Seasonal Water Quality Trends in Bayboro Harbor, a Humid Subtropical Urban Estuary in Tampa Bay, Florida

by

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Dedication

To my family, and to my friends who might as well be family. I wouldn’t have made it without you.

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Table of Contents

List of Tables

List of Figures

Abstract

The goal of this study was to track water quality in Bayboro Harbor through the transition from dry season to rainy season and to determine if there was a sharp decline in water quality as precipitation increased. Secondary goals were to examine the influence of several points of urban runoff that discharged to the harbor, and analyze those sites along with several open water sites to detect any trends in changing water quality parameters or nutrients and to establish the baseline water quality data for a continuous monitoring program of Bayboro Harbor.

To accomplish these goals, a monitoring program was designed that could identify water quality issues and begin establishing baseline water quality. Five sample sites were selected to represent Bayboro Harbor: the discharge zones of Booker Creek and Salt Creek, a large stormwater drain, the center of the harbor from the marina breakwater, and another open water sample site at the end of the University of South Florida (USF) College of Marine Science peninsula. The selected parameters for the study were salinity, dissolved oxygen, temperature, precipitation, pH, turbidity, nitrate-nitrite, and orthophosphate.

Dissolved oxygen concentration indicated a downward trend that was continuing at the close of the study, there was a constant influx of nitrate-nitrite from Booker Creek, and the stormwater drain findings showed a wide variation of water quality parameters across the study, illustrating the influence of urban runoff. The peninsula discharge zone usually

demonstrated the strongest ocean water characteristics, and the breakwater site had varied trends that were often in the middle of the other sites.

The results did not show a sharp decline in water quality at the beginning of the rainy season as hypothesized, but did show an overall trend of degradation for several parameters in response to pulses of runoff that followed precipitation events. The Booker Creek site was determined to be strongly influenced by freshwater (low pH), suggesting that the nitrate-nitrite concentration was due to urban runoff. The Salt Creek site experienced greater circulation and tidal influence from the mouth of the harbor than was expected. The central breakwater site appears to be the most representative of mixed Bayboro Harbor water of the five sample sites. The results suggest many possibilities for further study, including a deeper look at each of the outflow sites, different times or tidal states for sampling, upstream research on Booker Creek, and additional study of the stormdrain system.

Introduction

Bayboro Harbor is an urban estuary located near the center of St. Petersburg, Florida. It is strongly influenced by natural and anthropogenic water sources and sinks but has been subjected to little monitoring. This work represents, to my knowledge, the first long-term study of water quality in Bayboro Harbor, and is designed to serve as a baseline for additional data collection and analysis.

Estuaries

Estuaries represent the coastal transition zone between fresh water and ocean water. Rivers and streams drain into semi-enclosed water bodies in coastal regions where a unique estuarine ecosystem houses a diverse array of plants and wildlife adapted to fluctuating water conditions. Estuaries are vastly productive habitats, supporting juvenile populations of marine species, shellfish habitats, and functioning as spawning grounds (PCWA, 2019). Estuaries support marine organisms in various life stages, and often serve as habitats for vulnerable species that are sensitive to contaminants and eutrophication (Ohrel and Register, 2006; Paerl et al., 2006). Changes in water quality can interrupt the ecosystem balance by altering biodiversity (EPA, 2002).

An estuary is bounded by land on one side and open to the ocean on the other, and thus is influenced by tides. Water quality in any estuary is subject to overland flow that makes its way to rivers, lakes, and tributaries, which can drain regions spanning hundreds of square kilometers. In a heavily urbanized area with significant precipitation, local stormwater runoff can exhibit significant influence on estuarine health (Jeng et al., 2005).

Unlike relatively consistent water quality parameters found in rivers and lakes, a constant variation of physical and chemical variables can produce a wide range of environmental conditions which fluctuate throughout an estuarine environment (Ohrel and Register, 2006). Estuary conditions are strongly influenced by ocean tides and meteorological events, causing abrupt and changing conditions (Bricker et al., 2008). Tidal flushing is the net transport of water out of the estuary and the net flow of incoming freshwater that moves water through the estuary (Guo and Lordi, 2000), which can degrade water conditions as sediments and other contaminants move into the estuary from adjacent rivers, creeks, and storm drains. Seasonal variance can result in stratification of the water body, often with a warmer surface layer and cooler lower layers (Dolgopolova and Isupova, 2010). Other influences on estuary water quality can result from anthropogenic activity, such as barriers intentionally constructed to control and modify circulation, or dredging and disposal of spoil, which alters bathymetry and may modify flow patterns in unpredictable ways (Goodwin, 1987).

Continuous changes to estuarine habitats come from natural and anthropogenic sources (Bricker, 2007). Anthropogenic activities introduce contaminants and excess nutrients. The continual push-pull of saltwater and freshwater can promptly transport waters from the estuary to the ocean, but the oscillatory nature of tidal flushing in estuaries can impede the transport of estuary waters that have been contaminated by runoff (Ketchum and Rawn, 1951). Additionally, continued influx of pollutants can hold an estuary in a perpetual state of poor water quality, with long-term exposure adversely affecting inhabitants (Ohrel and Register, 2006). With half of the growing human population dwelling in coastal regions, the stress of industrial pollutants, destruction of habitats, and an increase of impervious surfaces leads to "urban stream syndrome." Urban stream syndrome is defined as flash floods or water pulses with high nutrient and contaminant concentration, and pose an increasing threat to estuary health (Walsh et al. 2005). Such factors as bathymetry, tidal range, estuary mouth-width, shape of the estuarine basin, population density, topography, and regional climate combine to make each estuary system a unique habitat (Ohrel and Register, 2006).

Water Quality

Estuaries all have unique hydrology, bathymetry, and climate variables when compared to open ocean systems. The productive nature of estuaries makes them particularly vulnerable to changes in water quality (Hauxwell et al., 2001). In a balanced coastal aquatic system, biodiversity is strong, providing marine nurseries, plentiful habitat, and sustenance for many organisms (Courrat et al., 2009). Systemic stress can force a previously healthy ecosystem out of balance, and may cause a cascade of failures (Duarte et al., 2009). Highly urbanized coastal ecosystems are at greater risk of systemic stress because of increased exposure to the concentration of activity in urban environments. Stressors can be monitored using water quality analysis, and monitored parameters often include temperature, pH, turbidity, dissolved oxygen, salinity, and nutrients (Table 1). Monitoring sensitive coastal regions can provide information on the status of estuary health, water quality, biodiversity, and pollutants (Ohrel and Register, 2006).

Table 1. Estuary Water Quality Parameters (Taken from NOAA Estuary Water Quality Parameters Information Sheet).

Parameter	Natural Reading	Danger Reading
Temperature	0-30°C	27°C
pH	Freshwater 6-8; Salt 8+	Below 6 or above 8.5
Turbidity (NTU)	0-10	Above 20 NTU
Dissolved Oxygen (mg/L)	5-12	<5 = Stress 1-3 = Poor 0 = Anoxic
Dissolved Oxygen %Sat	0%-200%	<70% = Stress <50% = Poor 0% = Anoxic >120% May be harmful
Salinity (PSU)	Freshwater 0; Estuaries 5-30; Ocean 35	40 = lethal

Common water quality issues in estuaries come from excess nutrients, such as nitrogen and phosphorus, which can hasten eutrophication (Nixon, 1995). Eutrophication is a condition in which over-enrichment of nutrients in a water body accelerates the production of organic matter. Nutrients stimulate an overgrowth of aquatic plants, particularly algae, which causes a disruption in the ecosystem balance, and begins a cycle of overgrowth, mortality, growth of decomposer bacteria populations, decay, and hypoxia (overuse and subsequent decline of available dissolved oxygen). Depletion of dissolved oxygen (DO) and algal blooms are indicators of eutrophic conditions (Bricker et al., 1999; Paerl et al., 2006).

Table 2. Eutrophication Survey Parameters for Nutrients (Bricker et al., 1999).

Nutrient	High	Medium	Low
NOx (nitrogen)	≥ 1 mg/l	≥ 0.1 to < 1 mg/l	> 0 to < 0.1 mg/l
P (phosphorus)	≥ 0.1 mg/l	≥ 0.01 to <0.1 mg/l	≥ 0 to < 0.01 mg/l

Dissolved oxygen (DO) in a healthy water body usually rises during daytime as sunlight supports photosynthetic activity (with phytoplankton and aquatic plants releasing oxygen), and falls overnight when plants cease photosynthesis and as organism respiration consumes the available DO (Board, 2000). Hypoxic conditions occur when the needs of the aquatic community begin to exceed the DO produced. Low dissolved oxygen can suffocate sensitive invertebrates and fishes (EPA, 2002). Dissolved oxygen can be measured as a concentration ($mg\ l^{-1}$), often used to report stress to organisms, or as percent saturation, which can be used to determine biological activity (Kemp et al., 1980). A healthy, natural range of DO concentration in an estuary is 5-12 $mg\ l^{-1}$; DO below 5 $mg\ l^{-1}$ indicates a stressed system (NOAA, n.d.).

Like any ecosystem, coastal systems require balance in order to thrive. Nutrients (such as nitrogen and phosphorous) are necessary to sustain life, and are provided naturally from the environment through weathering, atmospheric deposition, recycling of waste products, and decomposition of organisms. Estuary systems are naturally nutrient-rich, which is one of the factors that makes them so productive. Nutrient loading disrupts the ecosystem balance by causing an overproduction of algae (“algal blooms”), decreases water quality by reducing the dissolved oxygen needed by the marine community, and limits water clarity due to the excess algae. A limiting nutrient, or any environmental parameter that is not present in a quantity adequate to support growth, is referred to as “limiting” (Board, 2000).

Nitrogen and phosphorus are common limiting elements for biological growth in estuaries, and thus are a primary concern in coastal waters. They are also responsible for both healthy productivity and eutrophic conditions when present in excess (Hauxwell et al., 2001).

Although nitrogen is plentiful on Earth, it is largely in a form that is not useful to aquatic organisms. The nitrogen species nitrate (NO_3^-) and nitrite (NO_2^-) are collectively known as NOx ("nox"). Nitrite is short-lived as a nitrogen species, and can be measured in environments of low DO. Nitrate is highly water-soluble, which makes it a focal point in the study of discharge into estuarine environments. Certain algae and bacteria can also fix nitrogen gas (N_2) into an inorganic species that makes it available, and in oxic environments, ammonium will usually undergo nitrification, converting first to nitrite, and then nitrate through *Nitrosomonas sp*. and *Nitrobacter sp*. of bacteria respectively, thereby lowering dissolved oxygen levels (Board, 2000; Ohrel and Register, 2006).

Phosphorus in water is often transported as the inorganic dissolved chemical species orthophosphate (PO_4^{3-}). Fertilizer is a main source of orthophosphate, and phosphorus nutrient loading to estuaries often comes by way of stormwater and urban runoff from lawns and agricultural operations (Ohrel and Register, 2006). Though nitrogen is typically the limiting nutrient in marine waters and phosphorus is the limiting nutrient in fresh waters, the phosphorus-rich geology and phosphate mining in Florida can create exceptions to this normal pattern. It is possible for phosphorus to become limiting when present in certain proportions relative to nitrogen (Redfield, 1958). The Tampa Bay watershed overlaps one of the world's largest phosphate mining regions (Greening and Janicki, 2006). Due to the unusual elemental makeup of the area, either element could be responsible for primary productivity, and both nutrients are commonly monitored as water quality indicators in urban regions (Hauxwell et al., 2012; Greening et al., 2014).

One of the most naturally varied water quality parameters in an estuary is salinity, or the amount of salt dissolved in water. Salinity is one of the most influential water quality parameters, as many marine and freshwater species cannot survive outside of specific zones of tolerance for salinity, and it is another parameter that can impact the amount of DO in the water column, as an increase in salinity reduces the solubility of oxygen (EPA, 2002). Salinity in an estuary will naturally exhibit a graduation or decline with distance from ocean water inflow (where salinity is expected to be higher) to fresh water tributaries (where salinity is expected to be quite low). The distribution of marine organisms is according to tolerance levels. (Ohrel and Register, 2006).

Temperature fluctuations in an estuary strongly affect biological and chemical processes. Higher temperatures lead to the decreased capacity of water to hold dissolved oxygen. Cooler water can hold more DO. Temperature can influence the rate of photosynthetic activity and the metabolism of marine organisms, and can regulate the life cycles of certain aquatic species (EPA, 2002). Plants and animals may be able to adapt to a slow, seasonal temperature shift, but may be intolerant of spikes or drops in temperature, and become stressed, leaving some organisms more susceptible to parasites and toxins (Ohrel and Register, 2006).

Turbidity is the measurement of water clarity due to particles in the water – if light transmission is limited, the photic zone is reduced and primary producers will not have access to sufficient light, nor will they generate an ideal amount of O_2. Turbidity is measured by light scattered by particles in the water column. The units are nepheloid turbidity units, which is based on the concentration of a set size range of particles suspended within a standard. Turbidity fluctuates naturally with tides, storms, and erosion, but can also demonstrate water that is degraded in other ways if it remains elevated or excessive (EPA, 2002).

Another parameter of importance is pH, which is the scale of how acidic or basic a solution is. Most marine animals and plants are tolerant of pH shifts within a modest range, but cannot survive substantial shifts (EPA, 2002). The pH of water can be affected by such factors as dissolved organics, dissolved minerals, wastewater, stormwater runoff, bacteria, chemical constituents, and industrial runoff. Algal blooms can cause a rapid pH fluctuation due to a drawdown of CO_2 lowering carbonic acid concentration. The pH varies naturally between different sections of each estuary depending on salinity; areas more defined by freshwater have a pH in the 7.0-7.5 range, and more saline zones have a pH in the 8.0-8.6 range (alkalinity due to natural carbonate and bicarbonate buffering). Changes in the pH of an estuary can be detrimental to survival of the eggs of spawning fish, the shells of mollusks, and can make metals more readily available, leading to potential toxicity or bioaccumulation (Ohrel and Register, 2006).

The salinity gradient in an estuary is largely dependent on hydrology – flow rates and how the tides move water in and out of the water body. As denser ocean water moves into an estuary during an incoming high tide, the more buoyant fresh water tends to move toward the surface, resulting in a stratified water arrangement. However, tides of higher magnitude may work with the hydrology of the estuary to create well-mixed water with uniform salinity throughout. Strong tides, wind, and storms may create well-mixed regions throughout the water column, wherein salinity is uniform and non-layered. How the water layers mix and flow alters the physical and chemical characterization of an estuary (Ohrel and Register, 2006). Circulation of the estuary can also create areas of different mixing categories within the same estuary system (Ohrel and Register, 2006). Many marine flora and fauna have limited tolerance to salinity variation, though some are highly adaptable; therefore, salinity is a key factor in estuary characterization, a significant water quality indicator, and is highly influential on the health and productivity of a water body (Ohrel and Register, 2006).

