**Delaware Department of Natural Resources
and Environmental Control**

MURDERKILL RIVER WATERSHED REVISED NUTRIENT AND DISSOLVED OXYGEN TMDLs

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PREFACE

As required by the Federal Clean Water Act, the Delaware Department of Natural Resources and Environmental Control (DNREC) is responsible for implementing water quality monitoring and assessment activities in the State and also for establishing Total Maximum Daily Loads (TMDLs) on impaired State surface waters as indicated on the State's 303(d) List.

On May 12, 2005, the Cabinet Secretary of DNREC issued Order No. 2005-W-0025 adopting amended Total Maximum Daily Load (TMDL) Regulations for nutrients and oxygen consuming compounds for the entire Murderkill River Watershed. Since promulgation of the 2005 amended TMDL, a multi-year monitoring, research and modeling study of the Murderkill River Watershed by DNREC and other cooperating agencies and institutions resulted in proposing scientifically-based, site-specific dissolved oxygen (DO) criteria and nutrient targets for the tidal Murderkill River. This multi-year effort necessitated revisions to the 2005 TMDL that will comply with the proposed site-specific DO criteria and nutrient targets for the tidal Murderkill River.

The proposed revisions to the Murderkill River Watershed nutrient and DO TMDL will be presented during a Public Hearing to be held on April 29, 2014 at the DNREC main office in Dover. All comments received before and during the Public Hearing process will be considered by DNREC. Based on the comments received, the report may be modified accordingly.

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SECTION 1

INTRODUCTION

The Murderkill River watershed is situated in the southeastern portion of Kent County in Delaware and includes several main tributaries (Double Run, Spring Creek, Browns Branch) and five lakes/ponds (McGinnis Pond, Andrews Lake, Killen Pond, Coursey Pond, McColley Pond). The river has tidal reaches from its mouth at Bowers Beach upstream to locations just downstream from the pond/lake dams and near Barratts Chapel Road on Double Run. At Bowers Beach, the Murderkill River connects to Delaware Bay. The river is bounded by the St. Jones River watershed to the north and the Mispillion River watershed to the south. There are large tidal marshes interfacing with the river from Bowers Beach upstream to near Route 1. Figure 1 presents a study area map of the Murderkill River watershed.

Historical water quality monitoring conducted by the Delaware Department of Natural Resources and Environmental Control (DNREC) has shown that waters in the tidal portions of the Murderkill River do not meet their designated uses because of low dissolved oxygen (DO) levels that are below the State water quality standards of 5 mg/L as a daily average and 4 mg/L as an instantaneous minimum. Based on these DO violations, DNREC listed the tidal segments of the Murderkill River on the State's 1996 303(d) list of impaired waters that required the development of a Total Maximum Daily Load (TMDL) to bring the river into compliance with State water quality standards. In 2001, DNREC completed development of a water quality model of the Murderkill River and used it to propose TMDLs for sources of oxygen consuming compounds and nutrients in the watershed. This 2001 TMDL was later amended by DNREC in 2005 (DNREC, 2005).

Since promulgation of the 2005 TMDL, significant additional monitoring, modeling and related studies have been completed (HDR|HydroQual, 2013) that have advanced the science and understanding of the water quality dynamics in the river. This effort has been coordinated through the activities of the Murderkill Study Group through the leadership of DNREC and the Kent County Department of Public Works (KCDPW). Members of this Study Group that have been involved in the new research and development include: DNREC; KCDPW; University of Delaware; United States Geological Survey (USGS); Delaware Geological Survey (DGS); University of Maryland; Stroud Water Research Center; Academy of Natural Science; and HDR|HydroQual. The purpose of these additional efforts was to establish site-specific DO criteria and nutrient targets for the tidal portion of the Murderkill River and to revise the 2005 TMDL for the tidal Murderkill River, if necessary.

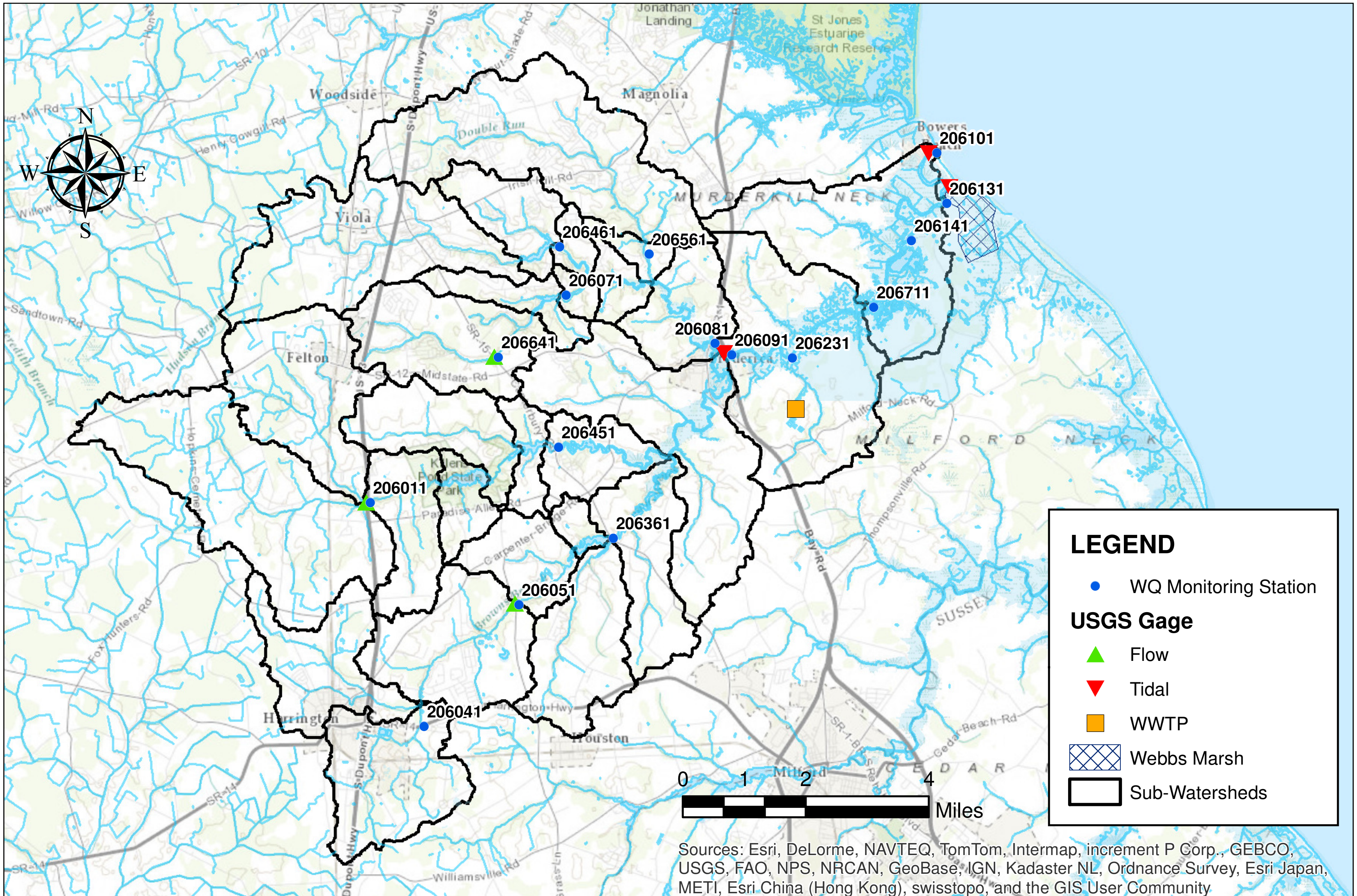

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Figure 1. Murderkill River Watershed Study Area

A TMDL is defined as the maximum amount of a pollutant that a water body can receive and still meet water quality standards along with an allocation of that load among the various sources of the pollutant. It is comprised of three components: a waste load allocation (WLA) for point source and municipal separate storm sewer system (MS4) loads; a load allocation (LA) for nonpoint source loads; and a margin of safety (MOS). Numerically, the TMDL is defined with the following equation:

$$TMDL = \Sigma WLA + \Sigma LA + MOS$$

To assist with this process, HDR|HydroQual developed mathematical models of the Murderkill River watershed. These mathematical models included a landside watershed model to calculate runoff quantity and nonpoint source (NPS) loads, a hydrodynamic model to calculate the movement of water in the tidal reaches of the Murderkill River, and a water quality model with a sediment flux sub-model that is coupled to the hydrodynamic model to calculate water quality in the tidal reaches of the river. DNREC used the above modeling tools, along with findings from other monitoring and research studies, to propose site-specific DO criteria and nutrient targets for the tidal Murderkill River that reflect the natural processes associated with the extensive tidal marshes that affect DO levels in the tidal river. These research studies, data collection/analysis and model development are presented in the following reports and journal articles:

- Murderkill River Watershed TMDL Model Development and Calibration (HDR|HydroQual, 2013);
- Tidal Murderkill River Site-Specific Dissolved Oxygen Criteria (HDR|HydroQual, 2014);
- Primary Production in the Murderkill River. A Report to Kent County and DNREC by the School of Marine Science and Policy, College of Earth, Ocean, and Environment, University of Delaware, Lewes DE (Sharp, J.H., 2011);
- Temporal and Spatial Variability of Sea Level and Volume Flux in the Murderkill Estuary (Wong, K-C., B. Dzwonkowski and W.J. Ullman, 2009. Estuarine, Coastal and Shelf Science, 84 (2009) 440-446);
- Water Level and Velocity Characteristics of a Salt Marsh Channel in the Murderkill Estuary, Delaware (Dzwonkowski, B., K-C. Wong and W.J. Ullman, 2013. Journal of Coastal Research, in press);
- Nutrient Exchange between a Salt Marsh and the Murderkill Estuary, Kent County, Delaware (Ullman, W., A. Aufdenkampe, R.L. Hays and S. Dix, 2013);

- Nutrient Flux Study Results from the Murderkill River-Marsh Ecosystem, Final Report. Prepared for Kent County Levy Court (Chesapeake Biogeochemical Associates, 2010);
- Characterization of Tidal Wetland Inundation in the Murderkill River Estuary. Delaware Geological Survey, University of Delaware. Submitted to Kent County Levy Court (McKenna, T.E., 2013); and
- Vertical Profiles of Radioisotopes, Nutrients and Diatoms in Sediment Cores from the Tidal Murderkill River Basin: A Historical Analysis of Ecological Change and Sediment Accretion. PCER Report No. 10-01. Patrick Center for Environmental Research, The Academy of Natural Sciences (Velinsky, D., C. Sommerfield and D. Charles, 2010).

In addition, continuous tidal monitoring for salinity, temperature, DO, pH, water elevation and volume flux was completed by the USGS in the tidal Murderkill River near Frederica and at Bowers Beach along with the installation of three stream gaging stations to monitor flow in the watershed on the Murderkill River, Pratt Branch and Browns Branch. Increased sampling in the Murderkill River watershed by DNREC was also completed for this study along with the completion of long-term BOD studies on river samples and Kent County Regional Wastewater Treatment Facility (KCRWTF) effluent. The DNREC sampling frequency was increased to bi-weekly or monthly with the addition of a few additional monitoring locations.

A summary of some of the data and modeling information related to the Murderkill River Watershed TMDL is presented in the following sections but detailed information relating to the research studies, data collection and modeling are contained in the above references.

1.1 303(D) LISTED WATERBODIES

The water bodies listed on the State of Delaware's 2012 303(d) List for nutrient and DO impairments in the Murderkill River Watershed are presented in Table 1 (DNREC, 2013). There are a total of 12 listed water segments: 3 tidal segments of the Murderkill River (lower Murderkill, Spring Creek, mid Murderkill); 4 freshwater stream segments (Browns Branch, upper Murderkill, Fan Branch, Black Swamp Creek); and 5 freshwater lakes or ponds (McGinnis Pond, Andrews Lake, Coursey Pond, Killens Pond, McCauley Pond). These segments are listed for nutrients, ammonia and/or DO with the most probable source of pollutants identified as point source (PS) and nonpoint source (NPS) loads. The TMDL development in the Murderkill River watershed and presented in this report was completed to address the nutrient and DO impairments in the tidal Murderkill River (DE 220-001).

Table 1. Murderkill River Watershed Nutrient and DO TMDL Segments					
Water Body ID	**Segment (Category)**	**Size Affected**	**Description**	**Parameters**	**Probable Source**
DE 220-001	Lower Murderkill (4A)	7.6 miles	From the confluence with Spring Creek to the mouth at Delaware Bay	Nutrients, DO	PS, NPS
DE 220-002	Spring Creek (5)	15.8 miles	From the headwaters to the confluence with Murderkill River, excluding Andrews Lake and McGinnis Pond	Nutrients, DO	PS, NPS
DE 220-003	Mid Murderkill River (5)	9.2 miles	From McCauley and Coursey Pond to the confluence with Spring Creek	Nutrients	PS, NPS
DE 220-004	Browns Branch (5)	8.8 miles	From the headwaters adjacent to Harrington to the confluence with McCauley Pond	Nutrients, DO Ammonia	NPS PS, NPS
DE 220-005	Upper Murderkill River (5)	7.4 miles	From the headwaters to the confluence with Coursey Pond, excluding Killens and Coursey Ponds	Nutrients, DO	NPS
DE 220-005	Upper Murderkill River (5)	2.31 miles	Fan Branch - from the headwaters to the confluence with Murderkill River	DO	NPS
DE 220-005	Upper Murderkill River (5)	0.75 miles	Black Swamp Creek - from the headwaters of Black Swamp to the confluence with the next larger stream	DO	NPS
DE 220-L01	McGinnis Pond (4A)	31.3 acres	Pond east of Viola	Nutrients, DO	NPS
DE 220-L02	Andrews Lake (4A)	17.5 acres	Pond west of Frederica	Nutrients	NPS
DE 220-L03	Coursey Pond (4A)	58.1 acres	Pond southwest of Frederica	Nutrients	NPS
DE 220-L04	Killens Pond (4A)	75.1 acres	Pond southwest of Felton	Nutrients	NPS
DE 220-L05	McCauley Pond (4A)	49.0 acres	Pond northeast of Harrington	Nutrients	NPS

1.2 DESIGNATED USES

According to the “State of Delaware Surface Water Quality Standards (Amended June 1, 2011)”, the designated uses applicable to the Murderkill River that must be maintained and protected through the application of appropriate criteria are uses for: industrial water supply; primary contact recreation; secondary contact recreation; fish, aquatic life and wildlife including shellfish propagation; and agricultural water supply in freshwater segments only (DNREC, 2011). These designated uses are applicable to the Murderkill River and are achieved and maintained through the application of water quality standards, site-specific criteria or targets.

1.3 EXISTING WATER QUALITY STANDARDS AND NUTRIENT TARGETS

According to the “State of Delaware Surface Water Quality Standards (Amended June 1, 2011)”, water quality standards (WQS) for dissolved oxygen (DO) exist. The existing DO WQSs in freshwater are a daily average of not less than 5.5 mg/L (minimum of 4 mg/L) and in marine waters a daily average of not less than 5 mg/L (minimum of 4 mg/L).

For nutrients, some site-specific or basin-specific standards exist but acceptable nutrient levels are determined based on their ultimate effect on DO or algal levels through nutrient-algal-DO relationships (eutrophication) and/or threshold levels. The nutrient standards are currently in narrative form for controlling nutrient over enrichment and are stated as:

> "Nutrient over enrichment is recognized as a significant problem in some surface waters of the State. It shall be the policy of this Department to minimize nutrient input to surface waters from point sources and human induced nonpoint sources. The types of, and need for, nutrient controls shall be established on a site-specific basis. For lakes and ponds, controls shall be designed to eliminate over enrichment."

Although national numeric nutrient criteria have not been established, DNREC has used target levels of 2.0-3.0 mg/L for total nitrogen (TN) and 0.1-0.2 mg/L for total phosphorous (TP) for listing water bodies on the State's 303(d) List and 305(b) assessment reports. Nutrient related algal effects typically require sufficient time for impacts to be noticed (i.e., impacts are long term in nature rather than instantaneous), therefore, the nutrient targets are applied on a long-term average basis (i.e., generally annual average).

1.4 SITE-SPECIFIC DISSOLVED OXYGEN CRITERIA AND NUTRIENT TARGETS

Since the development of the original Murderkill River Watershed TMDL in 2001 and the TMDL Amendment in 2005, significant additional monitoring, modeling and related studies have been completed (HDR|HydroQual, 2013) that have advanced the science and understanding of the water quality dynamics in the river. This effort has been coordinated through the activities of the Murderkill Study Group through the leadership of DNREC and the Kent County Department of Public Works (KCDPW). The purpose of these additional efforts was to establish site-specific criteria for DO in the tidal portion of the Murderkill River and amend the 2005 TMDL for the tidal Murderkill River, if necessary. The development of and resulting site-specific DO criteria developed for the tidal Murderkill River are presented in the report titled *"Tidal Murderkill River Site-Specific Dissolved Oxygen Criteria"* (HDR|HydroQual, 2014). The development of and resulting site-specific nutrient targets are presented in Section 6 of this report. These site-specific criteria and targets, which will be the subject of a Public Hearing on April 29, 2014, are used to develop and propose nutrient and DO TMDLs for the tidal Murderkill River as presented in this report.

The proposed site-specific DO criteria for the tidal Murderkill River only are as follows:

- Summer daily average DO greater than or equal to 3.0 mg/L;
- Summer daily minimum (1-hour average) DO greater than or equal to 1.0 mg/L; and
- Existing DO standards to apply during winter months (daily average of 5.0 mg/L and daily minimum of 4.0 mg/L).

The summer "warm" period is defined as May 15 through September 30 and the winter "cool" period as October 1 through May 14. The spring transition from winter "cool" to summer "warm" conditions (May 15) is based on the Chesapeake Bay Ambient DO Criteria (EPA, 2003) migratory fish spawning and nursery designated use season (February 1 through May 31) but modified slightly to reflect site-specific DO data in the tidal Murderkill River. It should be noted that these site-specific DO criteria do not apply to the upstream freshwater reaches of the watershed (i.e., tidal reach only). Figure 2 presents the tidal reach of the Murderkill River where the site-specific DO criteria will apply.

The proposed site-specific nutrient targets (as will be discussed in Section 6 of this report) are as follows:

- Annual average TN less than or equal to 2.0 mg/L; and
- Annual average TP less than or equal to 0.20 mg/L.

These proposed site-specific DO criteria and nutrient targets are based on two very important findings that emerged from the Murderkill River studies. First, the high natural turbidity in the tidal Murderkill River that occurs as a result of the high tidal energy in the river significantly suppresses algal production as compared to systems with better water clarity regardless of the concentration of nutrients. The result is that phytoplankton populations (as measured by chlorophyll-a) are light limited such that nutrient controls have limited effect on phytoplankton levels. That is, nutrient reductions will have limited effect on reducing phytoplankton populations because algal growth is limited by the available light conditions. Therefore, since algal production is light limited, the nutrient-algal effect on river DO levels is also minimized due to the associated limited phytoplankton oxygen production and respiration. For these reasons, DO was considered an important nutrient endpoint (i.e., nutrient related effect) for the tidal Murderkill River as opposed to chlorophyll-a or algal levels. In addition, DO levels have a direct link to aquatic life protection.

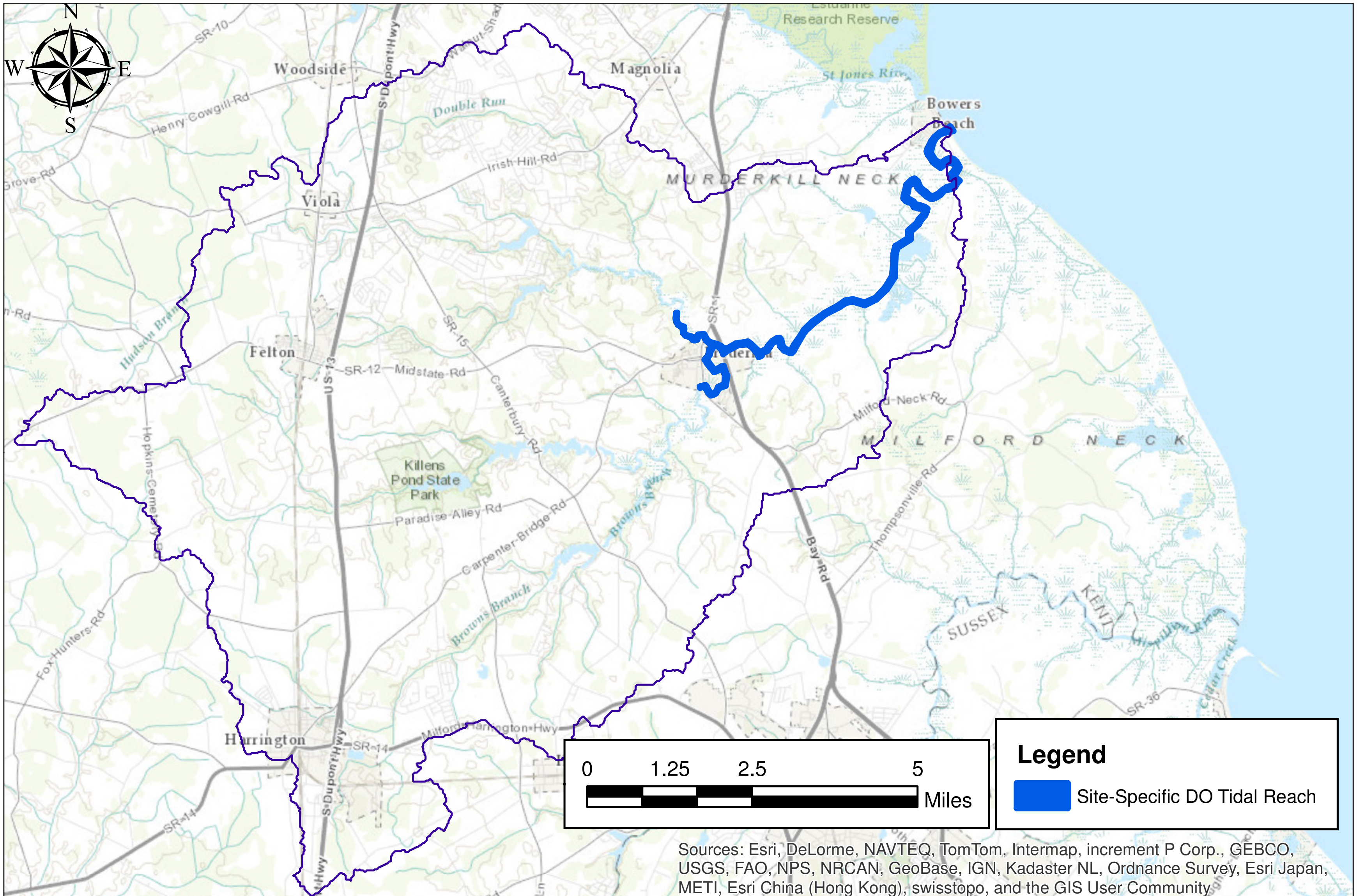

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Figure 2. Murderkill River Tidal Reaches where Site-Specific DO Criteria Apply

Secondly, the extensive acreage of freshwater and tidal marshes in this watershed contributes large loadings of organic carbon and anoxic wetland ebb waters (i.e., leaving the tidal marshes on the outgoing tide) that affect DO levels in the river. In addition, the marshes can be a nutrient sink or source depending on the season or tidal inundation level. The tidal Murderkill River models were used to estimate the summer average impact of the tidal marshes and found that DO decreases from 1.3-2.2 mg/L occurred as a result of the natural organic carbon and low DO loading associated with the tidal marshes. In the middle of the river where minimum DO levels occur, the summer average DO decrease is approximately 2 mg/L. Therefore, DO levels in the tidal Murderkill River are significantly impacted by interactions with the tidal marshes and are the dominant factor controlling DO levels.

In response to these findings, the Murderkill Study Group recommended that:

1. The 2005 TMDL reduction levels for nonpoint sources and for the non-tidal part of the Murderkill River Watershed remain unchanged in order to address impairments in the freshwater portion of the system, especially the upstream ponds and lakes;
2. DNREC amend the Surface Water Quality Standards Regulation to include site-specific DO criteria; and
3. DNREC establish site-specific nitrogen and phosphorus target values for the tidal Murderkill River.

Although changes in nutrient concentrations have little impact on DO levels, the Murderkill Study Group decided that there is a continued need to limit the input of nutrients to the tidal Murderkill River and to minimize the downstream impact of nutrients. The proposed nutrient targets correspond to the maximum nutrient reduction levels from point and nonpoint sources that are practical and achievable. In this respect, the proposed nutrient targets minimize downstream nutrient impacts and prevent any significant increases in river nutrient levels due to anthropogenic sources.

SECTION 2

WATERSHED CHARACTERISTICS

2.1 LAND USE

The land use information used in the HSPF watershed model for the year 2007 was obtained from DNREC and is presented in Figure 3. The Murderkill River watershed is primarily non-urban (85%) with approximately 55% agricultural land use for a total area of approximately 62,000 acres (97 mi^2). The 2007 land use information included 47 categories which were regrouped into 10 categories for use in the HSPF model setup (Table 2). Land use areas for the 6 major sub-watersheds are presented in Figure 4.

