Pre-Project Water Quality Monitoring

Post 45 Project, Charleston, SC

Prepared for:

US Army Corps of Engineers
Charleston District

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Prepared by:

Water Environment Consultants
Mount Pleasant, SC

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Executive Summary

This report summarizes the monitoring data that establishes the pre-project conditions for the Post 45 Charleston Harbor Deepening Project. The Post 45 project will deepen and widen the federal navigation channel. The US Army Corps of Engineers (USACE) completed an Environmental Impact Statement (EIS) for the project that evaluated the potential impacts of the project on the salinity and dissolved oxygen (DO) concentrations in the harbor. The Mitigation Planning and Monitoring and Adaptive Management Plan for the project includes a water quality monitoring program that is intended to document the project effects and to determine if the impacts are consistent with those estimated in the EIS.

The SC Ports Authority contracted Water Environment Consultants (WEC) to complete an analysis of the pre-project monitoring data. WEC subcontracted Dr. Dennis Helsel, the lead scientist of Practical Stats, to provide assistance with statistical analysis methods.

The objectives of this pre-project monitoring data analysis are to:

1. Compile and analyze the monitoring data using the methods specified in the USACE's October 2017 *Water Quality Monitoring Program Methodology*;
2. Estimate what minimum amount of change might be able to be detected with the monitoring data; and
3. Identify any necessary revisions to the data collection and/or statistical analyses methods.

WEC compiled and reviewed the pre-project monitoring data for the period between 2006 and 2017. This data includes all of the variables listed in a summary table in Section 2 of this report. The monitoring data includes explanatory variables (i.e., the background variables that affect salinity and DO in the harbor) and direct measurement of salinity and DO in the project impact area. The data was organized into Excel spreadsheet format for delivery to the USACE.

To provide watershed runoff data, WEC used the Loading Simulation Program C++ (LSPC) watershed model to simulate watershed flows for the period from 2006 through 2017. This model was previously developed for the Total Maximum Daily Load (TMDL) study of the estuary completed by the SC Department of Health and Environmental Control (SCDHEC). Land use data input to the model were updated based on the 2011 National Land Cover Database (NLCD). The updated model was confirmed by comparing modeled flows to available measured non-tidal freshwater flow data, which is limited to flows in Turkey Creek (U.S. Geological Survey [USGS] gauge 02172035), a tributary to the East Branch Cooper River.

WEC completed statistical analyses of the data at 11 monitoring locations within the area potentially affected by the Post 45 Project. This included development of quantile regression models for the prediction of 10th percentile DO concentrations in the project impact area, and it included development of linear regression models for the prediction of average annual salinity in the project impact area.

The results of the statistical analyses demonstrate that multiple linear regression and quantile regression techniques can be used to account for the effects of explanatory variables on salinity and DO concentrations in the Charleston Harbor estuary. Once the project construction is completed and post-project monitoring data is collected, these methods can be used to estimate the DO and salinity in the estuary that would have occurred had the Post 45 Project not been constructed. These results can then be compared to the measured after-project DO and salinity in order to quantify the project impacts.

The uncertainty in the statistical models varies by location. For DO, the error in the annual March-October 10th percentile DO is a relatively small fraction of the observed DO (less than 10% error at all locations, except one). However, the absolute error in this measure of DO ranges between 0.15 mg/l and 0.43 mg/l at the long-term monitoring locations (at the 90% confidence level). This level of error is greater than the level of Post 45 Project impact predicted by the EIS (which estimated DO impacts less than 0.10 mg/l in the Cooper River and less than 0.12 mg/l in the Wando River). Therefore, the statistical analysis of the monitoring data will detect project-induced changes only if they are substantially greater than those estimated by the EIS.

For salinity, the models are generally within an error of 13 percent or less of the average annual salinity at each location, with one exception (the Ashley River below Summerville location has an error of ±0.11 ppt, which is 44 percent of the average annual salinity). The statistical model error varies by location and can be smaller or larger than the EIS estimates of Post 45 Project impacts. If the EIS predictions are accurate, then project effects at some locations will be within the error range for the statistical models and will not be detected by the monitoring data. However, if the project causes changes in salinity greater than the statistical model error estimates at each location, then the monitoring data will detect the project-induced changes.

No revisions to the field monitoring (e.g., USGS gauge locations) are recommended.

1 Introduction

This report summarizes the monitoring data that establishes the pre-project conditions for the Post 45 Charleston Harbor Deepening Project. The Post 45 project will deepen and widen the federal navigation channel. The USACE completed an EIS for the project that evaluated the potential impacts of the project on the salinity and DO concentrations in the harbor. Numerical modeling analyses indicate that DO impacts due to the Post 45 project will be *de minimis* as defined in R. 61-68, and the project will cause slightly increased salinities in some reaches of the harbor's tributary rivers. The Mitigation Planning and Monitoring and Adaptive Management Plan for the project (Appendix P to the EIS) includes a water quality monitoring program that is intended to document the project effects and to determine if the impacts are consistent with those estimated in the EIS. If the observed project impacts are greater than those estimated in the EIS, then suitable corrective action can be taken, if necessary. Furthermore, if the monitoring data show that the project caused dissolved oxygen impacts greater than the allowable cumulative impact of 0.1 mg/l or salinity impacts greater than those estimated in the EIS or the analysis is inconclusive, then the numerical model will be updated and used to reevaluate the project impacts and mitigation requirements. Because numerical modeling may be required to quantify, identify causes and evaluate the impacts, as well as support analysis of any corrective actions, a secondary goal of the water quality monitoring program is to also collect sufficient data to update the model.

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The following report sections describe the monitoring and statistical analysis methodology:

- Section 2, Monitoring Data Compilation and Review – summarizes the pre-project monitoring program, including duration, variables, and locations;
- Section 3, LSPC Watershed Modeling – summarizes modeling completed to estimate watershed flows using rainfall data;
- Section 4, Statistical Analysis – describes the development of statistical models to estimate 10th percentile DO and average annual salinity for the "without project" conditions, and provides estimates of the minimum amount of change that can be detected using statistical methods following project construction; and
- Section 5, Conclusions.

2 Monitoring Data Compilation and Review

This section summarizes the pre-project monitoring period, variables, and locations.

2.1 Monitoring Period

Post 45 Project construction started in March 2018, beginning with dredging of the offshore entrance channel. For the purposes of this analysis, the pre-project monitoring period ends on December 31, 2017. The pre-project monitoring period starts on January 1, 2006. Data prior to 2006 is not used because of the effects of the previous harbor deepening project, which was completed in 2005.

2.2 Monitoring Variables and Locations

Table 2-1 summarizes the variables of interest, the monitoring locations and the need for monitoring each of these variables. The monitoring data sources are each described in greater detail in the following sections.

2.2.1 Offshore Conditions

Offshore salinity and temperature data was collected from a buoy located about 5 miles offshore from Capers Island (Station 41029 - Capers Nearshore [CAP2]) (Figure 2-1). This buoy is part of the Carolinas Regional Coastal Ocean Observing System, and it is owned and maintained by the University of North Carolina Wilmington's (UNCW) Coastal Ocean Research and Monitoring Program. Observations from this buoy were used in the statistical analysis as explanatory variables potentially affecting DO and salinity in the harbor.

The measured water temperatures and salinity concentrations at the CAP2 buoy are shown in Figures 2-2 and 2-3, respectively. These figures include the observation data reported every two hours, plus the daily averaged values calculated by WEC.

DO concentrations in the lower estuary are affected by offshore DO concentrations. Offshore DO is a function of a number of variables, including salinity, temperature, wind and wave action, phytoplankton productivity and respiration, and biochemical oxygen demand. In addition, Peterson et al. (2015) present evidence that there is a naturally occurring discharge of saline, anoxic groundwater in areas offshore from Myrtle Beach, South Carolina that can affect DO concentrations in nearshore waters. It is unknown if there is any anoxic groundwater discharge that could affect Charleston Harbor DO concentrations. Continuous measured offshore DO concentrations would be ideal for this analysis, however, DO was not continuously measured in the ocean offshore from Charleston. Therefore, the best available indicator of offshore DO variations is the DO saturation concentration. DO saturation concentration varies in response to ocean temperature, salinity and atmospheric pressure. WEC calculated offshore DO saturation concentrations based on the daily-averaged measured temperature and salinity data from the CAP2 buoy, as shown in Figure 2-4. These values are corrected for atmospheric pressure using observations from Charleston International Airport. WEC calculated DO saturation concentrations using the formulation given by Benson and Krause (1980, 1984). No DO saturation values were calculated for days when temperature, salinity or pressure data are missing.

Table 2-1 Summary of variables of interest, monitoring data sources and the need for each variable

Variable	Monitoring Source	Need			
		Impact Observation	Explanatory Variable	Model Boundary	Model Calibration
Offshore:					
Offshore salinity and temperature	Buoy at Station 41029 - Capers Nearshore (CAP 2) - Continuous data		X	X	
Offshore DO	Assume constant % saturation (calculate % saturation based on measured salinity and temperature)		X	X	
Offshore mean water level	NOAA Customs House gauge		X	X	
Upstream Cooper River:					
Upstream DO and temperature	New USGS DO sensor at existing Tailrace Canal gauge		X	X	
Upstream loads	Santee Cooper monthly water chemistry monitoring (SC-033) and USGS flow rates at existing Tailrace Canal gauge		X	X	
Watershed:					
Local watershed flows and loads	Rainfall gaging stations throughout watershed		X	X	
Impact Areas:					
Wando River DO	USGS continuous monitoring stations - Existing mid-depth at I-526 - New bottom gauge at I-526 - New mid-depth gauge near Hwy 41	X			X
Cooper River DO	USGS continuous monitoring stations - Existing mid-depth at Hwy 17, I-526 and near Goose Cr. - New bottom gauge at I-526 - New mid-depth gauge between Hwy 17 and I-526 (at Navy Base)	X			X
Ashley River DO and salinity	USGS continuous monitoring station - Existing mid-depth at I-526 - New mid-depth 2 mi. downstream of Jessen Landing on private dock	X			X
Cooper River Salinity	Above listed USGS continuous monitoring stations for DO, plus - Existing mid-depth gauge at Mobay - Existing mid-depth gauge at Pimlico - New mid-depth gauge between Mobay and Goose Cr. gauges	X			X
Other variables:					
Point source discharges	Daily monitoring reports (maintained by individual dischargers) for flow, BOD, NH3		X		X
Estuary water chemistry	SCDHEC fixed water quality monitoring stations		X		X
Meteorological conditions	Airport and other monitoring stations		X		X

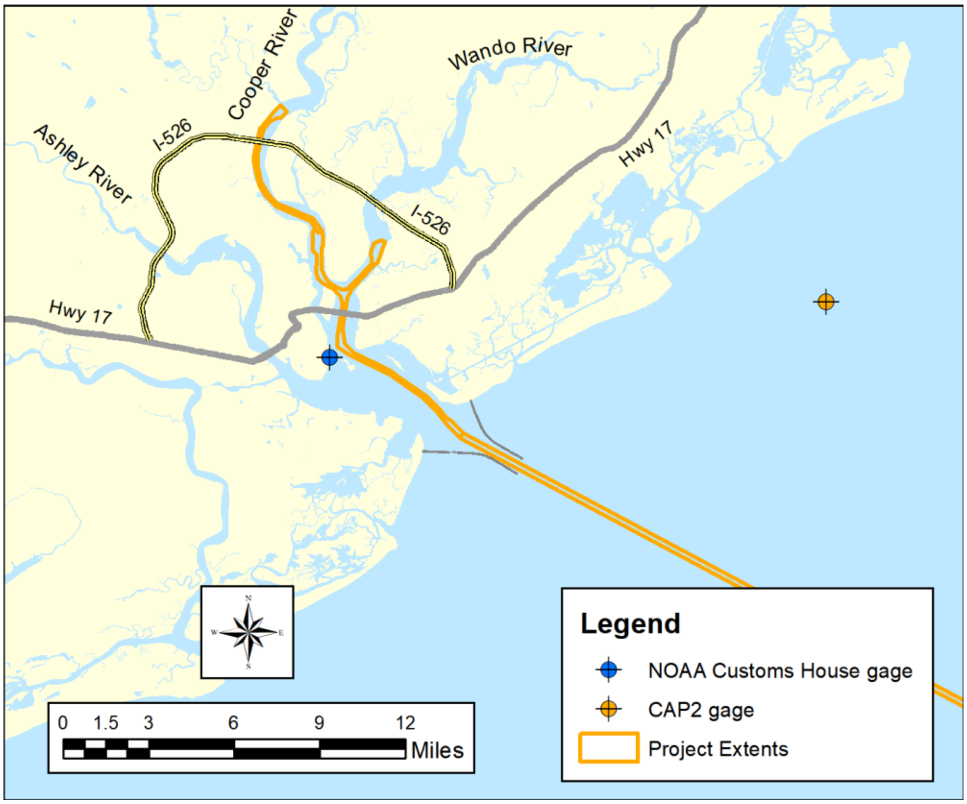

Figure 2-1. CAP2 buoy and NOAA Customs House gauge locations

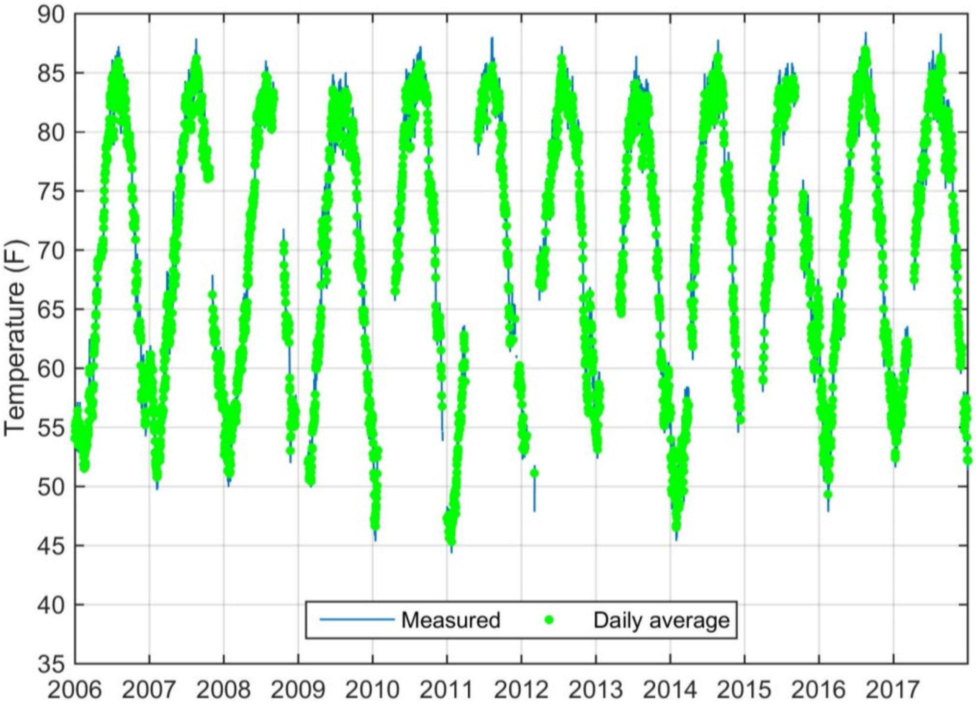

Figure 2-2. Offshore water temperature measurements at CAP2 buoy

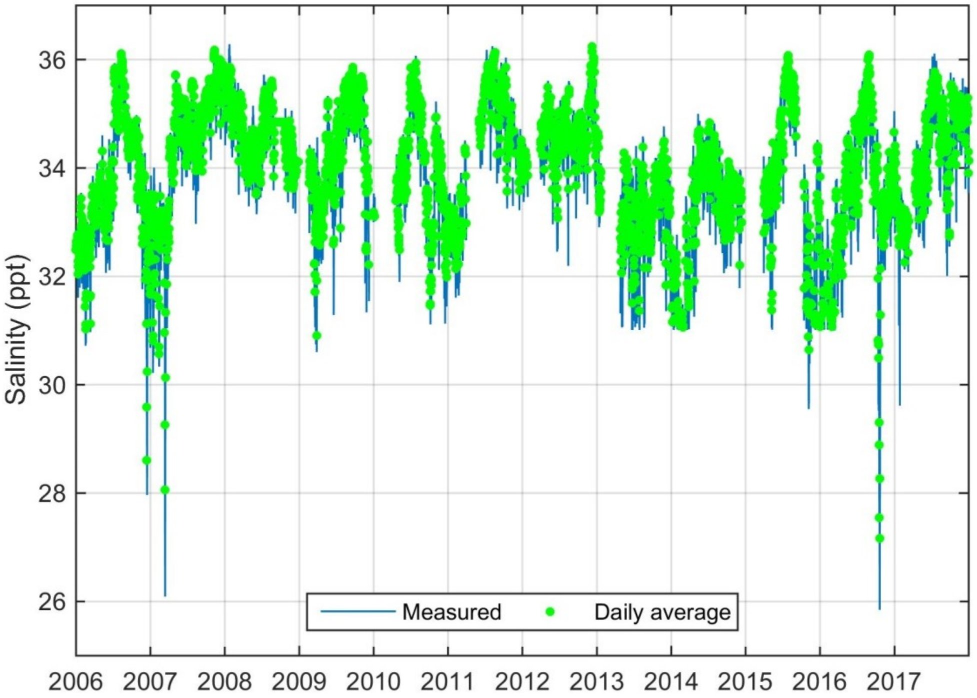

Figure 2-3. Offshore salinity measurements at CAP2 buoy

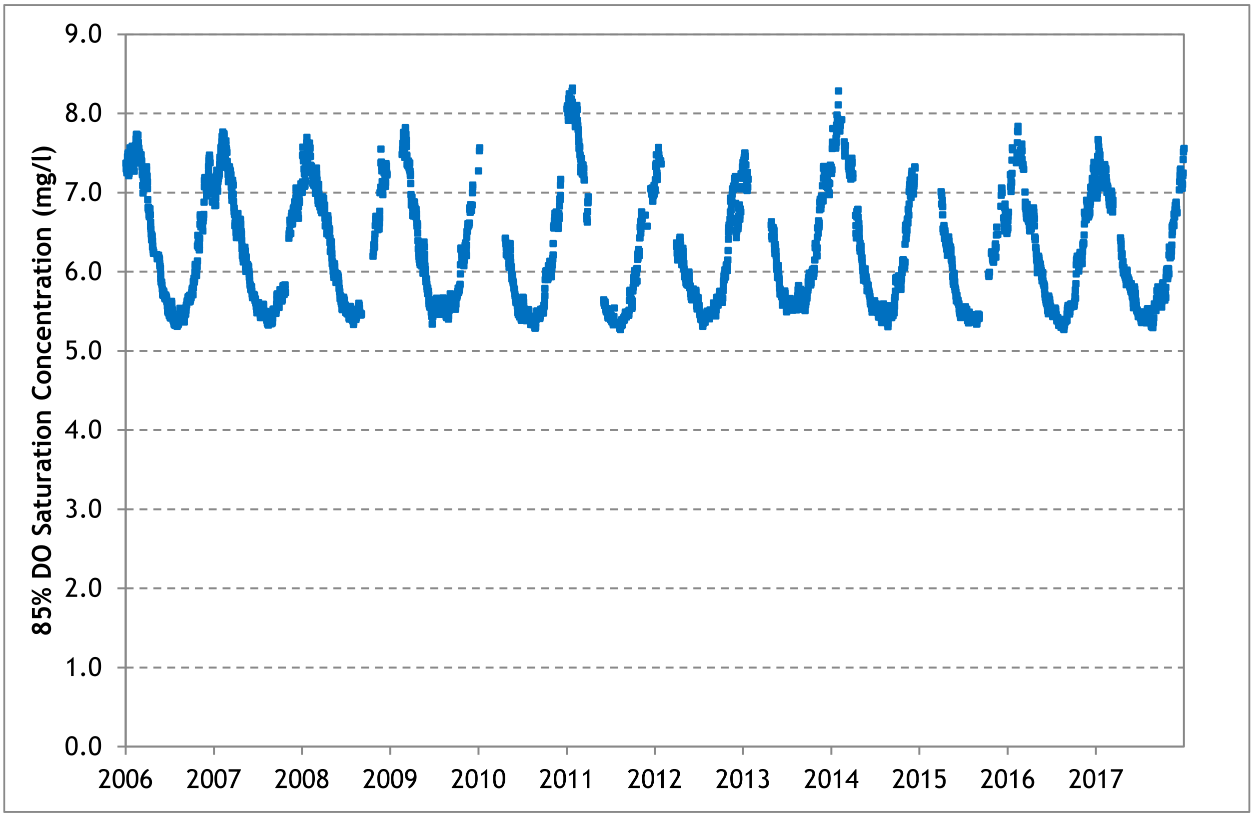

Figure 2-4. Offshore 85% DO saturation concentration at CAP2 buoy

WEC used a value of 85 percent of DO saturation concentration for this analysis. This is consistent with the TMDL model analysis, which assumes an offshore boundary concentration of 85 percent of DO saturation concentration. The actual fraction of DO saturation in the ocean varies; however, use of a different *constant* fraction of DO saturation will not change the statistical analysis results because the offshore DO saturation time series will still exhibit the same relative pattern of variance over time.

Measured water levels at the NOAA gauge at the Charleston Customs House (Station 8665530) provide an estimate of offshore water levels. The measured hourly water levels and calculated daily-averaged values are shown in Figure 2-5, in feet relative to the North American Vertical Datum of 1988 (NAVD 88). Daily averaging of tidally influenced variables can result in a phenomenon known as tidal aliasing (Godin 1972 *in* USGS 2011), which results in a low frequency variation on the order of 3 to 4 percent of the tidal component of the signal. Tidal aliasing is an artifact of the averaging process and it does not represent actual low frequency variation in the signal. Therefore, tidally influenced data were low-pass filtered to remove the effects of semi-diurnal tides prior to calculating daily averaged values. WEC used a Fourier low-pass filter with a 30-hr cutoff period using a Matlab program written by Jeff List at the USGS that applies the methodology given by Walters and Heston (1982). WEC also calculated the daily tidal range at the Customs House gauge (Figure 2-6).

2.2.2 USGS Gauges

The USACE, USGS, Berkeley-Charleston-Dorchester Council of Governments (BCDCOG) and other cooperators operate a system of water quality data collection stations within the Charleston Harbor system using 15-minute data collection. These gauges were installed and are maintained by the USGS. Data collected include temperature, water level, specific conductance (SC) and DO. SC data are used to calculate salinity at each gauge location. The gauges used to monitor DO and salinity impacts from the Post 45 project are shown in Figures 2-7 and 2-8, respectively.

The gauges include both long-term monitoring stations as well as newer gauges added specifically to monitor the Post 45 project impacts. The available 15-minute monitoring data for long-term gauges extends back to October 1, 2007. Instruments were installed at the new monitoring locations in July 2016, except for a gauge in the Ashley River, which was installed in January 2017. Table 2-2 lists the start date for data compiled for the various USGS gauges. New gauges installed to monitor Post 45 project changes in the anticipated impact areas include:

- Two bottom DO gauges added at the existing mid-depth gauge locations on the Cooper and Wando Rivers at the I-526 highway crossings;
- A new SC, temperature and water level gauge on the upper Cooper River in the vicinity of the existing 0.5 ppt contour (installed approx. 1 mile upstream from the Williams Station Steam Plant discharge);
- A new DO, SC, temperature and water level gauge on the upper Ashley River in the vicinity of the existing 0.5 ppt contour (installed on a private dock 2-miles downstream of the Herbert Jessen boat landing); and

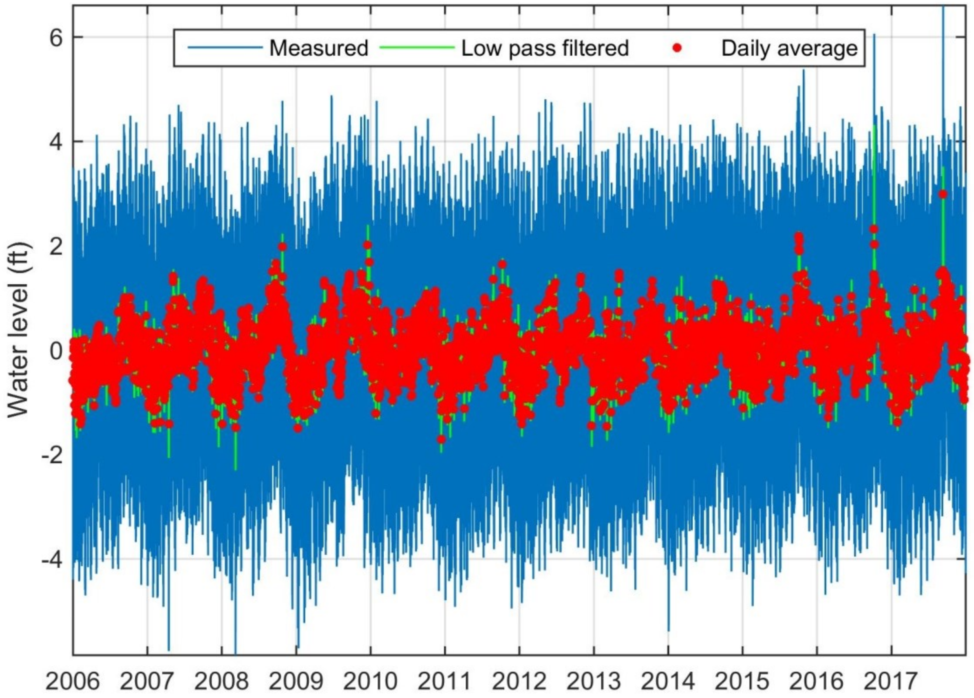

Figure 2-5. Water levels at NOAA Customs House gauge (feet NAVD88)

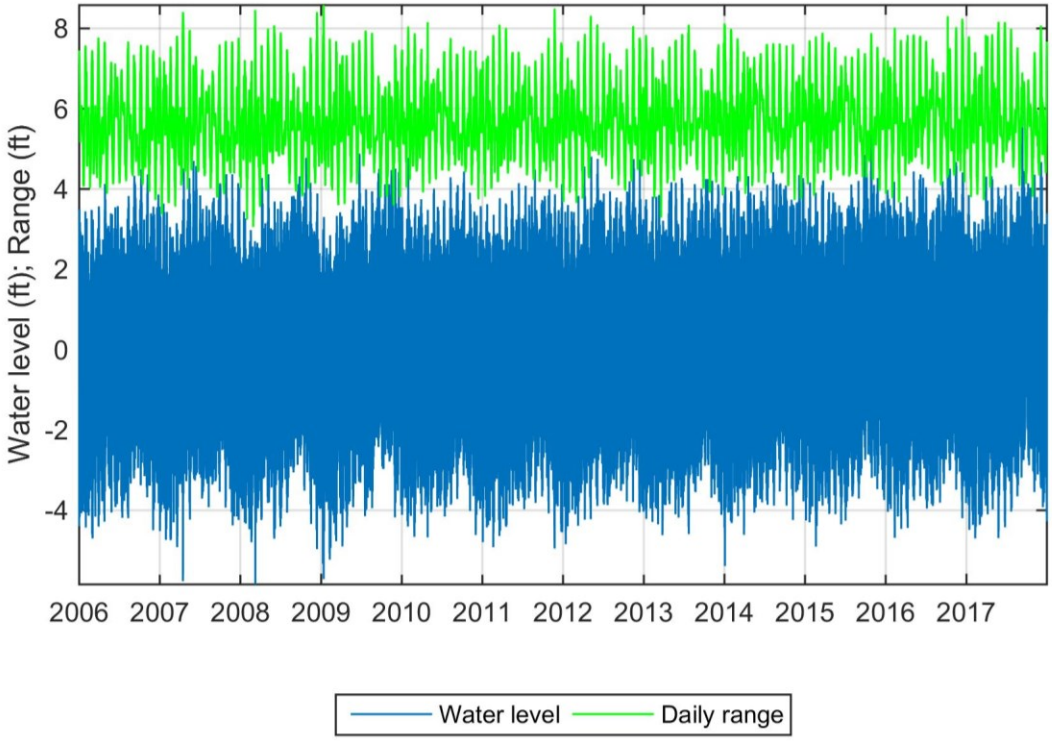

Figure 2-6. Tide ranges at NOAA Customs House gauge

- A new DO, SC, temperature and water level gauge on the Wando River located at the power lines just upstream from the State Highway 41 crossing.

In addition, a new DO sensor was installed at the existing gauge at the tailrace canal to monitor DO concentrations just downstream from the dam. This sensor monitors the DO concentrations entering the estuary from the upstream boundary.

