997). This approach has been independently validated by comparing photopigment quantifications with actual microscopic species enumerations using communities from diverse marine and freshwater habitats. More than 25 independent studies have concluded that photopigment composition is significantly (linearly) correlated with species cell counts (Jeffrey et al., 1997).

Mackey et al. (1996) have developed a factor analysis algorithm (CHEMTAX) for calculating algal class abundances (both in terms of relative and absolute numbers) based on biomarker photopigments. CHEMTAX is a useful and accurate statistical method for converting pigment concentrations into estimates of cell numbers (Wright et al., 1996). Photopigment analysis is an extremely useful tool for assessing both overall microalgal community responses as well as the responses of algal groups within the community. The low cost and short analysis time permit statistically robust experimental designs with suitable replication within and among experimental treatments. In addition, this approach is well suited for monitoring programs designed to assess long-term trends and inter-annual variability in microalgal community composition and biomass.

The results of our HPLC analysis of the relative abundance of algal photopigments in surface water collected at six fixed stations during each of our monthly sampling campaigns are presented in Figure 19. We characterized the major taxonomic groups typical of the Galveston Bay estuary based on the pigments most commonly found in each group (Jeffrey et al., 1997). At the beginning of the study period (February 2016), the pigment composition of the algal community was largely comprised of indicators typical of diatoms and dinoflagellates. After the influx of regular, prolonged freshwater pulse events in the spring, (April-June 2016) more pigments typical of cyanobacteria (blue-green algae) and chlorophytes (green algae)—taxa which are frequently associated with freshwater environments—were observed. In the summer months (July – September 2016), a large proportion of cyonobacteria pigments persisted despite decreasing flows. This trend can be explained by a potential weighting of the means to be more indicative of freshwater communities due to the majority of our six fixed sites' proximity to freshwater influence (two near the river mouths and two in mid-bay). Further, cyanobacteria are known to thrive in warm water conditions. By early autumn (October 2016), the relative pigment abundance returned to pattern typical of a diatom-dinoflagellate dominated community similar to the ratios seen before the spring freshets occurred. Pigment data for the fall and winter of 2016 have been collected and processed; however, the results did not meet the specifications of our quality assurance standards and so are not included in the report.

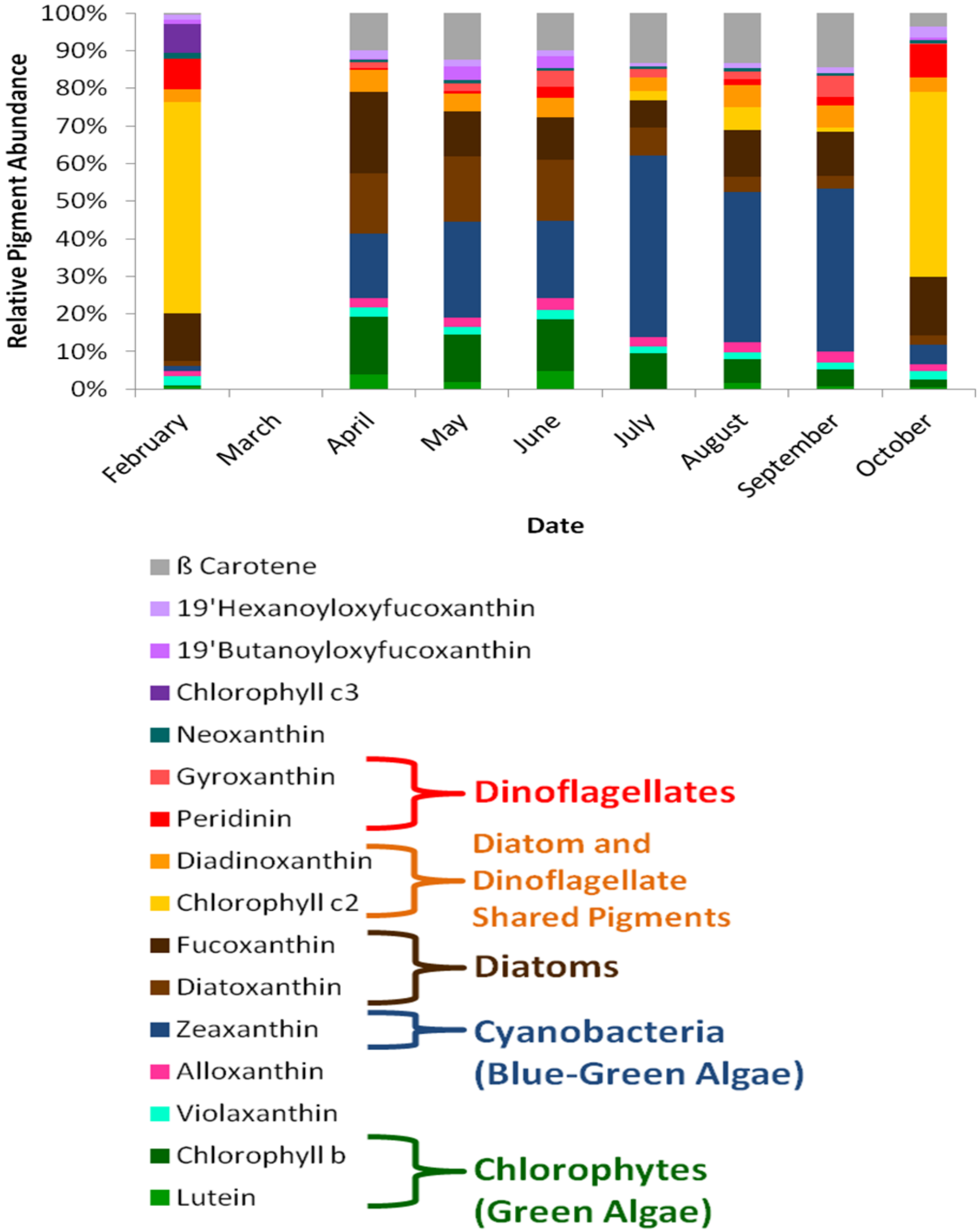


Figure 19. Mean monthly relative pigment abundance of algal groups in Galveston Bay, February - October 2016.

Imaging FlowCytobot

The Imaging FlowCytobot is a great tool for identifying phytoplankton species in near real time and for following the development of blooms at the entrance to Galveston Bay. While not all blooms are associated with harmful species, that is, those which produce toxins and/or lead to fish kills, and other losses to fauna, they are all important for providing information about the ecosystems responses to natural cycles and to perturbations. The two groups which dominate phytoplankton communities numerically are diatoms and dinoflagellates. Representative species are shown in Figure 20.