Highly industrialized areas, construction zones, and densely populated regions may experience urban stormwater runoff that causes excess nutrients, pesticides, metals, and other toxic materials to flow into estuary systems during precipitation events. Pollutant and nutrient concentrations due to runoff may follow the salinity gradient. Contaminant spikes can trigger dramatic events such as large-scale fish kills (Ohrel and Register, 2006). A constant inflow of contaminants and/or long retention times can cause biomagnification in marine species, wherein smaller organisms ingest contaminants over long periods, and the contaminants ascend the food chain through predation (Chen et. al, 2008). Contaminants and eutrophic conditions can reduce the usefulness of an estuary as a resource, causing losses to tourism, commercial fishing, boating and water recreation, and even human health risks from respiratory illness following exposure to waterborne pathogens or ingestion of contaminated marine species (Bricker et al., 1999; Board, 2000).

First Flush Phenomenon

Estuaries in highly urban settings are prone to an influx of toxic materials and nutrients when surface contaminants are mobilized by heavy rains known as the “first flush” phenomenon, when a build-up of contaminants is transported by runoff (Wilson, 2006). First flush definitions vary from a general concept that "most" of the pollutant load is carried out with the early discharge volumes (Taebi and Droste, 2004) to more specific parameters, identifying a first flush if 80% or more of the total pollutant mass discharges with the first 30% of runoff (Bertrand-Krajewski, Chebbo, and Saget, 1998). Most agree that defining first flush is challenging, and changes with factors such as rainfall totals, types of contaminants, level of urbanization, and watershed size (Wilson, 2006).

Statement of Problem

Despite the fact that Salt Creek, Booker Creek, and a major storm drain of the City of St. Petersburg discharge into Bayboro Harbor, there is little to no monitoring of annual or long-term water quality trends in the harbor, and little to no monitoring of seasonal fluctuations in water quality. There is no monitoring of urban nutrient trends in the harbor. There is no published data on the discharge from either of the heavily urbanized tidal creeks, nothing on chemical equilibrium shifts or recovery times, and no biodiversity studies. At this time, there are no known water quality studies published regarding Bayboro Harbor.

Though it is small in relation to the rest of Tampa Bay, Bayboro Harbor may be flushing a considerable amount of polluted runoff from St. Petersburg into Tampa Bay. The City of St. Petersburg has water quality monitoring stations upstream in Booker Creek, but no water quality monitoring is being performed in Bayboro Harbor by the City of St. Petersburg, Pinellas County, State of Florida, or any water regulatory agency. Without monitoring, any impacts of urban runoff on the water quality in Bayboro Harbor ecosystem will remain unknown.

Purpose of Study

An active monitoring program can identify water quality problems. Monitoring data from this study will begin to establish baseline water quality for Bayboro Harbor, its estuary characterization, and over time, will help to establish a record of water conditions and trends. This study may also provide site-specific, baseline information on water quality and nutrient sources from Salt Creek, Booker Creek, and the City of St. Petersburg stormwater system. A water quality analysis with nutrient trend data could provide a springboard for additional studies ranging from public health risk assessments to aquatic productivity and biodiversity tracking.

Since the campuses of the University of South Florida St. Petersburg (USFSP) and the USF College of Marine Science surround Bayboro Harbor, it is appropriate for the university to become a leader among the monitoring authorities on water conditions in the harbor. This study could pave the way for continued monitoring, which can provide data for development projects on shoreline improvement, and influence university activities, harbor businesses, and marinas. Water quality and nutrient concentration trends can be used as drivers for management strategies for infrastructure and urban planning. This analysis could serve to raise local awareness about contaminant transport and effect, and may contribute data to centralized water quality databases about the Tampa Bay estuary system. It is the hope that this study is the beginning of a multi-year monitoring program, which could provide training and research opportunities for students, and long-term data to water regulatory agencies to support environmental legislation for local waterways and urban planning for stormwater systems.

Research Questions and Objectives

The primary research question for this study focuses on determining whether there is a difference in the water quality in Bayboro Harbor during the dry season versus the wet season, and which water quality parameters demonstrate any such changes. A secondary research question is as follows: If water quality diminishes with the onset of the wet season, is it because of an identifiable "first flush" phenomenon, or are there gradual declines in water quality more directly related to periodic wet season precipitation events, or might both trends be observed?

Objectives include development of a monitoring strategy for Bayboro Harbor that measures water quality, develops a baseline of water quality parameters, and analyzes nutrient concentration (nitrate-nitrite and orthophosphate), as well as to develop conclusions regarding stormwater and the influence of urban runoff. Some of the water quality parameters in this study – temperature, precipitation, dissolved oxygen, pH, salinity, turbidity, nitrate-nitrite, and orthophosphate – may show trend correlation, and a statistical examination of the mean trends from multiple inflow and open water collection sites could serve to characterize the harbor. The trend comparing dry season to wet season from the collection sites may provide insight about significant influences on harbor water quality.

Hypotheses

Bayboro Harbor, as a receiving water body with two heavily-urbanized tidal creeks and one of St. Petersburg's largest storm drains, will likely experience decreased water quality and increasing nutrient concentrations at the beginning of the wet season. Nutrient levels are expected to spike with a distinct "first flush" phenomenon during the storms at the beginning of the rainy season in June as the higher water volume carries a more concentrated contaminant load into the harbor at the major discharge points (Wilson, 2016). According to the Pinellas County 2003-2010 Ambient Monitoring Program Annual Report, water quality tends to decrease during the wet season (Levy et al., 2011), so it is expected that Bayboro Harbor will demonstrate lower water quality and increased eutrophication due to higher nitrogen and phosphorous flux from increased urban runoff during the wet season. After the increase of contaminants transported by initial wet season runoff, the consistent seasonal precipitation may transport a lower, steady concentration of contaminants and nutrients before water quality begins to improve.

As the discharge point of Booker Creek is partially protected from harbor currents by a physical barrier on one side, and the stormdrain is the farthest sample point from the mouth of the harbor, these two locations are expected to contribute a more concentrated influx of poor-quality, nutrient-rich water, potentially driving poor water quality in the harbor. The discharge point of Salt Creek is close to the mouth of the harbor, and strong observed currents make it likely that the outflow zone at Salt Creek will be more mixed than the other two outflow locations, and may show water quality that is less degraded, and with lower nutrient concentration. The sample site at the marina's breakwater should show the most representative water sample for Bayboro Harbor due to its central location and observable current that will likely provide a well-mixed sample. The sample site near the mouth of the harbor will probably not demonstrate robust variance in water quality throughout the study, because this site is more often flushed by the changing tide in Tampa Bay; however, it is possible that the entire bay will also experience the first flush phenomenon.

Study Site, Materials, and Methods

Tampa Bay

The Tampa Bay Estuary system in located on the west-central coast of the Florida peninsula. The National Oceanographic and Atmospheric Administration (NOAA) collects weather data at St. Petersburg's Albert Whitted Airport, which is adjacent to the mouth of Bayboro Harbor as it empties into Tampa Bay. Based on historic data (1981-2010) from NOAA's Albert Whitted Station, the area receives approximately 130 *cm* (51 *in*) of rain per year. The humid subtropical climate has a pronounced rainy season from June through September, and a dry season from October to May. Elevated rainfall associated with weather fronts is not uncommon in the first few months of the year (Figure 1). More than half of the annual precipitation is received during the four-month wet season (Levy et al., 2011; NOAA 1981-2010; Morrison and Greening, 2011 Ch6).

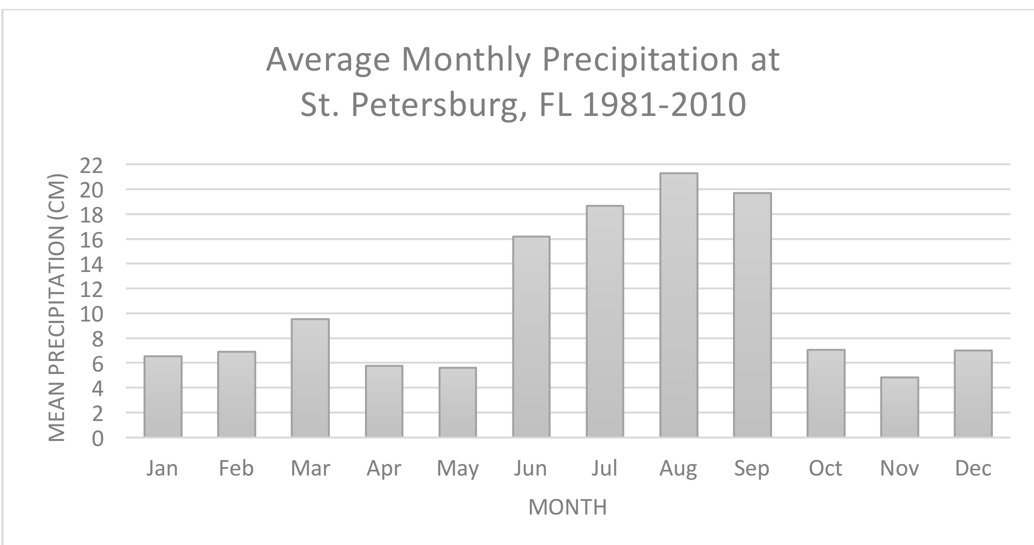


Figure 1. Average Monthly Precipitation at St. Petersburg, FL, 1981-2010 (NOAA Albert Whitted Station, St. Petersburg, Florida).

Tampa Bay has an area of approximately 1,000 km^2. The average water depth is a relatively shallow 4 *m*, though dredging and engineered shipping channels have created areas with depth to approximately 13-15 *m* to allow for the passage of ships and boats (Greening et al., 2014; Morrison et al., 2006). Along with the impact of astronomical tides, circulation in Tampa Bay is largely driven by wind, as the bay is wide and shallow. The watersheds discharge relatively low volumes of freshwater to the estuary, which enables wind-driven mixing of salt and fresh waters, increasing the likelihood of a better-mixed water column that is less reflective of the differing densities of ocean water and fresh water (Morrison and Yates, 2011 Ch2).

Tampa Bay houses one of Florida's busiest ports. Commercial shipping is a major part of the regional economy, and a network of shipping channels are maintained to support the economic benefits of this industry. Though necessary to support industry, this bathymetric re-engineering can contribute to hydrological shifts in the estuary system (Morrison and Yates, 2011 Ch2). A wide variety of salinities spread through Tampa Bay, ranging from 15-40 *ppt* (parts per thousand) (PCSM, 2017).

The Tampa Bay tides are primarily classified as semidiurnal-mixed, wherein there are two unequal high tides and two unequal low tides daily. The type of tides and the high and low points continually shift times of day throughout the year. True semidiurnal tides (with two equal daily highs and two equal daily lows) do occur. The bay also occasionally experiences diurnal tides, with only one high tide and one low tide occurring daily. Tidal combinations are also possible, with two high tides and one low tide (or vice versa) occurring in a 24-hour period (Goodwin, 1987; Morrison and Yates, 2011 Ch2).

Tampa Bay has multiple bays, lagoons and bayous forming one, large interconnected system, which is commonly segmented into named regions to allow for management and monitoring. The seven interconnected segments are Old Tampa Bay, Middle Tampa Bay, and Lower Tampa Bay, along with Boca Ciega Bay, Hillsborough Bay, Terra Ceia Bay, and the tidal reach zone of the Manatee river, which empties into the mouth of Tampa Bay and the Gulf of Mexico (Figure 2). The Tampa Bay estuary is the largest open-water estuary in Florida (Morrison and Yates, 2011 Ch2). Middle Tampa Bay is the largest of the segments by area, at 310 km^2 (Greening et al., 2014). The watershed that discharges freshwater to Tampa Bay is a region of approximately 5,700 km^2. The sub-tropical climate, broad coverage area, and wide range of salinities in Tampa Bay all provide support for robust levels of biodiversity and economic activity, making the bay a significant environmental and recreational resource. The Tampa Bay estuary has substantial mangrove and submerged aquatic vegetation habitats (Greening and Janicki, 2006).

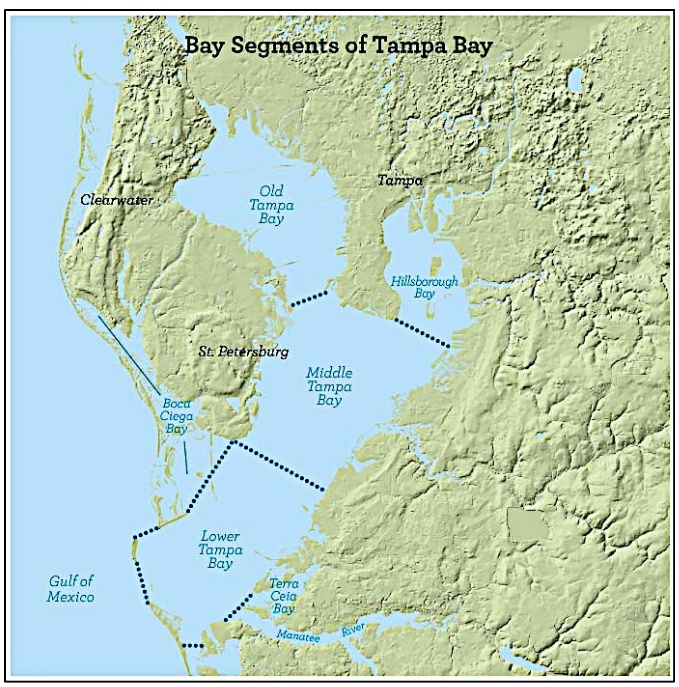


Figure 2. Segments of the Tampa Bay Estuary System (Source: swfwmd.state.fl.us).

The Tampa Bay region is highly urbanized, with densely populated cities and smaller municipalities surrounding the bay. A growing population of about 3 million people makes programs for protecting and cleaning up the estuary that much more crucial to the long-term health of Tampa Bay.

The increasing industrial, urban, and suburban land use that comes along with population density is of increasing concern, and has direct, measurable impacts on estuaries. Additionally, the bathymetry of the bay is continually modified to support active commercial port activities, and urban growth continues to encroach on the remaining natural shorelines. Increasing impervious surface area leads to increased stormwater runoff (Xian and Crane, 2005). Stormwater management practices help to reduce flooding from a widespread region, though older coastal areas often discharge untreated or minimally-treated stormwater into Tampa Bay; runoff that carries high concentrations of nutrients along with other contaminants.