Table 2. Murderkill River Watershed HSPF Land Use Summary

Land Use Type	Area (acres)	Area (mi^2)	% of Total
Agriculture	34,237	53.5	55.4%
Wetlands	8,949	14.0	14.5%
Residential	7,779	12.2	12.6%
Forest	7,077	11.1	11.4%
Urban	1,117	1.7	1.8%
Water	1,088	1.7	1.8%
Transitional	601	0.9	1.0%
Pasture	519	0.8	0.8%
Roadways	273	0.4	0.4%
CAFO	183	0.3	0.3%
Total	61,824	96.6	

2.2 POINT SOURCES

In the Murderkill River watershed there were two active point sources during the 2007-2008 modeling period: Kent County Regional Wastewater Treatment Facility (KCRWTF) and Harrington Sewage Treatment Plant (STP). There were two other point sources in the watershed (Canterbury Crossing and Southwood Acres Mobile Hone Park) that were eliminated before the 2007-2008 modeling period. The KCRWRF discharges into the tidal portion of the river and the Harrington STP discharges near the upstream end of Brown's Branch just east of the Town of Harrington. Given the locations of these two point sources, the KCRWRF flow and loads are assigned in the tidal hydrodynamic/water quality model (ECOMSED/RCA) model and the Harrington STP flow and loads are assigned in the HSPF watershed model. Table 3 presents the average flow and

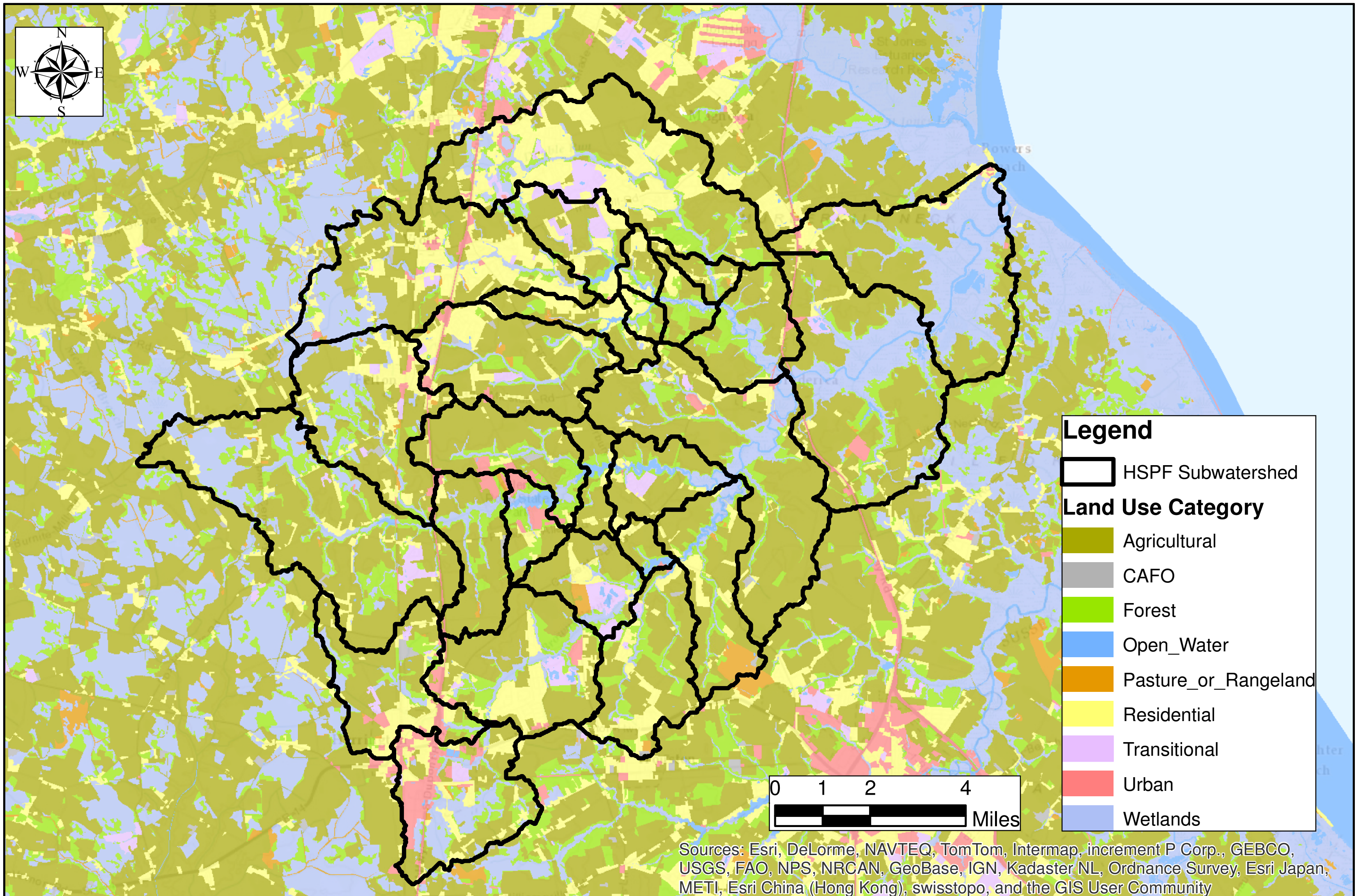

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Figure 3. Murderkill River Watershed HSPF Segmentation and Land Uses

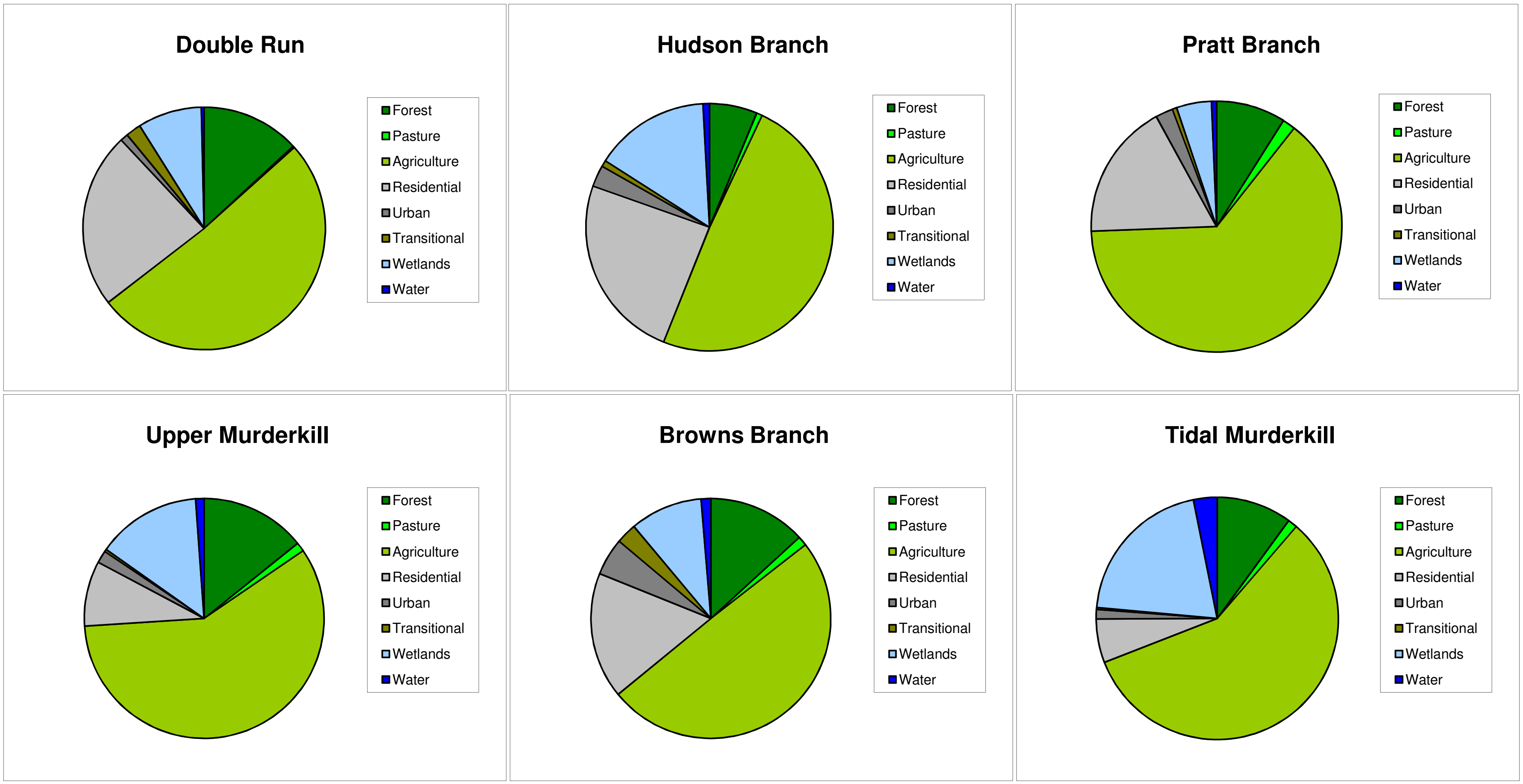

Figure 4. Murderkill River Watershed 2007 Land Use for Major Sub-watersheds

concentration data for each of the parameters from these point sources during the 2007-2008 modeling period. The total nitrogen (TN) and total phosphorus (TP) loads during the modeling period for the Harrington STP are 66.4 lb/d TN and 0.9 lb/d TP; and for the KCRWRF are 553.3 lb/d TN and 173.1 lb/d TP. Although the Harrington STP loads are less, this discharge is located in the headwaters of Browns Branch and given the high effluent NH_3 concentrations has a large impact on toxicity and DO levels in Browns Branch. Since the KCRWRF discharge is located in the tidal portion of the river with much greater rates of tidal mixing, the water quality impacts are less with current TP loads still being significant in the tidal river.

Table 3. Point Source Load Summary (2007-2008)

Parameter	Harrington STP	KCRWTF
Flow (MGD)	0.45	10.7
$CBOD_5$ (mg/L)	4.3	3.2
DO (mg/L)	n/a	8.4
TSS (mg/L)	6.9	6.2*
TN (mg/L)	17.7	6.2
NH_3 (mg/L)	17.6	1.0
NO_2+NO_3 (mg/L)	n/a	3.7
TP (mg/L)	0.24	1.94
PO_4 (mg/L)	n/a	1.66
* - VSS data		

Septic systems are also nutrient sources in the watershed both through groundwater contributions but also directly to the streams from failing or improperly operated systems. Therefore, septic nutrient loads were assigned in the model based on the location of septic systems throughout the watershed (2005 data) as provided by DNREC. Figure 5 presents the septic system locations along with the HSPF model sub-watershed segmentation. For each sub-watershed segment, NO_2+NO_3 and PO_4 loads from septic tanks were estimated and assigned as point sources in the HSPF model as a constant source. Septic loads were computed for each sub-watershed by multiplying the number of septic systems by the average number of people served by each system, typical septic overcharge flow rate, failure rate and concentration. A final scale factor of 25% of the original calculated septic system load was determined during the calibration process, which may represent the percentage of failing septic systems. The total septic system loads were 14.0 lb/d NO_2+NO_3 and 2.8 lb/d PO_4.

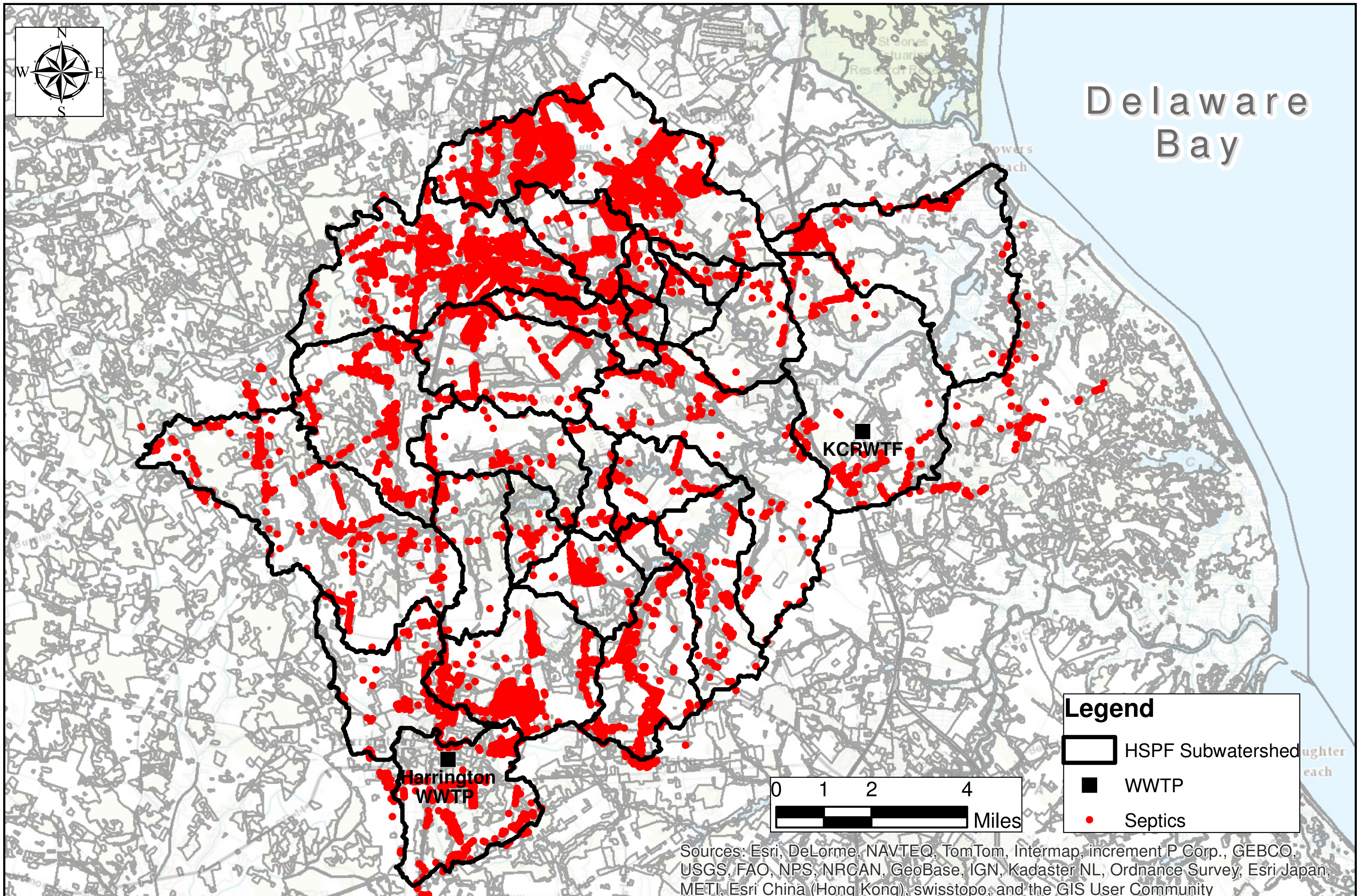

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Figure 5. Murderkill River Watershed Septic System Distribution

SECTION 3

WATERSHED MONITORING

Five project specific studies were completed to support the Murderkill River Study that provided data to support the water quality model setup and calibration/validation efforts. These data included: the USGS continuous monitoring at Bowers Beach (#01484085) and Frederica (#01484080); long term BOD (LTBOD) studies completed on river samples (DNREC) and KCRWTF effluent (KCDPW); algal production studies completed at seven tidal river stations (Sharp, 2011); tidal marsh nutrient, carbon and DO deficit load studies completed in Webb's Marsh (Ullman, W., et. al, 2013); and sediment flux studies completed on cores in the tidal river (Chesapeake Biogeochemical Associates, 2010).

The LTBOD studies were used to develop a relationship between the more frequently measured BOD_5 parameter and ultimate BOD (BODu), which is used for model calibration and conversion of model inputs to carbon units that are needed for model setup. This is required for both river and KCRWTF effluent samples. In addition, the LTBOD studies provide an estimate of the BOD oxidation rate, which is used to assign this constant in the model. LTBOD tests were completed at 16 river stations (5 freshwater sites, 4 lake/pond sites, 7 tidal sites) during 6 sampling events in 2007-2008. For the KCRWTF effluent, LTBOD tests were completed 15 times on a roughly monthly basis in 2007-2008.

The algal production data collected by the University of Delaware (Sharp, 2011) was used for adjusting the model phytoplankton growth rate during calibration/validation so that model calculated ambient growth rates compared favorably to the algal production data. Algal production tests were completed at seven tidal river stations from Bowers Beach to Frederica on 22 dates in the 2007-2008 modeling period. Primary production was estimated through incubation of samples over a 24-hour period at varying light levels to simulate different depths in the water column from the surface down to the 1.5% light depth.

The tidal marsh studies completed in Webb's Marsh (Ullman, W., et. al, 2013) provided estimates of nutrient, carbon and DO deficit loads that were then extrapolated to the rest of the Murderkill River tidal marsh area for use in assigning these loads in the model. The DO deficit load represents the difference between the ebb DO levels and the flood DO levels. Typically, the flood DO levels (incoming) are greater than the ebb DO levels (outgoing) due to oxygen consumption in the marsh and this process was reflected in the model input setup. The tidal marsh studies completed involved measurement of the various forms of organic and inorganic nitrogen and phosphorus, organic carbon, chlorophyll-a (chl-a), silica and suspended solids. For the organic forms both particulate and dissolved fractions were measured. The data were collected near the mouth of Webb's Marsh with the Murderkill River approximately every hour over roughly two to three complete tidal cycles in July 2007, October 2007, April 2008, May 2008 and August 2008. In addition, the USGS had a continuous gage located at the same location that recorded salinity, temperature, DO, water elevation and tidal volume flux over the 2007-2008 modeling period. Through analysis of both the water quality data and USGS tidal data at the mouth of the marsh, nutrient, carbon and DO deficit loads were calculated for each monitoring period. These loads were used to define the tidal marsh loads in the model by normalizing them with the active Webb's Marsh area (157 acres) and extrapolating to the rest of the Murderkill River tidal marsh area based on the LiDAR study (McKenna, 2013) that developed tidal marsh areas by zones in the river.

The sediment flux studies completed in the tidal Murderkill River (Chesapeake Biogeochemical Associates, 2010) provided estimates of sediment oxygen demand (SOD) and nutrient fluxes at four locations in the main stem of the river (July 2007) and six tidal marsh sites (July 2007 and April 2008). SOD and nutrient fluxes were determined from the collection of sediment cores that were incubated for approximately 5 hours with the measurement of DO and nutrients over time completed. From these data, regressions are completed to determine the sediment areal uptake or production rate of oxygen, NH_3, NO_2+NO_3, PO_4, N_2 gas and silica. The river data are used for calibration/validation of the sediment flux model and the marsh data used for an initial starting estimate of the tidal marsh denitrification rate. The final tidal marsh denitrification rate was determined from model calibration/validation and was assigned at 15 $gN/m^2/yr$.

In addition, continuous tidal monitoring for salinity, temperature, DO, pH, water elevation and volume flux was completed by the USGS in the tidal Murderkill River near Frederica and at Bowers Beach along with the installation of three stream gaging stations to monitor flow in the watershed on the Murderkill River, Pratt Branch and Browns Branch. Increased sampling in the Murderkill River watershed by DNREC was also completed for this study. The DNREC sampling frequency was increased to bi-weekly or monthly with the addition of a few additional monitoring locations.

3.1 OVERALL WATER QUALITY ASSESSMENT

In general, the water quality data analysis in the tidal Murderkill River watershed indicates that the watershed experiences low DO levels, less than the State WQS daily average of 5 mg/l and minimum of 4 mg/L at many stations. Potential oxygen demands include tidal marsh interactions, sediment oxygen demand (SOD), BOD oxidation, ammonia nitrification and/or algal respiration. These oxygen demands can originate from point and nonpoint sources but also potentially from tidal marsh loading of organic material. The data indicate sufficient nutrient concentrations at most of the stations to support algal growth. Table 4 presents a summary of the available tidal river water quality data as presented in the DNREC 2012 Integrated 305(b) and 303(d) List Report. These data show that DO levels are lowest in the middle of the river with TN levels generally decreasing in the downstream direction and TP levels decreasing in the upstream and downstream directions from roughly station 206213.

Table 4. Summary of Data for 305(b) and 303(d) Report[1]				
Tidal Station	TN (mg/L)[2]	TP (mg/L)[2]	DO (mg/L)[3]	# of DO samples <4 mg/L
206101 (Bowers Beach)	1.7	0.23	5.6	0
206131 (Webbs Landing)	1.6	0.20	5.3	2
206141 (Milford Neck)	2.1	0.24	3.9	10
206711 (Power Lines)	2.2	0.28	3.3	7
206231 (KC Canal)	3.3	0.80	3.4	15
206091 (Rte. 113)	3.0	0.27	4.1	8
206081 (Rte. 12)	2.8	0.28	4.6	5
1 – Data period is 9/1/2006 through 8/31/2011 2 – 5-year average 3 – 10th percentile				

3.2 SOURCES OF POLLUTION

Nonpoint source pollution can be defined as pollution that occurs over large areas as a result of common practices and land uses. Unlike a point source that discharge loads into a water body at a specific location, nonpoint sources will affect a water body at spatially variable locations, such as ground water seepage or agricultural runoff along a given stream length. In order to quantify nonpoint sources in the Murderkill River watershed, land areas were classified according to land use, pollutant build-up and wash-off coefficients, and groundwater concentrations using the HSPF watershed model. The land use distribution in the Murderkill River watershed was generalized into the groups shown in Table 2: agriculture, wetland, residential, forest, urban, water, transitional, pasture, roadways, and combined animal feeding operations (CAFO). Each of these land uses has different possible sources of pollution that are deposited directly or indirectly to the water system.

Approximately 55% of the Murderkill River watershed was classified as agriculture, including cropland, farm related buildings, idle fields, and orchard and nursery land uses. Possible nonpoint sources of pollution from these areas include nutrients from farm fields, organic material from plants, nutrients from applied fertilizers, and particulate and dissolved nutrients in runoff.

Wetland areas account for 15% of the watershed area and are home to many species of plants and wildlife that produce organic and nutrient material. The majority of the wetland area is associated with the tidal marshes that fringe the tidal river. Loadings from these wetland areas are assigned separately in the tidal river model based on data from the tidal marsh studies completed.

Residential and urban land uses often increase nonpoint pollution due to decreased perviousness and increased human development. The residential land use contains single and multiple family dwellings along with mobile home parks. The urban land use contains junk/salvage yards, mixed urban, retail/wholesale, commercial, communication, industrial, institutional/government, utilities, and recreational. Among the causes of pollution from residential/urban land uses are nutrients in runoff from impervious surfaces, nutrients and bacteria from septic systems, nutrients from residential fertilizers, industrial wastes and domestic pet wastes. Approximately 14% of the Murderkill River watershed is residential/urban land use.

Forested areas account for a little more than 11% of the watershed. The types of forest are deciduous, mixed and evergreen. Nutrients from wild animals and organic material from plants are common sources of nonpoint pollution.

Transitional, pasture, roadway and CAFO land uses each comprise less than 1% of the watershed and can provide nutrient and organic material runoff from these land surfaces.

Based on the land use data, the Murderkill River watershed is primarily non-urban (85%) and, therefore, NPSs are an important source of pollution in the watershed. There were two (2) active NPDES permitted PSs in the watershed (Harrington STP and KCRWTF) during the monitoring and model calibration/validation period of 2007-2008. Information on these two PSs is presented in Section 2.2.

SECTION 4

MODELING FRAMEWORKS

The Murderkill River modeling framework is comprised of three components: a watershed model; a hydrodynamic model; and a water quality model (HDR|HydroQual, 2013). The watershed model characterizes watershed processes in the watershed such as rainfall driven runoff and nonpoint source loadings including freshwater stream and lake/pond water quality interactions. The hydrodynamic model simulates the tidal movement of water due to tides and freshwater flow, density driven currents, and meteorology confined by a realistic representation of the systems bathymetry and also calculates salinity and temperature. The water quality model calculates nutrient mediated algal growth and death, DO, the various organic and inorganic forms of nitrogen, phosphorus, silica, and carbon (or BOD). In addition, the water quality model includes a sediment flux sub-model to calculate sediment oxygen demand (SOD) and sediment nutrient fluxes as a function of settling particulate organic matter (POM) and sediment diagenesis. Tidal salt marsh interactions were also included as loading functions based on the nutrient balance studies in Webb's Marsh.

The watershed model used in the study is the Hydrologic Simulation Program FORTRAN (HSPF) that is available with USEPA's multi-purpose BASINS package. It uses rainfall, air temperature, solar radiation, land use patterns, and land management practices to simulate the quantity and quality of runoff from urban, mixed and/or agricultural watersheds. The model results provide runoff flow and nonpoint source loadings to the hydrodynamic and water quality models.

The hydrodynamic model used in the study is the three-dimensional, time-dependent, estuarine and coastal circulation model, Estuary and Coastal Ocean Model (ECOMSED), which has been successfully applied in numerous studies. The water quality model used in the study is a state-of-the-art eutrophication model Row Column AESOP (RCA), which is very similar to the WASP model, and is directly coupled with the hydrodynamic model, allowing computation of water quality within the tidal cycle. In addition, a sediment flux sub-model is also included in the water quality model to allow calculation of SOD and sediment nutrient fluxes in response to settled organic matter and its subsequent decay in the sediment. This coupled hydrodynamic/water quality model has been successfully applied in numerous studies including: St. Jones River, Blackbird Creek, Leipsic River, Smyrna River, Little River and Broadkill River (DE); Delaware River (NJ/PA/MD/DE); South Atlantic Bight (NY/NJ); Jamaica Bay (NY); Hudson-Raritan Estuary (NY/NJ); Long Island Sound (NY/CT); Chesapeake Bay (MD/DE); Massachusetts Bay and Boston Harbor (MA); Upper Mississippi River (MN); San Joaquin River (CA); Tar-Pamlico Estuary (NC); Escambia/Pensacola Bay, Fenholloway River and St. Andrews Bay (FL).

The watershed, hydrodynamic and water quality models were calibrated and validated with data collected by DNREC and USGS over the 2007-2008 monitoring period. The year 2007 was considered as the calibration and year 2008 as the validation with a consistent set of model parameters developed that best represented the observed data. These data include Acoustic Doppler Current Profiler (ADCP) data (velocity, water elevation), temperature, salinity and water quality (nitrogen, phosphorus, carbon, DO, chlorophyll-a) data throughout the Murderkill River watershed. The calibrated and validated watershed, hydrodynamic and water quality models resulted in a reasonable representation of both the complex mixing and circulation patterns observed in the study area and the observed nutrient, phytoplankton, organic carbon, and DO dynamics of the system. The linked watershed, hydrodynamic and water quality models were developed to support continued TMDL and site-specific DO criteria and nutrient targets development in the Murderkill River watershed.

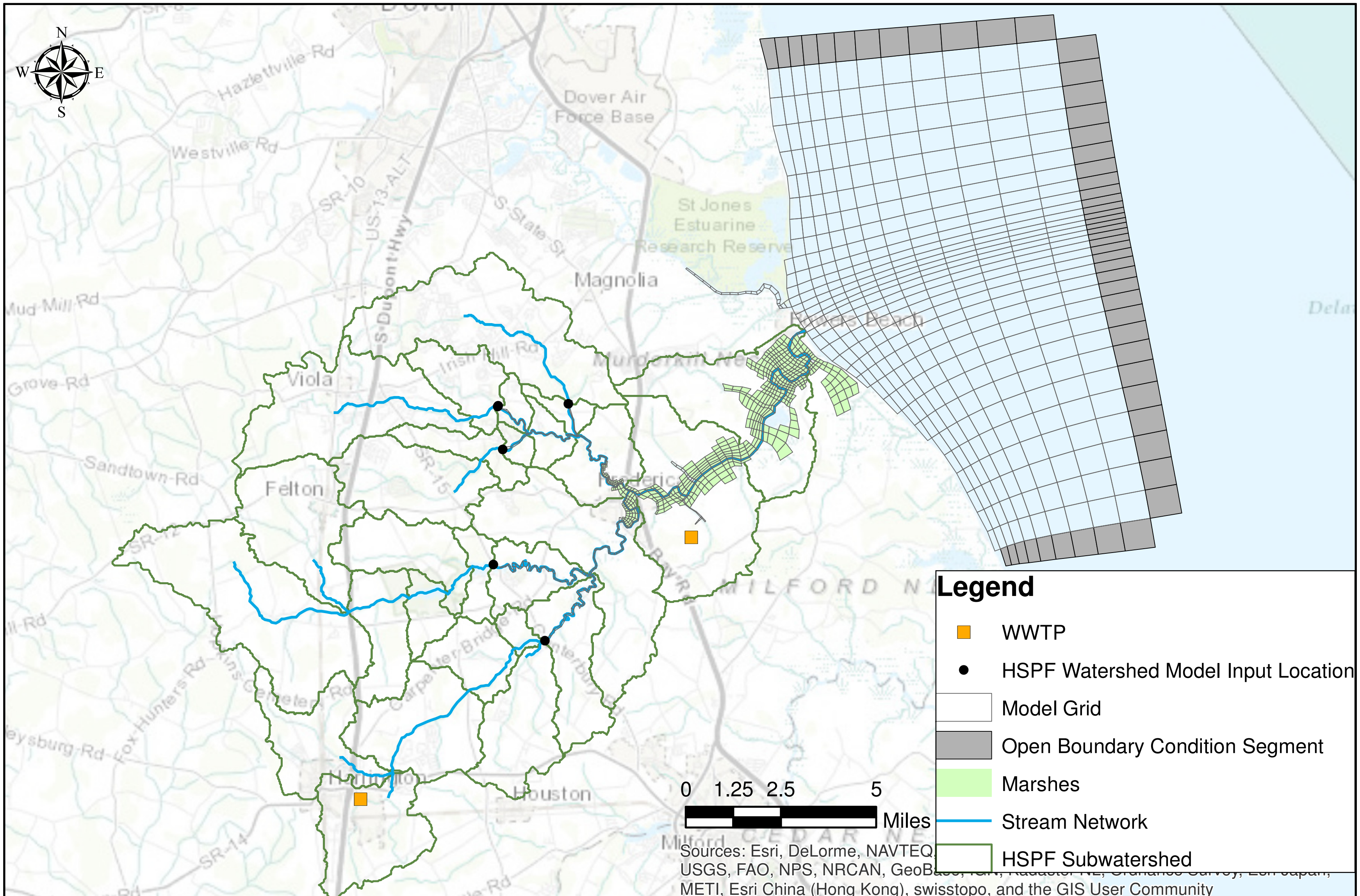
4.1 MODEL SEGMENTATION/DELINEATION

The HSPF model was delineated into 28 sub-watersheds in the Murderkill River watershed based on monitoring station locations, location of lakes and tributary watersheds (Figure 3). In each model sub-watershed, multiple land use types and different model parameters were applied along with stream geometry assigned as a set of functional relationships to flow between variables, such as stream surface area, volume and velocity. Land use information for the year 2007 was used for the watershed modeling and consisted primarily of 85% non-urban land uses (agriculture, wetlands, forest, pasture) with approximately 55% represented as agricultural land use.