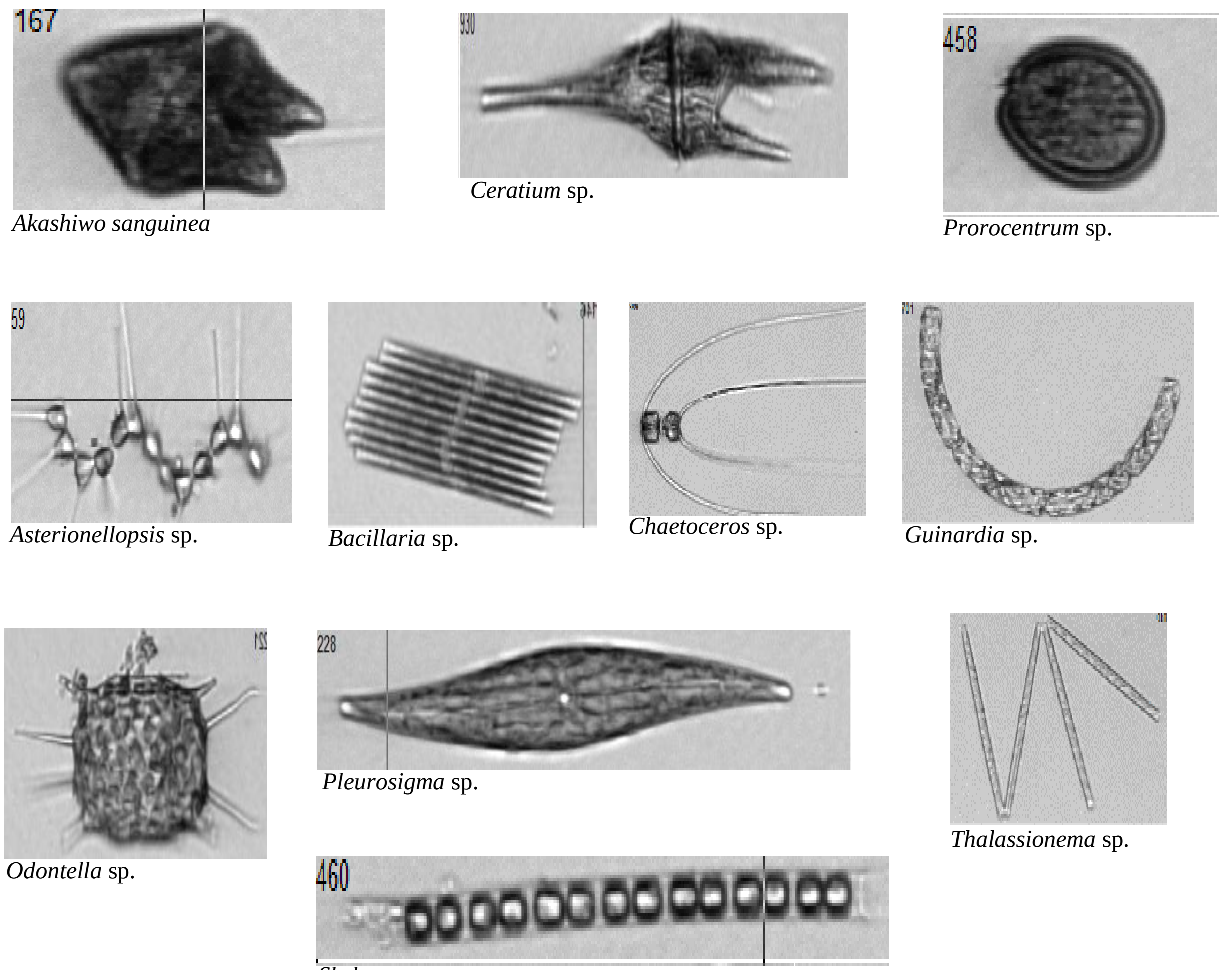


Figure 20. Representative dinoflagellates (top row) and diatoms (remaining) present in Galveston Bay.

Tracking HAB species

A look at the Imaging FlowCytobot from 2016 records for January 2016 to March 2017 reveals the following which can be found on the dashboard (http://dq-cytobot-pc.tamug.edu/TAMUG/dashboard/http://dq-cytobot-pc.tamug.edu/TAMUG/D20170401T153020_IFCB103)) and is included here in Fig. 21:

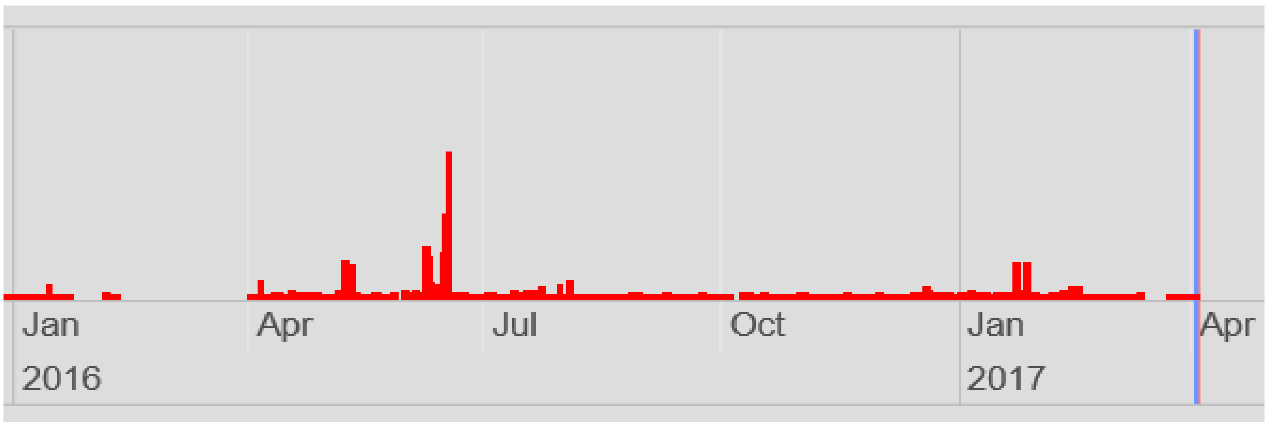


Figure 21. Representative view of dashboard output.

Texas Parks and Wildlife Department (TPWD) responds to an incident where fish or other animals have been harmed. They work with Texas Department of State Health Services if human health issues are suspected, the TCEQ for impacts to natural resources, and the governing authority that manages a particular area. The TPWD monitors harmful algal blooms as they progress; and as appropriate, works with us and other groups to determine the phytoplankton species responsible. The three species which are the top priorities in Texas are:

(i) Golden alga (*Prymnesium parvum*) occurs worldwide, primarily in coastal waters, but also in rivers and lakes. It can produce toxins that cause fish kills, harm freshwater mussels and clams, and the gill-breathing juvenile stage of frogs and other amphibians. There is no evidence that golden alga toxins pose a direct threat to humans, other mammals, or birds. (http://tpwd.texas.gov/). To the best of our knowledge, this species has not been reported in Galveston Bay, although it does occur in Texas water bodies, particularly lakes in northern Texas.

(ii) Red tide (*Karenia brevis*; synonyms: *Gymnodinium breve, Gymnodinium brevis*, and *Ptychodiscus brevis*) is a dinoflagellate found in the marine environment, frequently near Port Aransas, but less so near Galveston Bay (http://tpwd.texas.gov/) due to circulation patterns in the Gulf of Mexico. This species is toxin producing; brevetoxin can accumulate within zooplankton, fish, bivalves and crustaceans leading to die off of fish, invertebrates, sea turtles, birds and marine mammals. This toxin also causes respiratory irritation in humans. This species is observed from time to time in Galveston Bay but infrequently at concentrations which would cause fish kills or other harmful effects.

(iii) Texas brown tides (*Aureoumbra lagunensis*) at elevated cell densities discolors the water brown (http://tpwd.texas.gov/). Unique to the Gulf of Mexico, this species was first observed in the Laguna Madre and has also been reported in Florida and Mexico. This species has not been observed in Galveston Bay.

None of the harmful algal species referenced above were identified by the Imaging FlowCytobot through the course of the study period.

Other species, such as *Akashiwo sanguinea* (Synonyms: *Gymnodinium nelsonii*, *Gymnodinium splendens* and *Gymnodinium sanguineum*), a dinoflagellate (see above), have been suspected to have caused fish kills and marine mammal strandings in the Gulf of Mexico in the mid 1990's (Robichaux et. al., 1998, Steidinger et. al., 1998) and has been reported in the Galveston Bay. Along the west coast of the US it has been associated with bird mortalities (Jessup et al. 2009). It has the potential to smother fish by producing mucous from thecal pores on the surface of the cell rather than producing toxin (Voltolina, 1993, Robichaux et. al., 1998, Badylak et. al., 2014). *Akashiwo sanguinea* is well known for forming blooms that result in red tides which discolor the water. We observed relative high numbers of this dinoflagellate in January 2016 but we did not observe changes in the water color (Figure 22).

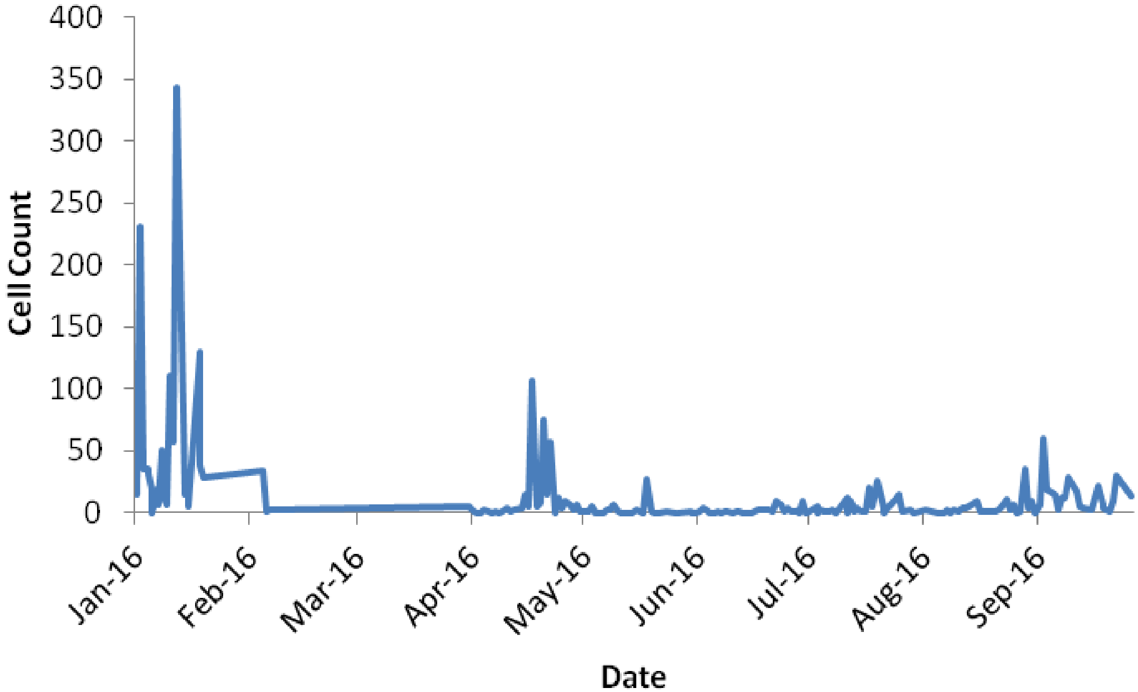


Figure 22. Cell count values of *Akashiwo sanguinea* collected via Imaging FlowCytobot, January -September 2016.

