CALICO CREEK HYDRODYNAMIC AND NUTRIENT RESPONSE MODEL

MODELING AND ASSESSMENT BRANCH
NORTH CAROLINA DIVISION OF WATER RESOURCES

JUNE, 2021

LIST OF ABBREVIATIONS

ADCP	Acoustic Doppler Current Profiler
AU	Assessment Unit
Bc	Cyanobacteria
Bd	Diatom Algae
Bg	Green Algae
Bm	Stationary Algae
BOD5	5-Day Biochemical Oxygen Demand
Chl-a	Chlorophyll a
CBOD5	5-Day Carbonaceous Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
CWA	Clean Water Act
DKN	Dissolved Kjeldahl Nitrogen
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
DON	Dissolved Organic Nitrogen
DOP	Dissolved Organic Phosphorus
DWR	(North Carolina) Division of Water Resources
EFDC	Environmental Fluid Dynamics Code
EPA	Environmental Protection Agency
FCB	Fecal Coliform Bacteria
LPOC	Labile Particulate Organic Carbon
LPON	Labile Particulate Organic Nitrogen
LPOP	Labile Particulate Organic Phosphorus
MGD	Million Gallons per Day
NH4	Ammonia Nitrogen
NOx	Nitrite and Nitrate Nitrogen
NPDES	National Pollutant Discharge Elimination System
ppt	part per thousand
PO4	Phosphate Phosphorus
SA	Dissolved Available Silica
SOD	Sediment Oxygen Demand
SU	Particulate Biogenic Silica
RPOC	Refractory Particulate Organic Carbon
RPON	Refractory Particulate Organic Nitrogen
RPOP	Refractory Particulate Organic Phosphorus
TAM	Total Active Metal
TDP	Total Dissolved Phosphorus
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus
TSS	Total Suspended Solids
WWTP	Waste Water Treatment Plant

1 INTRODUCTION

1.1 BACKGROUND

Calico Creek is a small tidal creek that runs approximately two miles east through Morehead City, North Carolina and empties into Calico Bay and the larger Newport River Estuary. 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 (Figure I-1).

In addition to the regular ambient monitoring program, an intensive survey was conducted by North Carolina Division of Water Resources (DWR) from May 2017 to April 2019 to collect extra physical and biogeochemical data at additional sampling sites within Calico Creek. Data analyses were conducted summarizing results from the ambient monitoring program, the intensive survey, and other data sources (Lin, 2020).

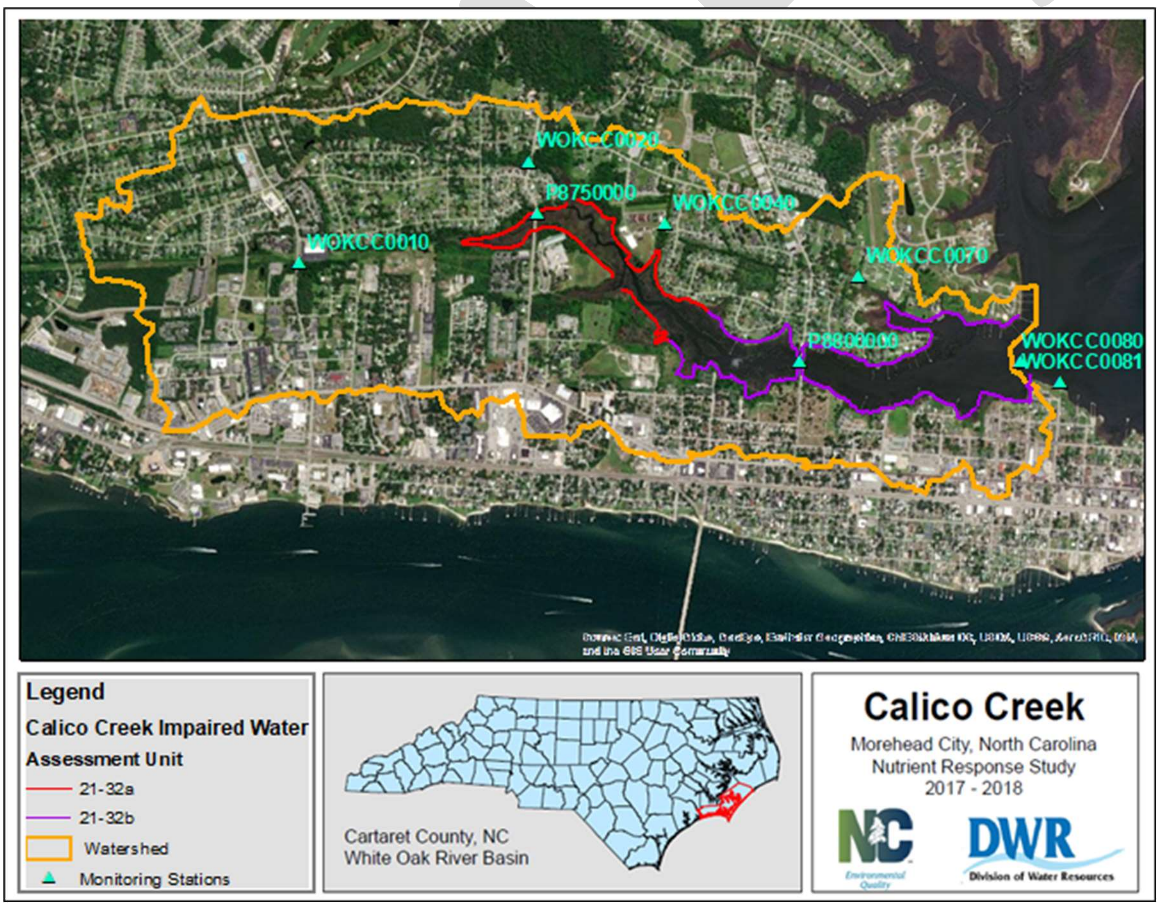


Figure I-1. Calico Creek impaired water assessment units and monitoring stations

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. Chlorophyll a concentrations are significantly higher in recent years, but no significant differences in Chlorophyll a concentrations were found during summer seasons only. Hydrodynamics of Calico Creek appears to be dominated by semidiurnal tides, seasonal wind, and event-driven freshwater inflow.

Morehead City Waste Water Treatment Plant (WWTP) is the single point source discharging directly into the estuary and has been historically identified as the major cause of water quality problems in Calico Creek (DWQ, 2005). The drainage basin is heavily developed. Stormwater runoff also delivers nutrients to the estuary. The Morehead City WWTP was upgraded between 2008 and 2010 with permitted flow increasing from 1.7 to 2.5 million gallons per day (MGD) and with tertiary treatment and UV disinfectant installed. Ammonia (NH4), Biochemical Oxygen Demand (BOD5), Total Suspended Solids (TSS), and Dissolved Oxygen (DO) concentrations and Total Nitrogen (TN) load limits are included in the current permit with extra nutrient monitoring requirements for TN, Total Phosphorus (TP), Total Kjeldahl Nitrogen (TKN) and Nitrate/Nitrite (NOx) (DWQ, 2013). Monitoring data from the Morehead City WWTP suggest that BOD, TSS, and NH4 concentrations in the effluent flow discharged into the Calico Creek appear lower after the WWTP upgrade finished in 2010, pH values are about 0.5 higher. However, no significant differences were found in both algal unit density and biovolume before and after the Morehead City WWTP upgrade (Lin, 2020).

A dynamic nutrient response model was developed to simulate hydrodynamic and water quality parameters including tide, flow, salinity, temperature, nutrient, dissolved oxygen and chlorophyll-a concentrations in the Calico Creek estuary. This report provides information on model development and model results.

1.2 PURPOSE OF MODELING PROJECT

The primary objective of the modeling project is to assess major processes controlling water quality conditions in Calico Creek, specifically, to examine the responses of chlorophyll a concentrations in Calico Creek to changes of nutrient loading.

2 MODEL DEVELOPMENT

2.1 EFDC MODEL DESCRIPTION

The three-dimensional, coupled hydrodynamic and water quality model Environmental Fluid Dynamics Code (EFDC), was selected to simulate phytoplankton dynamics in response to nutrient variations in Calico Creek. The EFDC version published in Ji (2008) was adopted for this project. A three-dimensional approach was used to have a reasonable representation of the complicated bathymetry of Calico Creek and to resolve the moderate vertical stratification observed in the lower part of the estuary.

EFDC has been identified as an acceptable tool for the development of Total Maximum Daily Loads by US Environmental Protection Agency (EPA, 1997). It has been successfully applied in many types of water courses in previous studies, including estuaries, lakes, and coastal seas (e.g., Kuo et al., 1996; Lin et al., 2007, 2008; Ji, 2008).

