Data Report for Calico Creek Estuary

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I. Introduction

Calico Creek is a tidal estuarine creek located in Morehead City, North Carolina. Calico Creek has been listed in Category 5 (impaired water list or 303(d) list) of the North Carolina Integrated Report since 2008 for nutrient related impairments. Two segments, or assessment units (AU 21-32a and 21-32b), of Calico Creek and its tributaries are included in the most recent 2018 North Carolina 303(d) List. The upper part of Calico Creek (AU 21-32a) was listed as impaired for Chlorophyll a, Dissolved Oxygen and Turbidity while the lower part (AU 21-32b) was listed for Chlorophyll a.

A dynamic nutrient response model is needed to assess the impact of nutrient loadings to the water quality conditions in Calico Creek Estuary. In addition to the long-term ambient monitoring program (AMS station sites in Figure I-1), the Intensive Survey Branch of NC DWR conducted intensive surveys from May 2017 to April 2019 to collect extra physical and biogeochemical data at additional sampling sites (Study sample sites in Figure I-1) within Calico Creek. Physical and biochemical data listed in Table I-1 were collected at the monitoring stations.

Two AMS monitoring stations, P8750000 and P8800000, are located along the channel of the Calico Creek Estuary, off two road bridges across the river. P8750000 is in a shallow area close to the head of the estuary and P8800000 is in a relatively deeper region in the lower part of the estuary. Results from these two stations characterize estuary conditions. An Acoustic Doppler Current Profiler (ADCP) was deployed about 250 feet west of P8800000 to collect flow information during a spring tide and a neap tide, respectively. Sediment Oxygen Demand (SOD) and nutrient fluxes from benthic sediment were measured on April 25, 2019 close to P8800000. During the intensive survey period, physical and biochemical parameters were also measured at stations WOKCC0010, WOKCC0020, WOKCC0040 and WOKCC0070 to help identify tributary inputs and at stations WOKCC0080 and WOKCC0081 for open boundary (i.e. estuary mouth) conditions.

In preparation of nutrient response model development, this report summarizes the data obtained from the surveys as well as other data sources including NPDES discharge monitoring report (DMR) and state climate office. Data analyses are conducted to identify major physical and biogeochemical features in Calico Creek. Since higher frequency of data was obtained during intensive survey, the analysis was based primarily on the data collected during the two-year period. Longer term data were also obtained and analyzed when there was a need to examine long-term trend and where data were available.

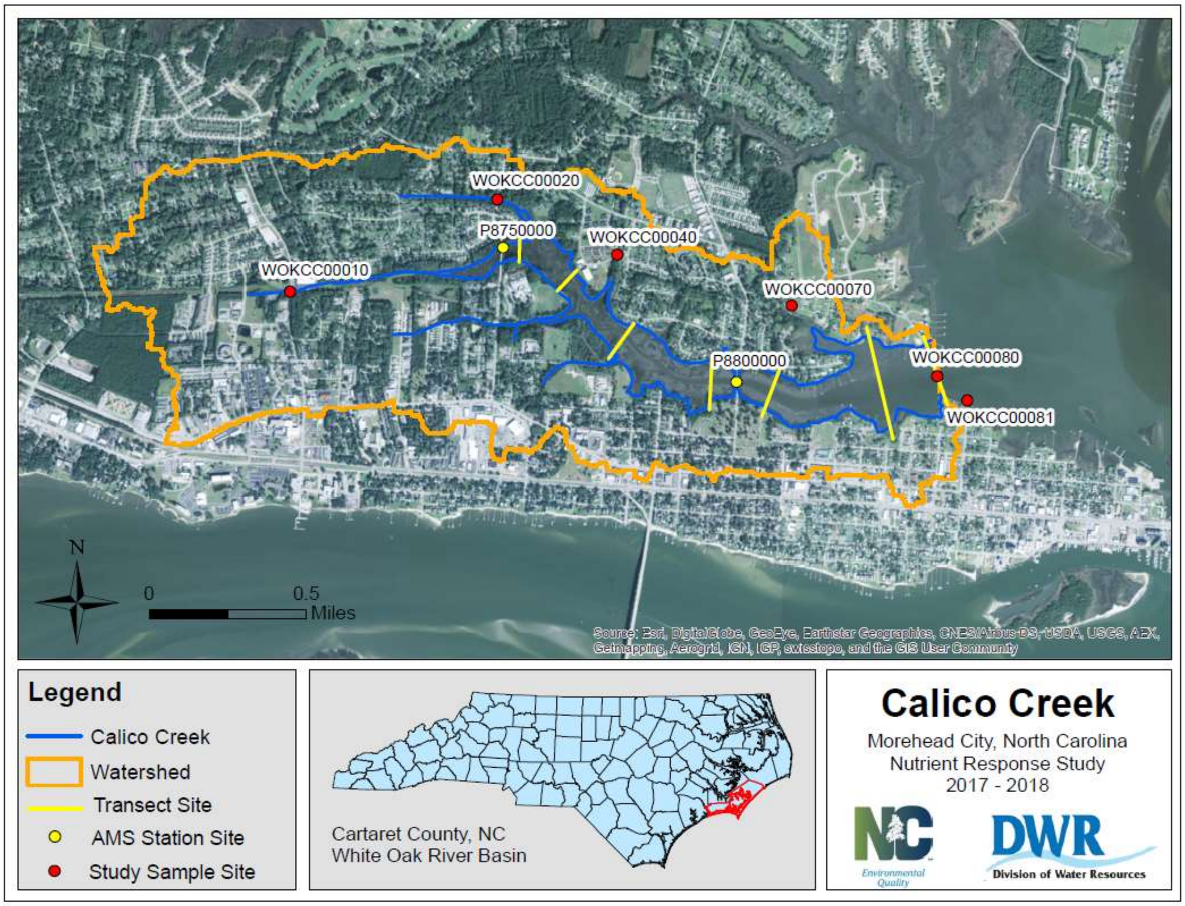


Figure I-1. Calico Creek Watershed and monitoring stations.

Table I-1. Monitoring stations and parameters monitored in Calico Creek.

Station Name	Station Type	Physical Parameters#	Discharge / Tidal stage	Biochemical Parameters*	Algal Assemblage
P8750000	AMS	surface	N/A	surface	surface
P8800000	AMS	multiple depths	N/A	photic composite^	photic composite^
WOKCC0010	Intensive Survey	surface	Discharge	surface	N/A
WOKCC0020	Intensive Survey	surface	Discharge	surface	N/A
WOKCC0040	Intensive Survey	surface	Discharge	surface	N/A
WOKCC0070	Intensive Survey	surface	Discharge	surface	N/A
WOKCC0080	Intensive Survey	multiple depths	N/A	photic composite^	N/A
WOKCC0081	Intensive Survey	multiple depths	Tidal stage	photic composite^	N/A

Physical parameters include: Temperature, Salinity, Specific Conductivity, pH and Dissolved Oxygen (DO)

*Biochemical parameters include: Chlorophyll a (Chl a), Ammonia (NH3), Nitrite nitrate (NOx), Total Kjeldahl Nitrogen (TKN), Total Phosphorus (TP), turbidity and Total Suspended Solids (TSS) from long-term ambient monitoring program (AMS); additional parameters such as Orthophosphate (PO4), 5-day Biochemical Oxygen Demand (BOD5), 5-day Carbonaceous Biochemical Oxygen Demand (CBOD5), Total Organic Carbon (TOC) and Dissolved Organic Carbon (DOC) were collected during intensive survey period.
^normally composite samples were collected in the photic zone (two times of Secchi depth), when water level was low, surface samples were collected instead.

II. Drainage Basin

The Calico Creek watershed covers about 2 square miles. Morehead City is within the watershed.

The 2011 National Land Cover Database (NLCD) was used to obtain land cover characteristics of the watershed. Land cover distribution is shown in Figure II-1 and land cover statistics are shown in Table II-1. The Calico Creek watershed is heavily (around 74%) developed, with some (13.6% of the watershed) wetlands areas.

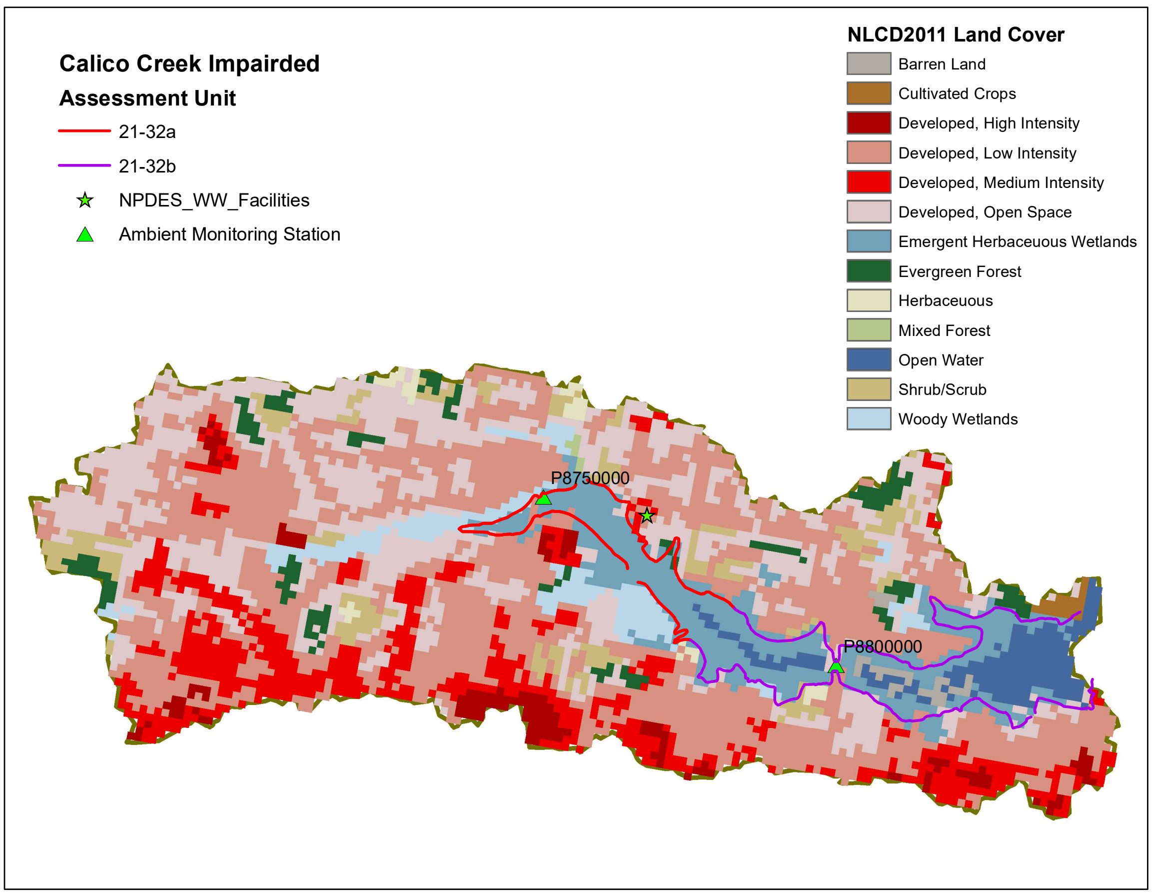


Figure II-1 – Calico Creek impaired assessment unit and 2011 NLCD Land Cover of the drainage basin.

Table II-1. 2011 Land Cover Distribution of the Calico Creek Watershed

Land Cover	Percentage
Barren Land	0.6%
Cultivated Crops	0.3%
Developed, High Intensity	2.8%
Developed, Low Intensity	36.4%
Developed, Medium Intensity	11.4%
Developed, Open Space	23.4%
Emergent Herbaceuous Wetlands	9.7%
Evergreen Forest	3.0%
Herbaceuous	0.7%
Mixed Forest	0.1%
Open Water	3.2%
Shrub/Scrub	4.4%
Woody Wetlands	3.9%

Point Source Assessment

All wastewater discharges to surface water in the State of North Carolina must receive a permit to control water pollution. The Clean Water Act (CWA) initiated strict control of wastewater discharges with responsibility of enforcement given to the Environmental Protection Agency (EPA). The EPA then created the National Pollutant Discharge Elimination System (NPDES) to track and control point sources of pollution. The primary method of control is by issuing permits to discharge with limitations on wastewater flow and constituents. The EPA delegated permitting authority to the State of North Carolina in 1975.

The Morehead City WWTP has been historically identified as the major cause of water quality problems in Calico Creek (DWQ, 1997). The treatment facility discharges treated 100% domestic wastewater into Calico Creek. Estimated from the Type A Current Public Sewer Systems GIS layer that was developed by the NC Center for Geographic Information and Analysis in 2004 (http://data.nconemap.gov/geoportal/catalog/search/resource/details.page?uuid=%7B5CF6143E-F6EA-4420-B18E-054415C3E108%7D), approximately 65% of the total area within Calico Creek watershed is connected to the Morehead City WWTP (Figure II-2). These include about 93% of the high intensity developed area, 96% of the medium intensity developed area and 80% of the low intensity developed area. Altogether, likely more than 90% of the residential homes within the Calico watershed are connected to the WWTP facility. The source of drinking water for Morehead City residents are primarily from groundwater (https://www.moreheadcitync.org/DocumentCenter/View/686/2019-Consumer-Confidence-Report).

An upgrade to the Morehead City WWTP facility happened between 2008 and 2010 with permitted flow increased from 1.7 to 2.5 MGD and with tertiary treatment and UV disinfectant installed. NH_3, BOD_5, TSS, and DO concentrations and TN and TP load limits are included in the current permit with extra nutrient monitoring requirements for TN, TP, TKN and NO_x (DWQ, 2013).

A North Carolina Water Quality Analysis Program (NCWQAP), a finite section model, was previously applied to Calico Creek to determine the effects of the Morehead City WWTP loadings on the dissolved oxygen concentration (DEM, 1990). The model results suggested that with the effluent limits at the time (30mg/L BOD_5, 10 mg/L NH_3, 5mg/L DO and 1.7 MGD of effluent flow), the waste was responsible for 45% of the DO deficit in the upstream portion of Calico Creek and approximately 66% of the deficit just below the outfall. However, with the facility upgrade and the expanded discharge limit, the impact of the WWTP to water quality conditions in Calico Creek was not assessed.

As shown in Figure II-3 and II-4, long-term discharge monitoring from the Morehead City WWTP suggests that BOD, TSS, and NH3 concentrations in the effluent flow and annual loads discharged into the Calico Creek appear to be substantially lower after the WWTP upgrade finished in 2010. The impacts of waste discharges from the Morehead City WWTP to water quality conditions in Calico Creek need to be investigated with model study based on more recent data (i.e. 2011 and after). It should also be noted that pH of the effluent flow appears to be higher after the WWTP upgrade.

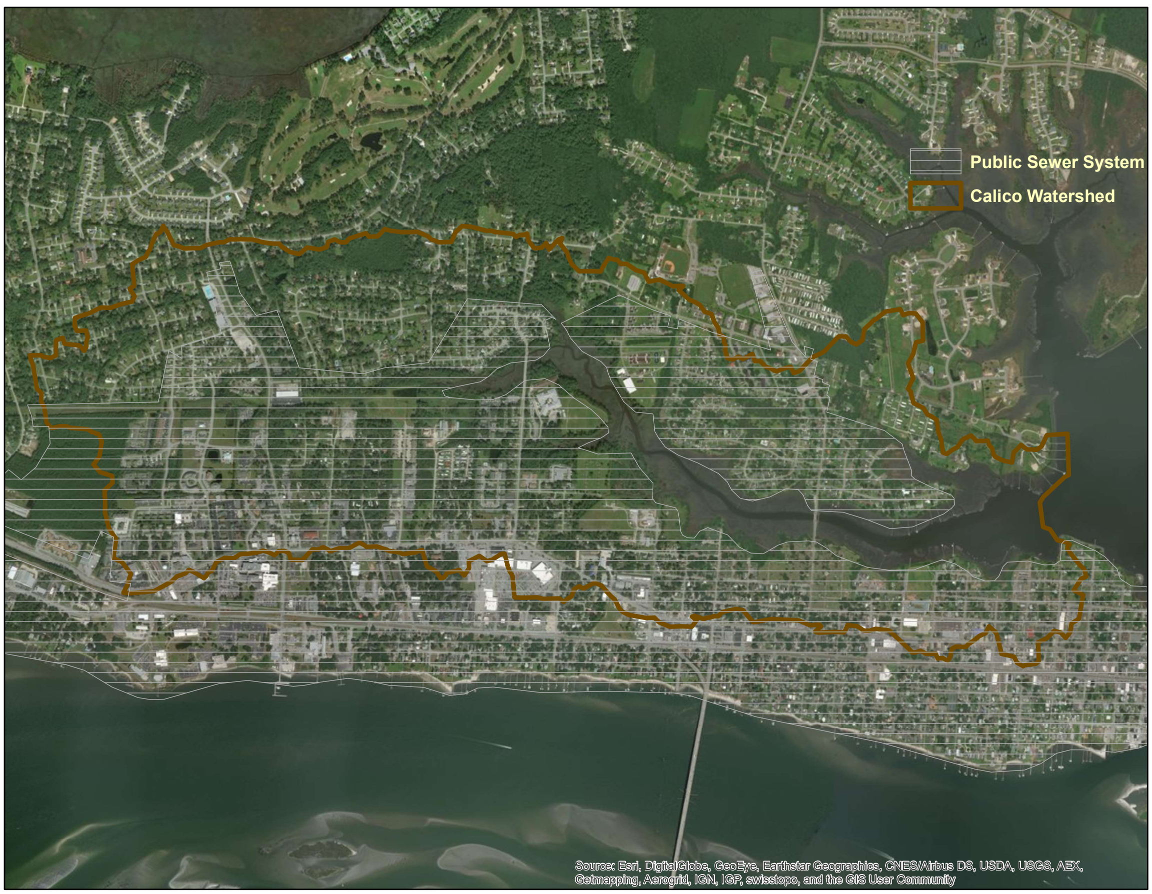


Figure II-2. Areas covered by Morehead City WWTP in Calico Creek Watershed.

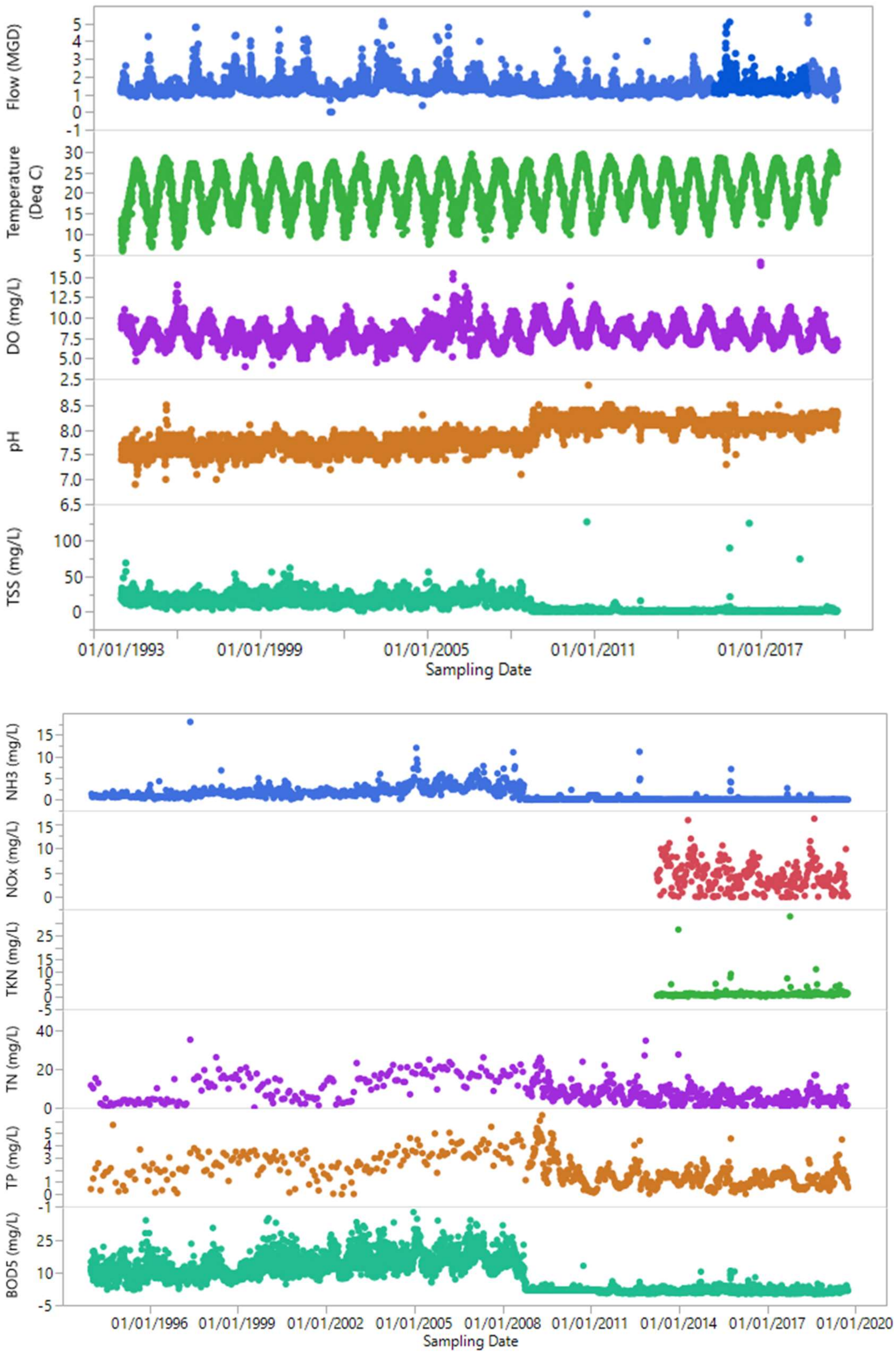


Figure II-3. Time series data from Morehead City WWTP.