***Objective 5:* Build a quantitative understanding of the current and historical nutrient inputs from domestic and industrial wastewater sources from the large number of discharges in the bay.**

We used data from the TCEQ Surface Water Quality Monitoring (SWQM) database to determine nutrient inputs into the bay since 1990 to gain an historical perspective. Specifically, we worked to determine if there have been changes in ammonia and nitrate inputs into the bay. Overall, there was no change in the concentration of NO_3^- +NO_2^- (µM) observed in Trinity Bay or Upper Galveston Bay (adjacent to San Jacinto River) (Figures 23 and 24). The overall mean measured from 1990-2014 for NO_3^- +NO_2^- concentration in Trinity and Upper Galveston Bays was 1.60 and 1.53 µM respectively, with minimum to maximum values of 0.05 to 5.98 µM and 0.19 to 4.47 µM respectively. The mean for ammonia concentration in Trinity and Upper Galveston Bays was 3.22 and 4.48 µM respectively, with minimum to maximums values of 0.30 to 10.88

μM and 1.27 to 12.64 μM respectively. The ammonia concentration in Trinity Bay also did not appear to change during the study period in Trinity Bay or Upper Galveston Bay (Figures 25 and 26).

Since nutrient loading into the bay, in large part, is dependent on riverine flows, surface inflow volumes calculated by the TWDB were examined relative to nutrient (seasonally averaged) concentrations (Figures 27 and 28). These inflow volumes (also seasonally averaged) were calculated by summing gaged inflows (USGS), ungaged inflows (modeled by TWDB), and return flows while subtracting the diversions (Guthrie et al., 2012). The ungaged inflows were estimated using the Texas Rainfall-Runoff (TxRR) model (Matsumoto, 1992). TWDB surface inflow data includes runoff, precipitation etc. summed for each month. In essence these provide a snap shot of inputs from all nutrient sources, including domestic and wastewater to the bay. There was no direct correlation between nutrient loading to the bay versus riverine flows when examined using this procedure.

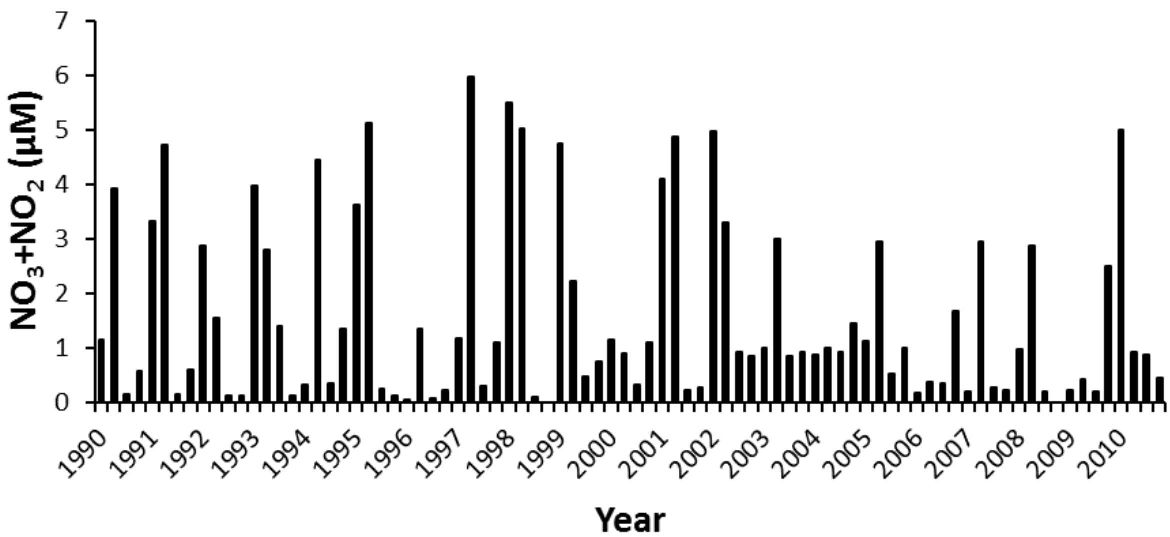


Figure 23. Concentration of $NO_3^- + NO_2^-$ (μM) in Trinity Bay from 1990-2010 (SWQM data collected and recorded by the TCEQ). The numbers shown represent seasonal averages calculated within Trinity Bay for the study period.

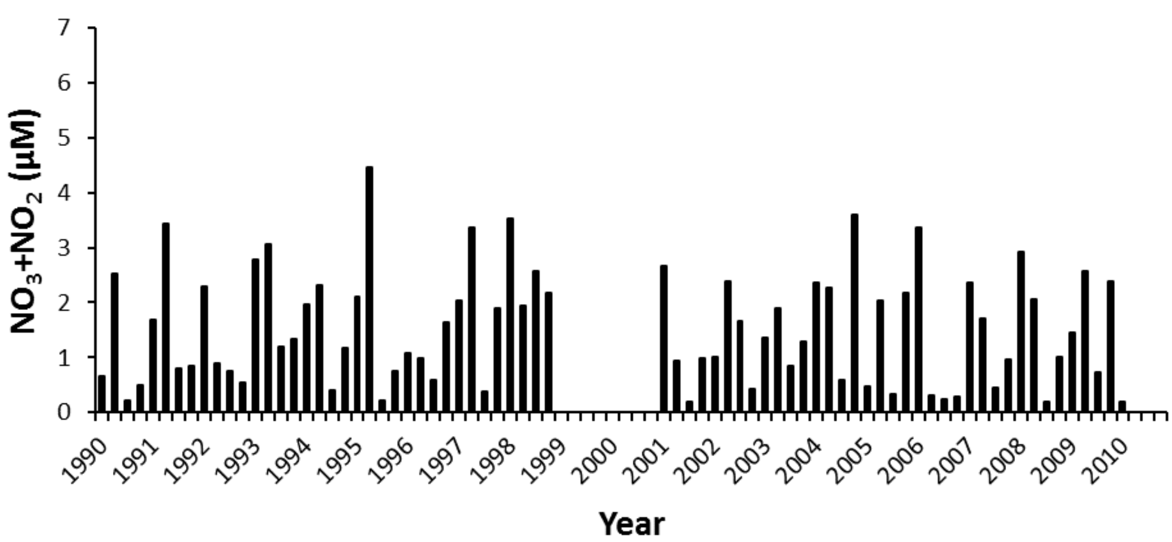


Figure 24. Concentration of $NO_3^- + NO_2^-$ (μM) in Upper Galveston Bay from 1990-2010 (SWQM data collected and recorded by the TCEQ). The numbers shown represent seasonal averages calculated within Upper Galveston Bay for the study period.

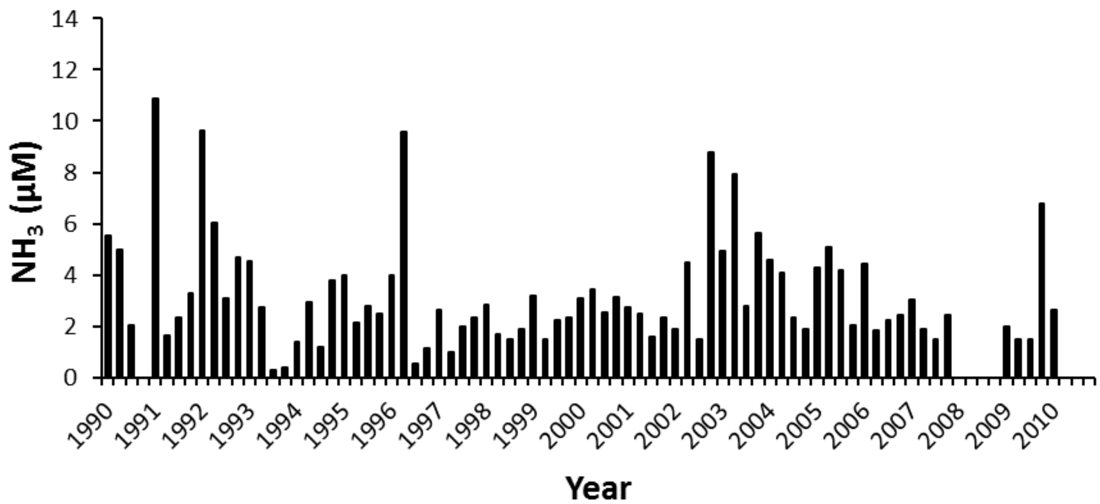


Figure 25. Concentration of NH_3 (μM) in Trinity Bay from 1990-2010 (SWQM data collected and recorded by the TCEQ). The numbers shown represent seasonal averages calculated within Trinity Bay for the study period.