An orthogonal, curvilinear modeling grid system was used for the hydrodynamic and water quality models in order to discretize the tidal reaches of the lower portion of the Murderkill River and nearshore Delaware Bay (Figure 6). The model downstream tidal boundary condition extends approximately 4-7 miles into Delaware Bay from the shoreline and 11 miles in the upstream/downstream direction in the bay. These tidal boundary condition segments are presented in Figure 6 as the shaded model cells. The grid system consists of an 89 x 63 segment model grid in the horizontal plane with 6 equally spaced σ-levels in the vertical plane (i.e., 5 vertical segments). In addition to water segments in the model, model segments were also included for the tidal marsh areas (shaded in Figure 6). The extension of the model grid into the bay is aimed at minimizing the bay boundary condition effects on the internal model calculations.

4.2 MODEL SETUP & CALIBRATION/VALIDATION

The watershed, hydrodynamic and water quality models all require various inputs that represent external forcing functions that drive the internal model calculations of watershed runoff (quantity and quality), watershed stream/lake and tidal river circulation and water quality. Due to the extensive monitoring programs designed to support the models developed for the Murderkill River, the modeling was very constrained from the perspective of model inputs that could be



HDR | HydroQual

Figure 6. Murderkill River ECOMSED/RCA Model Grid

adjusted for model calibration and validation. Many of the important model inputs and rate coefficients were measured as part of the study and, therefore, resulted in a more robust model calibration and validation process than typically available. The model inputs and coefficients that were measured included: tidal marsh loads; river bathymetry; SOD and nutrient fluxes; BOD oxidation rate; algal primary production; and tidal marsh inundation. In addition, an extensive water quality data set was available for calibrating and validating the models to observed data that included: bi-weekly water quality sampling of the watershed streams/lakes and tidal river; point source effluent monitoring (Harrington Sewage Treatment Plant and Kent County Regional Wastewater Treatment Facility); continuous data collection at Bowers Beach and Frederica for DO, salinity and temperature; continuous ADCP current speed and water elevation at Bowers Beach and Frederica; hourly meteorological data from the St. Jones Delaware National Estuarine Research Reserve (DNERR) in Dover; and Delaware Bay water quality collected as part of the DRBC Boat Run sampling.

All of these data were all available for calibration and validation of the Murderkill River models during the 2007-2008 modeling period with a consistent set of model parameters developed that best represented the observed data. The following sections present a brief summary of the model comparison to observed data.

4.2.1 WATERSHED MODEL

Daily flow data available at three USGS stations (Murderkill River, Browns Branch and Pratt Branch) were used for the watershed model flow calibration and validation. Percent differences between model and data for the long term flow volumes in 2007 and 2008 ranged from -24% to 7% with an overall percent difference of -10% for the June 2007 to December 2008 time period. In general, the HSPF model reproduces the observed flows in the watershed well and reasonably represents the hydrologic conditions in the Murderkill River watershed. After completing the model runoff calibration/validation, water quality simulations with the HSPF model were performed. Groundwater and interflow nutrient concentrations were based on data in Pratt Branch, Double Run and the Murderkill River near the headwaters of these tributaries and adjusted as part of the calibration/validation process. Overall the observed nutrient levels are fairly well reproduced by the model with some over and under estimation at the various stations. The model also reproduces the observed chlorophyll-a (chl-a) levels well over an annual cycle with the peak summer levels well reproduced. At most locations DO levels are also well reproduced by the model representing the typical seasonal DO pattern (i.e., lower DO during the warmer summer months). Based on the successful model comparison to the observed data, the HSPF model is well calibrated and validated and reflects the water quality dynamics in the watershed and the loadings to the tidal Murderkill River. Figure 7 presents the watershed model flow calibration/validation at the three available USGS gages and Figures 8 to 12 present the watershed model water quality calibration/validation at the five main tributaries to the tidal Murderkill River.

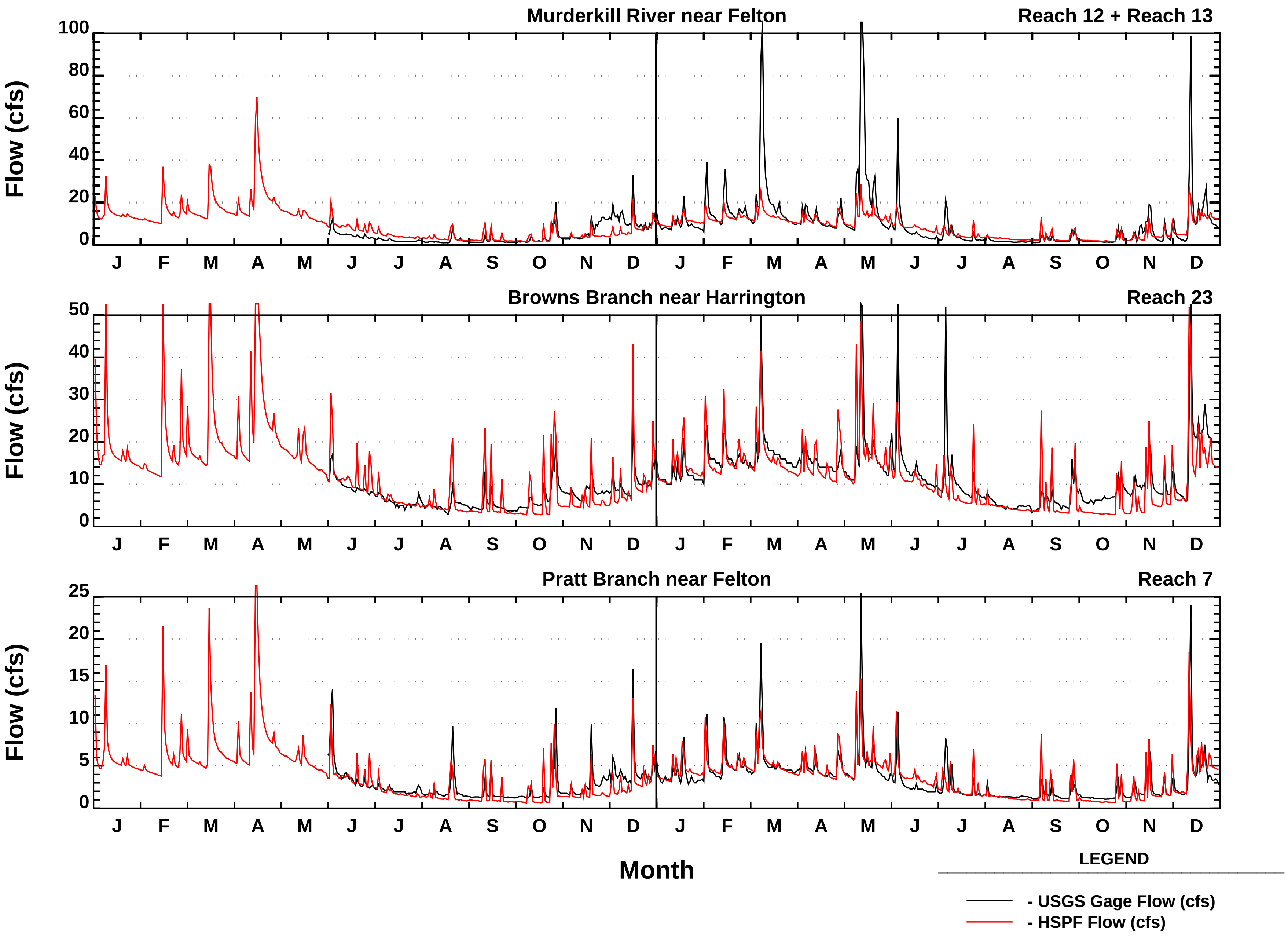


Figure 7. Murderkill River HSPF Flow Calibration/Validation (2007-2008)

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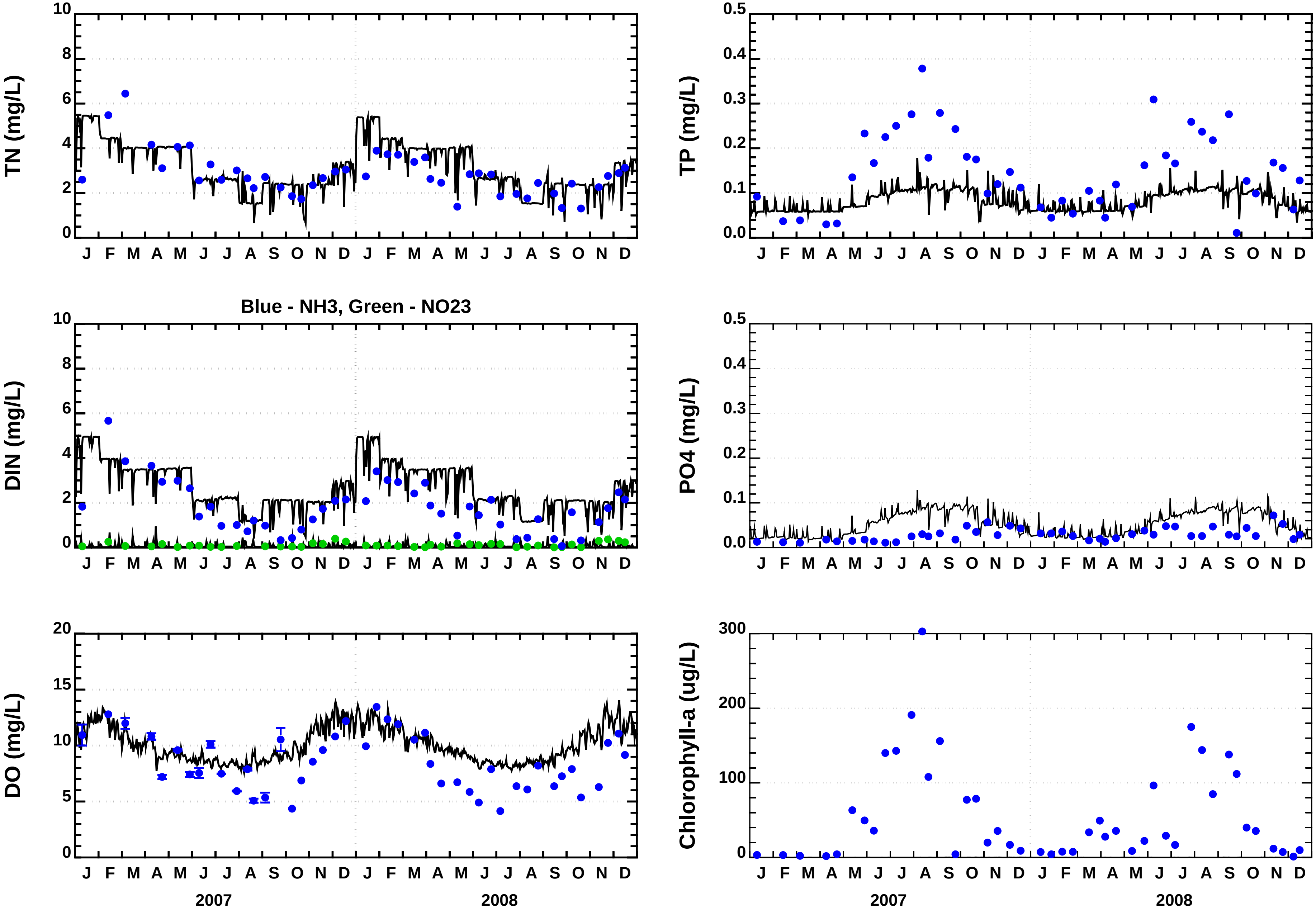

Figure 8. Water Quality Model Calibration at Station 206561, Double Run at Barratts Chapel Rd. (Rd. 371)

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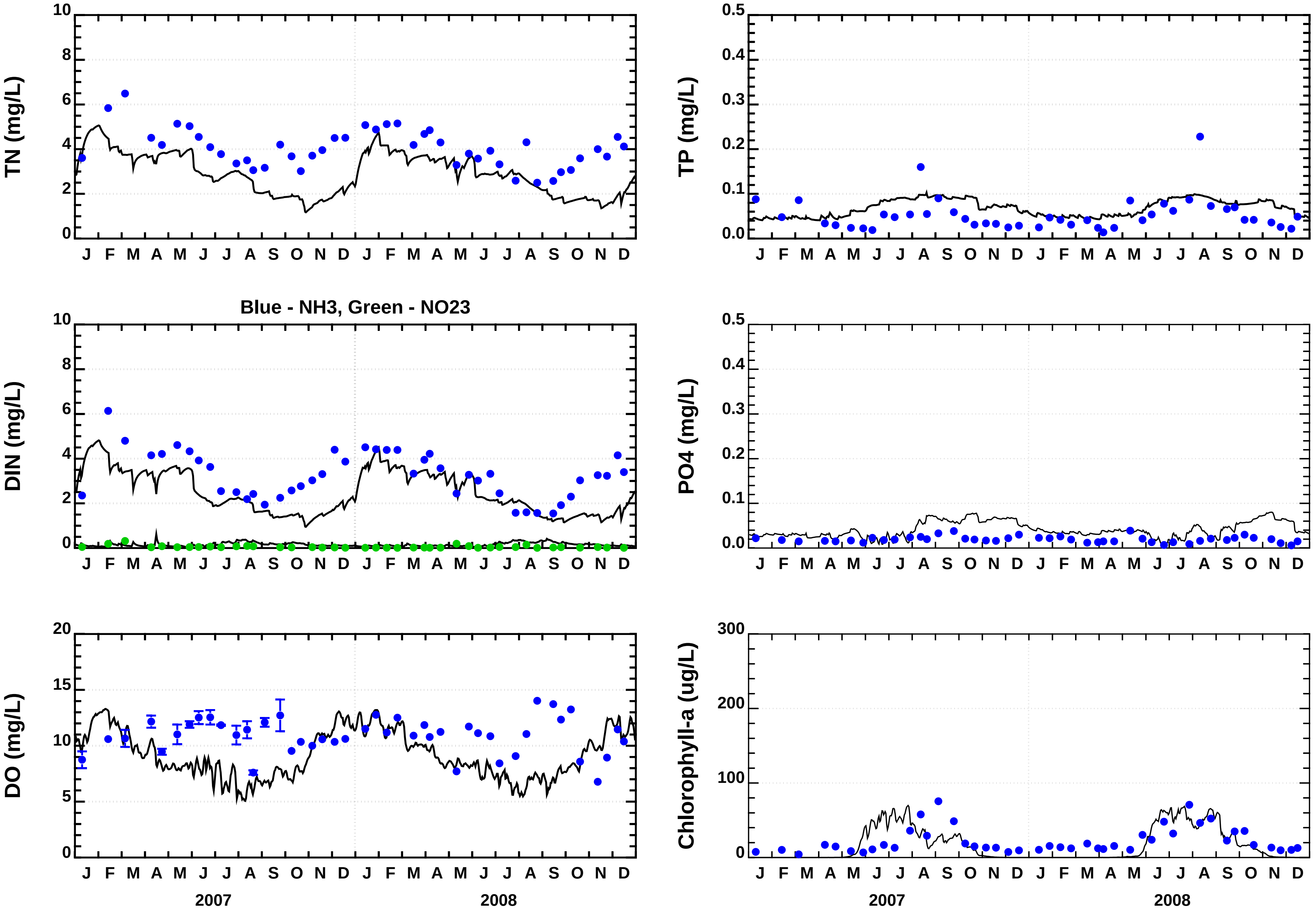

Figure 9. Water Quality Model Calibration at Station 206461, McGinnis Pond at McGinnis Pond Rd. (Rd. 378)

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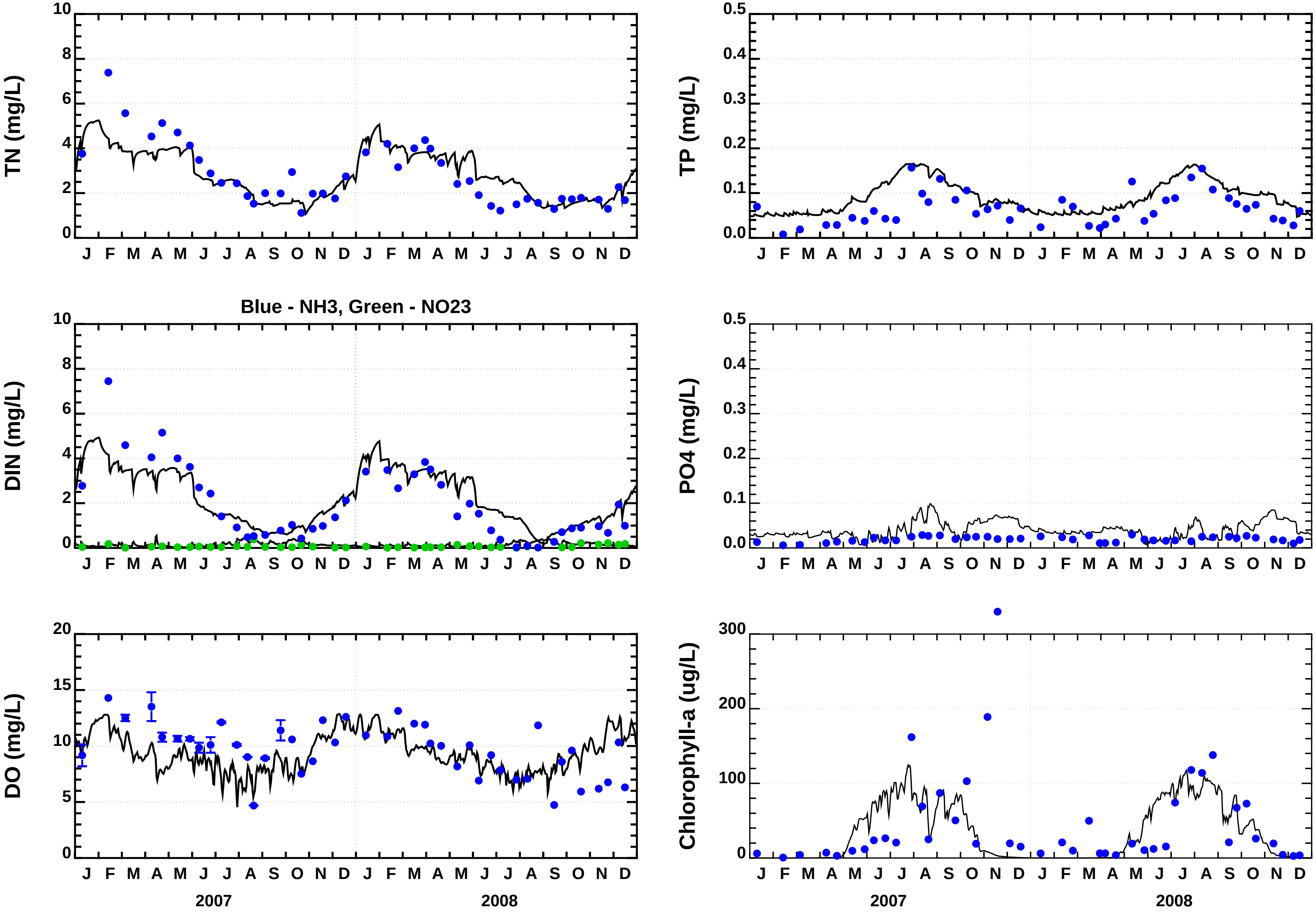

Figure 10. Water Quality Model Calibration at Station 206071, Andrews Lake at Rd. 380 Brdg.

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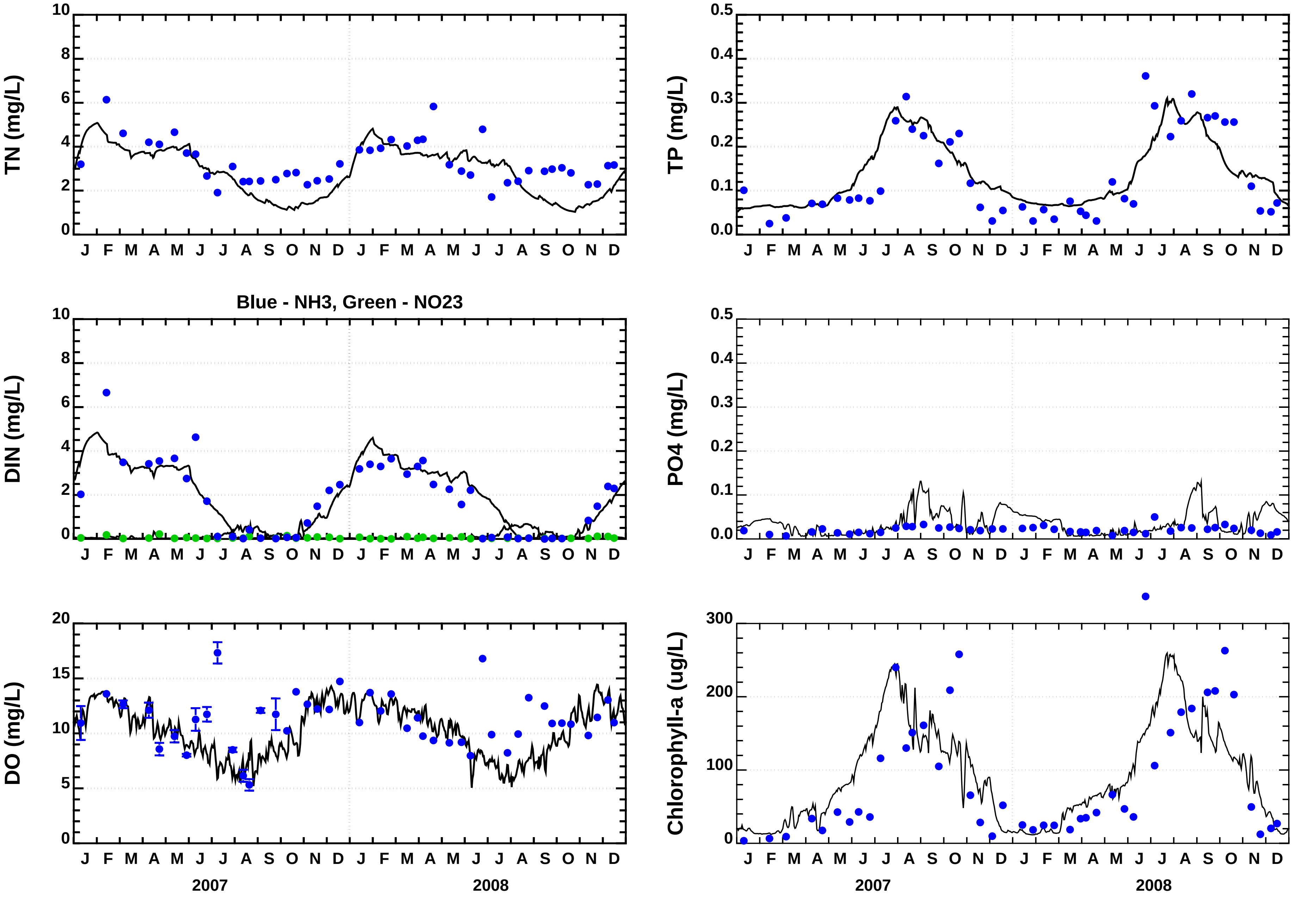

Figure 11. Water Quality Model Calibration at Station 206451, Coursey Pond at Canterbury Rd. (Rt. 15) at Rd. 388 Bridge

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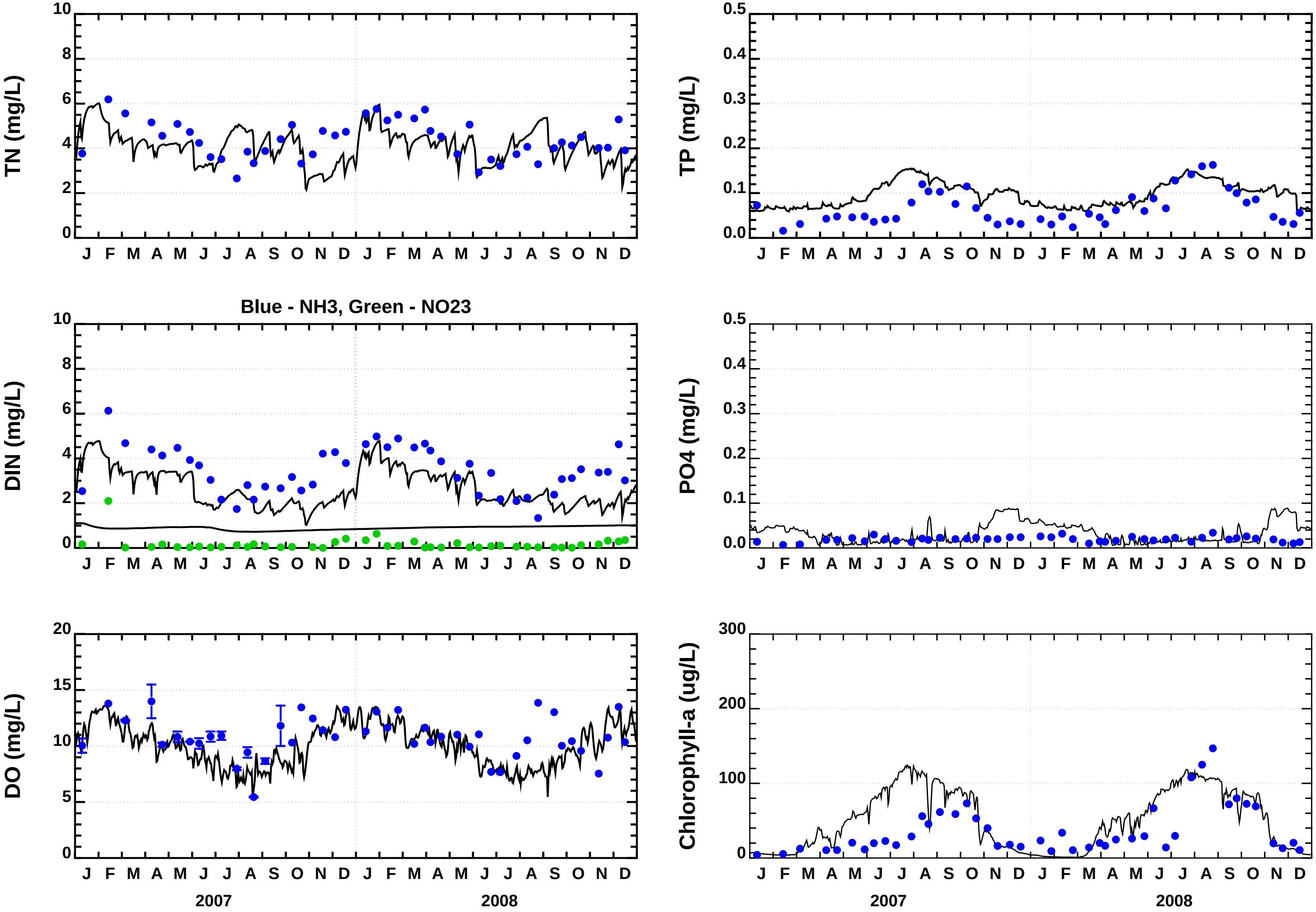

Figure 12. Water Quality Model Calibration at Station 206361, McColley Pond at Canterbury Rd. (Rt. 15) near Spillway

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4.2.2 TIDAL HYDRODYNAMIC MODEL

The ability of the hydrodynamic model to simulate advective and dispersive processes in the tidal Murderkill River was assessed by comparing model output and observed data that included: grab samples and continuous data for salinity and temperature; and continuous data for water elevation and tidal volume fluxes. The model comparison to observed salinity and temperature data is excellent over the 2-year calibration/validation period and the model reproduces the seasonal patterns very well (lower salinity and temperature in winter/spring, higher salinity and temperature in summer/fall). Comparison of the model output to the continuous data is also very good with the model reproducing intra-tidal features of the observed salinity and temperature variations. The hydrodynamic model calibration/validation to water elevations resulted in a good comparison level with the model comparison at Bowers Beach excellent and the model slightly over-predicting the tidal range during some time periods at Frederica due to the complicated tidal interaction between the marshes and the main channel of the river. Finally, the hydrodynamic model output was compared to the continuous tidal volume fluxes measured by the USGS at Frederica and Bowers Beach to assess whether the correct water volume is moving into and out of the river and coupled tidal marsh system. Overall, the model comparison to the data is very good with the model slightly over-predicting the tidal volume flux peaks during some time periods. Overall, the model reproduces the change in the tidal volume flux peaks between Bowers Beach and Frederica well (7,500 cfs at Bowers Beach to 2,500-5,000 cfs at Frederica), which suggests that the correct marsh volume is assigned in the model. Figures 13 and 14 present the hydrodynamic model flux or tidal flow calibration/validation and Figure 15 to 20 present the hydrodynamic model salinity calibration/validation.