EFDC simulates hydrodynamic, sediment transport, and eutrophication processes with three corresponding sub-models. The hydrodynamic model is the foundational sub-model, which simulates water surface elevation, current, salinity, and water temperature. These parameters are passed to the other sub-models, and at the same time, biogeochemical processes regarding the concerned variables (e.g., sediments and nutrients) are calculated in the corresponding sub-models. The sediment transport sub-model is not activated in this study.

The hydrodynamic sub-model in EFDC was developed by Hamrick (1992; 1996). The model solves the Navier-Stokes equations for a water body with a free surface. In the vertical direction, sigma coordinates, with the hydrostatic assumption, are used in the model. Horizontally, curvilinear orthogonal grids are used. Mellor and Yamada's level 2.5 turbulence closure scheme (Mellor and Yamada, 1982), which was modified by Galperin et al. (1988), is used in the model. Both turbulent kinetic energy and turbulent length scale are solved using dynamically coupled transport equations. A detailed description of the EFDC hydrodynamic model and its numerical solution scheme can be found in Hamrick (1992; 1996).

The eutrophication (water quality) sub-model of EFDC (Park et al., 1995a; Tetra Tech, 2007) consists of a water column water quality model and a sediment diagenesis model linked internally. Due to data limitation, the sediment diagenesis model is not activated in this study; however, sediment nutrient fluxes and sediment oxygen demands are specified through the model input file. The water column water quality model simulates the spatial and temporal distributions of 22 state variables in the water column (Table 2-1). While not all of these variables are chosen for simulation in the Calico Creek Model, in general, these variables include: suspended algae (3 groups: cyanobacteria as model state variable Bc, diatoms as Bd, and green algae as Bg); a stationary or non-transported algae (has been used to simulate macro-algae); organic carbon (refractory particulate organic carbon as RPOC, labile particulate organic carbon as LPOC, dissolved organic carbon as DOC); nitrogen (refractory particulate organic nitrogen as RPON, labile particulate organic nitrogen as LPON, dissolved organic nitrogen as DON, ammonium nitrogen as NH4, nitrite plus nitrate nitrogen as NOx); phosphorus (refractory particulate organic phosphorus as RPOP, labile particulate organic phosphorus as LPOP, dissolved organic phosphorus as DOP, total phosphate as PO4t); silica (particulate biogenic silica as SU, available silica as SA); dissolved oxygen (as DO); chemical oxygen demand (as COD); total suspended solids (as TSS, which is simulated in the hydrodynamic model); total active metal (as TAM); and fecal coliform bacteria (as FCB). For each state variable, a mass conservation equation is solved. The simulated kinetic processes in the water quality model include algal growth, metabolization, predation, hydrolysis, mineralization, nitrification, and denitrification. A detailed description of kinetic processes and their mathematical formulations used in the eutrophication sub-model can be found in Park et al. (1995), Tetra Tech (2007), and Ji (2008).

In Calico Creek, algal groups are primarily dominated by diatoms, especially during summer (Lin, 2020). One algal group which represents diatom was simulated in the model. Model simulation of cyanobacteria, green algae, and stationary algae were not activated. Total active metal and fecal coliform bacteria are not within the scope of this project and hence not simulated. Silica was not monitored in Calico Creek and silica limitation to algal growth was assumed not significant and hence silica simulation was not activated in Calico Creek model (Table 2-1).

Table 2-1. EFDC model water quality state variables

EFDC model water quality state variables	Simulated in Calico Creek Model
(1) cyanobacteria: Bc	No
(2) diatom algae: Bd	Yes
(3) green algae: Bg	No
(4) stationary algae: Bm	No
(5) refractory particulate organic carbon: RPOC	Yes
(6) labile particulate organic carbon: LPOC	Yes
(7) dissolved organic carbon: DOC	Yes
(8) refractory particulate organic phosphorus: RPOP	Yes
(9) labile particulate organic phosphorus: LPOP	Yes
(10) dissolved organic phosphorus: DOP	Yes
(11) total phosphate: PO4t	Yes
(12) refractory particulate organic nitrogen: RPON	Yes
(13) labile particulate organic nitrogen: LPON	Yes
(14) dissolved organic nitrogen: DON	Yes
(15) ammonia nitrogen: NH4	Yes
(16) nitrate nitrogen: NOx	Yes
(17) particulate biogenic silica: SU	No
(18) dissolved available silica: SA	No
(19) chemical oxygen demand: COD	Yes
(20) dissolved oxygen: DO	Yes
(21) total active metal: TAM	No
(22) Fecal coliform bacteria: FCB	No

2.2 MODEL CONFIGURATION

2.2.1 MODEL GRID

A curvilinear orthogonal grid was used in the Calico Creek model to approximately represent the actual shoreline. The size of individual grid cell varies from about 20 m near upriver end to approximately 90 m close to the mouth of the estuary. The horizontal grid generally approximates the mean sea level shoreline of Calico Creek. Totally 264 horizontal model cells are in the model grid (Figure 2-1). The sizes of the model cells are chosen as a tradeoff between accuracy of shoreline representation and computational requirement. Smaller model cells would fit the shoreline better but at the same time require shorter model time step and longer model simulation time.

Vertically, sigma coordinate was used and the model cells are equally divided into three layers to represent vertical differences in hydrodynamic and water quality parameters. Bathymetric data were collected along several cross-sections in Calico Creek during the intensive survey period. 2014 NOAA topobathy DEM data (Post-Sandy (SC to NY)) were also downloaded to provide depth information for each model grid. Average depths were obtained from all the data points dwell inside each model cell and assigned to the specific grid. Smoothing and interpolation or extrapolation were then conducted especially for the model cells where data are not available.

Figure 2-1. Model grid with intensive survey stations and tributary locations in Calico Creek.

2.2.2 MODEL SIMULATION TIME PERIOD

The Calico Creek model was set up to simulate two time periods: summers (June to August) of 2017 and 2018.

A couple of factors contributed to the selection of model simulation periods. First of all, intensive survey was conducted from May 2017 to April 2019 in Calico Creek estuary. Higher frequency (bi-weekly) data were obtained during growing seasons (May to September) and monthly data were obtained during non-growing seasons. Model boundary conditions are better represented during the data-abundant growing seasons. Secondly, algal blooms appeared to be most severe during summer than other seasons, and algal groups are dominated by diatoms, especially during summer. Model simulation of summer seasons can be regarded as the representation of critical conditions in Calico Creek. In addition, much climate data is missing from September 17-19 of 2017 and September 13 -28 of 2018. Salinity and temperature data was not recorded together with the tide gauge pressure data and hence the estimated tidal stage time series may have minor errors. Such error, in a shallow estuary with strong tidal and wind flow, may cause model instability with long time simulation. Therefore, summers of 2017 and 2018 were chosen to be the time periods for Calico Creek model simulation.

2.2.3 Point Sources

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, the single point source discharges directly into the Calico Creek estuary, has been historically identified as the major cause of water quality problems in Calico Creek (DWQ, 1997; 2005). The treatment facility discharges treated 100% domestic wastewater into Calico Creek. Approximately 65% of the total area within Calico Creek watershed is connected to the Morehead City WWTP and more than 90% of the residential homes within the Calico Creek watershed are connected to the WWTP facility (Lin, 2020).

Point source loads from the Morehead City WWTP are estimated using daily effluent flow, daily (during week days) BOD5 and DO concentrations, and weekly NOx, NH4, TKN, TN and TP concentrations from discharge monitoring report. Daily loads of state variables simulated in the model are estimated by multiplying daily flow and estimated concentration. For state variables that are directly monitored, linear interpolation is used for the days when data is not available. For state variables that are not directly monitored, they are estimated from other parameters as shown in Table 2-2. Since most particulate matters are removed through wastewater treatment processes, measured concentrations are assumed in the dissolved forms.

Table 2-2. Point source estimation

State Variables	Estimation	Parameter Value	Parameter Range	Reference
Bd	0.0			
RPOC	0.0			
LPOC	0.0			
DOC	a*BOD5	a=0.3	0.2-0.5	Technische University Hamburg
RPOP	0.0			
LPOP	0.0			
DOP	0.0			
PO4t	TP			Dueñas, et al., 2003
RPON	0.0			
LPON	0.0			
DON	TKN-NH4			Sattayatewa et al., 2010
NH4	NH4			
NOx	NOx			
COD	0.0			
DO	DO			

2.2.4 Nonpoint Sources and River Boundary Condition

River Discharge

Types of nonpoint sources in Calico Creek watershed and land use land cover information are discussed in Lin (2020). A watershed model was not developed for Calico Creek. All nonpoint sources are assumed to accumulate into five small tributaries which empty into Calico Creek estuary.