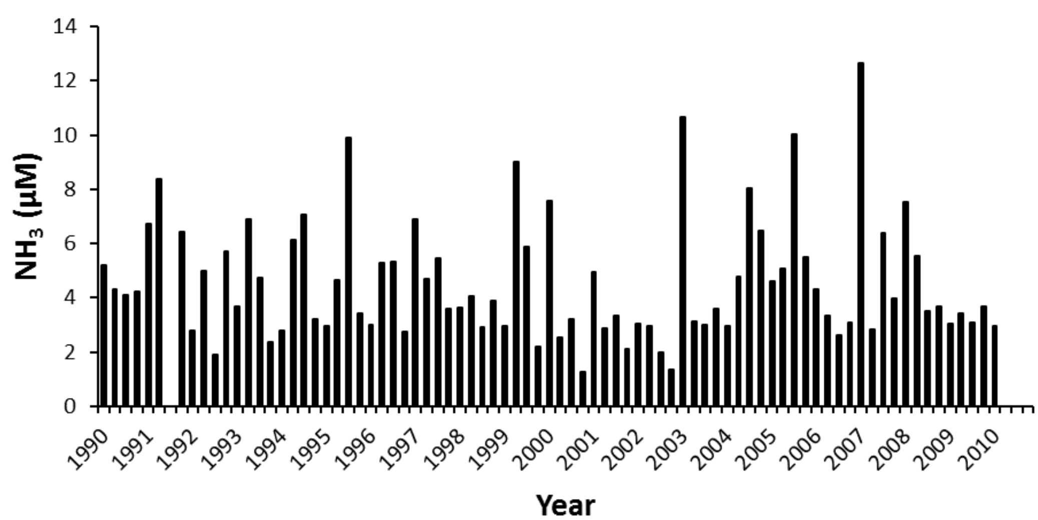


Figure 26. Concentration of NH_3 (μM) in Upper Galveston Bay from 1990-2010 (SWQM data collected and recorded by the TCEQ). The numbers shown represent seasonal averages calculated within Upper Galveston Bay for the study period.

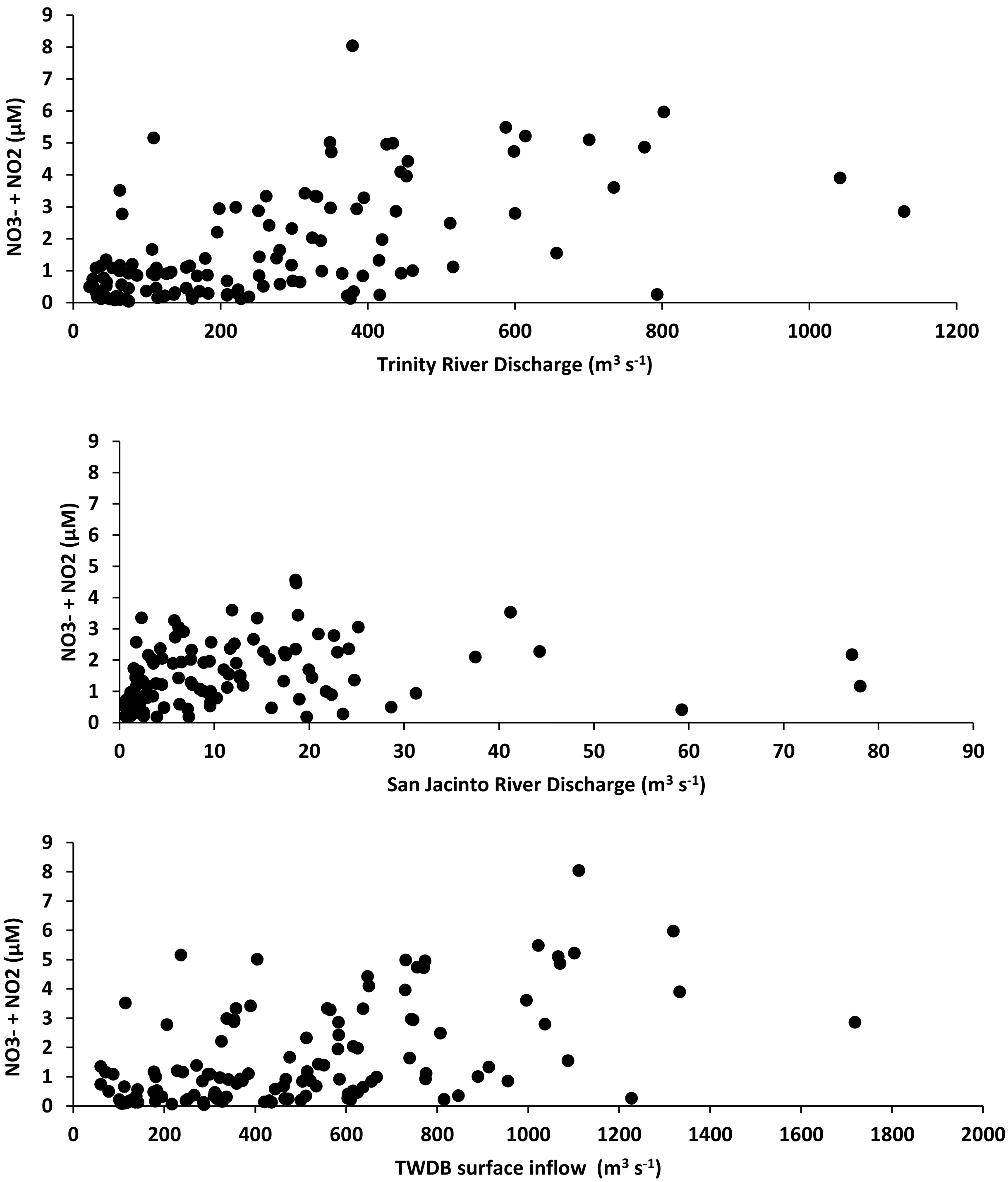


Figure 27. Concentration of $NO_3^- + NO_2^-$ (µM) (the TCEQ SWQM data) versus River Discharge in Trinity Bay, Upper Galveston Bay, and the entire Bay from 1990-2010 (USGS and TWDB data).

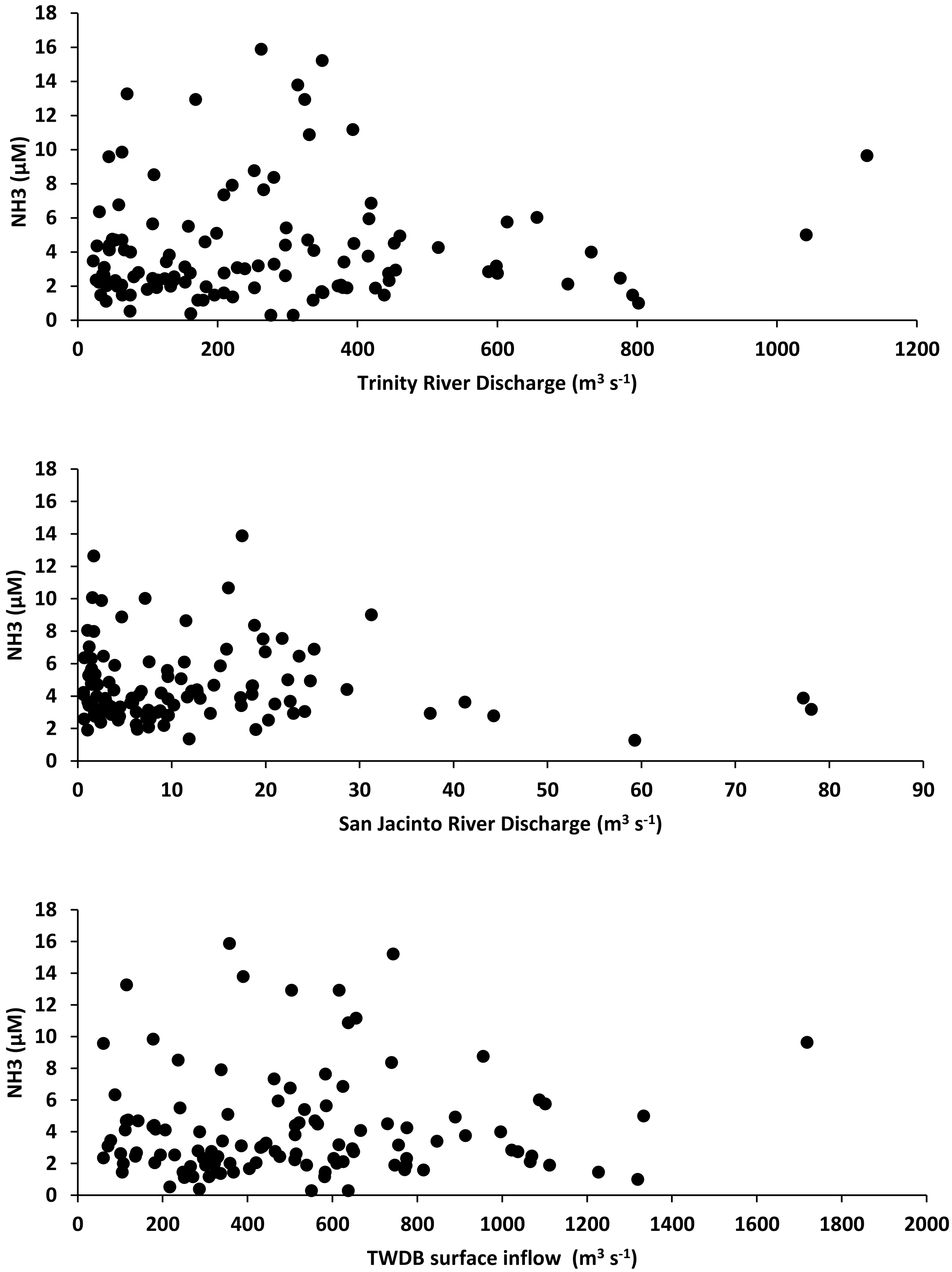


Figure 28. Concentration of NH_3 (μM) (the TCEQ data) versus River Discharge in Trinity Bay, Upper Galveston Bay, and the entire bay from 1990-2010 (USGS and TWDB data).