4.2.3 TIDAL WATER QUALITY MODEL

The calibrated/validated water quality model reproduces the observed nitrogen data (TN, NH3 and NO2+NO3) and phosphorus data (TP and PO4) very well with respect to the seasonal and spatial variation in the tidal river. The model captures the higher nitrogen levels during the winter/spring season when watershed runoff is greatest and the lower levels observed during the summer/fall period when watershed loads are less and nutrient uptake/loss is greatest in the tidal river and surrounding tidal marshes. Also, the greater levels of phosphorus during the summer/fall period due to the lower freshwater water flow entering the tidal river coupled with the Kent County Regional Wastewater Treatment Facility (KCRWTF) phosphorus load near the middle of the river are observed and reproduced by the model. The overall increase in nutrient levels from the mouth of the river in upstream direction is also reproduced by the model. The water quality model captures the algal growth in the river and reproduces the seasonal and spatial patterns of chl-a levels well with higher levels occurring during the spring/summer/fall period and near the mouth and upstream as opposed to the middle of the river due to the spatial variations in turbidity that affect the available light for algal growth. At all stations where algal primary production data was available,

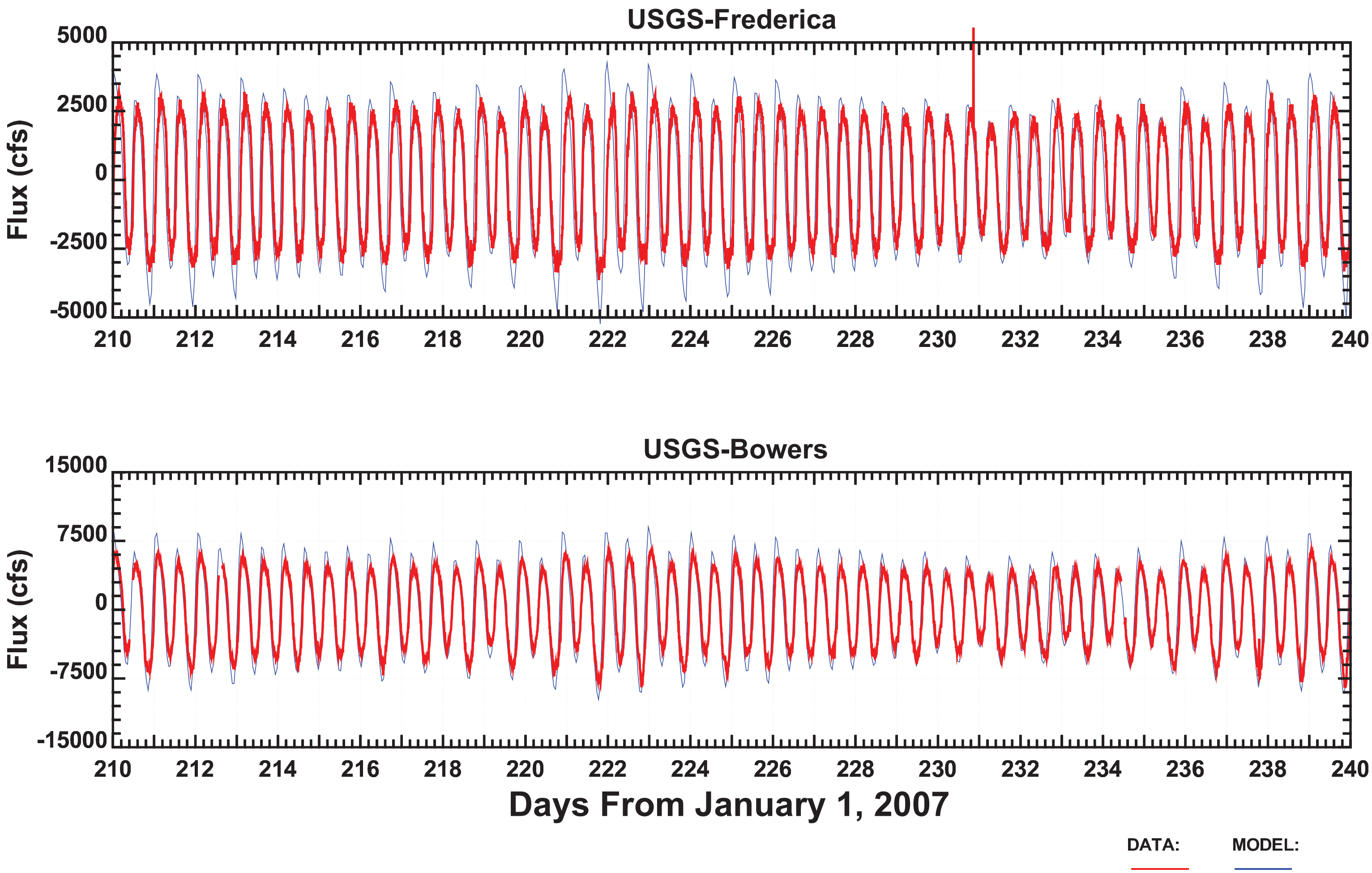


Figure 13. Hydrodynamic Model Flux Calibration for August 2007

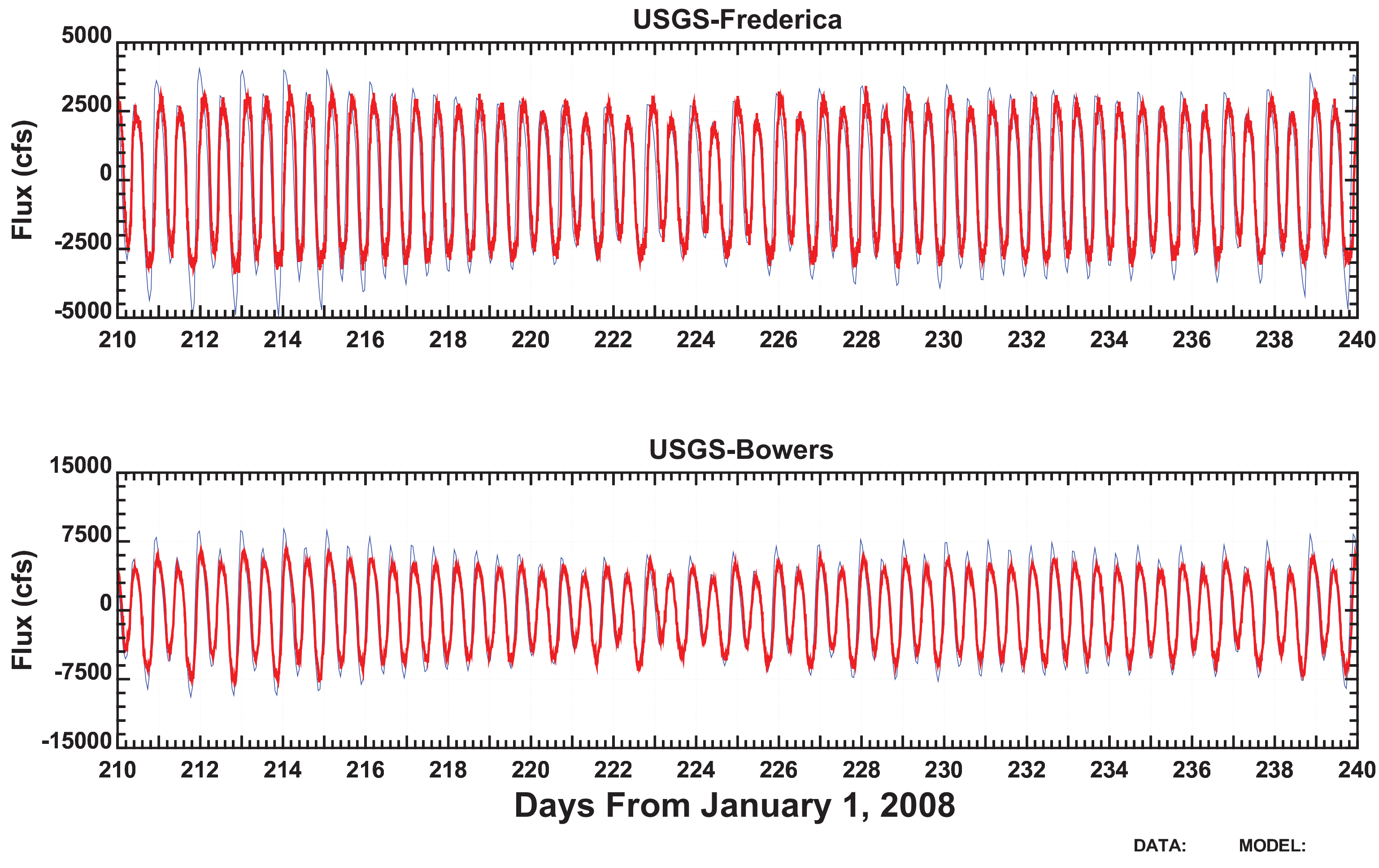


Figure 14. Hydrodynamic Model Flux Validation for August 2008

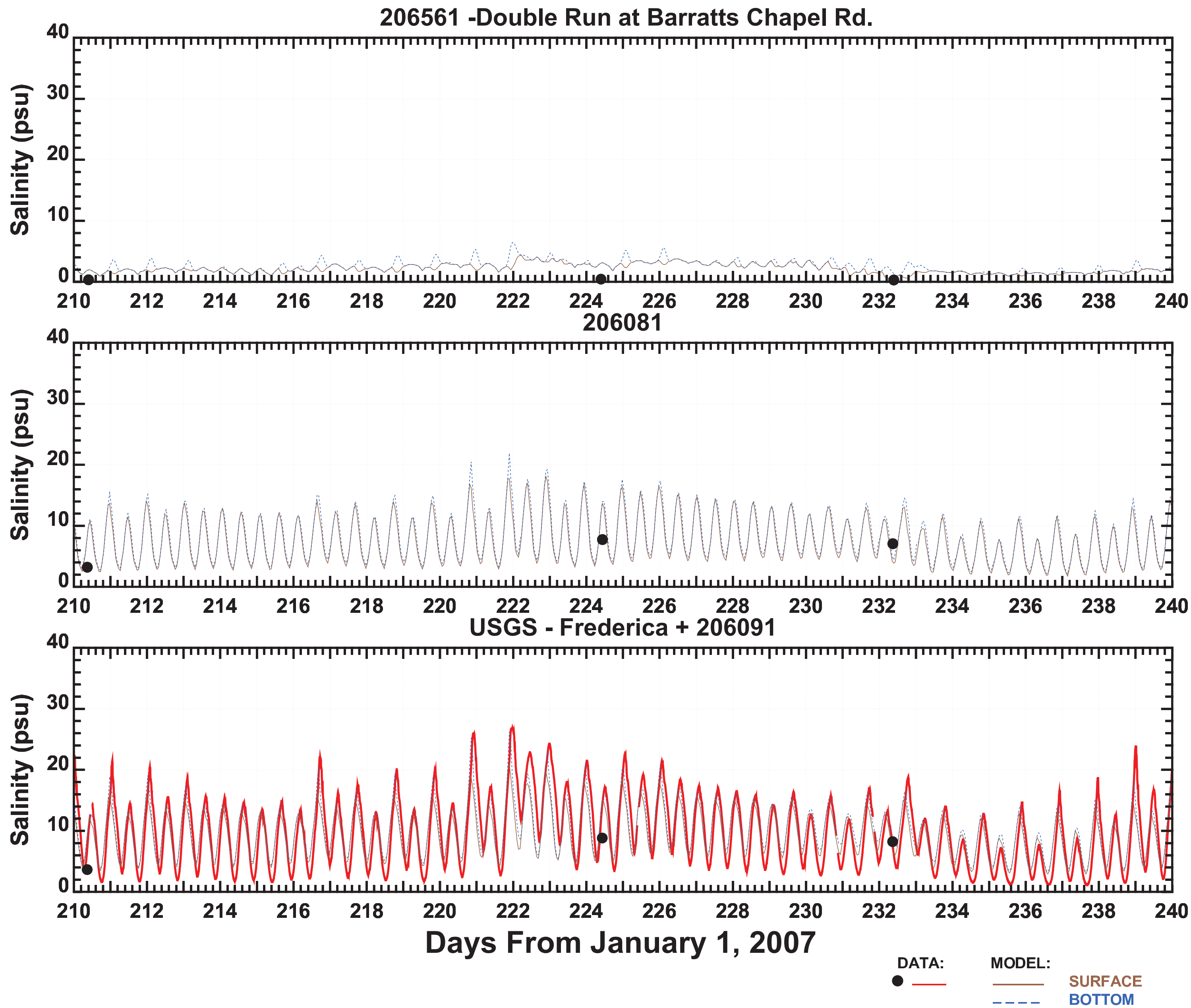


Figure 15. Hydrodynamic Model Salinity Calibration for August 2007

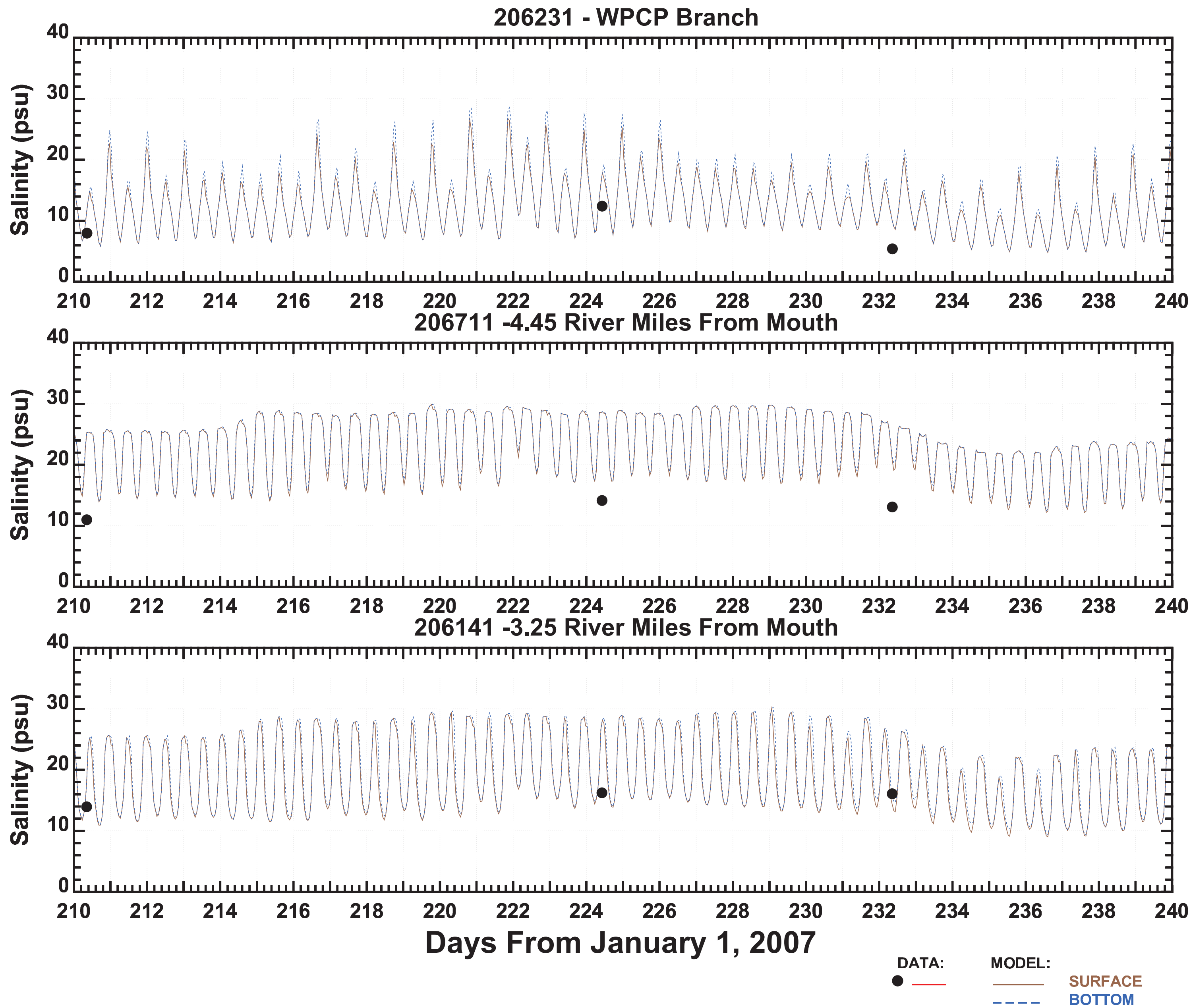


Figure 16. Hydrodynamic Model Salinity Calibration for August 2007

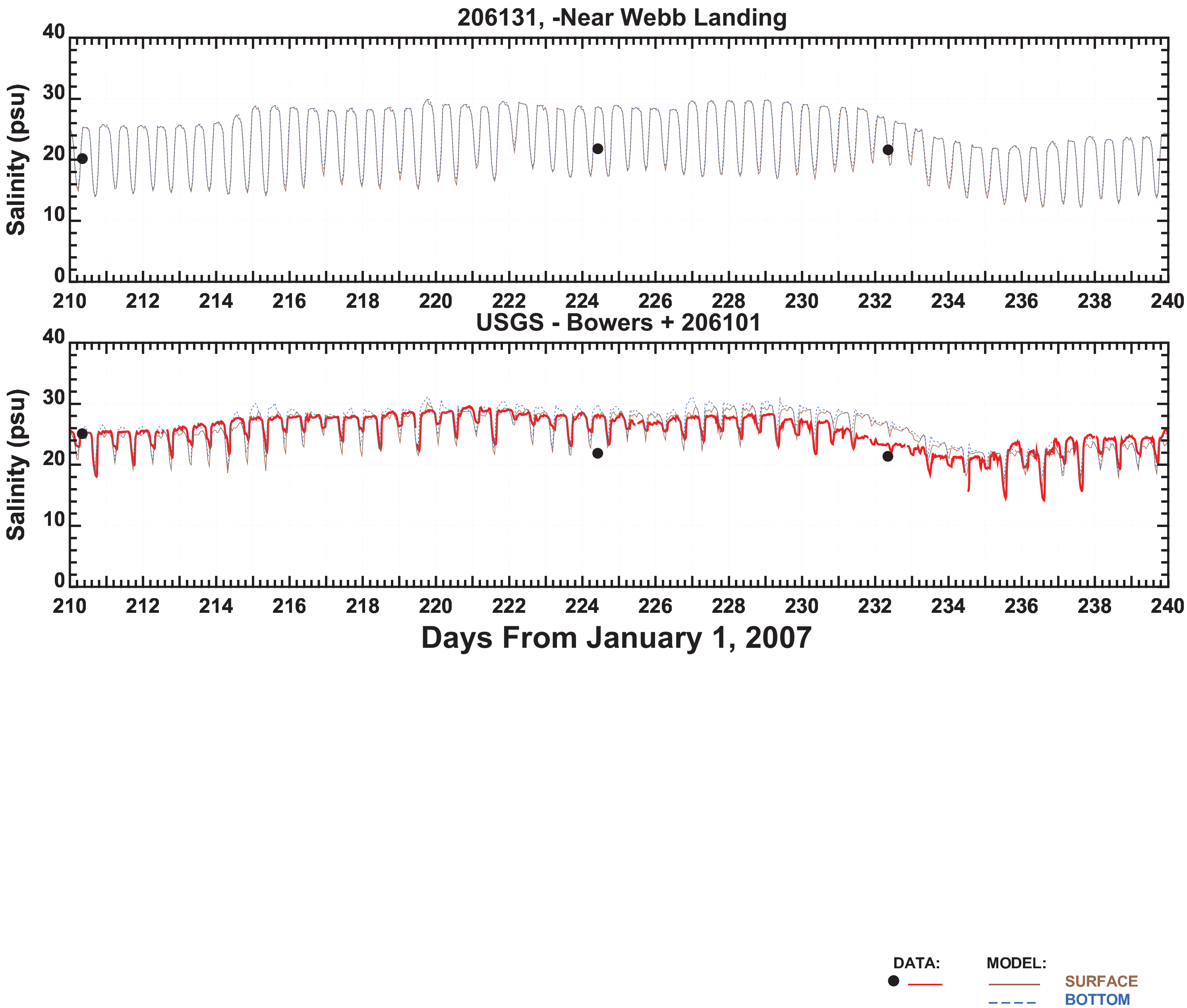


Figure 17. Hydrodynamic Model Salinity Calibration for August 2007

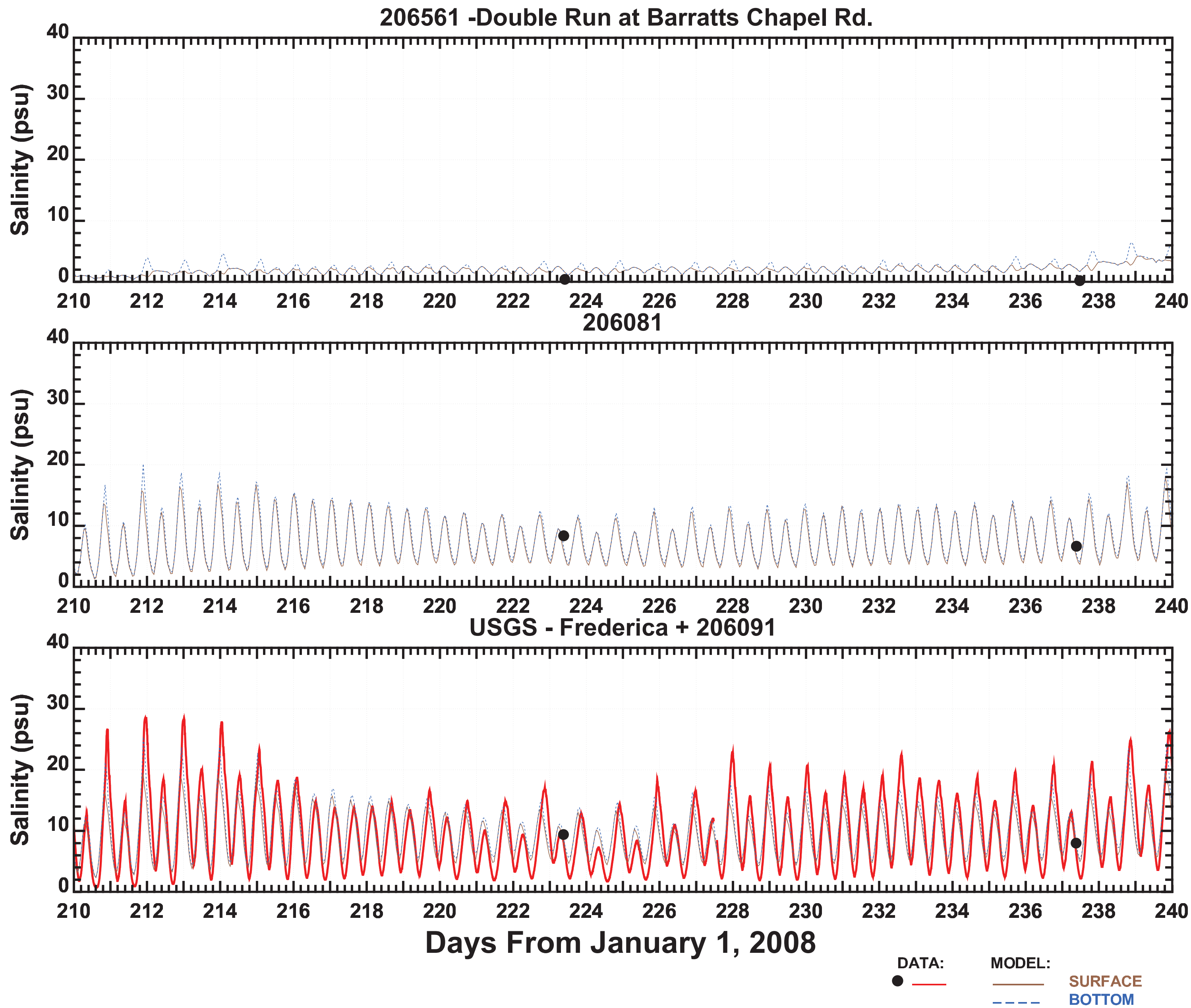


Figure 18. Hydrodynamic Model Salinity Validation for August 2008

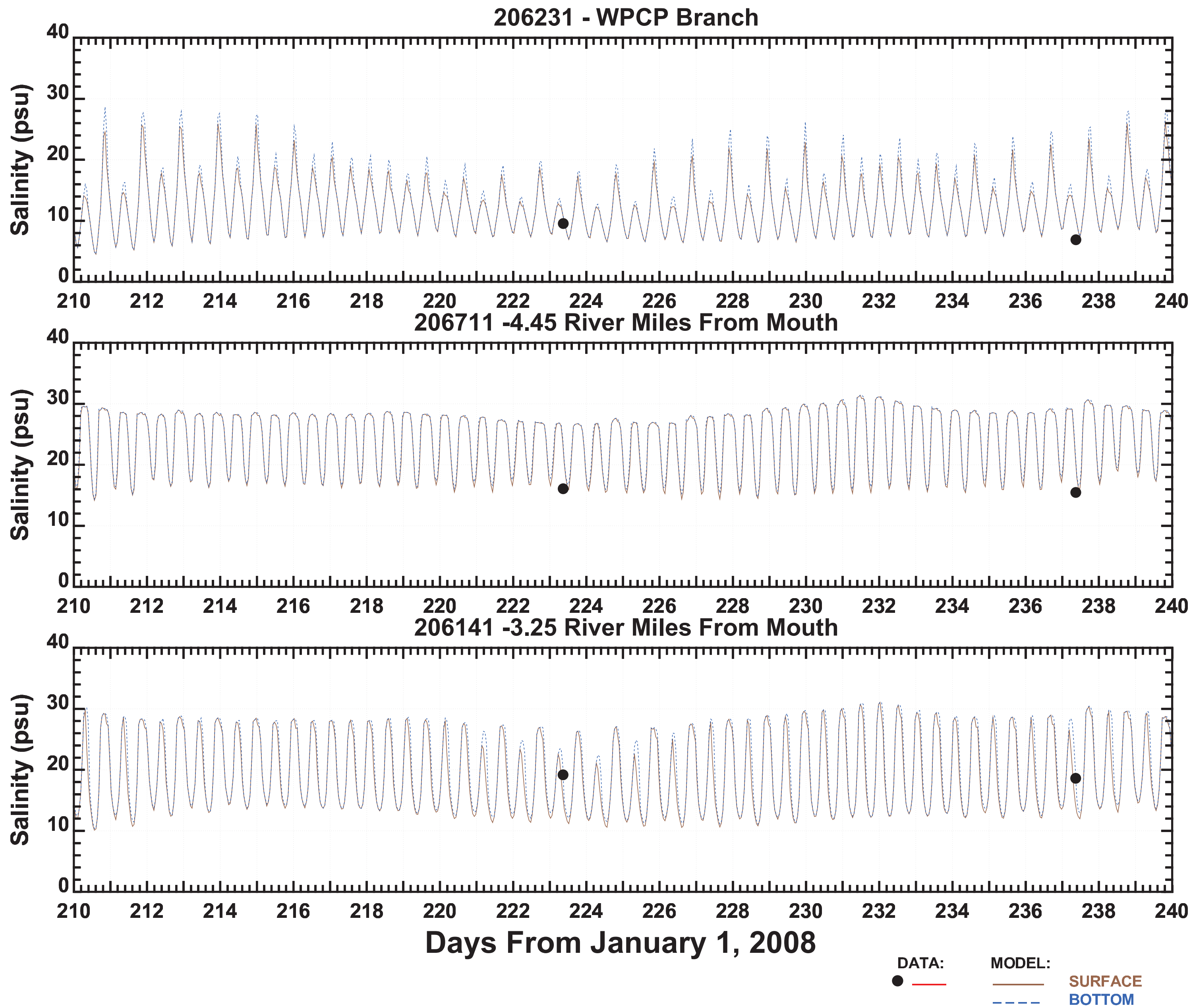


Figure 19. Hydrodynamic Model Salinity Validation for August 2008

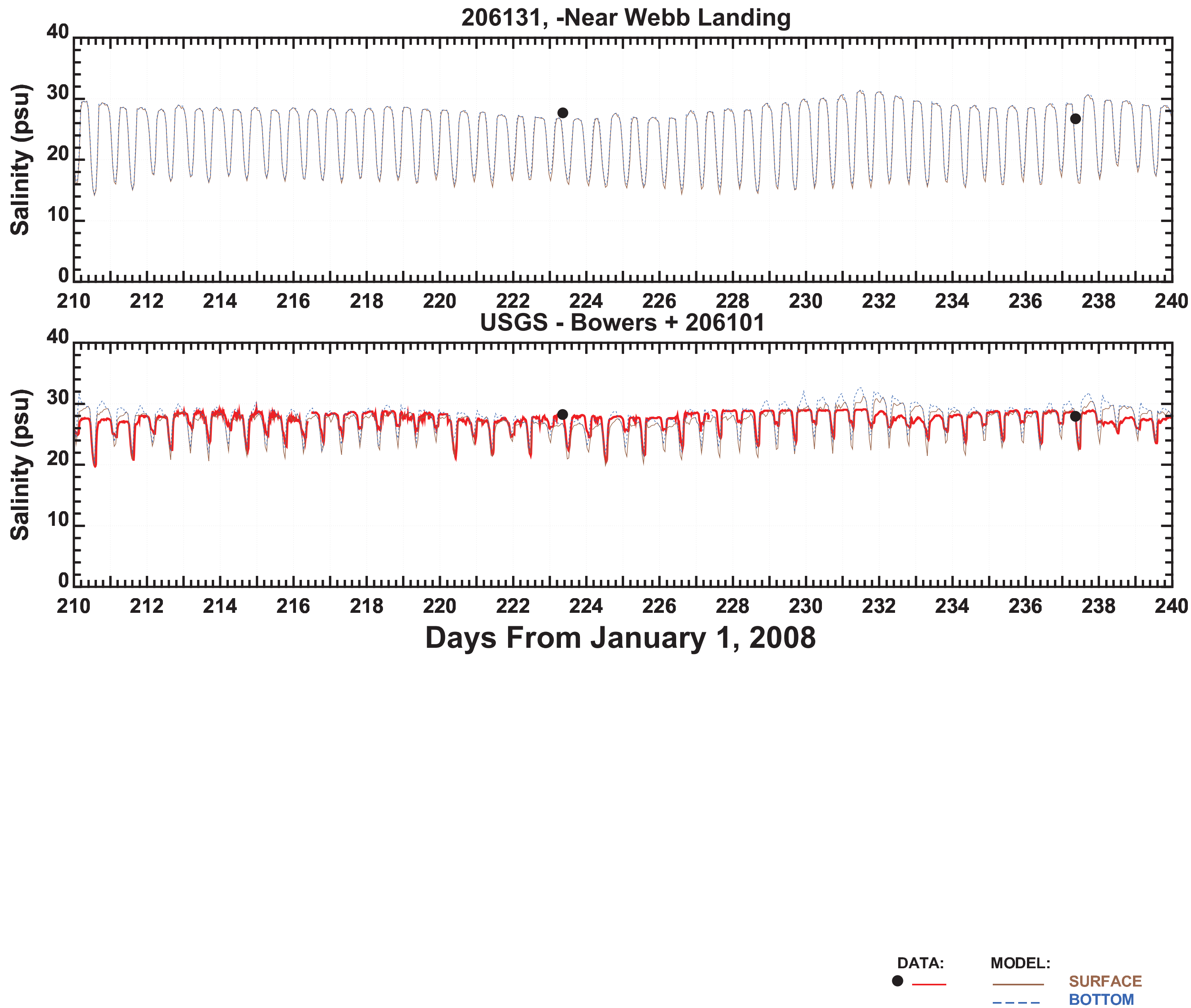


Figure 20. Hydrodynamic Model Salinity Validation for August 2008

the model reproduces the data very well both seasonally and spatially in the river. The model also reproduces the observed dissolved organic carbon (DOC) and BOD5 data very well at all of the monitoring stations. On an annual average basis at all of the stations: the model under-calculates the TN levels by about 0.4 mg/L and under-calculates the TP levels by about 0.004 mg/L. If measured chl-a levels greater than 50 μg/L are excluded, the model slightly over-calculates the chl-a levels by about 0.2 μg/L (KCRWTF canal to the mouth of the river) and under-calculates the chl-a levels by about 9 μg/L from Bay Road and upstream.

The model reproduces the observed grab sample DO data very well at most locations and captures the seasonal and spatial variations observed. At a few of the upstream stations (i.e., Frederica at the Route 12 Bridge and Bay Road), the model tends to under-calculate the observed DO levels during the summer. At the Bowers Beach continuous monitoring station, the model compares very well with the observed daily average data but under-calculates the daily range during certain periods of the year. The calculated DO at the Frederica continuous monitoring station is less than observed during certain time periods with the daily range under-calculated. This location in the river is complex due to the merging of the upper Murderkill River and Spring Creek from both a circulation and salt/fresh marsh interaction perspective. The under-calculation of DO upstream from the KCRWTF canal provides a level of conservatism to the analysis in that calculated DO levels under future scenarios will be lower than may be observed. Overall, the model under-calculates the observed summer average DO levels by roughly 0.6 mg/L, the minimum grab sample DO levels by about 1.8 mg/L, and the minimum continuous DO levels (USGS continuous data) by about 0.2 mg/L. Overall, the model under-calculates the observed DO by 0.5 mg/L at all of the tidal river monitoring locations (Bowers Beach to Frederica). When just considering the critical middle part of the river (Rte. 12 Bridge to Power Lines stations) where the lowest DO levels occur in the river, the model under-calculates the observed DO by 0.8 mg/L and this model bias will be used when assessing compliance with the site-specific DO criteria.