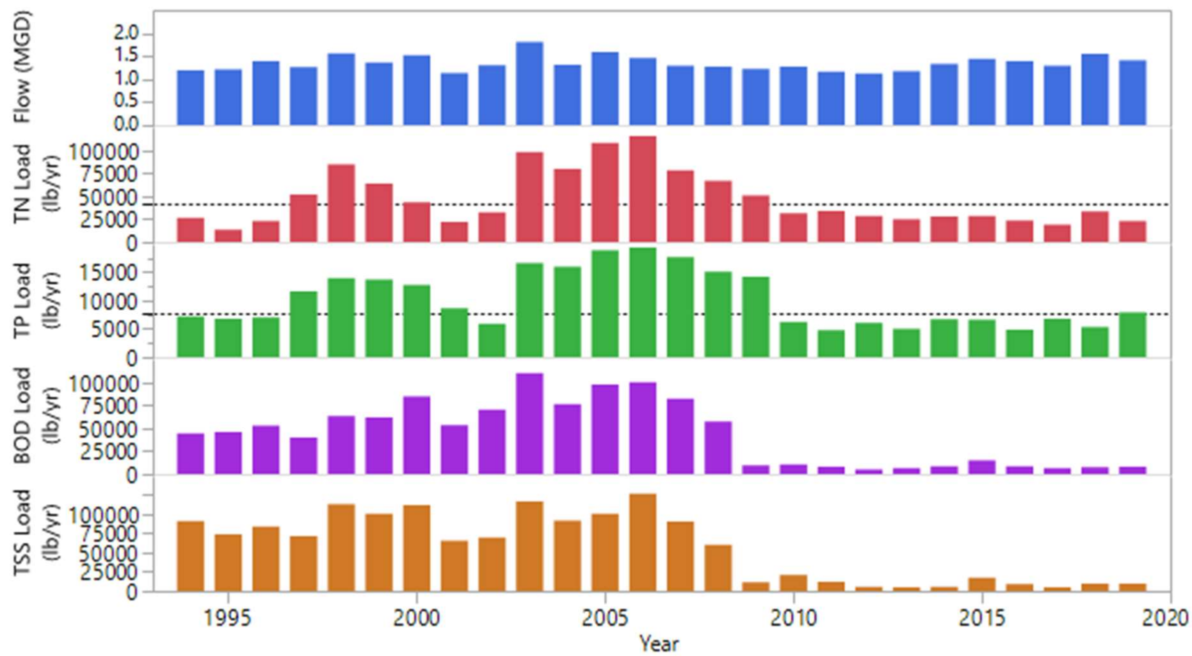


Figure II-4. Annual average of effluent flow, TN, TP, BOD and TSS loads from Morehead City WWTP. The dotted lines are the TN/TP load limits in the current permit.

The NC Department of Transportation (NCDOT) has a number of roads in the project area, and has a statewide Phase I NPDES stormwater permit (NCS000250). Stormwater has previously been considered to be a nonpoint source; however, NPDES-permitted sources are to be included in the wasteload allocation (WLA) per EPA guidance (USEPA, 2002). NCDOT (2018) performed Right-of-Way (ROW) and impervious area land use analysis within the Calico Creek Watershed. The estimated NCDOT ROW areas within the watershed is about 0.1 square mile (approximately 5% of the entire watershed) and the estimated NCDOT impervious areas is about 0.04 square mile (approximately 2% of the entire watershed).

Nonpoint Source Assessment

Non-point sources are diffuse sources that typically cannot be identified as entering a water body at a single location. Nonpoint source loading typically occurs during rain events (i.e. stormwater runoff) when surface runoff transports water carrying pollutants over the land surface and discharges it into the stream network.

The Calico Creek watershed is heavily developed. Much of the land surface is covered by buildings, pavement and compacted landscapes. These surfaces do not allow rain and snow melt to soak into the ground which greatly increases the volume and velocity of stormwater runoff. In addition, some residential areas to the north of the upper reaches of the creek and part of areas east side of N 20th St. are on septic tanks (DWQ, 2005). Nutrients from lawns and gardens, pet wastes and failing septic system are all potential nonpoint sources of pollutants contributing to water quality problems in Calico Creek.

III. Phytoplankton Data

Algae Abundance

Algal data were collected by DWR for algal species unit density and biovolume (as an indication of algae abundance) at stations P8750000 and P8800000 in Calico Creek estuary. Monthly distributions of total unit density (in units/ml) and total biovolume (in mm^3/m^3) are presented in Figure III-1 for the periods of 2003 to 2010 and 2011 to 2019. Algal abundances were in general much higher during summer months than the rest of the year. Occasional algal blooms occurred during spring.

T-tests were performed for differences in means between two monitoring stations and between the two time periods using the Analysis of means (ANOM) with Transformed Ranks method of JMP software. No significant differences were found in either total unit density or total volume between the two time periods of 2003-2010 and 2011-2019. However, algal abundances were higher at station P8750000 (upper part of Calico Creek) than at station P8800000 (lower part of Calico Creek) (Figure III-2).

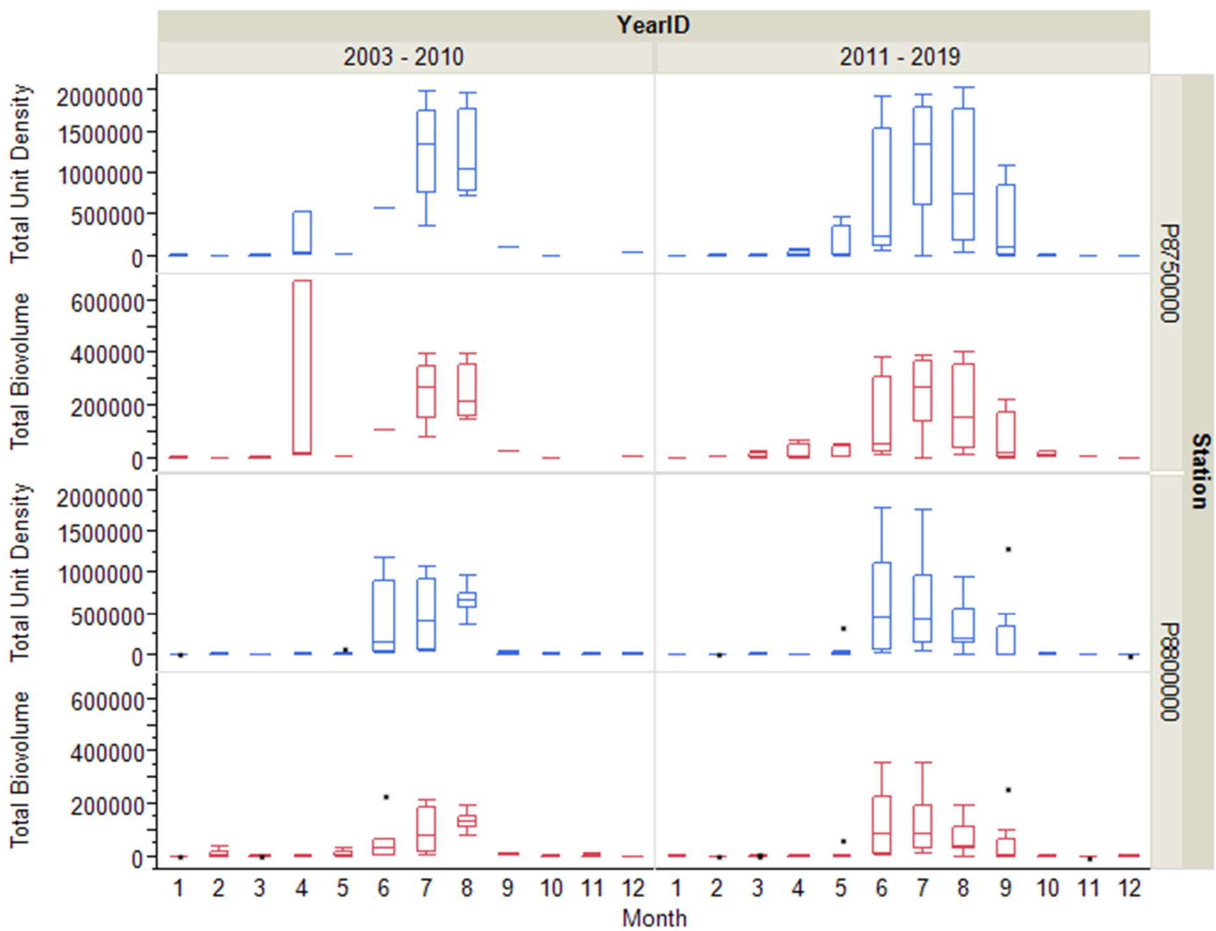


Figure III-1. Monthly distributions of algae total unit density (units/ml) and total biovolume (mm^3/m^3) at stations P8750000 and P8800000 in Calico Creek.

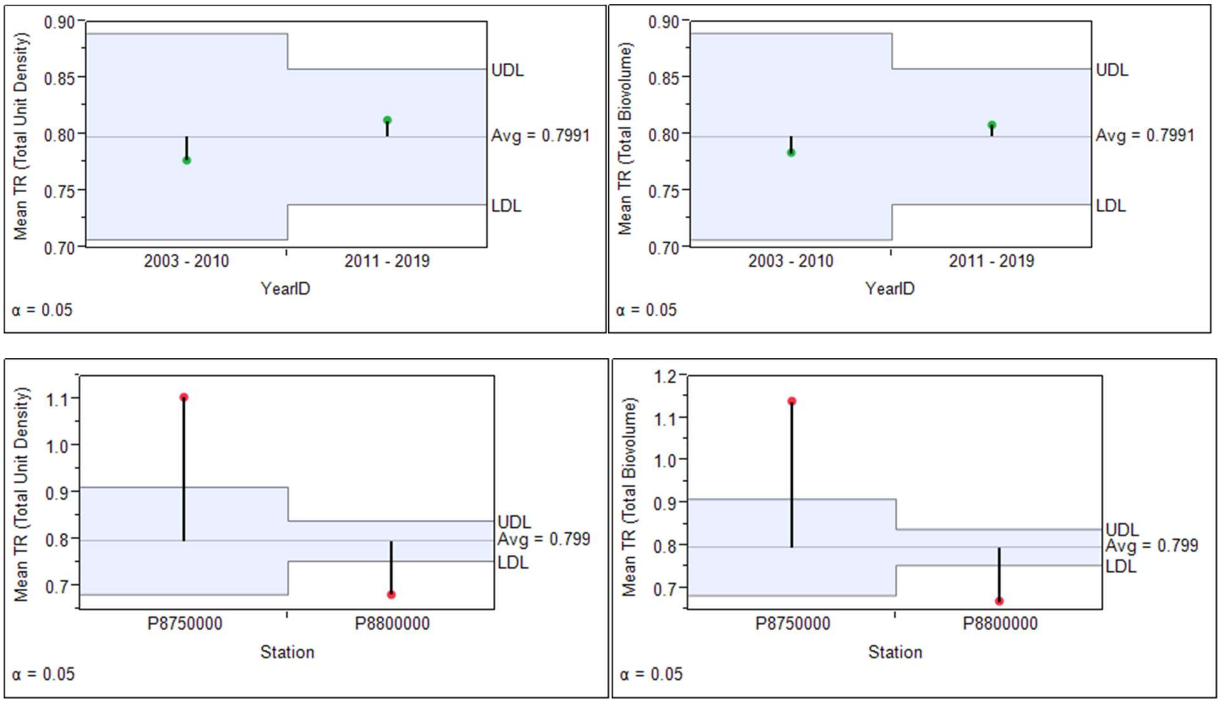
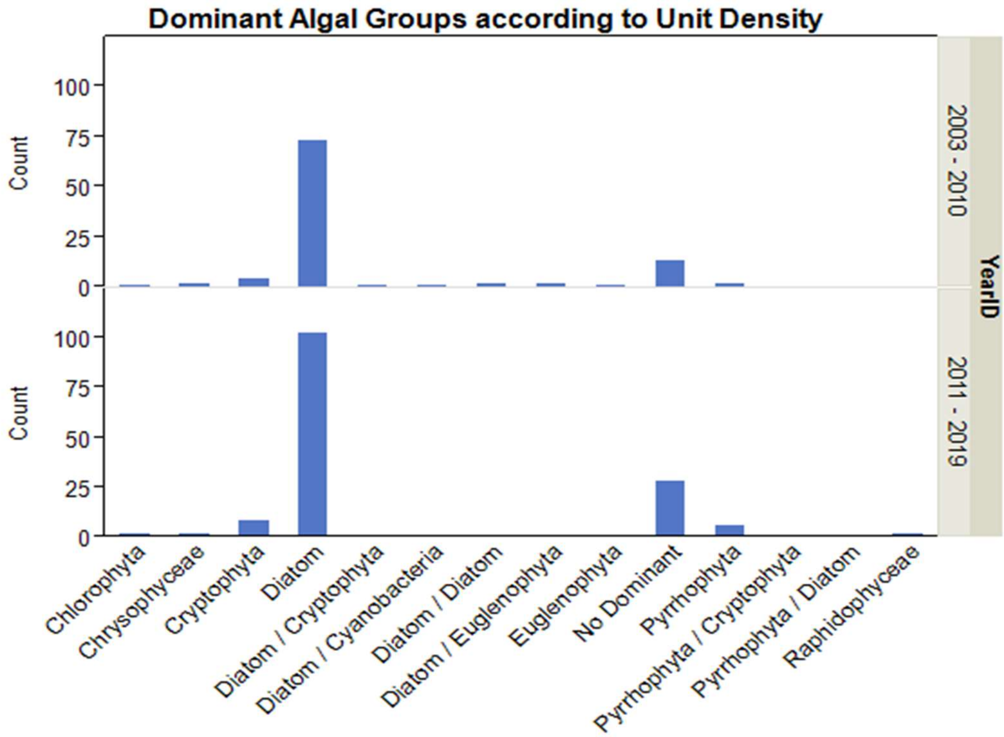


Figure III-2. Analysis of means (ANOM) with Transformed Ranks (TR) method of JMP software was used to compare the means of total unit density and biovolume between two time periods 2003-2010 and 2011-2019 (upper panel) and between two monitoring stations (lower panel). Dots indicate means of specific group, horizontal lines indicate the overall mean, shaded area covers the area between lower decision limit and upper decision limit. There are significant differences between means if the dots fall outside of the decision limits.

Dominant Algal Groups

In this analysis, a dominant algal group is defined as the algal group which contributes at least 40% of total algal unit density or total algal biovolume. Around 77% of the observations during 2003 to 2010 were dominated by diatoms or co-dominated by diatoms and another algal group according to unit density and 63% according to biovolume. During the most recent period of 2011 to 2019, about 68% of the total observations were dominated by diatom or co-dominated by diatom and another algal group according to unit density, and around 63% according to biovolume (Figure III-3). Interestingly, during summer months of June to August, algal abundance seems to be solely dominated by diatoms, only one out of eighty-seven summer observations was not dominated by diatoms according to unit density (two according to biovolume) (Figure III-4). The percent dominance by diatoms for most summer observations are above 90% according to both unit density and biovolume, with the median percent dominance as 99%.



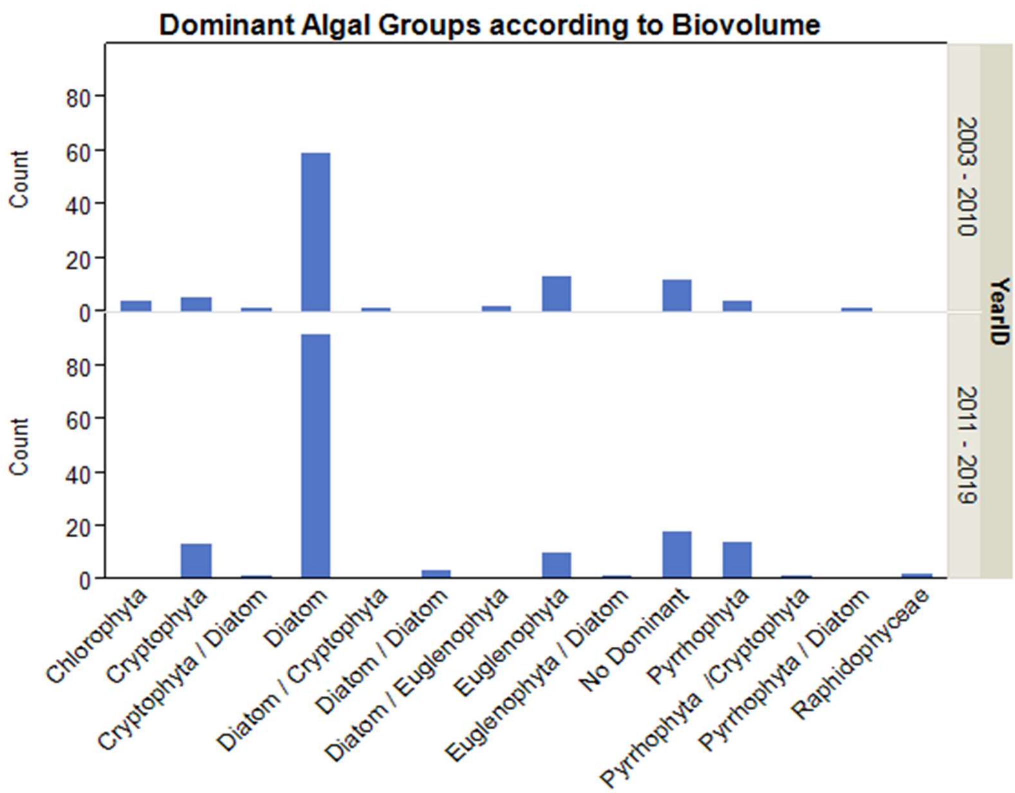
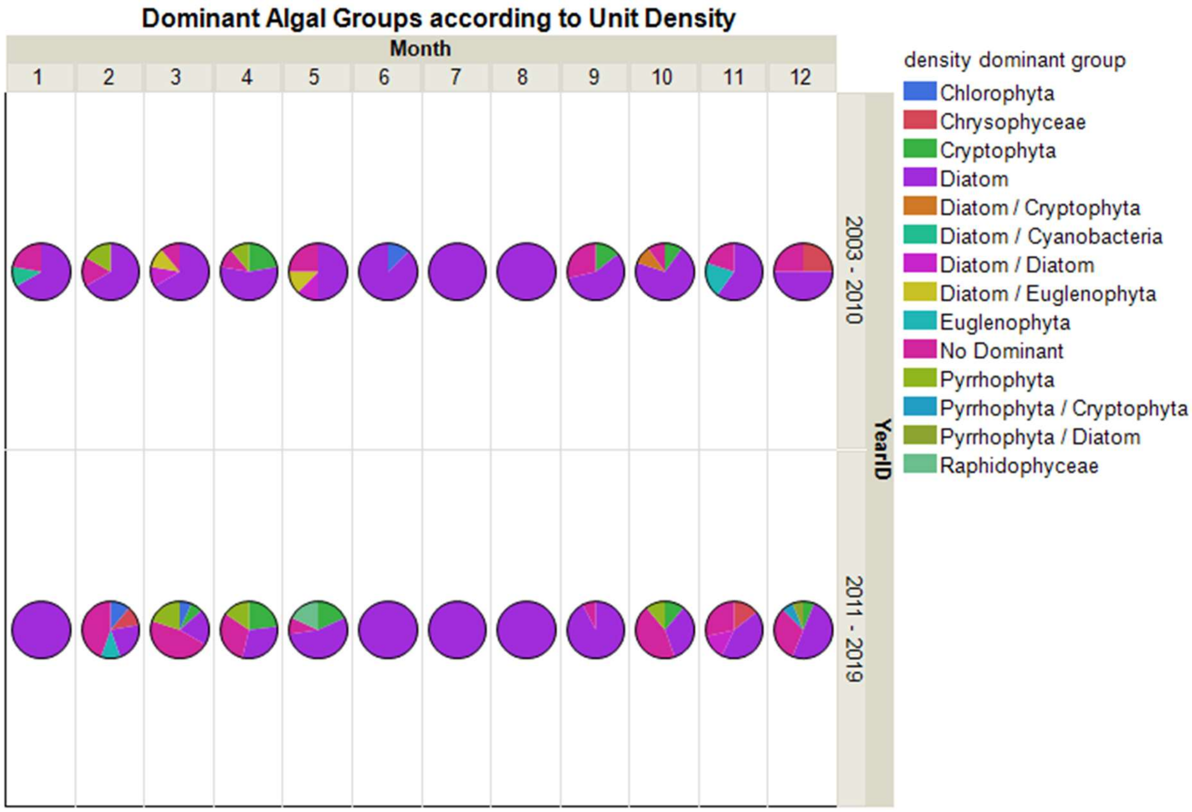


Figure III-3. Number of observations specific algal group dominates.



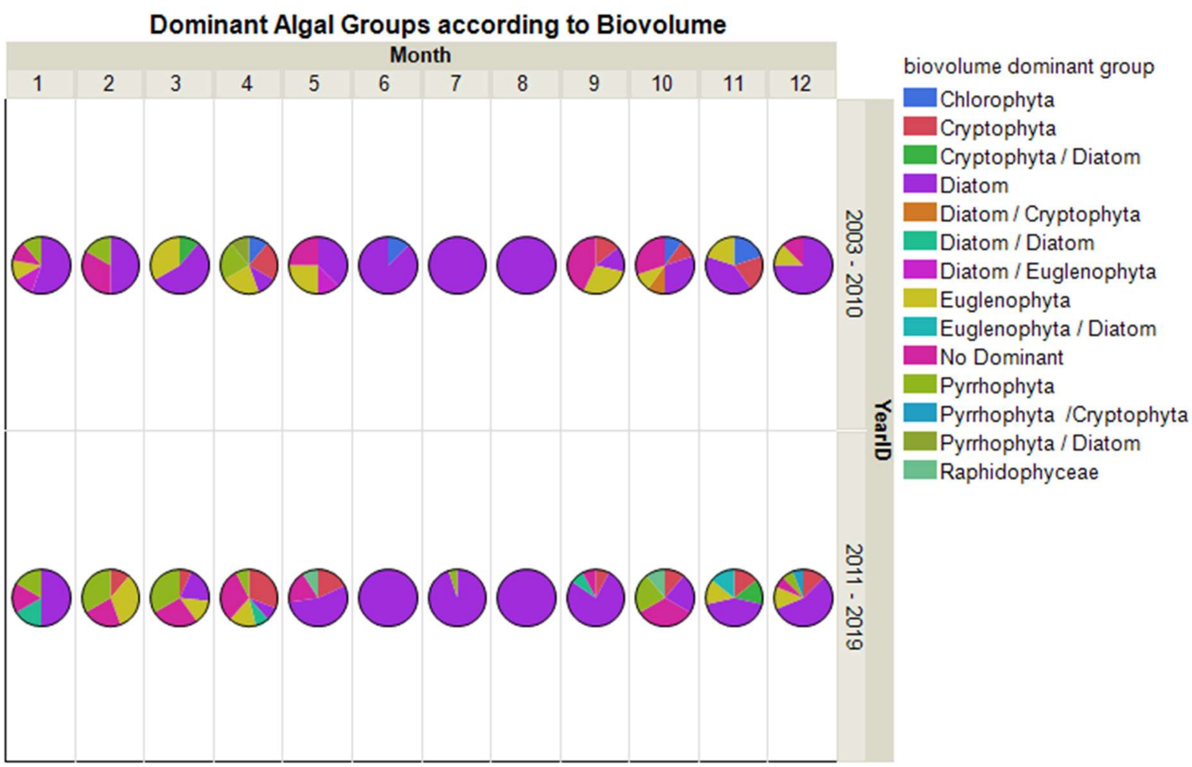


Figure III-4. Monthly distributions of percent of times a specific algal group dominates.