The Calico Creek watershed is heavily developed with much of the land surface covered by buildings, pavement and compacted landscapes. Surface water runoff are expected to have good relationship with rainfall. This relationship mainly depends on the dynamic interaction between rainfall intensity, surface storage and soil infiltration. Discharge data were recorded at several intensive survey stations especially at station WOKCC0010 where the linear regression between recorded river discharge and daily precipitation data from Beaufort Smith Field can reach a R^2 of 0.95 (Lin, 2020). The relationship is used here to estimate river discharges from the tributaries. Total storm water runoff into Calico Creek was estimated by multiplying the WOKCC0010 discharge with the ratio between total drainage area and drainage area into WOKCC0010. The total runoff was then multiplied with the area ratio listed in Table 2-3 to come up with the river discharges into each tributary.

WOKCC0010 Discharge (cfs) = 0.1428755 + 3.5860449*precipitation (in/day)

Table 2-3. Tributary drainage area and area ratio in Calico Creek

Tributary	Model Cell	Drainage area (m^2)	Area ratio
WOKCC0010	N/A	841,854	
Total	N/A	5,136,853	
Trib1	(11,5) (11,6)	1,806,451	0.57
Trib2	(17,8)	441,626	0.14
Trib3	(30,4)	357,604	0.11
Trib4	(32,9)	190,824	0.06
Trib5	(66,9) (67,9)	385,735	0.12

Data is not available regarding groundwater input into the Calico Creek estuary. Relatively small amount of base flow was added into tributary input as a result of salinity calibration.

Nutrient Loading

Nutrient concentrations were collected at tributary stations every two weeks during growing seasons (May to September) of 2017 and 2018. To calculate nutrient loading, the estimated daily flow from each tributary is multiplied by measured nutrient concentration when available or, if not, the linearly interpolated nutrient concentration for that day. For state variables that are not directly measured, they are estimated from other parameters as shown in Table 2-4. Crump et al (2017) suggested that the refractory portion of organic matter appeared to have good relationship with suspended particulate material. If similar relationship is applied to Calico Creek data, refractory portion of organic carbon would mainly vary between 9% to 35% at majority of time. Refractory portion of particulate organic nitrogen would vary between 7% and 23% at majority of time. The median value of 18% is used to estimate refractory portion of POC and 10% is used to estimate refractory portion of PON and POP in model input.

Table 2-4. Tributary nutrient loading estimation

State Variables	Estimation	Parameter Value	Parameter Range	Reference
Bd	Chlorophyll*Cchl	Cchl=0.065	0.02-0.05	Wool et al. (2001)
RPOC	A*(TOC-DOC)	A=0.18		Crump et al. (2017)
LPOC	B*(TOC-DOC)	B=0.82		
DOC	DOC			
RPOP	A*(TP-TDP)	A=0.1		
LPOP	B*(TP-TDP)	B=0.9		
DOP	TDP-PO4			
PO4t	PO4			
RPON	A*(TKN-DKN)	A=0.1		Crump et al. (2017)
LPON	B*(TKN-DKN)	B=0.9		
DON	DKN-NH4			
NH4	NH4			
NOx	NOx			
COD	0.0			
DO	DO			

2.2.5 Open Boundary Condition

The open boundary is located at the mouth of the Calico Creek estuary. Time series of water surface elevation is specified at the open boundary to allow tidal propagation into and out of the estuary. Tidal gage data collected at station WOKCC0081 (shown in Figure 2-1) is used.

Nutrient concentrations at the open boundary are in general much lower than values observed inside the estuary. Constant values that represent average nutrient conditions observed at WOKCC0081 are specified at the open boundary of Calico Creek model.

2.2.6 Surface Boundary Condition

Meteorological Forcing

A variety of weather data are required to simulate water temperature and flow of the lake model. Hourly time series for precipitation, air temperature, dewpoint, relative humidity, wind, cloud cover, and atmospheric pressure were obtained from NC State Climate Office at Beaufort Smith Field Station (KMRH), which is about 3 miles to the east of the Calico Creek watershed. Hourly solar radiation data were from station Croatan (NCRN). Missing values were replaced by linear interpolation if a missing period was short, or by inserting a long-term average value.

Cloud cover was estimated from Level 1 clouds report at Beaufort Smith Field. Table 2-5 presents the assumptions used to estimate numerical cloud cover for model input.

Table 2-5. Numerical Interpretation of Cloud Cover Report

Cloud Cover Description	Numeric Assignment
Clear	0.05
Few	0.15
Scattered	0.35
Broken	0.65
Overcast	0.8
Vertical visibility at 200/300 ft	0.9

<u>Direct Atmospheric Deposition</u>

Atmospheric inorganic nitrogen deposition can be a significant source of nitrogen to lakes and estuaries. EFDC represents the atmospheric deposition as constant areal loading rates including wet and dry deposition. Precipitation weighted annual average NO3 and NH4 concentrations from wet deposition were obtained from the National Atmospheric Deposition Program (NADP) National Trends Network (NTN) at Beaufort Station (NC06), located to the northeast of the Calico watershed. Annual dry deposition data were obtained from the Clean Air Status and Trends Network (CASTNET) for station Beaufort (BFT142), also located to the northeast of the Calico watershed. Table 2-6 shows the air deposition values used for Calico Creek model.

Table 2-6. Atmospheric deposition for Calico Creek Model

	Wet Deposition Concentration (mg /L)/ (mg N/L)		Dry Deposition Flux (kg N/ha/yr)/(g N/m^2/day)	
	NH4	NOx	NH4	NOx
2017	0.114 / 0.089	0.409 / 0.091	1.103/3.02e-4	1.886/5.17e-4
2018	0.148 / 0.115	0.392 / 0.087	1.098/3.01e-4	1.788/4.90e-4

2.2.7 Benthic Boundary Condition

Sediments in estuaries can play an important role in nutrient regeneration and in recharging the water column with dissolved inorganic nutrients. Benthic nutrient fluxes and SOD were measured in Calico Creek estuary close to station P8800000 on April 25th 2019. Average values (over replicate samples) were used in the Calico Creek model for model initial setup.

Spatial and temporal variations on benthic nutrient fluxes are typical in estuaries. Sediment resuspension, which is not simulated in Calico Creek model, may also have important impacts on benthic nutrient fluxes. Study has shown that resuspension could induce effluxes of one to two orders of magnitude higher than the diffusive fluxes from a shallow estuary (Niemistö and Lund-Hansen, 2019).

Changes were made during model calibration period. The final values of benthic nutrient fluxes and SOD used in the Calico Creek model are listed in Table 2-7.

Table 2-7. Nutrient fluxes across the sediment-water interface used for Calico Creek model.

	NH4 ($g/m^2/day$)	NOx ($g/m^2/day$)	PO4 ($g/m^2/day$)	SOD ($g/m^2/day$)
Measured average	0.065	-0.0026	0.0375	-0.72
Bailey (2005)	-0.027 to 0.84	N/A	-0.15 to 0.67	-14 to 0
Model	0.3	0.1	0.15	-2.5

2.2.8 ALGAL GROUP

Algal data in Calico Creek show that during summer months of June to August, algal abundance seems to be solely dominated by diatoms. 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% (Lin, 2020). Therefore, only one algal group, diatom, is simulated in the Calico Creek model.

3 MODEL RESULTS

3.1 MODEL UNCERTAINTY AND CALIBRATION PROCESS

A number of factors may contribute to model uncertainty, including errors in monitoring data, model formulation, model parameter estimation, and propagation of prediction errors. Model calibration and validation processes are typically conducted to ensure a model can be used for prediction purposes.

Model calibration normally refers to the iterative process of comparing the model results and observations, adjusting model parameters and forcing functions within the margin of model uncertainties, until model results reasonably match with the observed values. Calibration tunes the models to represent conditions appropriate to the waterbody under study. However, especially when the calibration period is not long enough to cover various environmental conditions, model validation is conducted to help evaluate the uncertainty associated with the calibration, and to assess the predictive capability of the model. During validation process, the model is applied to a set of data different from those used in calibration.

Model calibration and validation are particularly challenging in Calico Creek due to several factors. First of all, Calico Creek is a relatively shallow tidal estuary impacted by both freshwater inflow and tidal effects. Although daily rainfall data were obtained, no long term discharge data is available for any of the tributaries. Good correlation was obtained between a few discharge data from the intensive survey and the rainfall data, however the linear relationship is heavily dependent on two data points with relatively higher discharge. The uncertainty involved with estimated freshwater and unknown groundwater input would not only affect hydrodynamic simulation, but also would introduce errors toward nonpoint source loading of oxygen-consuming particulate matter and nutrients. In addition, the variation of surface elevation at the mouth of Calico Creek is specified as the model open boundary. The surface elevations should be calculated from bottom pressure and water column salinity and temperature monitored at station WOKC0081. Unfortunately, in situ time series of salinity and temperature were not available and constant salinity and temperature were assumed at the site. This procedure likely would add uncertainty into model input. Furthermore, Calico Creek has widespread tidal marsh areas where much interaction between water column and sediment bed are expected but little is known. The sediment nutrient fluxes and SOD were measured at one site in the main channel and for one time (April 25, 2019). Spatial and temporal variations of sediment nutrient fluxes and SOD were not known in Calico Creek. A wide range of values were reported in other estuaries and coastal areas (Bailey, 2005). In general, higher sediment nutrient fluxes are expected with higher temperature and polyhaline waters. Sediment nutrient fluxes and SOD during the modeling period of summers of 2017 and 2018 are expected to be higher than the values measured on April 25, 2019.