Figures 21 through 24 present the model comparisons to observed data for the 2007-2008 modeling period at four stations in the tidal river: Bowers Beach (mouth); Milford Neck Levee; KCRWTF canal; and Frederica at Bay Road. These figures present the model output and data as time-series for TN, dissolved inorganic nitrogen (DIN), chl-a; TP, dissolved inorganic phosphorus (DIP) or PO4, and DO. These stations are roughly equally spaced along the length of the tidal Murderkill River and provide a good representation of spatial variations in the river.

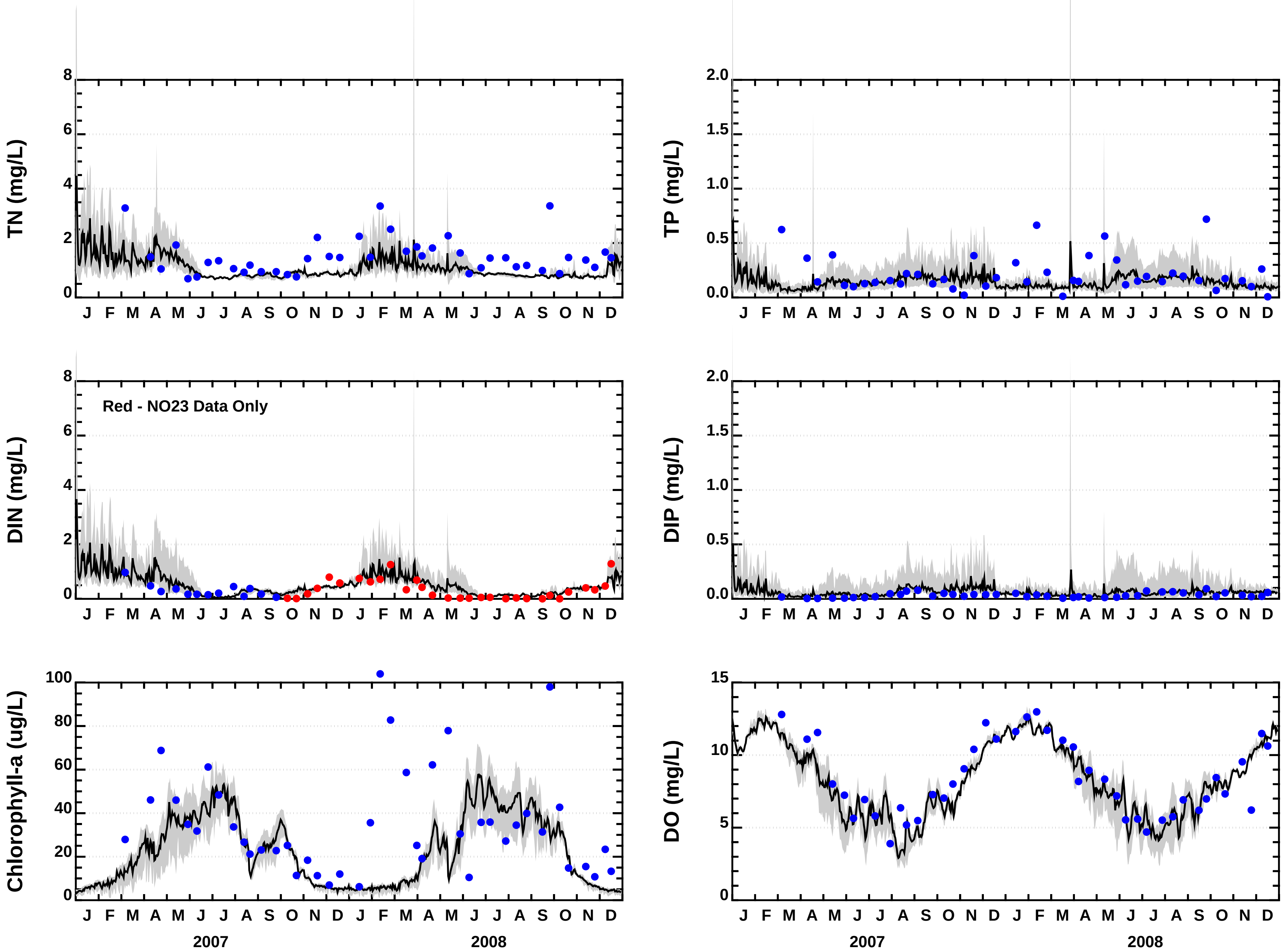


Figure 21. Water Quality Model Calibration/Validation (2007-2008)
Station 206101, Murderkill River at Bowers Beach Warf (Mouth), (74,41)

Solid Line - Model Daily Average
Shaded Region - Model Daily Range
Blue Circle - Observed Data

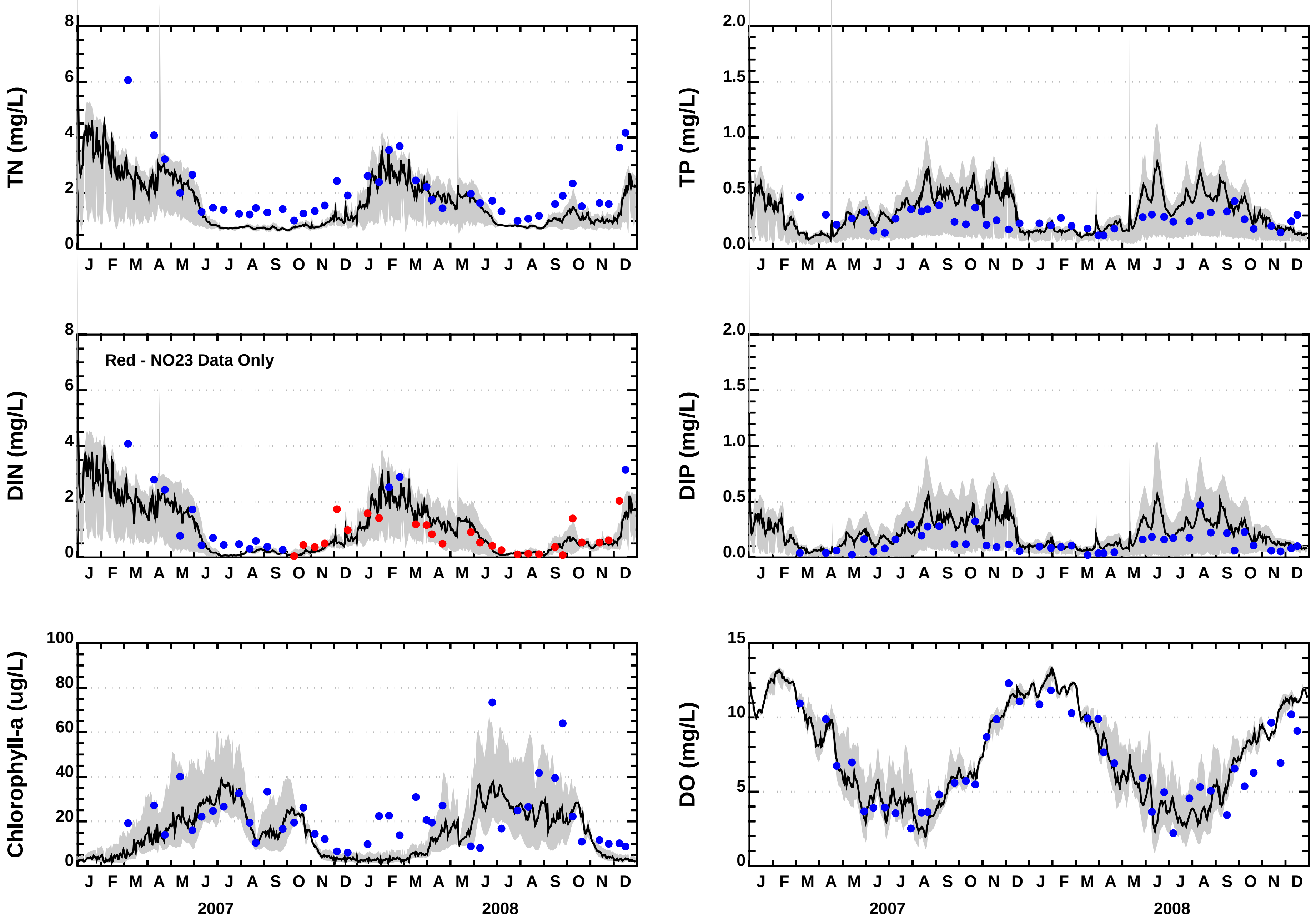


Figure 22. Water Quality Model Calibration/Validation (2007-2008)
Station 206141, Murderkill River near Levee at Milford Neck Wildlife, (54,32)

Solid Line - Model Daily Average
Shaded Region - Model Daily Range
Blue Circle - Observed Data

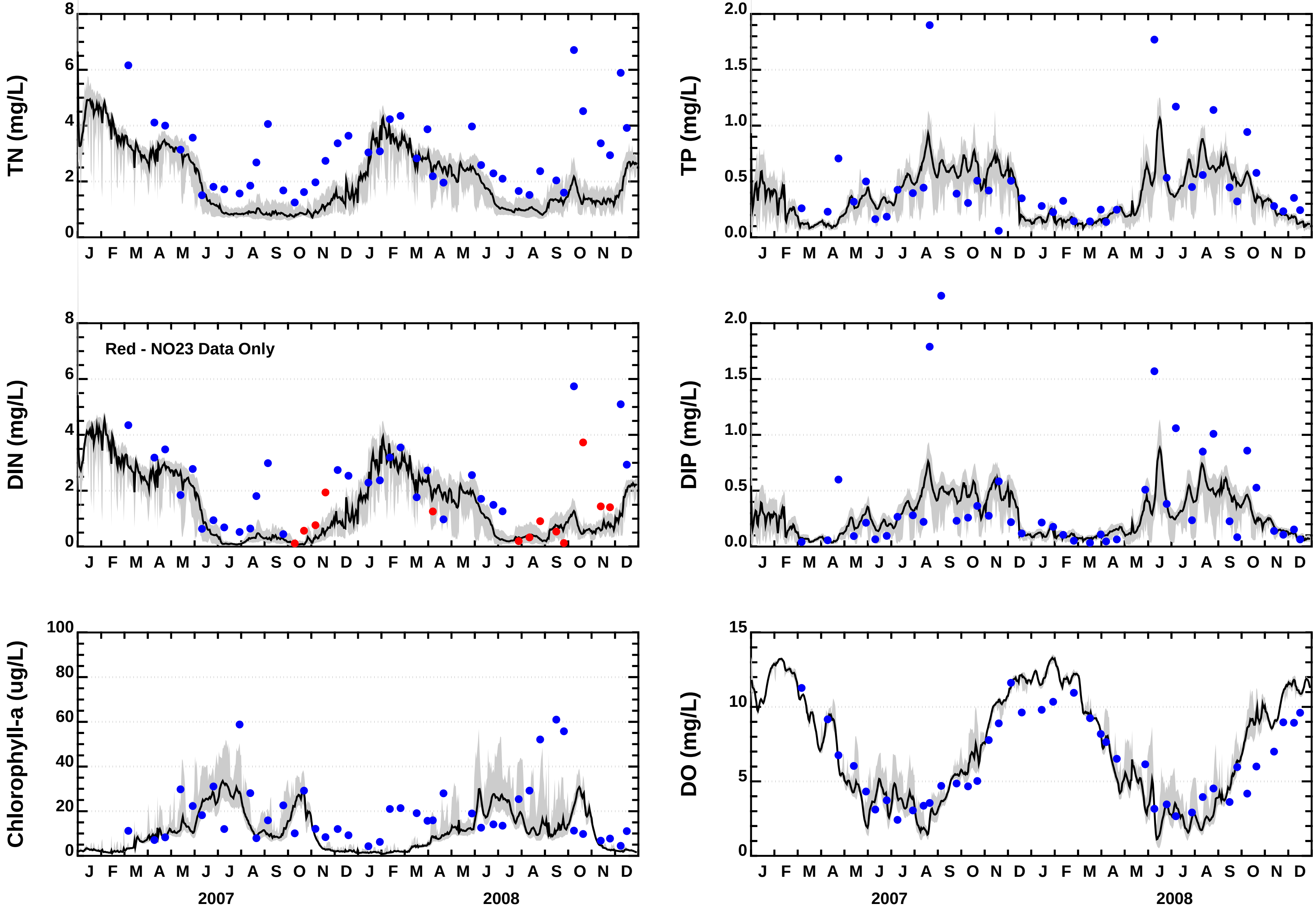


Figure 23. Water Quality Model Calibration/Validation (2007-2008)
Station 206231, Murderkill River at Confluence of Kent County WWTF, (36,33)

Solid Line - Model Daily Average
Shaded Region - Model Daily Range
Blue Circle - Observed Data

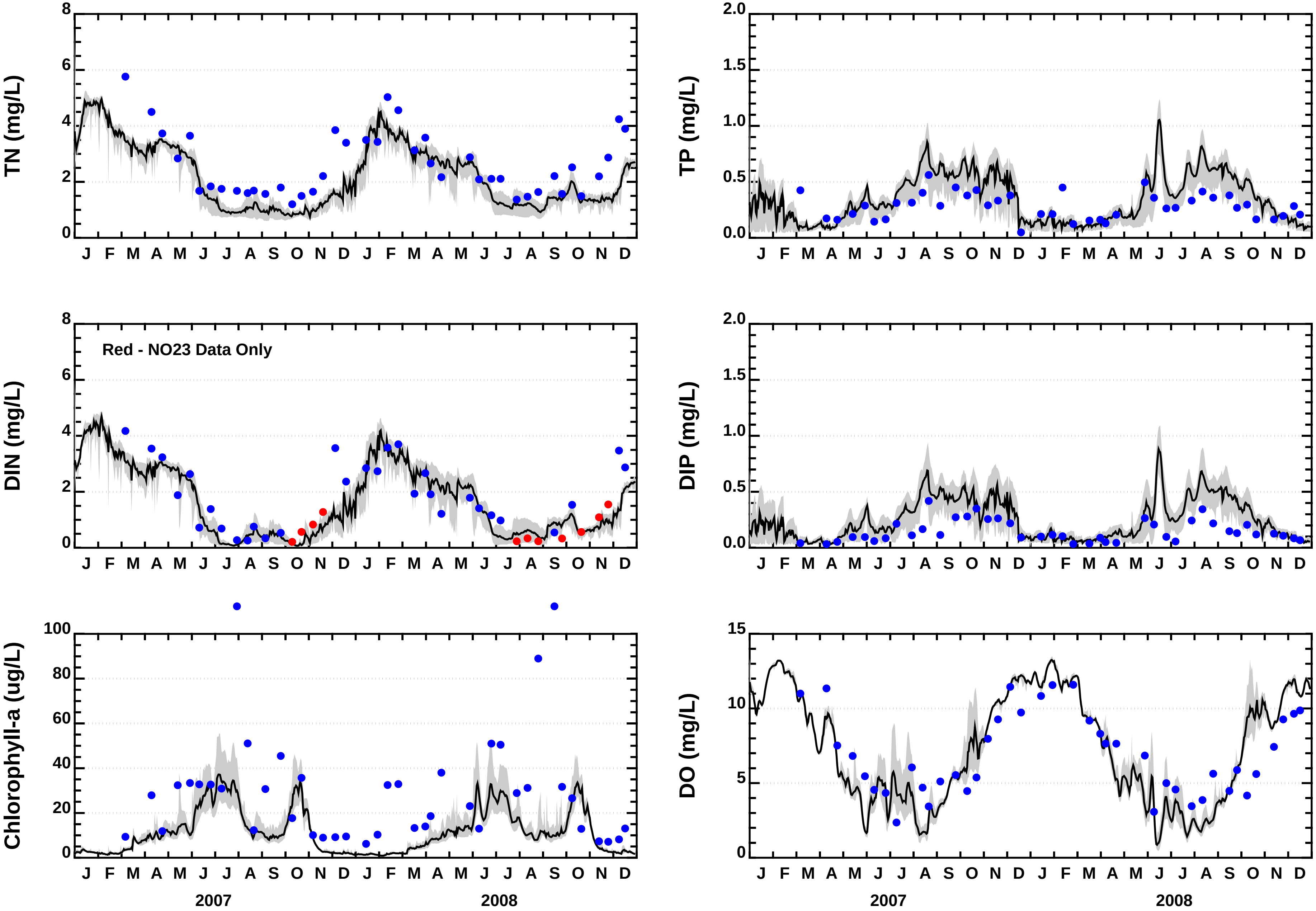


Figure 24. Water Quality Model Calibration/Validation (2007-2008)
Station 206091, Murderkill River at Bay Road (Rt 1/113), (27,39)

Solid Line - Model Daily Average
Shaded Region - Model Daily Range
Blue Circle - Observed Data

4.3 MODEL DEVELOPMENT SUMMARY

A coupled set of numerical models were developed for the Murderkill River watershed to investigate the factors influencing the low DO levels in the tidal reach of the Murderkill River, assist in setting site-specific nutrient targets and DO criteria, and in setting total maximum daily loads (TMDLs) in the watershed. The watershed model (HSPF) was used to represent the rainfall driven runoff processes in the watershed; the hydrodynamic model (ECOMSED) was used to represent the tidally driven circulation in the tidal river; and the eutrophication model (RCA) was used to represent the water quality interactions between nutrients, carbon or BOD, algae (phytoplankton) and DO. Development of these models was supported by an extensive monitoring program both in the watershed and tidal river along with special project-specific studies to further study important processes occurring in the watershed. These project-specific studies included:

- Water column algal primary production studies (Sharp, 2011);
- Water, salt and nutrient studies in Webb's Marsh (Wong et al., 2009; Dzwonkowski et al., 2013; Ullman et al., 2013);
- Nutrient sediment flux studies (CBA, 2010);
- Tidal marsh inundation studies (McKenna, 2013);
- LTBOD studies in the river and KCRWTF effluent;
- Continuous tidal monitoring near Frederica and at Bowers Beach and expanded DNREC monitoring in the watershed; and
- Vertical profiling of sediment cores (Velinsky, et al., 2010).

The data available to develop the Murderkill River models was very extensive and not typically available for model development. In this respect, the data collected and the models developed for the Murderkill River provided very valuable information on the factors influencing the interactions between nutrients and DO. It is expected that the results from these studies and the modeling should be useful in other tidal river systems dominated by tidal marshes around Delaware Bay.

Based on the results from the modeling studies, the Murderkill River models (HSPF, ECOMSED and RCA) are well calibrated/validated to the observed data collected during the 2007-2008 modeling period. The models represent the important features and interactions that control the nutrient and DO dynamics in the tidal river from the upstream watershed to the extensive downstream tidal marshes and connection with Delaware Bay. Given the successful calibration/ validation of the model, they are appropriate to use in supporting site-specific nutrient targets and DO criteria and in developing TMDLs for the Murderkill River watershed.