Chlorophyll a Concentrations

Estuary Conditions

Chlorophyll a (Chl a) concentration data at stations P8750000 and P8800000 within Calico Creek estuary are presented here for the period of 2002 to 2018. Monthly distributions of Chl a in general follow the same pattern as that of algal biovolume, except that high Chl a were also observed during May (2011-2018) at station P8750000 (in addition to high concentrations during summer of June to August). This is mostly due to an algal bloom event that occurred on May 18, 2017, during which time especially high Chl a concentrations were observed at station P8750000 (Figure III-5).

No significant differences in Chl a were observed at station P8800000 between 2002-2010 and 2011-2018. However, significantly higher Chl a concentrations were observed at station P8750000 during 2011-2018 than during 2002-2010 (Figure III-6). Monitoring data indicates that several severe algal blooms occurred on 5/18/17, 8/2/17, 8/17/17 and 10/16/18 at station P8750000. During those days, greater than 500 µg/L to 1000 µg/L Chl a concentrations were reported. The observed Chl a values during 2002-2010 were by contrast only up to a maximum of 370 µg/L. However, if the comparisons are carried out for different seasons, despite the very high peaks of Chl a concentrations observed during recent years (2011-2018), mean Chl a concentrations during summer and spring seasons of 2011-2018 are not significantly higher than summer mean and spring mean Chl a values observed during 2002-2010.

Excluding the extremely high Chl a values (>500 µg/L), good linear relationships were found between Chl a and algal unit density, and between Chl a and biovolume (Figure III-7), indicating Chl a is a good indicator of algal abundance in Calico Creek.

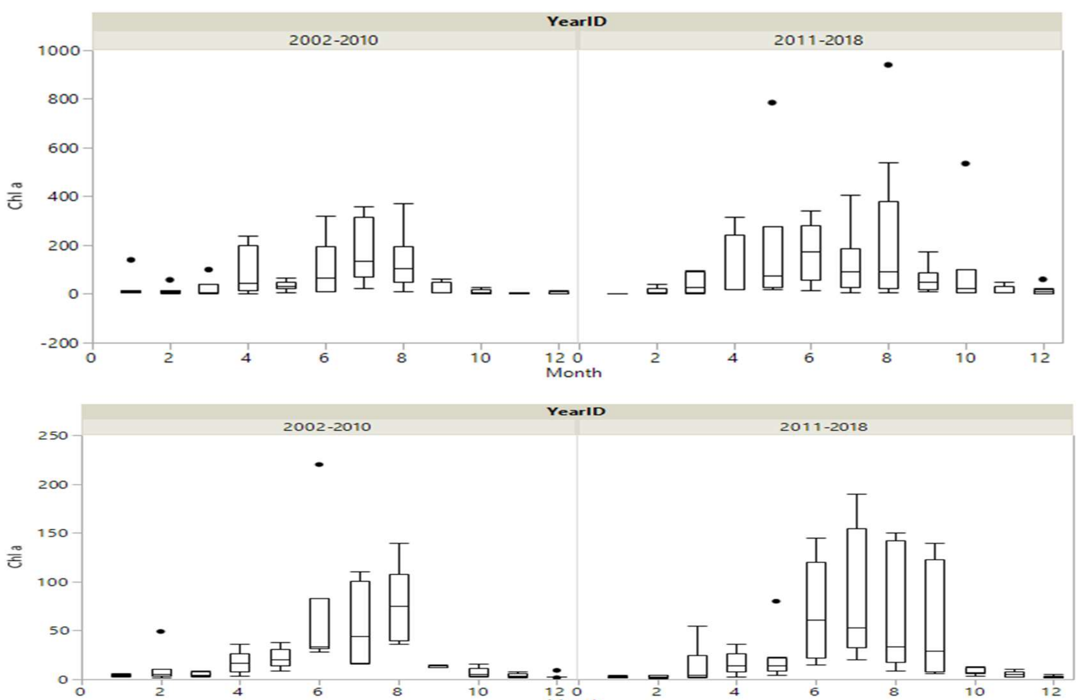


Figure III-5. Monthly box plots of Chl a concentrations (µg/L) at station P8750000 (upper panel) and P8800000 (lower panel) in Calico Creek.

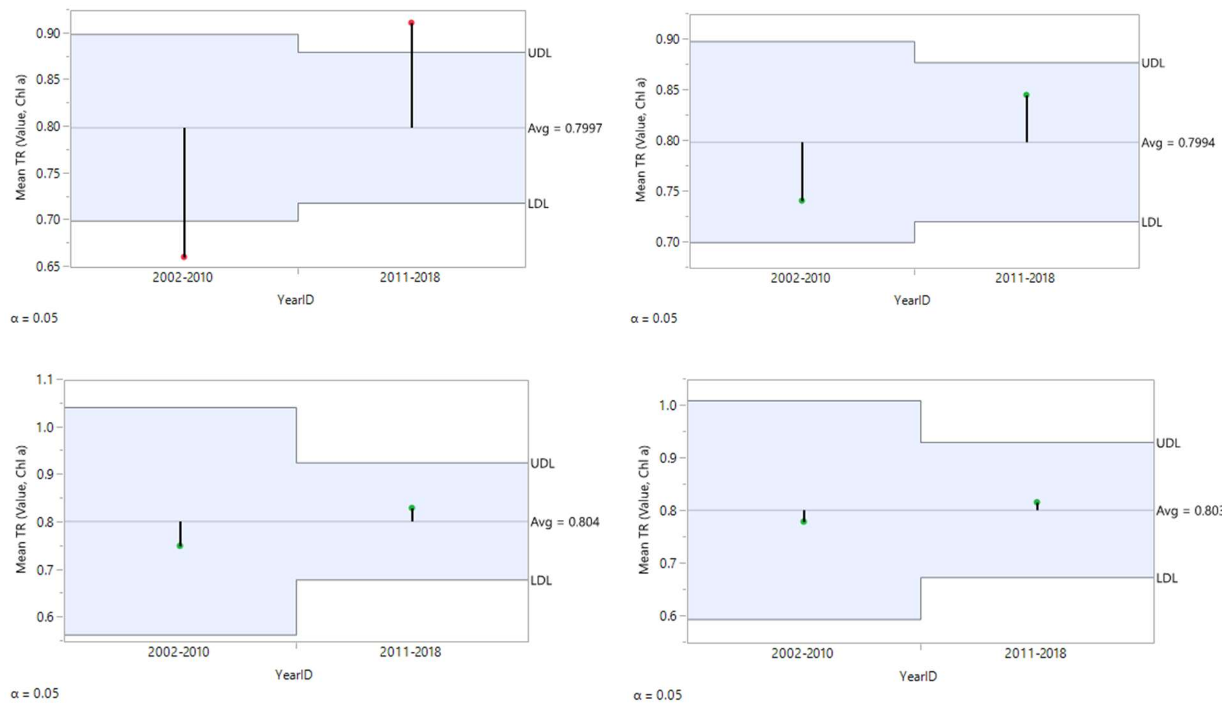


Figure III-6. Comparison of transformed ranks of means for chlorophyll-a concentrations between years of 2002-2010 and 2011-2018 (upper panel) and between summer seasons of 2002-2010 and 2011-2018 (lower panel). Left panel shows results for station P8750000 and right panel is station P8800000. Analysis of means (ANOM) with Transformed Ranks (TR) method of JMP software is used here. Dots indicate means of specific group, horizontal lines indicate the overall mean, shaded area covers the area between lower decision limit and upper decision limit. There are significant differences between means if the dots fall outside of the decision limits.

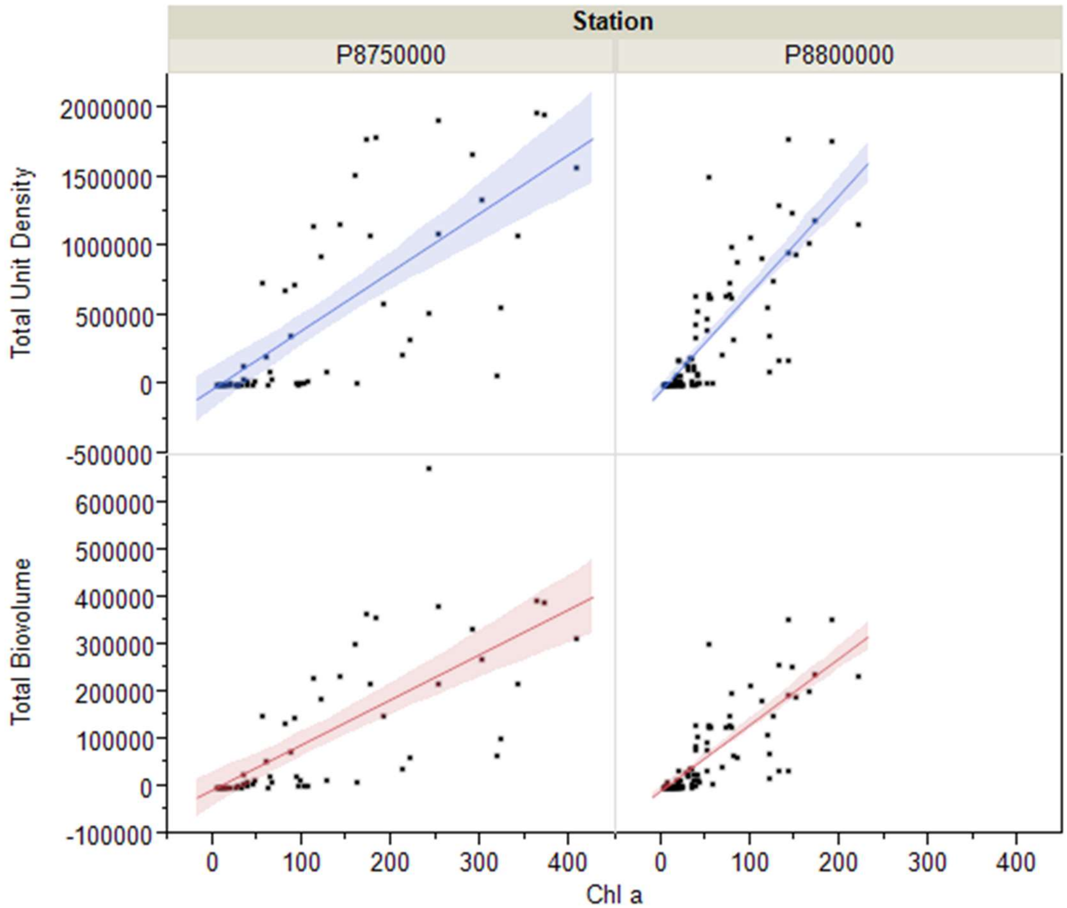


Figure III-7. Linear regression plots between total unit density and chlorophyll a (R^2 = 0.56 and 0.70 for stations P8750000 and P8800000, respectively) and between total biovolume and chlorophyll a (R^2 = 0.53 and 0.70 for stations P8750000 and P8800000, respectively). Shaded areas indicate confidence of fit. Four data points where chlorophyll a > 500 ug/L were excluded from this analysis.

Open Boundary and Tributary Conditions

Chlorophyll a concentrations were collected at monitoring stations at the open boundary (estuary mouth) as well as at the tributaries during the intensive survey period (Figure III-8). High chlorophyll a values close to or above 40 µg/L were observed during growing season at most of the stations.

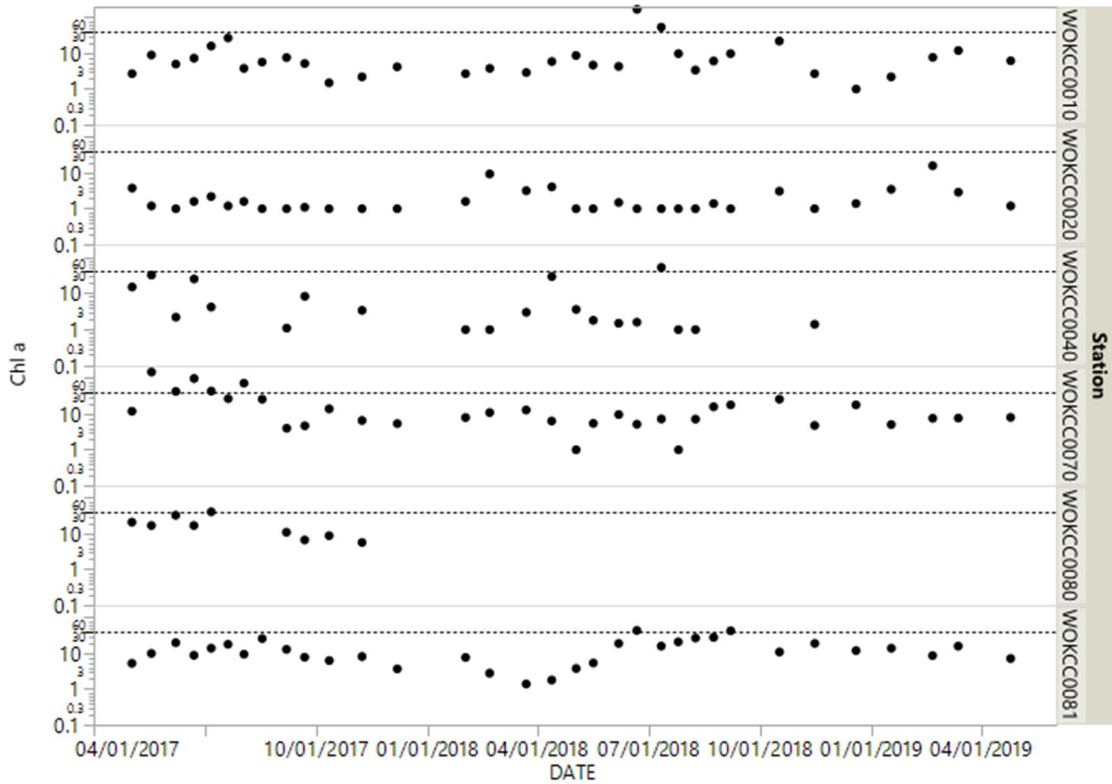


Figure III-8. Time series of Chl a concentrations (µg/L) during the intensive survey period at monitoring stations located at the open boundary (WOKCC0080 and WOKCC0081) and the tributaries (WOKCC0010, WOKCC0020, WOKCC0040 and WOKCC0070) of Calico Creek. Dotted lines are where Chl a concentrations equal 40 µg/L.

IV. Nutrient Data

Estuary Conditions

Long-term nutrient data are available at the two estuary stations P8750000 and P8800000 from the ambient monitoring program for NH3, NOx, TKN and TP. PO4 and other additional water quality parameters (i.e. BOD5, CBOD5, TOC and DOC) were collected during the intensive survey period. These additional water quality parameters (including PO4) will be discussed under Section V.

Time series plots are presented in Figure IV-1 for NH3, NOx, TKN and TP concentrations. Note that different vertical scales were used for station P8750000 and P8800000. Much higher peaks of nutrient concentrations were observed at P8750000, which is in the upper estuary, around 0.3 mile upstream of Morehead City WWTP, than values observed at station P8800000, which is in the lower estuary.

Nutrient concentrations appear to be higher during warmer months, especially April to August, at the upper estuary station P8750000 and in recent years (2011-2018) at P8800000. During 2002 to 2010 before the Morehead City WWTP upgrade was completed, high nutrient concentrations were observed almost all year round at P8800000 (Figure IV-2).

Accordingly, at station P8800000, year round nutrient concentrations are significantly lower during 2011-2018 than during 2002-2010 for all the nutrient forms mentioned above. However, there are no significant differences in mean nutrient concentrations between the summers of the two time periods. At station P8750000, lower NH3 and NOx concentrations were observed during most recent years (2011-2018). During summer months, significantly lower NOx and TP concentrations were observed in recent years (Figures IV-3 and IV-4).

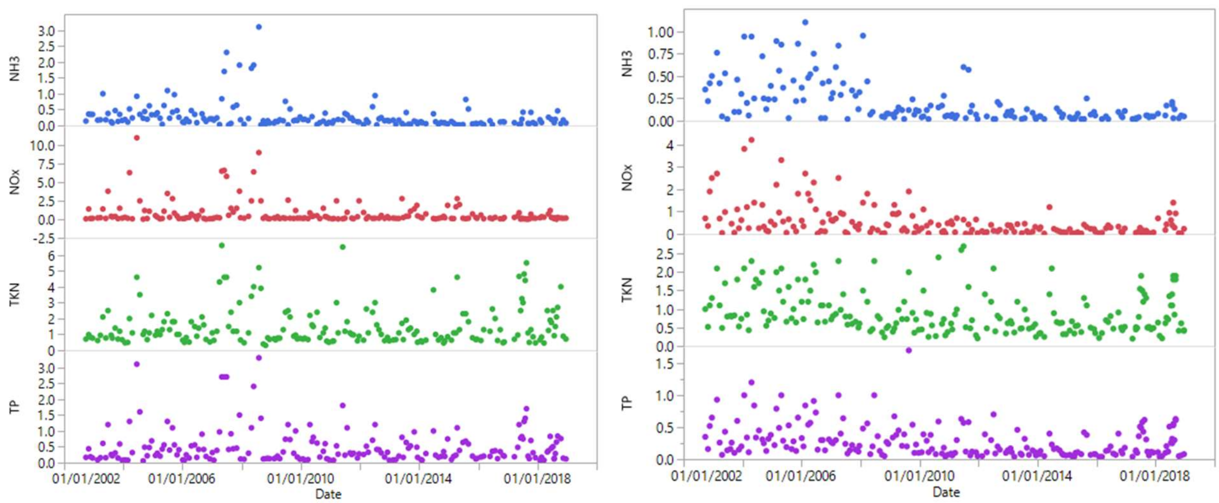
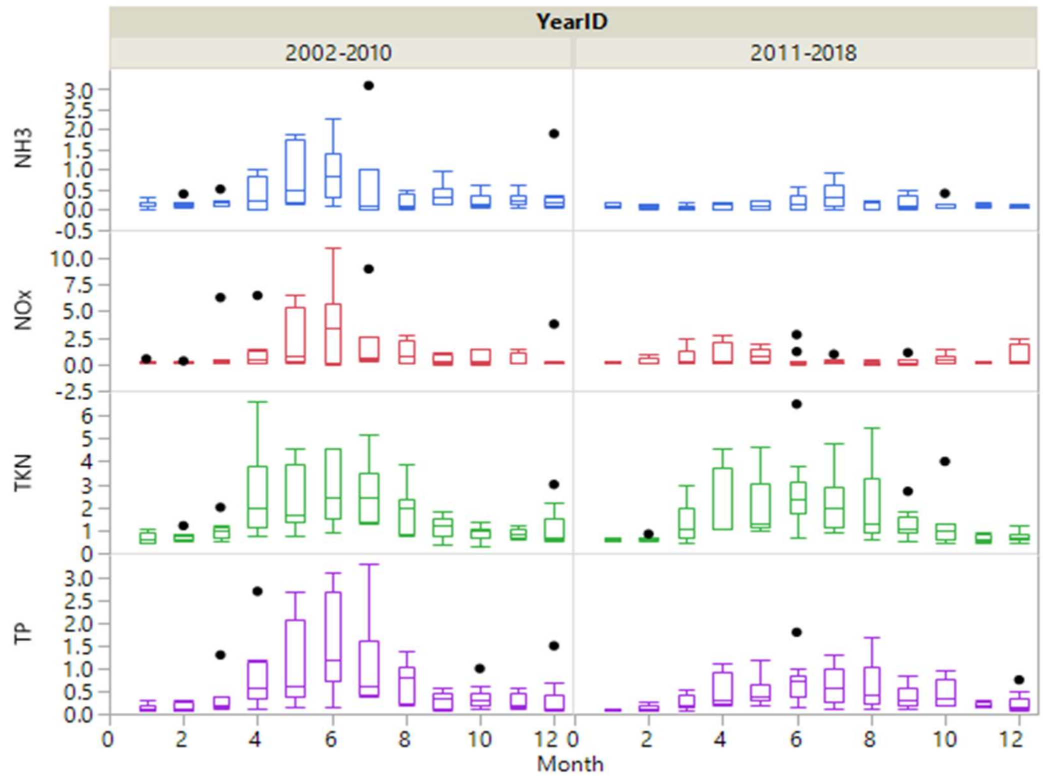


Figure IV-1. Time series plots of nutrient concentrations (in mg/L) at station P8750000 (left panel) and P8800000 (right panel).