In summary, a fair amount of uncertainty exists in river boundary, open boundary and sediment boundary inputs of the Calico Creek model. Calibration and validation of the Calico Creek model were hence conducted qualitatively, with two major goals: to represent Calico Creek water quality parameters on the right order of magnitude and with similar ranges of field data; and to represent the general trend and overall dynamics of water quality conditions in Calico Creek. Specifically, time series model outputs were visually compared with field observations, statistical analysis was not performed. Calibration of the Calico Creek model focused on the summer 2017 period. Model validation used data collected in summer of 2018. The EFDC hydrodynamic sub-model was examined for water temperature and salinity. Flow velocities recorded with ADCP were also referenced. The water quality sub-model was then checked regarding chlorophyll a, nutrients (totals and individual species) and dissolved oxygen.

3.2 MODEL DIAGNOSTIC APPLICATION

Prediction models normally require quantitative model calibration criteria to ensure a model is reliable enough to provide appropriate and pertinent insights into potential management strategies. Ideally, the models should attain tight calibration to observed data; however, a less precise calibration can still provide useful information for management decisions.

The Calico Creek model, calibrated to represent overall trend and dynamics, is recommended to be used primarily for diagnostic evaluation of the system. For example, scenario model runs can be conducted to evaluate relative importance of different sources of nutrient loads. Due to model uncertainty, management goals developed based on model results are recommended to be adopted with adaptive management strategies.

3.3 HYRODYNAMIC MODEL RESULTS

Model simulated temporal variations of surface elevation is presented in Figure 3-1. Tidal signal is pretty uniform within Calico Creek, with daily tidal range between 0.7 to 1.5 m. This is consistent with tidal ranges recorded by ADCP, which was deployed during a neap tide (6/24/2019, tidal range 0.69 m) and a spring tide (8/1/2019, tidal range 1.45 m) in 2019.

The model simulated maximum flow speed (Figure 3-2) is lower than the value reported by ADCP. Flow speeds simulated by the model are in general within 20 cm/s during summers of 2017 and 2018 while the ADCP recorded values can reach around 30 cm/s during a neap tide and 50 cm/s during a spring tide in summer 2019. The model simulated flow represents average flow of the corresponding model segment while ADCP records flow at a specific point. The two are hence not directly comparable and lower values are expected for model simulated flows.

The model simulated water temperature mainly varied between 20 to 30°C at station P8750000, and between 25 to 35°C at station P8800000 and at the open boundary. The range of field data for water temperature is within the range of model simulations (Figure 3-3).

The model simulated surface salinity at station P8750000 is mostly between 0 to 20 ppt, which is also within the range of observed salinity data. At station P8800000, salinity ranged between 20 to 35 ppt during summer of 2017 and between around 5 to 35 during summer of 2018 (Figure 3-4). The lowest salinity occurred around Julian day 204 to 205 (7/24 to 7/25, 2018), corresponding to some high rainfall events from Julian days 200 to 210, and peaked on Julian day 204 (Figure V-23, Lin, 2020).

Zoomed in time series plots are provided in Figure 3-5 for Julian day 180 to 200 of summer 2017. Salinity appeared to be influenced by tide and has a semi-diurnal cycle. Rising salinities are associated with flood tide and decreased during ebb tide. Higher discharge also led to lower salinities. By contrast, water temperature appeared to mainly have a diurnal cycle. The lack of tidal signal in water temperature is likely because the longitudinal temperature gradient is much lower than that of salinity.

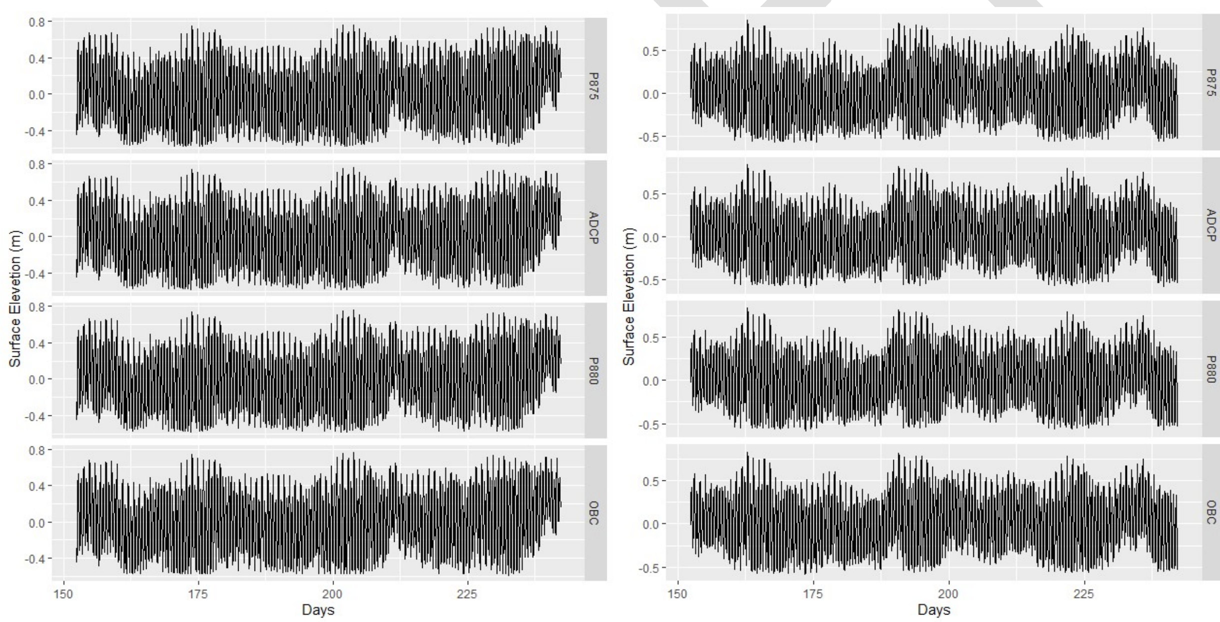


Figure 3-1. Model simulated time series (in Julian Days) of surface elevation in summer 2017 (left panel) and summer 2018 (right panel) at monitoring station P8750000 (P875), station where ADCP was deployed (ADCP), monitoring station P8800000 (P880) and at the mouth of Calico Creek (open boundary, OBC).

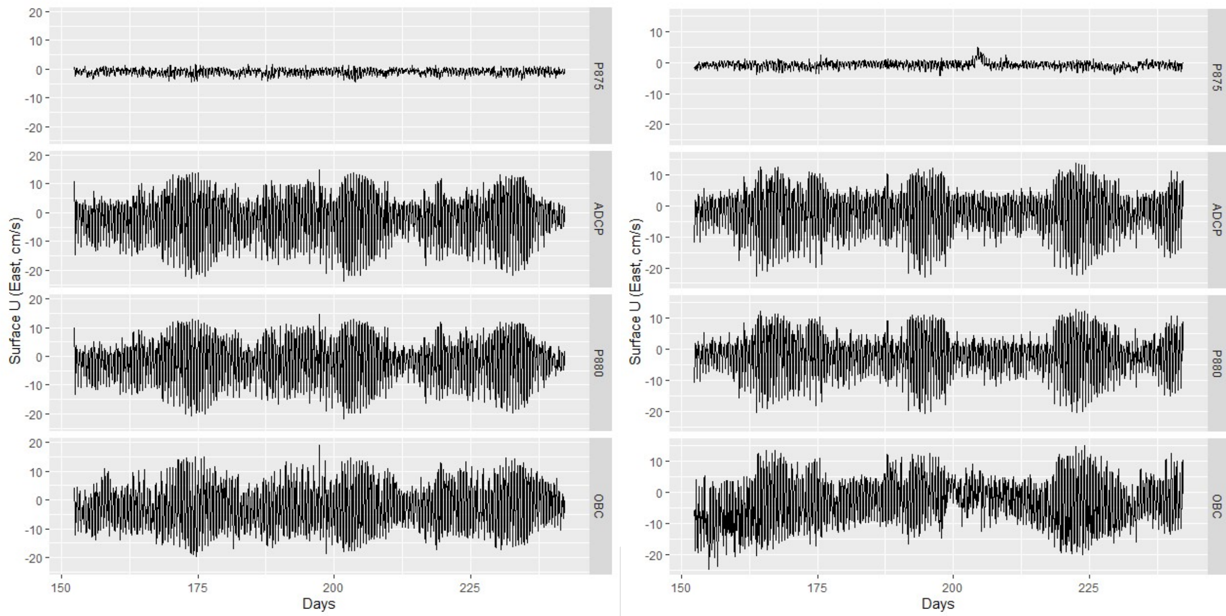


Figure 3-2. Model simulated time series (in Julian Days) of surface layer flow to the east velocities in summer 2017 (left panel) and summer 2018 (right panel) at monitoring station P8750000 (P875), station where ADCP was deployed (ADCP), monitoring station P8800000 (P880) and at the mouth of Calico Creek (open boundary, OBC).