SECTION 5

LOADING SCENARIO ASSESSMENT

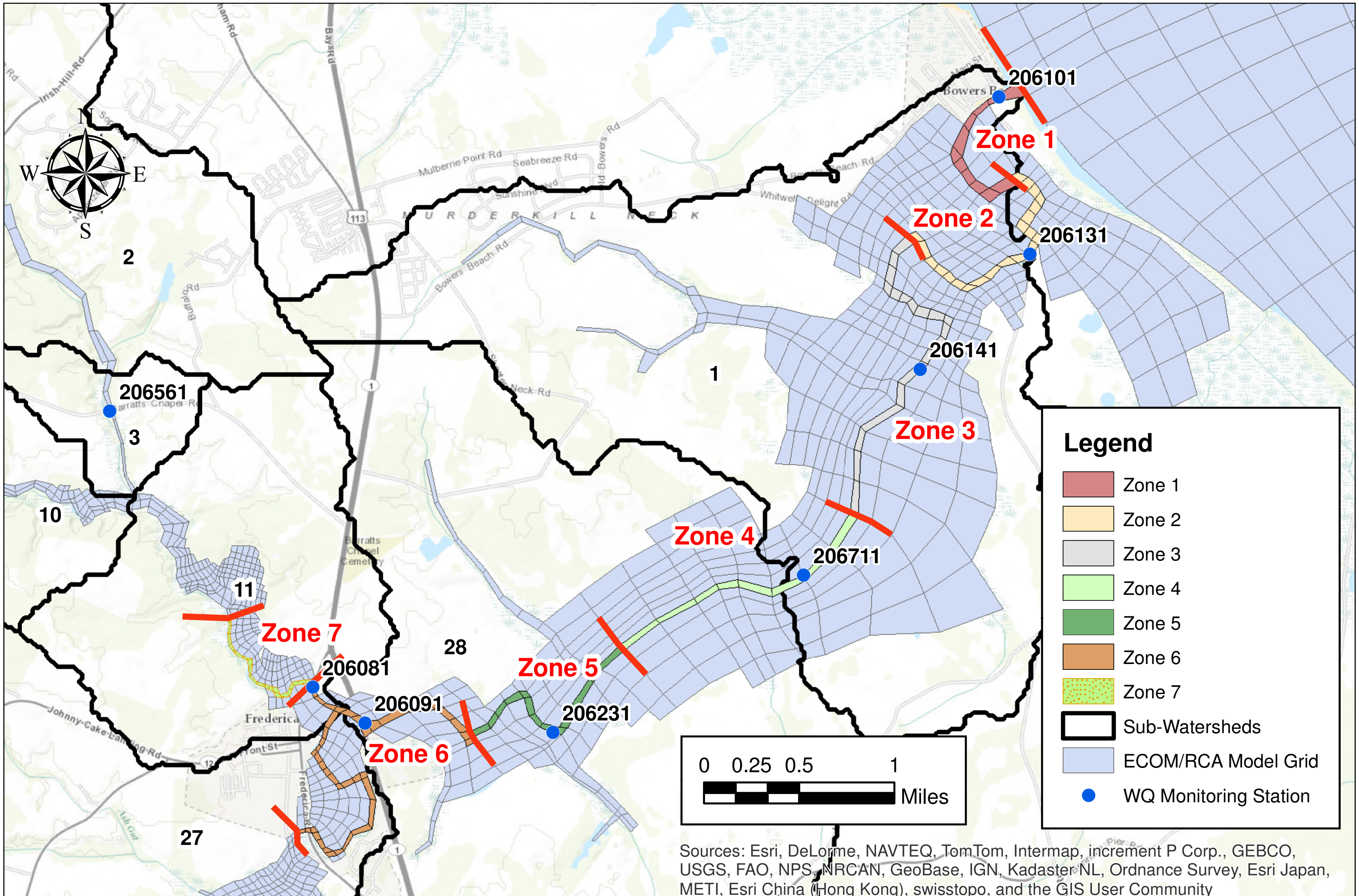
One use of the calibrated and validated tidal water quality model (RCA) is to estimate the impact of different sources controlling DO and other parameters in the river. This is accomplished by running the model with changes to various sources (e.g., KCRWTF discharge and tidal marsh loads) and comparing the results to the calibration/validation results. The value in completing this type of analysis is to better understand the primary factors controlling observed water quality levels in the tidal Murderkill River. It should be noted that due to the non-linear response between nutrients and DO, the DO response differences to the various sources are not additive but rather provide an estimate of the DO impact associated with different sources. The following sections present the model calculated DO, total nitrogen (TN), total phosphorus (TP) and chlorophyll-a (chl-a) impacts due to the KCRWTF discharge and tidal marsh loadings. In addition, the calculated water quality associated with an estimated "natural background" conditions is also presented.

In order to establish the TMDL for the Murderkill River Watershed that is in compliance with the proposed site-specific DO criteria for the tidal Murderkill River, a number of loading scenarios were considered. Furthermore, to assist with analyzing model results, the tidal river was divided into 7 river zones. These tidal river zones were also centered around the DNREC monitoring stations in the river to aid with future water quality compliance assessments. Table 5 and Figure 25 present the tidal river zones and DNREC monitoring stations. These zones will be used to present the model results. It should be noted that with regard to DO levels, zones 5 and 6 have the lowest DO among all zones and are considered to be the critical segments where the DO sag occurs in the river.

The following sections discuss the results of loading scenarios analyzed.

Table 5. Tidal River Zones

Tidal River Zone	DNREC Station
1	Bowers Beach (#206101)
2	Webbs Landing (#206131)
3	Milford Neck (#206141)
4	Power Lines (#206711)
5	KC Canal (#206231)
6	Bay Road (#206091)
7	No station available



HDR | HydroQual

Figure 25. Tidal Murderkill River Zones

5.1 NO KCRWTF DISCHARGE SCENARIO

During the 2007-2008 modeling period, the KCRWTF loads averaged 553.3 lb/d of TN, 89.2 lb/d of ammonia nitrogen (NH_3), 330.2 lb/d of nitrite plus nitrate nitrogen (NO_2+NO_3), 173.1 lb/d TP, 148.1 lb/d of orthophosphate (PO_4), 285.6 lb/d of carbonaceous BOD5 ($CBOD_5$), and 222.0 lb/d of particulate organic carbon (POC). The average effluent flow during this period was 10.7 MGD. The water quality model was re-run without the KCRWTF loads and the model results compared to the calibration/validation period (2007-2008). These results are presented at the seven tidal monitoring stations in Figure 26 as summer averages (May-September) for TN, dissolved inorganic nitrogen (DIN = NH_3 + NO_2+NO_3), TP, PO_4, chlorophyll-a (chl-a) and DO for both the calibration/validation and the no KCRWTF load model results.

The model sensitivity results show that DO and chl-a levels do not change significantly as a result of the removal of the KCRWTF nutrient and $CBOD_5$ loads. The calculated decrease in TN ranged from 0.09-0.40 mg/L and for TP ranged from 0.07-0.35 mg/L with the largest decreases occurring near the Kent County discharge canal station. Although these changes in nutrient levels, especially for phosphorus, are considerable, the nutrient reduction impact on DO and chl-a levels is minimal. The DO increases ranged from 0.17-0.70 mg/L while the chl-a decrease ranged from 0.9-1.2 μg/L. At the Kent County canal station (zone 5), summer average DO levels changed from 3.62 to 3.94 mg/L and at the Bay Road station (zone 6) they changed from 3.69 to 3.93 mg/L, respectively. Summer average chl-a levels changed from 17.0 to 16.0 μg/L (Kent County canal) and from 17.5 to 16.6 μg/L (Bay Road). The small chl-a decrease is due to the fact that the tidal Murderkill River is very turbid and results in light limiting algal growth as opposed to nutrients. In addition, even though nutrient levels are reduced with the removal of the KCRWTF load, the remaining nutrient levels are still well above algal growth nutrient limitation levels (i.e., 0.010 mg/L for DIN and 0.001 mg/L for PO_4).

The model sensitivity results are also presented as time-series figures over the 2007-2008 modeling period at four monitoring locations in the tidal river (Figures 27-30) and as summer daily average and daily minimum probability distributions in the seven tidal river zones (Figures 31-32). For reference, the water quality levels calculated for the 2007-2008 modeling time period are also presented in these figures for comparison. The time-series figures highlight the seasonal effects of removing the KCRWTF load along with the spatial variation in the river (i.e., larger impacts near the KCRWTF discharge canal). The nutrient reductions in the river are greater during the low flow periods of the year when the impact of the KCRWTF load is the greatest but the nutrient effects on chl-a and DO are minimal during these low flow periods due to light limiting algal growth as compared to nutrients. The small changes to the DO levels are also a function of the low KCRWTF $CBOD_5$ and NH_3 effluent levels. The DO probability distributions presented in Figures 31-32 show larger DO increases near the mouth of the river than near the KCRWTF discharge canal, which is related to the downstream travel time in the river and effect on the DO sag point (location of maximum DO decrease). In Zones 4-7, the summer daily average 10^{th} percentile DO levels are less than 3.0 mg/L for both the calibration and no KCRWTF load conditions. The summer daily minimum 10^{th} percentile DO levels are all greater than 1.0 mg/L for both conditions.

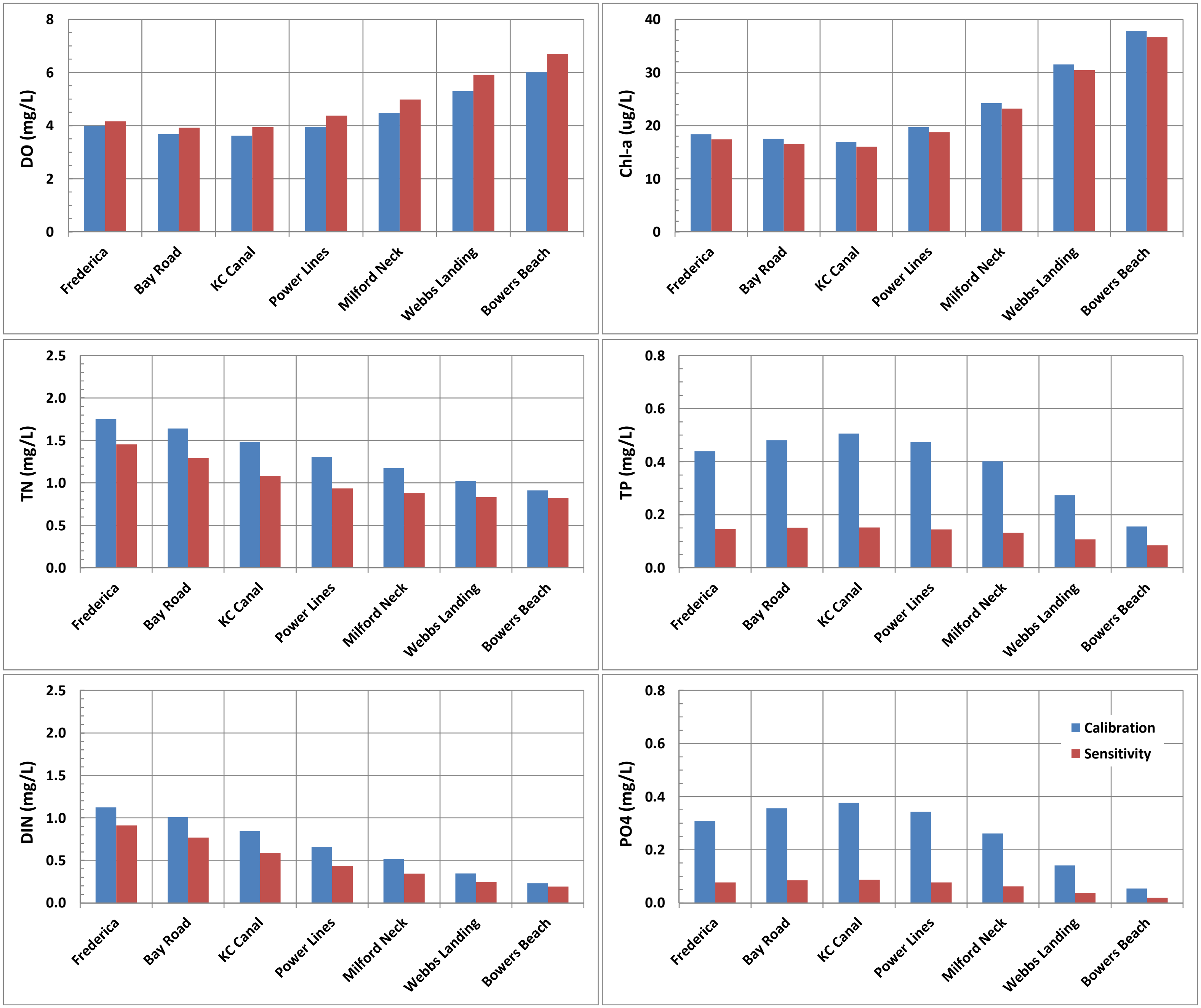


Figure 26. Model Sensitivity Run for No KCRWTF Loads (Summer Average Results)

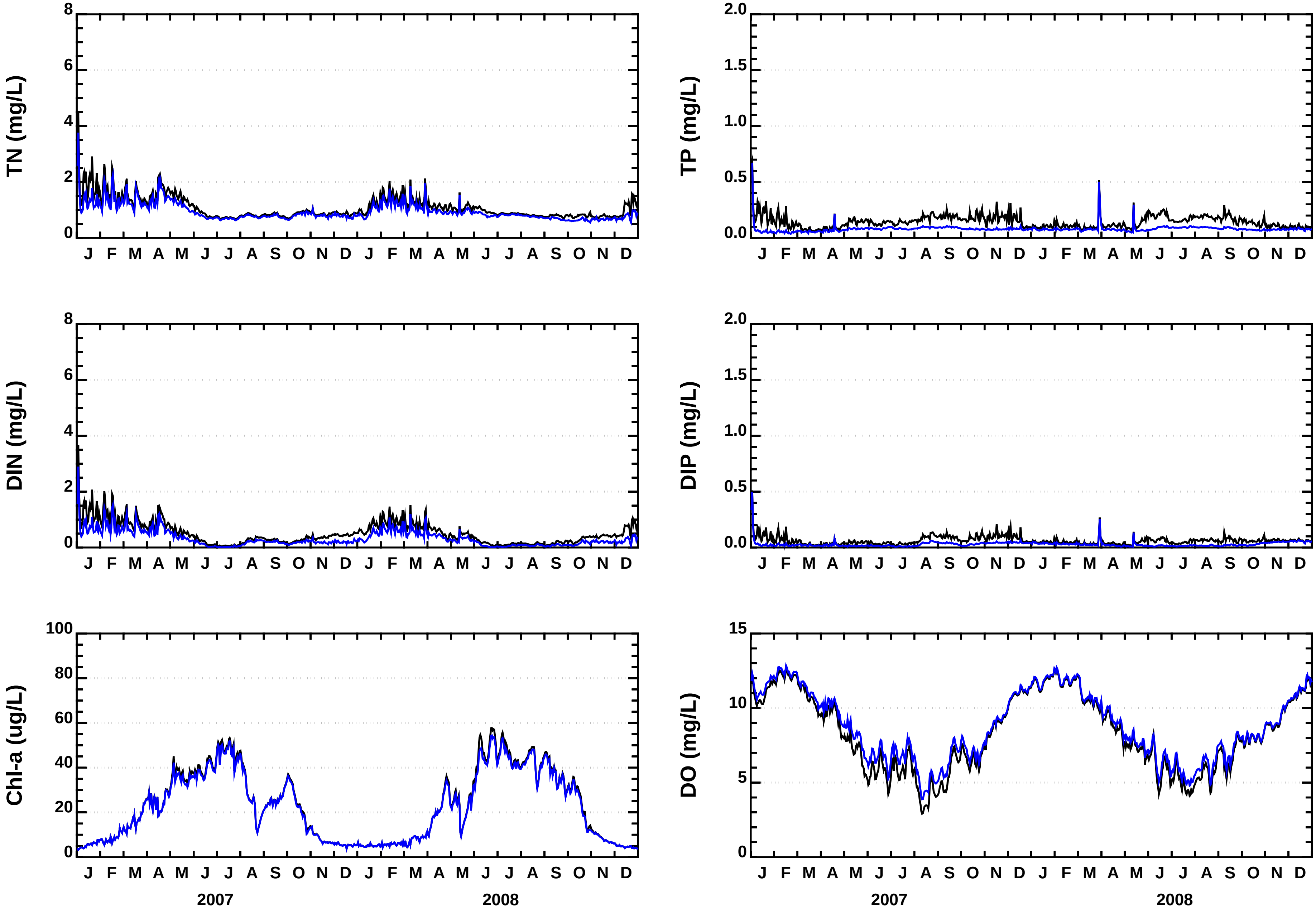


Figure 27. Loading Scenario Results at Bowers Beach (206101)

(Black - Calibration, Blue - No Kent County Loads)

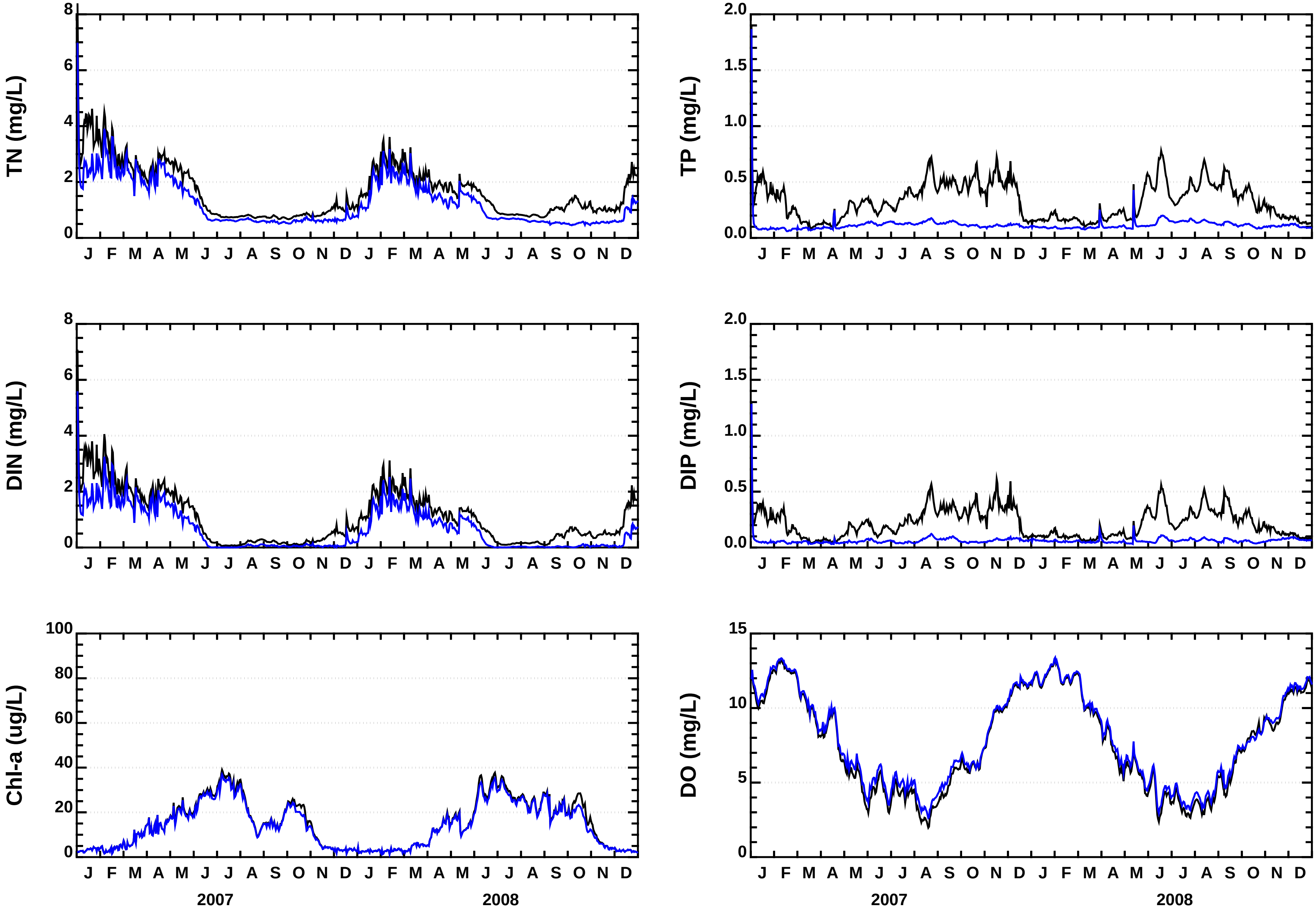


Figure 28. Loading Scenario Results at Milford Neck Wildlife Levee (206141)

(Black - Calibration, Blue - No Kent County Loads)

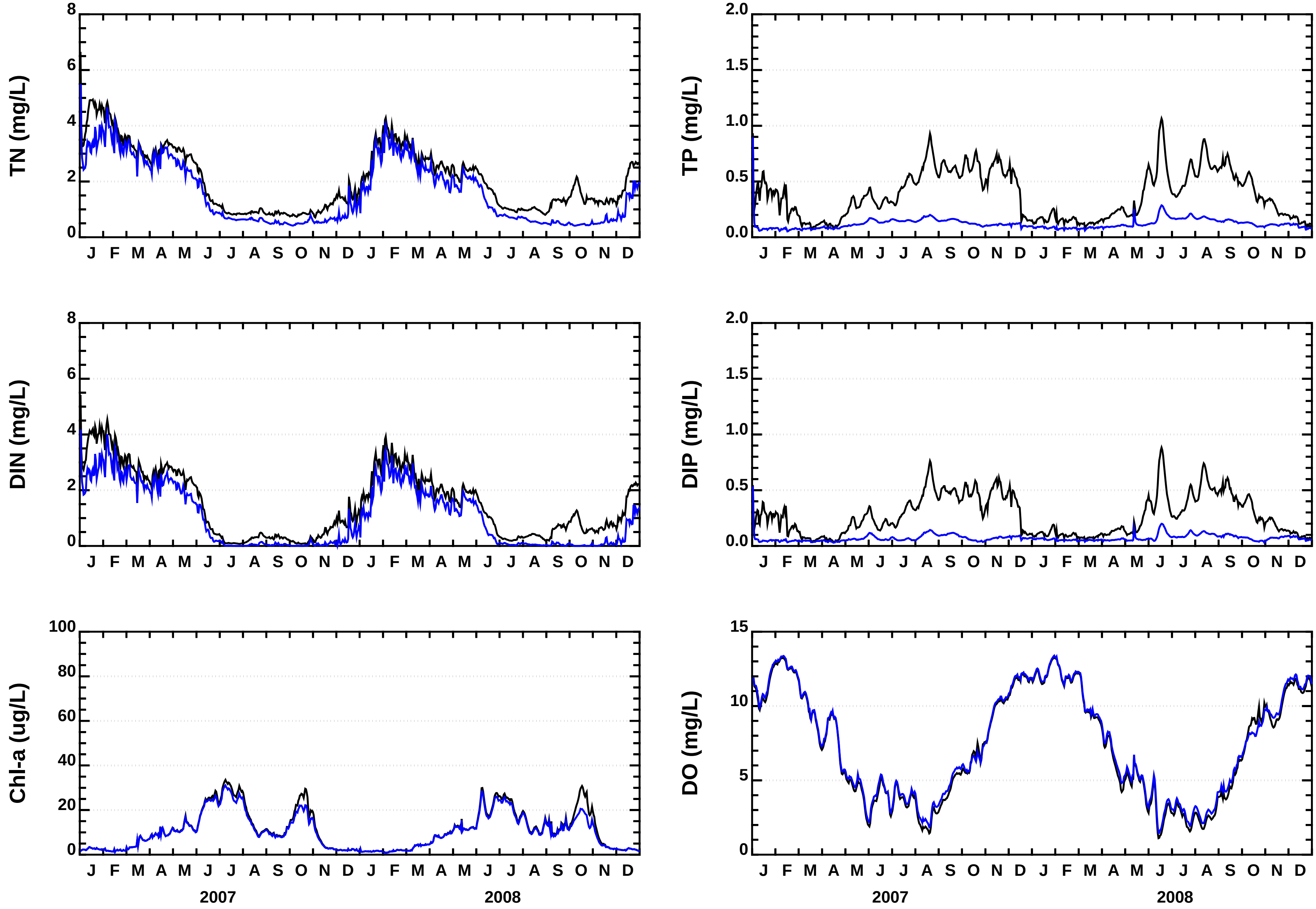


Figure 29. Loading Scenario Results at Kent County Canal (206231)

(Black - Calibration, Blue - No Kent County Loads)

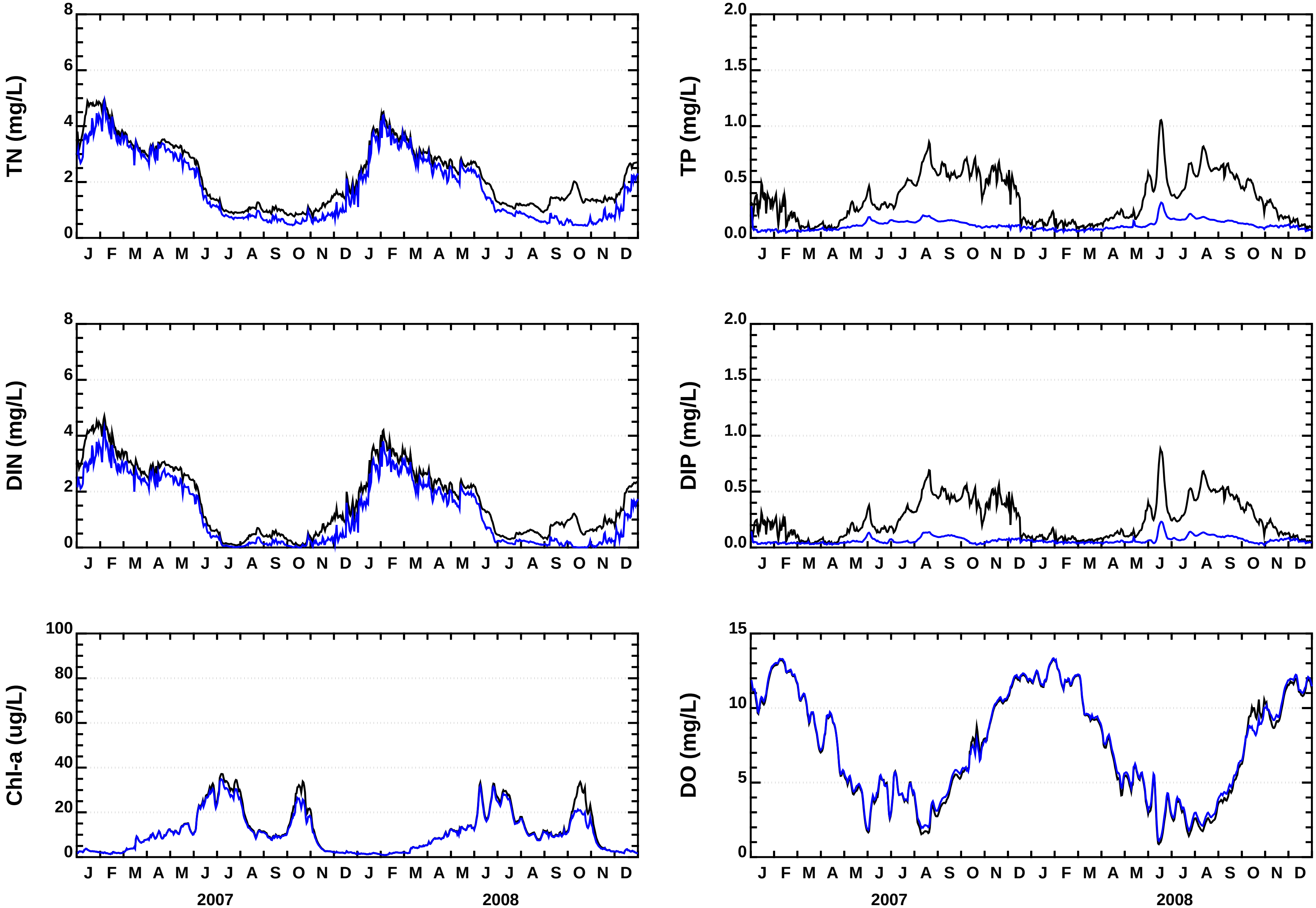


Figure 30. Loading Scenario Results at Bay Road (Frederica) (206091)

(Black - Calibration, Blue - No Kent County Loads)