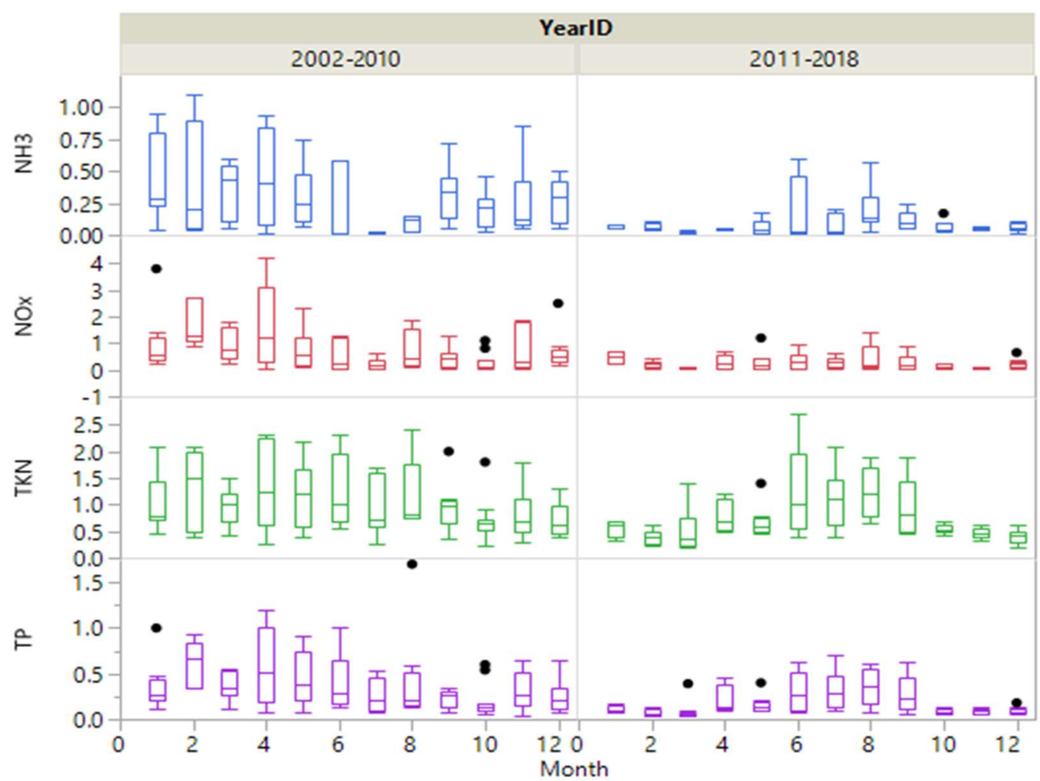


Figure IV-2. Monthly distributions of nutrient concentrations (in mg/L) during 2002-2010 and 2011-2018 periods at station P8750000 (upper panel) and P8800000 (lower panel).

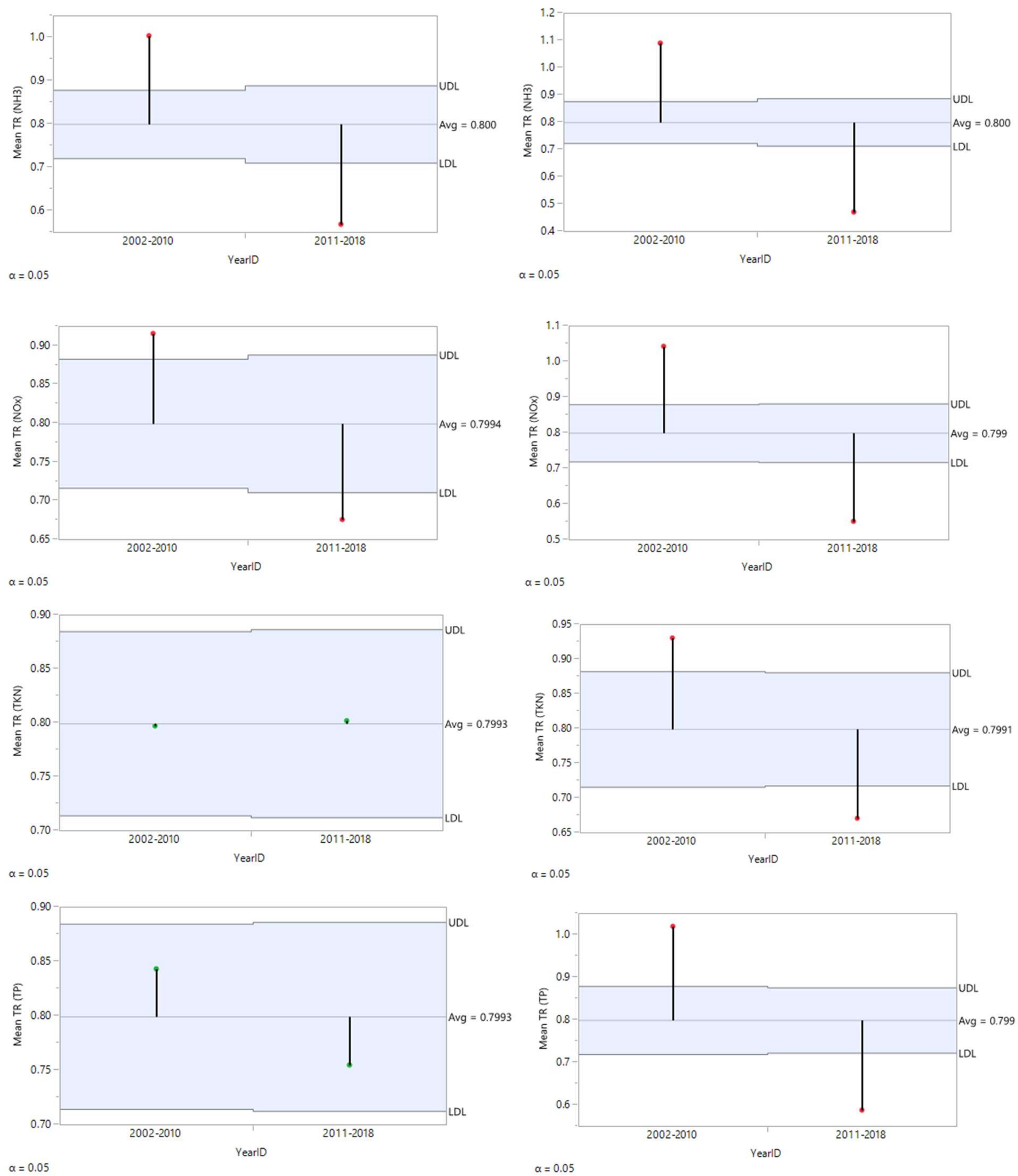


Figure IV-3. Comparison of mean nutrient concentrations from two time periods: 2002-2010 and 2011-2018 (before and after Morehead City WWTP upgrade) at station P8750000 (left panel) and P8800000 (right panel). Analysis of means (ANOM) with Transformed Ranks (TR) method of JMP software was used. Dots indicate means of specific group, horizontal lines indicate the overall mean, shaded area covers the area between lower decision limit and upper decision limit of no significant differences between the group mean and overall mean. There are significant differences between means if the dots fall outside of the decision limits.

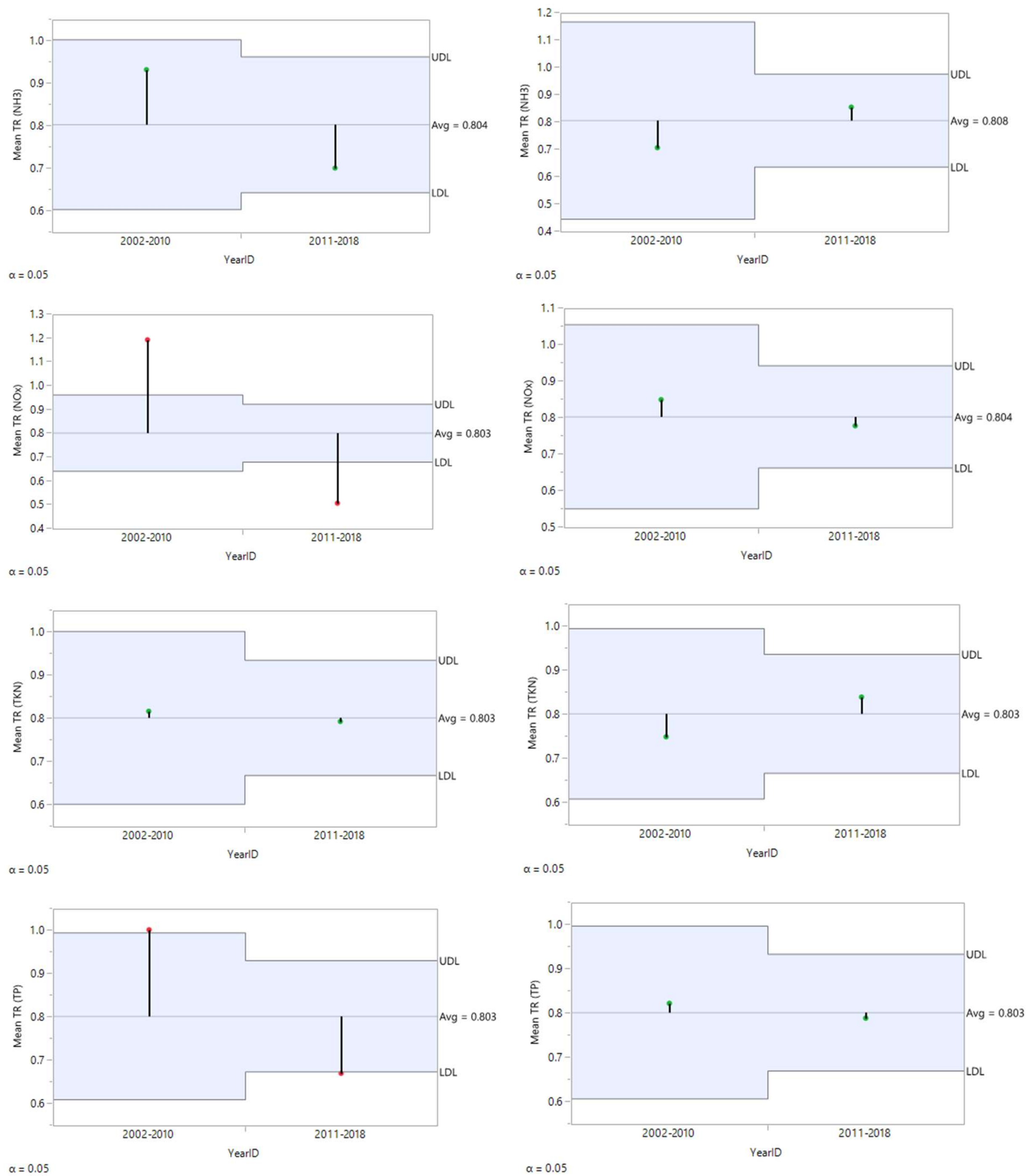


Figure IV-4. Comparison of mean nutrient concentrations from summer seasons of two time periods: 2002-2010 and 2011-2018 (before and after Morehead City WWTP upgrade) at stations P8750000 (left panel) and P8800000 (right panel). Analysis of means (ANOM) with Transformed Ranks (TR) method of JMP software was used. Dots indicate means of specific group, horizontal lines indicate the overall mean, shaded area covers the area between lower decision limit and upper decision limit of no significant differences between the group mean and overall mean. There are significant differences between means if the dots fall outside of the decision limits.

Open Boundary Conditions

Two monitoring stations, WOKCC0080 and WOKCC0081 are located at the mouth of the Calico Creek estuary. WOKCC0080 is in the main channel of the Calico Creek, and WOKCC0081 is close to the south shore off a pier. Physical and biochemical data were collected from both stations May through October 2017. Since no significant differences were found between the data from the two stations (except for DOC, p value was slightly larger than 0.05 indicating some slight differences), data collection from station WOKCC0080 was discontinued.

Time series of nutrient concentrations at WOKCC0080 and WOKCC0081 during the intensive survey period are presented in Figure IV-5. Nutrient concentrations including NH3, NOx, TKN, PO4 and TP are in general much lower than those observed within the estuary.

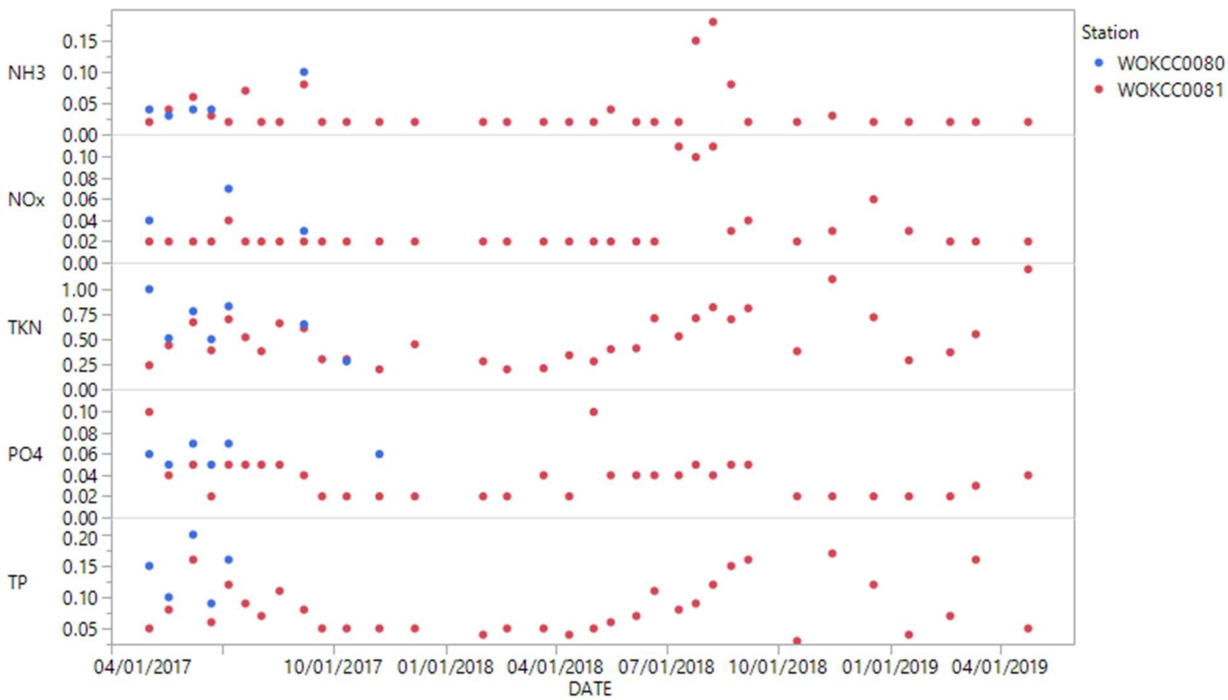


Figure IV-5. Time series of nutrient concentrations (in mg/L) at the open boundary monitoring stations of Calico Creek.

Tributary Conditions

Nutrient concentrations were also collected at monitoring stations in the tributaries of Calico Creek during the intensive survey period. Figure IV-6 suggests that NH3, TKN, PO4 and TP concentrations are relatively higher at stations WOKCC0040 and WOKCC0070 than at stations WOKCC0010 and WOKCC0020. The highest NH3, TKN and TP concentrations at WOKCC0040 and WOKCC0070 appear to occur during warm seasons. However, NOx concentrations show a different spatial and temporal pattern, likely being influenced from different landcover draining into the corresponding tributaries.

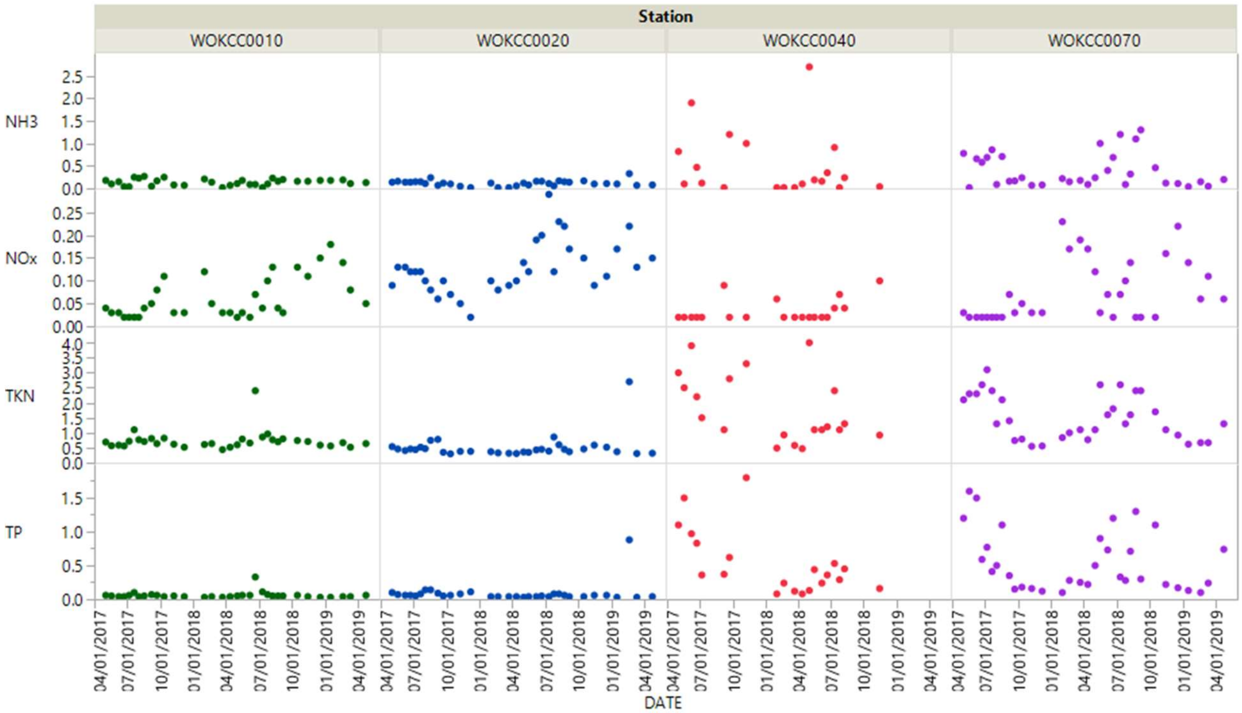


Figure IV-6. Time series of nutrient concentrations (in mg/L) at the tributary monitoring stations of Calico Creek.

Benthic Conditions

Nutrient fluxes and SOD across the sediment-water interface were measured on April 25th, 2019 near station P8800000 (Table IV-1). Five replicate chambers were deployed. Pump failure was recorded for one replicate sample (Replicate 3) and hence was excluded from the analysis. A much higher SOD benthic flux value was measured for Replicate 5 than the other 3 replicate samples. SOD benthic flux measured from Replicate 5 could be identified as an outlier from the group. The average SOD value (corrected to 20°C) was reported to be -0.72 $g/m^2/day$ with the outlier data point excluded. The average SOD becomes -1.35 $g/m^2/day$ if the outlier is included.

Table IV-1. Nutrient fluxes across the sediment-water interface measured on April 25th, 2019 near station P8800000.

	NH3 ($g/m^2/day$)	NOx ($g/m^2/day$)	TP ($g/m^2/day$)	SOD ($g/m^2/day$)
Replicate 1	0.0294	-0.0050	0.0240	-0.7641
Replicate 2	0.0432	0.0000	0.0382	-0.6704
Replicate 4	0.0497	-0.0003	0.0340	-0.7373
Replicate 5	0.1384	-0.0052	0.0537	-3.2413
Average	**0.065**	**-0.0026**	**0.0375**	**-0.72***

*SOD value from Replicate 5 was not included in the average.

V. Physical and Other Water Quality Parameters

Bathymetrical Data

Digital Elevation Model data from NC Floodplain Mapping program was used to generate boundary files for the Calico Creek drainage basin and sub-basins for the tributaries.

No detailed bathymetrical data are available for Calico Creek Estuary. NOAA NGS Post-Sandy Topobathy Lidar data covers only part of the estuary, which was used to provide reference for model grid development.

Across-channel depth profiles were collected by DWR Intensive Survey Branch in February 2018 along 6 transects and in July to August 2019 along 7 transects (Figure V-1).

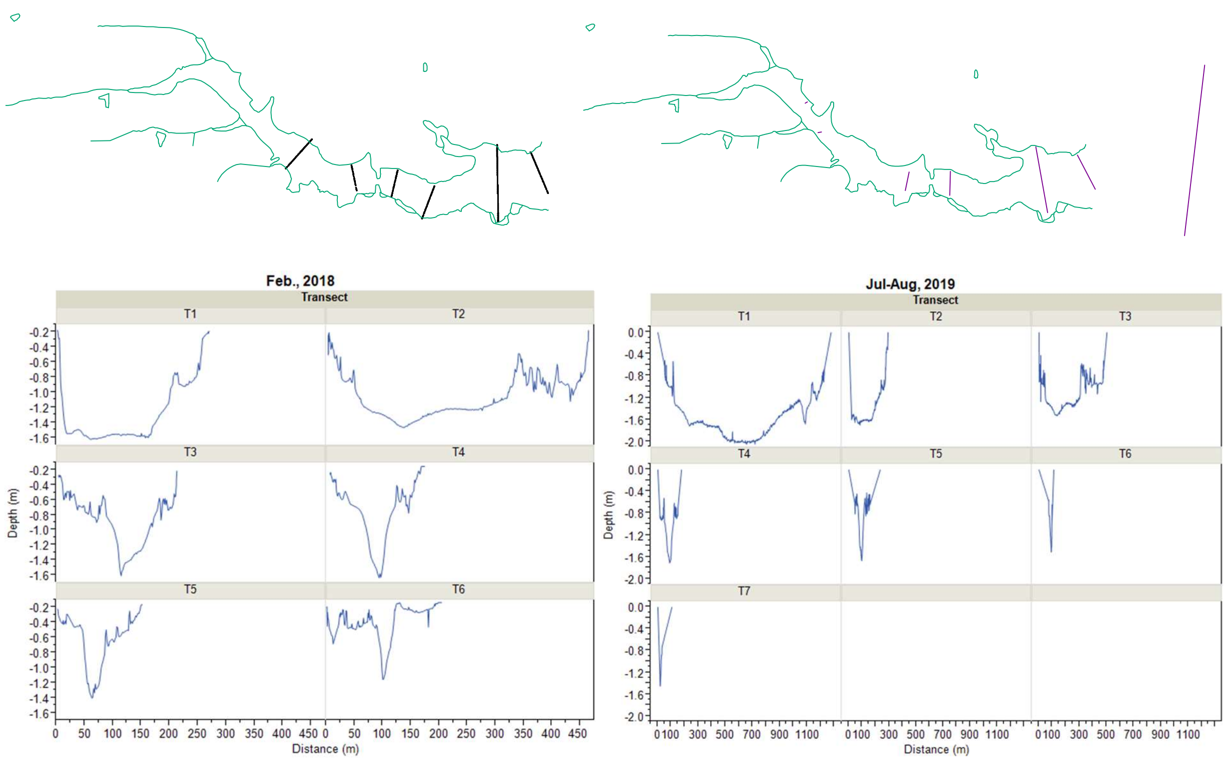


Figure V-1. Across-channel depth profiles collected during intensive surveys in Calico Creek. The position of the transects are shown in the maps above. Transect numbers are counted from the mouth of Calico Creek (T1) increasingly towards the head of the estuary (T6/T7).

Climate Data

Climate data were obtained from NC State Climate Office at Beaufort Smith Field Station, which is about 3 miles to the east of the Calico Creek watershed. Hourly precipitation, wind speed and direction, air temperature, wet bulb temperature, solar radiation, cloud cover, dew point, relative humidity, and sea level pressure were obtained for the period of May 2017 to April 2019 (intensive survey period, Figure V-2).