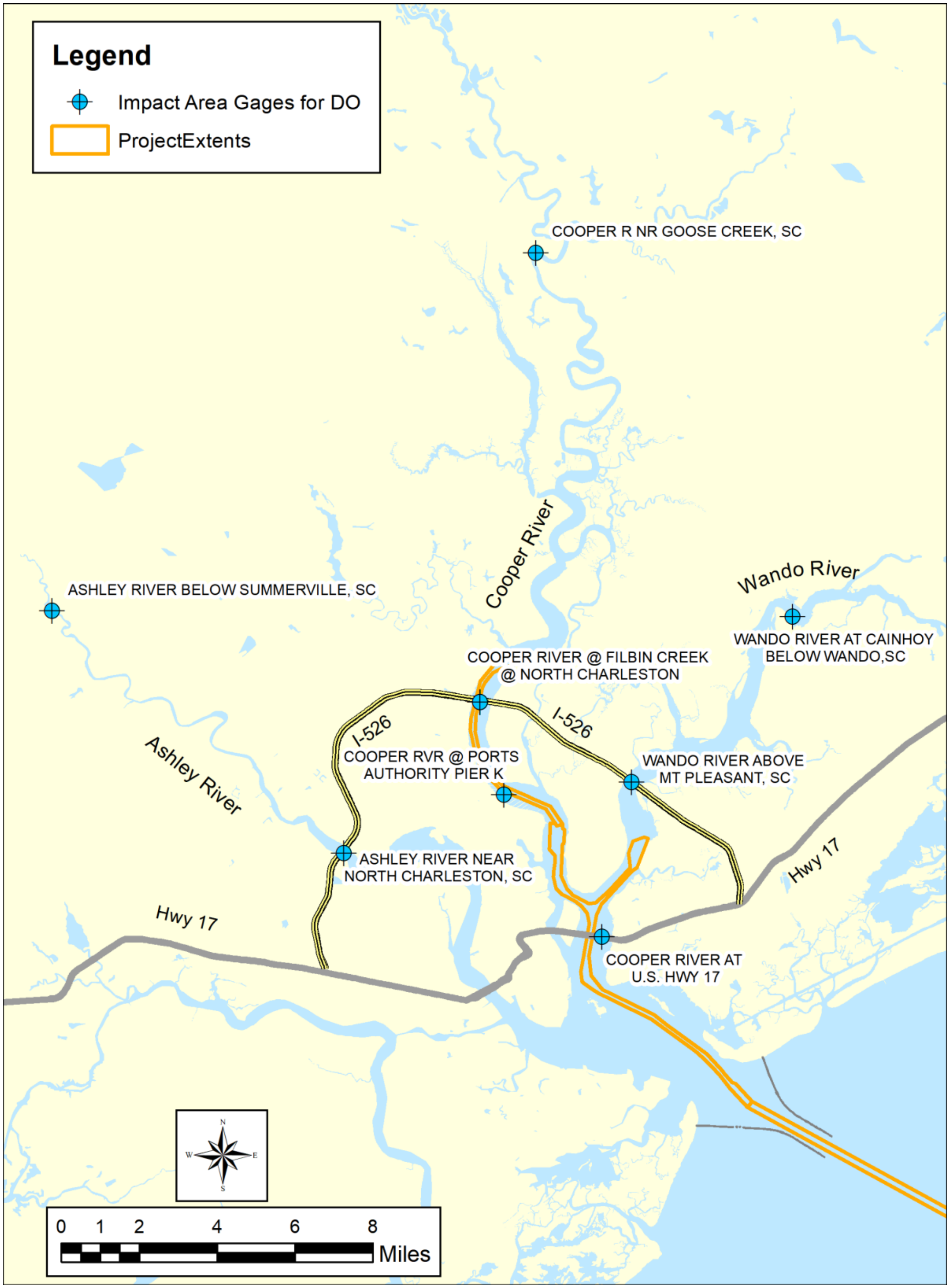

Figure 2-7. Impact area DO monitoring gauge locations

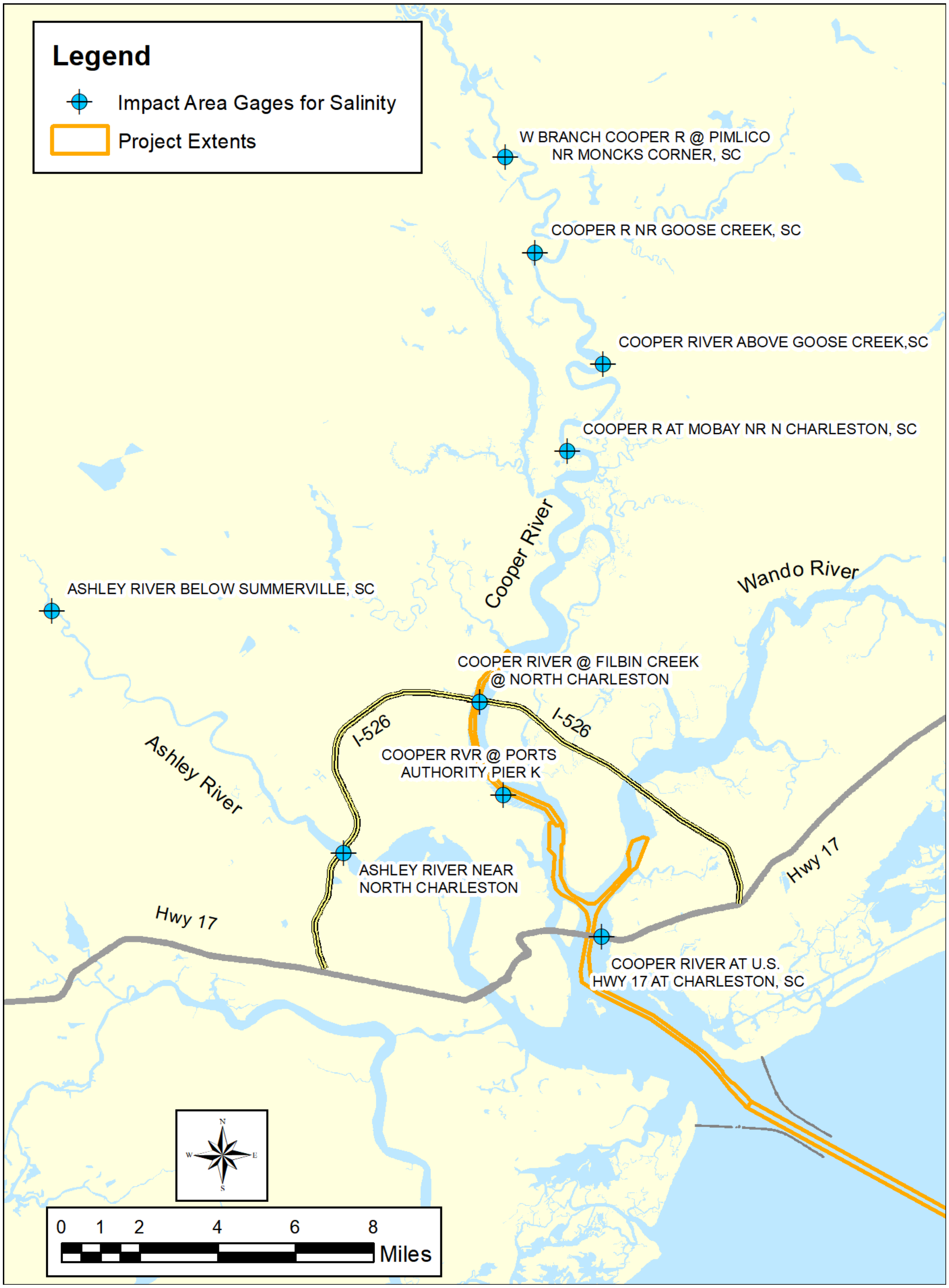

Figure 2-8. Impact area salinity monitoring gauge locations

Table 2-2 List of USGS gauge locations and data start dates for pre-project monitoring analysis

Gauge Location & Variables	Gauge No.	Start Date
Upstream boundary		
Lake Moultrie Tailrace Canal at Moncks Corner, flow rate	2172002	10/1/2007
Lake Moultrie Tailrace Canal at Moncks Corner, temperature and DO	2172002	6/24/2016
Impact area DO monitoring		
Ashley R. below Summerville	21720825	1/26/2017
Ashley R. nr North Charleston	21720869	10/3/2007
Cooper R. nr Goose Cr	2172050	10/3/2007
Cooper R. at Filbin Cr. @ North Charleston	21720677	10/3/2007
Cooper R. at Pier K, surface	217206935	7/2/2016
Cooper R. at Pier K, bottom	217206935	7/2/2016
Cooper R. at US 17, mid-depth	21720709	10/7/2007
Cooper R. at US 17, bottom	21720709	6/22/2016
Wando R. above Mt. Pleasant at I-526, mid-depth	21720698	10/3/2007
Wando R. above Mt. Pleasant at I-526, bottom	21720698	7/22/2016
Wando R. at Cainhoy	217206962	6/22/2016
Impact area salinity		
Ashley R. below Summerville	21720825	1/26/2017
Ashley R. nr North Charleston	21720869	10/12/2007
W. Branch Cooper R. @ Pimlico	2172020	10/3/2007
Cooper R. above Goose Cr	21720508	6/22/2016
Cooper R. at Mobay	2172053	10/3/2007
Cooper R. nr Goose Cr	2172050	10/3/2007
Cooper R. at Filbin Cr. @ North Charleston	21720677	10/3/2007
Cooper R. at Pier K, surface	217206935	7/1/2016
Cooper R. at Pier K, bottom	217206935	7/1/2016
Cooper R. at US 17, mid-depth	21720709	10/3/2007
Cooper R. at US 17, bottom	21720709	6/23/2016

2.2.3 Point Source Discharges

There were thirteen major point sources discharging to the Charleston Harbor estuary during the pre-project monitoring period. These discharges, shown in Figure 2-9, each have a National Pollutant Discharge Elimination System (NPDES) permit. The impacts from the discharges on DO in the estuary were evaluated in a Total Maximum Daily Load (TMDL) study completed by the South Carolina Department of Health and Environmental Control (SCDHEC). The TMDL study used the Environmental Fluid Dynamics Code (EFDC) water quality model to estimate the DO impacts from the point-source pollution discharges (Cantrell 2013). The TMDL established the permit limits for oxygen demanding substances for the point source discharges (measured as the Ultimate Oxygen Demand [UOD] of the discharges) such that the 90th percentile effects on the daily-averaged DO concentrations in the river will not exceed 0.1 mg/l during the March through October time period. Table 2-3 summarizes the major

Figure 2-9. Major NPDES permitted discharges

Table 2-3. Major NPDES point source discharges

Discharge Name	NPDES Permit No.	UOD[1] (lb/day)	% of DO impact in critical Cooper River Segment[1]	% of DO impact in critical Wando River Segment[1]
Summerville	SC0037541	2,745	0%	0%
DCPW/Lower Dorchester	SC0038822	2,365	0%	0%
Moncks Corner	SC0021598	5,730	8%	4%
BCWSA/Central Berkeley	SC0039764	3,788	7%	3%
DAK Americas & Dupont	SC0026506 & SC0048950	2,466	3%	2%
Sun Chemical	SC0003441	7,625	12%	9%
BP Amoco	SC0028584	4,736	4%	4%
BCWSA/Lower Berkeley	SC0046060	8,846	9%	10%
WestRock (formerly KapStone)	SC0001759	40,959	28%	25%
NCSD/Felix Davis	SC0024783	29,090	22%	29%
CWS/Plum Island	SC0021229	24,612	4%	7%
Mount Pleasant - CS & RR	SC0040771	11,415	4%	7%

[1] UOD loading rates and percent DO impact values are from the 2013 TMDL report (Cantrell 2013) based on constant discharges at maximum permitted rates.

NPDES discharges, their maximum UOD discharge rates from the TMDL report, and the relative effect in the critical segment of the river (i.e., the segment of the river where the greatest discharge effects occur).

To comply with the NDPES permit, the discharge flows and pollutant concentrations are monitored by the permittees and reported to SCDHEC on a monthly basis as Discharge Monitoring Reports (DMR). The DMRs typically include a monthly average and a maximum daily value for the month, and they do not include the daily monitoring data. However, this data was collected by the permittees and WEC obtained the data upon request to the permittees through the BCDCOG.

Figure 2-10 summarizes the point source discharge UOD loading rates into the estuary. The total UOD discharge rates to the Ashley River (i.e., Summerville and Lower Dorchester) are much smaller than those into the harbor (i.e., CWS Plum Island and Mount Pleasant), which in turn, are much smaller than the total UOD discharge rates to the Cooper River. The loading rates for individual discharges are plotted in Appendix A.

2.2.4 Local Watershed Flows

Watershed loads were estimated using monitored rainfall data and the LSPC watershed model developed as part of the TMDL model. Available monitoring data includes daily rainfall data collected by the National Weather Service (NWS), USGS, the Community Collaborative Rain, Hail and Snow network (CoCoRaHS) and Remote Automatic Weather Stations (RAWS). Rainfall monitoring gauges in the study area are shown in Figure 2-11. For the pre-project monitoring data analyses, rainfall data from the

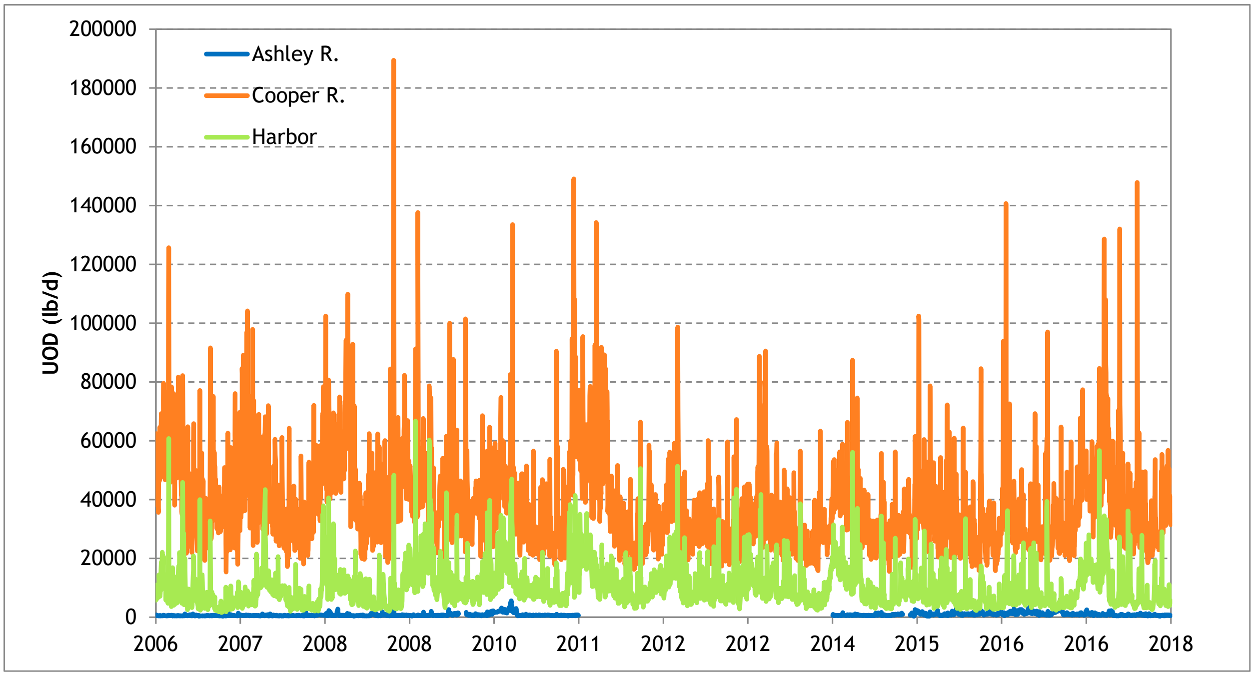

Figure 2-10. Summary of point source discharge loading rates

following sources were used: Charleston International Airport (NWS), Berkeley County Airport (NWS), Turkey Creek above Huger (USGS), Witherbee (RAWS), and Wambaw (RAWS). CoCoRaHS data were reviewed, but the data were not used for the LSPC modeling because it was not possible to distinguish zero rainfall values from non-operational periods for a given gauge. Additionally, the varying data availability at each station location is not well suited for use with a watershed model such as LSCP. The continuous records at the other monitoring locations were found to be sufficient for the LSPC modeling (discussed in detail in Section 3 of this report).

2.2.5 Estuary Water Chemistry

SCDHEC's Ambient Surface Water Physical & Chemical Monitoring Program includes ongoing fixed-location monitoring and statewide statistical survey monitoring. The fixed-location component of the monitoring network is comprised of Base Sites that are generally sampled every other month, year round. Statistical Survey Monitoring Sites are typically sampled once per month for one year and moved from year to year. The nine Base Sites in the estuary are shown in Figure 2-12. Bi-monthly variables analyzed include DO, pH, water temperature, air temperature, specific conductance, salinity, turbidity, BOD5, nitrate/nitrite nitrogen, total phosphorus, alkalinity, ammonia nitrogen and Total Kjeldahl Nitrogen (TKN). TKN is the sum of organic nitrogen and ammonia nitrogen, and it represents the total amount of oxidizable nitrogen in the water.

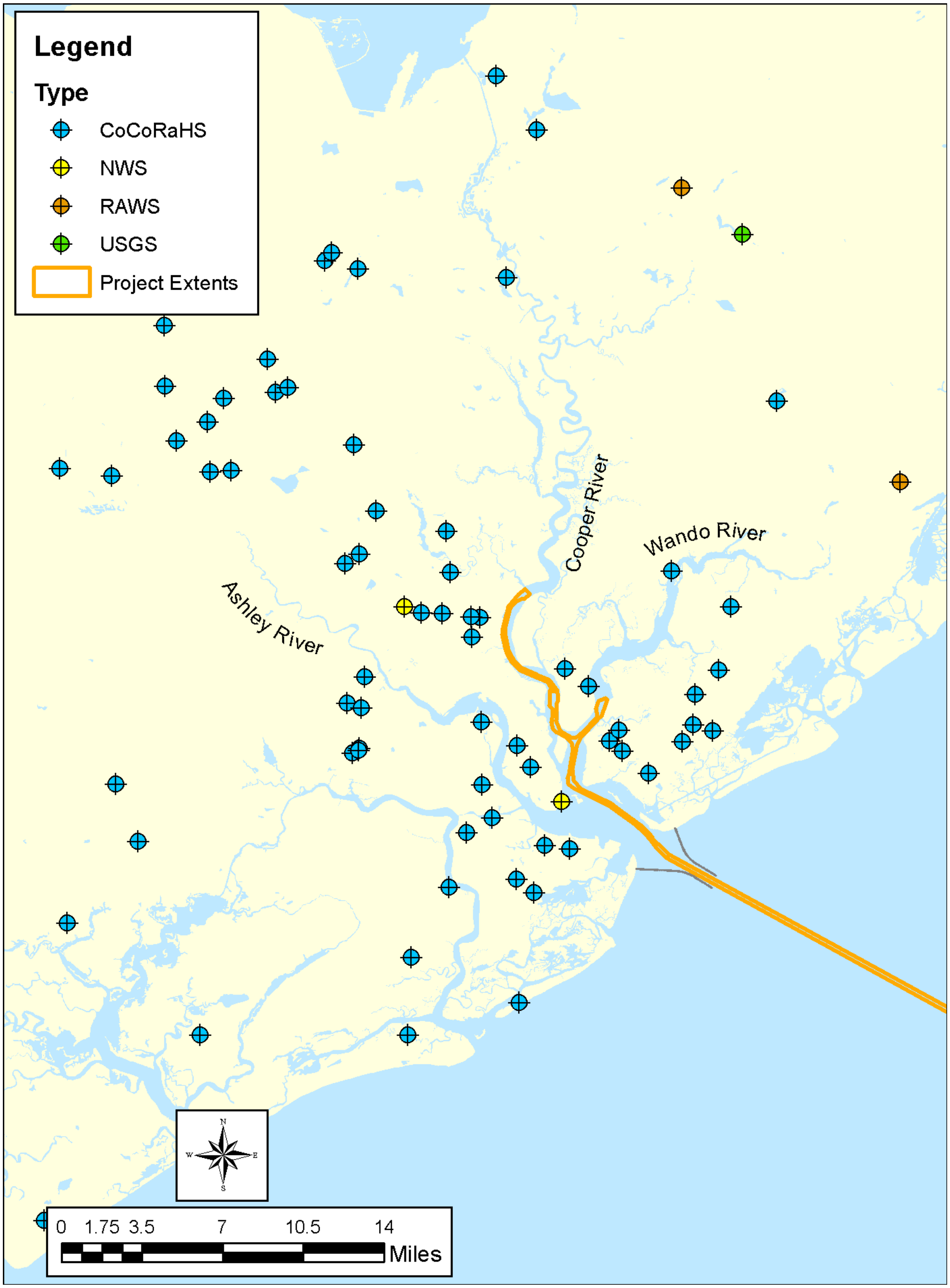

Figure 2-11. Rainfall monitoring gauges

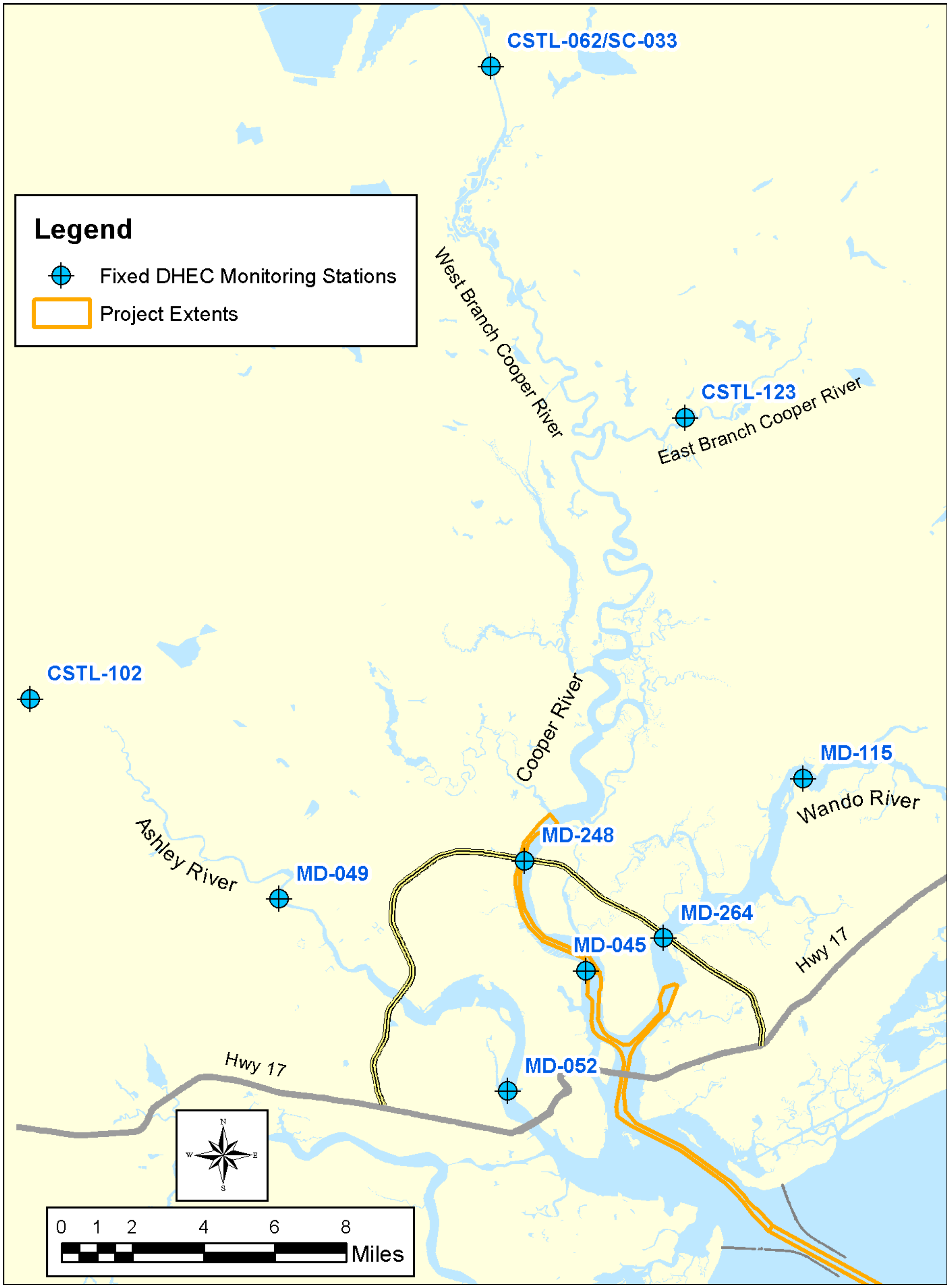

Figure 2-12. SCDHEC fixed water quality monitoring stations

The variables that are potential explanatory variables for DO concentrations in the estuary include BOD5, ammonia nitrogen and TKN. WEC reviewed the monitoring data and found that BOD5 and ammonia nitrogen values are predominantly below practical quantification limit (PQL). Data with a large fraction of values below the PQL are much less useful for developing statistical models than data that has few observations below the PQL. TKN has good coverage and is more often above the PQL than ammonia and BOD5 measurements. Therefore, the TKN concentration data were used as an explanatory variable. The ambient TKN concentrations for each monitoring station are plotted in Appendix B.

2.2.6 Upstream Load

The Biological Services group at Santee Cooper collects monitoring data at Station SC-033 (located on the Tailrace canal just below Highway 52) on a monthly basis. They collect the following *in situ* data: DO, pH, temperature and conductivity. They also collect samples analyzed by their in-house laboratory for: turbidity, color, alkalinity, bacteria, NH3, TKN, TP (total phosphorus), chlorides, fluorides, bromide, sulfate, nitrate, nitrite, solids data (TSS & TS), and various metals. SCDHEC also monitored Station CSTL-062 at the same location.

The UOD concentration at this boundary was estimated based on TKN from Station SC-033 and total organic carbon (TOC) measured at Station CSTL-062. Based on stoichiometric ratios, the relationship between UOD and these variables is:

$$UOD = 4.57\,TKN + 2.67\,TOC$$

The calculated UOD concentration is shown in Figure 2-13 along with the measured TKN and TOC concentrations. TOC data are not available after April 2009, and therefore the median concentration of 4.1 mg/l was used for the remainder of the time period, as shown by Figure 2-13. Also, TKN has not been reported at the SC-033 site since January 2016. There were three TKN measurements at CSTL-062 between September and November 2017 that were used in combination with the SC-033 data to fill in the end of the monitoring period.

Flow rates near the upstream boundary are monitored by a USGS continuous gauge (02172002 Lake Moultrie Tailrace Canal at Moncks Corner, SC). WEC calculated UOD mass loading rates based on the measured daily flow rates and the calculated UOD concentrations. The UOD loading rate estimates are plotted in Figure 2-14.

2.2.7 Meteorological Monitoring

In addition to rainfall monitoring, discussed previously, monitoring of other meteorological variables (including wind speed, wind direction and air temperature) is available at the two NWS monitoring stations shown in Figure 2-9, which includes the Charleston International Airport and downtown Charleston. Figures 2-15 and 2-16 show the air temperatures and wind speeds, respectively, measured at the Charleston International Airport.

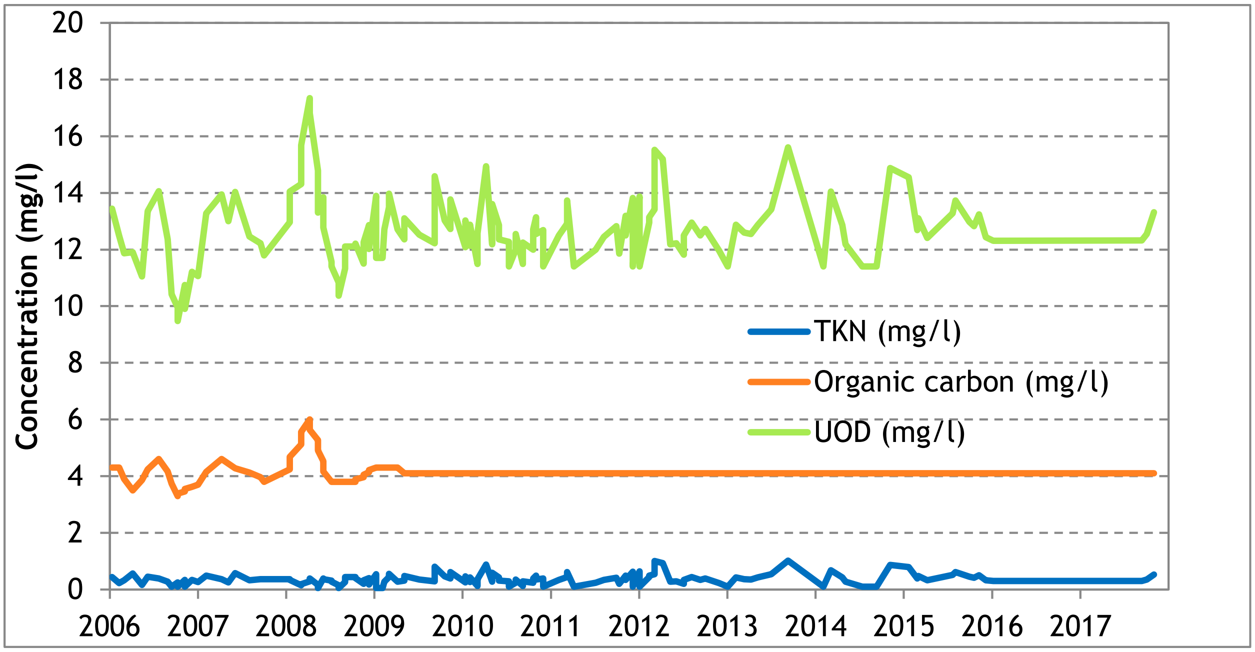

Figure 2-13. Upstream boundary UOD concentrations

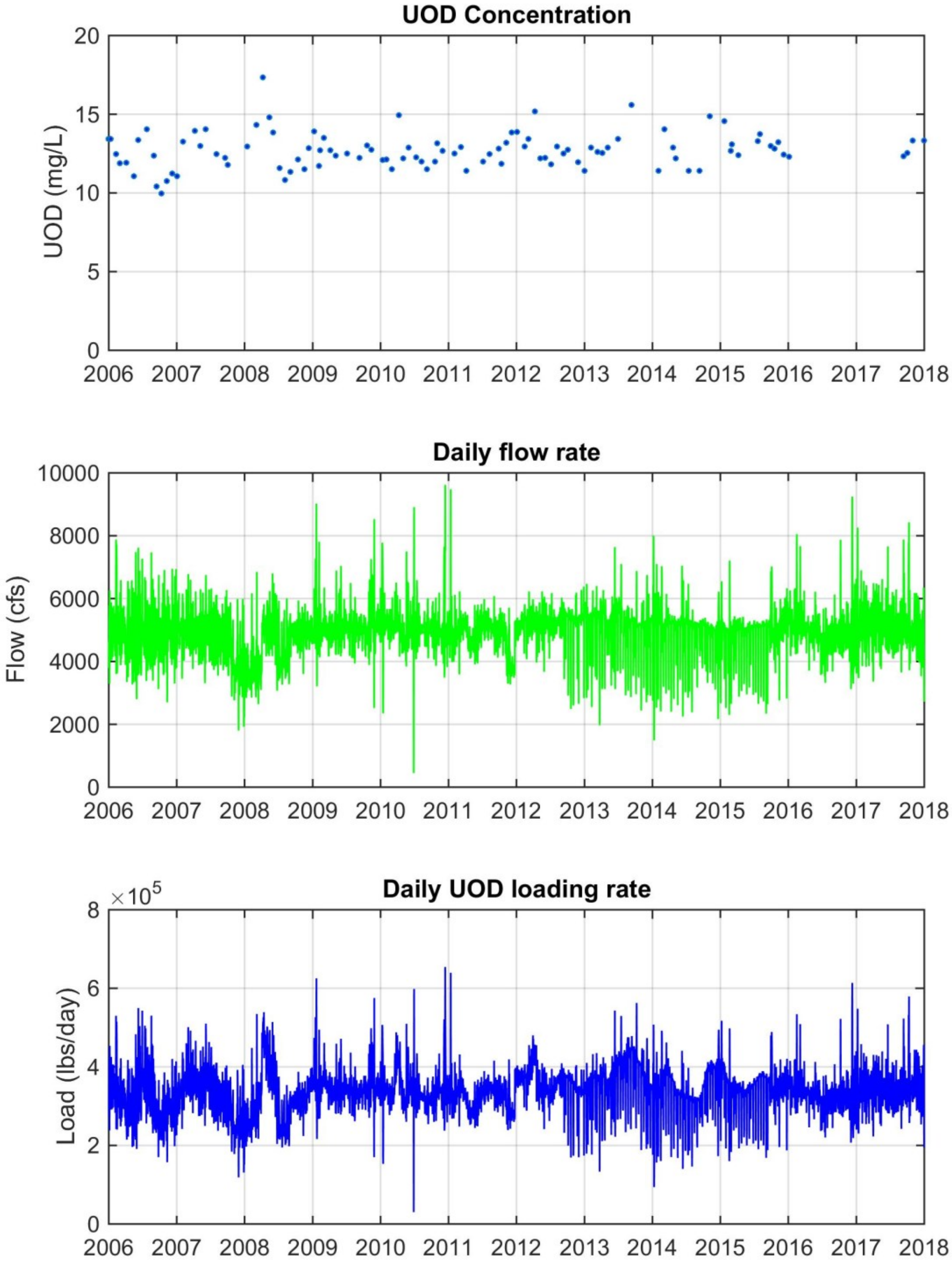

Figure 2-14. Upstream boundary flows and UOD concentrations and UOD loading rates

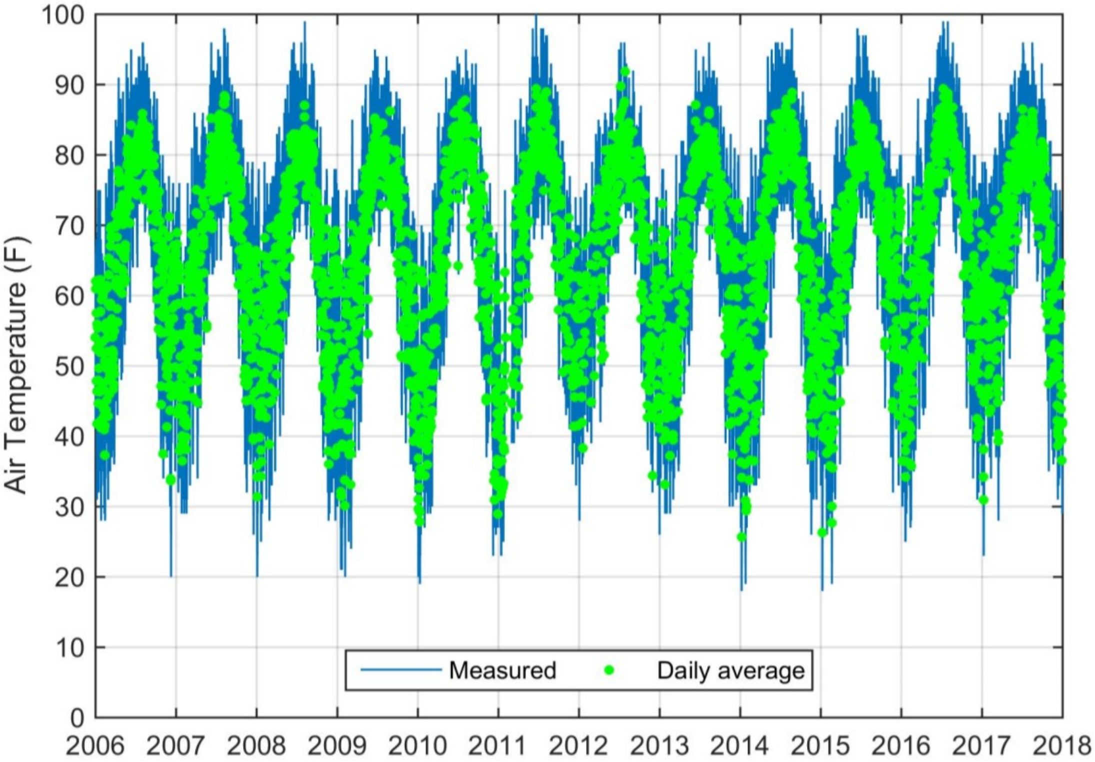

Figure 2-15. Charleston International Airport air temperatures

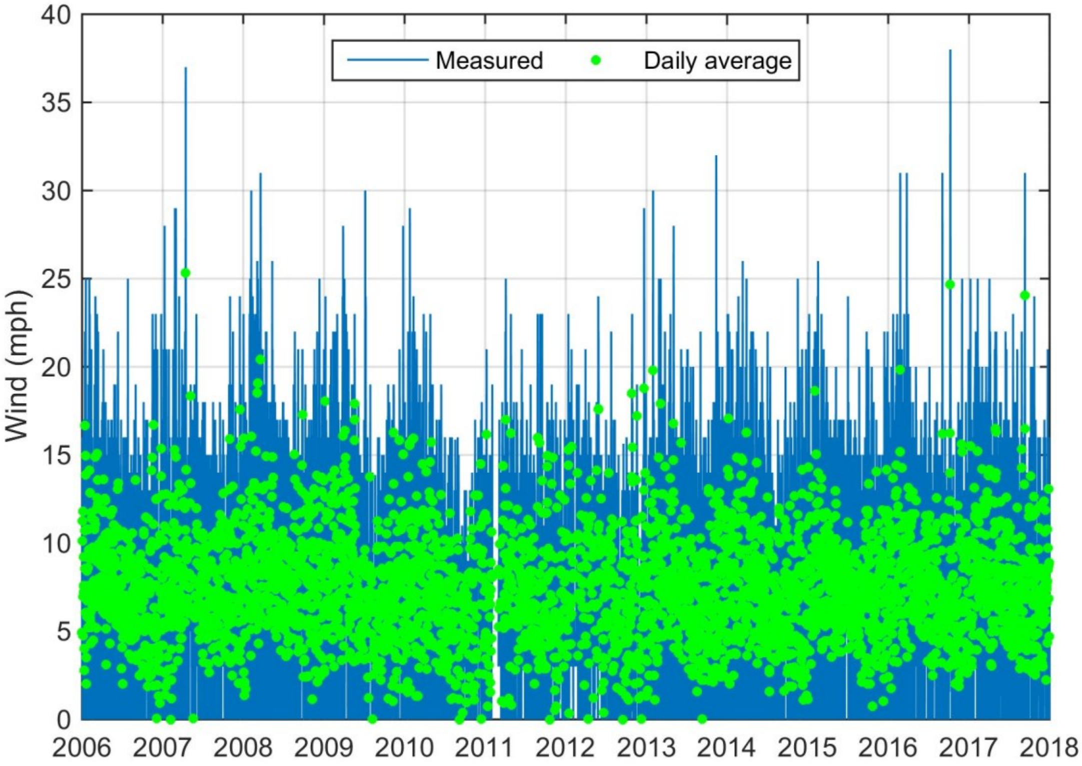

Figure 2-16. Charleston International Airport wind speeds

3 LSPC Watershed Modeling

To provide daily watershed runoff flow estimates, WEC modified the calibrated LSPC watershed model to simulate watershed flows for the period from 2006 through 2017. Refer to Tetra Tech and Jordan, Jones, and Goulding (2008) for a complete description of the LSPC watershed model setup for the Charleston Harbor Estuary DO TMDL. The LSPC watershed modeling system includes algorithms for simulating hydrology, sediment, and general water quality on land as well as a simplified stream transport model. For the purposes of this analysis, the water quality component of LSPC was not used, and the model was only used to estimate watershed hydrology. The following subsections describe the revisions to the model for this study and the resulting estimates of watershed flows.