Pinellas County covers only 725 km^2, and is home to approximately 1 million people (a third of the population of the Tampa Bay region), making Pinellas the most densely populated county in the state. Because of this urban density, development projects tend to focus on redevelopment, and the stormwater runoff from development projects wash high concentrations of contaminants through watersheds and stormwater systems, eventually entering Tampa Bay (PCSM, 2017). Resource managers have often emphasized nutrients, algal blooms, and eutrophication in recent years, but issues such as insufficient stormwater treatment infrastructure must be considered so that problems can be solved on a larger scale (Morrison and Greening, 2011 Ch5). To date, urban planning and legislation have focused on the flood control aspect of stormwater and the regulation of specific contaminants, without addressing the larger environmental issue of untreated wastewater entering coastal waterways (NRC, 2009). More thoughtful stormwater planning must be brought to the forefront of management strategies for coastal water restoration, as the Tampa Bay estuary system and its watershed still contain many waters classified as "impaired" based on the standards of the U.S. Environmental Protection Agency and the Florida Department of Environmental Protection (Morrison and Greening, 2011 Ch5).

Water regulatory agencies and private resource management organizations monitor and attempt to control and improve environmental quality in Tampa Bay, with millions of tax dollars dedicated annually to programs targeting pollution, stormwater, mitigation and restoration of wildlife habitats, wastewater, and land acquisition. Legislative approaches over the past 40 years have resulted in improved municipal wastewater and sewage treatment practices. These practices have improved water quality from a highly degraded state in the 1970s and served to improve habitats, as well as provide notable success in terms of seagrass coverage and reduced nitrogen loading after implementation of advanced wastewater treatment facilities (Greening and Janicki, 2006). Yet many parts of Tampa Bay continue to show poor water quality, and some regions have not been included in long-term monitoring (Yates and Greening, 2011 Ch1).

Bayboro Harbor

Located in the Middle Tampa Bay segment of the estuary system, Bayboro Harbor is a small harbor on the southeast coast of St. Petersburg, Florida. The harbor covers an area of approximately 0.14 km^2, with a perimeter of about 1.7 *km* including the open end (Google Maps, 2019).

Periodic dredging alters bathymetry, but current depths are estimated to vary from 0.5-5 *m* (NOAA 2017 Nautical Chart #11416), with the greatest depth in the entrance channel at the mouth of the harbor (Figure 3), and the shallowest waters near the living shorelines (Figure 4). A sea wall encapsulates most of the harbor, and there are only a few dozen meters of living shoreline where water levels transition freely to the shore.

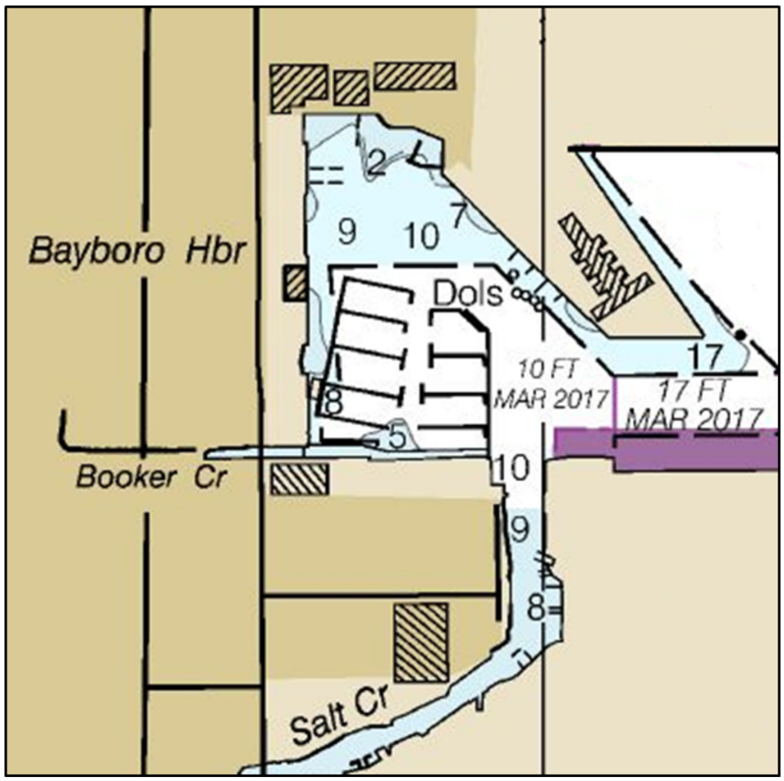


Figure 3. Bathymetry of Bayboro Harbor. Depth is displayed in feet. (Source: NOAA Office of Coast Survey. Extracted and modified from Nautical Chart 11416)

Bayboro Harbor is adjacent to the Port of St. Petersburg, and its shoreline is home to the University of South Florida St. Petersburg, Poynter Park, a U.S. Coast Guard auxiliary station, the USF College of Marine Science and its research vessels, the USFSP boathouse, an industrial fishing processing plant, and Harborage Marina, which has an 800-foot breakwater and 300 slips. Discharging into Bayboro Harbor are two tidal creeks – Booker Creek and Salt Creek – as well as a large storm drain (Figure 5).

Figure 4. Living Shoreline on the North Shore of Bayboro Harbor. This shoreline is adjacent to the University of South Florida St. Petersburg campus. Photo by author.

Booker Creek is fewer than 8 *km* long, but it drains several square kilometers of the City of St. Petersburg and discharges into the southwest corner of Bayboro Harbor. The creek's headwaters are the lake in Booker Creek Park near the convergence of I-275 and I-375 in Pinellas County. Booker Creek has nine monitoring stations, and the Pinellas County Water Atlas has data on a total of 2,391,804 samples, with collection dates from 10/1/1974 to 6/27/2019.

Salt Creek runs through the southern portion of the Lower Tampa Bay Watershed and discharges into the southern end of Bayboro Harbor. The creek's headwaters are Lake Maggiore, in south St. Petersburg. Salt Creek previously had six monitoring stations, and the Pinellas County Water Atlas has data on a total of 1,118 samples, with collection dates from 11/22/1988 to 11/9/2011.

Storm drains in heavily urbanized areas are a considerable source of untreated water that ends up in almost every water body. This untreated water often contains fertilizers, pesticides, domestic pet waste, and runoff from roofs, parking lots, and roads (Ocean, 2003). A major storm drain discharges into the north side of Bayboro Harbor. At 122x274 *cm* (48x108 *in*) in diameter (Figure 5), this storm drain is one of the largest in the city (personal conversation with Senior Engineer Carlos Frey, City of St. Petersburg), and has a vigorous storm water flow during and after heavy rain (Figure 6).

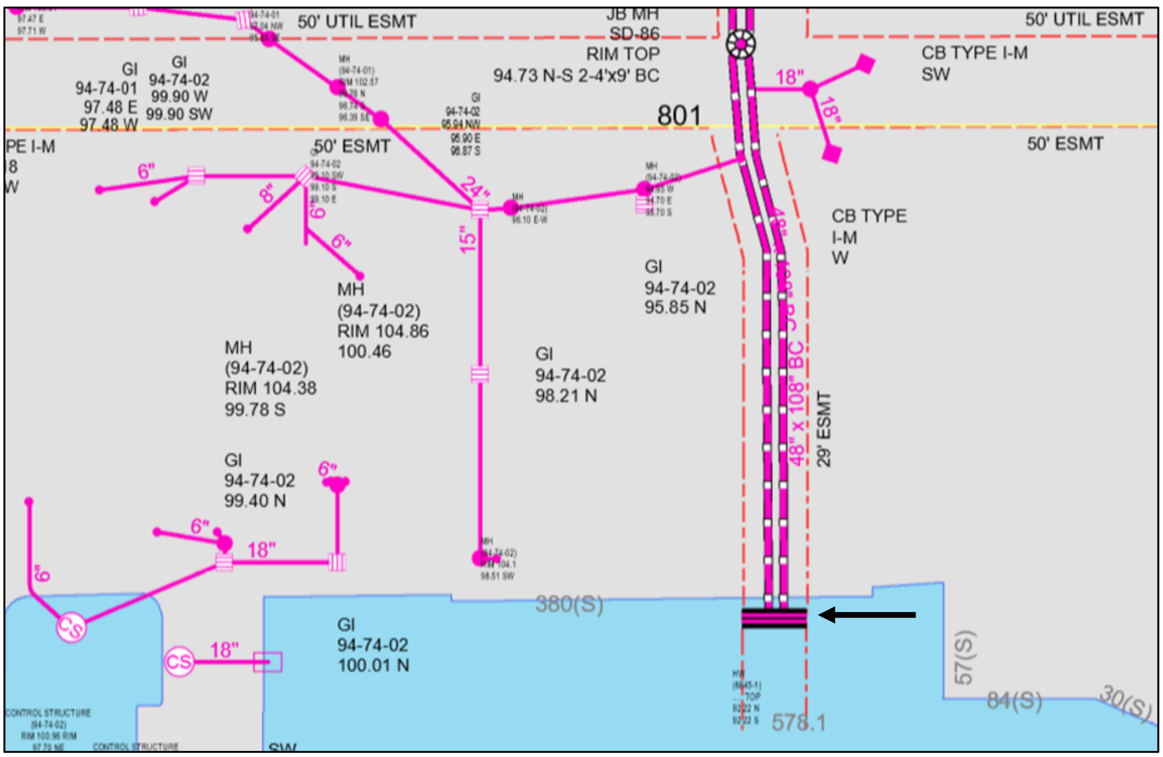


Figure 5. Stormwater Drain in Bayboro Harbor. Collection site BH05 indicated by black arrow. (Source: City of St. Petersburg Stormwater Utility Map E-5)

Figure 6. Stormwater Drain Outflow After Active Storm. Stormwater was observed to be rushing out of the storm drain with such high velocity that it created a roiling effect above the surface. Photo by author.

Site Selection and Tidal States

Data collection for this study took place over a 22-week period from mid-March through mid-August, 2019. Meteorological and tide readings came from NOAA Station SAPF1 #8726520 (Port of St. Petersburg/Albert Whitted Airport). Five sample sites were selected to represent the harbor water and its major points of net water transport (Figure 7). Site 1 is located on the west side where Booker Creek empties into the harbor. Site 2 is the farthest seaward point on the breakwater located in the approximate geographic center of the harbor. Site 3 is located at the southwest side where Salt Creek discharges into the harbor. Site 4 is located at the southernmost tip of the College of Marine Science peninsula, and is closest to Tampa Bay, intended to serve as a control site with water quality probably more like Tampa Bay than Bayboro Harbor. Site 5 is located at the northern side of the harbor at the discharge point of the large storm drain adjacent to the USFSP campus and proximal to the living shoreline.

Figure 7. Bayboro Harbor Sample Sites. (Google Earth, 2019). Site IDs: BH01 Booker Creek, BH02 Breakwater, BH03 Salt Creek, BH04 Peninsula, BH05 Storm Drain.

The mid-point of a falling tide (ebb tide) was expected to provide the most accurate characterization of Bayboro Harbor, as it would be less influenced by incoming water from Tampa Bay and more influenced by buoyant freshwater outflow at the surface. Since Tampa Bay experiences primarily mixed-semidiurnal tides, with two unequal high tides per day, the mid-ebb sampling took place after a lower high water tide or a higher high water tide depending on feasibility of access. On several occasions during the study, water quality readings took place shortly after a high water peak due to lack of access to a mid-ebb tide state. To minimize variation in nutrient concentration readings, water samples for nutrient analysis were only collected during mid-ebb tide states. In previous studies, water quality parameters measured during diurnal tides (one high tide and one low tide per day) demonstrated variations with a greater range than seasonal variations, illustrating the importance of tide state in developing a monitoring program (Yates et al., 2005), though no standard tidal state for sampling estuaries could be found in published literature.

Tides were predicted using information from the NOAA Tides & Currents Station #8726520 (tidesandcurrents.noaa.gov). To account for the mixed tides of Tampa Bay and Bayboro Harbor, site visits occurred during the same tide state (except as noted above) and on the same day of every week for 22 weeks. Water quality readings were taken weekly, and water samples were collected weekly or bi-weekly at the same time as the instrumental *in-situ* readings. The first half of data collection took place during the dry season, with weekly sonde readings and bi-weekly water sample collection. The second half of the data collection occurred during the rainy season. Water samples were collected weekly for the first six weeks to capture expected nutrient fluctuations that corresponded with influx from increased precipitation.

Materials and Methods

Prior to first use, polypropylene collection and storage containers were decontaminated and prepared by soaking for one week in 1.5% Decon™ Citrad™ acidic detergent bath, followed by a four-week 10% Trace Metal Grade (TMG) hydrochloric acid bath. Filtration apparatus components received a detergent and 10% TMG hydrochloric acid rinse prior to use. Decontamination steps were prepared with analyte-free water from a ThermoScientific Barnstead B-Pure ultrapure water system. Collection and storage containers were decontaminated between uses in 10% TMG hydrochloric acid for one week and then rinsed three times with analyte-free water. Decontaminated containers were filled with analyte-free water and stored until use. Preparation methods were modified from the standard operating procedures of the USF College of Marine Sciences Oceanic Nutrient Laboratory, which are based on sampling and sample-handling protocols for GEOTRACES cruises (Cutter et al., 2014). These stringent preparation methods were used in order to meet or exceed U.S. Environmental Protection Agency (EPA) and Florida Department of Environmental Protection (DEP) standards for surface water sampling.

A portable *In-Situ* Aqua TROLL 500 Multiparameter Water Quality Sonde (Figure 8) was used to capture water quality parameter readings in the field at five sample sites around Bayboro Harbor (Figure 7). The EPA-approved Aqua TROLL 500 has a sensor configuration that records optical dissolved oxygen (DO), pH, turbidity, temperature, conductivity, pressure, salinity, resistivity, total dissolved solids (TDS), and density, with data interface capabilities to download live readings to the VuSitu Android phone app via Bluetooth connection. The parameters recorded for analysis are salinity (PSU), temperature (°C), pH, turbidity (NTU), dissolved oxygen concentration ($mg\ l^{-1}$), and percent saturation of dissolved oxygen (%Sat). The Aqua TROLL 500 software records latitude and longitude to establish that site data is captured with minimal variance in location.

Figure 8. *In-Situ* Aqua TROLL 500 Showing Sensor Array (www.in-situ.com).

Field sample collections were carried out according to the Florida Department of Environmental Protection Standard Operating Procedures FS 1000 and FS 2100 (FDEP, 2017). Sonde readings were taken at depths of 0.21-0.24 *m* (Figure 9) to be compatible with the instrument parameters and the Pinellas County Public Works Standard Operating Procedures (PCPW, 2017). The collection radius was within 2.0 *m* at each sample site for duplication. Water grab samples were collected using United Scientific 500 *mL* polypropylene wide-mouth reagent bottles. To prevent biological activity from changing the nutrient concentrations after collection, samples were stored on ice in the field within 15 minutes of collection, then filtered within 2-3 hours of collection and stored in a -80 °C freezer (FDEP, 2017).