Monthly distributions of the climate data are presented in Figure V-3. Smaller variabilities were observed for air temperature, relative humidity, wind direction and sea level pressure during summer months (June to August) than the other months of the year. The majority of air temperature values are between 76°F to 83°F with median values around 80°F during June to August. The majority of relative humidity ranged between 77% to 94%, with median values around 85% to 88% during summer months. Most sea level pressure readings are within 1012 mb to 1020 mb with a median value around 1017 mb. Wind directions during the summer are dominated by South to Southwest winds with a median value around 210 degrees.

Long term (2002 to 2019) daily air temperature, wind, relative humidity and precipitation data were also obtained at Beaufort Smith Field Station to examine inter-annual variability of climate conditions in this region (Figure V-4). Annual average of air temperature tends to be higher in recent years (Figure V-5). The air temperature data were again grouped into two time periods: 2002-2010 and 2011-2019, and divided into four seasons. ANOM analysis were applied to each season between the two time periods. Results show that in recent years, air temperature is significantly higher than previous years during spring, summer and winter (Figure V-6). The median and average of annual mean air temperature during 2002 to 2019 are both 64.0 °F, while annual mean air temperatures during 2015-2019 are all above that, especially during 2017 and 2019, annual mean temperatures are more than 1.5°F higher than the long-term mean. The relatively high air temperatures in recent years were observed in all the four seasons (Figure V-7). No consistent long term trends were observed for other parameters though inter annual variability exists.

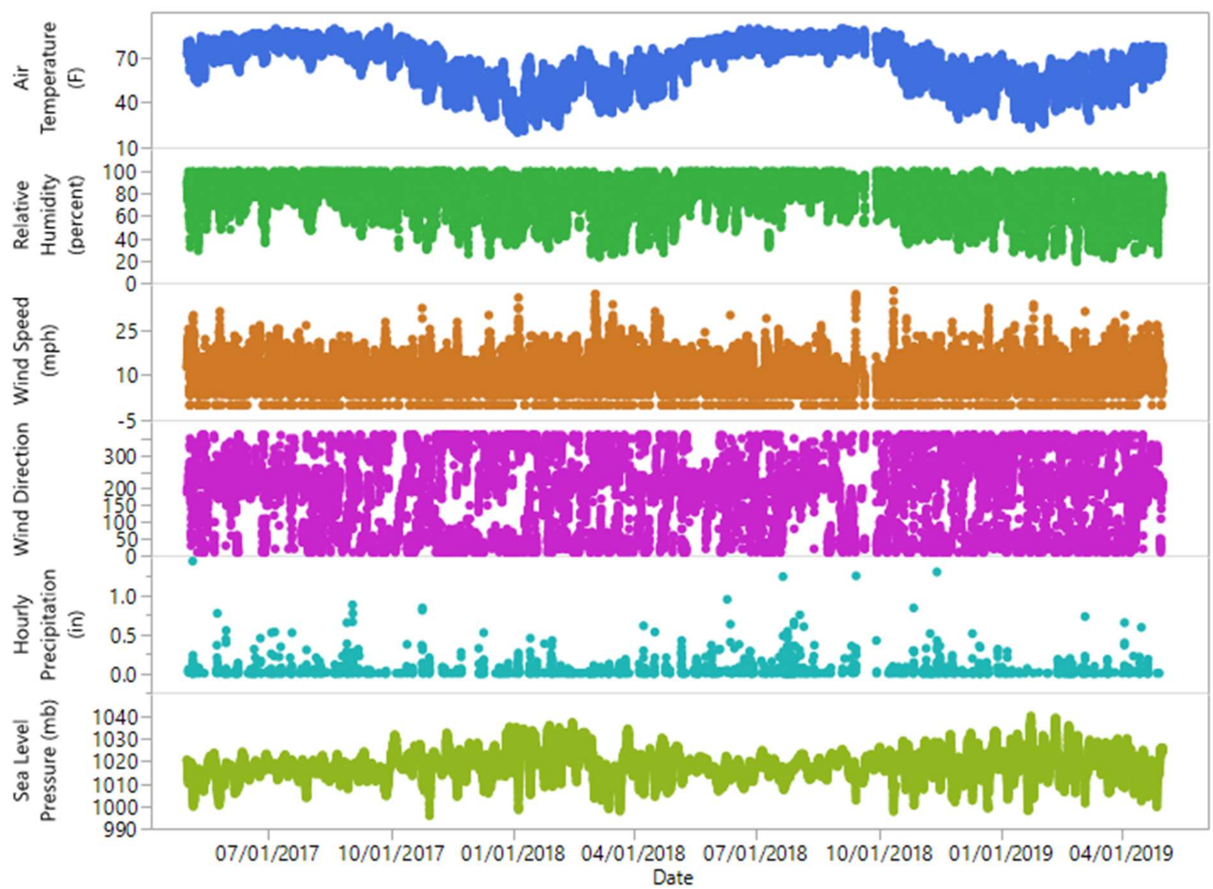


Figure V-2. Climate data at Beaufort Smith Field.

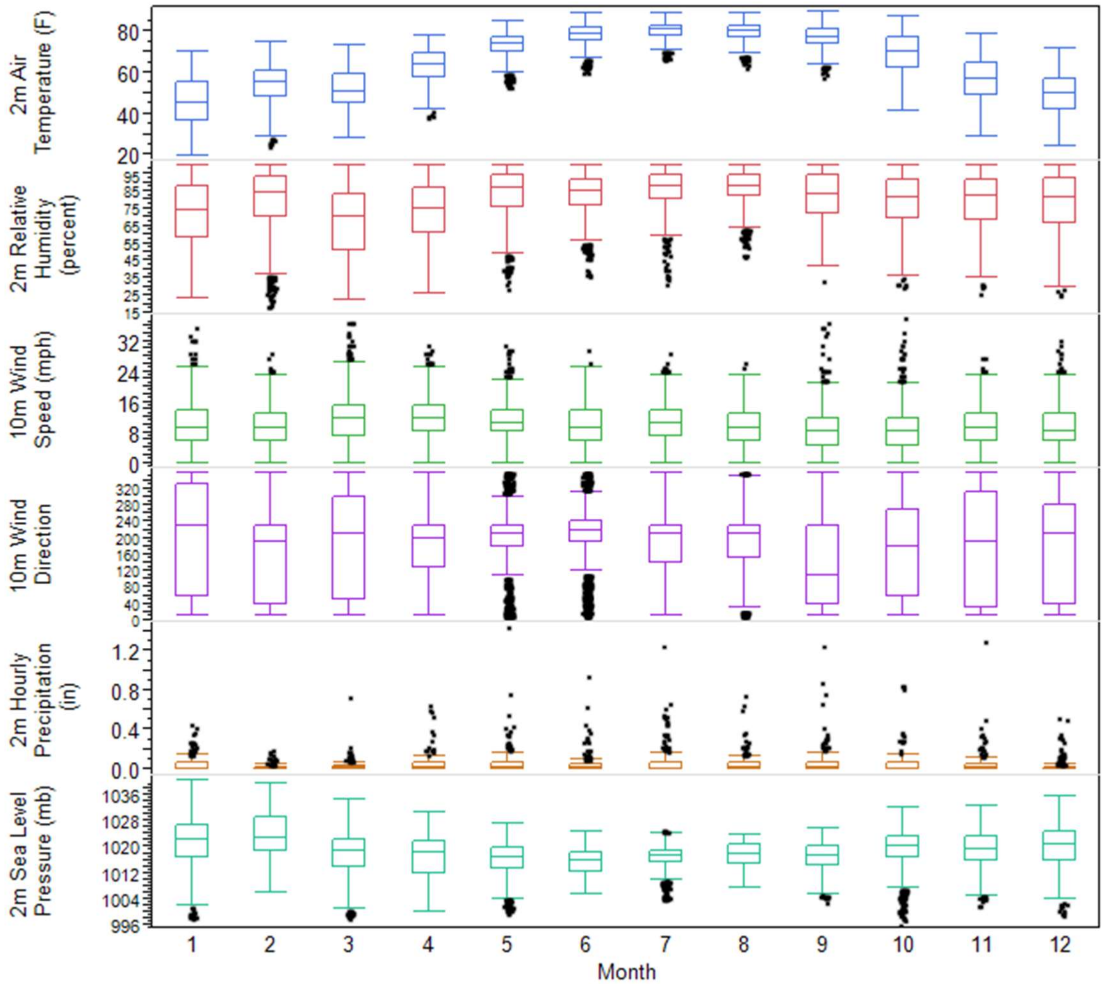


Figure V-3. Monthly distributions of climate data at Beaufort Smith Field during intensive survey period.

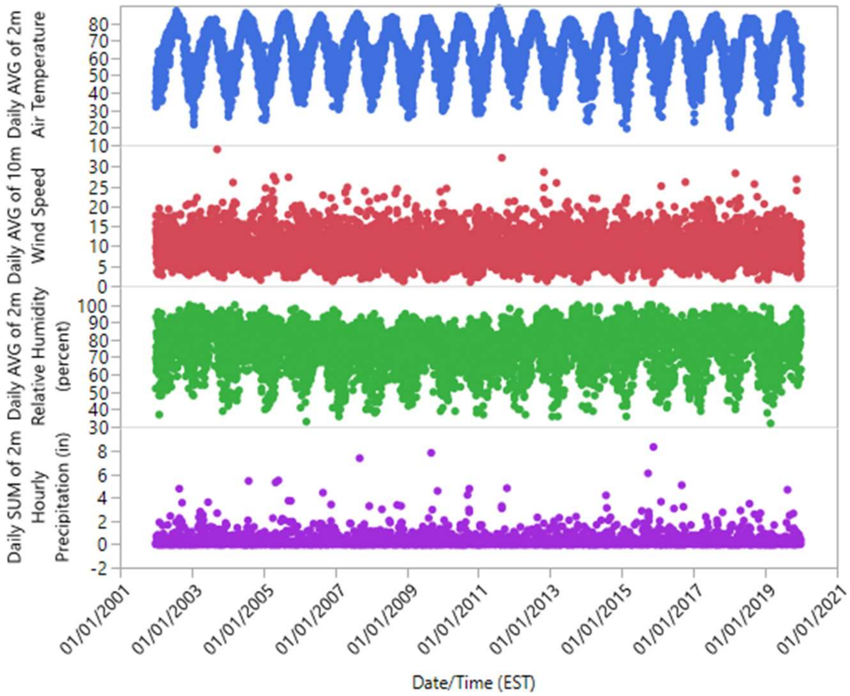


Figure V-4. Long term climate data for daily average air temperature, wind speed, relative humidity and daily sum of hourly precipitation.

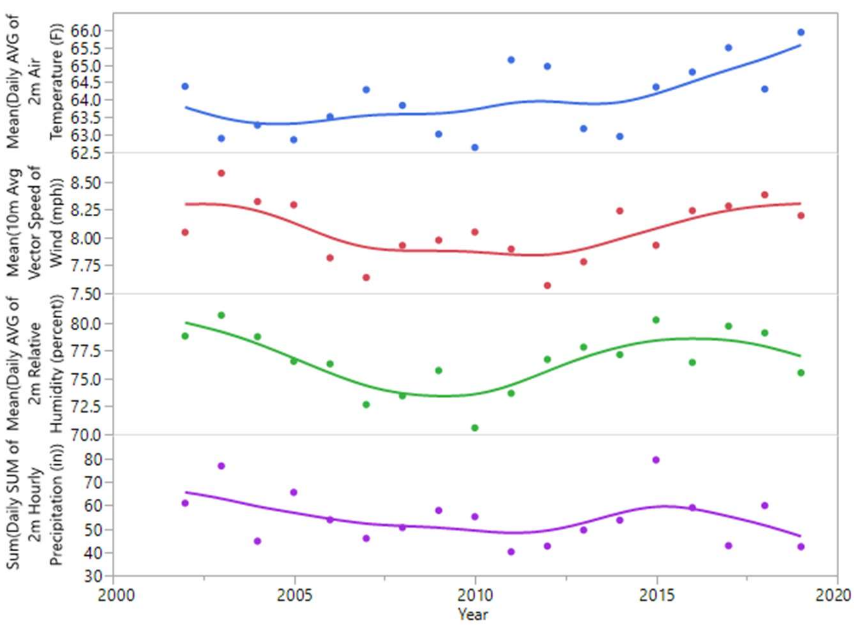


Figure V-5. Annual average of the air temperature, wind speed, relative humidity and annual sum of daily precipitation from 2002 to 2019.

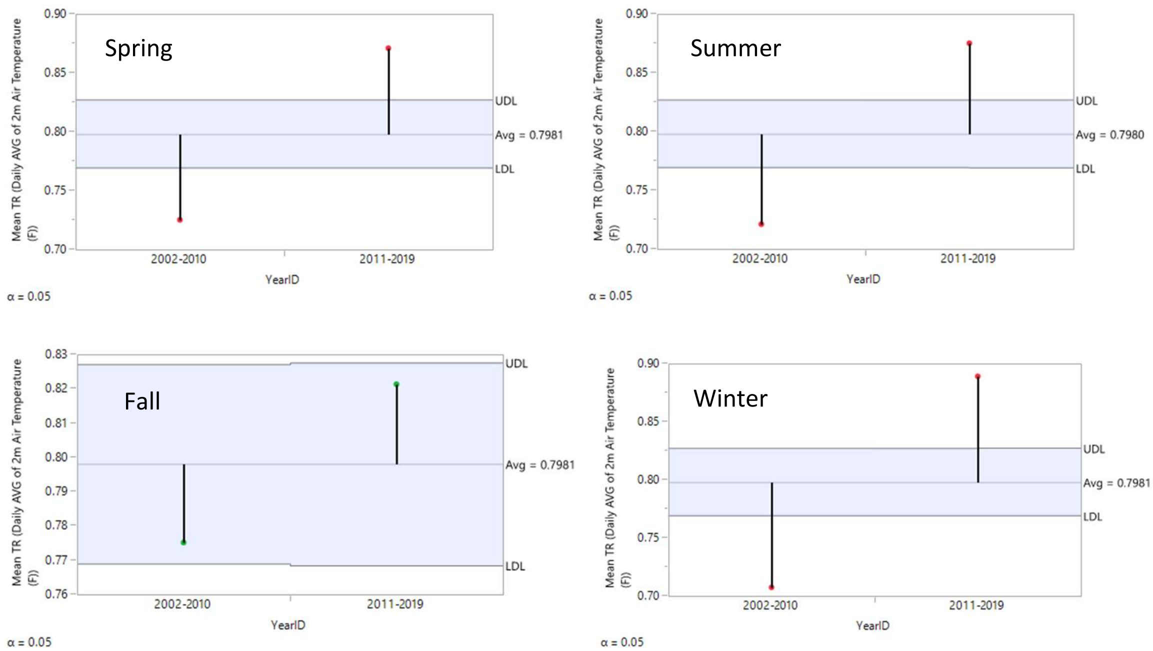


Figure V-6. Comparison of mean air temperature between two time periods: 2002-2010 and 2011-2019 during different seasons. Analysis of means (ANOM) with Transformed Ranks (TR) method of JMP software was used. Dots indicate means of specific group, horizontal lines indicate the overall mean, shaded area covers the area between lower decision limit and upper decision limit of no significant differences between the group mean and overall mean. There are significant differences between means if the dots fall outside of the decision limits.

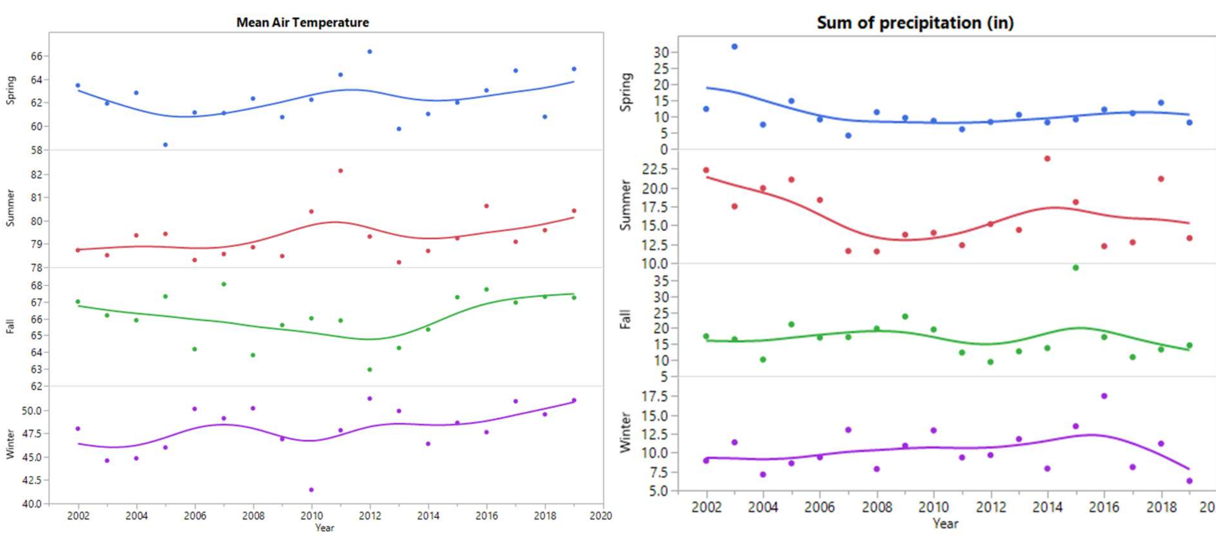


Figure V-7. Seasonal mean air temperature (°F) and seasonal sum of precipitation (in) distributions from 2002 to 2019.

Estuary Conditions

Long-term physical and other water quality data such as water temperature, salinity, pH, DO, turbidity and TSS concentrations are available at the two estuary stations P8750000 and P8800000 from the ambient monitoring program. Additional parameters such as PO4, TOC, DOC, BOD5 and CBOD5 were collected during the intensive survey period.

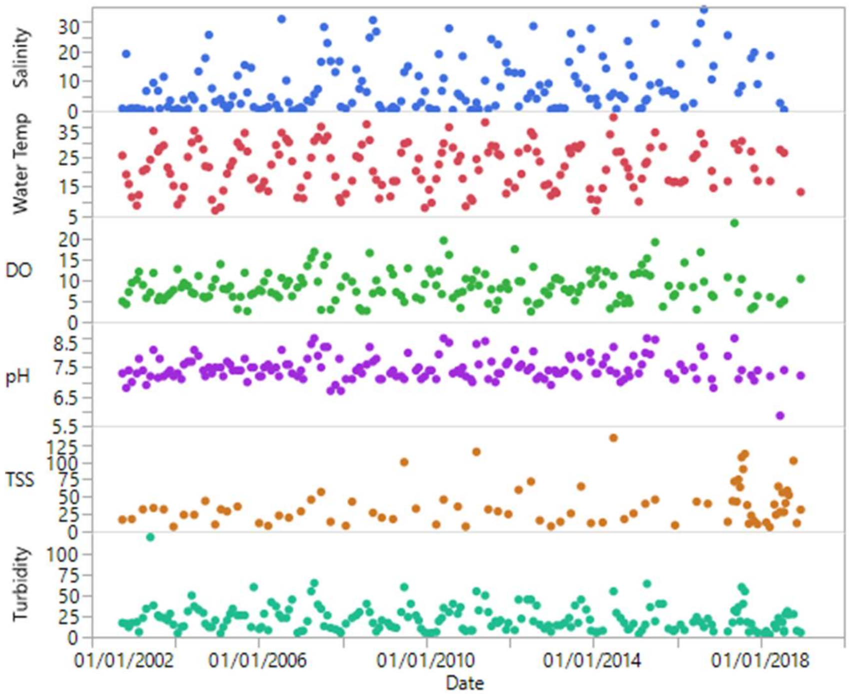
Seasonal variations of water temperature are similar at both stations (Figure V-8 and V-9). Salinity is typically a good indication on the combined impacts of freshwater inflow and tidal influences. High variabilities of salinity were observed at both stations, suggesting that freshwater input to the estuary is transient. DO values also show seasonal patterns at the two stations, ranged between 1.8 and 23.8 mg/L at station P8750000 and between 1.4 and 18.5 mg/L at station P8800000. pH ranged between 5.8 and 8.5 at the two stations with the vast majority between 7 and 8.

At the upstream station P8750000, significantly higher mean salinity values and higher TSS concentrations were observed during 2011-2018 compared with values observed during 2002-2010. The higher salinity values were observed especially during winter and spring months, indicating dryer wet-seasons during recent years (Figure V-10). Relatively high salinity values were also observed during winter and spring time at P8800000. In addition, water temperature tends to be higher in recent winters for both stations. By contrast, salinity and water temperature are both relatively low during summers of most recent years.

Strong ($r>0.5$) and statistically significant positive correlations are between pH and DO, and between turbidity and TSS at both stations (Figure V-11). The positive correlations between pH and DO suggest that the factors that control the variation of pH likely also affect DO dynamics. Strong and statistically significant positive correlations are also between water temperature and turbidity/TSS at station P8750000 suggesting high peaks of TSS/turbidity values occur during warm seasons and likely at least partly due to algal blooms. Water temperature and DO at both stations show negative correlations while water temperature is within certain range; beyond that, DO becomes higher when water temperature gets higher. The turning point is around 25 to 27 °C of water temperature. With higher temperature, DO production by photosynthesis likely dominates in the system.

Calico Creek appears to be a partially-mixed/stratified estuary, vertical stratifications were often observed at station P8800000. Vertical differences in water temperature are highest during summer, up to 3.7 °C. However, density stratification at this site is more influenced by salinity differences, which can reach 16.6 ppt (observed on 6/26/2006) (Figure V-12). Interestingly, the strongest salinity stratification does not correspond to very high salinity values (Figure V-13), likely influenced by both relatively high river input and tidal forcing. Weak to moderate salinity stratifications occurring during summer, together with moderate temperature differences, contribute to the bottom water hypoxia conditions.

BOD5 and CBOD5 observed during the intensive survey period show similar seasonal trends (Figures V-14 and V-15) with highest values observed during summer. The summer-time interquartile range of BOD5 is 15 mg/L to 21 mg/L at station P8750000 and 4.9 mg/L to 10 mg/L at station P8800000. Such seasonal pattern was also observed for TOC, DOC and PO4. At station P8750000, relatively high values of BOD5, CBOD5 and PO4 also occurred during spring and fall.