3.1 Model Update

3.1.1 Watershed Delineation

Figure 3-1 shows the watershed sub-basins used for the DO TMDL model. In this analysis, for the purpose of processing the LSPC model output and summing the total flows to each river, the sub-basins have been grouped into four watershed areas: Ashley River, Cooper River, Wando River and Harbor. The LSPC model input sub-basin delineations and areas were not changed from those established for the DO TMDL model study.

3.1.2 Land Use Data

In the DO TMDL model, watershed land use activities were defined for each sub-basin based on the 2001 Multi-Resolution Land Characteristics database. Land use for each basin was aggregated within the categories used by LSPC, including: barren land, cropland, forested areas, pasture, strip mining, urban pervious, wetlands, and urban impervious. For this analysis, the land use data input to the model were updated based on the 2011 NLCD. The NLCD is updated every four years, and the 2011 data set is assumed to be representative of the average conditions for the 2006 through 2017 time period.

3.1.3 Meteorological Inputs

LSPC calculates hydrologic conditions based on input precipitation and evapotranspiration rates in the watershed. The TMDL model used only the Charleston International Airport for input precipitation data. The LSPC model was updated for the pre-project monitoring time period (2006 through 2017) using available precipitation data at the five meteorological stations shown in Figure 3-1. Precipitation monitoring data includes daily rainfall data at:

- Charleston International Airport (NWS);
- Berkeley County Airport (NWS);
- Turkey Creek above Huger (USGS);
- Witherbee (RAWS); and
- Wambaw (RAWS).

WEC calculated evaporation rates based on the meteorological data at these stations using the Environmental Protection Agency's (EPA's) Better Assessment Science Integrating Point and Nonpoint Sources BASINS software package.

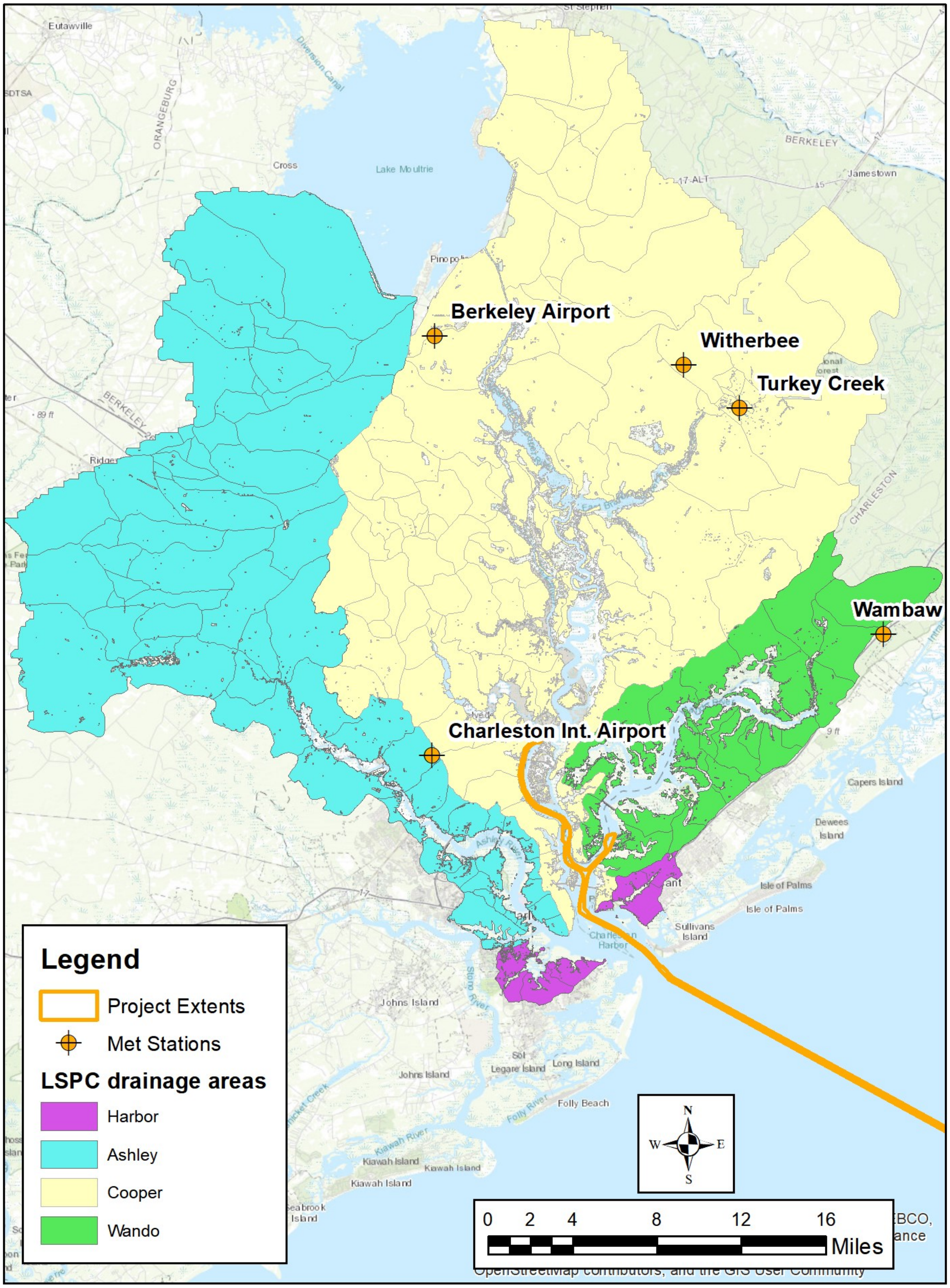

Figure 3-1. LSPC model drainage areas and meteorological stations

3.2 Model Calibration

The updated model calibration was checked by comparing modeled flows to available measured non-tidal freshwater flow data, which is limited to flows in Turkey Creek (USGS gauge 02172035), a tributary to the East Branch Cooper River. The Turkey Creek gauge location is shown in Figure 3-1.

The model hydrologic variables are listed in Table 3-1. This table includes the values used for the TMDL study, as well as the revised values used for this study. Figure 3-2 shows the modeled monthly flows in Turkey Creek using the TMDL model variables prior to re-calibration, and Figure 3-3 shows daily flows from the same model. As shown by these figures, the modeled base flow is too high, and the modeled peak flow rates are too low.

The model calibration was adjusted to increase runoff, decrease infiltration and decrease interflow rates. The resulting modeled monthly flows in Turkey Creek are shown in Figures 3-4, and daily flows are shown in Figures 3-5 and 3-6.

3.3 Model Results

The revised LSPC model was used to model daily flow rates in the three river basins for the period between 2006 and 2017. The resulting aggregated daily flows in each river basin are shown in Figures 3-7 and 3-8.

Table 3-1. Watershed model variables

Variable ID	Variable Description	TMDL Model Values	Revised Values
agwetp	Fraction of remaining potential ET that can be satisfied from active groundwater	0.007	0.2
agwrc	Base groundwater recession	0.99	same
agws	Initial active groundwater storage	0.01	same
basetp	Fraction of remaining potential ET that can be satisfied from baseflow	0.05	0.2
ceps	Initial interception	0.01	same
cepsc	Interception storage capacity (inches) –varied monthly	0.01-0.13	same
deepfr	Fraction of groundwater inflow that will enter deep groundwater	0	same
gwvs	Initial index to groundwater slope	0.01	same
ifws	Initial interflow storage	0.01	same
infexp	Exponent in the infiltration equation	1	2
infild	Ratio between the maximum and mean infiltration Capacities over the PLS	1	2
infilt	Index to the infiltration capacity of the soil (in/hr)	0.01-0.3	0.001-0.018
intfw	Interflow inflow parameter	3	same
irc	Interflow recession parameter	0.6	0.7
kvary	Variable groundwater recession (1/in)	0	same
lzetp	Lower zone ET parameter –varied monthly	0.2-0.65	0.25-0.72
lzs	Initial lower zone storage	1.5	same
lzsn	Lower zone nominal soil moisture storage (inches)	1-3.5	2.25-7.88
nsur	Manning's for the assumed overland flow plane	0.1-0.35	same
petmax	Air temperature below which ET is reduced (°F)	40	same
petmin	Air temperature below which ET is zero (°F)	35	same
surs	Initial surface (overland flow) storage	0.01	same
uzs	Initial upper zone storage	0.3	same
uzsn	Upper zone nominal storage (in) –varied monthly	0.2-0.8	0.3-1.1

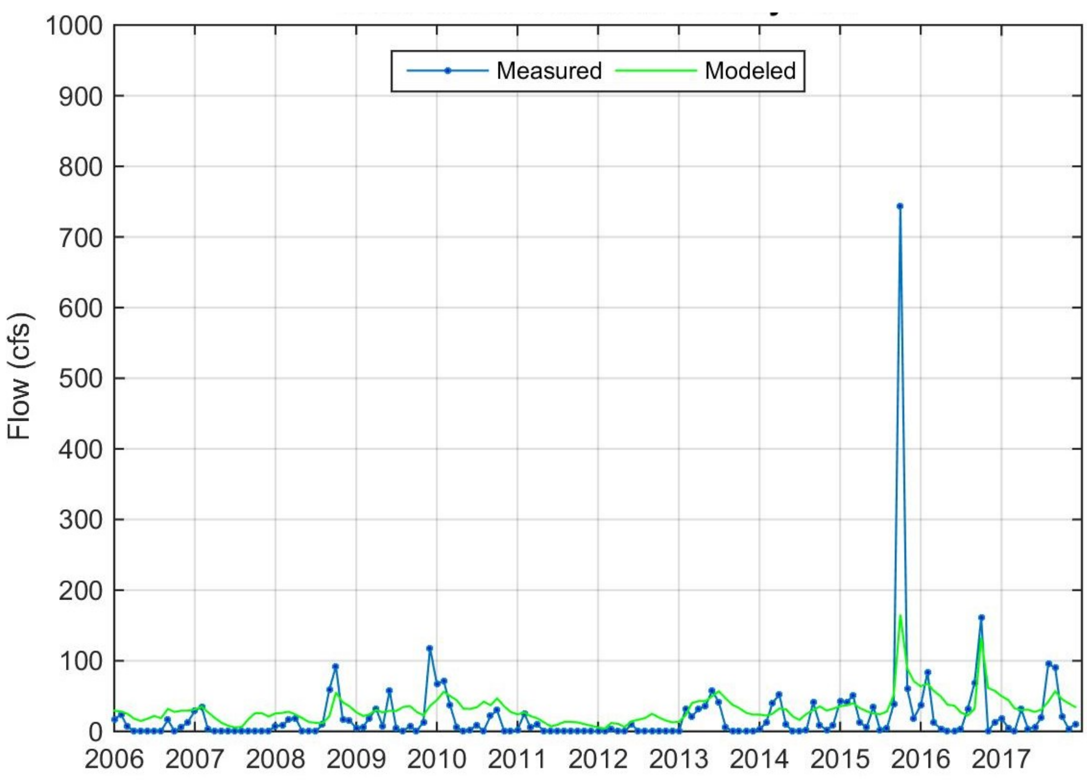

Figure 3-2. Modeled and measured monthly flows at Turkey Creek prior to recalibration

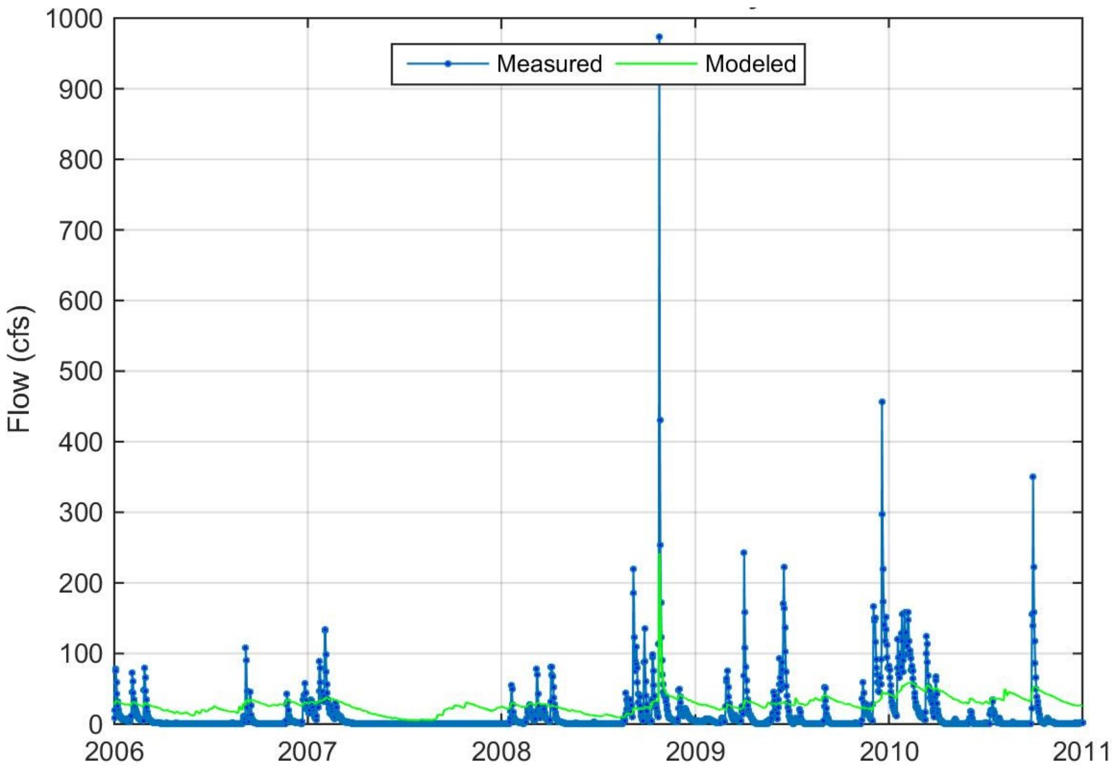

Figure 3-3. Modeled and measured daily flows at Turkey Creek prior to recalibration, 2006-2010

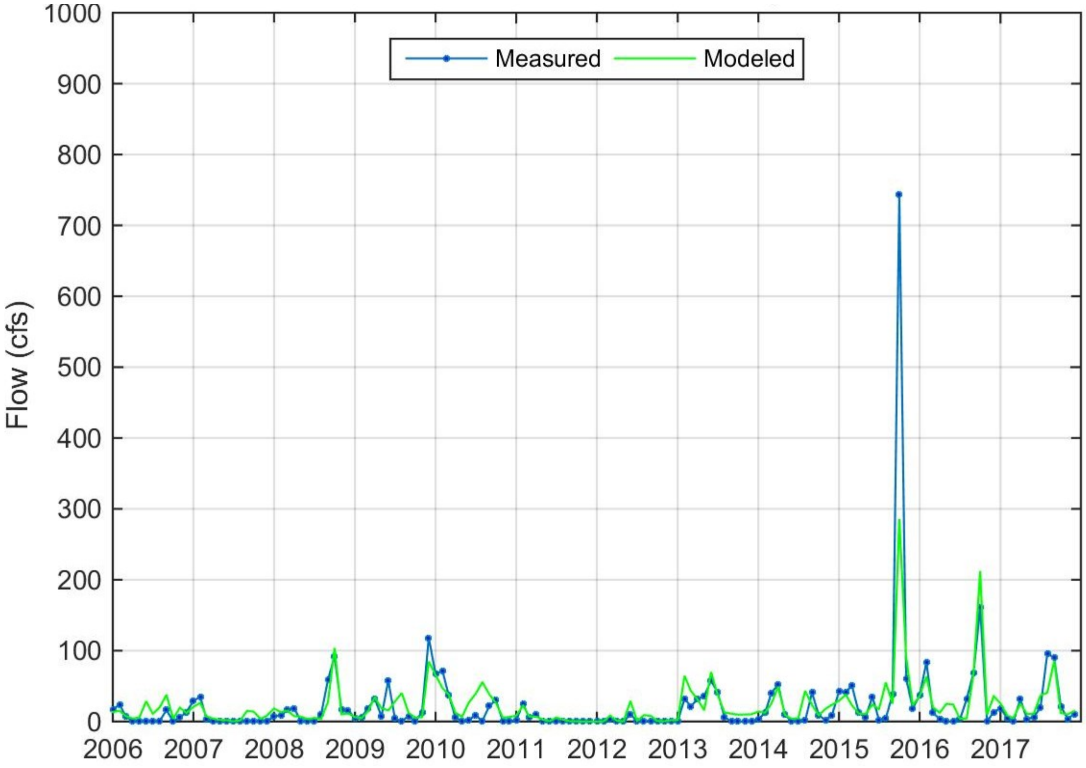

Figure 3-4. Revised modeled and measured monthly flows at Turkey Creek

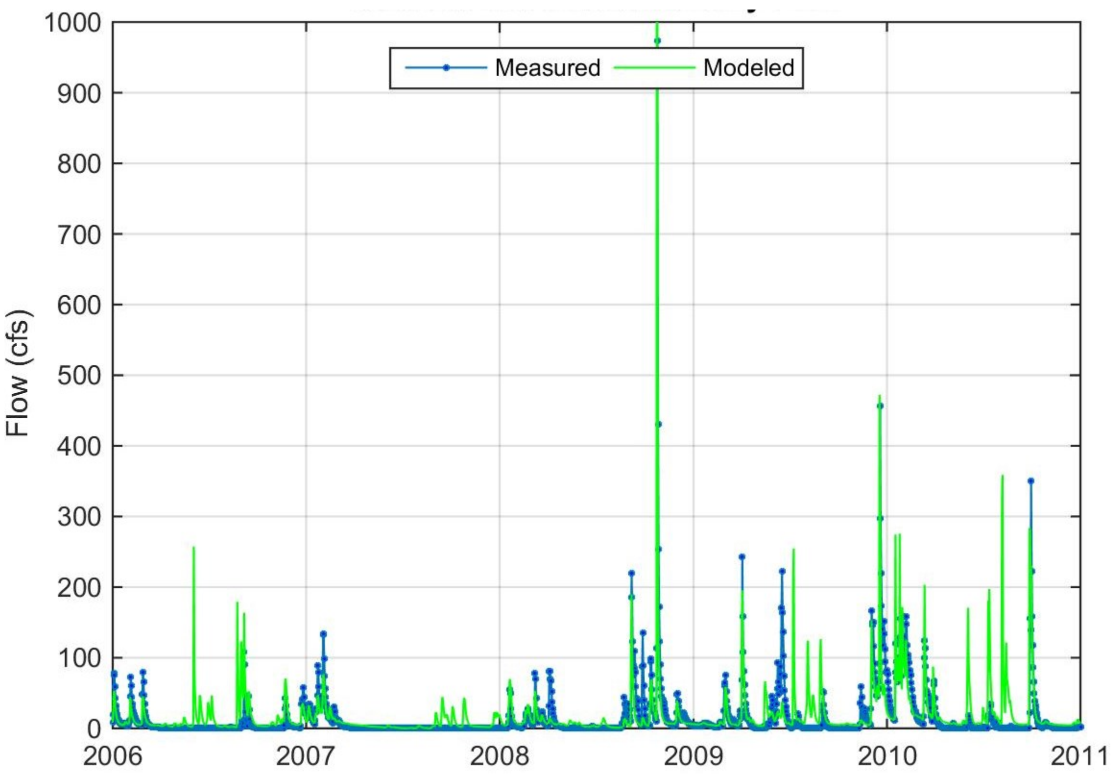

Figure 3-5. Revised modeled and measured daily flows at Turkey Creek, 2006-2010

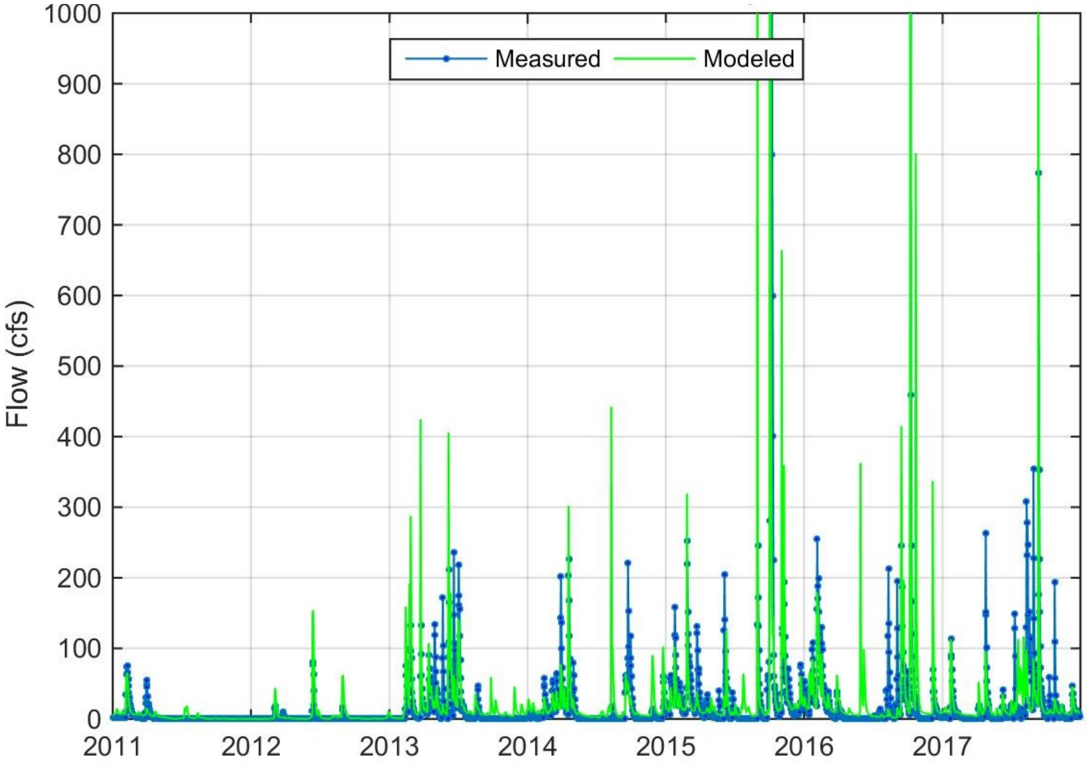

Figure 3-6. Modeled and measured daily flows at Turkey Creek, 2011-2017

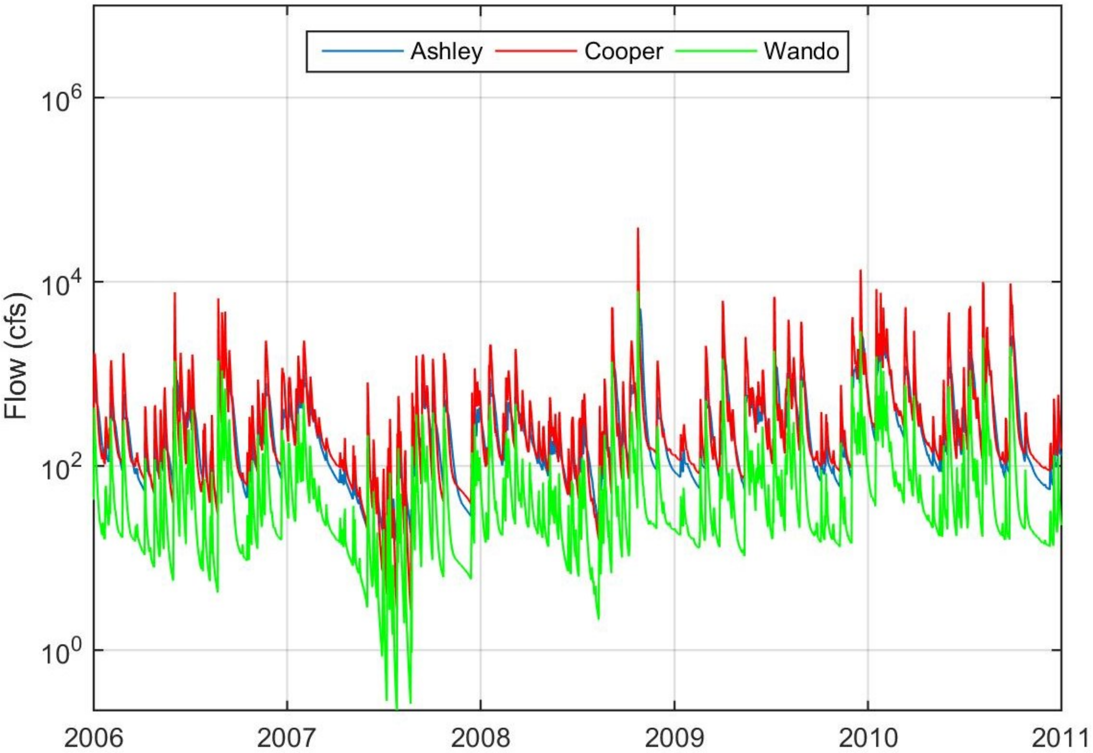

Figure 3-7. Modeled flows for each river basin, 2006-2010

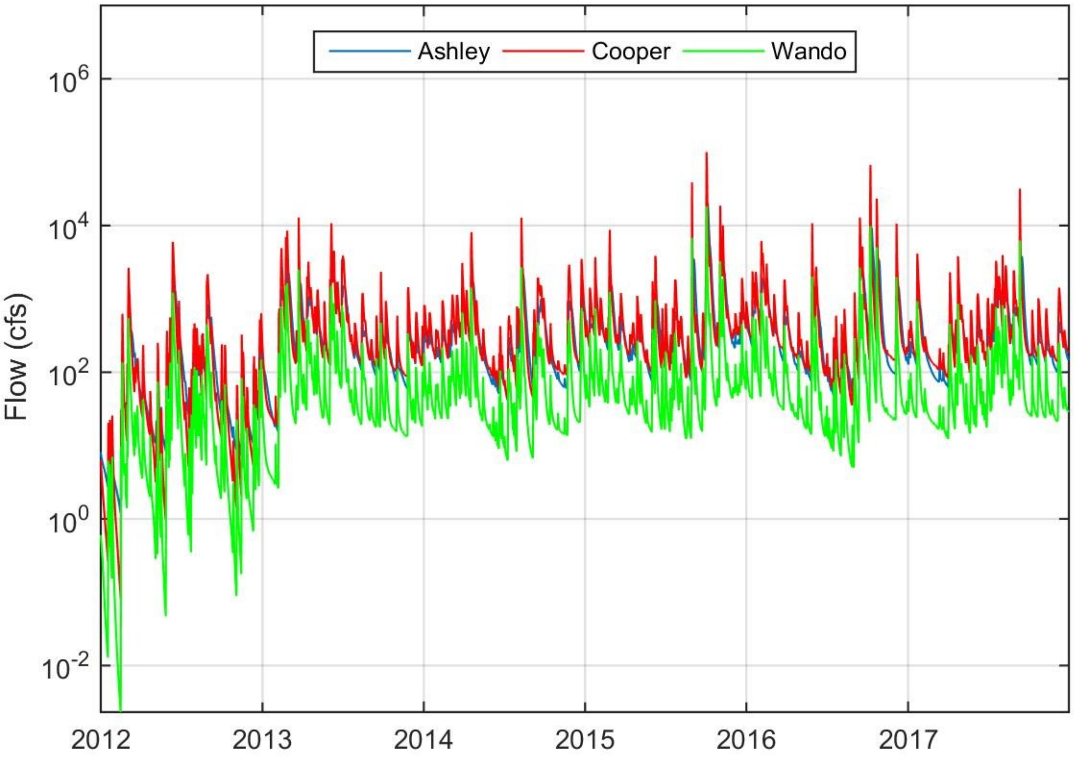

Figure 3-8. Modeled flows for each river basin, 2011-2017

4 Statistical Analysis

Following project construction, changes caused by the Post 45 project on estuary DO and salinity will be evaluated by using statistical models to separate out the project impacts from the effects caused by other factors (i.e., explanatory variables). This will be doing using regression models of effects from the explanatory variables listed in Table 2-1. These statistical models were created using pre-project monitoring data of explanatory variables and observed DO and salinity in the project impact area. Given the input explanatory variables (e.g., offshore water level, upstream flow, etc.) the statistical models provide estimates of the DO and salinity in the project impact area. Following the Post 45 Project construction and collection of the after-project monitoring data, the statistical models will then be used to estimate the DO and salinity in the project impact area that would have occurred had the project not been constructed. These results will be compared to the measured after-project DO and salinity in order to quantify the project impacts.