Objective 6: **Use the long term data set being established (since 2008) to understand how the inter-annual variability and extreme events (e.g., 2011 drought) need to be factored into an understanding of freshwater inflow effects on the bay. Long term data sets are key to understanding how much freshwater is going to be required for maintaining an ecologically sound bay.**

For this part of the project, we examined land use land change maps produced from 1992 to 2014 by National Oceanic and Atmospheric Administration (NOAA) National Land Cover Database (available on the HGAC webpage: http://www.h-gac.com/community/socioeconomic/land-use-data/default.aspx) and compared them to the corresponding water quality data collected by the TCEQ (https://www80.tceq.texas.gov/SwqmisPublic/public/default.htm) for the same period. The NOAA Land Cover Database was created to examine national land cover changes and trends across the United States. The 16-class land cover classification scheme has been applied consistently across the United States at a spatial resolution of 30 meters allowing researchers to visualize changes in land use and land cover over time. The 16-classes used are included as a legend in Figure 29.

We were particularly interested in changes in land use in counties immediately adjacent to Galveston Bay. In Figure 30, we show findings for three representative counties: Harris, Liberty and Galveston. The patterns were very distinctive in these three counties. In the northeast corridor above Galveston Bay in Harris County, there are mostly developed (urbanized) lands, and the area used for development has increased by 11% since the early 1990's. By contrast, in the northwest corridor in Liberty County, land use has remained relatively unchanged, with approximately an even one-third split between forest, agricultural and wetland areas. In the south, in Galveston County, waterways accounted for the largest land use, with the biggest changes in the land used for development, but this is not yet significant. While there is county specific variability, taking a step back and looking at the entire watershed, the three most notable changes since 1992 were:

i. forest land cover experienced the greatest loss, primarily due to development (urbanization)

ii. forests were also lost to grasslands and more shrubs; agricultural (cultivated) lands and wetlands also lost, and

iii. wetlands were converted into developed lands, to shrubs and grasslands associated with urban community centers connected to waterways.

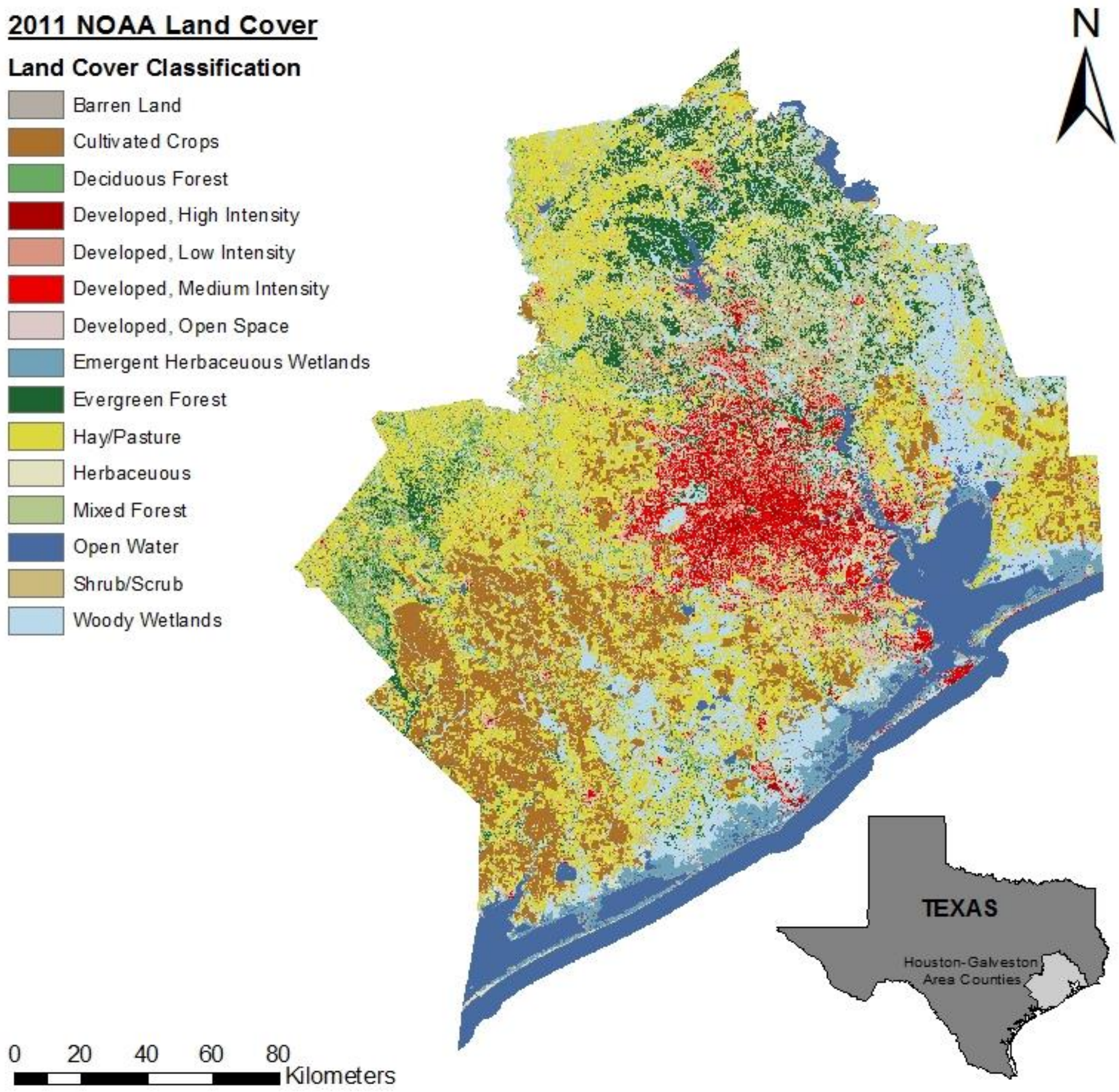
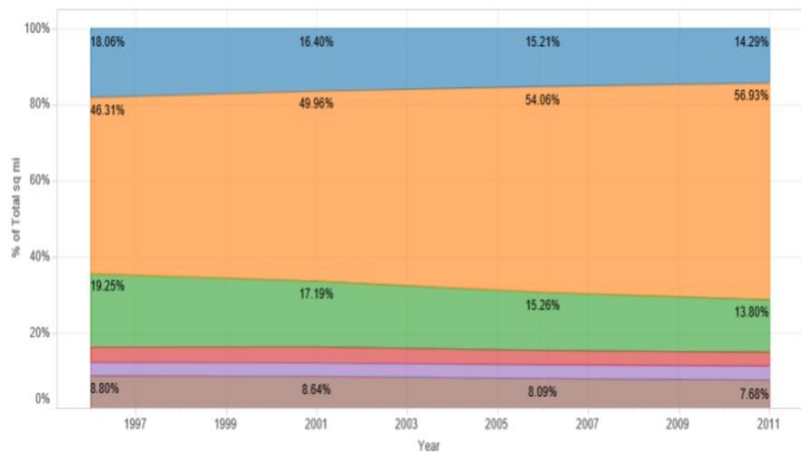
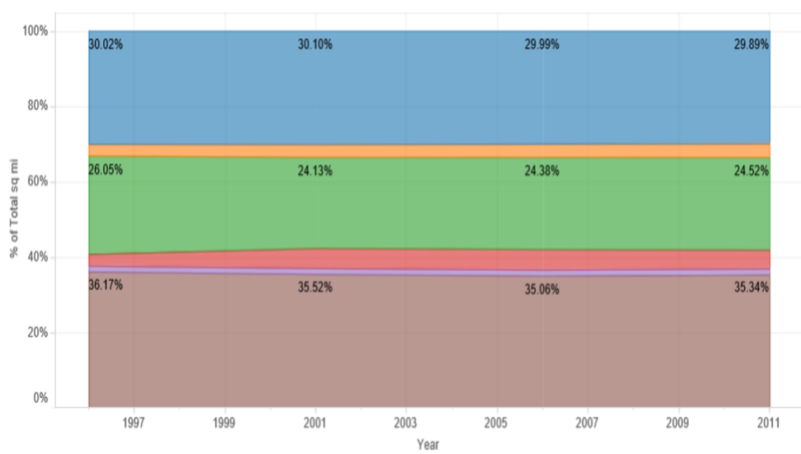