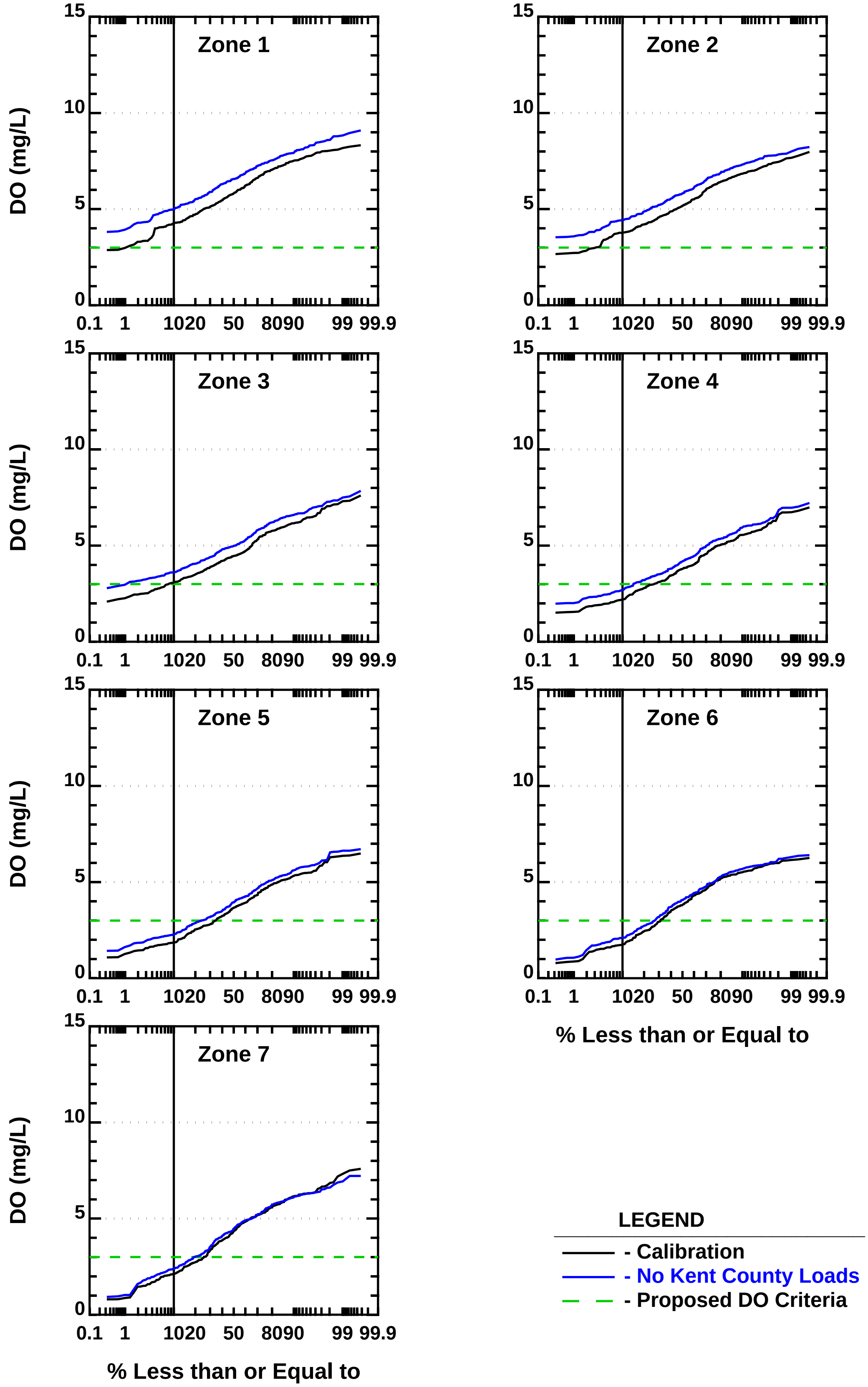


Figure 31. Summer Probability Distributions of Daily Average DO for No Kent County Loads

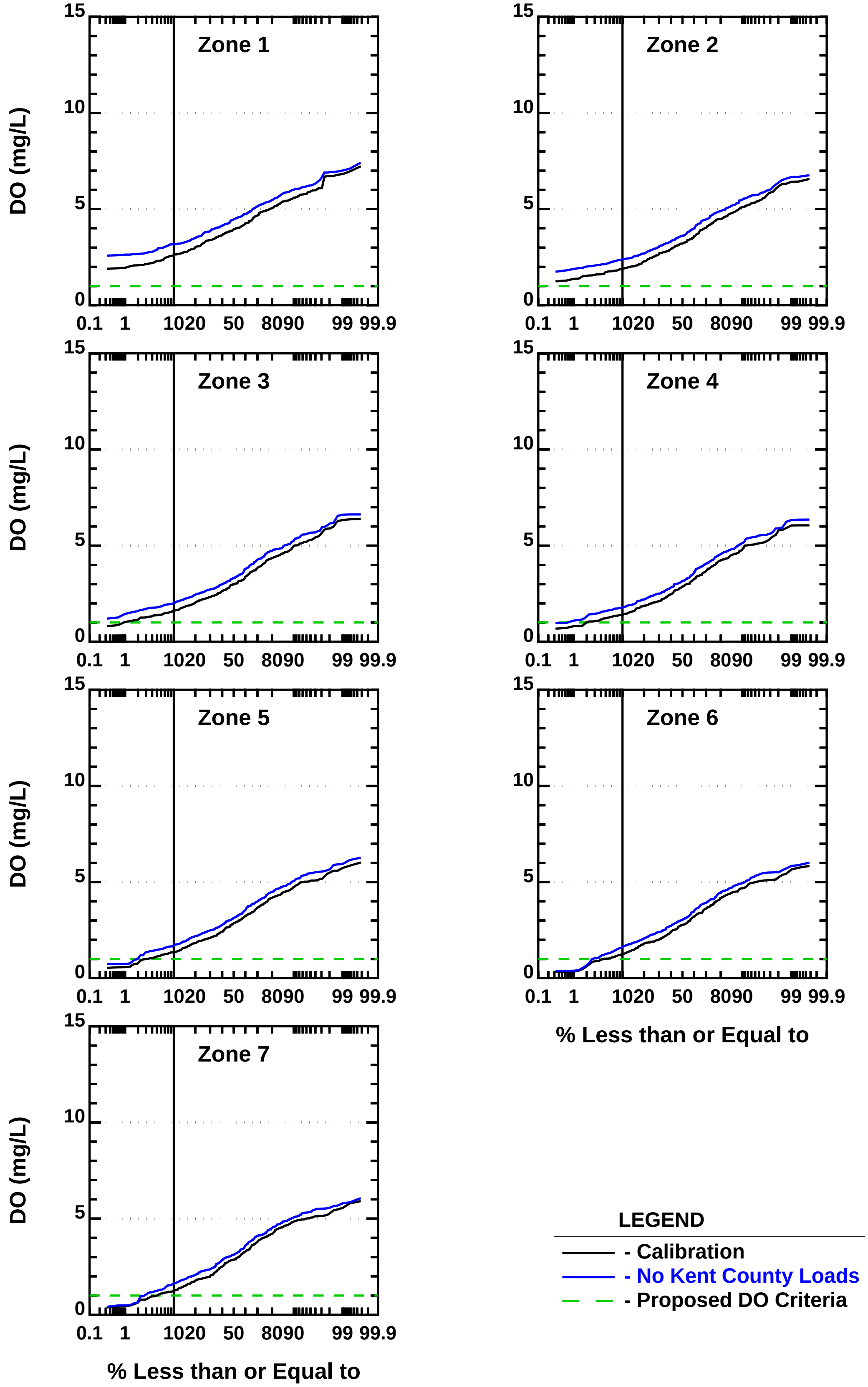


Figure 32. Summer Probability Distributions of Daily Minimum DO for No Kent County Loads

5.2 TIDAL MARSH LOAD IMPACT SCENARIO

The tidal marsh area in the Murderkill River is 2,930 acres based on the 2010 LiDAR results (McKenna, 2013) and the tidal marsh can either be a source or sink (loss) of nitrogen, phosphorus and carbon depending on the parameter. In addition, the tidal marshes are a significant DO sink that affect DO levels in the tidal river. During flood tide the tidal marshes fill with oxygenated river water but due to metabolic activity and oxygen consumption, the DO leaving the marshes on ebb tide are significantly depleted in oxygen levels. Figure 33 presents continuous DO and water elevation data collected by the USGS at the mouth of Webbs Marsh during August of 2007 and 2008. The location of Webbs Marsh is shown on Figure 1. This figure highlights the DO consumption that occurs in the tidal marsh over a tidal cycle. During flood tide the DO levels entering the tidal marsh are typically above 5 mg/L and during subsequent ebb tides the DO levels are much less than the DO levels that entered during flood tide and typically exit the tidal marsh near 1-2 mg/L. This oxygen consumption that occurs within the tidal marshes is an important factor influencing DO levels in the tidal river.

Nutrient, dissolved organic carbon (DOC), particulate organic carbon (POC), and DO deficit fluxes from Webbs Marsh were assigned in the model based on the study conducted in Webbs Marsh during 2007-2008. Using the 2,930 acre tidal marsh area and the average tidal marsh areal loading rates developed as part of this study (Wong et al., 2009; Dzwonkowski et al., 2013; Ullman et al., 2013), the tidal marsh loads averaged -950.9 lb/d of TN (loss), 37.2 lb/d of NH_3 (source), -1,073.2 lb/d of NO_2+NO_3 (loss), 49.4 lb/d of TP (source), 39.4 lb/d of PO_4 (source), and 49.4 lb/d of POC (source). The DOC source and DO deficit loads were assigned on a monthly basis and are presented in Table 6.

The time-variable marsh loading data presented in Table 6 was developed from DOC and DO deficit loads calculated from the Tidal Marsh Nutrient Exchange Study and were provided from August 2007 to August 2008 (bolded values in Table 6 below). The January-March and June-July 2007 loads were set equal to the 2008 loads; and the September and November-December 2008 loads were set equal to the 2007 loads. Because October 2007 experienced a large storm event, the October 2008 loads (green shaded cell) were interpolated between September and November 2007 loads. Similarly, because April-May 2008 experienced large storm events, the April-May 2007 loads (green shaded cells) were interpolated between March and June 2008 loads.

The water quality model was re-run without the tidal marsh loads and the model results compared to the calibration/validation period (2007-2008). These results are presented in Figure 34 as summer averages for TN, DIN, TP, PO_4, chl-a and DO for both the calibration/validation and the no tidal marsh load model results.

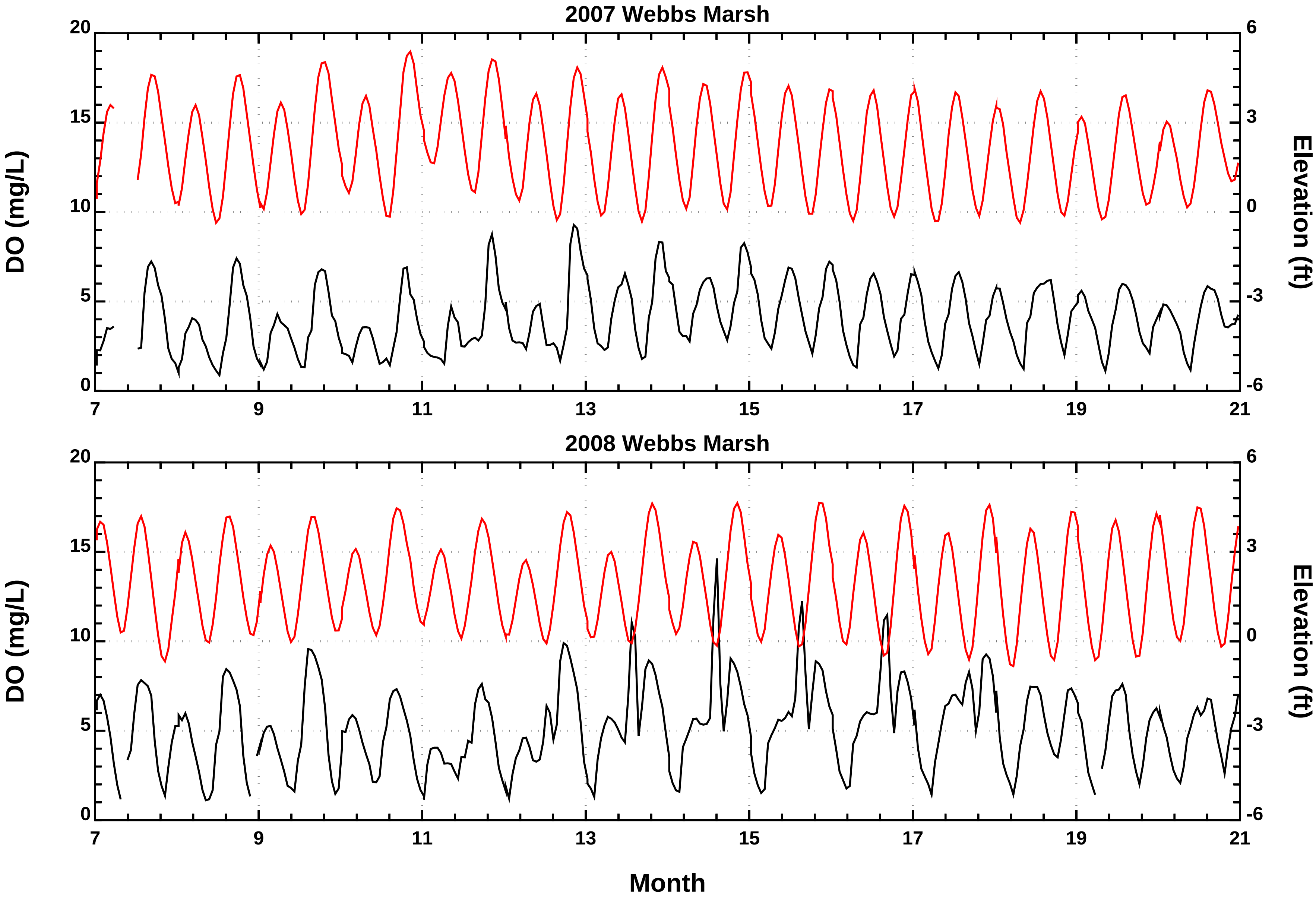


Figure 33. USGS Webbs Marsh Continuous DO Data (2007-2008) - August
(Black - DO, Red - Elevation)

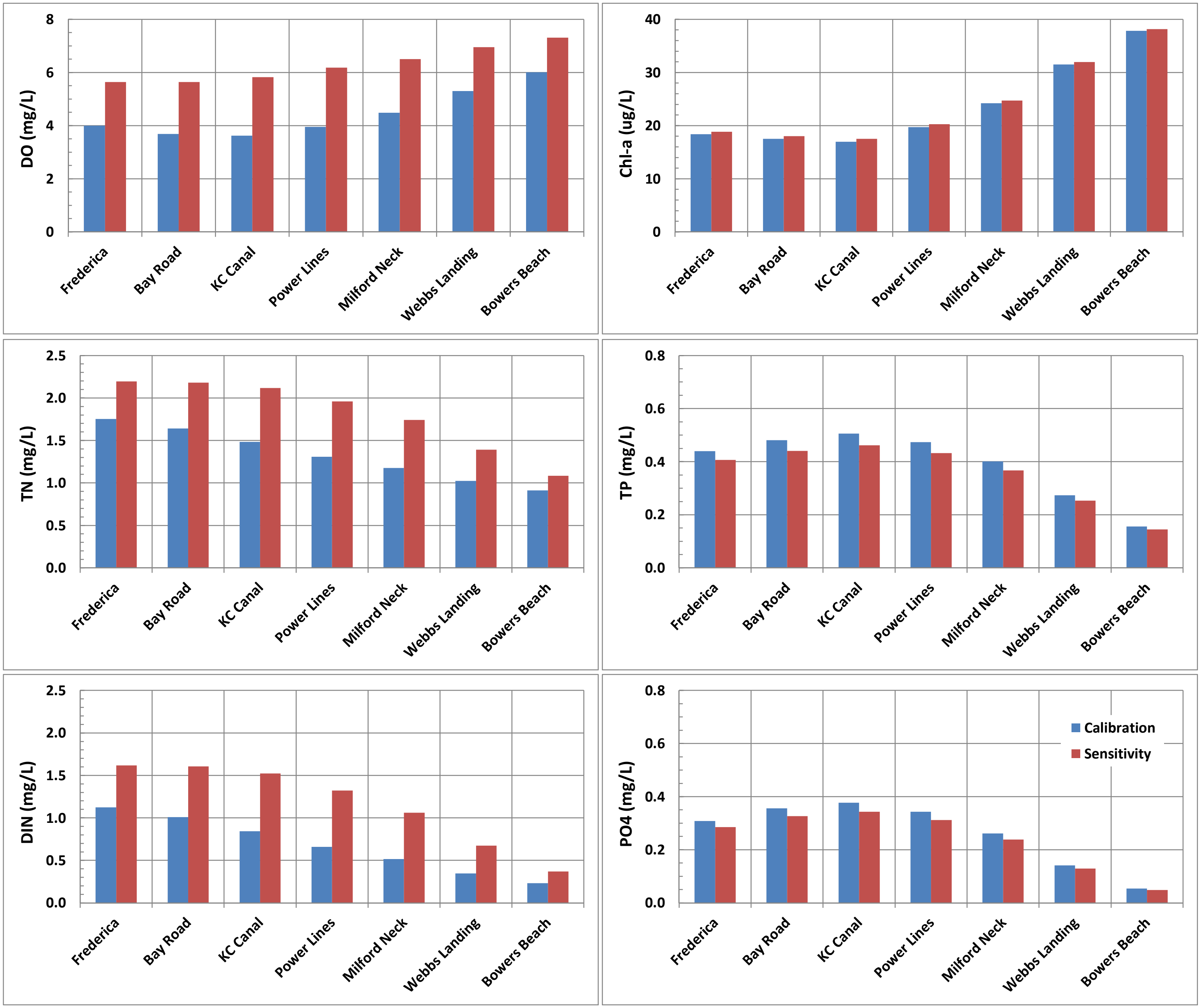


Figure 34. Model Sensitivity Run for No Tidal Marsh Loads (Summer Average Results)

Table 6. Time Variable Marsh DOC and DO Deficit Loads

Month	2007		2008	
	DOC (lb/d)	DO Deficit (lb/d)	DOC (lb/d)	DO Deficit (lb/d)
January	37.2	-93.2	**37.2**	**-93.2**
February	510.1	69.2	**510.1**	**69.2**
March	1099.7	925.0	**1099.7**	**925.0**
April	1789.2	1554.5	**3494.4**	**3638.1**
May	2478.6	2183.9	**5123.5**	**5186.0**
June	3168.1	2813.3	**3168.1**	**2813.3**
July	3346.3	3017.2	**3346.3**	**3017.2**
August	**4210.6**	**3932.9**	**3264.0**	**3326.6**
September	**1356.5**	**1670.8**	1356.5	1670.8
October	**3470.8**	**3456.9**	736.6	960.6
November	**116.6**	**250.5**	116.6	250.5
December	**587.4**	**628.5**	587.4	628.5

The model sensitivity results show that DO levels change significantly as a result of the removal of the tidal marsh loads with calculated increases in TN levels due to the loss of denitrification processes in the tidal marshes. The calculated increase in TN ranged from 0.17-0.65 mg/L and the calculated decreases in TP ranged from 0.01-0.04 mg/L with the largest changes occurring in the middle of the river. The DO increases ranged from 1.3-2.2 mg/L while the chl-a levels increased slightly ranging from 0.3-0.6 μg/L. The large increases in DO are due to the removal of the tidal marsh DOC, POC and DO deficit loads that are the primary factors influencing DO levels in the tidal Murderkill River. This model scenario shows that under the no tidal marsh load scenario, summer average DO levels in all zones including the critical zones of 5 (Kent County canal station) and 6 (Bay Road station) are above 5 mg/L. In addition, it is shown that the tidal marsh loads cause summer average DO levels at these two locations to decrease by 2.2 and 2.0 mg/L, respectively.

The model sensitivity results are also presented as time-series figures over the 2007-2008 modeling period at four monitoring locations in the tidal river (Figures 35-38) and as summer daily average and daily minimum probability distributions in the seven tidal river zones (Figures 39-40). The time-series figures highlight the spatial variation in the river (i.e., larger impacts in the middle of

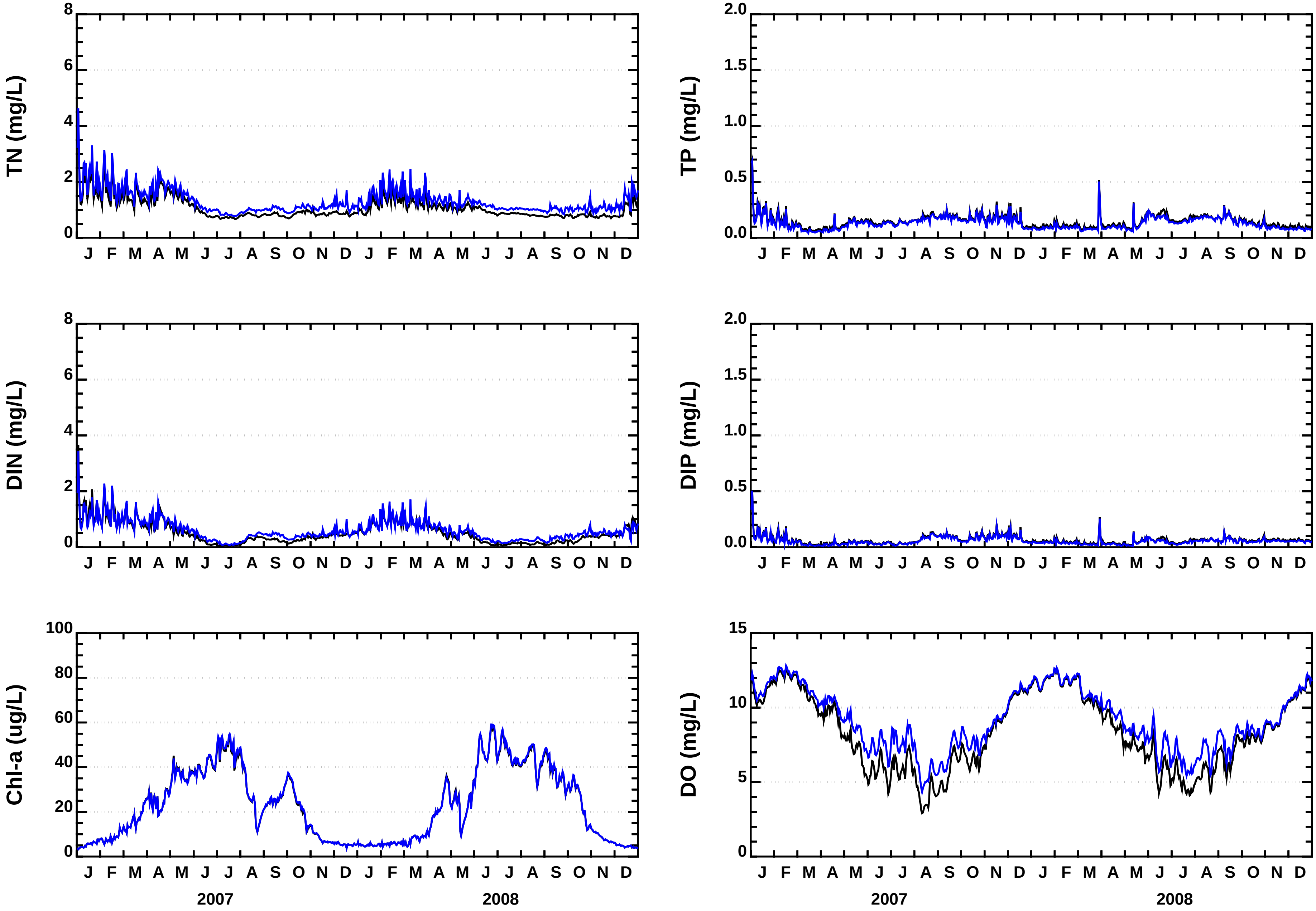


Figure 35. Loading Scenario Results at Bowers Beach (206101)

(Black - Calibration, Blue - No Tidal Marsh Loads)

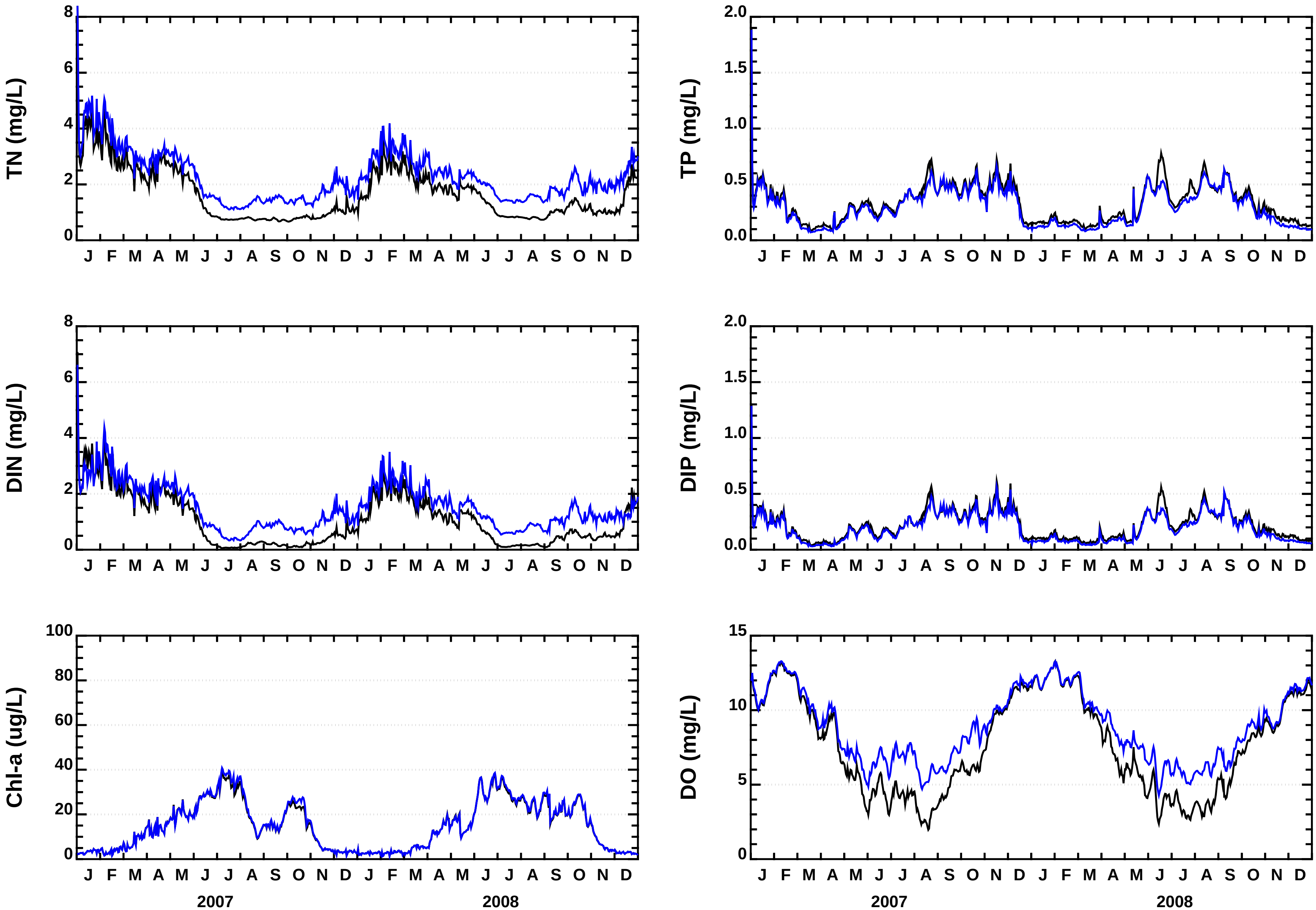


Figure 36. Loading Scenario Results at Milford Neck Wildlife Levee (206141)

(Black - Calibration, Blue - No Tidal Marsh Loads)