The sections below describe the development of the regression models for each of the 11 impact monitoring locations (i.e., the USGS gauges listed in the Table 2-1). In addition, based on the regression analyses, WEC estimated what minimum amount of project-induced change might be detected at each location using the monitoring data and statistical models.

WEC used the R statistical analysis software package to develop the regression models. When importing the data for the explanatory variables and the DO monitoring data in the project impact area to the software, WEC assigned the abbreviated variable names listed in Table 4-1. The sections below will reference these R variable names for brevity.

4.1 DO Analysis

WEC used the R software to develop regression models to predict 10th percentile of daily mean DO concentrations during the March through October time period. Evaluation of the 10th percentile daily mean DO for the March through October time period is consistent with the goal of the DO TMDL methodology, which is to evaluate impacts during warm water, low DO conditions. The evaluation used a variation of regression called quantile regression (QR). It is analogous to a typical linear regression model procedure except that instead of estimating the mean of the response variable Y, a percentile (quantile) of the Y variable is estimated. In the following discussions, the regression response variable Y is the daily mean DO in the project impact area, and the explanatory variables are referred to as the X variables. The R packages used include: Rcmdr, quantreg, and lubridate. WEC used the “rq” function with a tau value of 0.5 to predict the median DO value. Then, the 10th percentile value of the daily DO predictions was calculated for the March through October time period for each year. Low DO concentrations are the issue of concern, and therefore the R script “Tol_low2.R” provided by Dr. Helsel was used to calculate the lower confidence limit (LCL) below the predicted 10th percentile.

The following subsection provides a detailed description of the development of a regression model for DO concentrations in the Cooper River at Filbin Creek at I-526, which was identified as an area of concern in the Feasibility Study. WEC used similar processes to develop regression models at the other

Table 4-1. Monitoring variable labels used in R

Variable Type	Monitoring Variable	Variable in R
Offshore conditions	Water Level (ft)	WaterLevel
	Tide range (ft)	TideRange
	Salinity (ppt)	Salinity
	Temp (F)	Temp
	DO Saturation (mg/l)	DOSat
Upstream inflows at Pinopolis	Temp (C)	TempC
	DO (mg/l)	DO
	Flow (cfs)	Flow.cfs
	Upstream Load (lbs/day)	UpstreamLoadBOD
Met. Conditions	Wind Speed (mph)	WindSpeed
	Air Temp (F)	AirTempF
Watershed Inflows	Ashley Flow	AshleyFlow
	Cooper Flow	CooperFlow
	Wando Flow	WandoFlow
NPDES Point Source Loads	Ashley (lb/d UOD)	Ashley.UOD
	Cooper (lb/d UOD)	Cooper.UOD
	Harbor (lb/d UOD)	Harbor.UOD
Instream TKN Concentrations	MD-052	MD_052
	MD-045	MD_045
	MD-248	MD_248
	MD-264	MD_264
	MD-115	MD_115
	MD-049	MD_049
	CSTL-102	CSTL_102
	CSTL-123	CSTL_123
Impact Areas for Dissolved Oxygen	Ashley R. below Summerville	AshleyRbelowS
	Ashley R. nr North Charleston at I-516	AshleyRnrNCHS
	Cooper R. nr Goose Cr	CooperRnrGC
	Cooper R. at Filbin Cr. @ I-526	CooperR_at._I526
	Cooper R. at Pier K, surface	CooperRatPier Ksur
	Cooper R. at Pier K, bottom	CooperRatPier Kbot
	Cooper R. at US 17, mid-depth	CooperRat17mid
	Cooper R. at US 17, bottom	CooperRat17bot
	Wando R. above Mt. Pleasant at I-526, mid-depth	WandoRaboveMPmid
	Wando R. above Mt. Pleasant at I-526, bottom	WandoRaboveMPbot
	Wando R. at Cainhoy	WandoRatCain
Impact Areas for Salinity	Ashley R. below Summerville	AshleyRbelowS
	Ashley R. nr North Charleston at I-516	AshleyRnrNCHS
	Cooper R. at Pimlico	Pimlico
	Cooper R. above Goose Cr	CooperRaboveGC
	Cooper R. at Mobay	Mobay

Table 4-1. Monitoring variable labels used in R

Variable Type	Monitoring Variable	Variable in R
Impact Areas for Salinity	Cooper R. nr Goose Cr	CooperRnrGC
	Cooper R. at Filbin Cr. @ I-526	CooperRatI526
	Cooper R. at Pier K, surface	CooperRatPier Ksur
	Cooper R. at Pier K, bottom	CooperRatPier Kbot
	Cooper R. at US 17, mid-depth	CooperRat17mid
	Cooper R. at US 17, bottom	CooperRat17bot

project impact monitoring locations, and the resulting regression models for those locations are also provided.

4.1.1 DO Regression Modeling

If there are two strongly correlated explanatory variables, then only one of the two should be used in a regression. Both are not needed, because they model the same effect, and including both correlated variables decreases quality and increases error of the regression model estimates. Regression assumes independence of all explanatory variables – variables must not be strongly correlated with each other. Both DOSat and upstream DO are highly correlated, which is unsurprising (Figure 4-1). Because DOSat has more monitoring data, the upstream DO variable was dropped from the analysis.

Temp and TempC are even more strongly correlated (Figure 4-2). Because Temp has more data, the TempC variable was dropped from the analysis.

The first step of the model regression process is to determine if transformation of the Y variable is necessary. To do this, all of the remaining possible explanatory variables were put into a linear regression model, and the model residuals were plotted using three common types of residuals plots: a residuals vs. fitted plot to judge linearity (Figure 4-3); a Q-Q plot of residuals to judge normality (Figure 4-4); and scale-location plot to judge changing variance (the Y variable on this plot is the standard deviation) (Figure 4-5). The latter two involve the Y variable directly. For linear regression models, if data appear to be non-normal it can inflate *p*-values, causing important variables to be dropped from the regression model equation. The same effect is shown by increasing variance of residuals (shown as an upslope on the scale-location plot).

There is no upslope in Figure 4-5, so the residuals look like they have reasonably constant variance. Figure 4-4 shows the residuals follow a normal distribution in the middle predominant part. The residuals in Figure 4-4 are symmetric (the departures are on differing sides of the line in the upper and lower ends) though they are not a normal distribution. The boxplot in Figure 4-6 shows this clearly. No transformation of the Y variable would be helpful because the residuals are not skewed.

The next step in the regression model development process is to look for curvature in the relationships with the X variables. This is done with “component plus residuals plots” (crPlots), as shown in Figure 4-7 through 4-9 for each of the model X variables. The three flow variables have a smooth (pink line) that

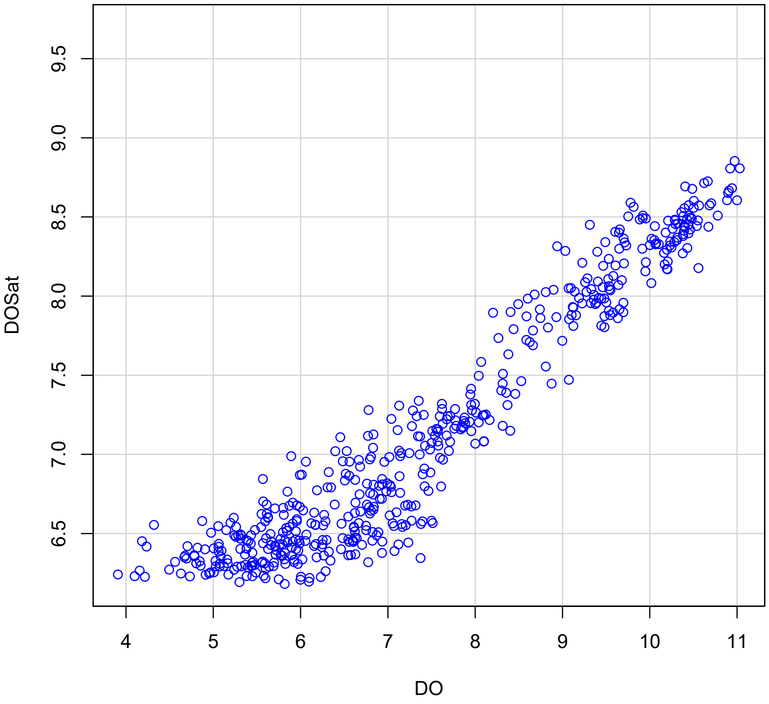

Figure 4-1. Offshore DO saturation versus upstream DO

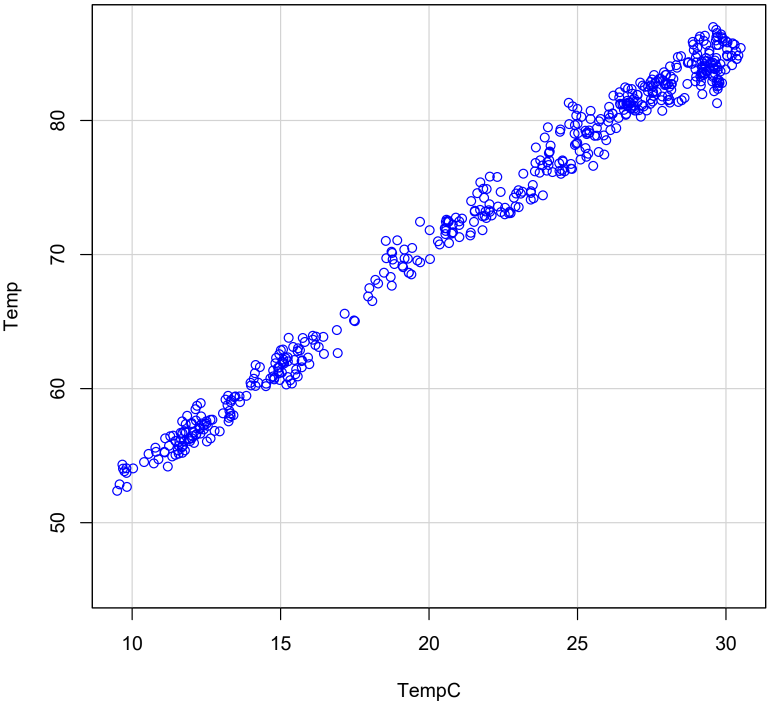

Figure 4-2. Offshore temperature versus upstream temperature

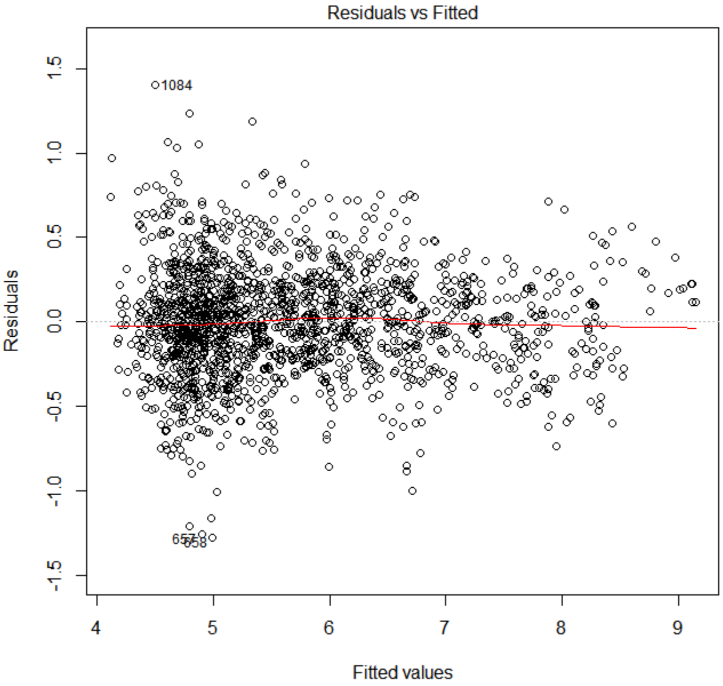

Figure 4-3. Residuals versus fitted plot for DO linear regression model

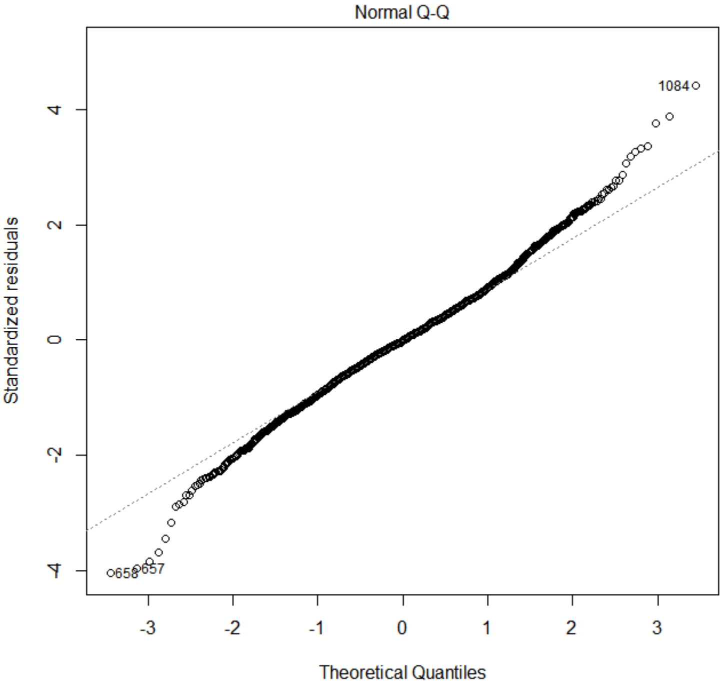

Figure 4-4. Normal Q-Q plot for DO linear regression model

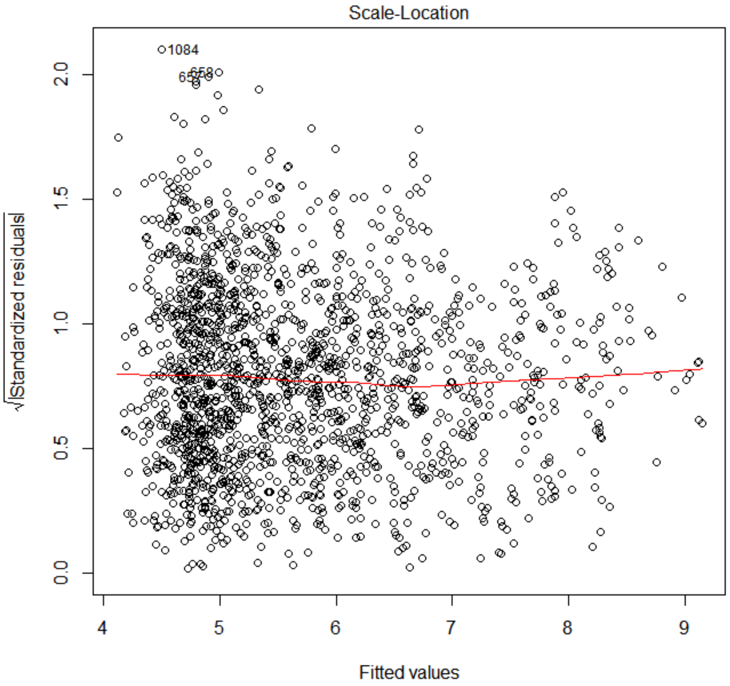

Figure 4-5. Scale-location plot for DO linear regression model

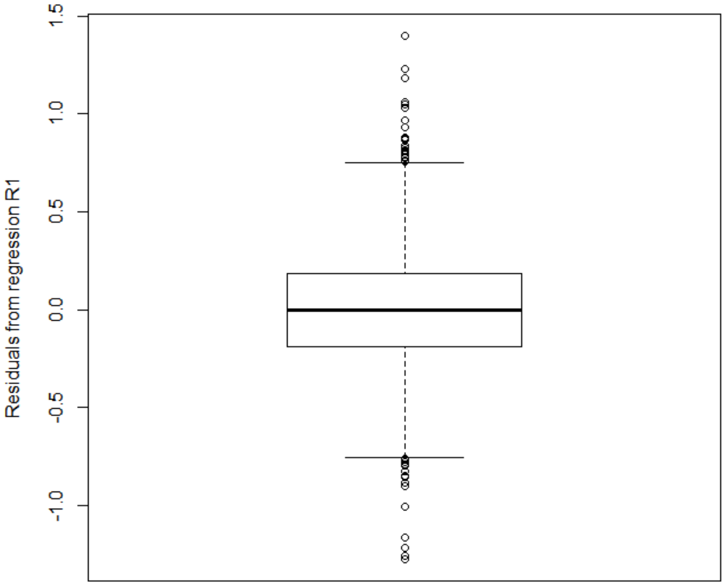

Figure 4-6. Boxplot of residuals from DO linear regression model

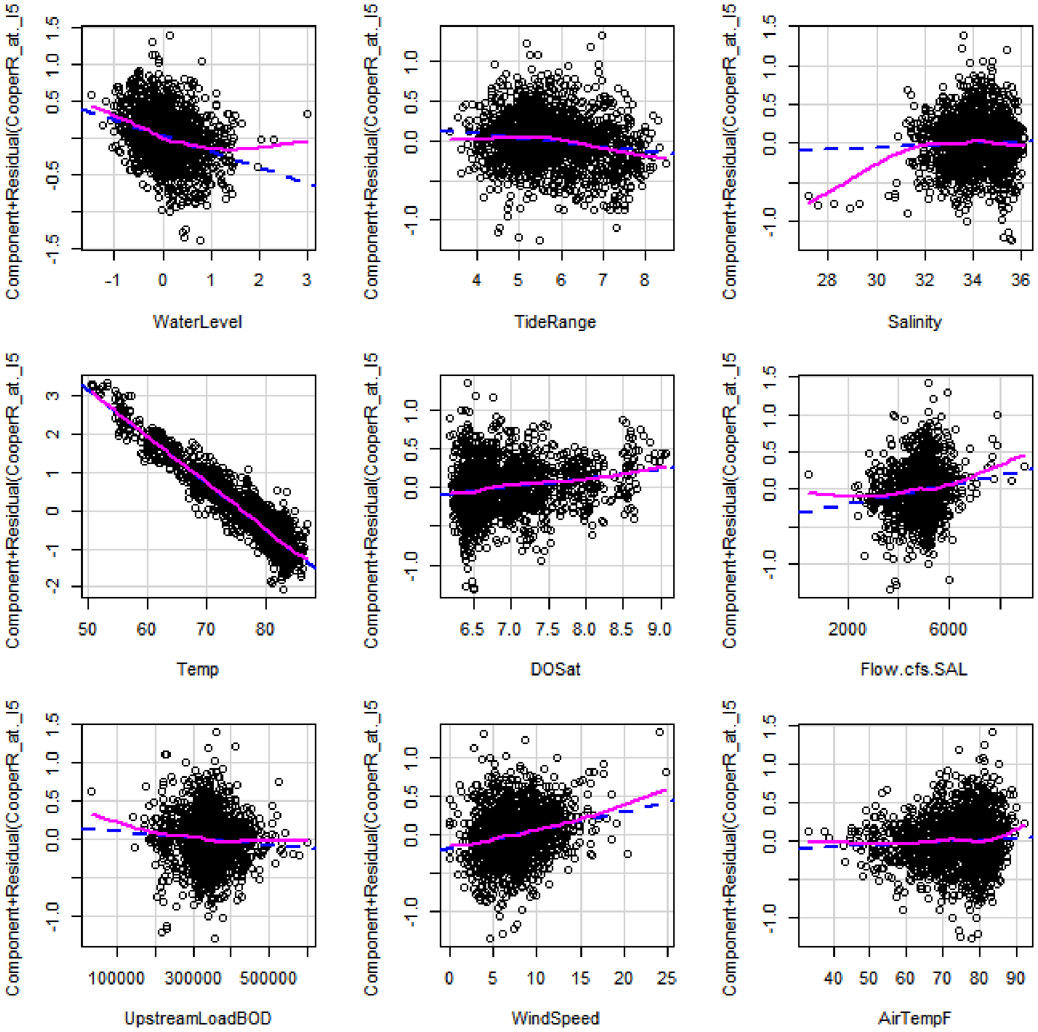

Figure 4-7. crPlots for DO linear regression model

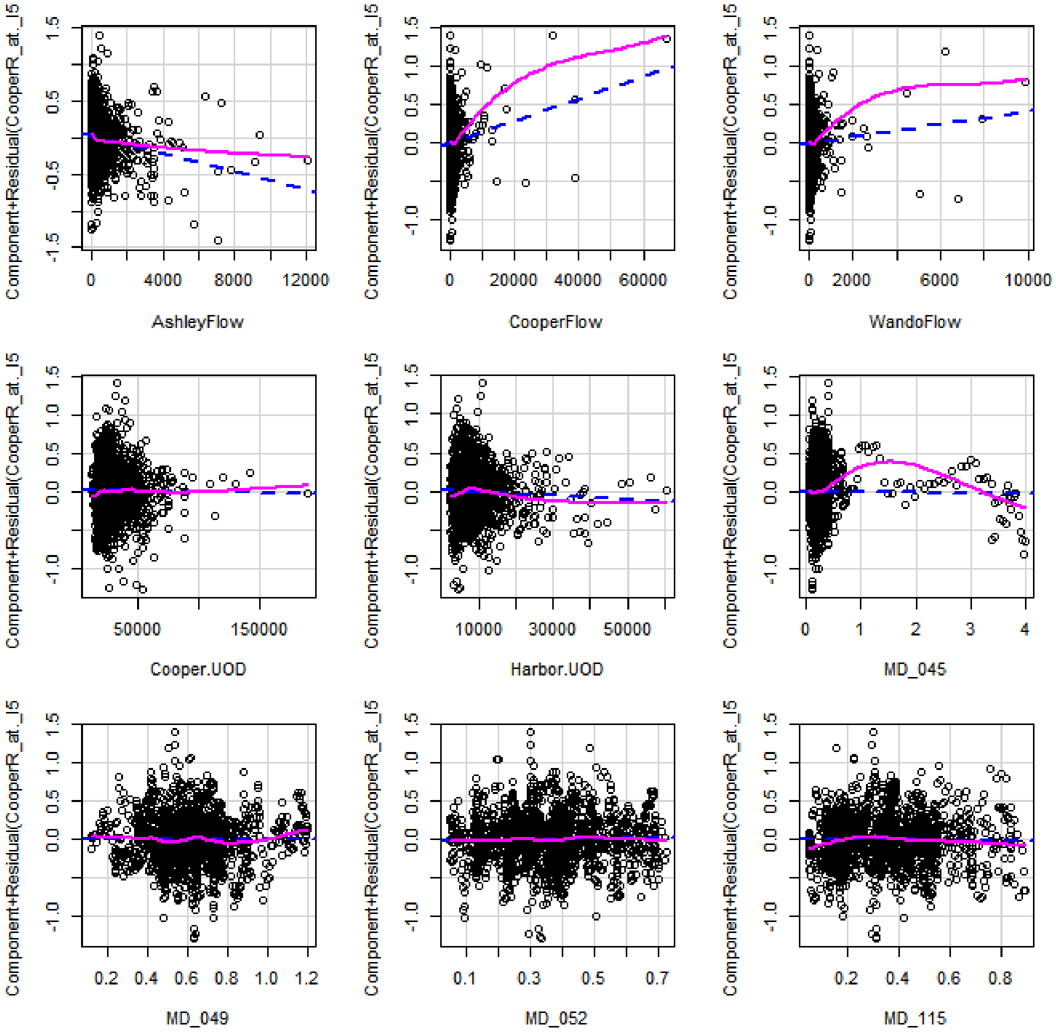

Figure 4-8. crPlots for DO linear regression model (continued)

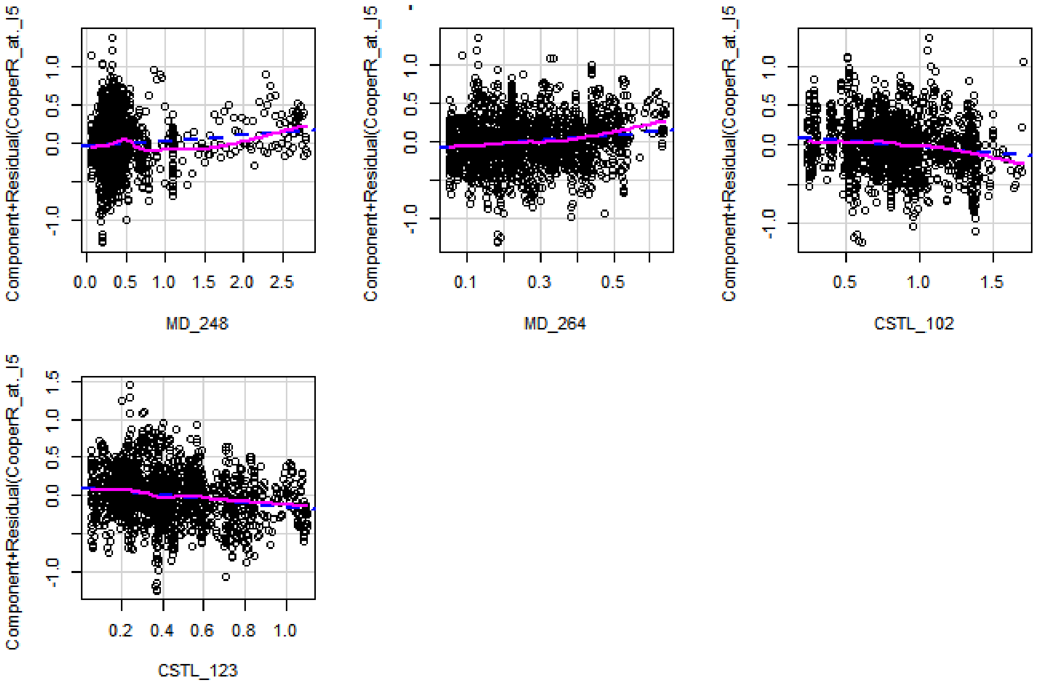

Figure 4-9. crPlots for DO linear regression model (continued)

isn't similar to the straight-line dashed lines representing the regression equation. Therefore, the three flow variables were log transformed to straighten the relationship. The relationship with MD_045 is strange too, so it was also log-transformed. The two UOD variables have all values grouped to the left, so a log was used to help those variables not be dominated by their highest values.

The logged variables replace the original variables in the next regression equation. crPlots of the model with the logged variables show improved relationships (Figure 4-10).

WEC created an initial QR model with the logged variables, which produced the regression model coefficients listed in Table 4-2. The model was then improved by eliminating the least significant X variables. The criterion we used to select the variables to eliminate is the Bayesian information criterion (BIC) statistic. This evaluates which of the X variables to use in a "cost-benefit" type of analysis. Better models have lower BIC. The X variables with the highest *p* values were dropped from the model to determine if it resulted in a lower BIC. If dropping a variable resulted in a higher BIC, it was added back into the model. The final QR model coefficients are shown in Table 4-3. All 13 remaining explanatory variables are significant.

QR models for the other DO monitoring locations in the project impact area were developed using a similar process. The QR model coefficients for these locations are listed in Appendix C.

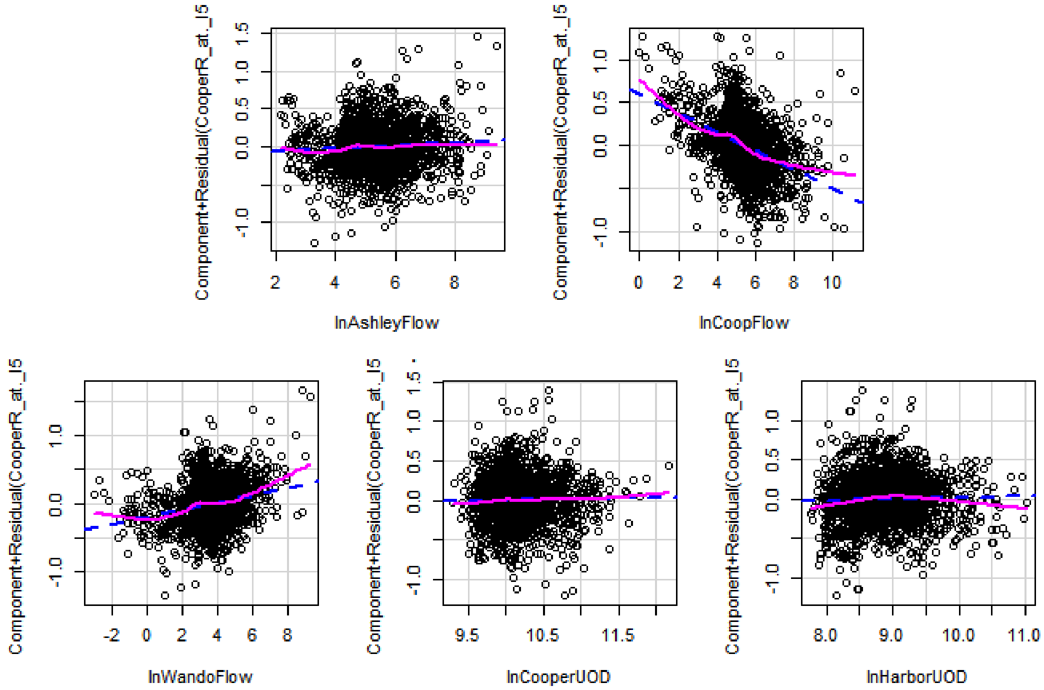

Figure 4-10. crPlots for logged variables in DO linear regression model

4.1.2 Minimum Level of Detectable Change in DO

Using the QR model, WEC predicted 10th percentiles of DO for each year during the March-October period. These modeled values are compared to observed 10th percentile DO values in Table 4-4. The variation around the annual 10th percentile depends on the number of daily observations. That has varied each year, as shown by the “days used” column in Table 4-4. The “days used” for the model comparisons depends on the number of days in the March through October time period that all of the X variables and Y variable have measured values (out of a maximum of 245 possible days). Any days with missing X or Y observations means that day can’t be used for model comparison to observed data. The differences in annual 10th percentile DO values are listed in the “Delta” column, which ranges between 0.01 and 0.24 mg/l and averages 0.10 mg/l. The difference is greater than 0.15 mg/l in one out of ten years. Based on this analysis, the predicted 10th percentile DO should be within 0.15 mg/l of the true value for the Cooper River at Filbin Creek location.

As discussed previously, the regression model will be used in the future to predict the annual 10th percentile DO for conditions in the post-project period (based on the observed explanatory variables) but without the effects of the project. The difference between the observed 10th percentile DO and the predicted 10th percentile DO is the estimate of project effects. At the Filbin Creek location, the predicted annual March - October 10th percentile DO was within ± 0.15 mg/L of the observed value 90% of the time, and therefore, we expect a similar variability of the predicted post-project estimate of the 10th percentile DO without project effects.