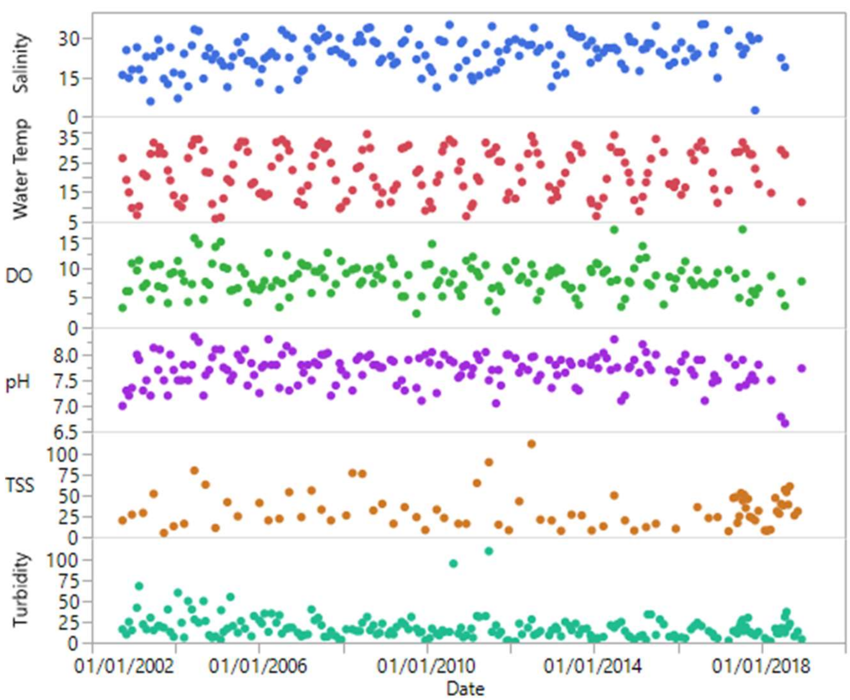
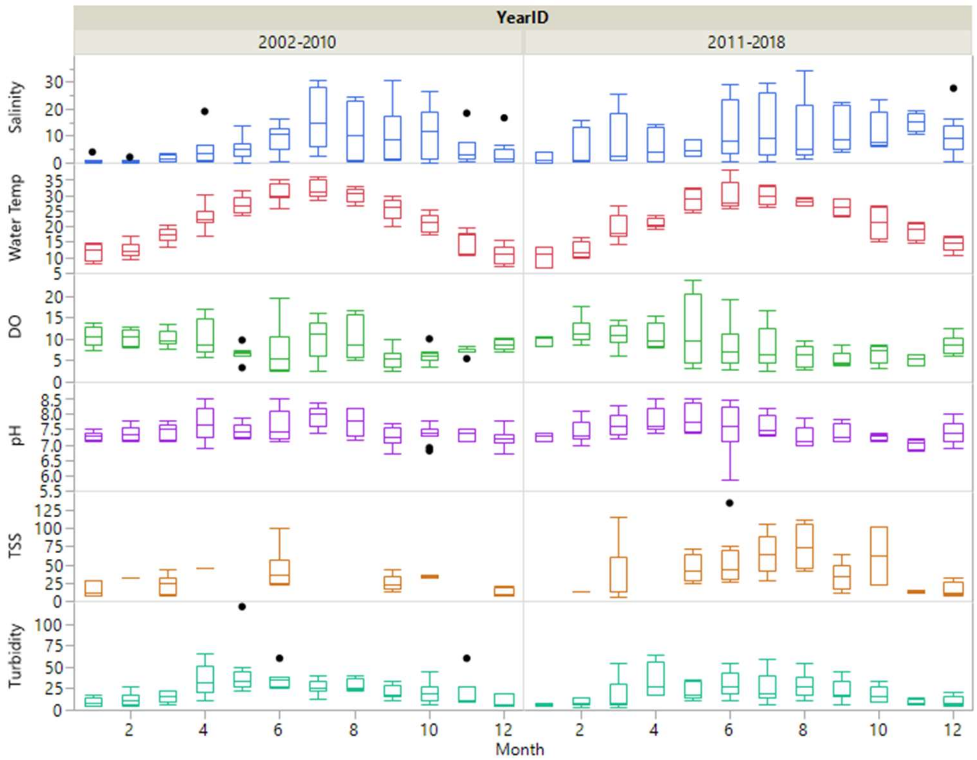


Figure V-8. Time series plots of salinity (ppt), water temperature (°C), DO (mg/L), pH, TSS (mg/L) and turbidity (NTU) at stations P8750000 (upper panel) and P8800000 (lower panel) in Calico Creek Estuary. At station P8750000, only one data sample close to water surface was collected for each sampling event (in the case of split samples, data are averaged in the graph), while at station P8800000, depending on the total water depth at the sampling time, 2-5 samples were collected at different water depths of this site. The data points included in the graph for P8800000 are depth averaged values.



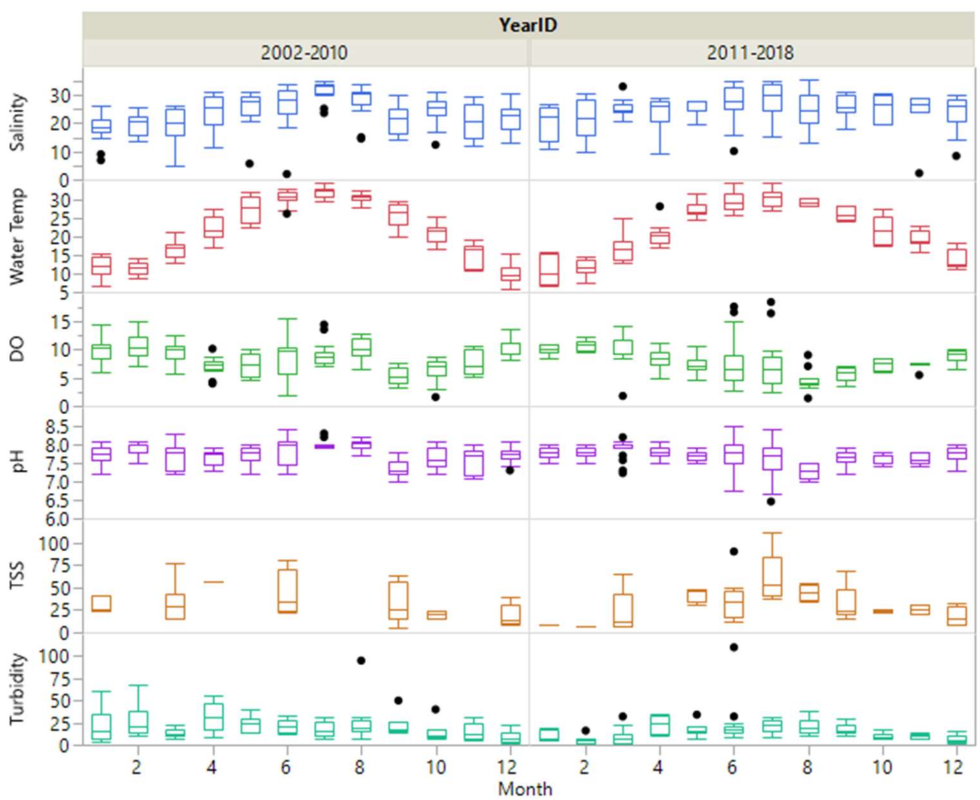


Figure V-9. Box plots of monthly distributions of salinity (ppt), water temperature (°C), DO (mg/L), pH, TSS (mg/L) and turbidity (NTU) during the time periods of 2002-2010 and 2011-2018 at station P8750000 (upper panel) and P8800000 (lower panel).

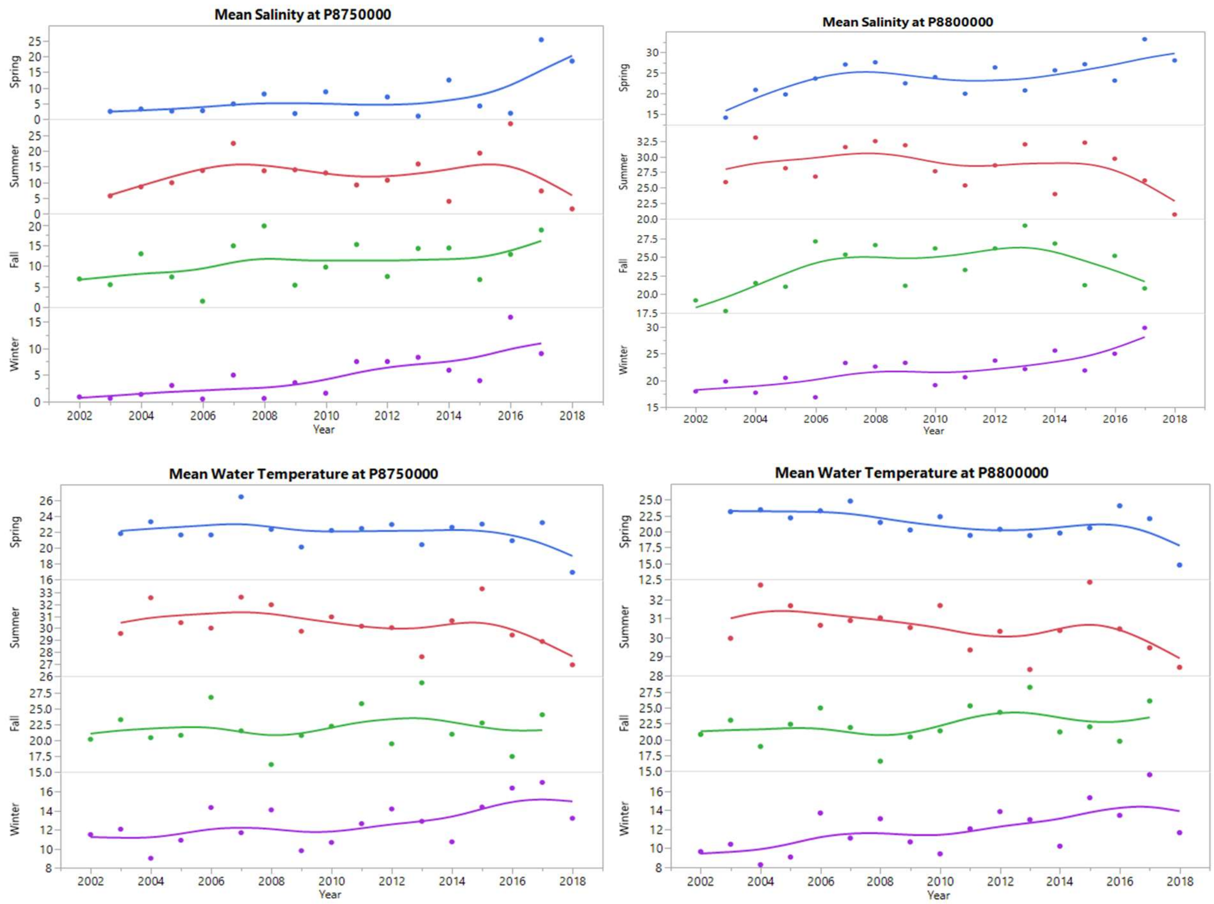


Figure V-10. Seasonal mean salinity (ppt) (upper panel) and water temperature (lower panel) distributions from 2002 to 2018 at stations P8750000 (left panel) and P8800000 (right panel).

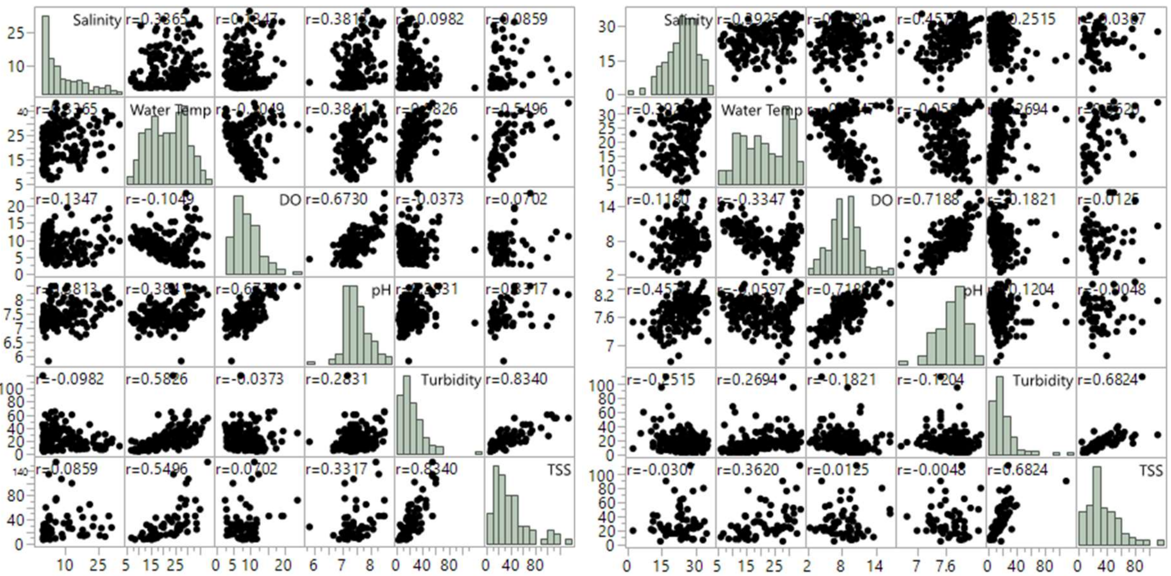


Figure V-11. Scatter plots of physical parameters at stations P8750000 (left panel) and P8800000 (right panel) (points indicate vertically averaged values at station P8800000).

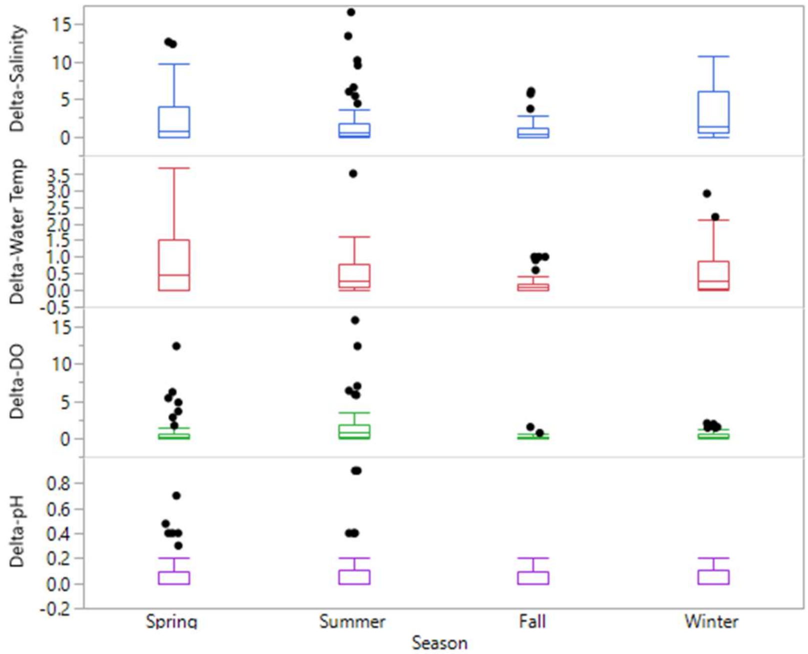


Figure V-12. Seasonal distributions of vertical differences (Delta-) in salinity (ppt), water temperature (°C), pH and DO (mg/L) concentrations at station P8800000 in Calico Creek.

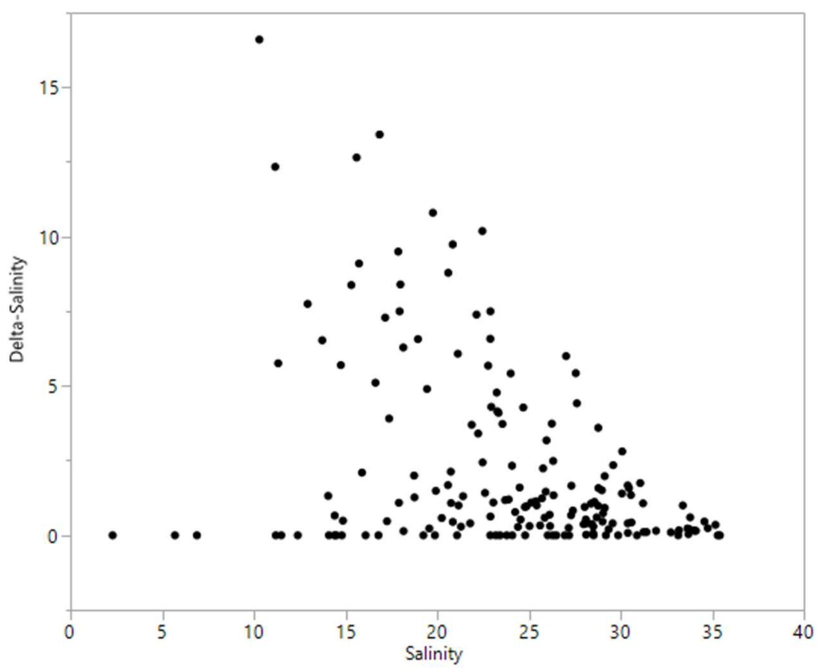


Figure V-13. Salinity (ppt) vertical stratification as a function of vertically averaged salinity at station P8800000 in Calico Creek.

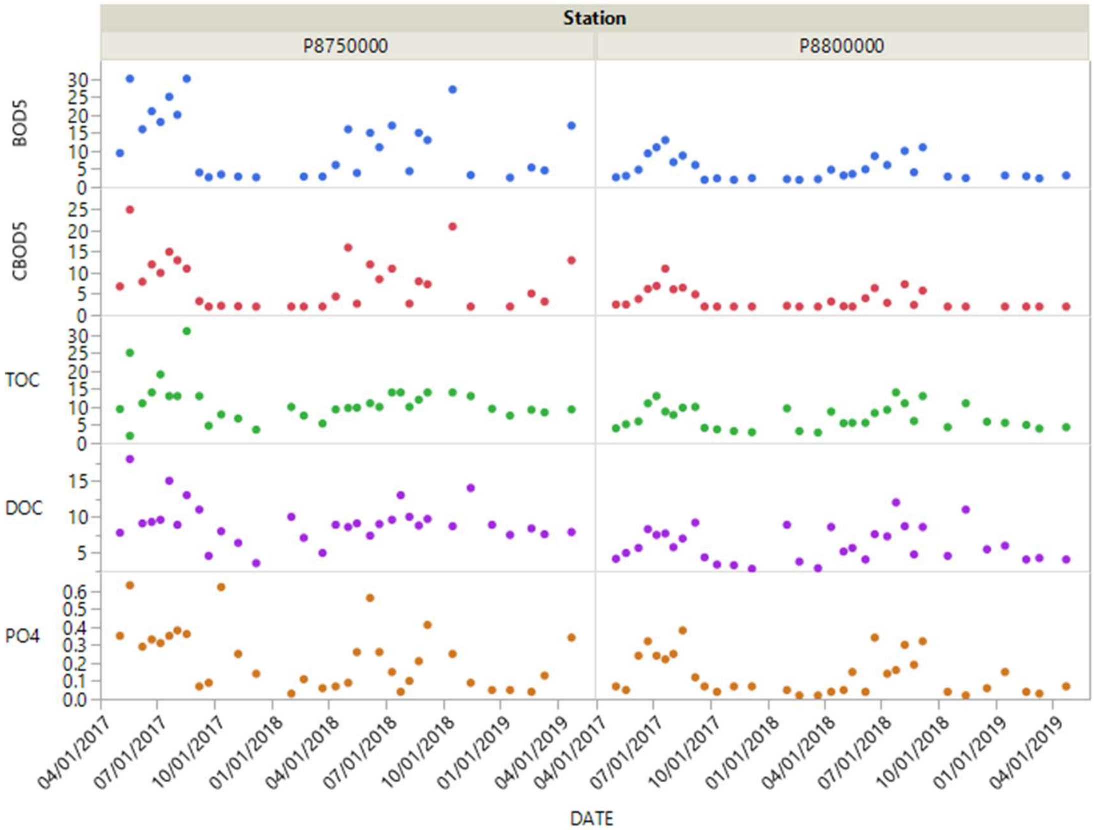


Figure V-14. Time series of BOD5, CBOD5, TOC, DOC and PO4 concentrations (in mg/L) collected during intensive survey period at stations P8750000 and P8800000.

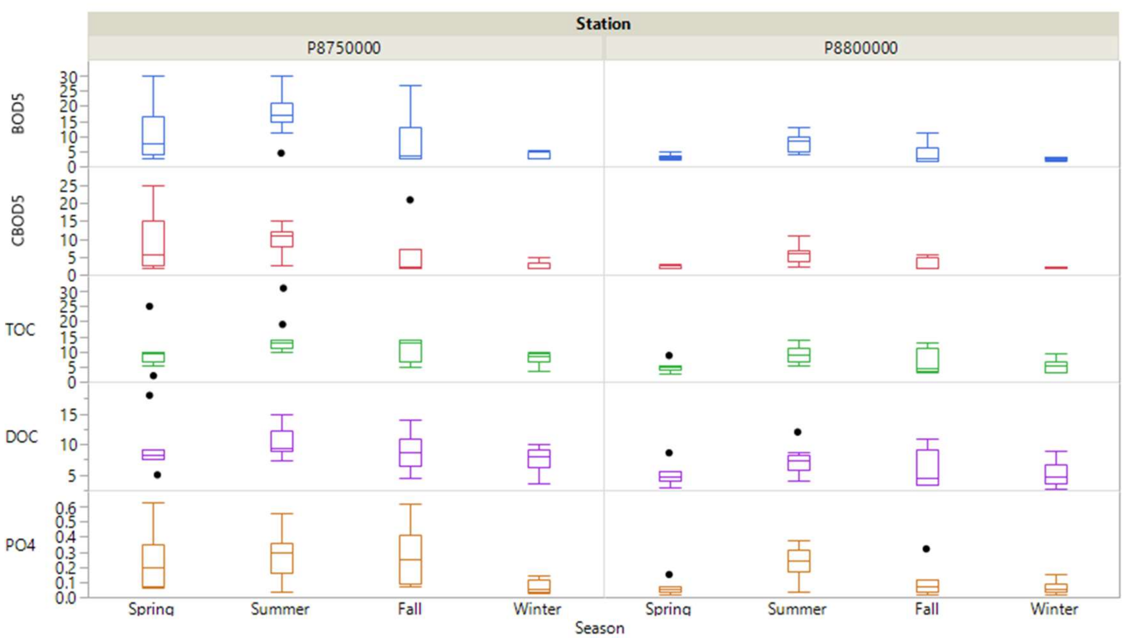


Figure V-15. Seasonal box plots of BOD5, CBOD5, TOC, DOC and PO4 concentrations (in mg/L) collected during intensive survey period at stations P8750000 and P8800000.