Filtration was executed using an Advantec #43301050 Wide-Mouth Polysulfone Filter Holder, attached borosilicate side-arm flask with diaphragm pump, and Simsii Nylon Membrane Filters (47 *mm* diameter, pore size 0.22 μm). Filtrate volume of 40-45 *mL* from each sample site was transferred to a 50 *mL* Falcon polypropylene conical tube and stored in a -80˚C freezer pending autoanalyzer analysis.

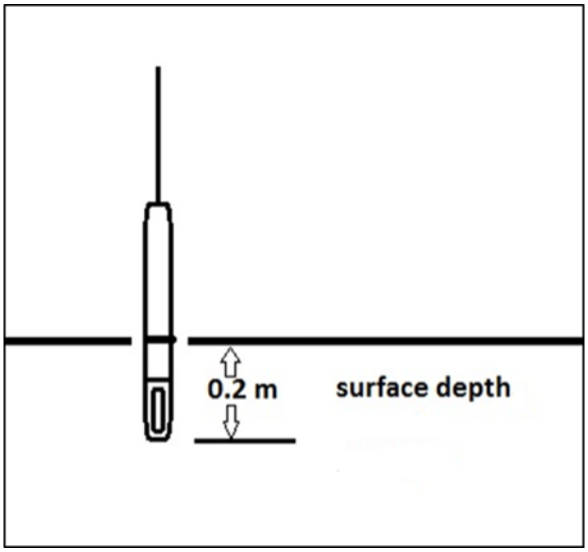


Figure 9. Depth for Sonde Readings (Taken from Pinellas County Public Works Surface Water Sampling Manual SOP 2017).

Reagents for autoanalyzer analysis were prepared the day before testing in order to degas. Samples were thawed the day of testing in a cool water bath and analyzed for nutrient concentration (NO_x and PO_4^{3-}) in the USF College of Marine Sciences Oceanic Nutrient Laboratory using a Lachat QuikChem® 8500 Flow Injection Analysis system with a Lachat XYZ Autosampler. Concentrations were reported in micromolar units (μM).

Data Analysis

Analysis included time series trend assessments of the mean water quality parameters from a combination of the five sample sites to evaluate differences between the 11-week dry season and 11-week wet season data sets. Time series plots were also performed to examine trends of individual parameters, comparing the mean from all five sites. Additional time series analysis was applied to the data from individual sample sites to explore trends in the parameters. When applicable, site findings were paired for analysis. Analysis included descriptive statistics as well as graphical observations. Precipitation events were charted weekly and were incorporated as a statistical parameter.

Statistical analysis was performed using StatCrush (company) statistical software application to generate descriptive statistics and a correlation matrix on the combined mean using the parameters from all sample sites to determine statistically significant differences, which determines if there are any linear relationships between parameter pairs, and whether the pair correlates positively (both increase) or negatively (one increases as the other decreases). Descriptive statistics were generated to find mean values for each parameter in dry versus wet season. Two sample *t*-tests of the mean data for each parameter by season were generated to determine any statistically significant differences between dry and wet season parameter means. *T*-test results were considered statistically significant when probabilities (*p*-values) were ≤ 0.05 (confidence interval $\geq 95\%$). Additional descriptive statistics and graphs were generated with Microsoft Excel 2013 to compare data by sample site and investigate specific parameters.

Results

Seasons

The transition from dry season to wet season over the course of the study can be observed in a time series graph of weekly precipitation totals (Figure 10) with data from the closest meteorological station to Bayboro Harbor (NOAA SAPF1 #8726520, Port of St. Petersburg/Albert Whitted Airport). A two-sample *t*-test comparing mean dry season weekly precipitation to mean wet season weekly precipitation determined a statistically significant difference (p-value ≤ 0.05; confidence interval $\geq 95\%$), meaning that the 22-week study was an appropriate representation for the longer seasons. The mean dry season weekly precipitation total was 1.11 *cm* and the mean wet season weekly total was 5.04 *cm*.

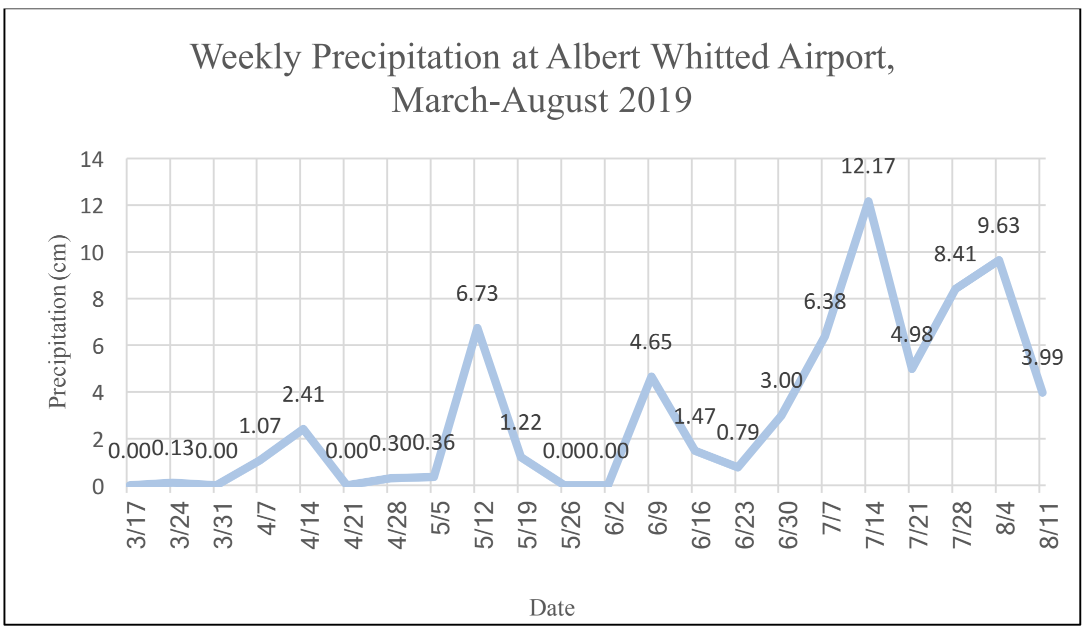


Figure 10. Weekly Mean Precipitation Totals (NOAA Albert Whitted Station).

A time series graph of *in-situ* surface water temperatures (Figure 11) demonstrates lower temperatures during the dry season, a few weeks with minimal change in May, and warmer temperatures during the wet season. The wet season trends in the graph display an alternating weekly high-low pattern of temperatures. A two-sample *t*-test comparing dry season weekly mean temperatures to wet season weekly mean temperatures determined a statistically significant difference (p-value ≤ 0.05; confidence interval $\geq 95\%$). The overall mean dry season weekly surface water temperature was 26.3°C and the overall mean wet season weekly surface water temperature was 29.7°C.

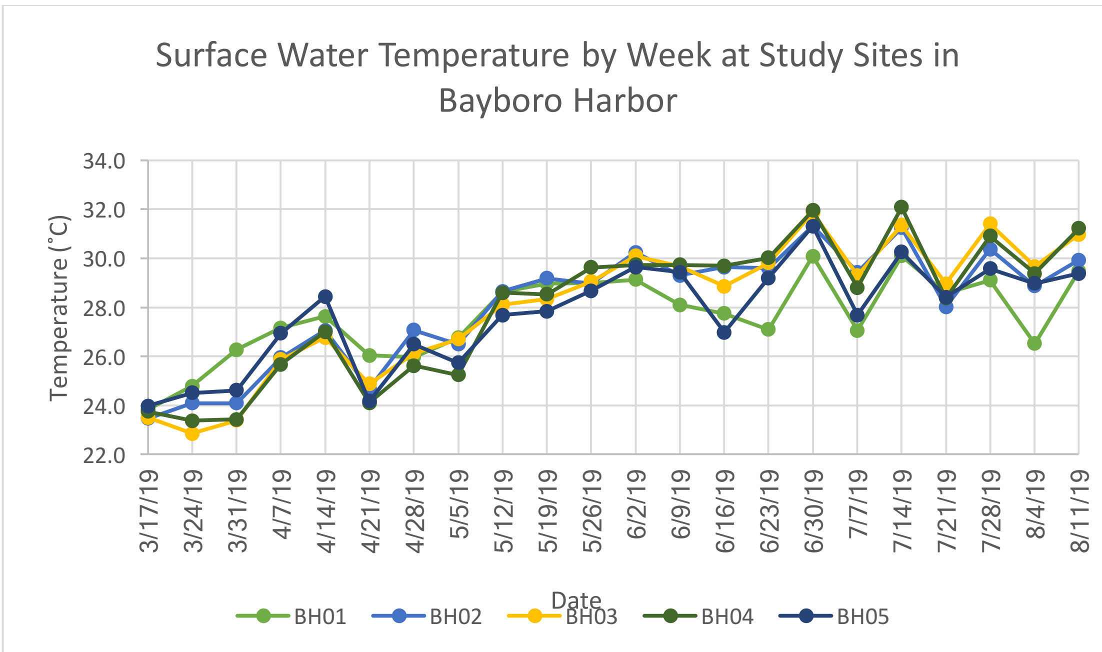


Figure 11. Surface Water Temperature by Week at Study Sites in Bayboro Harbor. Site IDs: BH01 Booker Creek, BH02 Breakwater, BH03 Salt Creek, BH04 Peninsula, BH05 Storm Drain.

Correlations and *T*-Tests

A correlation matrix generated with the mean values of all parameters was used to determine statistically significant correlations (linear relationships) between parameters. Results were considered significant when probabilities (p-values) were ≤ 0.05 (confidence interval $\geq 95\%$). Parameter pairings not demonstrating statistical significance are not included.

Salinity showed negative correlation with precipitation, meaning that when precipitation increased, salinity in the harbor decreased. Moreover, salinity was positively correlated with dissolved oxygen percent saturation, meaning that when salinity increased, DO%Sat increased as well. Finally, salinity displayed a positive correlation with orthophosphate concentration, which may be more linked to decreased precipitation than increased salinity.

Dissolved oxygen concentration is the measurement of mass of O_2 per volume unit of water. As expected, dissolved oxygen concentration showed a positive correlation with temperature because, when all else is equal—cooler water holds more DO than warmer water. A two-sample *t*-test comparing dry season dissolved oxygen concentration to wet season dissolved oxygen concentration determined a statistically significant difference.

The DO concentration is divided by the DO saturation in the water, and the resulting ratio converted to a percent to equal DO%Sat. Dissolved oxygen percent saturation is a way to calculate the equilibrium between the atmosphere at a given temperature and pressure, with water at a given salinity, assuming no biological activity. Dissolved oxygen %Sat showed a positive correlation with dissolved oxygen concentration (p-value ≤ 0.05; confidence interval $\geq 95\%$).

Nitrate-nitrite (NOx) showed a positive correlation with precipitation, which is not surprising because it is expected for precipitation to flush nitrogen from the landscape into the harbor. NOx had a negative correlation with dissolved oxygen concentration and with pH, meaning that when NOx increased, the other parameter decreased.

A positive correlation was detected between pH and dissolved oxygen concentration and %Sat.

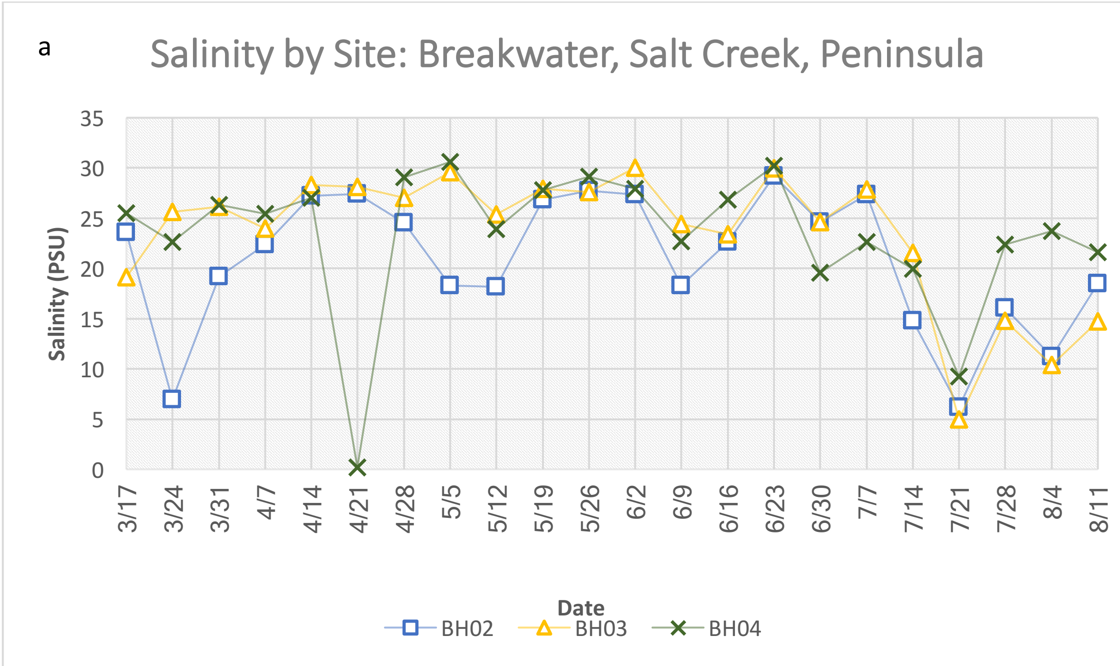
Turbidity did not show statistically significant correlations with any other parameter.

Parameters by Site and Combinations

The five sample sites were plotted on time series graphs by parameter in order to detect trends. Sites were evaluated together and in smaller combinations when noticeable trends presented. Some parameters are split into separate graphs so that sites with similar trends can be readily observed.

A temperature time series graph (Figure 11) showed an overall trend of higher water temperatures during wet season, which makes sense because the wet season coincides with the region's warmest months. The breakwater, Salt Creek, and peninsula maintained similar trends throughout the study period, with the stormwater drain following the same general trends, but with more variability. Booker Creek temperatures were observably higher than most sites during dry season and lower than most sites during wet season. A distinctive high/low temperature pattern is observable during dry season, but falls within the upward temperature trend throughout the study.

Salinity values at the breakwater, Salt Creek, and peninsula appear to follow a close trend on a time series graph (Figure 12a). Salinity at Booker Creek and the stormwater drain also trend similarly (Figure 12b), though the values vary by site. Booker Creek had lower salinity than all other sites with the exception of four sample dates during the study period. Mean salinity in the harbor during dry season was 21.1 PSU, and 17.4 PSU during the wet season.