Table 4-2. Initial QR model coefficients

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	7.92845	2.63342	3.0107	0.00264
WaterLevel	-0.17871	0.0147	-12.1586	0
TideRange	-0.05516	0.00686	-8.04373	0
Salinity	0.01276	0.0114	1.11928	0.26318
Temp	-0.08724	0.01379	-6.32521	0
DOSat	0.56805	0.19431	2.92344	0.00351
Flow.cfs	0.00005	0.00002	3.128	0.00179
UpstreamLoadBOD	0	0	-1.67314	0.09448
WindSpeed	0.0231	0.002	11.53863	0
AirTempF	0.0012	0.00122	0.98443	0.32504
MD_049	0.0127	0.05273	0.24086	0.80969
MD_052	-0.07929	0.06747	-1.17523	0.24007
MD_115	0.0419	0.05774	0.72568	0.46813
MD_248	0.05217	0.01551	3.36365	0.00079
MD_264	0.31896	0.06115	5.21638	0
CSTL_102	-0.12368	0.02711	-4.56214	0.00001
CSTL_123	-0.27508	0.05324	-5.16662	0
lnAshleyFlow	-0.02229	0.01588	-1.40335	0.16069
lnCoopFlow	-0.06223	0.02843	-2.18886	0.02874
lnWandoFlow	0.04074	0.02253	1.80826	0.07074
lnCooperUOD	0.04945	0.01581	3.12855	0.00179
lnHarborUOD	-0.00385	0.01479	-0.26025	0.7947
lnMD_045	0.05596	0.01606	3.48566	0.0005

Table 4-3. Final QR model coefficients for DO at Cooper River at Filbin Creek and I-526

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	9.17193	1.78801	5.12968	0
WaterLevel	-0.1802	0.01105	-16.304	0
TideRange	-0.05312	0.00703	-7.55371	0
Temp	-0.09114	0.01019	-8.94259	0
DOSat	0.48371	0.1408	3.43541	0.00061
Flow.cfs	0.00003	0.00001	2.85511	0.00435
WindSpeed	0.02375	0.00188	12.61018	0
MD_248	0.05417	0.01937	2.79634	0.00523
MD_264	0.33381	0.06079	5.49114	0
CSTL_102	-0.10068	0.02267	-4.44164	0.00001
CSTL_123	-0.29237	0.0439	-6.65974	0
lnAshleyFlow	-0.0451	0.00402	-11.2269	0
lnCooperUOD	0.04814	0.01832	2.62748	0.00868
lnMD_045	0.04283	0.01276	3.35558	0.00081

Table 4-4. Modeled and observed 10th percentile DO concentrations for Cooper River at Filbin Creek at I-526

	Year	Observed (mg/l)	Predicted (mg/l)	Days used	Delta (mg/l)	Delta >0.15 mg/l	95th LCL (mg/l)
1	2008	4.59	4.74	184	0.15		4.70
2	2009	5.35	5.36	137	0.01		5.12
3	2010	4.38	4.46	164	0.09		4.40
4	2011	4.59	4.70	106	0.11		4.63
5	2012	4.73	4.81	153	0.08		4.76
6	2013	4.49	4.73	173	0.24	*	4.70
7	2014	4.42	4.55	216	0.13		4.50
8	2015	4.43	4.52	149	0.08		4.47
9	2016	4.38	4.46	241	0.07		4.39
10	2017	4.46	4.56	215	0.09		4.47
	Average	4.58	4.69		0.10		

Given that low DO is the issue of concern, WEC computed a one-sided 95% lower confidence limit (LCL) below the predicted 10th percentile. Dr. Helsel provided the Tol_low2.R script for this calculation (Appendix E). The LCL is a value that we are 95% confident that the 10th percentile will not go below, assuming nothing has changed. Table 4-4 includes the calculated LCL for each year.

Comparisons for the other project impact locations are shown in Tables 4-5 through 4-14. A summary of the model error estimates is provided in Table 4-15. For the locations with a 10-year record for comparison, the Table 4-15 error estimate is the annual March-October 10th percentile DO error not exceeded 90% of the time. For the locations with only two years of data for comparison, the Table 4-15 error estimate is the maximum error value between the two years, and a level of confidence for the error prediction is not provided for those short-term gauge locations. The error is also estimated as a percentage of the observed March-October 10th percentile DO at each location. The errors are less than 10 percent at each location, with the exception of the Ashley River near North Charleston at I-526, which has an error of 11%. At the long-term gage locations, which provide the most data to assess model performance, the error levels are between 0.15 mg/l (Cooper River at Filbin Creek at I-526) and 0.43 mg/l (Ashley River near North Charleston at I-526).

Table 4-5. Modeled and observed 10th percentile DO concentrations for Ashley R. below Summerville

	Year	Observed (mg/l)	Predicted (mg/l)	Days used	Delta (mg/l)	Delta >0.1 mg/l	95th LCL (mg/l)
1	2017	3.84	4.02	190	0.18	*	3.90
	Average	3.84	4.02		0.18		

Table 4-6. Modeled and observed 10th percentile DO concentrations for Ashley R. nr North Charleston at I-516

	Year	Observed (mg/l)	Predicted (mg/l)	Days used	Delta (mg/l)	Delta >0.43 mg/l	95th LCL (mg/l)
1	2008	4.01	4.35	196	0.35		4.29
2	2009	4.00	4.24	140	0.24		4.02
3	2010	3.45	3.74	166	0.29		3.65
4	2011	3.61	4.04	139	0.43		3.94
5	2012	3.83	4.20	164	0.37		4.11
6	2013	3.63	4.08	181	0.45	*	4.03
7	2014	3.70	3.75	200	0.05		3.70
8	2015	3.83	4.07	169	0.24		4.02
9	2016	3.76	4.04	230	0.28		3.95
10	2017	3.68	3.96	215	0.28		3.83
	Average	3.75	4.05		0.30		

Table 4-7. Modeled and observed 10th percentile DO concentrations for Cooper R. nr Goose Cr

	Year	Observed (mg/l)	Predicted (mg/l)	Days used	Delta (mg/l)	Delta >0.38 mg/l	95th LCL (mg/l)
1	2008	5.62	5.70	168	0.08		5.66
2	2009	5.68	5.92	148	0.24		5.76
3	2010	5.52	5.30	165	-0.22		5.19
4	2011	5.57	5.52	139	-0.05		5.43
5	2012	5.72	5.83	164	0.11		5.77
6	2013	4.83	5.56	181	0.73	*	5.54
7	2014	5.45	5.48	164	0.03		5.40
8	2015	5.36	5.44	169	0.08		5.38
9	2016	5.52	5.50	234	-0.03		5.47
10	2017	4.80	5.18	204	0.38		5.11
	Average	5.41	5.54		0.13		

Table 4-8. Modeled and observed 10th percentile DO concentrations for Cooper River at Pier K, surface

	Year	Observed (mg/l)	Predicted (mg/l)	Days used	Delta (mg/l)	Delta >0.1 mg/l	95th LCL (mg/l)
1	2016	4.58	4.58	122	-0.01		4.47
2	2017	4.63	4.65	215	0.01		4.56
	Average	4.61	4.61		0.00		

Table 4-9. Modeled and observed 10th percentile DO concentrations for Cooper River at Pier K, bottom

	Year	Observed (mg/l)	Predicted (mg/l)	Days used	Delta (mg/l)	Delta >0.1 mg/l	95th LCL (mg/l)
1	2016	4.43	4.39	122	-0.03		4.34
2	2017	4.22	4.25	215	0.03		4.14
	Average	4.32	4.32		0.00		

Table 4-10. Modeled and observed 10th percentile DO concentrations for Cooper River at US 17, mid-depth

	Year	Observed (mg/l)	Predicted (mg/l)	Days used	Delta (mg/l)	Delta >0.23 mg/l	95th LCL (mg/l)
1	2008	5.41	5.53	229	0.13		5.48
2	2009	5.48	5.59	159	0.11		5.47
3	2010	4.91	5.07	162	0.16		4.93
4	2011	4.97	5.10	134	0.13		5.03
5	2012	5.13	5.37	161	0.25	*	5.27
6	2013	5.09	5.32	175	0.23		5.29
7	2014	4.94	5.08	197	0.13		5.02
8	2015	5.03	5.23	160	0.20		5.10
9	2016	5.10	5.28	226	0.19		5.22
10	2017	4.98	5.16	215	0.19		5.04
	Average	5.10	5.27		0.17		

Table 4-11. Modeled and observed 10th percentile DO concentrations for Cooper River at US 17, bottom

	Year	Observed (mg/l)	Predicted (mg/l)	Days used	Delta (mg/l)	Delta >0.1 mg/l	95th LCL (mg/l)
1	2016	5.05	5.15	132	0.10		5.08
2	2017	5.09	5.26	21	0.17	*	5.11
	Average	5.07	5.20		0.13		

Table 4-12. Modeled and observed 10th percentile DO concentrations for Wando R. above Mt. Pleasant at I-526, mid-depth

	Year	Observed (mg/l)	Predicted (mg/l)	Days used	Delta (mg/l)	Delta >0.26 mg/l	95th LCL (mg/l)
1	2008	5.01	5.18	212	0.17		5.12
2	2009	5.59	5.57	119	-0.02		5.49
3	2010	4.71	4.75	164	0.04		4.63
4	2011	4.55	4.84	130	0.29	*	4.80
5	2012	4.99	5.16	155	0.17		5.09
6	2013	4.81	5.00	169	0.19		4.93
7	2014	4.67	4.83	216	0.16		4.70
8	2015	4.59	4.84	159	0.26		4.79
9	2016	4.78	4.98	236	0.20		4.89
10	2017	4.57	4.82	206	0.25		4.74
	Average	4.83	5.00		0.17		

Table 4-13. Modeled and observed 10th percentile DO concentrations for Wando R. above Mt. Pleasant at I-526, bottom

	Year	Observed (mg/l)	Predicted (mg/l)	Days used	Delta (mg/l)	Delta >0.1 mg/l	95th LCL (mg/l)
1	2016	4.34	4.56	102	0.22	*	4.39
2	2017	4.50	4.54	206	0.04		4.46
	Average	4.42	4.55		0.13		

Table 4-14. Modeled and observed 10th percentile DO concentrations for Wando R. at Cainhoy

	Year	Observed (mg/l)	Predicted (mg/l)	Days used	Delta (mg/l)	Delta >0.1 mg/l	95th LCL (mg/l)
1	2016	3.93	4.12	129	0.20	*	4.05
2	2017	3.89	3.89	193	0.00		3.76
	Average	3.91	4.01		0.10		

Table 4-15. Summary of error estimates for annual March-October 10th percentile DO concentrations

Location	Average Observed DO (mg/l)	Model Error (mg/l)	Model Error as Percent of Observed DO
Ashley R. below Summerville**	3.84	0.18	5%
Ashley R. nr North Charleston at I-516	3.75	0.43	11%
Cooper R. nr Goose Cr	5.41	0.38	7%
Cooper R. at Filbin Cr. @ I-526	4.58	0.15	3%
Cooper R. at Pier K, surface*	4.61	0.01	0%
Cooper R. at Pier K, bottom*	4.32	0.03	1%
Cooper R. at US 17, mid-depth	5.10	0.23	5%
Cooper R. at US 17, bottom*	5.07	0.17	3%
Wando R. above Mt. Pleasant at I-526, mid-depth	4.83	0.26	5%
Wando R. above Mt. Pleasant at I-526, bottom*	4.42	0.22	5%
Wando R. at Cainhoy*	3.91	0.20	5%

Note: * indicates only 2 years of comparisons; ** only 1 year of comparisons

4.2 Salinity Analysis

The primary salinity impact concerns are related to wetland vegetation impacts and the effects on DO. For wetland impacts, the EIS used the change in average annual salinity to estimate changes in wetland vegetation. Therefore, WEC used the R software to develop regression models to predict average annual salinity concentrations.

The following subsection provides a detailed description of the development of a linear regression model for salinity concentrations in the Cooper River at Mobay, which was identified as an area of concern in the Feasibility Study. WEC used similar processes to develop the regression models at the other project impact monitoring locations, and the resulting regression models for those locations are also provided.

4.2.1 Salinity Regression Modeling

The explanatory variable set was modified for the salinity analysis. The water chemistry monitoring variables (i.e., TKN concentrations) were dropped. The explanatory variables were modified to included sine and cosine of time-of-year. Salinity is often seasonal, so the wave pattern of the seasonal variation can be picked up using sine and cosine. In addition, the 3-day average of the upstream flow was added as an explanatory variable (listed as Flow.3day in the R analysis).

All of the explanatory variables were put into a linear regression model for Cooper River salinity at Mobay, and the model residuals were plotted using the same three types of residuals plots described previously in the DO analysis (Figures 4-11 through 4-13). Figure 4-11 shows that the residuals are non-normal (smiling shape to the distribution), and Figure 4-12 shows that the residuals are increasing in variance. Therefore, either the Y variable should be transformed, or the statistical model should include variables with a *p*-value a bit higher than 0.05, because the non-normality will be increasing *p*-values for the t-tests. The latter is the alternative used in this analysis. The other option is to take logs of Y, which may correct the non-normality, but will predict the geometric mean of Y (which is a median), requiring a subsequent bias correction in order to predict a mean. That is more complicated, and therefore our preferred method is to obtain the relations with all X variables linear and use an alpha of 0.10 in order to get a good regression that predicts the mean of Y.

Figures 4-14 and 4-15 show crPlots of a linear regression model with all of the X variables. The three river flow variables were log transformed, similar to the DO analysis. Figure 4-16 shows the crPlot of the logged variables.

WEC created an initial linear regression model with the logged variables, which produced the regression model coefficients listed in Table 4-17. The model was improved by eliminating the least significant X variables. Similar to the DO analysis, the criterion we used to select the variables to eliminate is the BIC statistic.

The final model coefficients for the Cooper River at Mobay location are shown in Table 4-18. All 9 remaining explanatory variables are significant. The regression model coefficients for the other salinity monitoring locations in the project impact area are listed in Appendix D.

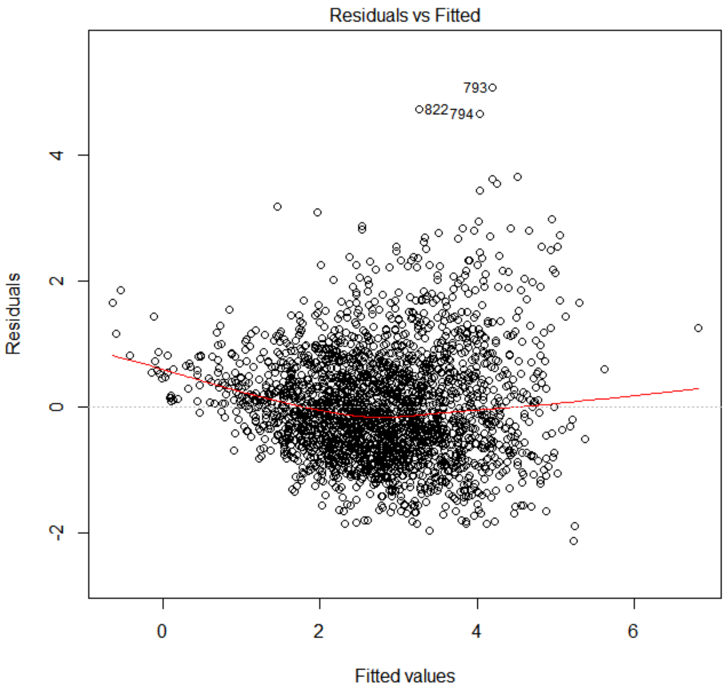

Figure 4-11. Residuals versus fitted plot for salinity linear regression model

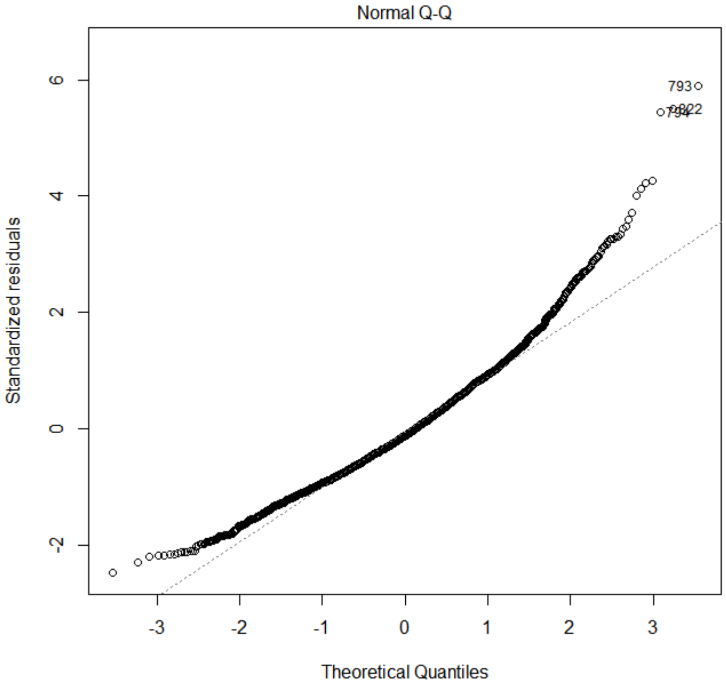

Figure 4-12. Normal Q-Q plot for salinity linear regression model

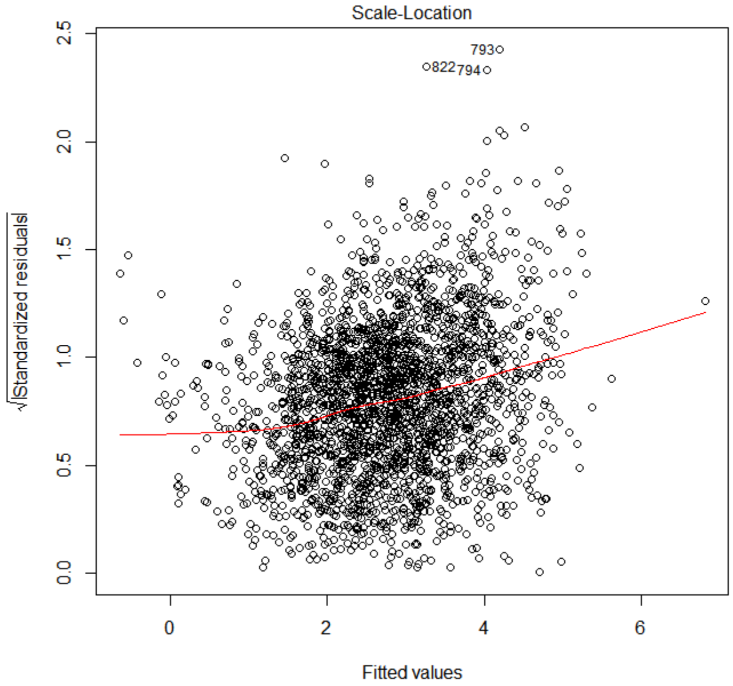

Figure 4-13. Scale-location plot for salinity linear regression model

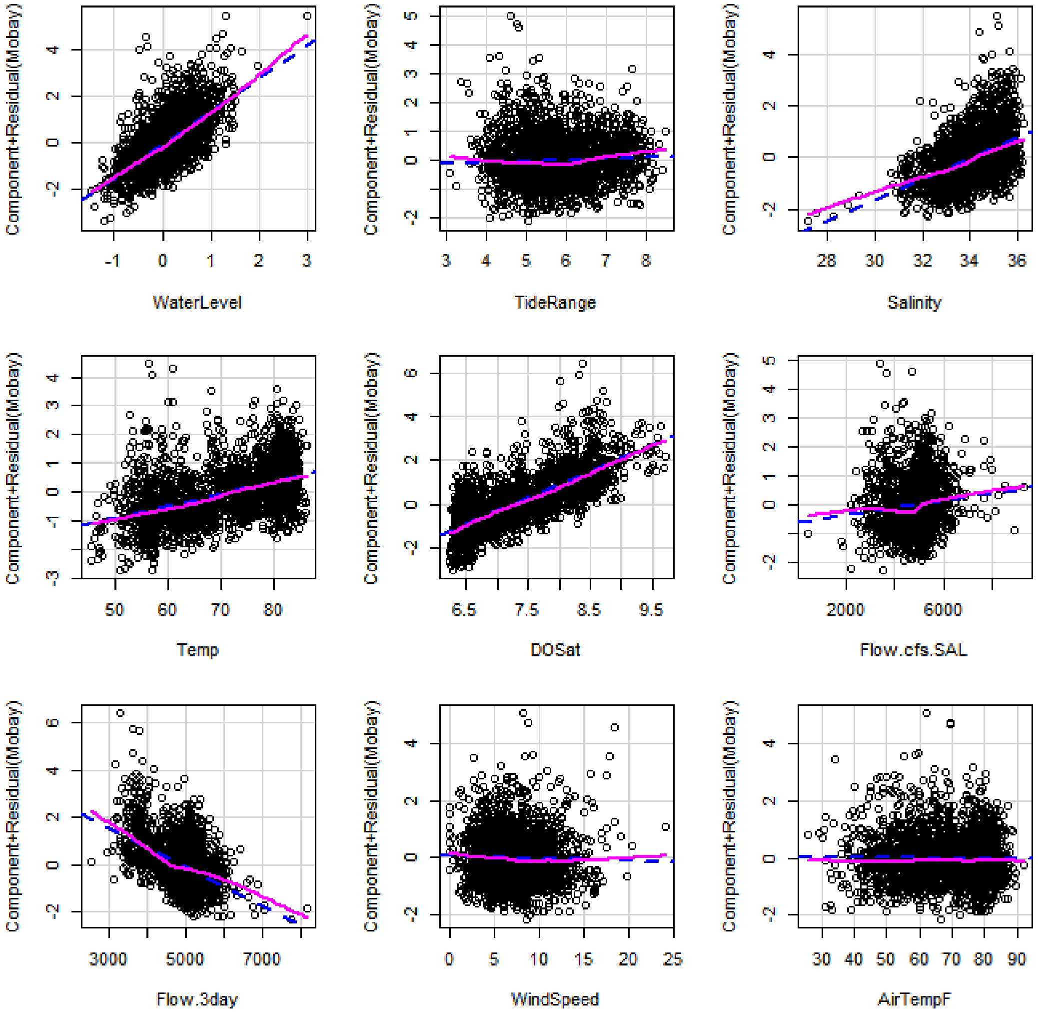

Figure 4-14. crPlots for salinity linear regression model

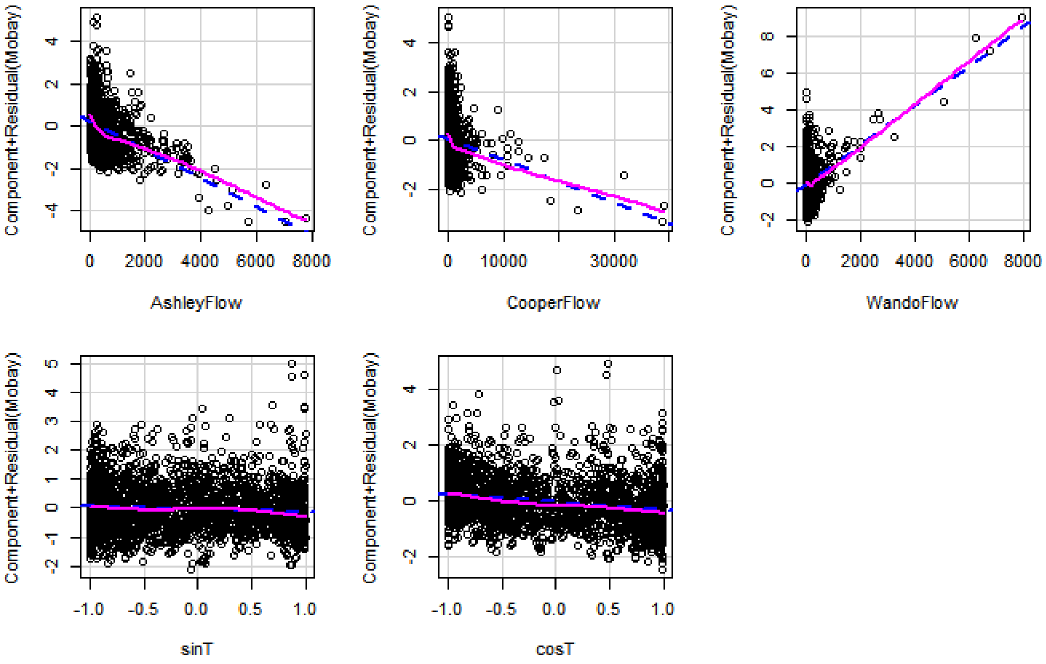

Figure 4-15. crPlots for salinity linear regression model (continued)

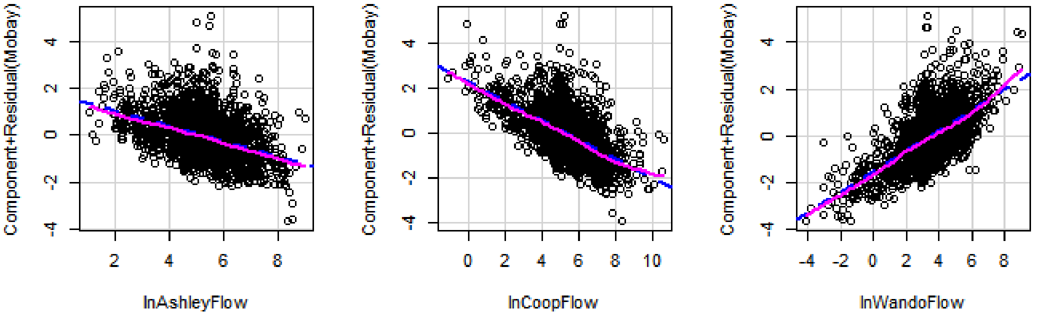

Figure 4-16. crPlots for logged variables in salinity linear regression model

Table 4-16. Initial salinity regression model coefficients

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	-23.62221398	4.15889263	-5.68	1.51E-08
WaterLevel	1.46492351	0.04112161	35.624	< 2e-16
TideRange	0.03652507	0.01807412	2.021	0.043404
Salinity	0.38777897	0.02159711	17.955	< 2e-16
Temp	0.08454207	0.02454657	3.444	0.000582
DOSat	1.80002195	0.27965294	6.437	1.46E-10
Flow.cfs	0.00012918	0.00003203	4.033	5.67E-05
Flow.3day	-0.00086631	0.00004531	-19.118	< 2e-16
WindSpeed	-0.0054731	0.00609137	-0.899	0.369007
AirTempF	-0.00205781	0.00313728	-0.656	0.511935
lnAshleyFlow	-0.32100342	0.04264633	-7.527	7.25E-14
lnCoopFlow	-0.42944437	0.09802767	-4.381	1.23E-05
lnWandoFlow	0.43685329	0.08212115	5.32	1.13E-07
sinT	-0.06147952	0.06411349	-0.959	0.337695
cosT	-0.35721154	0.10416263	-3.429	0.000615

Table 4-17. Final regression model coefficients for Cooper River salinity at Mobay

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	1.89052355	0.85772456	2.204	2.76E-02
WaterLevel	1.37488622	0.03812661	36.061	< 2e-16
Salinity	0.3122782	0.01804795	17.303	< 2e-16
Temp	-0.06640642	0.00678739	-9.784	< 2e-16
Flow.cfs	0.0001211	0.00003145	3.851	0.00012
Flow.3day	-0.00085328	0.00004454	-19.156	< 2e-16
lnAshleyFlow	-0.3499792	0.03701969	-9.454	< 2e-16
lnWandoFlow	0.06994843	0.0273157	2.561	0.0105
sinT	-0.21253856	0.05793139	-3.669	0.000249
cosT	-0.54073267	0.09632784	-5.613	2.19E-08

4.2.2 Minimum Level of Detectable Change in Salinity

Using the regression model, WEC predicted average annual salinity for each year from 2008 through 2017. These modeled values are compared to observed average annual salinity values in Table 4-19. The differences in annual average salinity values are listed in the “Delta” column, which ranges between -0.27 and 0.30 ppt and averages 0.0 ppt. The difference is greater than 0.3 ppt in one out of ten years.

WEC also calculated the width of confidence interval around annual average salinity. The equation for the standard error of the annual average is $s/\sqrt{n}$, where s is the residual standard error of the regression, and n is the number of independent observations used to compute the average. The number of independent observations each year depends on the autocorrelation in the daily salinity time

Table 4-18. Modeled and observed average annual Cooper River salinity at Mobay

	Year	Observed (ppt)	Predicted (ppt)	Days used	Delta (ppt)	Delta >0.27 ppt
1	2008	3.48	3.26	299	-0.21	
2	2009	2.85	2.97	283	0.12	
3	2010	2.73	2.52	187	-0.21	
4	2011	3.17	3.22	206	0.05	
5	2012	3.09	3.10	277	0.01	
6	2013	2.55	2.28	251	-0.27	
7	2014	2.65	2.55	287	-0.10	
8	2015	2.34	2.41	202	0.07	
9	2016	2.23	2.50	261	0.27	
10	2017	2.20	2.50	310	0.30	*
	Average	2.73	2.73		0.00	

series data. WEC used Pearson's product-moment correlation to calculate the correlation between each salinity measurement and the measurement value the day before. Using the calculated Pearson's correlation of 0.766, a year of daily values (365) is equivalent to 49 independent observations in terms of information. Therefore, for the Mobay case, 49 was used as n in the standard error computation. Multiplying $s/\sqrt{n}$ by the 95% confidence interval t-statistic for 365 daily measurements of 1.97 yields an estimated annual average salinity error of ±0.24 ppt at the 95% confidence interval level. This error is 9% of the average salinity at that location. Table 4-19 shows that 7 out of 10 values are within that range, and 9 out of 10 are within ±0.27 ppt.

Comparisons for modeled and observed average annual salinities are shown for the other monitoring locations in Tables 4-20 through 4-28. The locations with newly installed monitoring gauges have only one to two years of annual average salinity comparison data (i.e., Tables 4-20, 4-23, 4-26, 4-27). The bottom instrument in the Cooper River at US 17 is an exception, because 63 days are available from monitoring in 2012 that was conducted for the Post 45 hydrodynamic and water quality modeling analysis.

Table 4-29 summarizes the estimated annual average salinity errors at the 95% confidence interval level for each of the monitoring locations. With the exception of the Ashley River below Summerville location, the error levels are a reasonably small percentage (13 or less) of the average annual salinity at each location. Table 4-29 also includes estimates of increases in annual average salinity caused by the Post 45 Project. These estimates were calculated for the EIS using the EFDC hydrodynamic model.