ADCP Data

Acoustic Doppler Current Profiler (ADCP) data were collected using River Surveyor M9 from SonTek on 6/24/2019 (neap tide) and 8/1/2019 (spring tide) about 250 ft upstream (west) of monitoring station P8800000. Positive velocities are during flood tide and negative values during ebb. Flow speeds are in general less than 0.36 m/s during neap tide and less than 0.55 m/s during spring tide. Maximum flow speeds normally occurred close to surface of the water column (Figure V-16). The recorded tidal range is 0.69 m during neap tide and 1.45 m during spring tide. The depth-averaged velocity values were between -0.33 m/s (ebb) to 0.48 m/s (flood) during spring tide and between -0.27 m/s (ebb) and 0.33 m/s (flood) during neap tide. Stronger flow speeds occurred during flood time (not ebb) for both the two time periods at the monitoring station, suggesting tidal floods are likely dominate in the channel where ADCP was deployed while freshwater outflow is likely dominate in shallow shore areas.

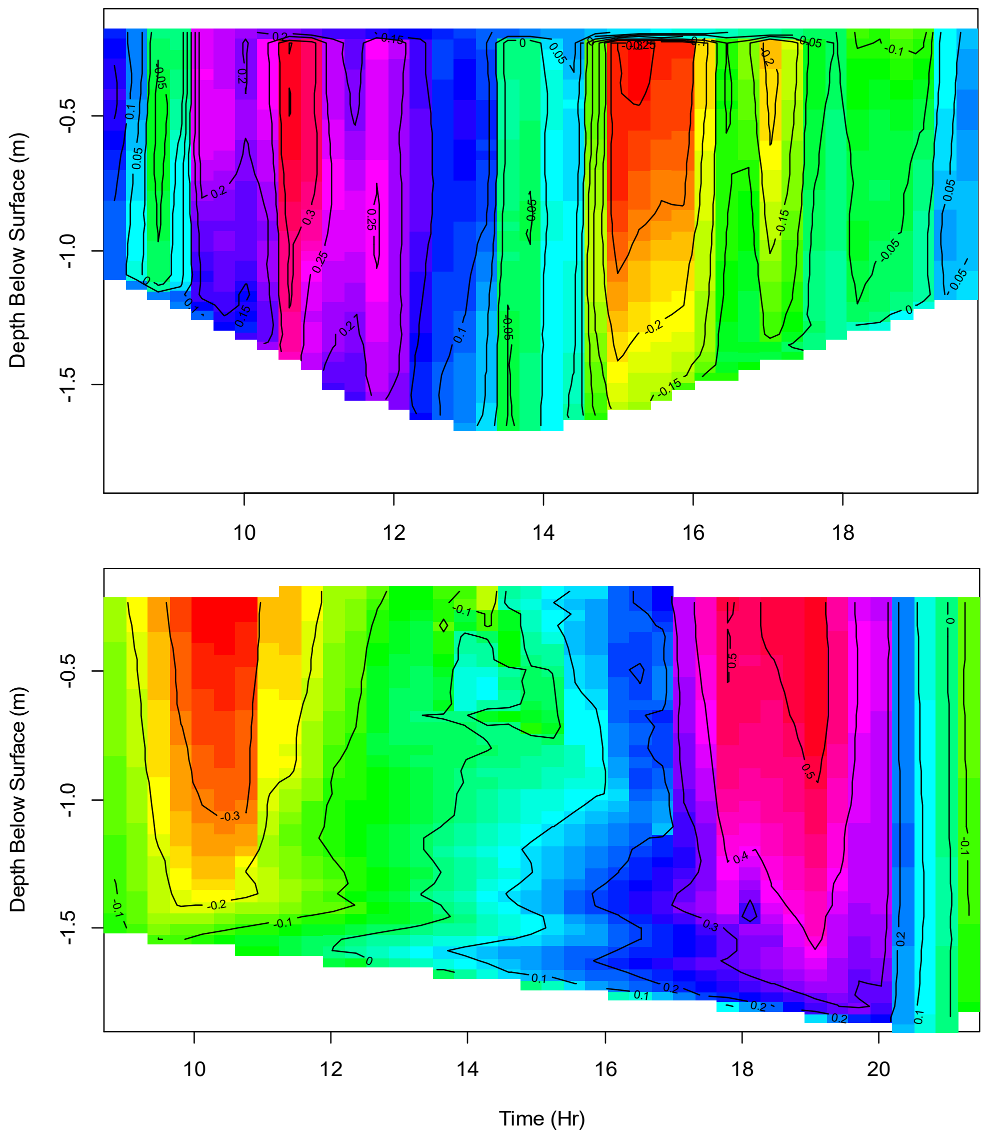


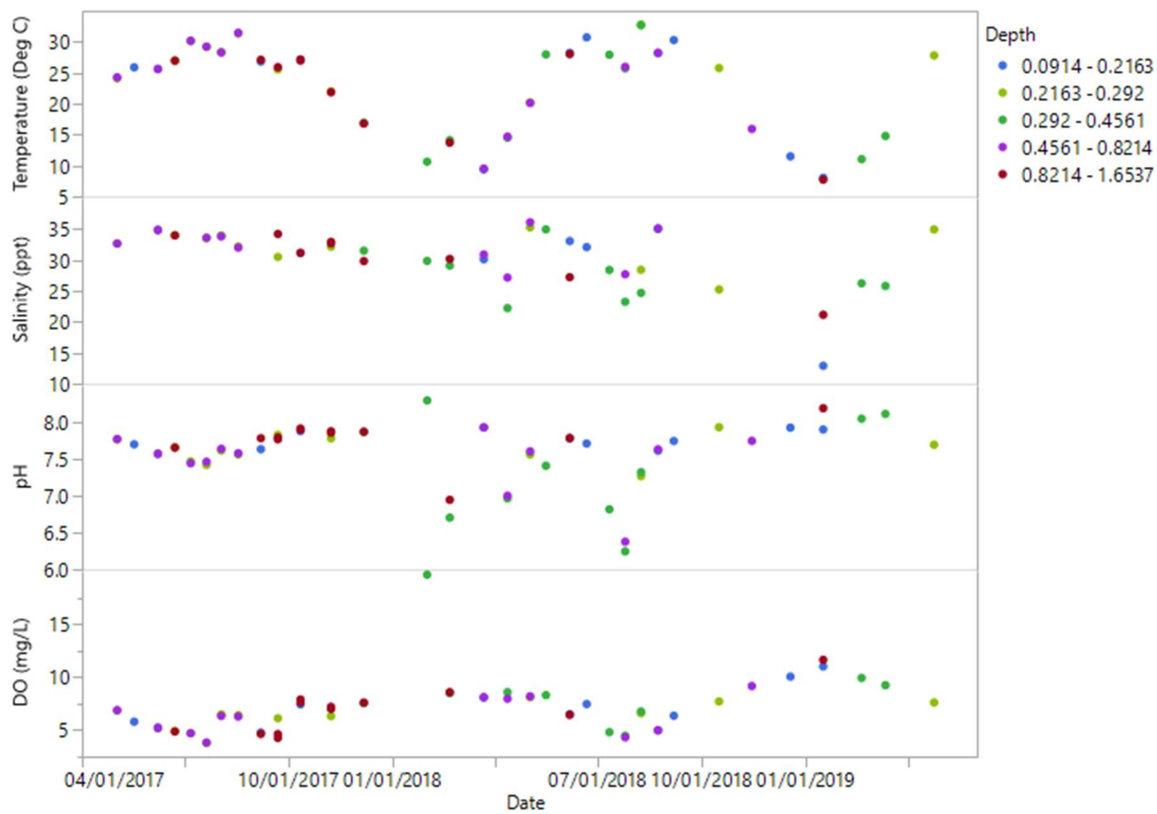
Figure V-16. Along-channel depth profile of velocity (m/s) on 6/24/2019 (upper panel) and 8/1/2019 (lower panel) about 250 ft west of P8800000. Positive velocities are during flood tide and negative values indicate ebb tide.

Open Boundary Conditions

As described above, two monitoring stations, WOKCC0080 and WOKCC0081 are located at the mouth of the Calico Creek estuary. WOKCC0080 is in the main channel of the Calico Creek, and WOKCC0081 is close to the south shore off a pier.

Time series of physical and water quality parameters at station WOKCC0081 are presented in Figure V-17. Water temperature, salinity, pH and DO concentrations were measured at multiple water depths at WOKCC0081 when water depths are high enough. Vertical differences in water temperature, pH and DO are small, up to 0.4 °C, 0.3, and 1.8 mg/L, respectively. In addition, the 90th percentile of delta-DO is 0.6 mg/L, suggesting DO is well-mixed at the site for most of the time. By contrast, moderate to strong salinity stratification occurred occasionally, the top quantile (75th to 100th percentile) of delta-salinity ranged between 1.7 and 8.2 ppt.

Photic composite samples were normally collected for turbidity, TSS, BOD5, CBOD5, TOC and DOC measurement, surface grabs were collected instead when water levels were low.



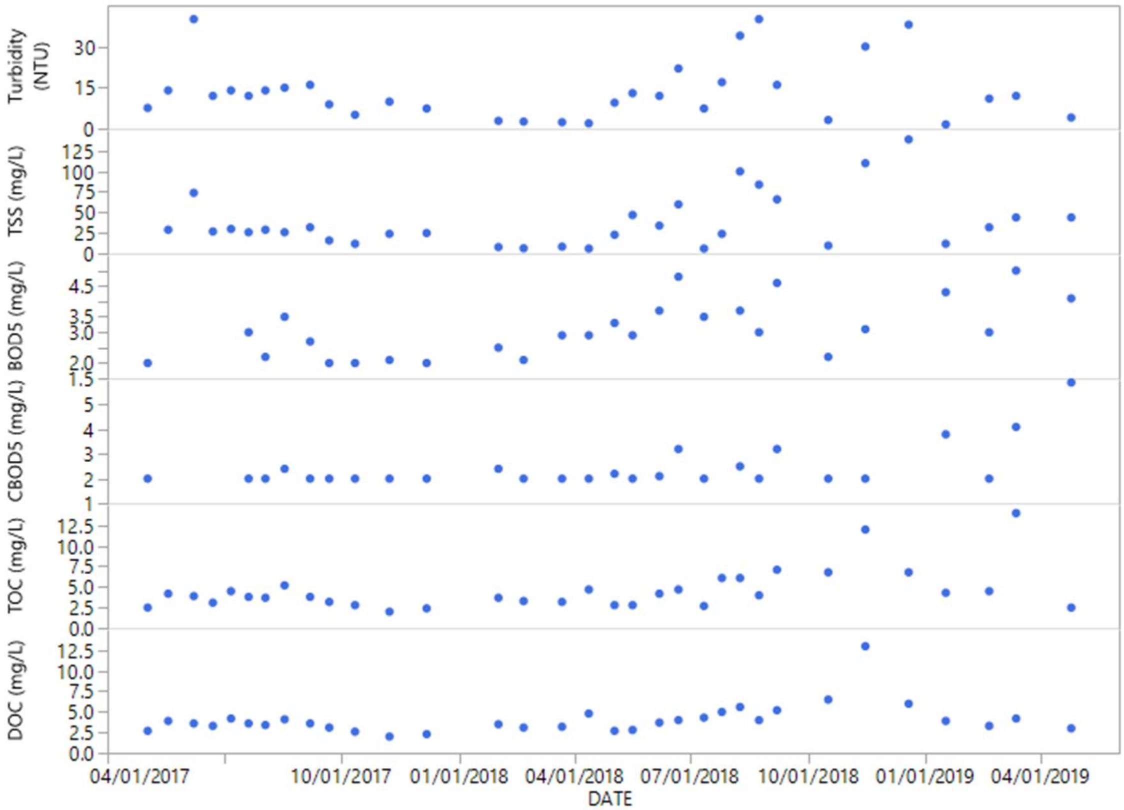


Figure V-17. Time series plots of physical and water quality parameters at WOKCC0081 in Calico Creek.

Tide Gauge Data

The changes of water level at the estuary mouth in general reflect the combined physical effects of tide, freshwater input, and wind-driven circulation. A long-term NOAA tide gauge station is located at Beaufort Duke Marine Lab, around 5km to the east of Calico Creek. The mean tidal range at the site is recorded as 0.95 m. The sea level at the site appears to have risen more than 0.1 m since 2000 (Figure V-18).

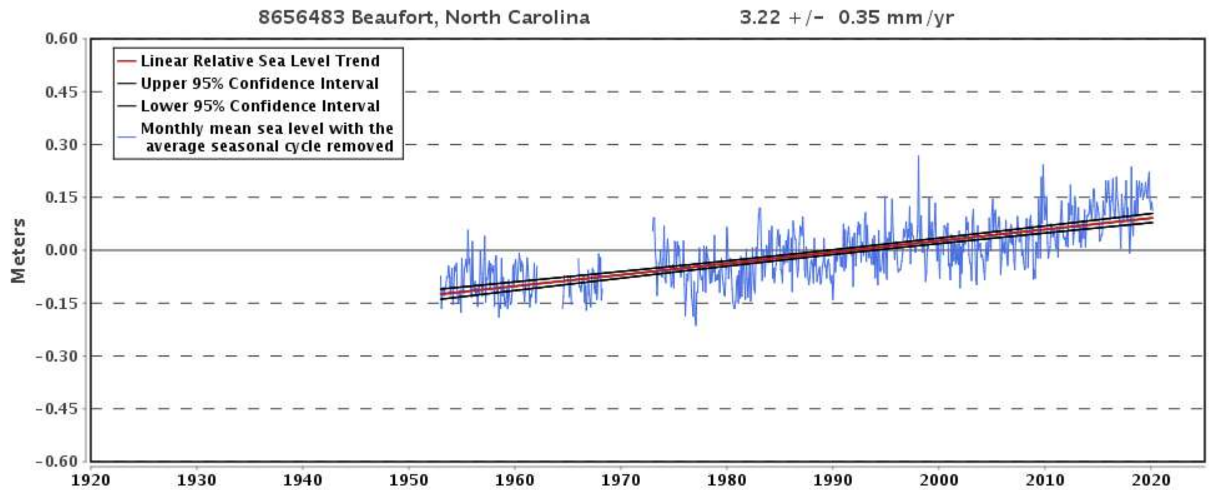


Figure V-18. Long term sea level change at NOAA station 8656483 Beaufort, Duke Marine Lab, NC.

A U20 HOBO level logger was deployed at WOKCC0081 from 5/1/17-12/23/18 during the intensive survey period. Unfortunately, part of the data (salinity) was not recorded successfully and raw pressure readings were extracted from the logger. Sea level air pressure was downloaded from State Climate Office and salinity was assumed to be a constant of 30 ppt for the water level calculation, we estimate that the error on water depth estimation caused by the constant salinity assumption is less than 2 centimeters (Lin, Memo, December 2019).

Harmonic analysis was conducted on 2017 summer record of estimated water level at the mouth of Calico Creek (station WOKCC0081) (Figure V-19). Tidal harmonics of seven constituents with highest tidal amplitudes are presented in Table V-1.

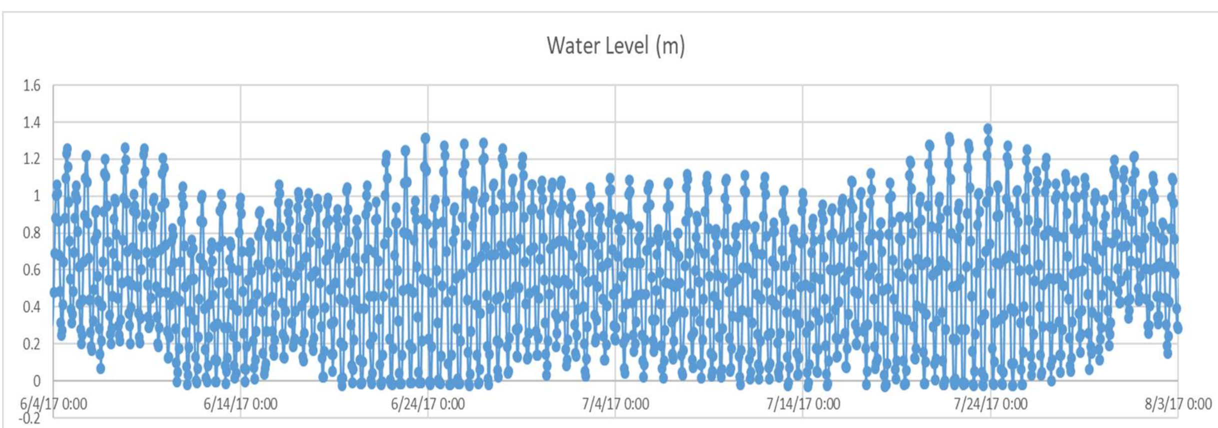


Figure V-19. Time series of water level data at station WOKCC0081 in Calico Creek.

Table V-1. Tidal harmonics at station WOKCC0081 in Calico Creek. Amplitude is in m, phase is in degrees and speed is the rate change in the phase of a constituent, in degrees per hour.

HARMONICS	AMPLITUDE	PHASE	SPEED	DESCRIPTION
M2	0.460081	283.800137	28.984104	Principal lunar semidiurnal constituent
N2	0.105571	272.104639	28.43973	Larger lunar elliptic semidiurnal constituent
K1	0.081357	137.175240	15.041069	Lunar diurnal constituent
O1	0.065725	175.587052	13.943035	Lunar diurnal constituent
S2	0.062214	284.614467	30.0	Principal solar semidiurnal constituent
P1	0.031354	124.379281	14.958931	Solar diurnal constituent
K2	0.015958	291.364255	30.082138	Lunisolar semidiurnal constituent

MLWS (m)	MLWN (m)	MSL (m)	MHWN (m)	MHWS (m)
0.05484956	0.17927706	0.57714468	0.97501230	1.09943980

MLW: mean low water; MHW: mean high water; S: spring tide; N: neap tide; MSL: mean sea level

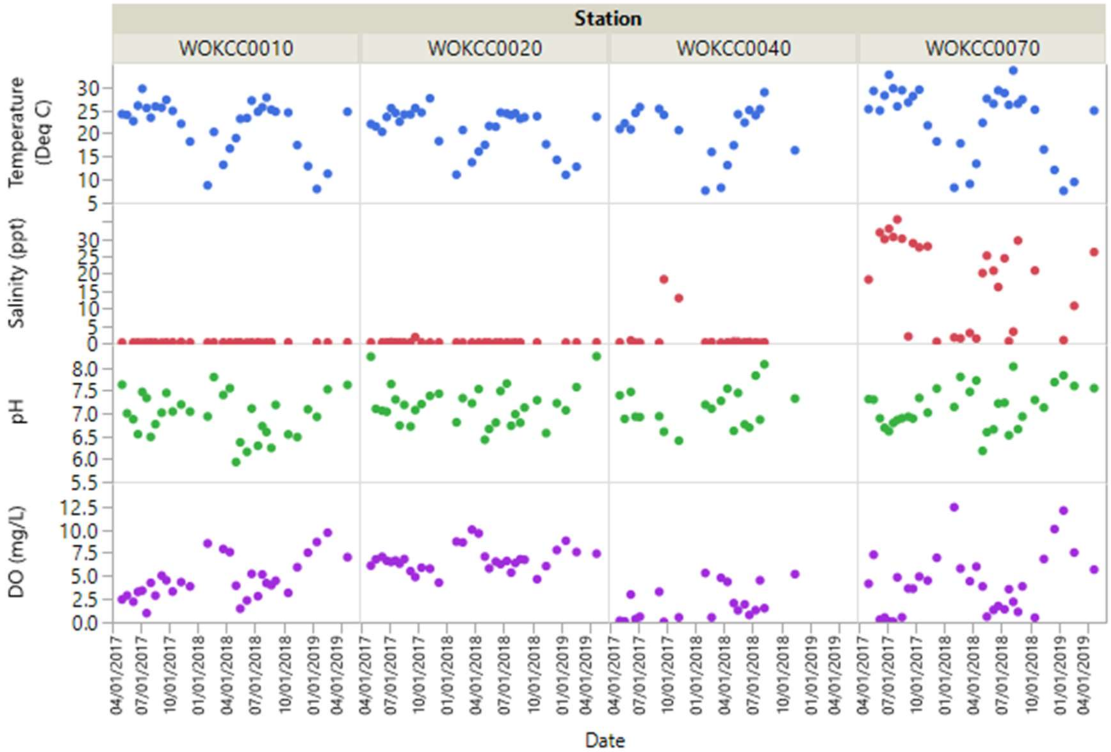
Tributary Conditions

Physical and water quality concentrations were measured at WOKCC0010, WOKCC0020, WOKCC0040, and WOKCC0070 stations to examine tributary inputs to the estuary. Quite often, water samples and measurements were not collected at station WOKCC0040 due to dry channel. Surface water runoff through this site appears to be very low.

Water temperature varied seasonally at all four stations with high temperature observed during summer and fall and lowest values in winter. Salinity is at, or close to, zero at stations WOKCC0010 and WOKCC0020 all the time, indicating freshwater runoff flowing through these two stations. Salinity was low most of the time when there were measurements at station WOKCC0040 except occasionally tide may have brought in salt water in this region. By contrast, at station WOKCC0070, salinity was typically higher during summer and fall and lower during winter and spring, indicating higher tidal influence at this site, especially during warm seasons (Figure V-20 and V-21).

Relatively lower values of pH and DO concentrations were observed during warm seasons and higher values during cold seasons at stations WOKCC0010 and WOKCC0070, suggesting seasonal variabilities at these two sites. By contrast, at station WOKCC0040, DO concentrations were consistently very low, accordingly, TSS, turbidity, BOD and organic carbon concentrations were relatively high at this site, indicating high amount of pollutant input to the estuary from this site.

An especially high value was observed on 2/19/2019 for turbidity (510 NTU) and TSS (623 mg/L), respectively, at station WOKCC0020. The two points were not plotted in Figure V-20 to avoid distortion of y-axis.