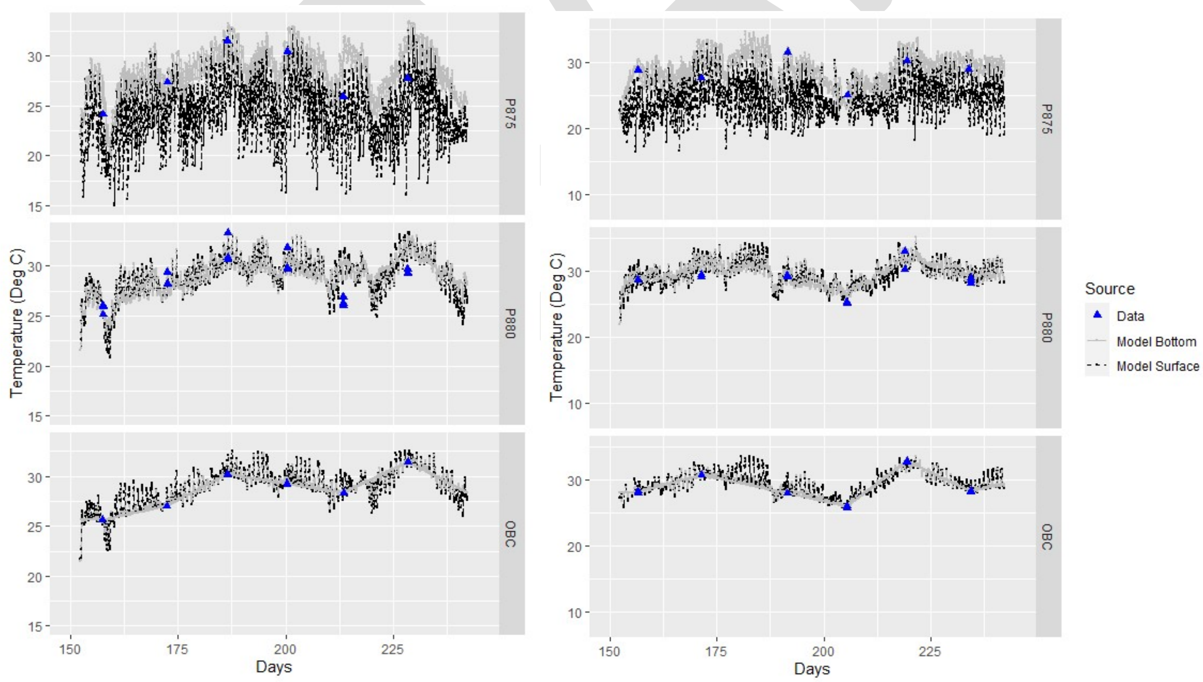


Figure 3-3. Model simulated and field data of water temperature in summer 2017 (left panel) and summer 2018 (right panel) at monitoring stations P8750000 (P875), P8800000 (P880) and at the mouth of Calico Creek (open boundary, OBC).

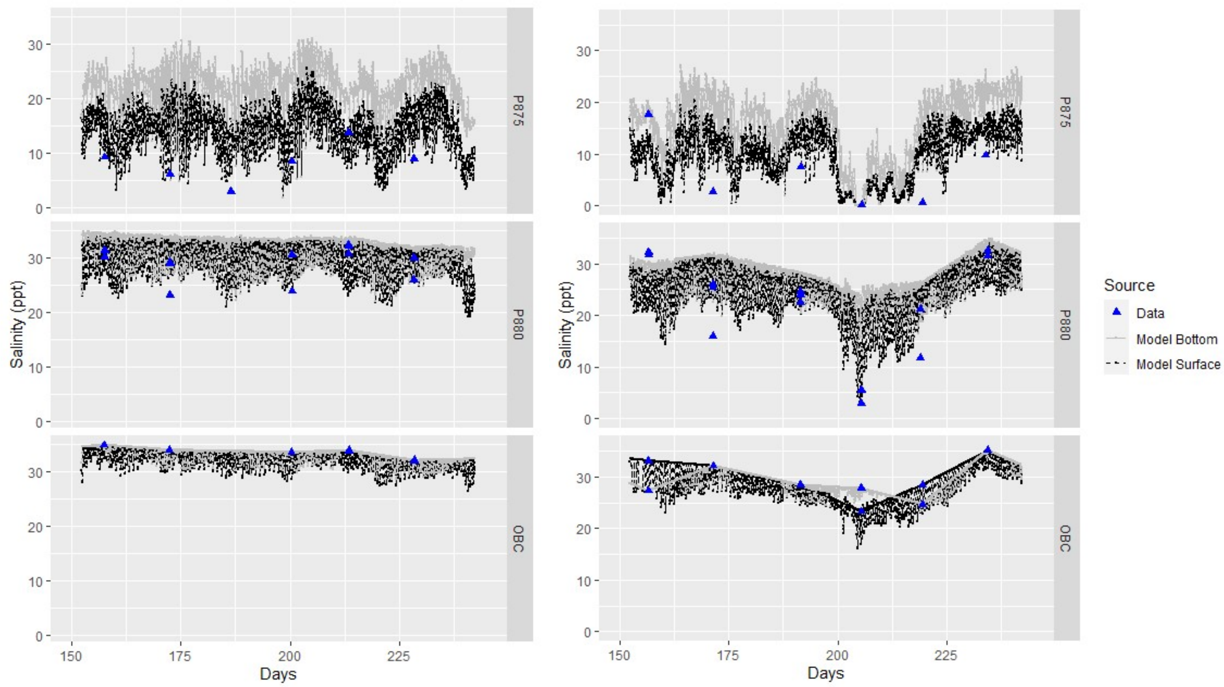


Figure 3-4. Model simulated and field data of salinity in summer 2017 (left panel) and summer 2018 (right panel) at monitoring stations P8750000 (P875), P8800000 (P880) and at the mouth of Calico Creek (open boundary, OBC).