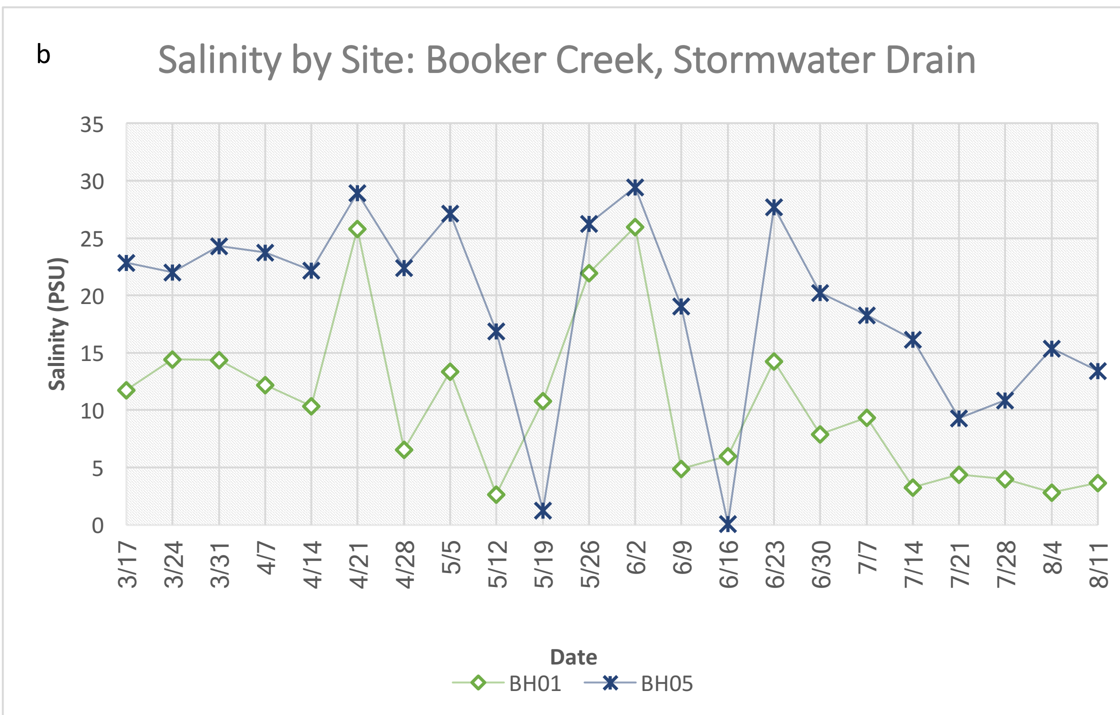
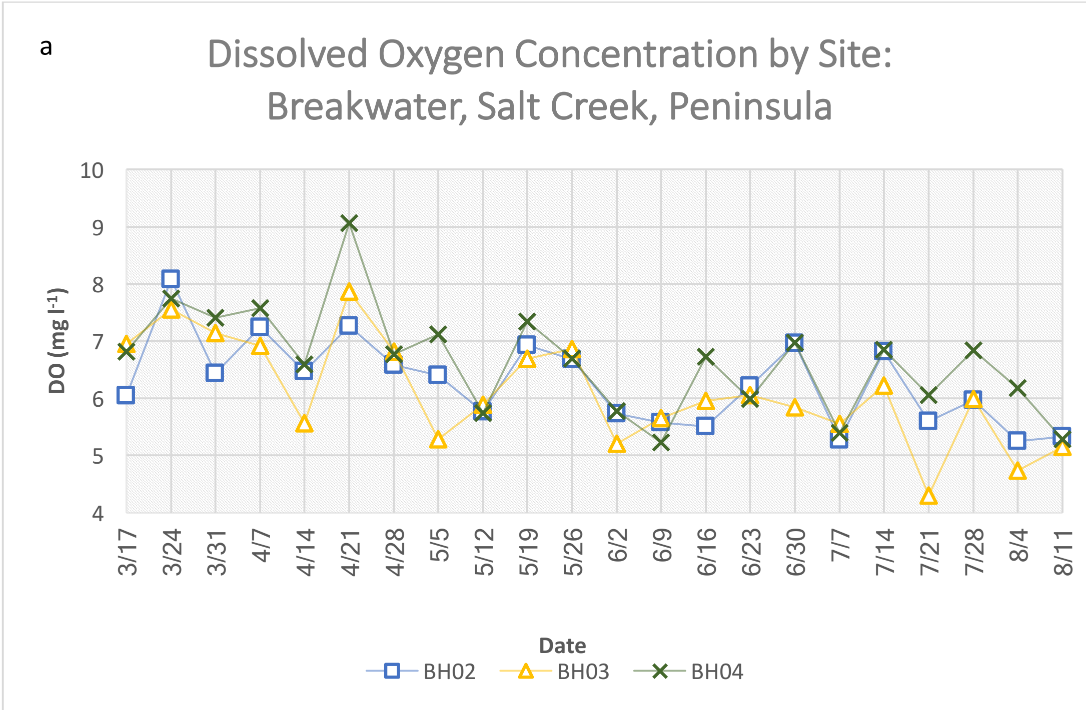


Figure 12. Salinity by Site. (a) Breakwater, Salt Creek, Peninsula. (b) Booker Creek, Stormwater Drain. Site IDs: BH01 Booker Creek, BH02 Breakwater, BH03 Salt Creek, BH04 Peninsula, BH05 Storm Drain.

Dissolved oxygen concentrations varied widely. Using a time series graph, the breakwater, Salt Creek, peninsula, and stormwater drain all show an overall downward trend (Figure 13a), compared to a slight rising DO concentration trend that can be observed in Booker Creek (Figure 13b). The downward trend is expected because as summer progresses and water becomes warmer, it holds less DO. The high, increasing DO may indicate higher photoautotroph activity in Booker Creek influenced by higher nitrate fluxes. The stormwater drain showed multiple dramatic peaks and valleys compared to the other sites (Figure 13b. The mean DO concentration for dry season was 6.6 $mg\ l^{-1}$, and the mean DO concentration for wet season was 6.0 $mg\ l^{-1}$.).

Dissolved oxygen %Sat appeared to be widely varied. Using a time series graph, similar trends in DO%Sat can be observed at the breakwater, Salt Creek, and peninsula sites (Figure 14a). The peninsula never had the lowest percent saturation compared to the other sites, and Booker Creek had the lowest percent saturation on half of the sample dates (Figure 14b). The stormwater drain had the highest range in values, from 61-119% saturation. The mean DO%Sat during dry season was 92% and the mean DO%Sat during wet season was 86%.



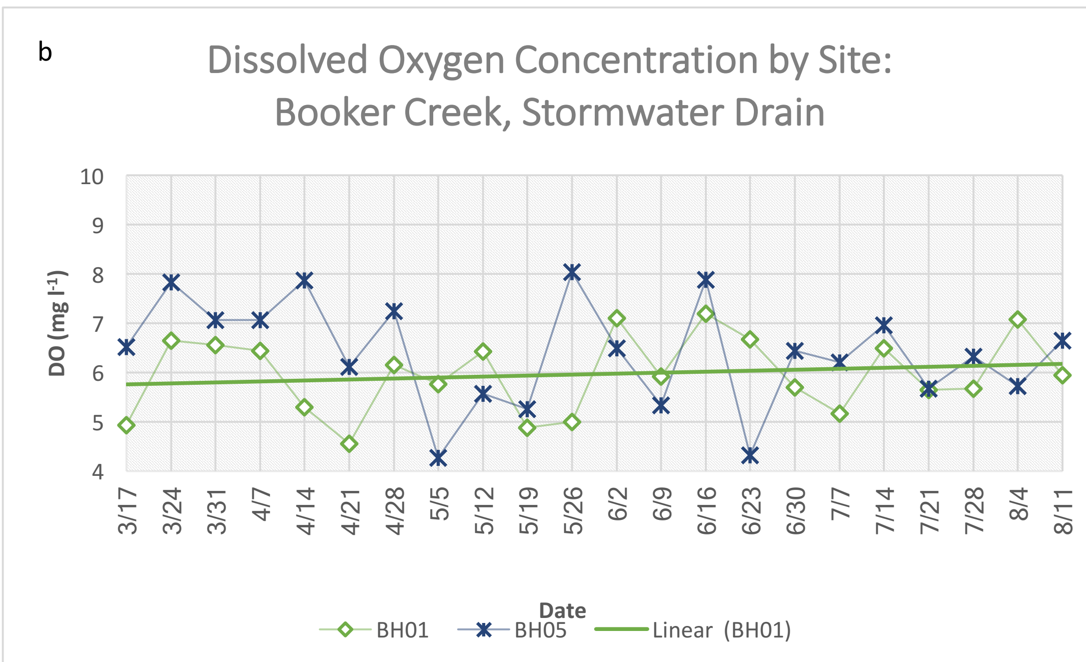


Figure 13. Dissolved Oxygen Concentration (*mg l*$^{-1}$) by Site. (a) Breakwater, Salt Creek, Peninsula. (b) Booker Creek, Stormwater Drain. Site IDs: BH01 Booker Creek, BH02 Breakwater, BH03 Salt Creek, BH04 Peninsula, BH05 Storm Drain.

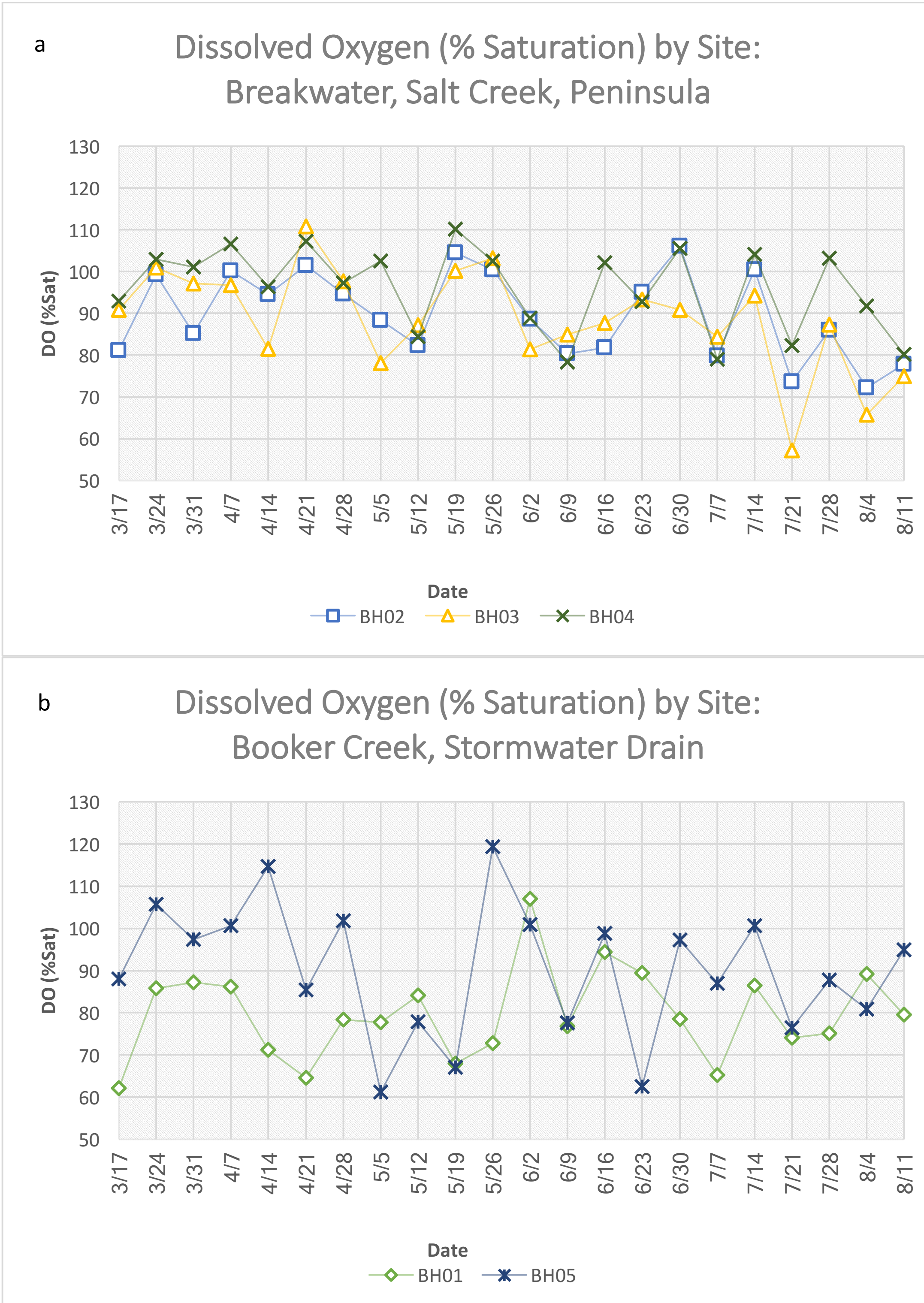


Figure 14. Dissolved Oxygen (% Saturation) by Site. (a) Breakwater, Salt Creek, Peninsula. (b) Booker Creek, Stormwater Drain.

The recorded pH values varied widely, though time series graphs did exhibit several trends (Figure 15). Salt Creek and the peninsula held a similar pH trend throughout the study, with more variation observed during the wet season than during the dry season. The stormwater showed several dramatic rises in pH in May and June. Booker Creek had the lowest pH on all sample dates with the exception of the stormwater drain dropping lower on one occasion. The peninsula had the highest pH with three exceptions, when it was surpassed by the stormwater drain. The mean pH of the harbor during dry season was 8.1, and the mean pH during wet season was 7.9. This makes sense because precipitation is naturally acidic (pH about 5.5).