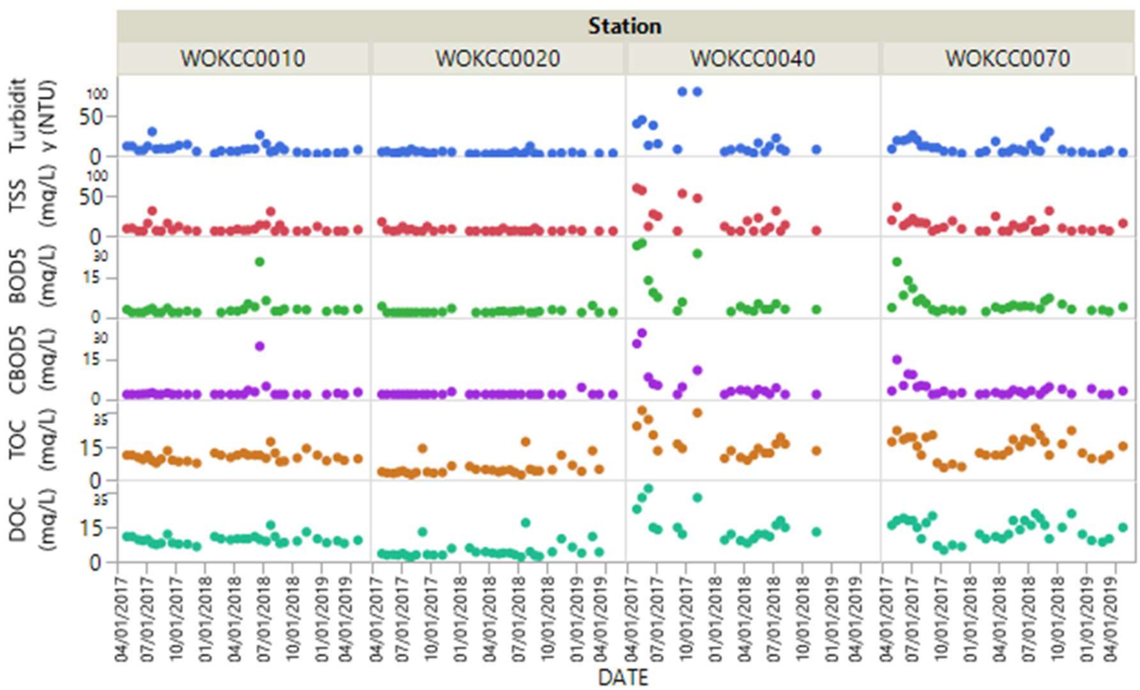


Figure V-20. Time series of physical and water quality parameters at tributary stations in Calico Creek. Especially high turbidity (510 NTU) and TSS (623 mg/L) values observed on 2/19/2019 at station WOKCC0020 were not included in the plot.

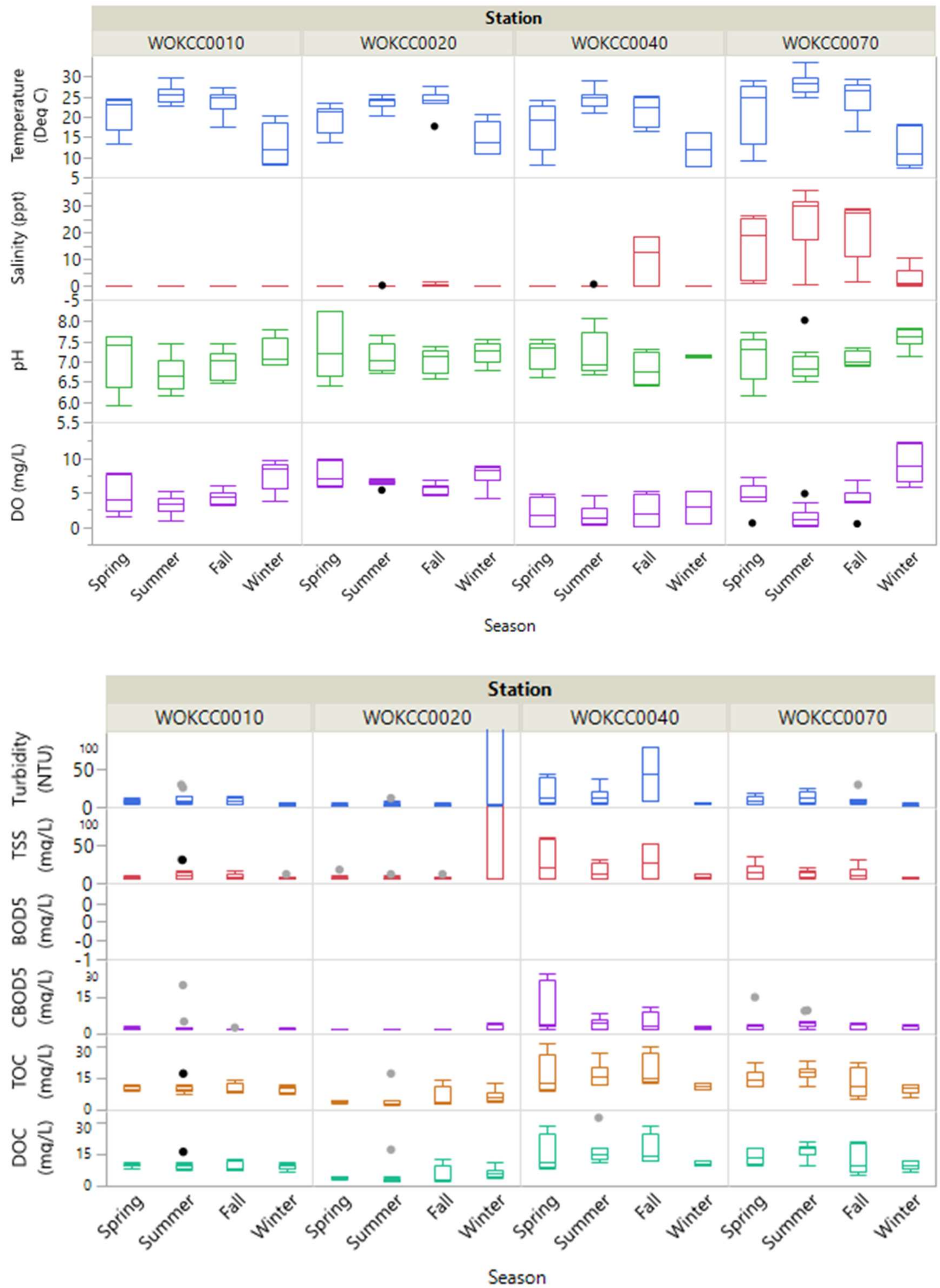


Figure V-21. Seasonal box plots of physical and water quality parameters observed at the tributary stations in Calico Creek during intensive survey period. Especially high turbidity (510 NTU) and TSS (623 mg/L) values were observed on 2/19/2019 at station WOKCC0020, which made the corresponding boxes out of the plotting area.

Tributary Inflow

Tributary flow and discharge were also recorded at the four stations at WOKCC0010, WOKCC0020, WOKCC0040, and WOKCC0070 when enough flows were in the stream for the measurement. These measurements help quantify surface water runoff from the drainage basins, but do not account for groundwater inflow, whose magnitudes are still unknown. In most cases, the recorded discharge values were below 1 cfs, except two data points (9/6/2017 and 7/25/2018) at WOKCC0010 (Figure V-22). An examination of the daily precipitation data at Beaufort Smith Field shows that rainfall events were recorded on both days with higher river discharges. In addition, rainfall also occurred before high river discharges (Figures V-23 and V-24). There are only two recorded tributary discharge data points at each station of WOKCC0020, WOKCC0040, and WOKCC0070. All recorded discharge values at these stations were very low, less than 1 cfs. Surface water runoff from these small tributary basins are likely negligible.

Relationships between tributary discharges and precipitation are shown in Figure V-25. Linear regressions were performed between river discharge at WOKCC0010 and precipitation from Beaufort Smith Field (Figure V-26 and Table V-2). Statistically significant linear relationships were found between river discharge and precipitation on the measurement day, as well as between discharge and average daily precipitation recorded from 2 days before, from 5 days before and from 9 days before the measurement day. Highest R^2 was obtained between river discharge and precipitation when precipitation occurred during the day of the measurement.

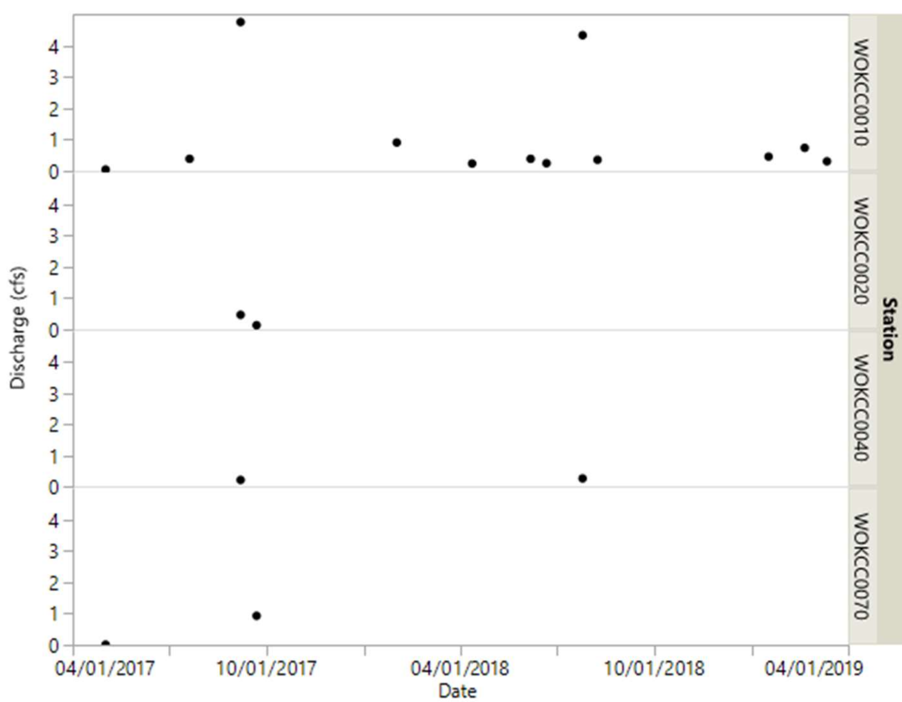


Figure V-22. Measured tributary river discharge to Calico Creek estuary.

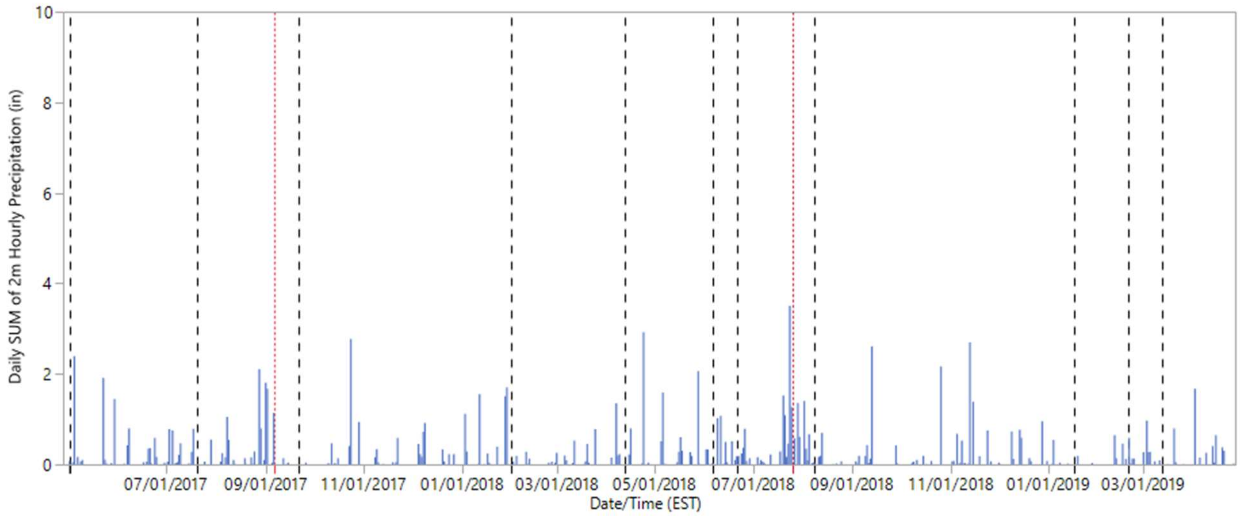


Figure V-23. Daily precipitation records at Beaufort Smith Field during intensive survey period. Dotted lines indicate the dates when flow record is available at least at one station. The red dotted lines are the dates when discharges were recorded greater than 4 cfs, while black dotted lines are the dates when discharges were less than 1 cfs.

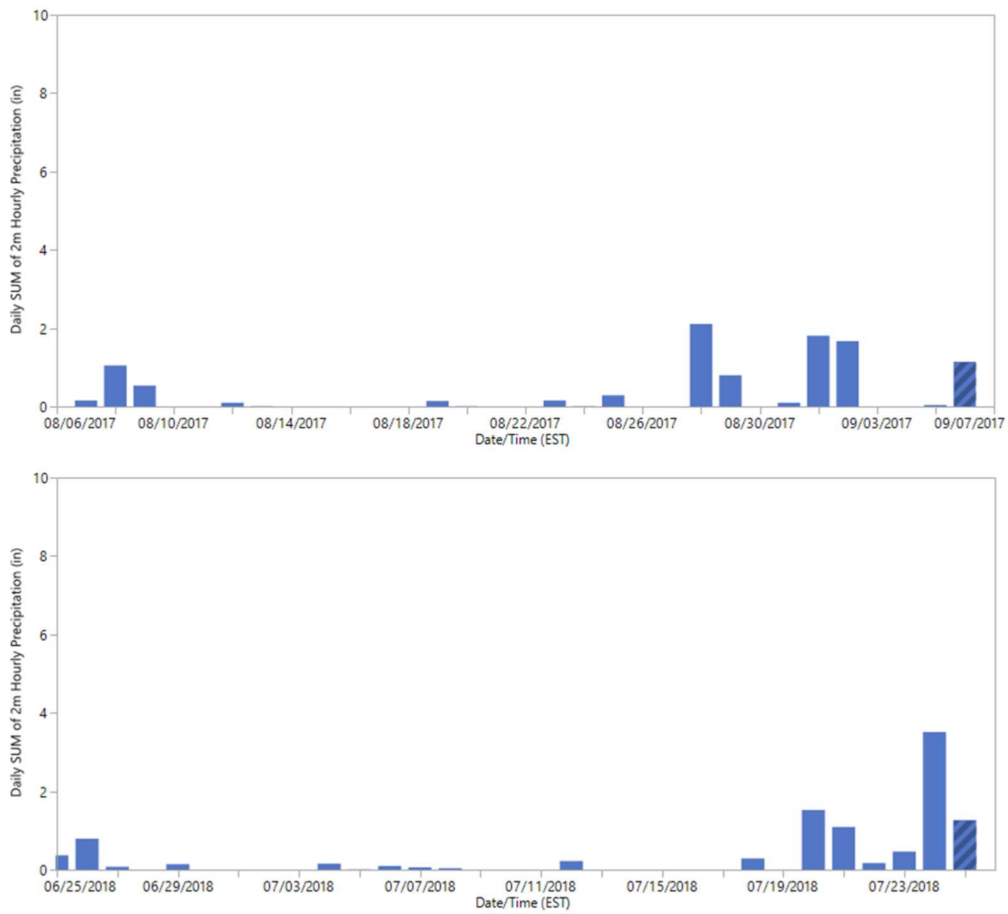


Figure V-24. Daily precipitation records at Beaufort Smith Field one month before the recorded high tributary discharge days.

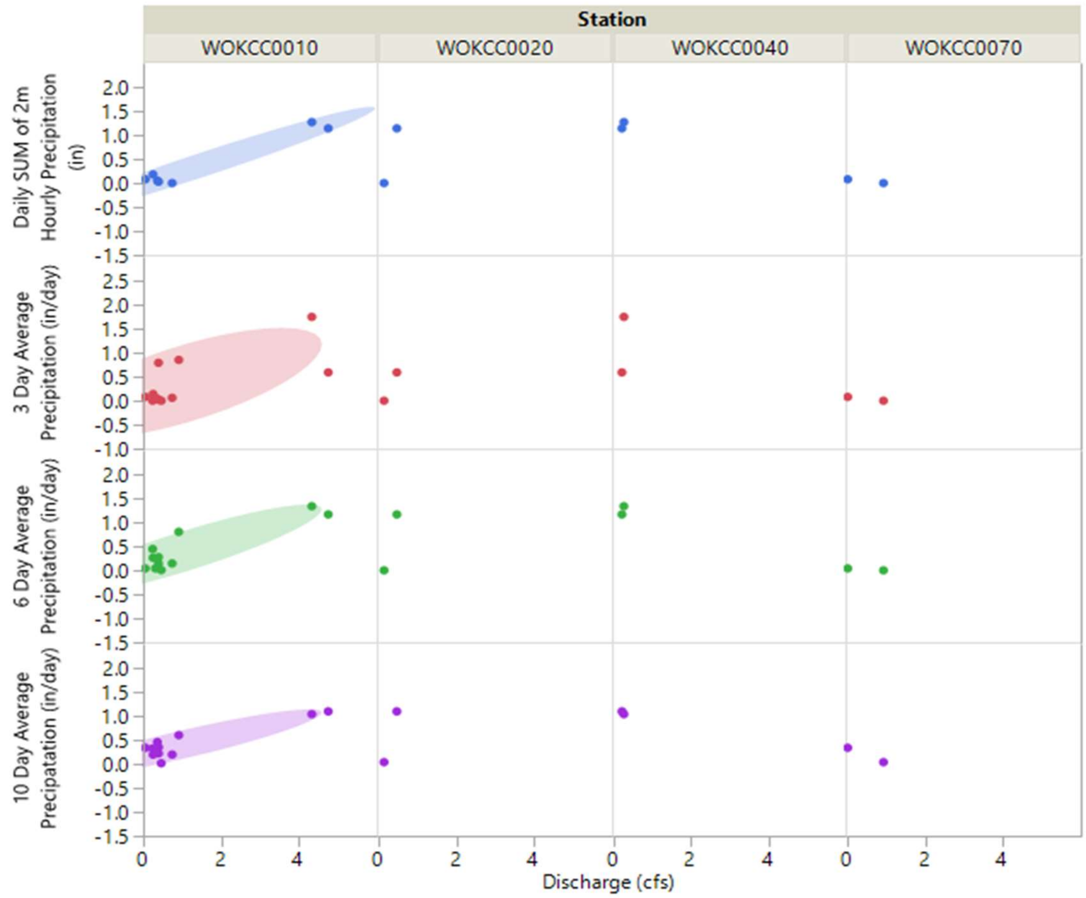


Figure V-25. Relationship between precipitation and tributary discharge.

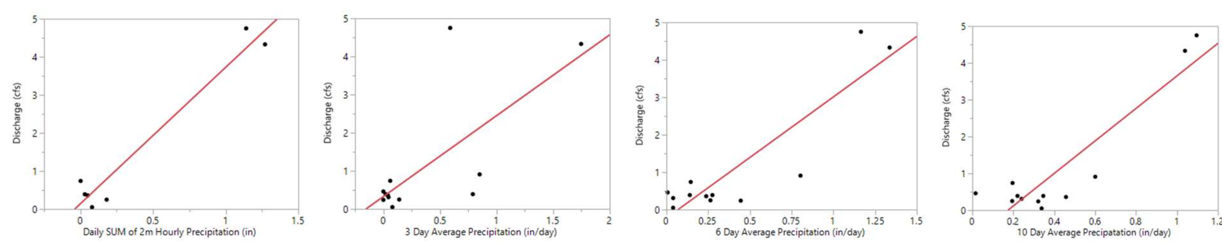


Figure V-26. Linear regressions between precipitation (Beaufort Smith Field) and discharge (WOKCC0010). All 4 linear relationships are statistically significant.

Table V--2. Linear equations between precipitation (Beaufort Smith Field) and discharge (WOKCC0010).

X (in/day)	Y - Discharge (cfs)	R^2
Daily Precipitation	Y = 0.1428755 + 3.5860449*X	0.95
3 Day Average Precipitation	y = 0.3268303 + 2.1211162*X	0.49
6 Day Average Precipitation	Y = -0.221651 + 3.2323574*X	0.80
10 Day Average Precipitation	Y = -0.765731 + 4.4156971*X	0.83

VI. Summary

Calico Creek estuary is highly eutrophic. It is included in the 303(d) list for chlorophyll a, dissolved oxygen and turbidity.

Morehead City WWTP is the single point source discharging directly into the estuary. The drainage basin is heavily developed. Stormwater runoff also delivers nutrients to the estuary. An upgrade to the Morehead City WWTP facility happened between 2008 and 2010 with permitted flow increased from 1.7 to 2.5 MGD and with tertiary treatment and UV disinfectant installed. The effluent NH_3, BOD5 and TSS concentrations appear to be lower in recent years than before the upgrade, but pH values are about 0.5 higher.

Algal blooms occurred most often in summers in Calico Creek. Algal blooms are in general more severe in the upstream part of the estuary. Algal groups are primarily dominated by diatoms, especially during summer. No significant differences were found in both algal unit density and biovolume before and after the Morehead City WWTP upgrade. Chl a concentrations are significantly higher in recent years, but no significant differences in Chl a concentrations were found during summer seasons only. Significantly lower nutrient concentrations were observed at both estuary monitoring stations (for NH_3 and NO_x at upstream station P8750000 and for NH_3, NO_x, TKN and TP at downstream station P8800000) during recent years. NO_x and TP concentrations were significantly lower during recent summers at P8750000 but no significant differences were found during summers at P8800000. In short, nutrient concentrations were in general lower in recent years especially during non-summer seasons.

Long-term records show that sea level at Beaufort appears to have risen more than 0.1 m since 2000. Air temperature has also increased from 2002 to 2019, up around 2 °F. Calico Creek appears to be partially mixed, vertical stratifications were often observed at station P8800000. Observed freshwater inflow appears to be very low in most cases, except when rainfall events occurred during and before the day of the measurement. The salinity and water temperature records also suggest warm and dry winters and springs in recent years. The influence by freshwater inflow in Calico Creek appears to be limited to rainfall events in the basin. Tide gauge and ADCP measurement suggests that hydrodynamics in Calico Creek is likely mainly controlled by semidiurnal tide.

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