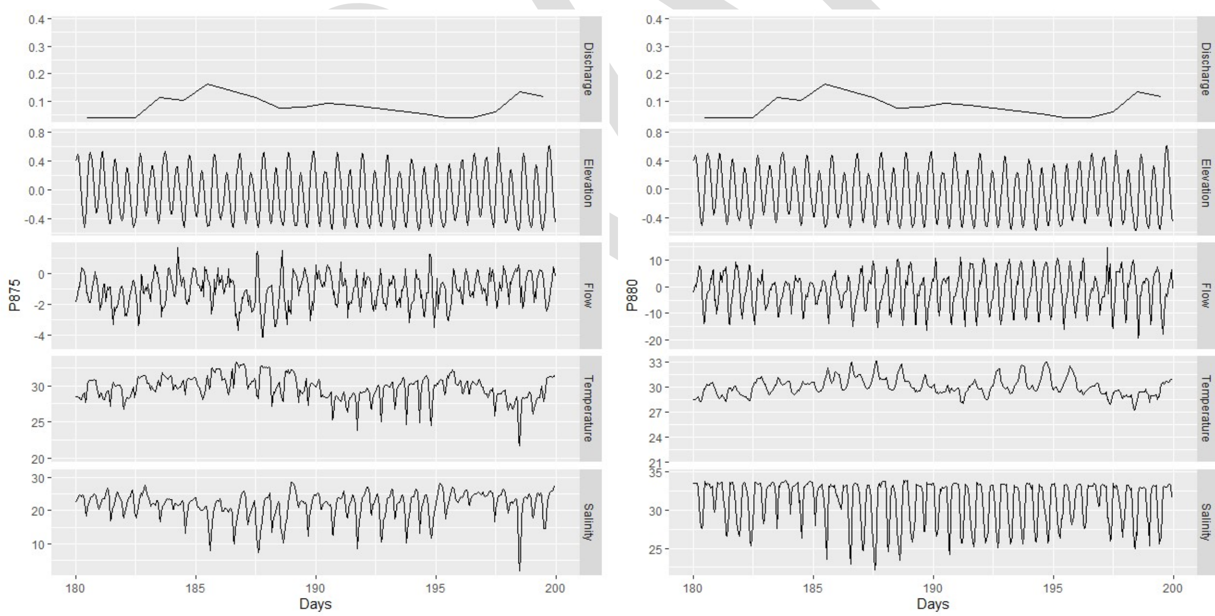


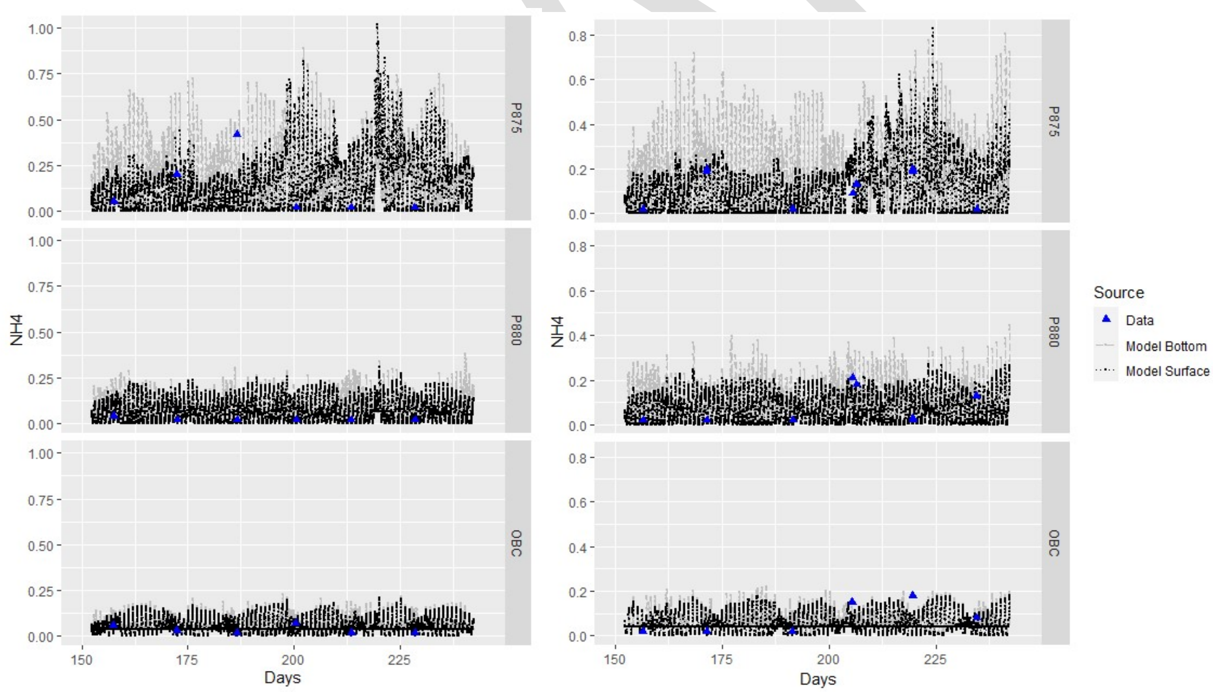
Figure 3-5. Time series of river discharge (m^3/s) as model input, model simulated surface elevation (m), flow speed (towards east, cm/s), water temperature (°C) and salinity (ppt) at the surface layer in summer 2017 at station P8750000 (P875, left panel) and at station P8800000 (P880, right panel).

3.4 WATER QUALITY MODEL RESULTS

3.4.1 Nitrogen

Model simulated ammonia (NH4), nitrite nitrate (NOx), and total nitrogen (TN) concentrations in general cover the range of observed values (Figure 3-6). NH4, NOx and TN concentrations appear to be higher towards the upstream of the Calico Creek close to station P8750000 and lower close to the mouth. The spatial pattern showed up in both field data and model results. In addition, model simulated ammonia concentrations are in general higher in the bottom layers at P8750000 and P8800000, suggesting benthic flux is an important ammonia source to the overlaying water column. Similarly, model simulated NOx concentrations are also higher in the bottom layer of P8750000.

However, a couple of observed high peak NOx concentrations, especially at station P8800000 during summer of 2018, are under-predicted in the model, suggesting some NOx sources are not well represented in the model. In addition, during summer of 2017, model simulated TN is in general lower than the observed data. Point source loading from Morehead City WWTP is estimated based on biweekly monitoring data, underestimation may occur if unmonitored discharges are higher than the concentrations represented in the monitoring results. Stormwater runoff of nutrient loadings are estimated with very limited data in the Calico Creek watershed, errors may exist in estimated nonpoint source loadings as well.



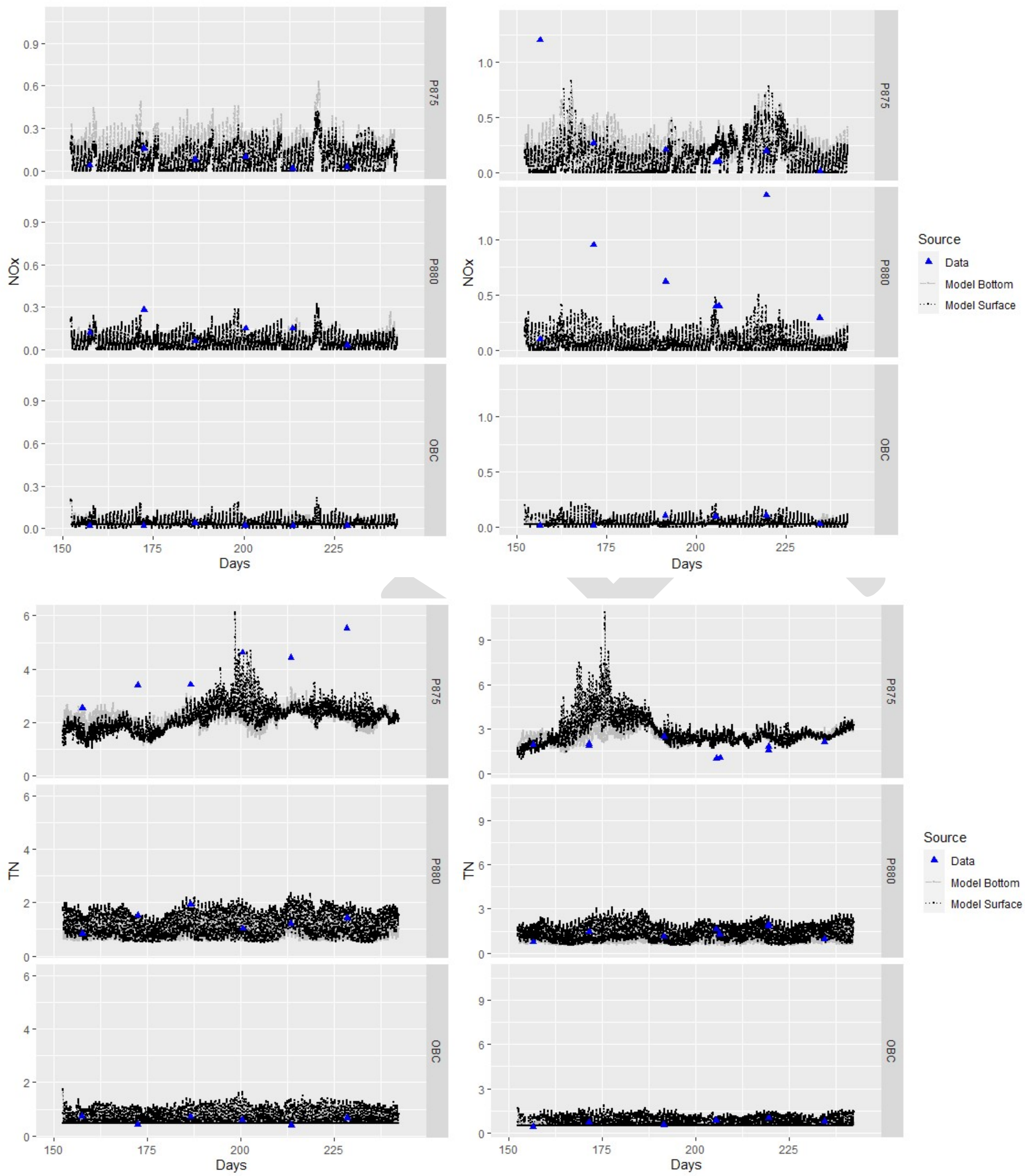
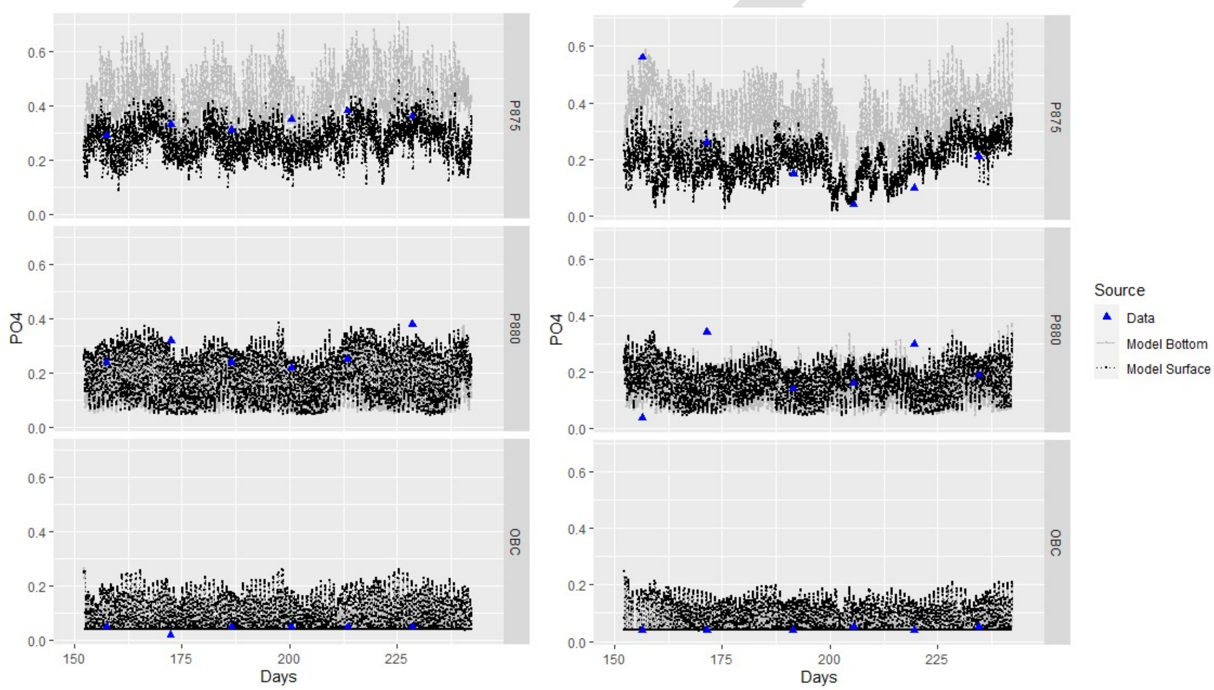