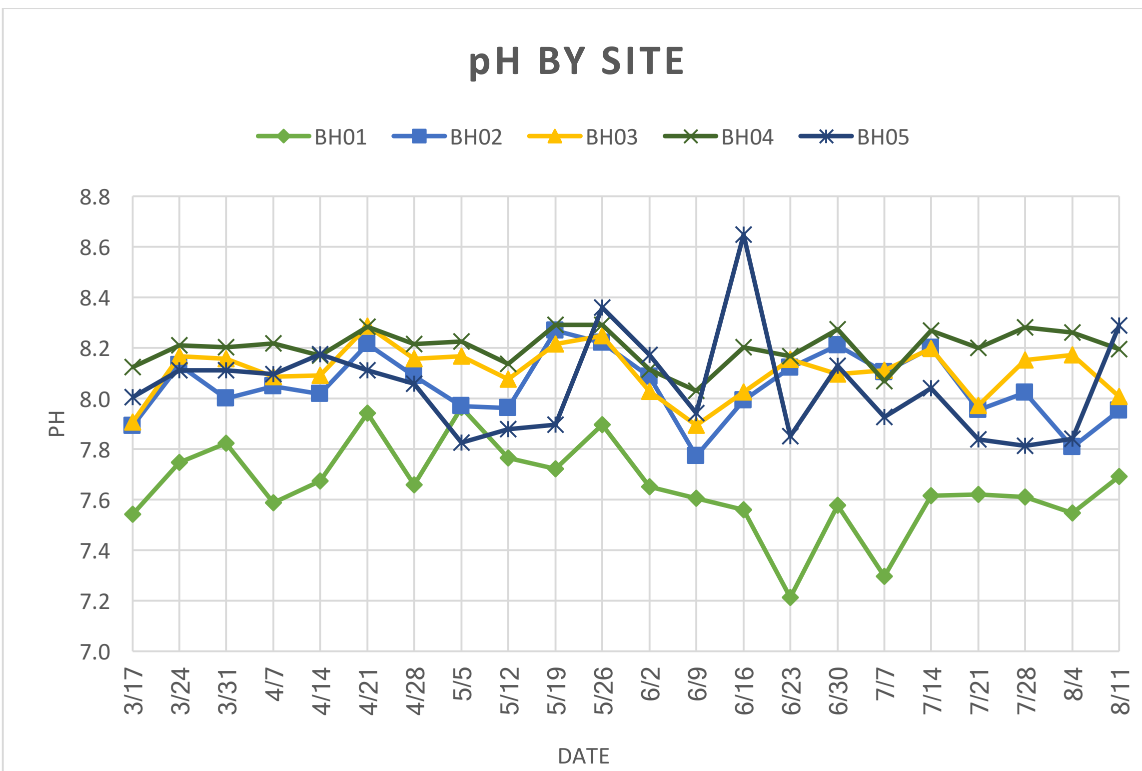
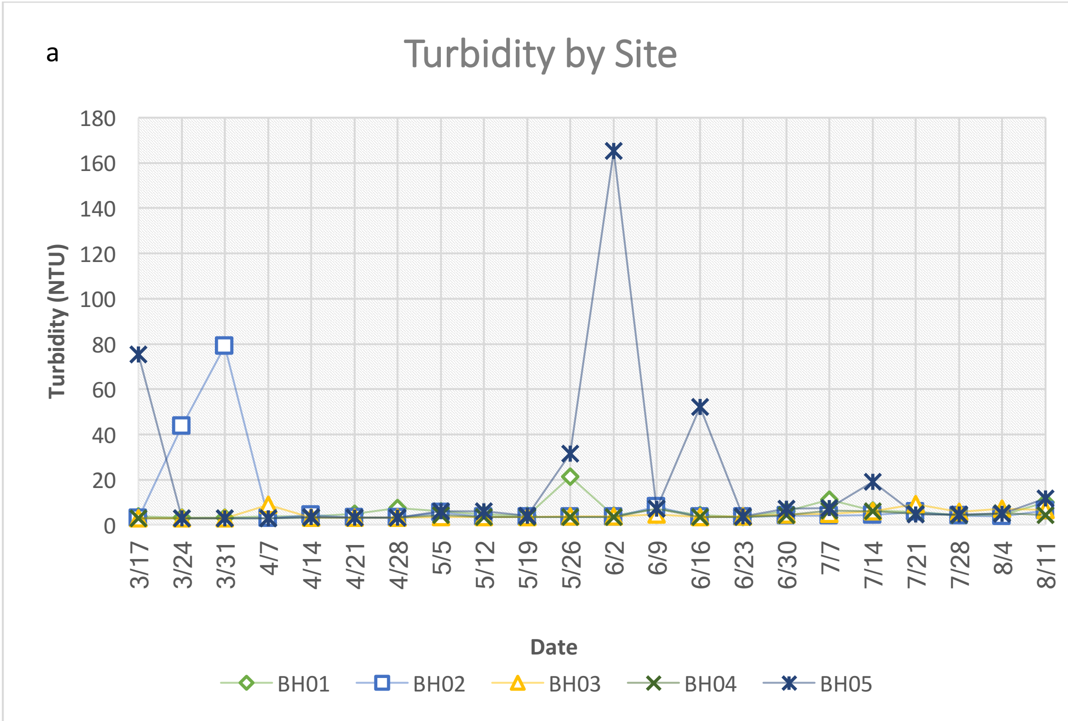


Figure 15. pH by Site. Site IDs: BH01 Booker Creek, BH02 Breakwater, BH03 Salt Creek, BH04 Peninsula, BH05 Storm Drain.

Turbidity at the breakwater and stormwater drain showed several high magnitude peaks (Figure 16a). Additionally, Salt Creek and the peninsula (Figure 16b) showed a nearly identical trend throughout the duration of the study until July, with the exception of a few peaks earlier in the season. The mean turbidity during the dry season was 8.02 NTU, and 9.44 NTU during the wet season.

Nitrate-Nitrite concentrations (NOx) showed several graphical trends. Precipitation is included in the nutrient graphs to illustrate runoff trends. The breakwater, Salt Creek, and peninsula followed a positive trend, where the NOx at each site increased and decreased with precipitation trends (Figure 17a). Their NOx readings were lower than the other two sites; often below 5 μM and never more than 11 μM. Booker Creek had the highest NOx concentration (Figure 17b) throughout the duration of the study, with the exception of one sample date when it was overtaken by the stormwater drain. These two stations featured the highest NOx readings, and Booker Creek often reached levels between 10-24. The mean NOx concentration for all stations during dry season was 6.8 μM, and the mean NOx concentration during wet season was 7.4 μM. This clearly reflects the fact that runoff sweeps nitrogen from the landscape and deposits it in Bayboro Harbor when it rains.

Time series graphs of orthophosphate concentration show site trend similarities. The peninsula and stormwater drain displayed similar trends over much of the study (Figure 18a), as did the breakwater and Salt Creek (Figure 18b), which also appear related to precipitation trends. Booker Creek demonstrated a nearly inverse relationship with precipitation (Figure 18c). The mean orthophosphate concentration during dry season was 2.1 μM, and the mean concentration during wet season was 2.0 μM.



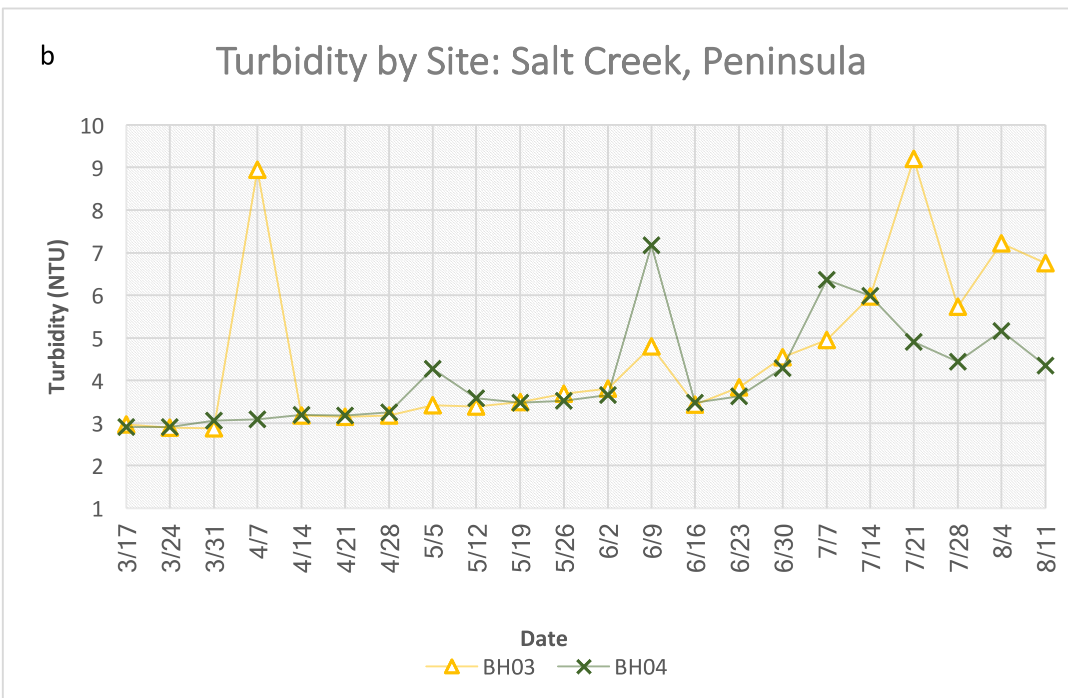
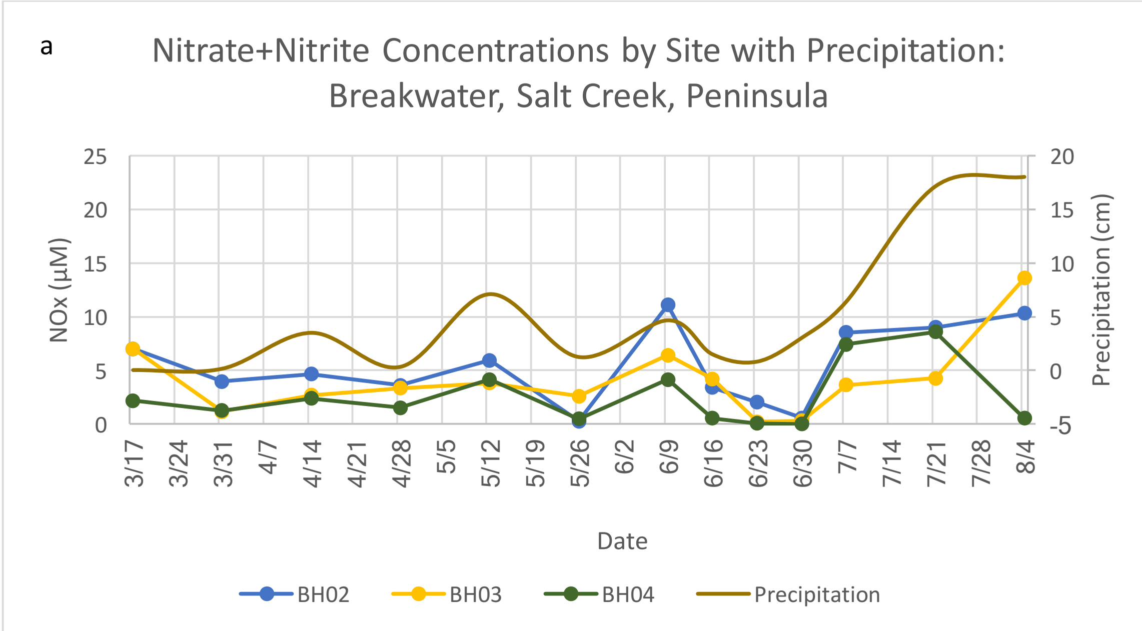


Figure 16. Turbidity by Site. (a) All sites. (b) Salt Creek, Peninsula. Site IDs: BH01 Booker Creek, BH02 Breakwater, BH03 Salt Creek, BH04 Peninsula, BH05 Storm Drain.



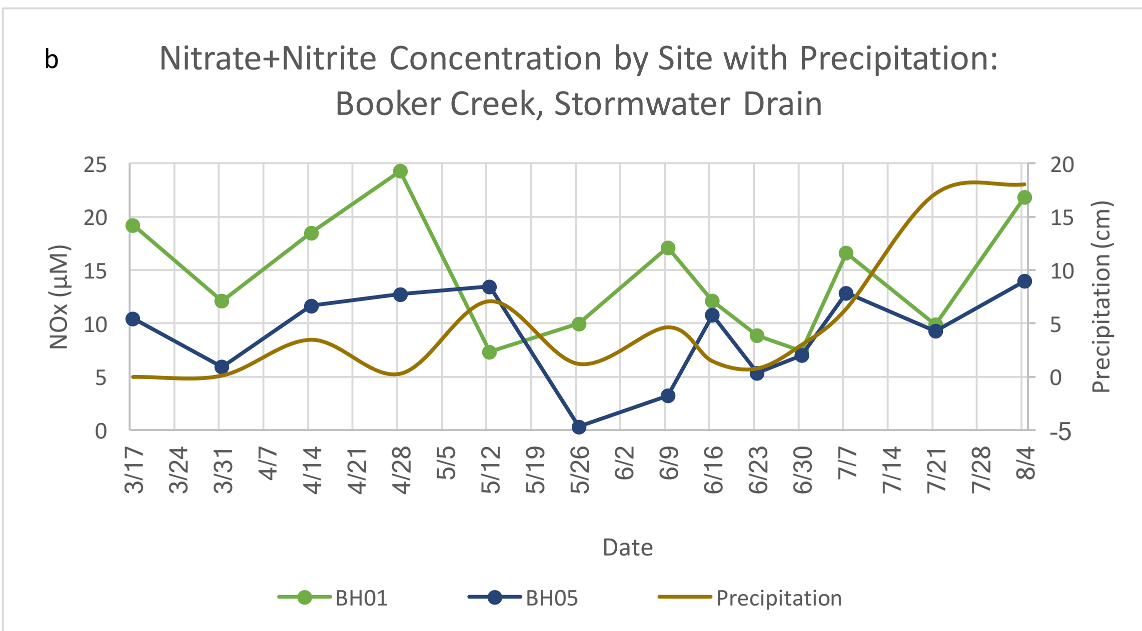
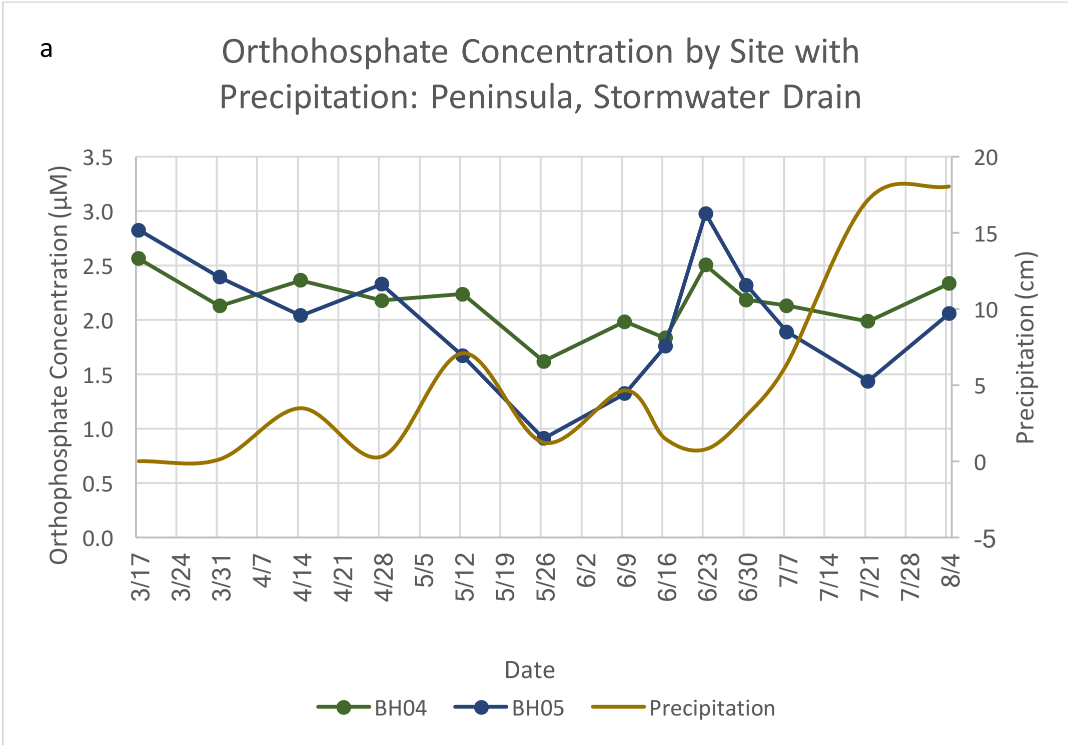


Figure 17(a) and (b). Nitrate-Nitrite Concentration by Site with Precipitation. (a) Breakwater, Salt Creek, Peninsula. (b) Booker Creek, Stormwater Drain. Site IDs: BH01 Booker Creek, BH02 Breakwater, BH03 Salt Creek, BH04 Peninsula, BH05 Storm Drain.