The regression model at the Ashley River below Summerville location has a much greater relative error (44 of the average annual salinity at that location). This is because the regression model does not reproduce the spikes in salinity that occurred at that location. This may be because the LSPC model does not accurately represent the variation in the base freshwater flow rate into the river. Tetra Tech and JJG (2008) found that the LSPC watershed model developed for the TMDL over-estimated the base

Table 4-19. Modeled and observed average annual Ashley R. salinity below Summerville

	Year	Observed (ppt)	Predicted (ppt)	Days used	Delta (ppt)
1	2017	0.25	0.26	273	0.012

Table 4-20. Modeled and observed average annual Ashley R. salinity near North Charleston at I-526

	Year	Observed (ppt)	Predicted (ppt)	Days used	Delta (ppt)	Delta >1.2 ppt
1	2008	16.25	15.77	299	-0.48	
2	2009	14.42	14.65	172	0.22	
3	2010	15.23	14.11	228	-1.12	
4	2011	18.40	17.57	212	-0.83	
5	2012	17.87	18.42	266	0.55	
6	2013	13.62	13.27	257	-0.35	
7	2014	13.87	13.49	273	-0.38	
8	2015	11.83	13.06	209	1.24	*
9	2016	12.49	12.54	317	0.05	
10	2017	12.98	14.00	323	1.02	
	Average	14.70	14.69		-0.01	

Table 4-21. Modeled and observed average annual Cooper River salinity at Pimlico

	Year	Observed (ppt)	Predicted (ppt)	Days used	Delta (ppt)	Delta >0.005 ppt
1	2008	0.059	0.049	299	-0.0106	*
2	2009	0.045	0.045	290	-0.0004	
3	2010	0.038	0.043	210	0.0050	
4	2011	0.051	0.048	221	-0.0032	
5	2012	0.052	0.048	277	-0.0041	
6	2013	0.039	0.041	257	0.0024	
7	2014	0.039	0.042	292	0.0035	
8	2015	0.040	0.043	186	0.0028	
9	2016	0.037	0.042	325	0.0046	
10	2017	0.043	0.044	318	0.0005	
	Average	0.044	0.044		0.000	

Table 4-22. Modeled and observed average annual Cooper River salinity above Goose Creek

	Year	Observed (ppt)	Predicted (ppt)	Days used	Delta (ppt)
1	2016	0.24	0.23	193	-0.007
2	2017	0.19	0.22	325	0.028
	Average	0.22	0.23		0.002

Table 4-23. Modeled and observed average annual Cooper River salinity near Goose Creek

	Year	Observed (ppt)	Predicted (ppt)	Days used	Delta (ppt)	Delta >0.025 ppt
1	2008	0.156	0.131	281	-0.025	
2	2009	0.114	0.114	281	0.000	
3	2010	0.092	0.100	228	0.008	
4	2011	0.129	0.126	221	-0.003	
5	2012	0.125	0.124	277	-0.002	
6	2013	0.099	0.087	251	-0.012	
7	2014	0.101	0.098	292	-0.003	
8	2015	0.097	0.097	209	0.001	
9	2016	0.08	0.10	323	0.016	
10	2017	0.08	0.10	312	0.026	*
	Average	0.11	0.11		0.001	

Table 4-24. Modeled and observed average annual Cooper River salinity at Filbin Cr. and I-526

	Year	Observed (ppt)	Predicted (ppt)	Days used	Delta (ppt)	Delta >0.42 ppt
1	2008	17.198	16.831	287	-0.367	
2	2009	16.034	16.451	186	0.417	
3	2010	16.214	15.744	189	-0.470	*
4	2011	16.861	17.183	139	0.322	
5	2012	16.726	16.942	222	0.217	
6	2013	15.156	15.144	248	-0.012	
7	2014	15.713	15.526	292	-0.186	
8	2015	15.590	15.455	189	-0.134	
9	2016	15.32	15.41	326	0.091	
10	2017	15.76	15.95	306	0.186	
	Average	16.06	16.06		0.006	

Table 4-25. Modeled and observed average annual Cooper River salinity at Pier K, surface

	Year	Observed (ppt)	Predicted (ppt)	Days used	Delta (ppt)
1	2016	18.73	18.73	178	0.001
2	2017	19.09	19.09	324	-0.001
	Average	18.91	18.91		0.000

Table 4-26. Modeled and observed average annual Cooper River salinity at Pier K, bottom

	Year	Observed (ppt)	Predicted (ppt)	Days used	Delta (ppt)
1	2016	21.06	21.52	181	0.46
2	2017	21.97	21.71	325	-0.26
	Average	21.51	21.62		0.020

Table 4-27. Modeled and observed average annual Cooper River salinity at US 17, mid-depth

	Year	Observed (ppt)	Predicted (ppt)	Days used	Delta (ppt)	Delta >0.76 ppt
1	2008	25.712	25.549	289	-0.164	
2	2009	25.452	25.243	188	-0.209	
3	2010	25.842	24.779	189	-1.063	*
4	2011	26.611	26.316	169	-0.294	
5	2012	25.862	26.178	222	0.316	
6	2013	24.810	24.305	257	-0.505	
7	2014	24.641	24.588	273	-0.054	
8	2015	23.808	24.559	200	0.752	
9	2016	24.05	24.38	293	0.329	
10	2017	24.32	24.87	315	0.552	
	Average	25.11	25.08		-0.034	

Table 4-28. Modeled and observed average annual Cooper River salinity at Cooper R. at US 17, bottom

	Year	Observed (ppt)	Predicted (ppt)	Days used	Delta (ppt)	Delta >0.20 ppt
1	2012	26.64	26.28	63	-0.362	*
2	2016	25.28	25.08	184	-0.197	
3	2017	25.23	25.41	316	0.187	
	Average	25.72	25.59		-0.037	

Table 4-29. Summary of error estimates for average annual salinity

Location	Observed Mean Salinity (ppt)	EIS Estimate of Project Impacts (ppt)	Statistical Model Standard Error (ppt)	Standard Error as Percent of Average Annual Salinity
Ashley R. below Summerville	0.25	0.05	0.11	44
Ashley R. nr North Charleston at I-516	14.70	0.4	1.1	7
Cooper R. at Pimlico	0.04	0.0	0.0049	11
Cooper R. above Goose Cr	0.22	0.4	0.027	13
Cooper R. at Mobay	2.73	0.5	0.24	9
Cooper R. nr Goose Cr	0.22	0.04	0.012	11
Cooper R. at Filbin Cr. @ I-526	16.06	0.6	0.52	3
Cooper R. at Pier K, surface	18.91	0.9	0.50	3
Cooper R. at Pier K, bottom	21.51	0.9	0.46	2
Cooper R. at US 17, mid-depth	25.11	0.3	0.63	3
Cooper R. at US 17, bottom	25.72	0.3	0.51	2

flow rate into the Ashley River and therefore they modified the base flow rate input to the EFDC water quality model for the river. Improvements in regression model salinity predictions at this location would likely require additional monitoring and analysis of base flow into the Ashley River. Nonetheless, the regression model presented herein for this location should be suitable for detecting project-induced changes in salinity that exceed 0.11 ppt at this location.

As shown by Table 4-29, the statistical model error varies by location and can be smaller or larger than the EIS estimates of Post 45 Project impacts. If the EIS predictions are accurate, then project effects at some locations will be within the error range for the statistical models and will not be detected by the monitoring data. However, if the project causes greater impact than the statistical model error estimates at each location in Table 4-29, then the monitoring data will detect the project-induced changes.

5 Conclusions

The statistical analyses in this report demonstrate that multiple linear regression and quantile regression techniques can be used to account for the effects of explanatory variables on salinity and DO concentrations in the Charleston Harbor estuary. Once the post-project monitoring data is collected, these methods can be used to estimate the DO and salinity in the estuary that would have occurred had the Post 45 Project not been constructed. These results can then be compared to the measured after-project DO and salinity in order to quantify the project impacts.

The uncertainty in the statistical models varies by location. For DO, the error in the annual March-October 10th percentile DO is a relatively small fraction of the observed DO (less than 10% error at all locations, except one). However, the absolute error in this measure of DO ranges between 0.15 mg/l and 0.43 mg/l at the long-term monitoring locations (at the 90% confidence level). This level of error is greater than the level of Post 45 Project impact estimated in the EIS (which estimated DO impacts less than 0.10 mg/l in the Cooper River and less than 0.12 mg/l in the Wando River). Therefore, the statistical analysis of the monitoring data will detect project-induced changes only if they are greater than those estimated in the EIS.

For salinity, the models are generally within an error of 13 percent or less of the average annual salinity at each location, with one exception (the Ashley River below Summerville location has an error of ±0.11 ppt, which is 44 percent of the average annual salinity). The statistical model error varies by location and can be smaller or larger than the EIS estimates of Post 45 Project impacts. If the EIS predictions are accurate, then project effects at some locations will be within the error range for the statistical models and will not be detected by the monitoring data. However, if the project causes changes in salinity greater than the statistical model error estimates at each location, then the monitoring data will detect the project-induced changes.

No revisions to the field monitoring (e.g., USGS gauge locations) are recommended.

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Appendix A. NPDES Point Source Discharge UOD Loading Rates