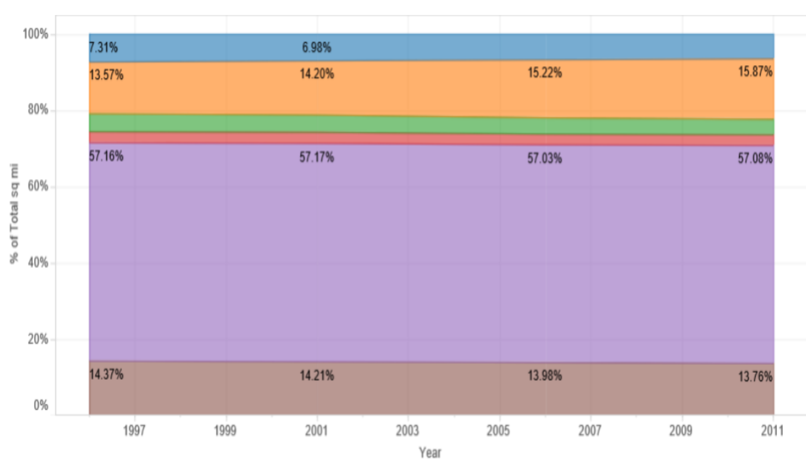
Figure 29. Most recent map of land uses in the Galveston Bay watershed produced by HGAC. (webpage: http://www.h-gac.com/community/socioeconomic/land-use-data/default.aspx)



Harris County



Liberty County



Galveston County

Figure 30. Average land use in the above counties located in the lower Galveston Bay watershed. Maps taken from the HGAC webpage: http://www.h-gac.com/community/socioeconomic/land-use-data/default.aspx).

The hydrological consequences of land use land change to water quality in the bay were examined by assessing spatial and temporal patterns of salinity, nutrients, sediments, chlorophyll and other measured parameters on the lower Galveston Bay watershed. For this analysis, we grouped water quality data into the years following each land use-land change map, eg., 1996 map plus water quality from 1996 to 2000, 2001 map plus water quality from 2001 to 2005 (Brody et al. pers comm). In addition, we used PRIMER 6 to look for relationships between the water quality within Galveston Bay in response to the changing land use around the bay. The land change data (HGAC) was Log(x+1) transformed and used to construct a Euclidean distance resemblance matrix. The data was transformed to lessen any skewness in the data before analysis. The resemblance matrix was used to run a Principal Coordinates analysis. The water quality data also underwent a Log(x+1) transformation and was normalized before constructing a Euclidean distance matrix. The corresponding water quality data that was recorded by the TCEQ and retrieved from the SWQM database was overlain as vectors. This displays the changes in water quality in relation to the changes in land cover during the study period. For a detailed layout of methods please refer to Quigg and Steichen, 2015. Six main land use changes with corresponding water quality data are presented in Figure 31 .

We found, not unexpectedly, that land became more developed over time (1992 to 2011) (Figure 31A). With this, there was also a positive correlation with salinity, which we hypothesize is the result of reduced freshwater inflows (total volume) to the bay as a result of diversions for upstream uses. In addition, despite this development, there were corresponding lower nutrients present. This may be the result of the Clean Water Act and other policies from the 1960’s and 1970’s to improve water quality in bays and estuaries. Consistent with these observations, we found that in 1996, agricultural land was associated with high nutrient loads in the bay while in 2011, this was no longer the case (Figure 31B). There has been a decrease in land use for agricultural lands in the lower watershed in the last 30 plus years.

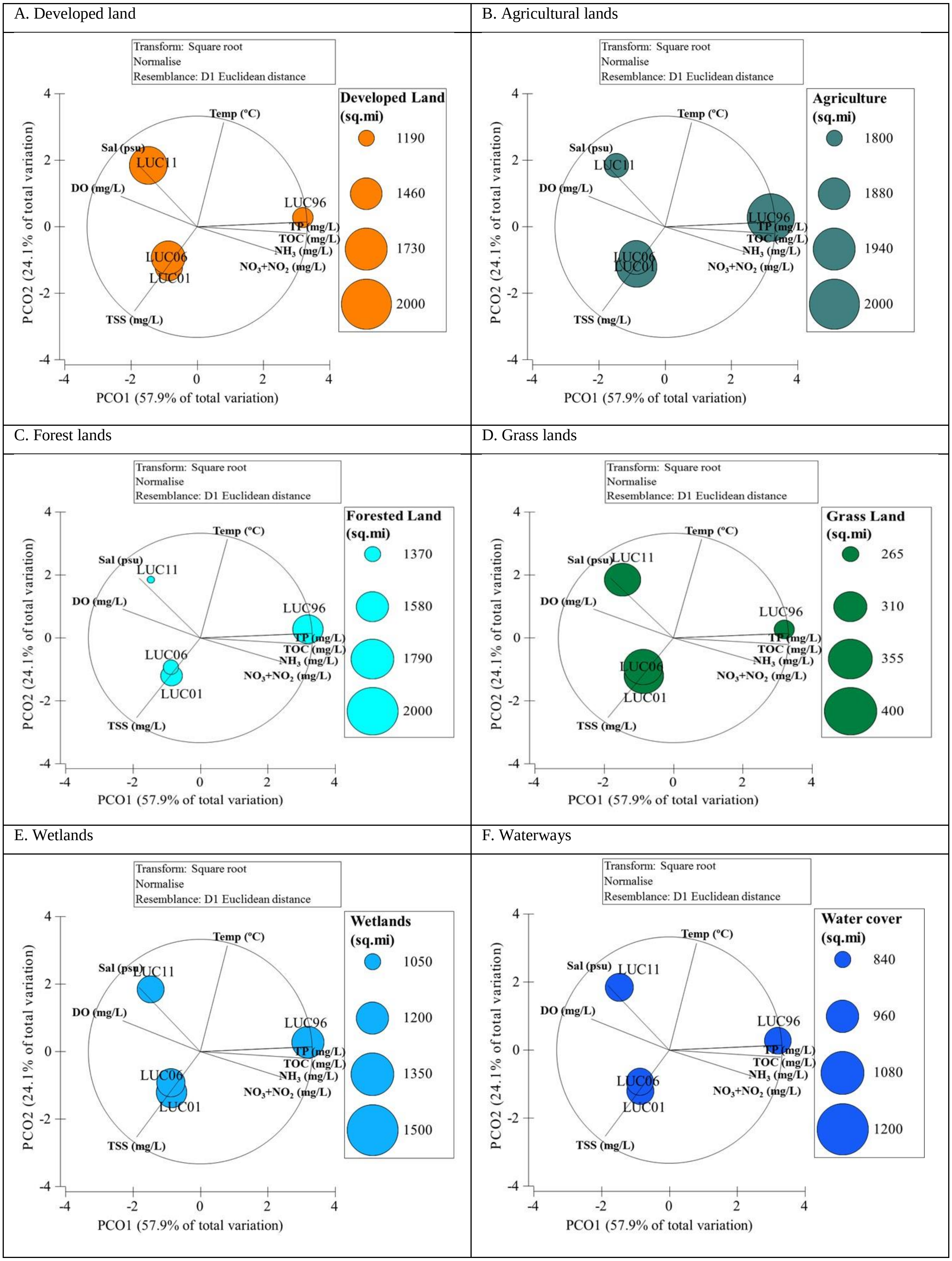


Figure 31. Principle Coordinate Ordination maps of land use and water quality parameters.

Throughout the period of study, forested land decreased while grass lands increased (Figures 31C and 31D respectively). This reflects development of housing communities, particularly along the northern corridor. Those communities have both green spaces and retention ponds. This has impacted both land use and nutrient loading patterns across the watershed. At this time, we can speculate, but there are no definitive studies on the phenomenon.

Unfortunately, as with many other estuaries, land cover in the lower Galveston Bay watershed has experienced significant losses in wetland areas from the 1996 to 2011 (Figure 31E). Increasing salinities as shown in this figure indicate that residents cannot functionally replace freshwater wetlands. Restoration efforts are typically focused on brackish/marine species such as *Spartina alterniflora*. These kinds of changes in both habitat quality and salinity driven food web dynamics are likely to impact higher trophic levels.

We did not expect to find increased population growth leading to greater areas defined as waterways (Figure 30F). However, given development of communities and residential complexes – with detention ponds and lakes – this perhaps is not surprising. The advantage of this building mode may be that the increased impervious surfaces associated with development are now directing storm-water runoff toward filling ponds; protecting the bay.