Figure 3-6. Model simulated and field data of ammonia (NH4, in mg/L), nitrite nitrate (NOx, in mg/L), and total nitrogen (TN, in mg/L) in summer 2017 (left panel) and summer 2018 (right panel) at monitoring stations P8750000 (P875), P8800000 (P880) and at the mouth of Calico Creek (open boundary, OBC).

3.4.2 Phosphorus

Model simulated phosphate (PO4) and total phosphorus (TP) concentrations in general cover the range of observed values (Figure 3-7). PO4 and TP concentrations appear to be higher towards the upstream of the Calico Creek close to station P8750000 and lower close to the mouth. The spatial pattern showed up in both field data and model results. Similar to NH4 and NOx, the model simulated PO4 concentrations are in general higher in the bottom layers at P8750000, suggesting benthic flux is an important PO4 source to the overlaying water column. In addition, during summer of 2017, the model seems to under-predict TP concentrations especially at station P8750000 after Julian day 200.



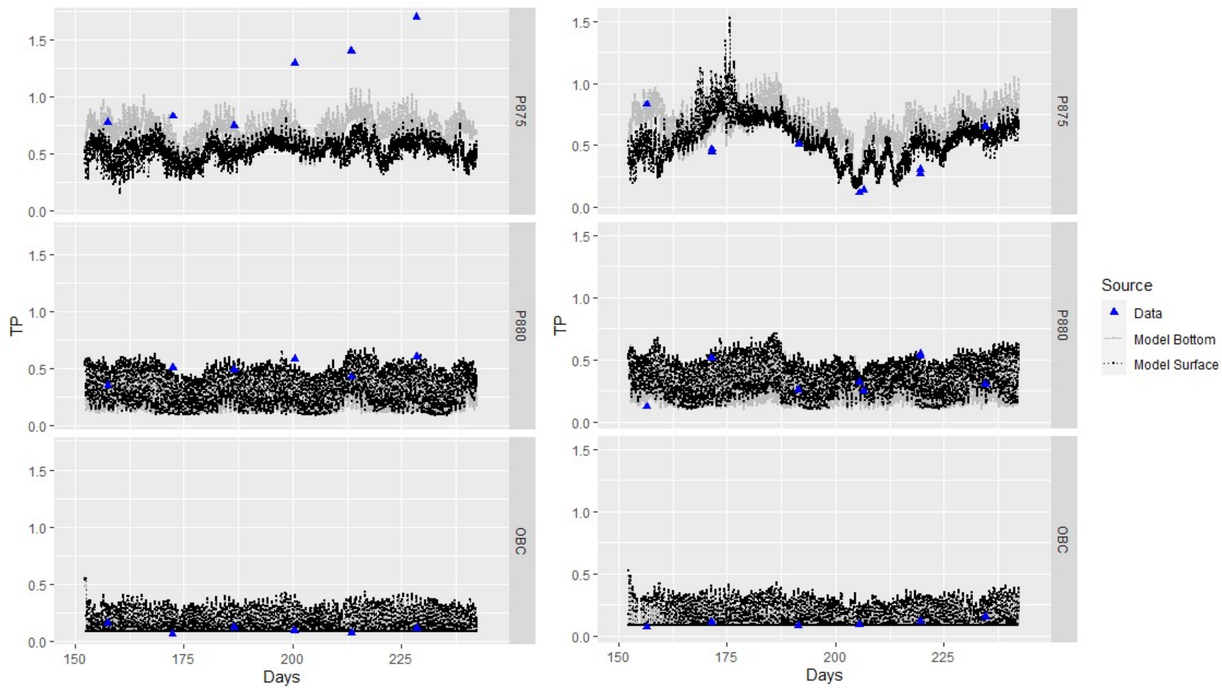


Figure 3-7. Model simulated and field data of phosphate (PO4, in mg/L) and total phosphorus (TP, in mg/L) in summer 2017 (left panel) and summer 2018 (right panel) at monitoring stations P8750000 (P875), P8800000 (P880) and at the mouth of Calico Creek (open boundary, OBC).

3.4.3 Dissolved Oxygen

Model simulated dissolved oxygen (DO) concentrations in general cover the range of observed values (Figure 3-8). However, during summer of 2017, at station P8800000, much higher vertical variations were observed than were simulated by the model. Observed DO concentrations can sometimes reach above 15 mg/L with bottom DO below 2 mg/L, suggesting high algal growth in surface waters and excessive DO consumption in bottom waters. These events may have been under estimated in the model.

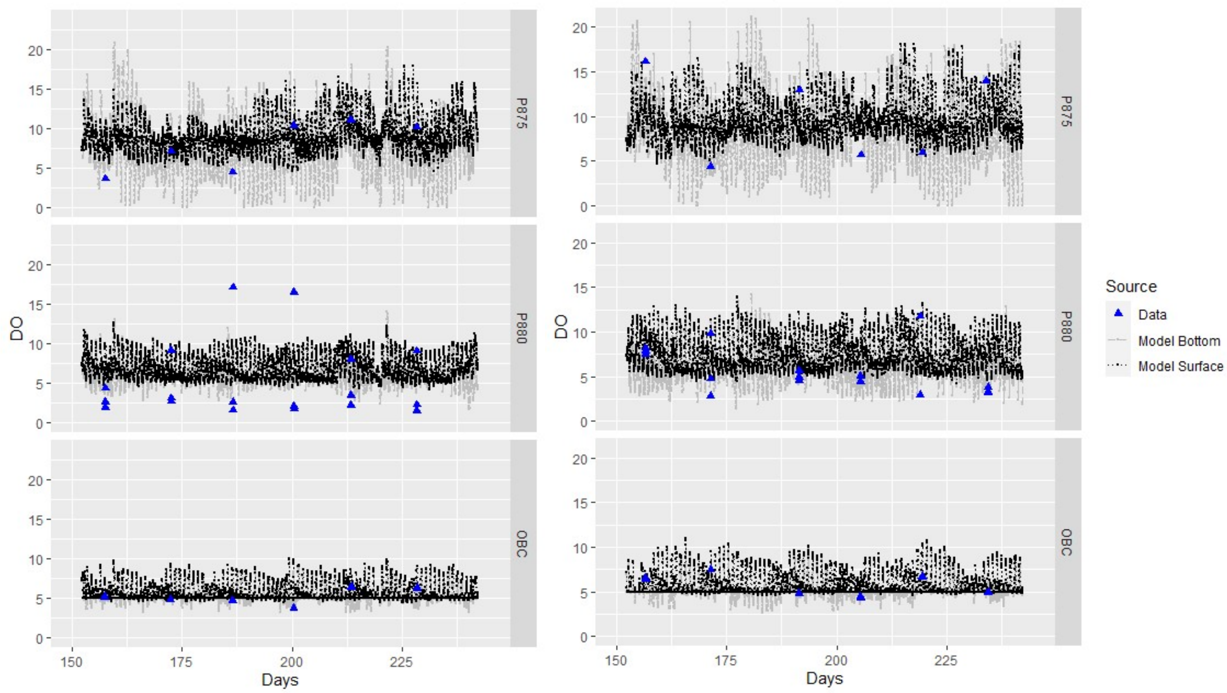


Figure 3-8. Model simulated and field data of dissolved oxygen (DO, in mg/L) in summer 2017 (left panel) and summer 2018 (right panel) at monitoring stations P8750000 (P875), P8800000 (P880) and at the mouth of Calico Creek (open boundary, OBC). Surface DO was reported from field data for station P8750000; vertical profiles of DO concentrations were recorded for station P8800000 (water depth up to 2m); Surface DO or surface and bottom DO concentrations were reported at station WOKCC0081 (water depth in general < 1 m and DO vertical differences in general < 0.2 mg/L).