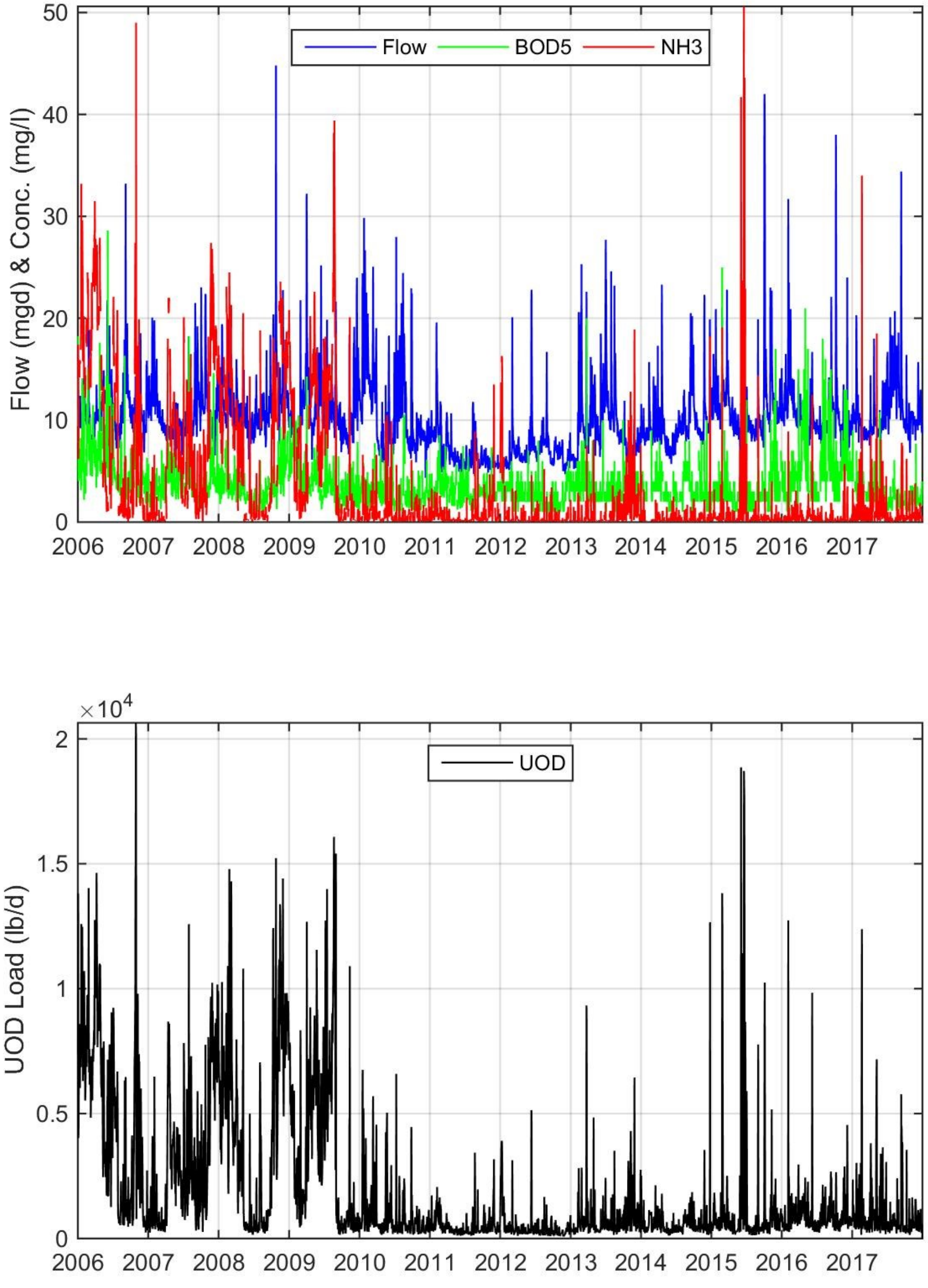

Figure A-1 BCWSA Lower Berkeley WWTF discharge data

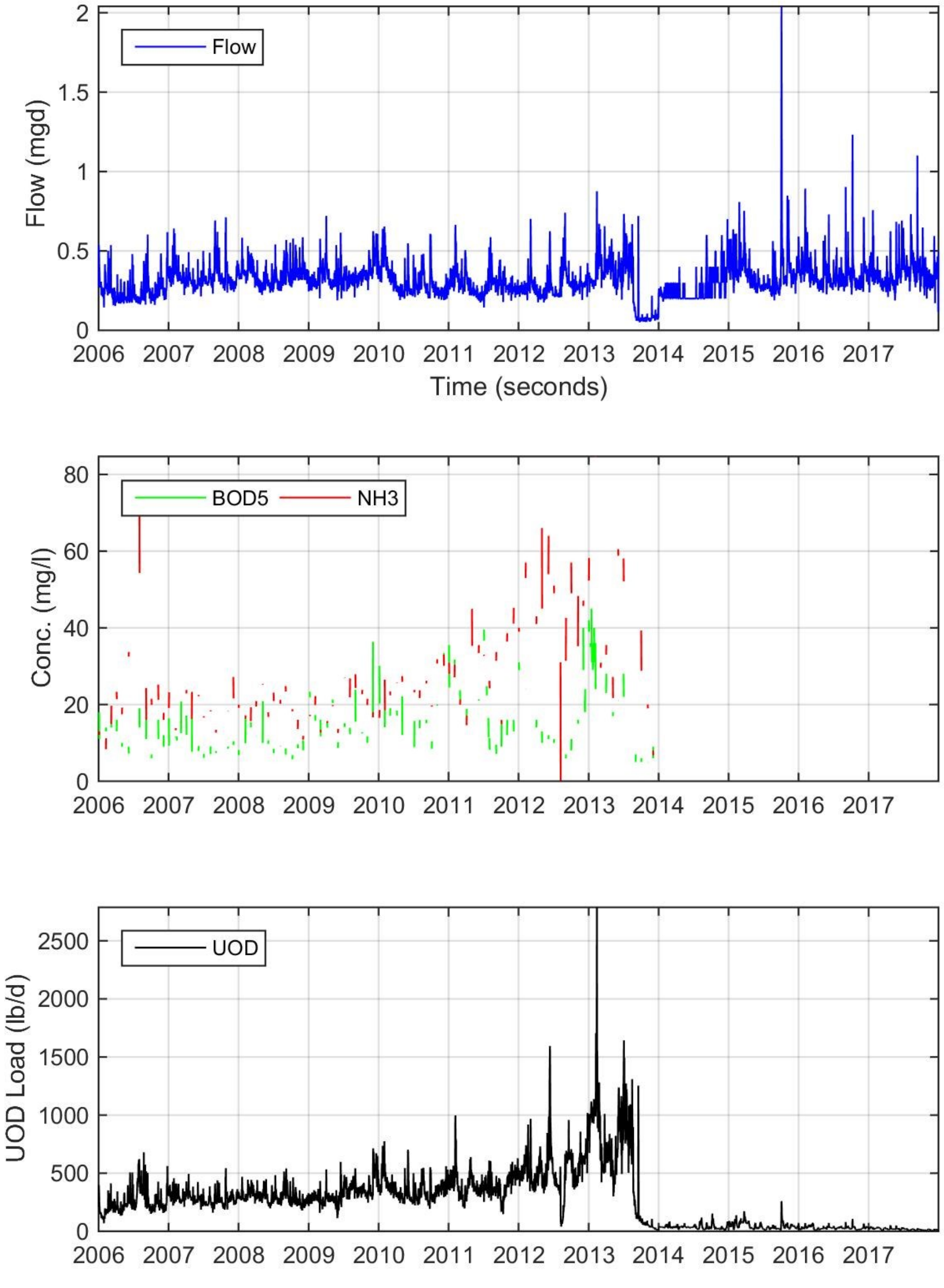

Figure A-2 BCWSA Central Berkeley WWTF discharge data

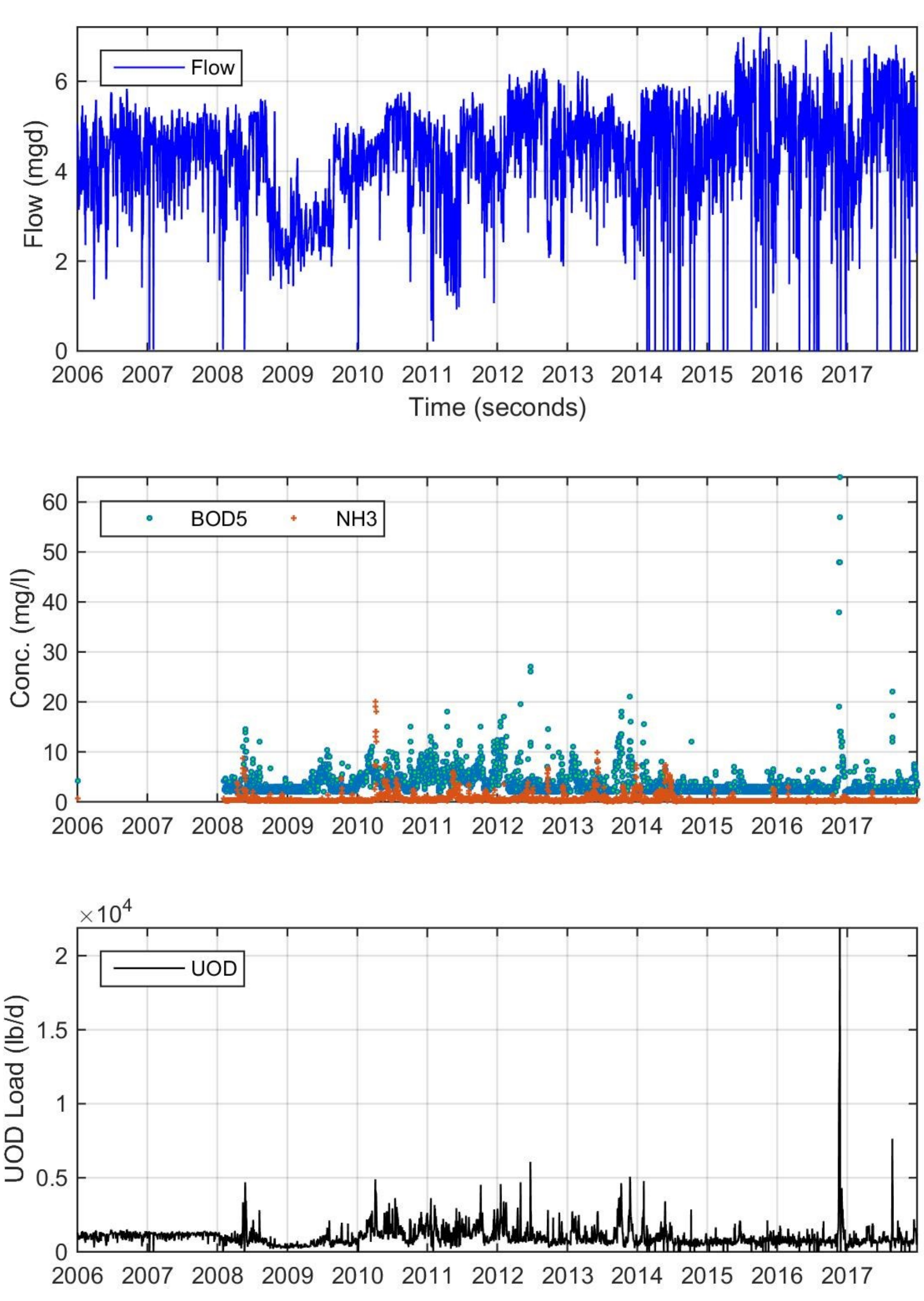

Figure A-3 BP Amoco discharge data

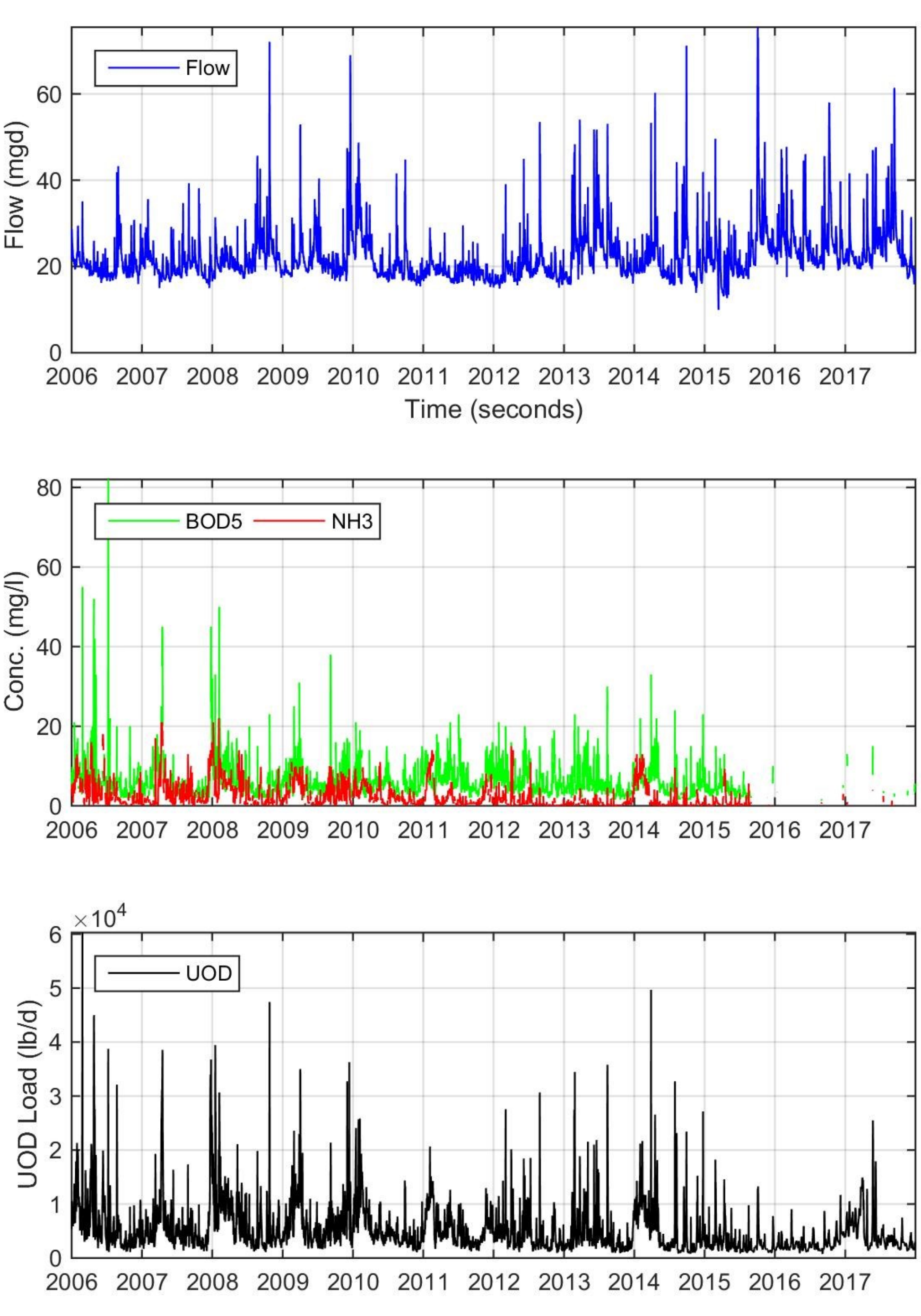

Figure A-4 CWS Plum Island discharge data

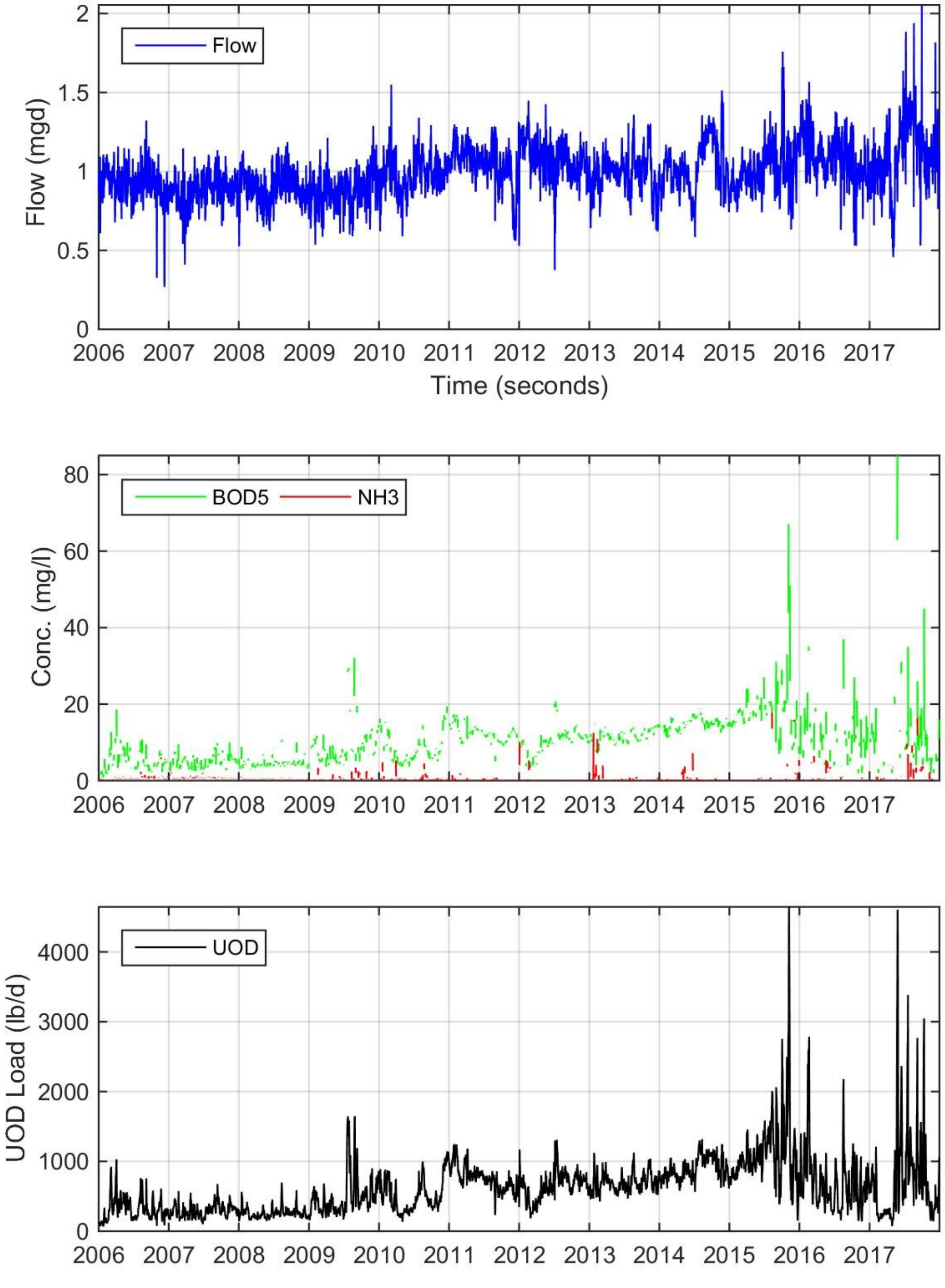

Figure A-5 DAK Americas discharge data

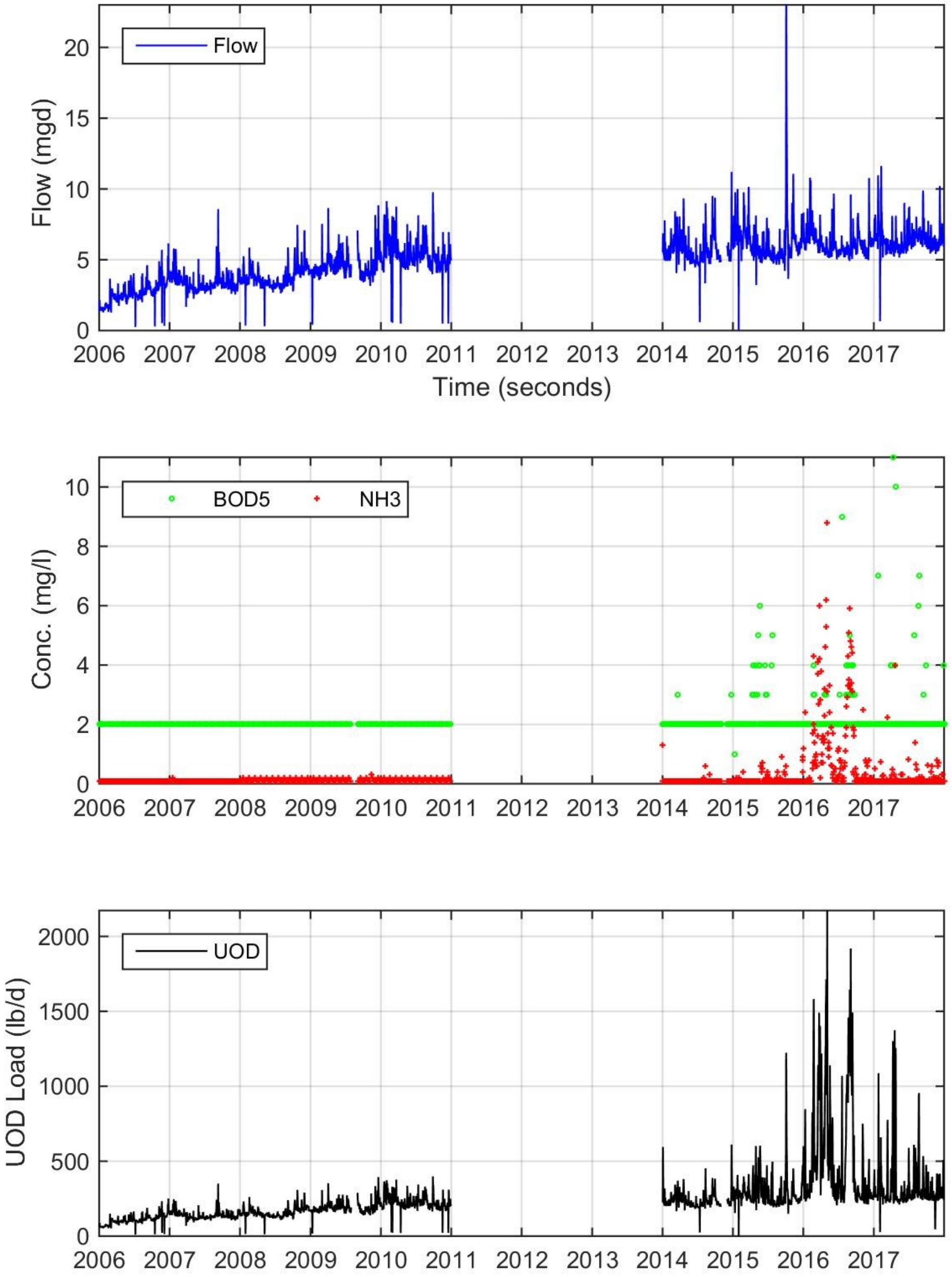

Figure A-6 Lower Dorchester discharge data

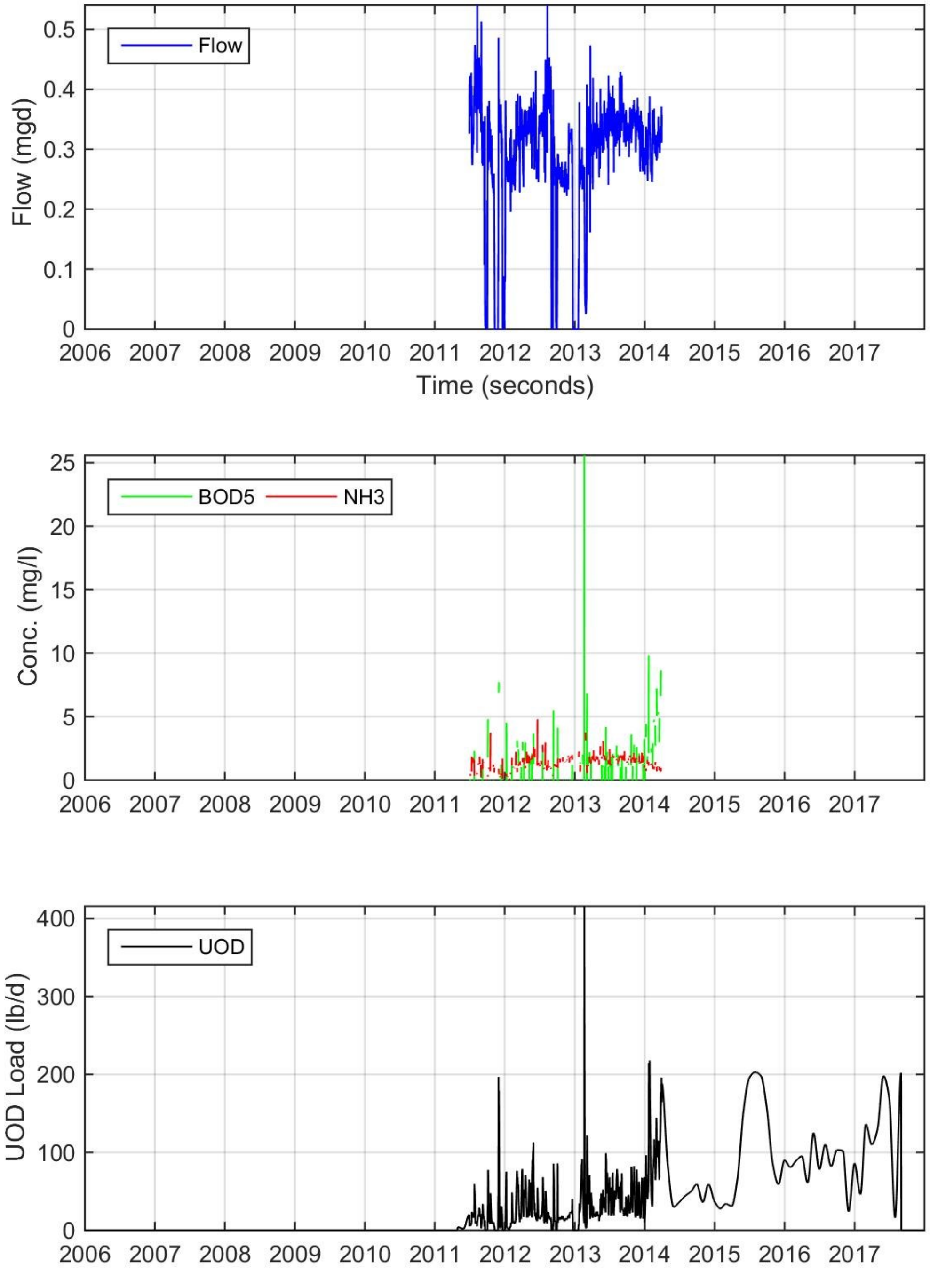

Figure A-7 Dupont discharge data

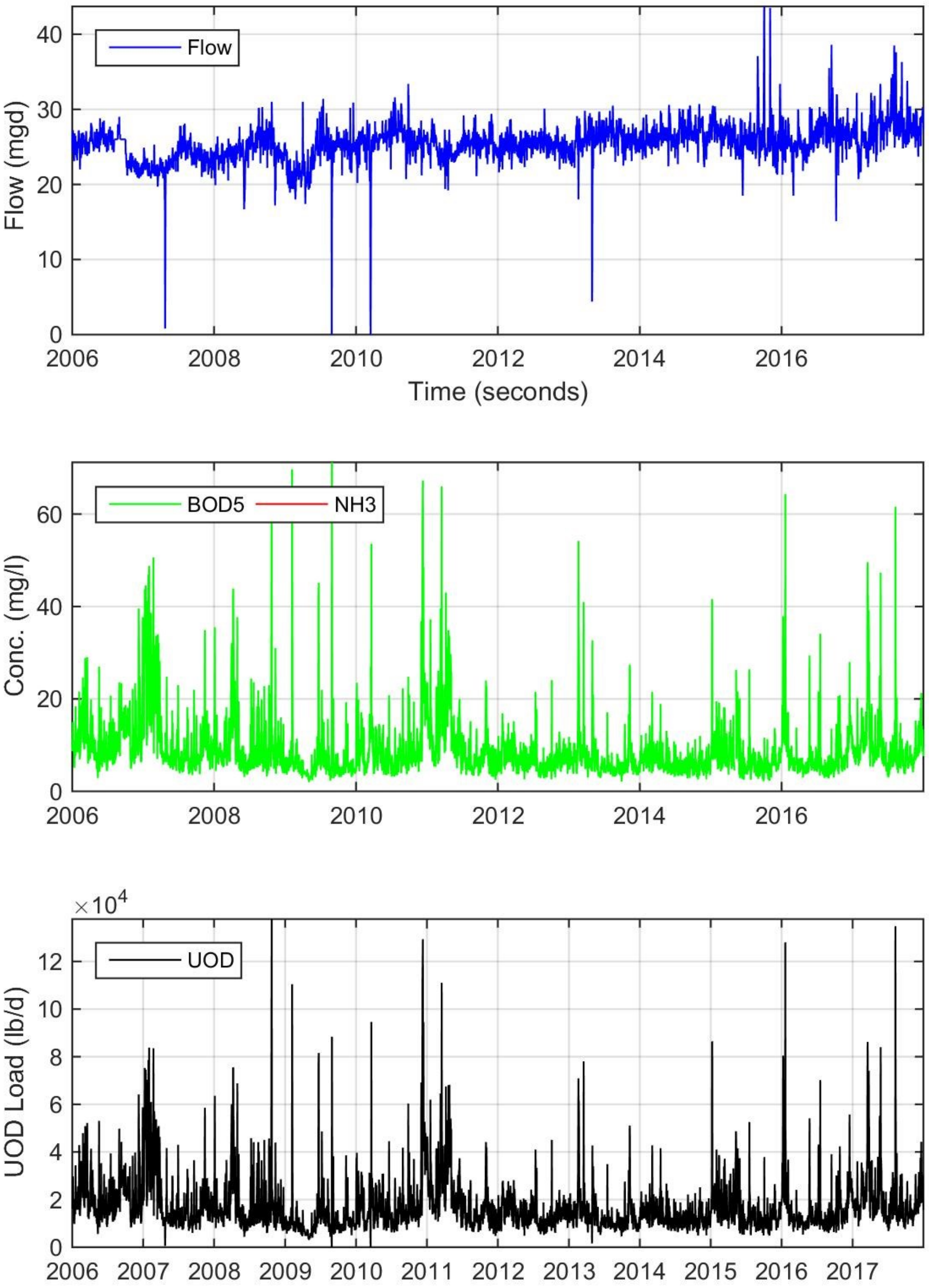

Figure A-8 WestRock discharge data

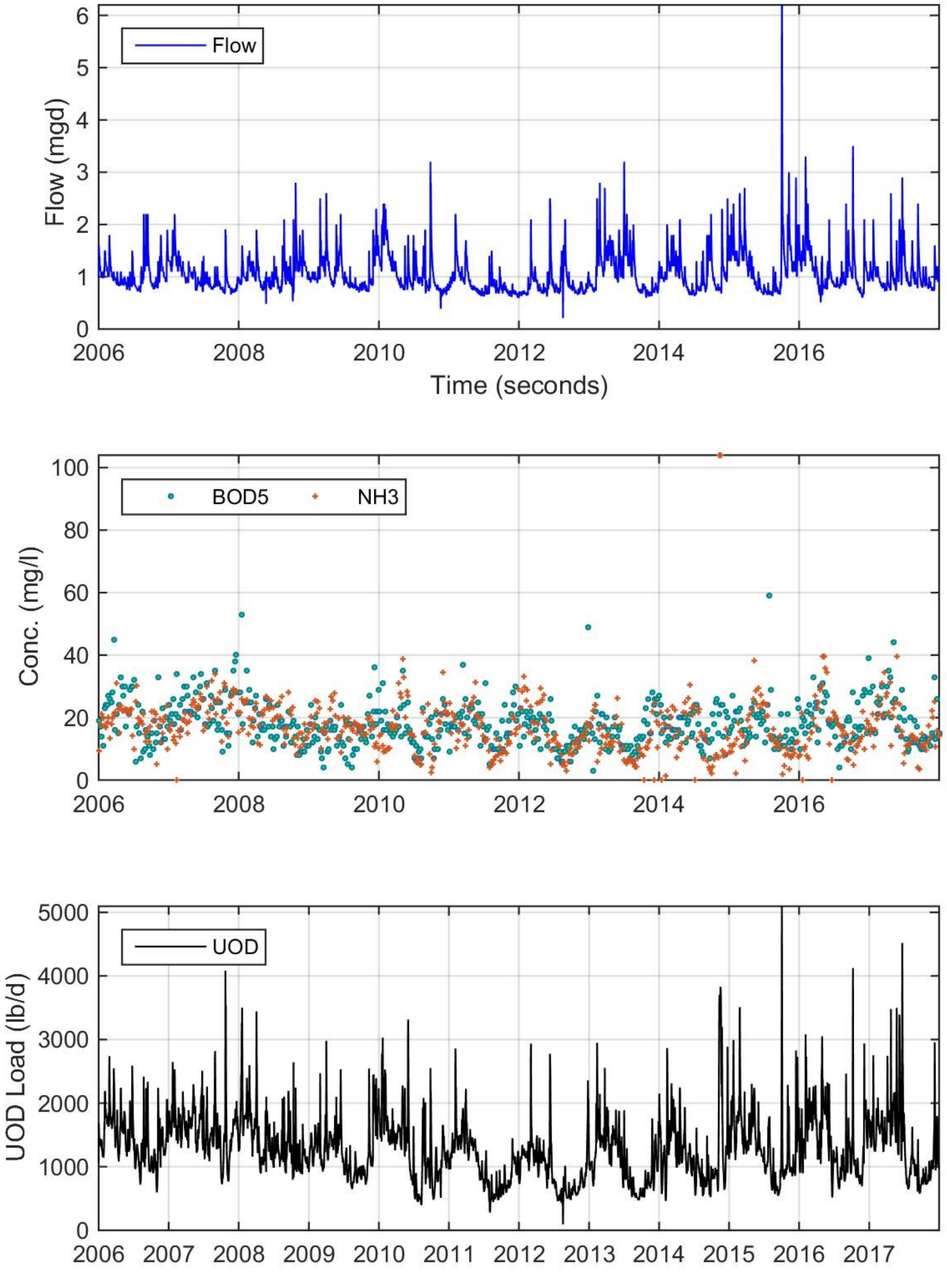

Figure A-9 Moncks Corner discharge data

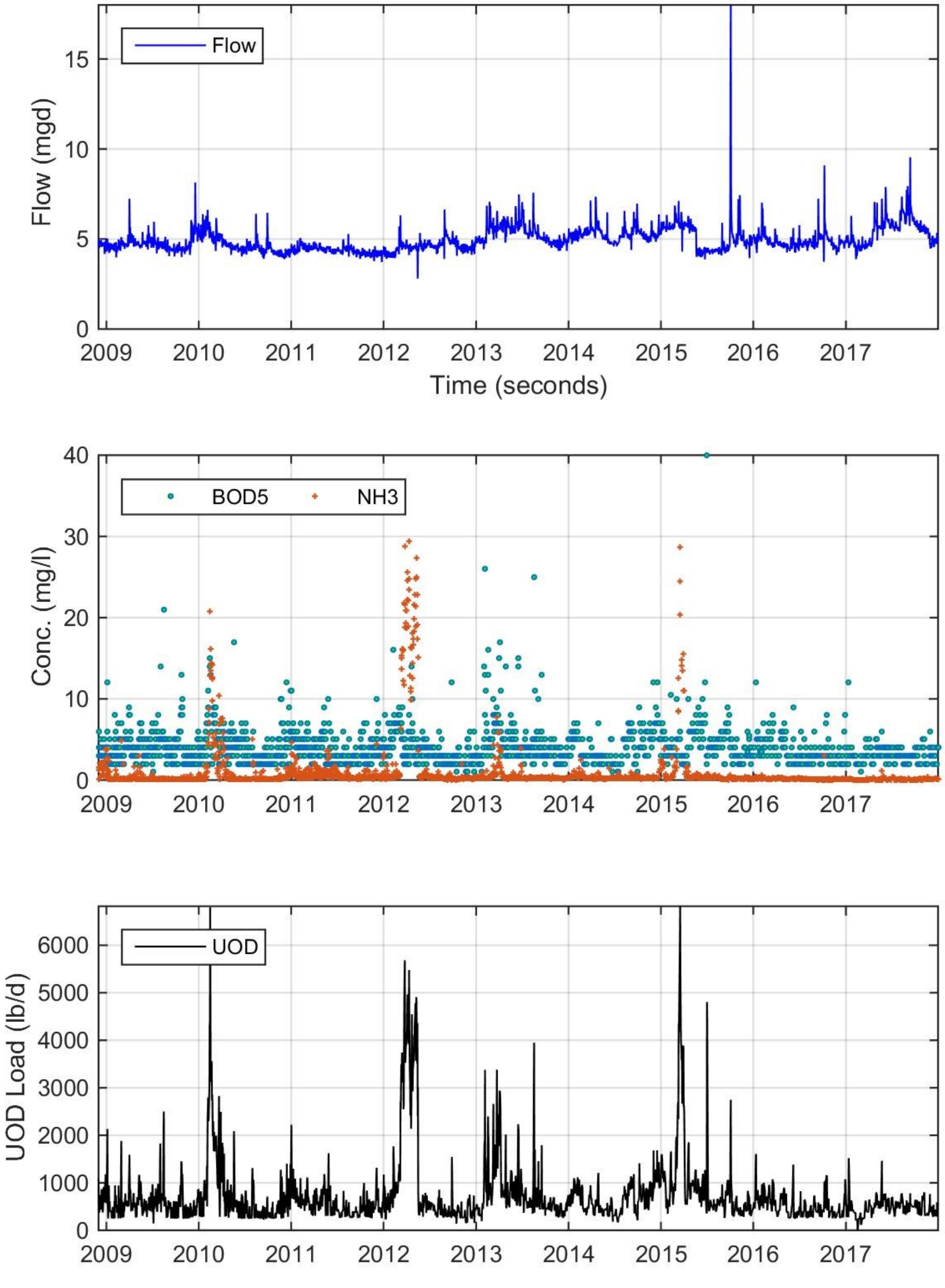

Figure A-10 Mount Pleasant RR discharge data

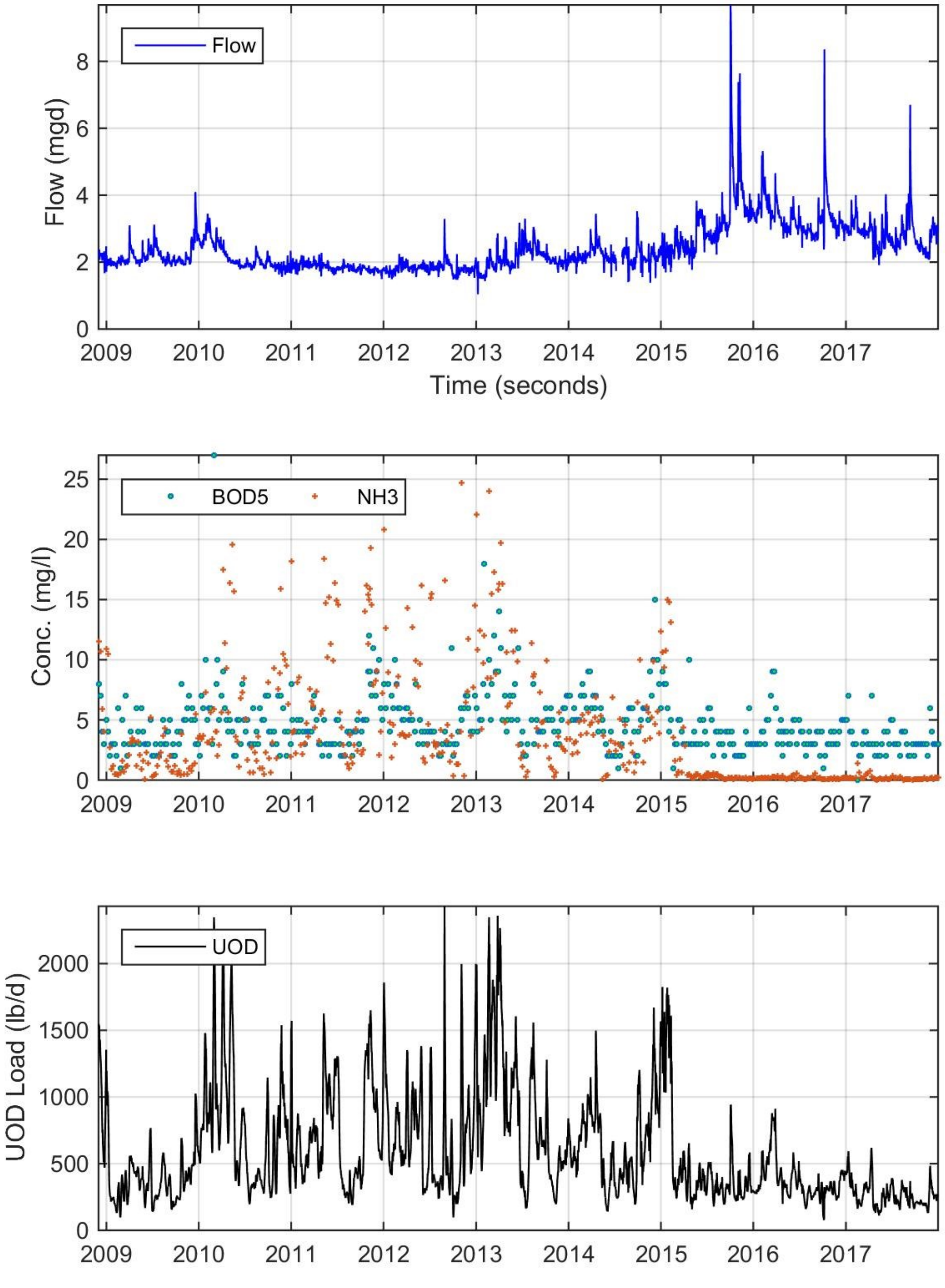

Figure A-11 Mount Plesant Center Street discharge data

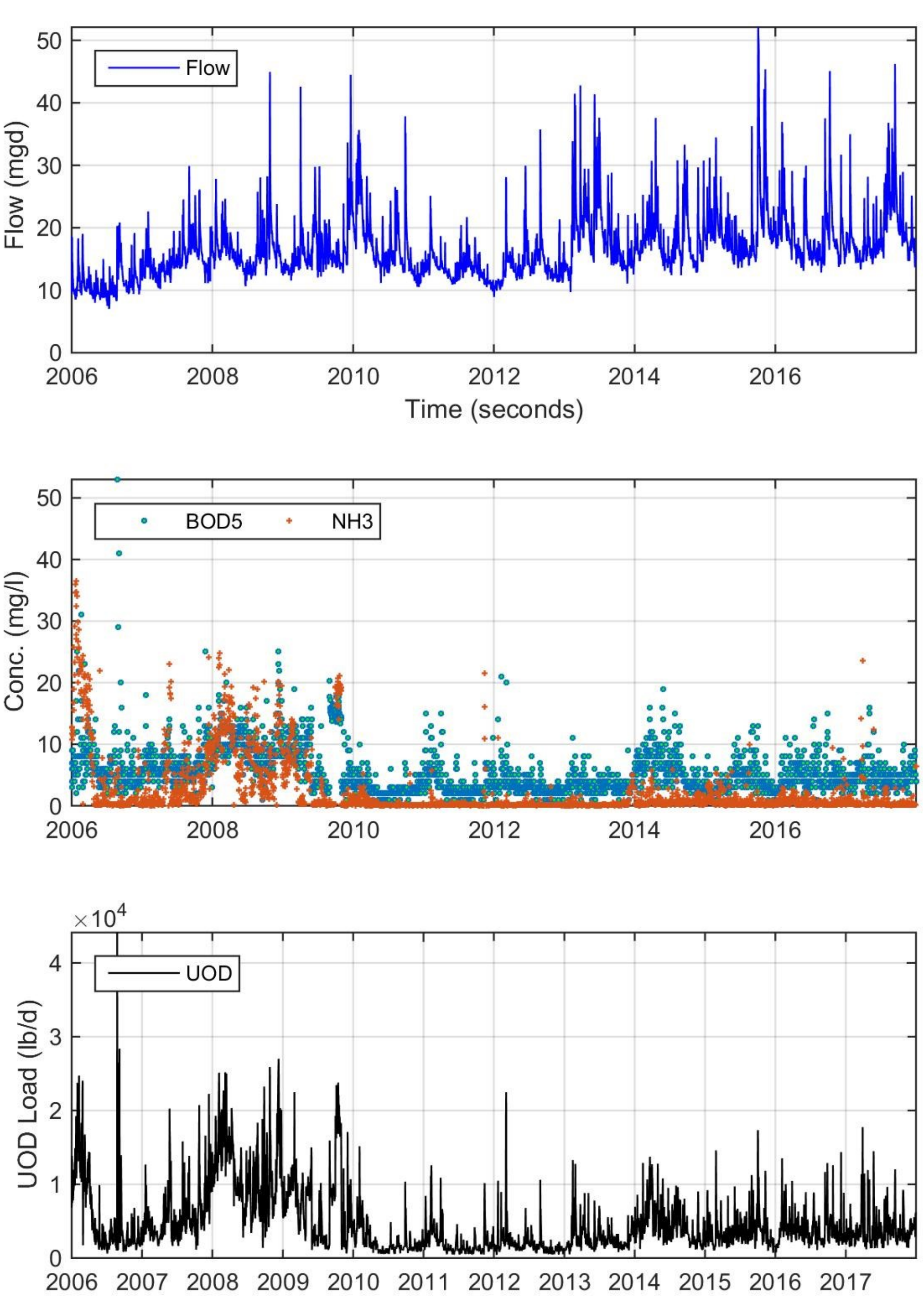

Figure A-12 NCSD Felix Davis WWTP discharge data

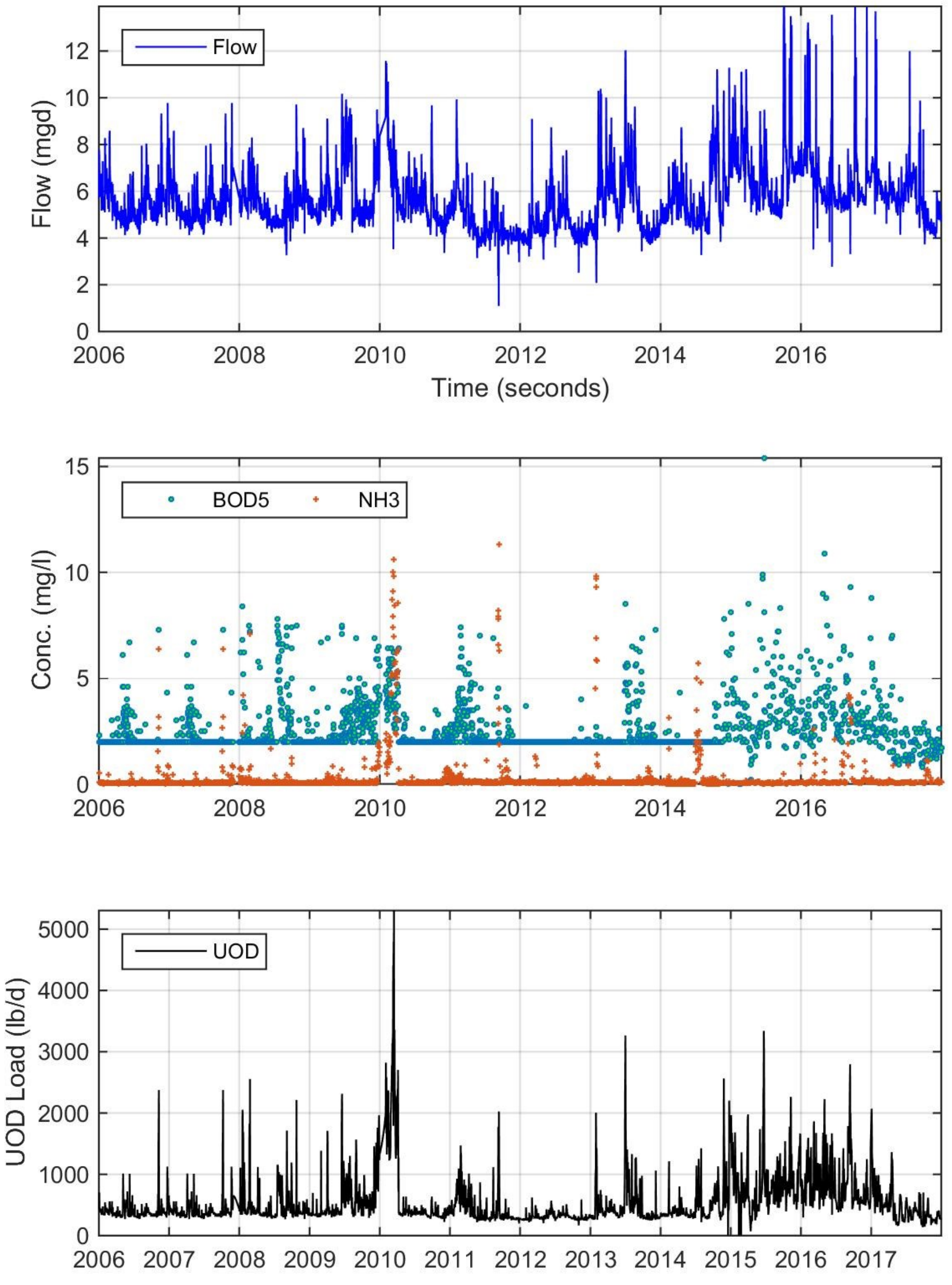

Figure A-13 Summerville WWTF discharge data

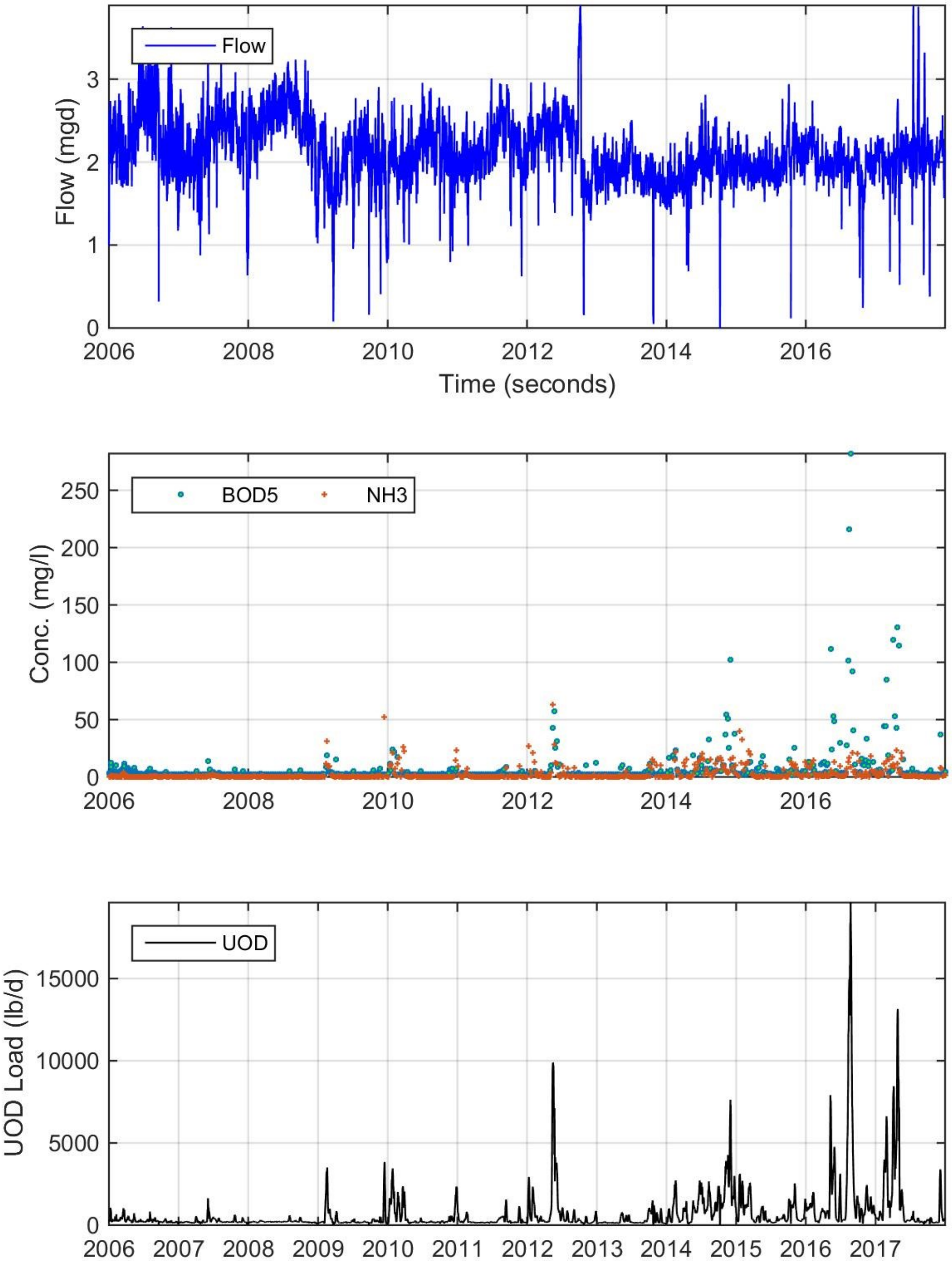

Figure A-14 Sun Chemical discharge data

Appendix B. Ambient TKN Concentrations

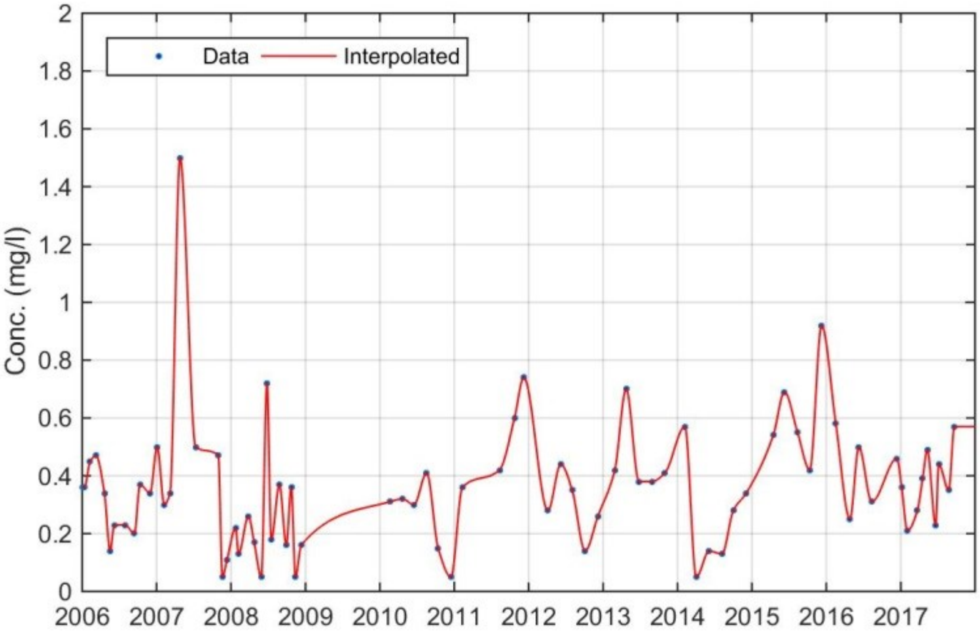

Figure B-1 Station MD-052 TKN Concentrations

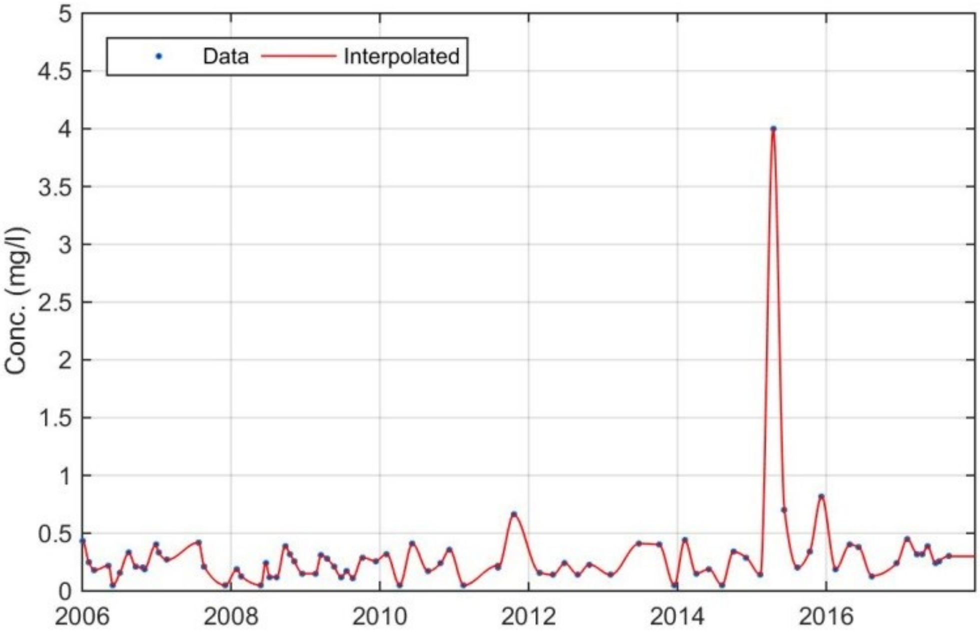

Figure B-2 Station MD-045 TKN Concentrations

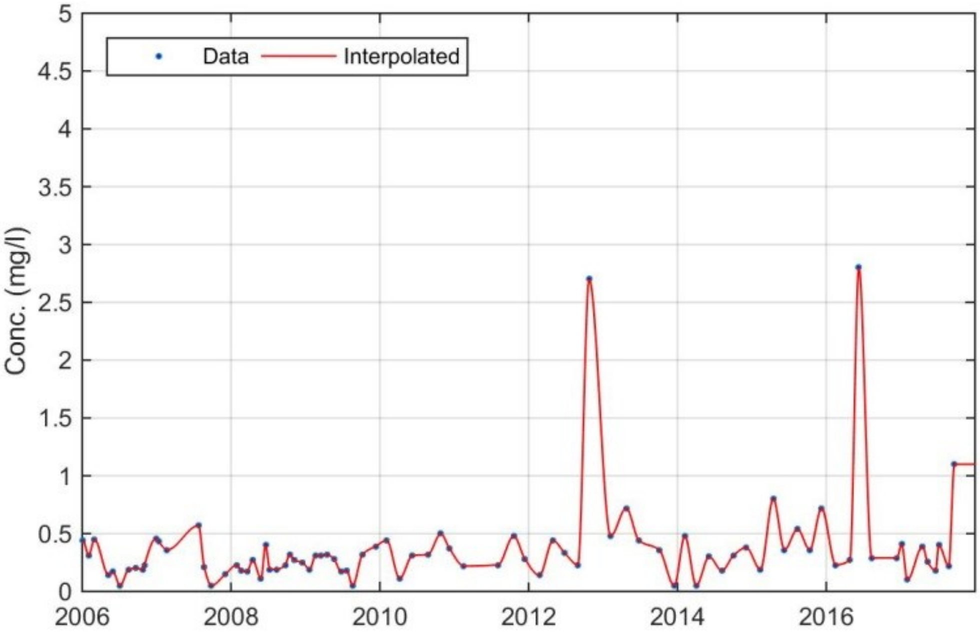

Figure B-3 Station MD-248 TKN Concentrations

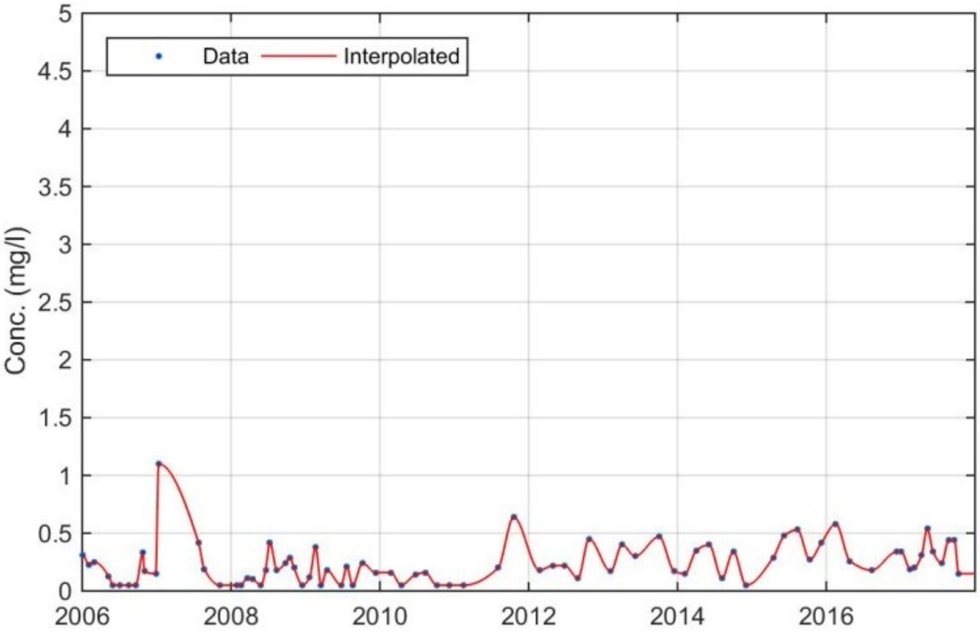

Figure B-4 Station MD-264 TKN Concentrations

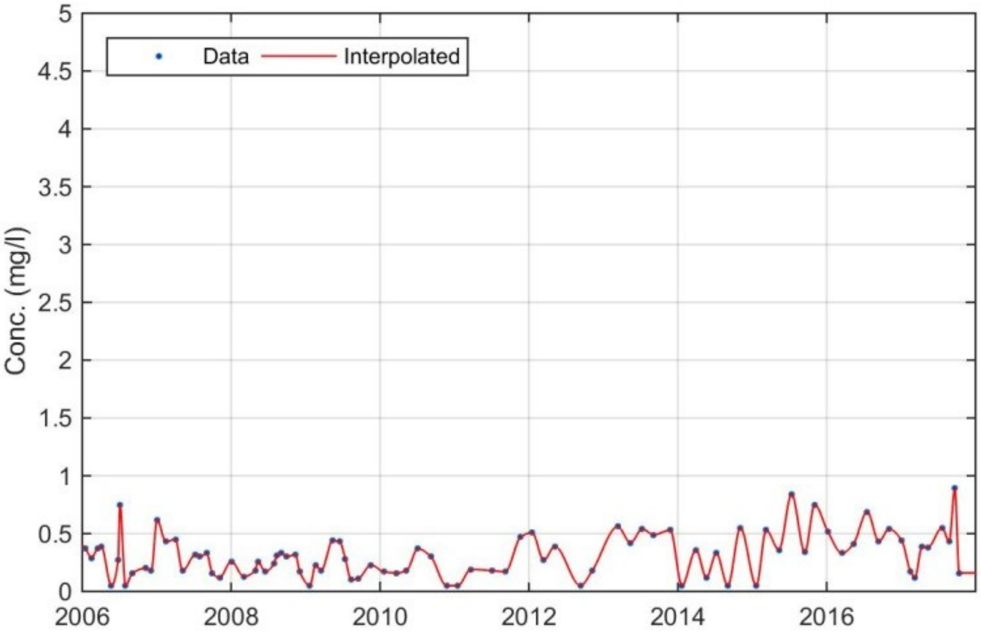

Figure B-5 Station MD-115 TKN Concentrations

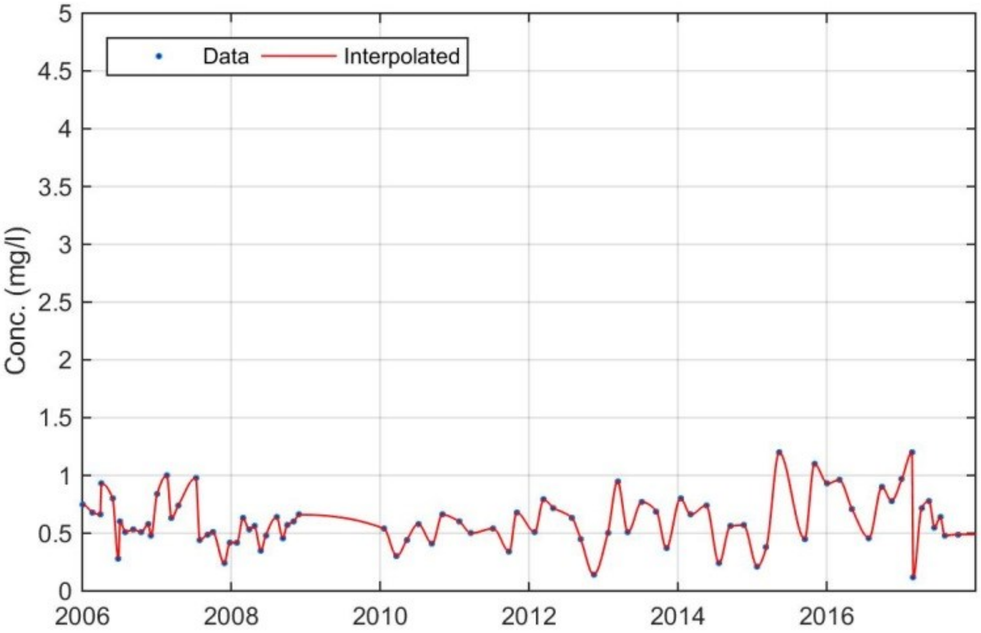

Figure B-6 Station MD-049 TKN Concentrations

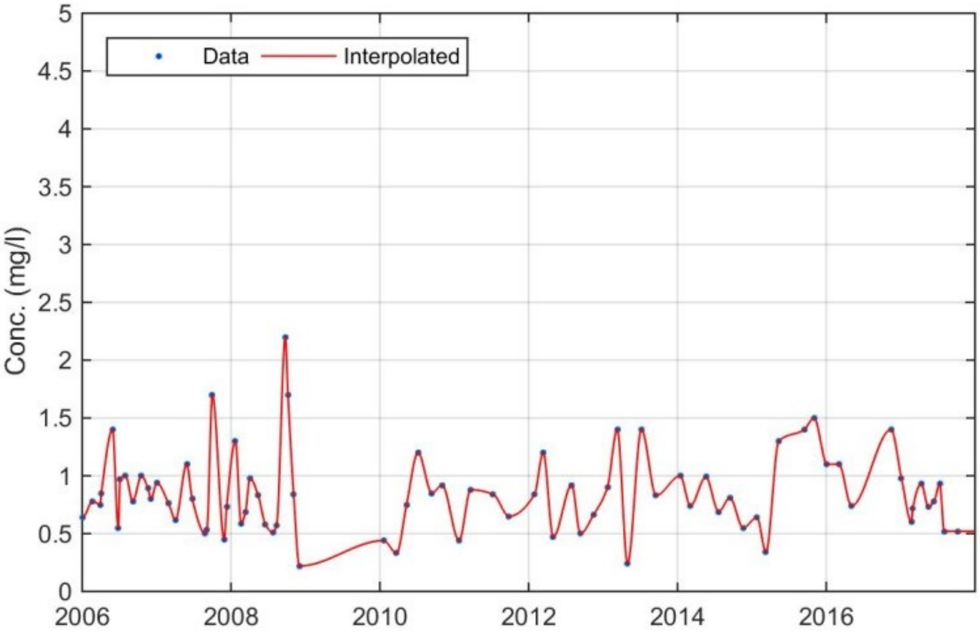

Figure B-7 Station CSTL-102 TKN Concentrations

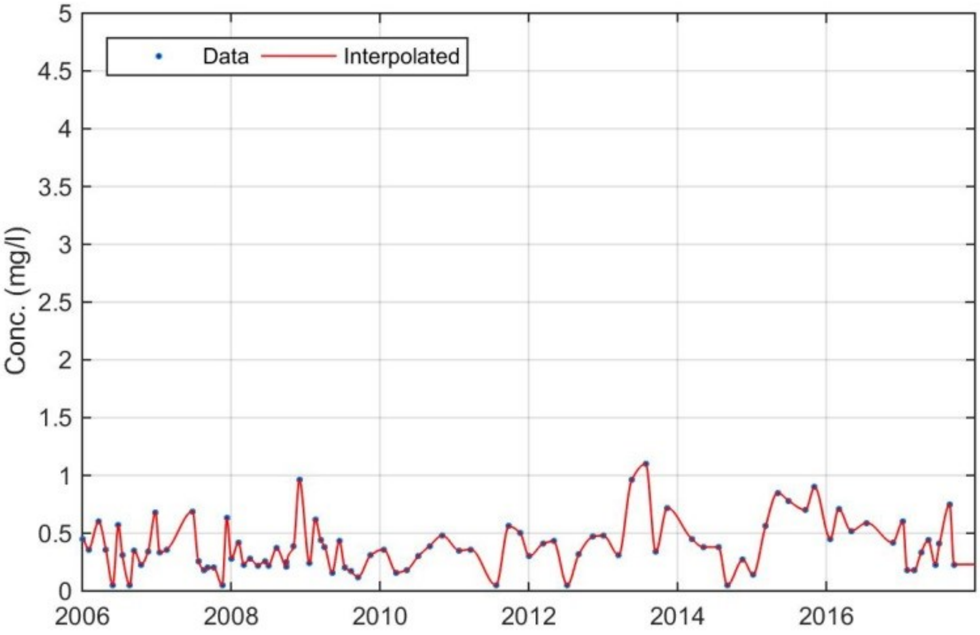

Figure B-8 Station CSTL-123 TKN Concentrations

Appendix C. Dissolved Oxygen QR model coefficients

Table C-1. QR model coefficients for DO at Ashley R. below Summerville

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	39.89538	2.75973	14.45624	0
WaterLevel	-0.3107	0.11791	-2.63504	0.00916
Salinity	-0.17604	0.04462	-3.94507	0.00011
Temp	-0.23531	0.01941	-12.121	0
Flow.cfs	-0.00188	0.00078	-2.41084	0.01694
UpstreamLoadBOD	0.00003	0.00001	2.4133	0.01683
MD_045	-40.2798	4.31316	-9.33882	0
MD_049	-3.28881	0.76756	-4.28474	0.00003
MD_052	14.0077	1.84264	7.60196	0
MD_115	-2.25049	0.60555	-3.71641	0.00027
MD_248	-4.24129	0.58524	-7.24713	0
MD_264	4.55474	1.32968	3.42543	0.00076
CSTL_102	-1.42762	0.62473	-2.28516	0.02349

Table C-2. QR model coefficients for DO at Ashley R. nr North Charleston at I-516

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	3.61598	2.83519	1.27539	0.20234
WaterLevel	-0.30102	0.02685	-11.2123	0
TideRange	-0.10342	0.01347	-7.67495	0
Salinity	0.06753	0.01159	5.82846	0
Temp	-0.08538	0.01537	-5.55572	0
DOSat	0.74742	0.23865	3.13188	0.00176
WindSpeed	0.04495	0.00482	9.32408	0
MD_248	0.10403	0.03395	3.06439	0.00221
MD_264	0.35751	0.10786	3.31456	0.00094
lnAshleyFlow	-0.12305	0.01152	-10.6835	0
lnCooperUOD	0.2012	0.03842	5.23704	0
lnMD_045	-0.06615	0.02086	-3.17153	0.00154

Table C-3. QR model coefficients for DO at Cooper R. nr Goose Cr

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	-7.83026	0.53928	-14.5199	0
WaterLevel	-0.21262	0.02276	-9.34132	0
TideRange	-0.08879	0.0114	-7.78693	0
Salinity	0.08032	0.01281	6.2701	0
DOSat	2.17386	0.02641	82.29994	0
WindSpeed	0.00366	0.00368	0.99517	0.31979
MD_115	-0.43625	0.06949	-6.2783	0
lnMD_248	0.09262	0.01544	5.99994	0
CSTL_102	0.10443	0.04069	2.56618	0.01037
lnCoopFlow	-0.12079	0.00769	-15.7161	0
lnMD_045	-0.11217	0.0177	-6.33557	0

Table C-4. QR model coefficients for DO at Cooper River at Filbin Creek and I-526

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	9.46536	1.36033	6.95815	0
WaterLevel	-0.17779	0.01273	-13.9679	0
TideRange	-0.059	0.00732	-8.05477	0
Temp	-0.09227	0.00802	-11.5003	0
DOSat	0.5418	0.12619	4.29351	0.00002
Flow.cfs.SAL	0.00002	0.00001	2.71506	0.00669
WindSpeed	0.02489	0.00198	12.54748	0
MD_248	0.05406	0.02064	2.61968	0.00888
MD_264	0.33708	0.06021	5.59826	0
CSTL_102	-0.10662	0.0227	-4.69694	0
CSTL_123	-0.27735	0.0429	-6.46571	0
lnAshleyFlow	-0.04618	0.00587	-7.86503	0
lnCooperUOD	0.04672	0.01489	3.13858	0.00173
lnMD_045	0.04199	0.01183	3.55076	0.00039

Table C-5. QR model coefficients for DO at Cooper R. at Pier K, surface

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	8.02925	2.97337	2.70039	0.00729
WaterLevel	-0.28788	0.04223	-6.8174	0
TideRange	-0.10861	0.01507	-7.2049	0
Salinity	0.05042	0.0142	3.55066	0.00044
Temp	-0.11266	0.0071	-15.8582	0
DO	0.10505	0.03812	2.75589	0.00619
Flow.cfs	0.00114	0.00048	2.37039	0.01836
lnFlow.3day	0.5689	0.3218	1.7679	0.07802
UpstreamLoadBOD	-0.00002	0.00001	-2.353	0.01922
WindSpeed	0.04601	0.00707	6.50503	0
lnAshleyFlow	-0.05995	0.01815	-3.30376	0.00106
MD_049	0.78364	0.32161	2.43662	0.01537
MD_264	-1.12341	0.39591	-2.83753	0.00483
CSTL_102	-0.70017	0.26008	-2.6921	0.00747

Table C-6. QR model coefficients for DO at Cooper R. at Pier K, bottom

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	5.2937	2.29384	2.30779	0.02164
WaterLevel	-0.15145	0.05505	-2.75128	0.00627
Salinity	0.10494	0.0205	5.11859	0
Temp	-0.1225	0.01409	-8.69476	0
lnFlow.3day	0.65892	0.2861	2.30314	0.0219
WindSpeed	0.02574	0.00766	3.3599	0.00087
DO	0.09575	0.05634	1.69951	0.09018
lnAshleyFlow	-0.06905	0.02696	-2.56061	0.0109
lnMD_045	-0.3097	0.14226	-2.17697	0.0302
MD_052	-1.86473	0.31849	-5.85483	0
MD_248	0.44777	0.10123	4.4231	0.00001
MD_264	1.53991	0.34494	4.46429	0.00001
CSTL_123	-0.92361	0.19945	-4.63076	0.00001

Table C-7. QR model coefficients for DO at Cooper R. at US 17, mid-depth

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	8.83861	1.8382	4.80829	0
WaterLevel	-0.23616	0.02043	-11.558	0
TideRange	-0.12279	0.00844	-14.5405	0
Temp	-0.07591	0.00991	-7.66219	0
DOSat	0.7563	0.15142	4.99482	0
Flow.cfs	0.00009	0.00003	3.23337	0.00125
lnFlow.3day	-0.2554	0.09793	-2.60787	0.00919
UpstreamLoadBOD	0	0	-3.41351	0.00066
WindSpeed	0.0179	0.00318	5.6289	0
AirTempF	0.0095	0.00173	5.47858	0
lnCoopFlow	-0.05461	0.0076	-7.18228	0
lnCooperUOD	0.15539	0.03288	4.72539	0
lnHarborUOD	-0.11763	0.02075	-5.66789	0
lnMD_045	-0.0992	0.01435	-6.91171	0
MD_049	0.2821	0.05963	4.7312	0
MD_052	0.23289	0.09254	2.51676	0.01193
MD_115	0.28748	0.0777	3.70006	0.00022
MD_248	0.04838	0.02161	2.23916	0.02527
CSTL_123	-0.19092	0.05292	-3.60785	0.00032

Table C-8. QR model coefficients for DO at Cooper R. at US 17, bottom

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	-15.9213	3.11746	-5.10712	0
WaterLevel	-0.13228	0.04289	-3.08424	0.00221
TideRange	-0.09392	0.02047	-4.58693	0.00001
Salinity	0.07174	0.02104	3.40904	0.00073
DOSat	2.19814	0.13873	15.84523	0
lnFlow.3day	0.75157	0.35786	2.10017	0.03647
WindSpeed	0.04261	0.00763	5.58603	0
lnAshleyFlow	-0.09973	0.02185	-4.56538	0.00001
lnHarborUOD	0.10563	0.04128	2.55909	0.01094
MD_049	1.37347	0.31712	4.33112	0.00002
MD_115	0.99791	0.26807	3.72259	0.00023
MD_264	-1.64798	0.34673	-4.75293	0
CSTL_102	-0.92438	0.20547	-4.49882	0.00001
CSTL_123	0.53274	0.19388	2.7477	0.00633

Table C-9. QR model coefficients for DO at Wando R. above Mt. Pleasant at I-526, mid-depth

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	-0.06922	2.30174	-0.03007	0.97601
WaterLevel	-0.3513	0.02349	-14.9565	0
TideRange	-0.17095	0.01034	-16.5404	0
Salinity	0.05458	0.0127	4.29615	0.00002
Temp	-0.05036	0.01239	-4.06363	0.00005
DOSat	1.31484	0.19531	6.7322	0
Flow.cfs	0.00014	0.00002	5.85277	0
UpstreamLoadBOD	0	0	-6.67748	0
WindSpeed	0.02124	0.00364	5.83478	0
AirTempF	0.01352	0.00221	6.12469	0
lnAshleyFlow	0.05894	0.02663	2.21353	0.02699
lnCoopFlow	-0.08915	0.0215	-4.14731	0.00004
MD_049	0.34066	0.06746	5.04979	0
MD_115	0.25088	0.08449	2.96956	0.00302
MD_248	0.05653	0.02628	2.15086	0.03163
CSTL_123	-0.28896	0.05339	-5.41211	0

Table C-10. QR model coefficients for DO at Wando R. above Mt. Pleasant at I-526, bottom

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	-19.1077	2.71855	-7.02866	0
WaterLevel	-0.37745	0.04598	-8.20965	0