6. Discussion

The goal of this project was to work toward understanding how changing land use patterns and nutrient loading into Galveston Bay have influenced water quality, quantity, and patterns. In particular, we considered causal or casual relationships between changes in urbanization and increased nutrient loading. We combined a mixture of traditional field based measurements (Objectives 1-4) and historical data (Objectives 5-6) in order to examine this issue.

Land use land cover data are an important element in helping us to understand the environmental and anthropogenic influences affecting waterways and watersheds. Urbanization, industrialization, agriculture, deforestation, loss of wetlands, and several other types of land use change have taken place in response to human population growth in the watershed of Galveston Bay. Currently, Houston is ranked 4th, Dallas 9th and Fort Worth 16th, in terms of largest cities and fastest growing cities in the US – and these cities are all within the boundaries of the Galveston Bay watershed. Further, the population density is expected to double by 2050 in Texas, with most growth in coastal zones. Yet unlike Chesapeake Bay and San Francisco Bay, we do not see clear environmental pressures such as eutrophication induced hypoxia or elevated numbers of invasive species replacing the environment of native species (Dauer et al., 2000; Kemp et al., 2005; Smith et al., 2003; Glibert et al., 2014 a, b).

The sources of freshwater for Trinity Bay and Upper Galveston Bay are the Trinity River and San Jacinto River respectively. The Trinity River flows to the Bay from the Dallas/Fort Worth region. Agriculture and forested land are the primary land types along the Trinity River whereas the San Jacinto River flows through the metropolitan area of Houston. The nitrogen data within the bay system showed an overall increase of NO_3^- + NO_2^- in Trinity Bay compared to that in Upper Galveston Bay (Figures 23 and 24). In Dallas, Texas the NH_3 levels have decreased in response to improved and upgraded wastewater treatment plants. These wastewater treatment plants convert the NH_3 to NO_3^- (USGS, 1999). Conversely there was an increase in the concentration of NH_3 in Upper Galveston Bay compared to Trinity Bay (Figures 25 and 26). In regions of increased population comes increased volume of wastewater which can lead to an increase in the concentration of NH3 being delivered to the bay (USGS, 1999). The nutrient concentrations near the mouth of the Trinity and San Jacinto are likely influenced by the land type along each of the respective rivers.

We propose that until now, Galveston Bay appears to have been resilient to the upstream changes in land use and land cover. This may be due to vast majority of developed lands in the watershed flushing into the river which contributes the least freshwater inflows into Galveston Bay – the San Jacinto River. However, the resilience of Galveston Bay may be due to other factors: short residence times, regular wind mixing throughout the relatively shallow (2.5 m) estuary, or other factors which we have not yet considered. This is certainly an area which requires future investigation. As regional planning and natural resource management endeavor to determine the appropriate amount of freshwater inflows for Galveston Bay, understanding the balance between land use land change and water quality will be key to maintaining ecosystem services and functions for future generations. The complex and dynamic nature of estuarine systems makes this very challenging as direct responses of water quality parameters to land-use change are unlikely.

7. References

Alberti, M., 2005. The effects of urban patterns on ecosystem function. *International Regional Science Review* 28, 168-192.

Alberti, M., Booth, D., Hill, K., Coburn, B., Avolio, C., Coe, S., Spirandelli, D., 2007. The impact of urban patterns on aquatic ecosystems: An empirical analysis in Puget lowland sub-basins. *Landscape and Urban Planning* 80, 345-361.

Allan, J.D., 2004. Landscapes and riverscapes: The influence of land use on stream ecosystems. *Annual Review of Ecology Evolution and Systematics* 35, 257-284.

Arar, E.J. and Collins, G.B. 1997. Method 445.0, *In Vitro* Determination of Chlorophyll *a* and Pheophytin *a* in Marine and Freshwater Algae by Fluorescence. *In* Methods for the Determination of Chemical Substances in Marine and Estuarine Environmental Matrices, 2nd Edition. National Exposure Research Laboratory, Office of research and development, USEPA. Cincinnati, Ohio (EPA/600/R-97/072, Sept. 1997).

Armstrong, F.A.J., Stearns, C.R., et al. 1967. The measurement of upwelling and subsequent biological processes by means of the Technicon AA and associated equipment. *Deep-Sea Research.* 14, 381-389.

Badylak S., Philips E. J., Mathews A. L. and K. Kelley. 2014. *Akashiwo sanguinea* (Dinophyceae) extruding mucous from pores on the cell surface. *Algae* 29, 197-201.

Bernhardt, H. and A. Wilhelms. 1967. The continuous determination of low level iron, soluble phosphate and total phosphate with the AA. Technicon Symposium.

Bruno, D., Belmar, O., Sanchez-Fernandez, D., Guareschi, S., Millan, A., Velasco, J., 2014. Responses of Mediterranean aquatic and riparian communities to human pressures at different spatial scales. *Ecological Indicators* 45, 456-464.

Carpenter, S.R., Caraco, N.F., Correll, D.L., Howarth, R.W., Sharpley, A.N., Smith, V.H., 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications* 8, 559-568.

Census Bureau 2012 (https://www.census.gov/)

Chang, H., 2008. Spatial analysis of water quality trends in the Han River basin, South Korea. *Water Research* 42, 3285-3304.

Chang, H., Thiers, P., Netusil, N.R., Yeakley, J.A., Rollwagen-Bollens, G., Bollens, S.M., Singh, S., 2014. Relationships between environmental governance and water quality in a growing metropolitan area of the Pacific Northwest, USA. *Hydrology and Earth System Sciences* 18, 1383-1395.

Clement, C., Bricker, S., Pirhalla, D., 2001. Eutrophic Conditions in Estuarine Waters. National Oceanic and Atmospheric Administration. Silver Spring, MD.

Dauer, D.M., Ranasinghe, J.A., Weisberg, S.B., 2000. Relationships between benthic community condition, water quality, sediment quality, nutrient loads, and land use patterns in Chesapeake Bay. *Estuaries* 23, 80-96.

DeFires, R. S., Asner, G.P., Houghton, R. A. 2004 Ecosystems and land use change. Geophysical Monograph Series. pp. 344.

Dietz, M.E., Clausen, J.C., 2008. Stormwater runoff and export changes with development in a traditional and low impact subdivision. *Journal of Environmental Management* 87, 560-566.

Espey, W. H., Lester, L. J., Browning, R., Buzan, D., Frossard, W., Guillen, G., McFarlane,R. W., Reedy, M., Plummer, A. H., Quigg, A., Ray, S., Smith, T. L., Trungale, J. F., Turco, M. and Woodrow, J. O. Jr. 2009 *Environmental Flows Recommendations Report. Trinity and San Jacinto and Galveston Bay Basin and Bay Expert Science Team.* Final Submission to the Trinity and San Jacinto Rivers and Galveston Bay and Basin Stakeholder Committee, Environmental Flows Advisory Group, and Texas Commission on Environmental Quality. pp. 172.

Galveston Bay Estuary Program (GBEP) 1994. The Galveston Bay Plan. The comprehensive conservation and management plan for the Galveston Bay Ecosystem. Galveston Bay National Estuary Program (GBNEP). pp. 457.

Galveston Bay Estuary Program (GBEP) 2009. Charting the Course to 2015: Galveston Bay Strategic Action Plan. Galveston Bay National Estuary program (GBNEP). pp. 32.

Gburek, W.J., Folmar, G.J., 1999. Flow and chemical contributions to streamflow in an upland watershed: a baseflow survey. *Journal of Hydrology* 217, 1-18.

Glibert, P.M., R.C. Dugdale, F. Wilkerson, A.E. Parker, J. Alexander, E. Antell, S. Blaser, A. Johnson, J. Lee, T. Lee, S. Murasko and S. Strong. 2014a. Major-but rare- spring blooms in San Francisco Bay Delta, California, a result of the long-term drought, increased residence times, and altered nutrient loads and forms. *Journal Experimental Marine Biology and Ecology* 460, 8-18.

Glibert, P.M., F. Wilkerson, R.C. Dugdale, A.E. Parker, J.A. Alexander, S. Blaser and S. Murasko. 2014b. Microbial communities from San Francisco Bay Delta respond differently to oxidized and reduced nitrogen substrates – even under conditions that would otherwise suggest nitrogen sufficiency. *Frontiers in Marine Science* 1, 1-17.

Gonzalez, L.A., L. J. Lester. 2011. State of the bay: A characterization of the Galveston Bay ecosystem, Third Edition. Texas Commission on Environmental Quality, Galveston Bay Estuary Program. Houston, Texas. pp. 356.

Gove, N.E., Edwards, R.T., Conquest, L.L. 2001. Effects of scale on land use and water quality relationships: A longitudinal basin-wide perspective. *Journal of the American Water Resources Association* 37, 1721-1734.

Guthrie, C.G., Matsumoto, J. and R.S. Solis. 2012. Analysis of the Influence of Water Plan Strategies on Inflows and Salinity in Galveston Bay. Final report to the United States Army Corps of Engineers, Contract #R0100010015. Texas Water Development Board, Austin, TX.