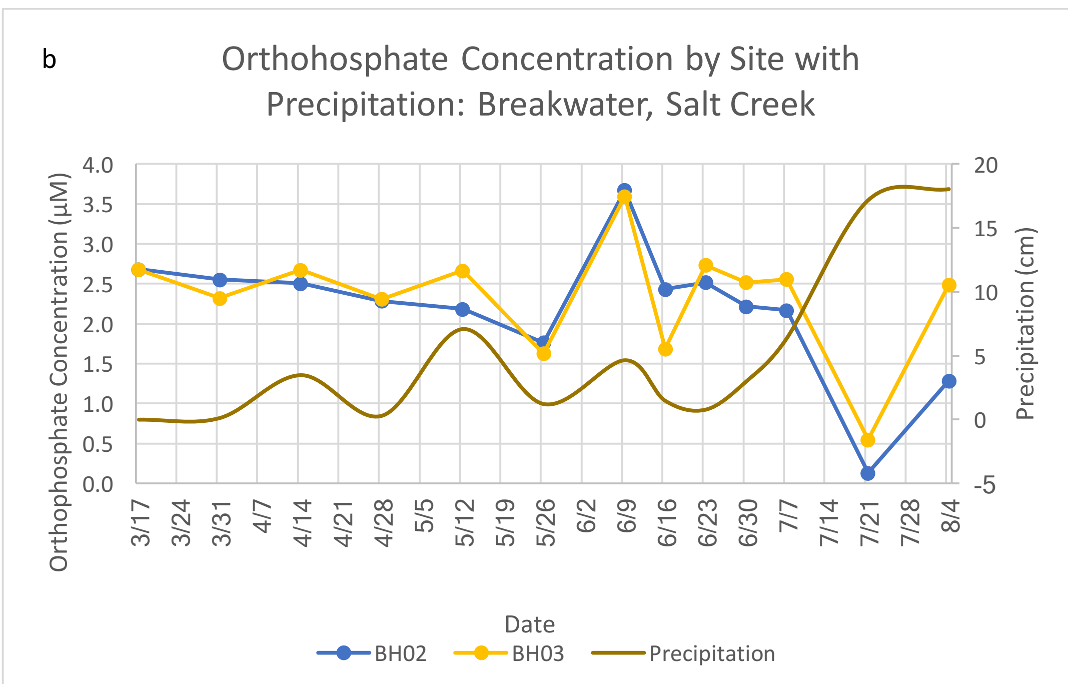


Figure 18(a) and (b). Orthophosphate Concentration by Site with Precipitation. (a) Peninsula, Stormwater Drain. (b) Breakwater, Salt Creek. Site IDs: BH01 Booker Creek, BH02 Breakwater, BH03 Salt Creek, BH04 Peninsula, BH05 Storm Drain.

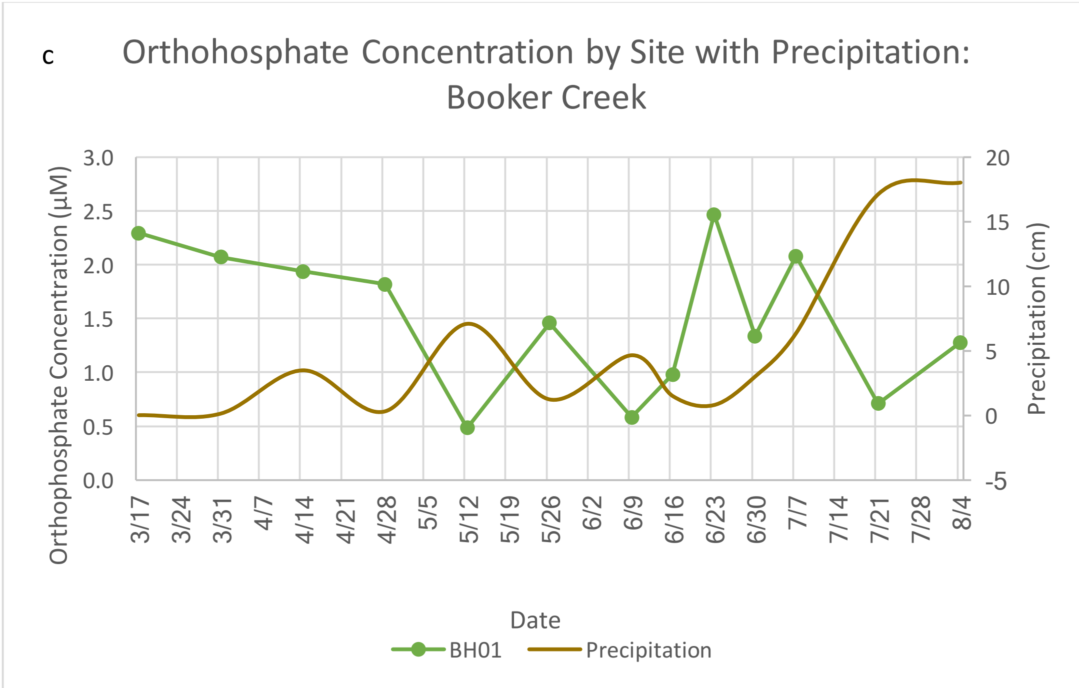


Figure 18(c). Orthophosphate Concentration by Site with Precipitation. (c) Booker Creek. Site IDs: BH01 Booker Creek, BH02 Breakwater, BH03 Salt Creek, BH04 Peninsula, BH05 Storm Drain.

Discussion

Precipitation

The Tampa Bay region has a dry season from October to May and a wet season from June to September. (Levy et al., 2011; Morrison and Greening, 2011 Ch6). Though this study used shortened seasons (11 weeks each), the approach was validated by a statistically significant difference in the mean weekly precipitation when comparing the dry season to the wet season.

Temperature

The increasing surface water temperature trend at the study sites from March through August was expected (Figure 11), as the Tampa Bay regional wet season stretches across warmer summer months. Though following the overall upward temperature trend of the harbor as May turned into June, July, and August, Booker Creek exhibited observably higher temperatures than the other sample sites during the dry season (mean was 0.5-1.0°C higher than all other sites) and lower temperatures during the wet season (mean was 0.7-1.7°C lower than all other sites). This suggests that Booker Creek may be less influenced by harbor circulation, and less mixed than the open water collection sites, or that it had more shade during the summer and less in the winter due to changes in sun angle. Booker Creek could also have a higher flow rate than the other sites, as it draws from a large watershed with a greater slope than the other areas. The distinctive high/low alternating pattern of water temperatures at all sites in the wet season data (Figure 11) correlated directly to the time of day the samples were collected – the lower temperature samples were collected between 8-11am during the mid-ebb of a lower high water, and the higher temperature samples were collected between 2-4pm during the mid-ebb of a higher high water. The mean dry season weekly surface water temperature was 26.3°C and the mean wet season weekly surface water temperature was 29.7°C, which is within the parameters for healthy estuary waters (NOAA Water Quality Information Sheet). The decrease in DO concentration that trends with increased temperature was observed at all but the Booker Creek sites.

Salinity

Salinity values around the harbor varied from almost 0 PSU to just under 31 PSU (Figure 12), and showed a significant negative correlation with precipitation as expected with an influx of freshwater from a storm, though the trend varied from site to site. The strong trend similarity between Salt Creek and the peninsula was high on the PSU scale throughout most of the study, suggesting that the circulation in the harbor at Salt Creek is heavily influenced by water from Tampa Bay, or that Salt Creek has a well-mixed water column. There was one unexplained drop in salinity at the peninsula on 21 April 2019, but otherwise the two sites trend closely until heavier rains in late-July were significant enough to drive the Salt Creek salinity down. Booker Creek and the stormwater drain follow a trend strongly linked to precipitation, with the stormwater drain having the most dramatic peak as freshwater rushes out following a storm. Though not as dramatic a response to precipitation as the stormwater drain, Booker Creek had the lowest salinity value of all sites with the exception of four dates during the study (two of those instances were following storms and a drop to 0 PSU at the stormwater drain). This suggests again that the mouth of Booker Creek is the least influenced by incoming tides, and is more influenced by stormwater runoff. The breakwater often trends with Salt Creek and the peninsula, and sometimes trends with Booker Creek and the stormdrain. This “in-between” salinity behavior at the breakwater site strongly suggests that it would be a favorable location for harbor characterization. The mean salinity in the harbor during dry season was 21.1 PSU, and 17.4 PSU during wet season. The two-year trends for Middle Tampa Bay show readings from 18-33 PSU during the drier parts of the year (October-June), and 5-25 PSU (mostly 15-25 PSU) during the rainy parts of the year (July-September), revealing a decreasing salinity gradient from Middle Tampa Bay to Bayboro Harbor.

Dissolved Oxygen

Dissolved oxygen concentration and percent saturation demonstrated overall downward trends (Figure 13, Figure 14) as the dry season ended and the wet season progressed at the breakwater, Salt Creek, and peninsula. A drop in DO as water warms is expected since cooler water holds more DO than warmer water, and cooler water lowers the biological use of oxygen. Conversely, an overall rising DO concentration was observed in Booker Creek, which also demonstrated a significant rise in temperature over the course of the study, so a trend of rising DO concentration in Booker Creek (illustrated by the solid line) suggests autotrophic activity that is sometimes plentiful enough to overcome the warming water. The harbor had a mean DO concentration of 6.6 $mg\ l^{-1}$ in dry season, and 6.0 $mg\ l^{-1}$ in wet season – just slightly within the healthy estuary range of 5-12 $mg\ l^{-1}$ (NOAA Estuaries Water Quality Information Sheet) – so it is possible that any reductions in DO concentrations would put the harbor organisms at risk. The stormwater drain showed dramatic shifts in DO concentration and had the highest range in DO percent saturation, from 61-119%. Discharge from precipitation events bring nutrient-laden runoff, which can support production and respiration, replenishing DO along with the aeration activity that comes from the active water source. Overload of nutrients can cause the opposite conditions if too much DO is consumed (Janicki, 2011).

pH

All Bayboro Harbor stations combined for a dry season mean pH of 8.1 and a wet season mean of 7.9, demonstrating the influence of stormwater and freshwater runoff, as salt water is generally above 8.0. Precipitation is often around 5.0-5.5 pH, so runoff could decrease the mean harbor pH. Trends in the pH time series graph (Figure 15) demonstrate the Tampa Bay salt water influence on Salt Creek and the peninsula, with pH levels on the higher side, and to a lesser extent, the breakwater, suggesting again that this central location is representative of a mixture of water influences in the harbor. The mouth of Booker Creek had a relatively low pH that never reached as high as 8.0, another indicator that it is strongly influenced by freshwater runoff and is minimally influenced by harbor circulation with salt water. The stormwater drain varied widely, with one significant spike to 8.6 on 19 June, showing a relationship to the increased, consistent precipitation during wet season. This was unexpected and indeed, a stormwater pH of 8.6 is high enough to suggest chemical interaction from runoff activity and transport.

Turbidity

Turbidity generally fell within the accepted ranges of 0-10 NTU. Several extreme peaks (50-165 NTU) were recorded at different stations, but could not be directly tied to storm activity. Visible particles sometimes increased dramatically during or after storm activity, and at times, evidence of algal blooms could be observed as a green film after filtration of the samples, most commonly with Booker Creek water.

Nitrate-Nitrite

The NOx concentration at the breakwater, Salt Creek, and peninsula trend up and down directly with precipitation across the entire study period (Figure 17), demonstrating a close trend in runoff or mixing. Booker Creek maintained the highest NOx concentration except for one sample, which indicates that Booker Creek is the most consistent source of NOx for the harbor as compared to the other sites, though discharge volume would need to be explored to determine if it is the most significant source of NOx input. Since the mouth of Booker Creek appears less influenced by harbor circulation, it also suggests that the NOx is from urban runoff. Booker Creek had a similar trend pattern as the stormwater drain, though it is apparent that there are some lag-times when NOx data is overlain with precipitation data (Figure 17). NOx trends from the stormwater drain have an apparent delay of 1-2 weeks unless the precipitation is sufficiently high (5+ *cm*), and then it trends more closely to Booker Creek, indicating that Booker Creek undergoes more of a flush of precipitation, whereas the storm drain discharges at a slower pace unless there is sufficiently high flow in a short time period (a few days).

Orthophosphate

The sites do not appear related in terms of orthophosphate and in any case, concentrations are low (Table 2) with minimal variance (2.1 μM dry season mean, 2.0 μM wet season mean), suggesting that of the two algal nutrients, nitrogen (NOx) is the limiting nutrient for Bayboro Harbor. The mouth of Booker Creek orthophosphate concentrations showed a nearly inverse trend with precipitation, and had the lowest mean concentration of all sites. Since nitrogen is limiting, it is likely that phosphorus remains unused until nitrogen becomes available from runoff that allows for biological uptake of both nutrients, which would account for the drop in orthophosphate concentration when a rise in precipitation is observed on the graph.

Conclusion

The primary research question for this study was to determine whether or not there was a difference in the water quality in Bayboro Harbor between dry and wet seasons, and which water quality parameters influenced the harbor.

It was anticipated that water quality would diminish with the beginning of wet season (Levy et al., 2011), and that there would be a distinct "first flush" phenomenon. The data collected did detect diminished water quality, such as a downward trend of dissolved oxygen, significant spikes or drops in salinity, strong peaks of turbidity that could not always be attached to a specific event, and an NOx concentration that demonstrates a strong positive correlation with precipitation. While there were some peaks in the parameters around the beginning of wet season, it probably rains enough in much of the dry season to prevent a dramatic "first flush" phenomenon at the beginning of the wet season, though the water quality deteriorated as the rainy season progressed.