3.4.4 Chlorophyll a

Model simulated chlorophyll a (Chl-a) concentrations in general agree well with the observed values during summer 2018 but are under-predicted during summer 2017 (Figure 3-9). Such under-prediction also occurred in TN and TP simulations. The observed chlorophyll a concentrations during summer 2017 were highly elevated at station P8750000. Longer term monitoring data (2003-2019) show that inter-quantile of year-round Chl-a concentrations at station P8750000 is between 7.5 and 96 µg/L, with 90th percentile at 250 µg/L. Only 6 samples out of 195 observations at P8750000 have Chl-a concentrations above 500 µg/L, 5 of them are in 2017 (2 on 5/18/2017, 1 on 8/2/2017 and 2 on 8/17/2017). Unusual algal blooms seem to have occurred in 2017. Model representation of summer 2017 is particularly challenging.

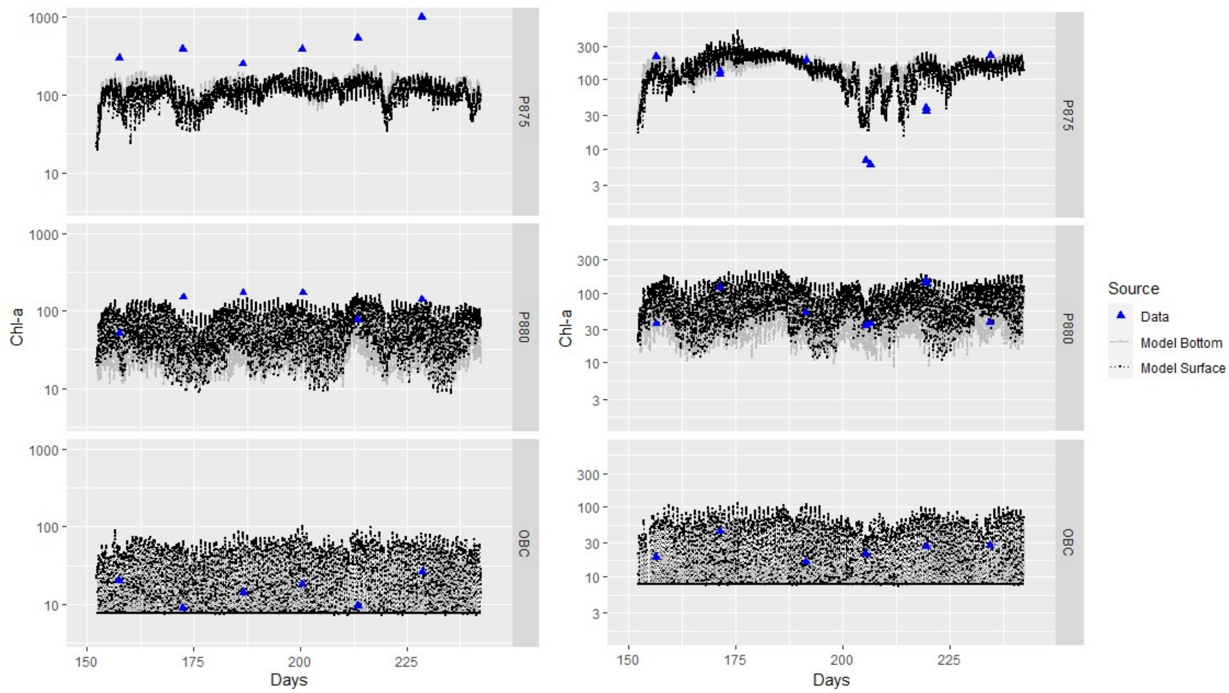


Figure 3-9. Model simulated and field data of chlorophyll a (Chl-a, in µg/L) in summer 2017 (left panel) and summer 2018 (right panel) at monitoring stations P8750000 (P875), P8800000 (P880) and at the mouth of Calico Creek (open boundary, OBC).

4 DIAGNOSTIC MODEL APPLICATION

Diagnostic model runs are conducted to investigate the relative importance of nutrient sources in the system. Scenario model runs are conducted to examine model responses of chlorophyll-a concentrations when different nutrient sources are eliminated. Table 4-1 summarizes model scenarios conducted and the corresponding model results.

Major nutrient sources to Calico Creek appear to be benthic nutrient fluxes, nonpoint sources and point source. A model scenario was run to turn off nutrient input from these sources and allow nutrient supply to Calico Creek estuary solely from its bay side at the open boundary (PS/NPS/Ben scenario in Table 4-1). This scenario resulted in very limited algal growth in Calico Creek and the model simulated Chl-a concentrations were very low. Atmospheric deposition appears to have minimal impact on algal growth in Calico Creek. The greatest Chl-a reduction by eliminating a single nutrient source was achieved at station P8750000 (river end of Calico Creek) when nonpoint sources were removed from model input. By contrast, for Chl-a at station P8800000 (mid-Calico Creek), greatest reduction was achieved when benthic nutrient fluxes were removed from model input.

When both point source and nonpoint sources are removed from model input (PS/NPS), benthic nutrient fluxes become the major nutrient source in Calico Creek, in this case, the model simulated summer-averaged Chl-a concentrations are still above 50 µg/L at both monitoring stations of P8750000 and P8800000. In reality, as point source and nonpoint sources are reduced, sediment nutrient fluxes would be gradually decreased as well. However, the decrease of sediment nutrient fluxes (or recycled nutrient) in response to reduction of external nutrient input (point source and nonpoint sources) may take a much longer time, likely in the order of decades. The rate of change in sediment nutrient fluxes in response to change of other nutrient sources is not known.

The model scenarios listed in Table 4-1 aim to investigate the relative importance of nutrient sources based on current (summer 2018) conditions. The only scenario that resulted in 90th percentile Chl-a concentrations below the standard of 40 µg/L involved removing all point source, nonpoint source, and benthic loadings from the system; which in reality is not achievable.

Table 4-1. Model scenarios and results

Scenario Name	Description	90th percentile/average model simulated surface Chl-a concentrations in summer 2018 (µg/L)	
		P875	**P880**
Base	Calibrated summer 2018 model simulation	223/143	133/81
PS	Total point source load removed	197/121	106/67
NPS	Total nonpoint source load removed	133/82	108/65
Ben	Benthic nutrient fluxes removed	163/90	68/41
Atmospheric Deposition	Atmospheric deposition removed	223/143	133/81
PS/NPS	Total point source and nonpoint source are removed	99/60	81/51
PS/NPS/Ben	Total point source, nonpoint source and benthic nutrient fluxes are removed	10/7	15/12

5 SUMMARY

Calico Creek estuary is a highly eutrophic system. Observed chlorophyll-a concentrations can reach up to 1000 µg/L (i.e. station P8750000 in summer 2017). Measured chlorophyll-a concentrations in Calico Creek are some of the highest concentrations seen across the state.

A three-dimensional hydrodynamic and eutrophication model, EFDC, was set up to simulate water quality conditions in Calico Creek in summers of 2017 and 2018. The model in general simulated water quality conditions well in summer 2018, however under-predicted peaks of Chl-a, TN, and TP in summer 2017.

Scenario model runs based on summer 2018 base case were conducted to investigate the relative importance of nutrient sources to Calico Creek estuary. Model results suggest sediment nutrient fluxes, nonpoint sources and the single point source from Morehead City WWTP all contribute to nutrient enrichment in Calico Creek estuary. Furthermore, current conditions of sediment nutrient fluxes by itself (both point source and nonpoint source eliminated) could support algal growth and result in high summer average chlorophyll-a concentrations (above 50 µg/L at both monitoring stations of P8750000 and P8800000). Reductions on all three major nutrient sources are expected to improve water quality conditions in Calico Creek. In reality, as point source and nonpoint sources are reduced, sediment nutrient fluxes will be gradually decreased as well. However, the decrease of sediment nutrient fluxes (or recycled nutrient) in response to reduction of external nutrient input (point source and nonpoint sources) may take a much longer time, likely in the order of decades.

Model results suggest that adaptive management strategies are an appropriate tool to begin to address the impairments in the Calico Creek estuary.

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