Halstead, J.A., Kliman, S., Berheide, C.W., Chaucer, A., Cock-Esteb, A., 2014. Urban stream syndrome in a small, lightly developed watershed: a statistical analysis of water chemistry parameters, land use patterns, and natural sources. *Environmental Monitoring and Assessment* 186, 3391-3414.

Hansen, D.V. and M. Rattray Jr. 1966. New dimensions in estuary classification. *Limnology and Oceanography* 11, 319-326.

Harwood, J.E. and A.L. Kuhn. 1970. A colorimetric method for ammonia in natural waters. *Water Research* 4, 805-811.

Henrichs D. W., Scott, P. S., Steidinger, K. A., Errera, R. M., Abraham, A. and L. Campbell. 2013. Morphology and phylogeny of *Prorocentrum texanum* sp. *nov*. (Dinophyceae): A new toxic dinoflagellate from the Gulf of Mexico coastal waters exhibiting two distinct morphologies. *Journal of Phycology* 49, 143-155.

Hogan, D.M., Jarnagin, S.T., Loperfido, J.V., Van Ness, K., 2014. Mitigating the effects of landscape development on strems in urbanizing watersheds. *Journal of the American Water Resources Association* 50, 163-178.

Houston Galveston Area Council 2016. (http://www.h-gac.com/community/socioeconomic/land-use-data/default.aspx)

Jeffrey, S. W., Mantoura, R. F. C. and S.W. Wright, [Eds.] 1997. Phytoplankton Pigments in Oceanography: Guidelines to Modern Methods. UNESCO, Paris, pp. 450.

Jessup, D. A., Miller, M. A., Ryan, J. P., Nevins, H. P., Kerkering, H. A., Mekebri, A., Crane, D. B., Johnson, T. A. and R.M. Kudela. 2009. Mass stranding of marine birds caused by a surfactant-producing red tide. *PLoS ONE* 4 (2): e4550.

Kemp, W.M., Boynton, W.R., Adolf, J.E., Boesch, D.F., Boicourt, W.C., Brush, G., Cornwell, J.C., Fisher, T.R., Glibert, P.M., Hagy, J.D. 2005. Eutrophication of Chesapeake Bay: historical trends and ecological interactions. *Marine Ecology Progress Series* 303, 1-29.

King, K.W., Balogh, J.C., Agrawal, S.G., Tritabaugh, C.J., Ryan, J.A., 2012. Phosphorus concentration and loading reductions following changes in fertilizer application and formulation on managed turf. *Journal of Environmental Monitoring* 14, 2929-2938.

Lehman, J.T., Bell, D.W., Doubek, J.P., McDonald, K.E., 2011. Reduced additions to river phosphorus for three years following implementation of a lawn fertilizer ordinance. *Lake and Reservoir Management* 27, 390-397.

Lenat, D.R., Crawford, J.K., 1994. Effects of land-use on water-quality and aquatic biota of 3 North Carolina piedmont streams. *Hydrobiologia* 294, 185-199.

Mackey, M., Mackey, D., Higgins, H. and S. Wright. 1996. CHEMTAX-a program for estimating class abundances from chemical markers: application to HPLC measurements of phytoplankton. *Marine Ecology Progress Series* 144, 265-283.

Madden, C. and J. Day. 1992. An instrument for high speed mapping of chlorophyll–*a* and physico-chemical variables in surface waters. *Estuaries* 15, 421-427.

Matsumoto, J. 1992. User's manual for the TWDB's rainfall–runoff model. Austin, TX. Texas Water Development Board.

Millie, D. F., Paerl, H. W. and J. P. Hurley. 1993. Microalgal pigment assessments using high-performance liquid chromatography: a synopsis of organismal and ecological applications. *Canadian Journal of Fisheries Aquatic Sciences.* 50, 2513-2527.

Olson, R.J. and H.M. Sosik. 2007. A submersible imaging-in-flow instrument to analyze nano- and microplankton: Imaging FlowCytobot. *Limnology and Oceanography: Methods*. 5, 195-203.

Paul, M.J., Meyer, J.L., 2001. Streams in the urban landscape. *Annual Review of Ecology and Systematics* 32, 333-365.

Pinckney, J. L., Paerl, H. W., Harrington, M. B. and K. E. Howe. 1998. Annual cycles of phytoplankton community structure and bloom dynamics in the Neuse River Estuary, North Carolina. *Marine Biology* 131, 371-82.

Pinckney, J.L., Millie, D.F., Howe, K.E., Paerl, H.W. and J.P. Hurley. 1996. Flow scintillation counting of 14C-labeled microalgal photosynthetic pigments. *Journal of Plankton Research* 18, 1867-1880.

Quigg, A., Davis, S. E. and D.F. Roelke. 2007. Changes in Freshwater Inflows and How They Effect Texas Bays. Final Report of the Coastal Coordination Council pursuant to National Oceanic and Atmospheric Administration Award No. NA05NOS4191064. pp. 47.

Robichaux, R. J., Dortch, Q. and J. H. Wrenn. 1998. Occurrence of *Gymnodinium sanguineum* in Louisiana and Texas coastal waters, 1989-1994. NOAA Tech. Rep. NMFS 143:19-25

Smith, S.V., Swaney, D.P., Talaue-Mcmanus, L., Bartley, J.D., Sandhei, P.T., McLaughlin, C.J., Dupra, V.C., Crossland, C.J., Buddemeier, R.W., Maxwell, B.A., 2003. Humans, hydrology, and the distribution of inorganic nutrient loading to the ocean. *BioScience* 53, 235-245.

Sosik, H. M. and R. J. Olson. 2007. Automated taxonomic classification of phytoplankton sampled with imaging-in-flow cytometry. *Limnology and Oceanography: Methods*. 5, 204-216.

Steidinger, K. A., Stockwell, D. A., Truby, E. W., Wardle, W. J., Dortch, Q. and F. M. Van Dolah. 1998. Phytoplankton blooms off Louisiana and Texas, May-June 1994. NOAA Tech. Rep. NMFS 143, 13-17.

Tomas, C.R. [Ed] 1997. Identifying Marine Phytoplankton. San Diego: Academic Press, pp. 858.

Tong, S.T.Y., Chen, W.L., 2002. Modeling the relationship between land use and surface water quality. *Journal of Environmental Management* 66, 377-393.

Tran, C.P., Bode, R.W., Smith, A.J., Kleppel, G.S., 2010. Land-use proximity as a basis for assessing stream water quality in New York State (USA). *Ecological Indicators* 10, 727-733.

Valderrama, J.C., 1981. The simultaneous analysis of total nitrogen and total phosphorous in natural waters. *Marine Chemistry*. 10, 109-102.

Van Heukelem, L., Lewitus, A. J., Kana, T. M. and N.E. Craft. 1994. Improved separations of phytoplankton pigments using temperature-controlled high performance liquid chromatography. *Marine Ecology Progress Series* 114, 303-13.

Voltolina, D. 1993. The origin of recurrent blooms of *Gymnodinium sanguineum* Hirasaka in a shallow lagoon. *Journal of Experimental Marine Biology and Ecology*. 168, 217-222

Wetzel, R. G. and G.E. Likens. 2000. *Limnological Analyses* Third Edition, Springer. pp. 429.

Wright, S., Thomas, D., Marchant, H., Higgins, H., Mackey, M. and D. Mackey. 1996. Analysis of phytoplankton of the Australian sector of the Southern Ocean: comparisons of microscopy and size frequency data with interpretations of pigment HPLC data using the 'CHEMTAX' matrix factorization program. *Marine Ecology Progress Series* 144, 285-298.

Zampella, R.A., Procopio, N.A., Lathrop, R.G., Dow, C.L., 2007. Relationship of land-use/land-cover patterns and surface-water quality in the Mullica River basin. *Journal of the American Water Resources Association* 43, 594-604.

8. Appendix

USGS gage stations (https://waterdata.usgs.gov/nwis/)

USGS 08066500 Trinity Rv at Romayor, TX

Latitude 30°25'30", Longitude 94°51'02" NAD27
Liberty County, Texas,
Hydrologic Unit Code 12030202
Drainage area 17,186 square miles
Contributing drainage area 17,186 square miles
Gage datum 25.92 feet above NGVD29

USGS 08070000 E Fk San Jacinto Rv nr Cleveland, TX

Latitude 30°20'11", Longitude 95°06'14" NAD27
Liberty County, Texas,
Hydrologic Unit 12040103
Drainage area: 325 square miles
Contributing drainage area: 325 square miles,
Datum of gage: 107.98 feet above NGVD29.

USGS 08067650 W Fk San Jacinto Rv bl Lk Conroe nr Conroe, TX

Latitude 30°20'31", Longitude 95°32'34" NAD27
Montgomery County, Texas,
Hydrologic Unit 12040101
Drainage area: 451 square miles
Contributing drainage area: 451 square miles,
Datum of gage: 116.06 feet above NGVD29.