TideRange	-0.13024	0.02002	-6.50592	0
Salinity	0.09553	0.01994	4.79154	0
DOSat	2.18967	0.16096	13.60396	0
lnFlow.3day	1.10323	0.29816	3.70015	0.00026
WindSpeed	0.05431	0.0066	8.22327	0
DO	0.08937	0.04184	2.13627	0.03349
lnAshleyFlow	-0.12674	0.02214	-5.72549	0
MD_049	1.82267	0.38098	4.78412	0
MD_052	-3.22912	0.64191	-5.03045	0
MD_115	0.46628	0.1803	2.58621	0.01019
MD_248	0.92662	0.20527	4.51422	0.00001
CSTL_102	-1.0643	0.20054	-5.30731	0
CSTL_123	0.7494	0.17088	4.38559	0.00002

Table C-11. QR model coefficients for DO at Wando R. at Cainhoy

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	4.94344	2.62878	1.88051	0.06098
WaterLevel	-0.36999	0.05015	-7.37817	0
TideRange	-0.1008	0.02498	-4.03565	0.00007
Salinity	0.13113	0.03753	3.49389	0.00055
Temp	-0.14222	0.01159	-12.2721	0
DO	0.12882	0.04596	2.80283	0.00538
lnFlow.3day	0.69402	0.25869	2.68285	0.00769
WindSpeed	0.06871	0.00871	7.88937	0
lnAshleyFlow	-0.13297	0.0291	-4.56891	0.00001
MD_049	0.70447	0.20596	3.42049	0.00071
MD_248	0.40655	0.07161	5.67752	0
CSTL_123	0.62734	0.20172	3.10999	0.00204

Appendix D. Salinity regression model coefficients

Table D-1. Regression model coefficients for salinity at Ashley R. below Summerville

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	9.17193	1.78801	5.12968	0
(Intercept)	5.054055	0.585016	8.639	5.34E-16
WaterLevel	0.203025	0.033135	6.127	3.21E-09
TideRange	0.058498	0.016011	3.654	0.000312
Temp	-0.0578	0.007771	-7.437	1.42E-12
lnAshleyFlow	-0.18642	0.020608	-9.046	< 2e-16
sinT	-0.33267	0.049164	-6.767	8.37E-11
cosT	-0.71657	0.104498	-6.857	4.90E-11

Table D-2. Regression model coefficients for salinity at Ashley R. nr North Charleston at I-516

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	-12.7442	1.946274	-6.548	6.99E-11
WaterLevel	0.8875	0.10876	8.16	5.14E-16
TideRange	0.16754	0.050596	3.311	0.000941
Salinity	1.397547	0.051093	27.353	< 2e-16
Temp	-0.04309	0.00521	-8.271	< 2e-16
Flow.3day	-0.0003	9.51E-05	-3.126	1.79E-03
lnAshleyFlow	-4.04719	0.105349	-38.417	< 2e-16
lnWandoFlow	1.328222	0.079698	16.666	< 2e-16
sinT	-0.48982	0.081694	-5.996	2.30E-09

Table D-3. Regression model coefficients for salinity at Cooper R. at Pimlico

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	0.01654	0.011699	1.414	0.158
TideRange.3day	0.000339	0.000138	2.46	0.014
Salinity	0.003138	0.000132	23.828	< 2e-16
lnFlow.3day	-0.00855	0.001137	-7.518	7.41E-14
lnCoopFlow	-0.00138	8.85E-05	-15.633	< 2e-16
sinT	0.003153	0.000191	16.486	< 2e-16
cosT	0.001081	0.000189	5.711	1.24E-08

Table D-4. Regression model coefficients for salinity at Cooper R. above Goose Cr

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	0.568179	0.124392	4.568	6.19E-06
WaterLevel	0.274388	0.01761	15.582	< 2e-16
TideRange	0.098573	0.009168	10.752	< 2e-16
Temp	-0.0045	0.000865	-5.197	2.94E-07
Flow.3day	-4.9E-05	1.81E-05	-2.683	0.00754
lnAshleyFlow	-0.15159	0.017727	-8.551	< 2e-16
lnWandoFlow	0.123632	0.016221	7.622	1.23E-13

Table D-5. Regression model coefficients for salinity at Cooper R. at Mobay

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	1.890524	0.857725	2.204	2.76E-02
WaterLevel	1.374886	0.038127	36.061	< 2e-16
Salinity	0.312278	0.018048	17.303	< 2e-16
Temp	-0.06641	0.006787	-9.784	< 2e-16
Flow.cfs.SAL	0.000121	3.15E-05	3.851	0.00012
Flow.3day	-0.00085	4.45E-05	-19.156	< 2e-16
lnAshleyFlow	-0.34998	0.03702	-9.454	< 2e-16
lnWandoFlow	0.069948	0.027316	2.561	0.0105
sinT	-0.21254	0.057931	-3.669	2.49E-04
cosT	-0.54073	0.096328	-5.613	2.19E-08

Table D-6. Regression model coefficients for salinity at Cooper R. nr Goose Cr

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	-0.30657	0.033551	-9.137	< 2e-16
WaterLevel	0.052176	0.001904	27.398	< 2e-16
TideRange	0.027756	0.00089	31.202	< 2e-16
Salinity	0.016555	0.000895	18.494	< 2e-16
Temp	-0.00125	9.2E-05	-13.606	< 2e-16
Flow.cfs.SAL	1.21E-05	1.6E-06	7.579	4.74E-14
Flow.3day	-4.6E-05	2.28E-06	-20.208	< 2e-16
lnAshleyFlow	-0.0103	0.000755	-13.646	< 2e-16
sinT	0.004963	0.001451	3.42	0.000635

Table D-7. Regression model coefficients for salinity at Cooper R. at Filbin Cr. at I-526

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	0.383126	1.228791	0.312	0.755226
WaterLevel	1.524542	0.062895	24.239	< 2e-16
TideRange	0.153611	0.032058	4.792	1.75E-06
Salinity	0.74084	0.031978	23.167	< 2e-16
Temp	-0.03523	0.003248	-10.848	< 2e-16
Flow.cfs.SAL	0.000279	5.66E-05	4.936	8.49E-07
Flow.3day	-0.00111	8.02E-05	-13.828	< 2e-16
WindSpeed	-0.03593	0.010349	-3.472	0.000525
lnAshleyFlow	-0.89447	0.068059	-13.143	< 2e-16
lnWandoFlow	0.295952	0.051576	5.738	1.07E-08

Table D-8. Regression model coefficients for salinity at Cooper R. at Pier K, surface

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	3.890886	2.798867	1.39	1.65E-01
WaterLevel	1.439096	0.1536	9.369	< 2e-16
Salinity	0.736653	0.074937	9.83	< 2e-16
Flow.3day	-0.00062	0.000143	-4.338	1.75E-05
WindSpeed	-0.05904	0.023219	-2.543	0.011304
lnAshleyFlow	-1.52729	0.152592	-10.009	< 2e-16
lnWandoFlow	0.549531	0.132795	4.138	4.12E-05
sinT	0.550426	0.144985	3.796	0.000165
cosT	1.123487	0.103466	10.859	< 2e-16

Table D-9. Regression model coefficients for salinity at Cooper R. at Pier K, bottom

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	16.09683	3.94281	4.083	5.19E-05
WaterLevel	0.90048	0.14537	6.194	1.23E-09
TideRange	-1.04798	0.06733	-15.566	< 2e-16
Salinity	0.81743	0.07287	11.218	< 2e-16
Temp	-0.16059	0.03325	-4.83	1.82E-06
lnAshleyFlow	-1.14959	0.14405	-7.981	1.01E-14
lnWandoFlow	0.3573	0.12624	2.83	4.84E-03
sinT	-1.21506	0.24312	-4.998	8.05E-07
cosT	-1.78743	0.46249	-3.865	1.26E-04

Table D-10. Regression model coefficients for salinity at Cooper R. at US 17, mid-depth

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	9.976541	1.158884	8.609	< 2e-16
WaterLevel	1.357376	0.061922	21.921	< 2e-16
TideRange	0.651098	0.029224	22.279	< 2e-16
Salinity	0.619032	0.029266	21.152	< 2e-16
Temp	-0.0414	0.005846	-7.081	1.86E-12
Flow.3day	-0.00042	5.41E-05	-7.849	6.22E-15
WindSpeed	-0.03964	0.009649	-4.109	4.11E-05
lnAshleyFlow	-1.07694	0.062461	-17.242	< 2e-16
lnWandoFlow	0.321568	0.046909	6.855	8.98E-12
cosT	-0.26359	0.081839	-3.221	0.0013

Table D-11. Regression model coefficients for salinity at Cooper R. at US 17, bottom

Variable	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	9.17193	1.78801	5.12968	0

Appendix E. LCL Calculation Script (Tol_low2.R)

```
# version 1.2   D. Helsel 3/07/2019
Tol_low<- function(x,cover, conf,TYPE = 6){
xname = deparse(substitute(x))
xsort<-sort(x);
xx <- na.omit(xsort)
n = length(xx)
cat(" Your request",'\n')
cat(" cover = ", cover,"conf = ", conf, "data = ", xname, '\n')
cat("..........",'\n')
perc1 = as.character(cover)
conf = conf/100.0
perc = cover/100.0
ntest<-log(1-conf)/log(perc)
if(n < ntest){print("Number of samples insufficient to compute "); print(" requested distribution-free tolerance limit")
print(" You have "); print(n)
print ( " You need at least.."); print (ntest)}
if( n > ntest){k1<-(perc*(n+1));n1<-floor(k1); n2<-n1+1;
if(n2>n){qtlNP <- max(xx)};
if(n2<=n){qtlNP<- quantile(xx, probs = perc, type = TYPE)
}
knp<-qbinom(conf,n,perc, lower.tail = FALSE);knp1<-knp-1;lclnp1<-xx[knp];
trueconf1<-pbinom(knp1,n,perc, lower.tail = FALSE)
trueconf1 <- 100.0*trueconf1
#cat("lclnp1 =",lclnp1, '\n')
RESULTS3<-data.frame(PERCENT=perc1,TRUECONF = trueconf1,QUANTILE=qtlNP,LCLNP=lclnp1)
cat(perc1,"-th quantile = ",qtlNP,'\n')
cat("---------------",'\n')
cat("Two Nonparametric LCLs that bound the requested confidence",'\n')
cat("Exact  confidence not always attainable nonparametrically",'\n')
cat('\n')
cat("Nonparametric LCL . greater confidence ",'\n')
cat("Achieved Confidence = ",trueconf1, "Lower limit = ",lclnp1,'\n')
#print(RESULTS3)
knp2<-knp1+1

lclnp2<-xx[knp2+1];
trueconf2<-pbinom(knp2,n,perc,lower.tail =  FALSE)
trueconf2 <- 100.0*trueconf2

RESULTS4<-data.frame(PERCENT=perc1,TRUECONF=trueconf2,QUANTILE=qtlNP,LCLNP=lclnp2)
```

```
cat('\n')

cat("Nonparametric LCL ... lesser confidence",'\n')
cat("Achieved Confidence = ",trueconf2, "Lower limit = ",lclnp2,'\n')

#print(RESULTS4)
#cat("Percent   Actual Confidence  Quantile   Lower Confidence Limit",'\n')
#cat (" ", perc1, trueconf2,qtlNP, lclnp2, '\n')
}}
```