Secondary objectives included analysis of water quality parameters at the five sample sites both individually and in combination in order to observe trends and possibly identify significant sources of influence on the harbor, as well as how the sites respond to precipitation.

The data presented some specific insights about sample sites. Salt Creek was expected to show poor water quality, but in fact was generally similar to the open-water site at the peninsula near the mouth of the harbor, likely due to visible circulation between Salt Creek and the mouth of the harbor. The stormwater drain inflow appears to provide much freshwater input (although discharge was not measured), which would contribute to changes in pH, DO, and salinity. The breakwater site near the center of the harbor repeatedly displayed parameters that bounced between the more seaward or more freshwater sites, and appears to be the best choice of the five sites to represent Bayboro Harbor as a whole. Booker Creek appears minimally influenced by harbor circulation, however, it is a continual source of nitrate-nitrogen, as well as a significant source of freshwater inflow (with a pH continually in the freshwater range).

Booker Creek may have a significant influence on the nitrogen loading in Bayboro Harbor, though more study on flow rate is necessary to discover if this is so. While Salt Creek and the storm drain exhibited episodic events, Booker Creek appeared to have a steady flow with high nitrate load. In the early 1980s, Tampa Bay suffered from eutrophication and declining sea grass beds from high input nitrogen sources (Cicchetti and Greening, 2011). Reductions in nitrogen loading to Tampa Bay facilitated recovery of sea grasses (Greening and Janicki 2006). Identification of Booker Creek as a high nitrate source entering Bayboro Harbor could provide a path for reducing the influx of nitrate into Bayboro Harbor by modifying upstream regions, potentially improving the overall health of Middle Tampa Bay.

One of the concerns brought up by this study is the low dissolved oxygen concentration: almost always above the "healthy" estuarine parameters (5-12 $mg\ l^{-1}$) with only a few low measurements, but the mean DO concentration was just above the minimum. It was still on a downward trajectory at the close of the study with weeks of rainy season remaining. The data collected in this study were only sampled during daylight hours near the surface. Dissolved oxygen concentrations would be even lower at night due to lower photosynthetic activity. Dissolved oxygen concentrations at depth may be lower due to lower light level and higher heterotrophic activity.

There are many indications for additional research and new questions that have emerged from this study. At the end of the study, dissolved oxygen was still on a downward trend, and it was nearing the “stressed” estuary concentration, so the question remains: what is the dissolved oxygen profile during the transition to the dry season? Time of day for samples and deeper profiles could provide additional information on DO. Salt Creek is worthy of further study to find out if it is a source of degraded water disguised by tidal flushing (fast circulation and quick transport out into Tampa Bay). Since Booker Creek has presented as a consistent source of nitrate-nitrite, and has more freshwater inflow (consistently low pH), what other parameters does it influence through the year following its heavily urbanized journey through St. Petersburg? This study suggests that there is much more to be learned about the discharge and water quality coming out of Booker and Salt Creeks, as well as the storm drain, including testing on flow rates and discharge volume.

The breakwater appears to be the most characteristic of Bayboro Harbor overall with its moderate, fluctuating trends, and a study of the breakwater site compared to the peninsula could provide information about how Bayboro Harbor is impacting Tampa Bay, or vice versa.

During this study, a monitoring strategy that minimized tidal influence as a variable was developed, and initial baseline water quality parameters for Bayboro Harbor were established. It is my hope that an active monitoring program will continue in Bayboro Harbor, and that future students and scientists can use this study as a platform for additional research, which could significantly impact the future ecosystem health of Bayboro Harbor.

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Appendix

Table A1. Sample Sites: Latitude and Longitude

Site Name	Site ID	Latitude	Longitude
Booker Creek*	BH01	27.75843	-82.63631
Breakwater	BH02	27.75985	-82.63398
Salt Creek*	BH03	27.75801	-82.63383
Peninsula	BH04	27.75980	-82.63134
Stormwater Drain*	BH05	27.76237	-82.63556

*Outflow site names represent mixing zone in Bayboro Harbor at discharge point

Table A2. Temperature Readings (°C) by Site and Date

	BH01	BH02	BH03	BH04	BH05
3/17/19	23.8	23.5	23.5	23.8	24.0
3/24/19	24.8	24.1	22.9	23.4	24.5
3/31/19	26.3	24.1	23.4	23.4	24.6
4/7/19	27.2	25.9	25.9	25.7	26.9
4/14/19	27.6	27.1	26.8	27.0	28.4
4/21/19	26.0	24.7	24.9	24.1	24.2
4/28/19	26.0	27.1	26.1	25.6	26.5
5/5/19	26.8	26.5	26.7	25.2	25.7
5/12/19	28.6	28.7	28.1	28.6	27.7
5/19/19	29.0	29.2	28.3	28.5	27.8
5/26/19	29.0	29.0	29.1	29.6	28.7
6/2/19	29.1	30.2	30.1	29.7	29.6
6/9/19	28.1	29.3	29.7	29.7	29.4
6/16/19	27.8	29.6	28.9	29.7	27.0
6/23/19	27.1	29.6	29.8	30.0	29.2
6/30/19	30.1	31.3	31.9	32.0	31.3
7/7/19	27.1	29.4	29.3	28.8	27.7
7/14/19	30.1	31.2	31.3	32.1	30.3
7/21/19	28.6	28.0	29.0	28.4	28.4
7/28/19	29.1	30.4	31.4	30.9	29.6
8/4/19	26.5	28.9	29.7	29.4	29.0
8/11/19	29.5	29.9	31.0	31.2	29.4

Table A3. Salinity Readings (PSU) by Site and Date

	BH01	BH02	BH03	BH04	BH05
3/17/19	11.7	23.6	19.1	25.5	22.9
3/24/19	14.4	6.9	25.6	22.7	22.0
3/31/19	14.4	19.2	26.2	26.3	24.3
4/7/19	12.2	22.4	23.9	25.4	23.8
4/14/19	10.3	27.2	28.3	27.0	22.2
4/21/19	25.8	27.4	28.1	0.2	29.0
4/28/19	6.6	24.6	27.0	29.0	22.4
5/5/19	13.4	18.3	29.6	30.6	27.1
5/12/19	2.7	18.2	25.4	23.9	16.9
5/19/19	10.8	26.8	27.9	27.8	1.3
5/26/19	22.0	27.8	27.6	29.1	26.3
6/2/19	26.0	27.4	30.0	27.9	29.4
6/9/19	4.9	18.3	24.4	22.7	19.0
6/16/19	6.0	22.6	23.4	26.8	0.1
6/23/19	14.3	29.2	30.0	30.2	27.7
6/30/19	7.9	24.6	24.6	19.6	20.2
7/7/19	9.3	27.3	27.9	22.7	18.3
7/14/19	3.3	14.8	21.6	19.9	16.2
7/21/19	4.4	6.2	5.0	9.3	9.3
7/28/19	4.0	16.1	14.8	22.3	10.8
8/4/19	2.8	11.2	10.4	23.7	15.4
8/11/19	3.7	18.5	14.7	21.6	13.4

Table A4. Dissolved Oxygen Readings (*mg l^{-1}*) by Site and Date

	BH01	BH02	BH03	BH04	BH05
3/17/19	4.94	6.05	6.95	6.81	6.52
3/24/19	6.66	8.08	7.55	7.75	7.83
3/31/19	6.57	6.44	7.14	7.41	7.07
4/7/19	6.45	7.24	6.92	7.58	7.07
4/14/19	5.30	6.47	5.56	6.59	7.87
4/21/19	4.56	7.27	7.87	9.07	6.11
4/28/19	6.16	6.58	6.82	6.77	7.25
5/5/19	5.77	6.40	5.29	7.12	4.27
5/12/19	6.44	5.77	5.89	5.75	5.58
5/19/19	4.89	6.93	6.69	7.34	5.25
5/26/19	5.00	6.68	6.86	6.69	8.04
6/2/19	7.11	5.73	5.20	5.78	6.49
6/9/19	5.93	5.57	5.65	5.23	5.34
6/16/19	7.19	5.51	5.95	6.72	7.89
6/23/19	6.67	6.21	6.05	5.99	4.33
6/30/19	5.71	6.96	5.84	6.97	6.45
7/7/19	5.17	5.27	5.56	5.40	6.21
7/14/19	6.49	6.81	6.23	6.85	6.97
7/21/19	5.65	5.60	4.30	6.05	5.67
7/28/19	5.68	5.96	5.98	6.84	6.33
8/4/19	7.08	5.25	4.73	6.18	5.73
8/11/19	5.96	5.33	5.15	5.29	6.65

Table A5. Dissolved Oxygen Readings (%Sat) by Site and Date

	BH01	BH02	BH03	BH04	BH05
3/17/19	62	81	91	93	88
3/24/19	86	99	101	103	106
3/31/19	87	85	97	101	97
4/7/19	86	100	97	107	101
4/14/19	71	94	81	96	115
4/21/19	65	102	111	107	85
4/28/19	78	95	98	97	102
5/5/19	78	88	78	103	61
5/12/19	84	82	87	84	78
5/19/19	68	105	100	110	67
5/26/19	73	100	103	102	119
6/2/19	107	89	81	89	101
6/9/19	77	80	85	78	78
6/16/19	94	82	88	102	99
6/23/19	89	95	93	93	62
6/30/19	78	106	91	106	97
7/7/19	65	80	84	79	87
7/14/19	86	101	94	104	101
7/21/19	74	74	57	82	76
7/28/19	75	86	87	103	88
8/4/19	89	72	66	92	81
8/11/19	79	78	75	80	95

Table A6. pH Readings by Site and Date

	BH01	BH02	BH03	BH04	BH05
3/17/19	7.5	7.9	7.9	8.1	8.0
3/24/19	7.7	8.1	8.2	8.2	8.1
3/31/19	7.8	8.0	8.2	8.2	8.1
4/7/19	7.6	8.0	8.1	8.2	8.1
4/14/19	7.7	8.0	8.1	8.2	8.2
4/21/19	7.9	8.2	8.3	8.3	8.1
4/28/19	7.7	8.1	8.2	8.2	8.1
5/5/19	8.0	8.0	8.2	8.2	7.8
5/12/19	7.8	8.0	8.1	8.1	7.9
5/19/19	7.7	8.3	8.2	8.3	7.9
5/26/19	7.9	8.2	8.2	8.3	8.4
6/2/19	7.7	8.1	8.0	8.1	8.2
6/9/19	7.6	7.8	7.9	8.0	7.9
6/16/19	7.6	8.0	8.0	8.2	8.6
6/23/19	7.2	8.1	8.2	8.2	7.9
6/30/19	7.6	8.2	8.1	8.3	8.1
7/7/19	7.3	8.1	8.1	8.1	7.9
7/14/19	7.6	8.2	8.2	8.3	8.0
7/21/19	7.6	8.0	8.0	8.2	7.8
7/28/19	7.6	8.0	8.2	8.3	7.8
8/4/19	7.5	7.8	8.2	8.3	7.8
8/11/19	7.7	8.0	8.0	8.2	8.3

Table A7. Turbidity Readings (NTU) by Site and Date

	BH01	BH02	BH03	BH04	BH05
3/17/19	3.83	2.86	2.97	2.91	75.40
3/24/19	3.20	43.79	2.89	2.91	3.04
3/31/19	3.13	78.90	2.88	3.05	3.08
4/7/19	3.75	2.88	8.95	3.09	3.08
4/14/19	3.88	4.27	3.18	3.19	3.54
4/21/19	5.05	3.25	3.14	3.18	3.13
4/28/19	7.54	3.11	3.17	3.25	3.28
5/5/19	6.01	5.59	3.41	4.28	5.96
5/12/19	4.55	3.49	3.38	3.59	6.07
5/19/19	4.15	3.51	3.50	3.48	4.05
5/26/19	21.44	3.56	3.68	3.52	31.51
6/2/19	4.19	3.59	3.81	3.67	165.22
6/9/19	7.11	7.93	4.79	7.17	7.07
6/16/19	4.26	3.39	3.44	3.47	52.09
6/23/19	3.49	3.57	3.83	3.63	3.73
6/30/19	6.10	4.07	4.55	4.29	7.16
7/7/19	11.02	4.04	4.95	6.36	7.50
7/14/19	6.25	4.41	5.98	5.99	19.00
7/21/19	5.65	5.88	9.20	4.91	4.79
7/28/19	4.26	3.95	5.73	4.44	4.74
8/4/19	4.48	3.90	7.22	5.17	4.90
8/11/19	10.10	6.31	6.76	4.36	11.68

Table A8. Nitrate-Nitrite (NOx) Readings (*μM*) by Site and Date

	BH01	BH02	BH03	BH04	BH05
3/17/19	19.2153	7.0006	6.9980	2.1811	10.4733
3/31/19	12.1073	3.9575	1.1571	1.2518	5.9187
4/14/19	18.4863	4.6595	2.6711	2.3962	11.6613
4/28/19	24.2953	3.6124	3.3530	1.5254	12.7423
5/12/19	7.3459	5.9352	3.8060	4.1390	13.4703
5/26/19	9.9743	0.2628	2.6056	0.4826	0.3083
6/9/19	17.1260	11.0780	6.4017	4.1401	3.2374
6/16/19	12.1160	3.4052	4.2141	0.5285	10.7770
6/23/19	8.8584	2.0229	0.2034	0.0594	5.3678
6/30/19	7.4277	0.5551	0.3102	0.0000	7.0055
7/7/19	16.6030	8.5363	3.6509	7.4090	12.8450
7/21/19	9.8823	9.0032	4.2499	8.5771	9.2898
8/4/19	21.8340	10.3200	13.6070	0.5317	13.9730

Table A9. Orthophosphate Readings (*µM*) by Site and Date

	BH01	BH02	BH03	BH04	BH05
3/17/19	2.2923	2.6831	2.6783	2.5636	2.8257
3/31/19	2.0702	2.5529	2.3198	2.1293	2.3915
4/14/19	1.9369	2.5067	2.6728	2.3630	2.0402
4/28/19	1.8174	2.2849	2.3097	2.1796	2.3292
5/12/19	0.4833	2.1831	2.6656	2.2382	1.6704
5/26/19	1.4594	1.7626	1.6251	1.6203	0.9117
6/9/19	0.5807	3.6740	3.5969	1.9844	1.3226
6/16/19	0.9797	2.4333	1.6852	1.8354	1.7594
6/23/19	2.4649	2.5183	2.7316	2.5052	2.9776
6/30/19	1.3371	2.2170	2.5181	2.1832	2.3184
7/7/19	2.0808	2.1692	2.5554	2.1306	1.8898
7/21/19	0.7098	0.1297	0.5483	1.9879	1.4370
8/4/19	1.2770	1.2865	2.4878	2.3335	2.0585