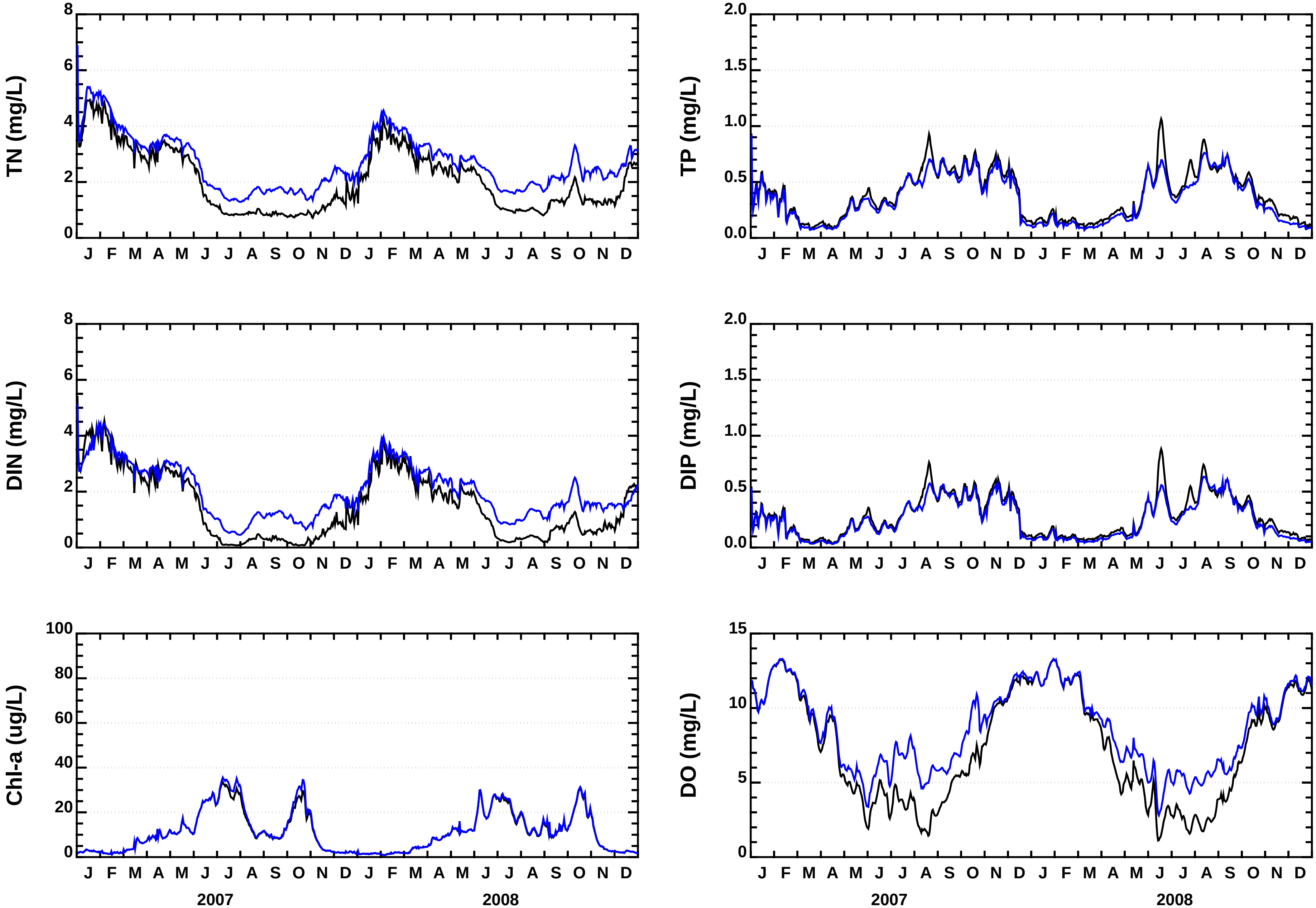


Figure 37. Loading Scenario Results at Kent County Canal (206231)

(Black - Calibration, Blue - No Tidal Marsh Loads)

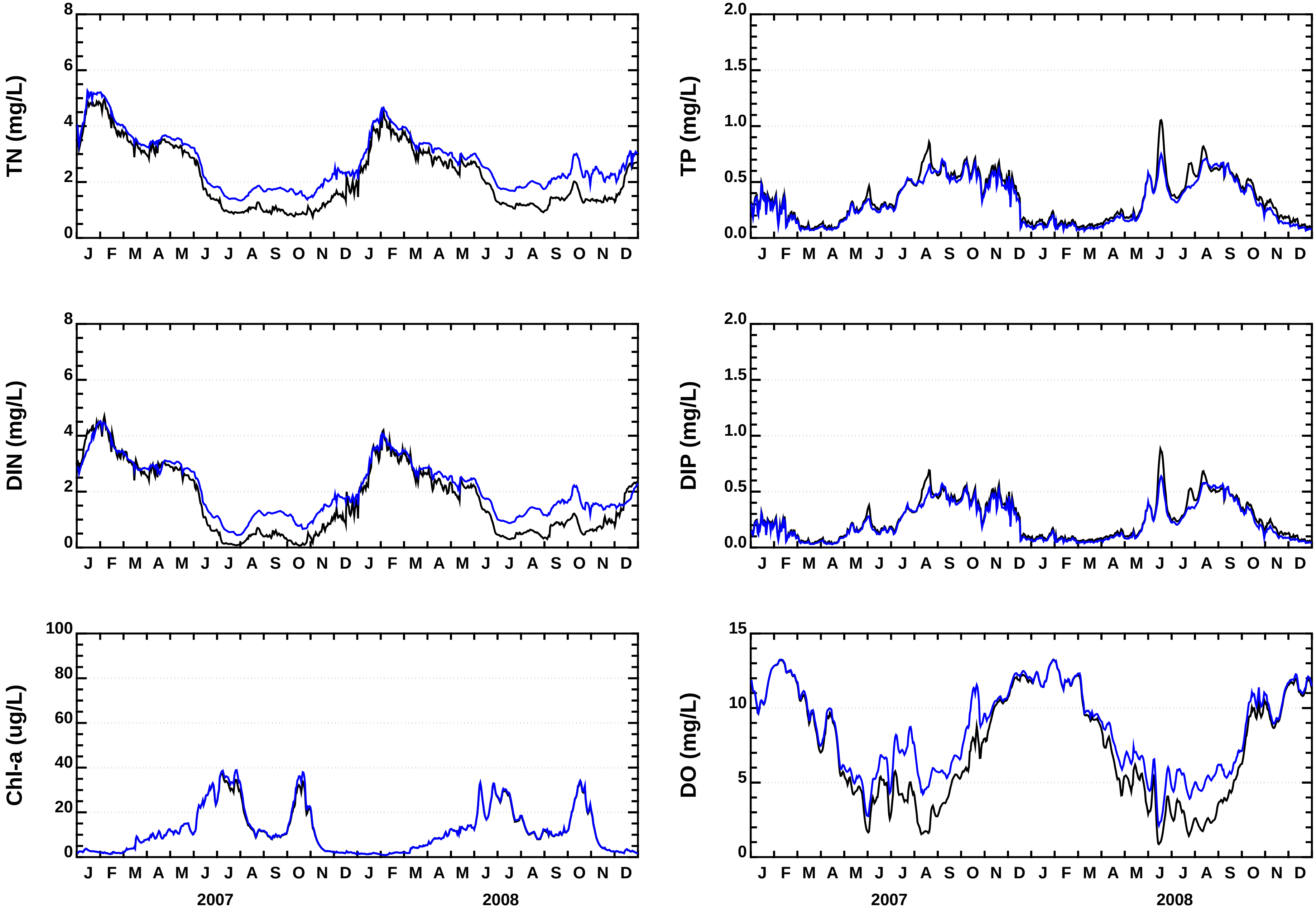


Figure 38. Loading Scenario Results at Bay Road (Frederica) (206091)

(Black - Calibration, Blue - No Tidal Marsh Loads)

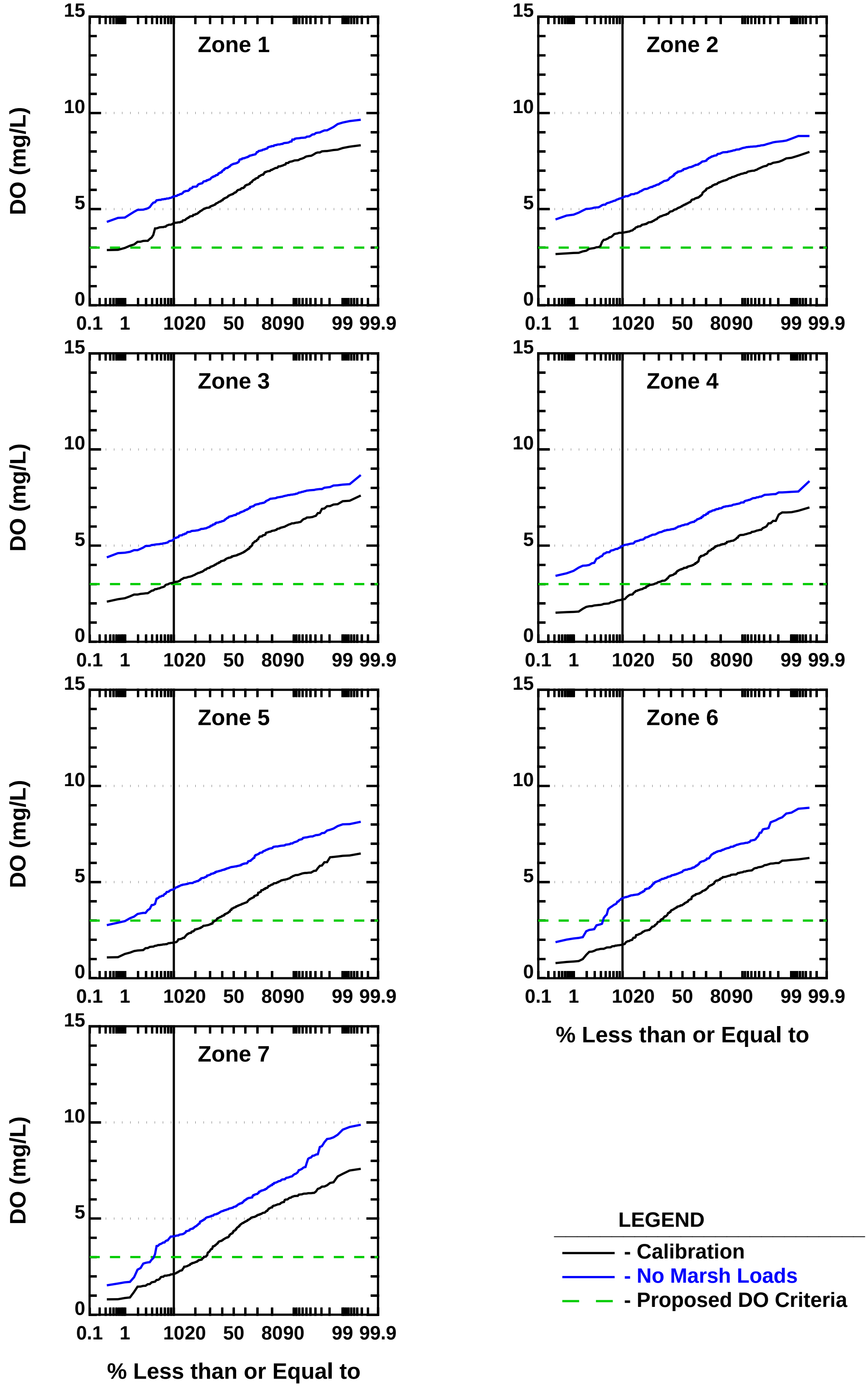


Figure 39. Summer Probability Distributions of Daily Average DO for No Marsh Loads

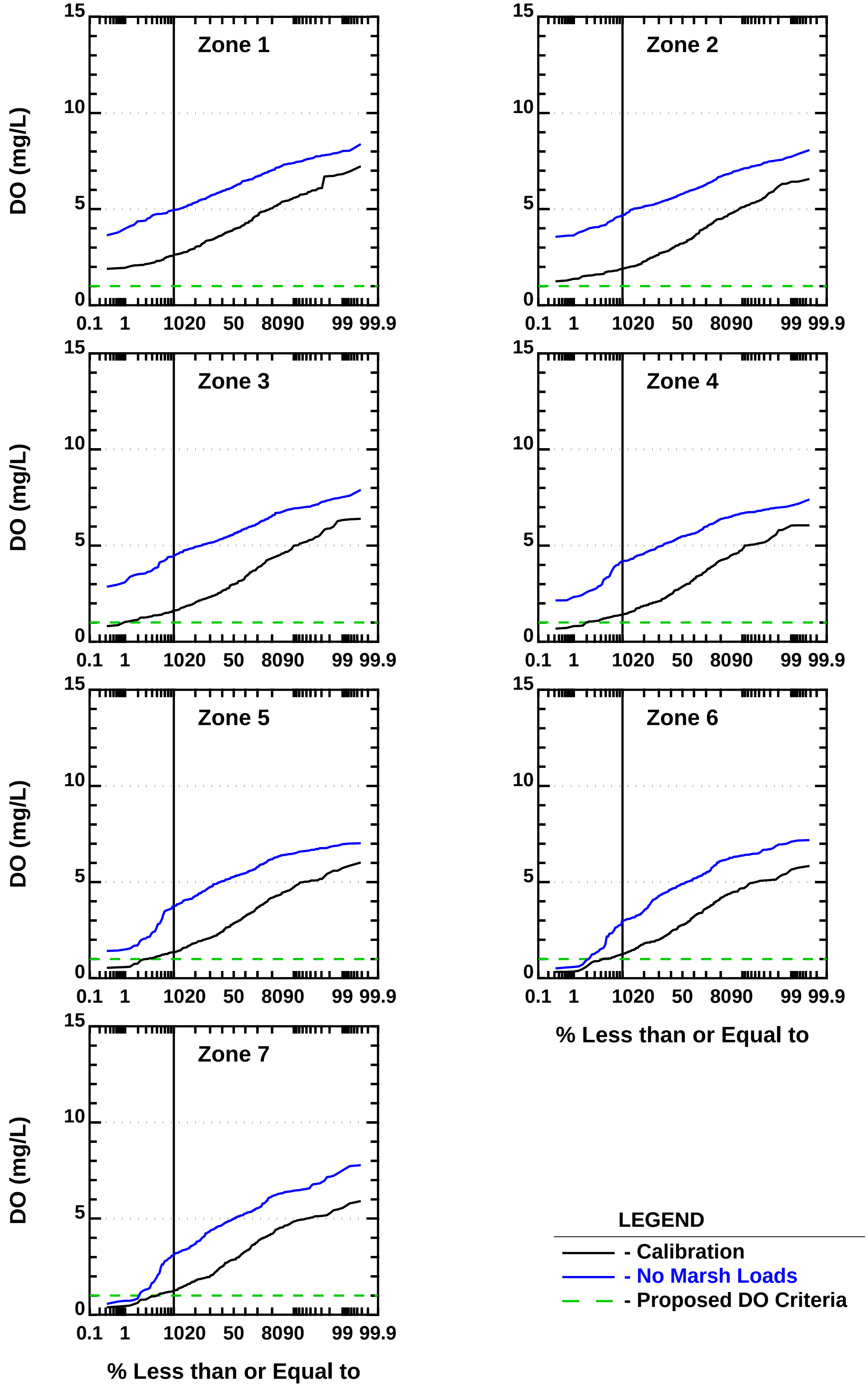


Figure 40. Summer Probability Distributions of Daily Minimum DO for No Marsh Loads

the river) and seasonal impacts on DO. Again, the nutrient changes (increase for nitrogen, decrease for phosphorus) in the river are greater during the low flow periods of the year when dilution from upstream river flows is small. Changes to the chl-a levels are shown to be very small throughout the year. The large increases in DO levels are very pronounced during the low flow, spring/summer/fall periods of the year. The DO probability distributions presented in Figures 39-40 show large DO increases throughout the entire tidal river zone (Bowers Beach to Frederica) with the summer daily average 10^{th} percentile DO levels greater than 3.0 mg/L and summer daily minimum 10^{th} percentile DO levels greater than 1.0 mg/L at all locations.

5.3 NATURAL BACKGROUND SCENARIO

In this scenario, water quality (i.e., nutrient, chl-a and DO levels) in the Murderkill River is predicted under a theoretical "natural background" condition. For this, the calibrated and validated tidal water quality model (RCA) was used to estimate what the best water quality could be without anthropogenic point and nonpoint sources in the watershed along with an adjustment of the downstream Delaware Bay boundary conditions to reflect non-anthropogenic influenced bay water quality characteristics.

The modeled "natural background" condition was setup in the model as follows.

- The KCRWTF discharge to the tidal river and the Harrington Sewage Treatment Plant (STP) discharge to Browns Branch were removed from the RCA and HSPF models, respectively.
- The current land use assigned in the watershed model (HSPF) was converted to a forested land use and assigned groundwater concentrations were reduced to reflect an undeveloped watershed. The watershed model calibration used time varying groundwater and interflow concentrations that ranged from 1.0-5.0 mg/L NO_2+NO_3, 0.015-0.04 mg/L NH_3, and 0.01-0.04 mg/L PO_4. For the "natural background" scenario, the groundwater and interflow concentrations were reduced to 0.4 mg/L NO_2+NO_3, 0.01 mg/L NH_3, and 0.005-0.007 mg/L PO_4. The reduced groundwater and interflow concentrations were based on groundwater data from forested, undeveloped and/or background sites in the region or from national studies (Ator and Denis, 1997; Ator, 2008; Debrewer et. al, 2007; Dubrovsky et. al, 2010).
- The downstream Delaware Bay water quality boundary condition for the calibration/validation period was based on DRBC Boat Run data from three stations (Elbow of Crossledge Shoal, RM 22.75; South Joe Flogger Shoal, RM 16.5; South Brown Shoal, RM 6.5). For the "natural background" scenario, the downstream bay boundary condition was based on the South Brown Shoal data since the station is closest to the mouth of the bay, represents more coastal Atlantic Ocean water quality, and was felt to represent the "natural background" condition in the bay for this scenario.

- The tidal marsh loadings developed for the model calibration/validation period were not changed for the "natural background" scenario.

These model input changes were used to simulate the "natural background" condition and compare it to the model calibration/validation results. Figure 41 presents the "natural background" model results as summer averages (May-September) for TN, DIN, TP, PO_4, chl-a and DO. The model sensitivity results show that DO levels do not change significantly, but chl-a levels are calculated to decrease by 7.7-14.8 μg/L when compared to the calibration (2007-2008 condition) scenario. The calculated decrease in TN under natural-background condition ranged from 0.49-1.37 mg/L and for TP ranged from 0.09-0.36 mg/L with the largest decreases occurring in the upper reaches of the tidal river. The average nutrient levels calculated in the tidal river for the "natural background" scenario were 0.38 mg/L TN, 0.06 mg/L DIN, 0.12 mg/L TP and 0.07 mg/L PO_4.

The model sensitivity results are also presented as time-series figures over the 2007-2008 modeling period at four monitoring locations in the tidal river (Figures 42-45) and as summer daily average and daily minimum probability distributions in the seven tidal river zones (Figures 46-47). For reference, the water quality levels calculated for the 2007-2008 modeling time period are also presented in these figures for comparison. The time-series figures highlight the overall annual effect of significantly reducing nutrient levels in the tidal river due to the removal of all anthropogenic nutrient sources in the Murderkill River watershed including the reductions in groundwater nutrient levels to reflect the undeveloped watershed. Due to the large reductions in river nutrient levels, there is also decrease in the chl-a levels due both to nutrient load reductions and the decreased chl-a levels in the upstream watershed ponds and lakes. Although there were significant reductions in river nutrient and chl-a levels, the DO levels do not change as dramatically, which is due to the dominant effect that the tidal marshes have on DO levels in the river. The DO probability distributions presented in Figures 46-47 show that the median DO levels do not increase as much as the 10^{th} percentile DO levels, which again indicate the minimal changes to the DO levels under the "natural background" condition. In Zones 4-7, the summer daily average 10^{th} percentile DO levels are less than 3.0 mg/L for the "natural background" condition with the summer daily minimum 10^{th} percentile DO levels all greater than 1.0 mg/L. The DO probability distributions also indicate that daily minimum DO levels increase to greater extent than do the daily average DO levels.

Although these changes in nutrient levels are considerable, the nutrient reduction impact on DO is minimal (0.20-0.49 mg/L). The minimal change in DO levels is due to the fact that the tidal marsh loadings (nutrients, carbon and DO deficit) are the dominant factors controlling DO levels in the tidal river. The "natural background" scenario results indicate that the low DO levels in the tidal Murderkill River (i.e., below the current DO standards) occur naturally due to the interaction between the river and surrounding tidal marshes. One measure of the importance of the tidal marshes in the tidal Murderkill River is the ratio of the tidal marsh area to the river surface area. Considering the area between Frederica (Route 1 Bridge) and the river mouth at Bowers Beach, the

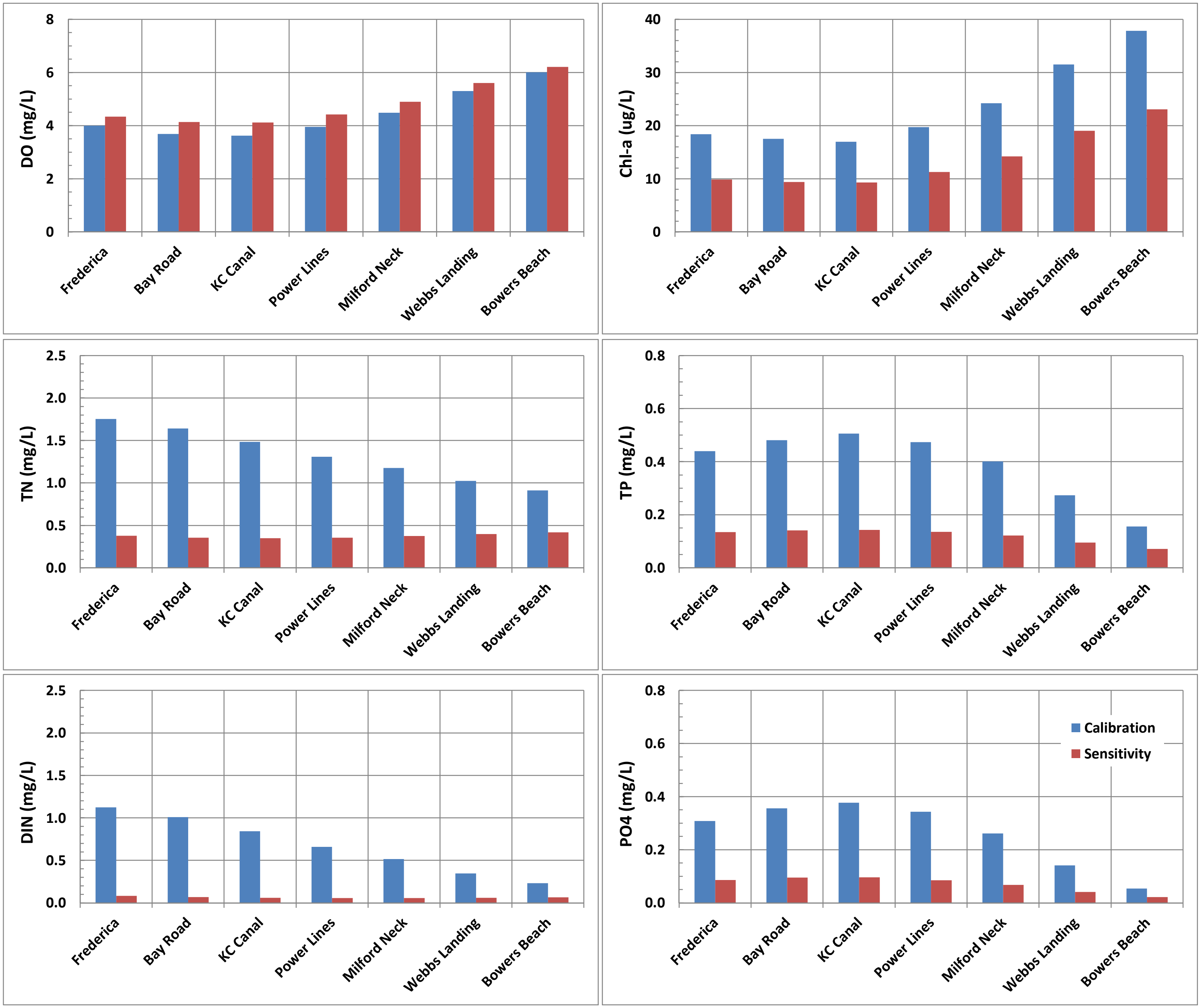


Figure 41. Model Sensitivity Run for "Natural Background" Scenario (Summer Average Results)

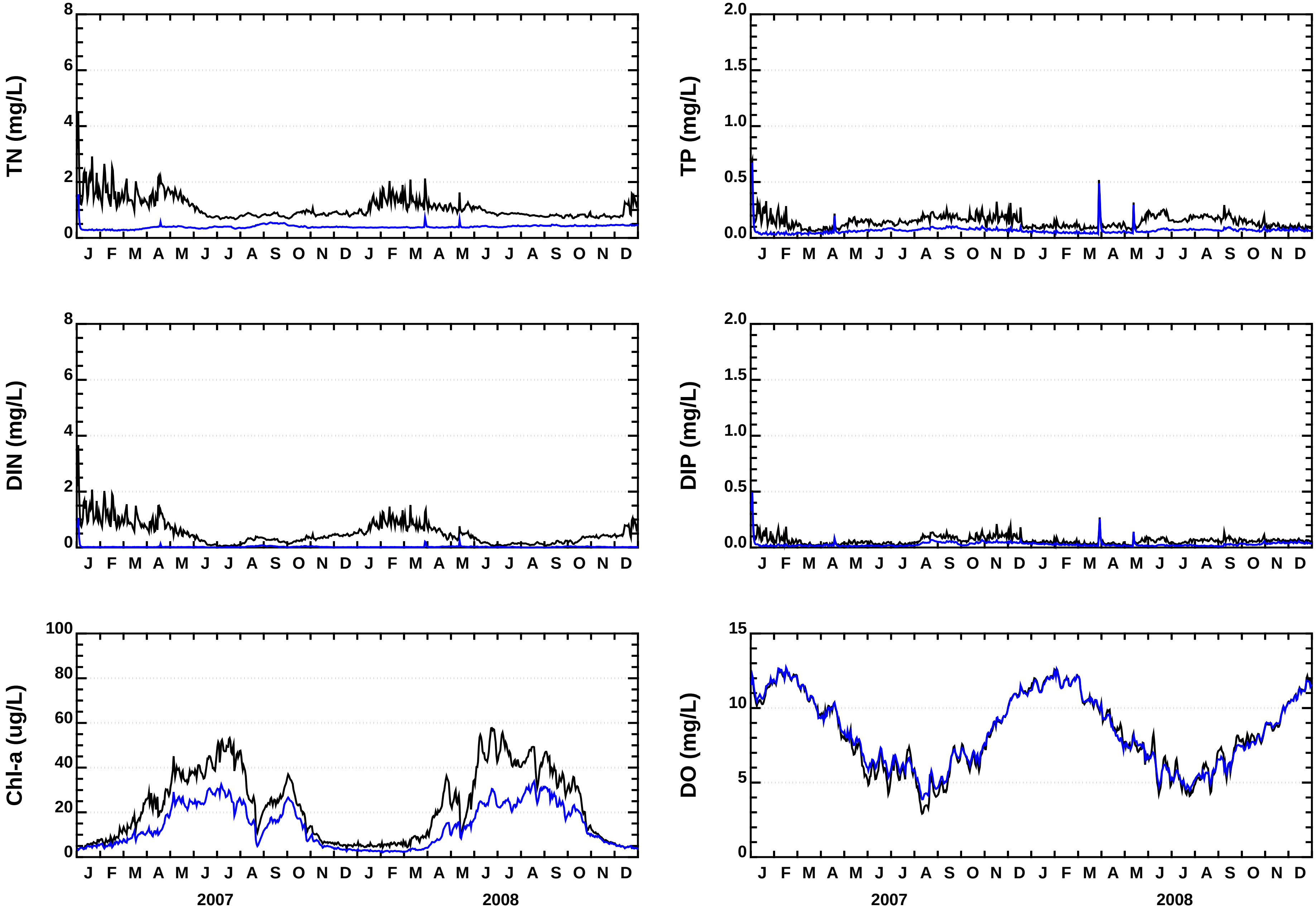


Figure 42. Loading Scenario Results at Bowers Beach (206101)

(Black - Calibration, Blue - Natural Background)

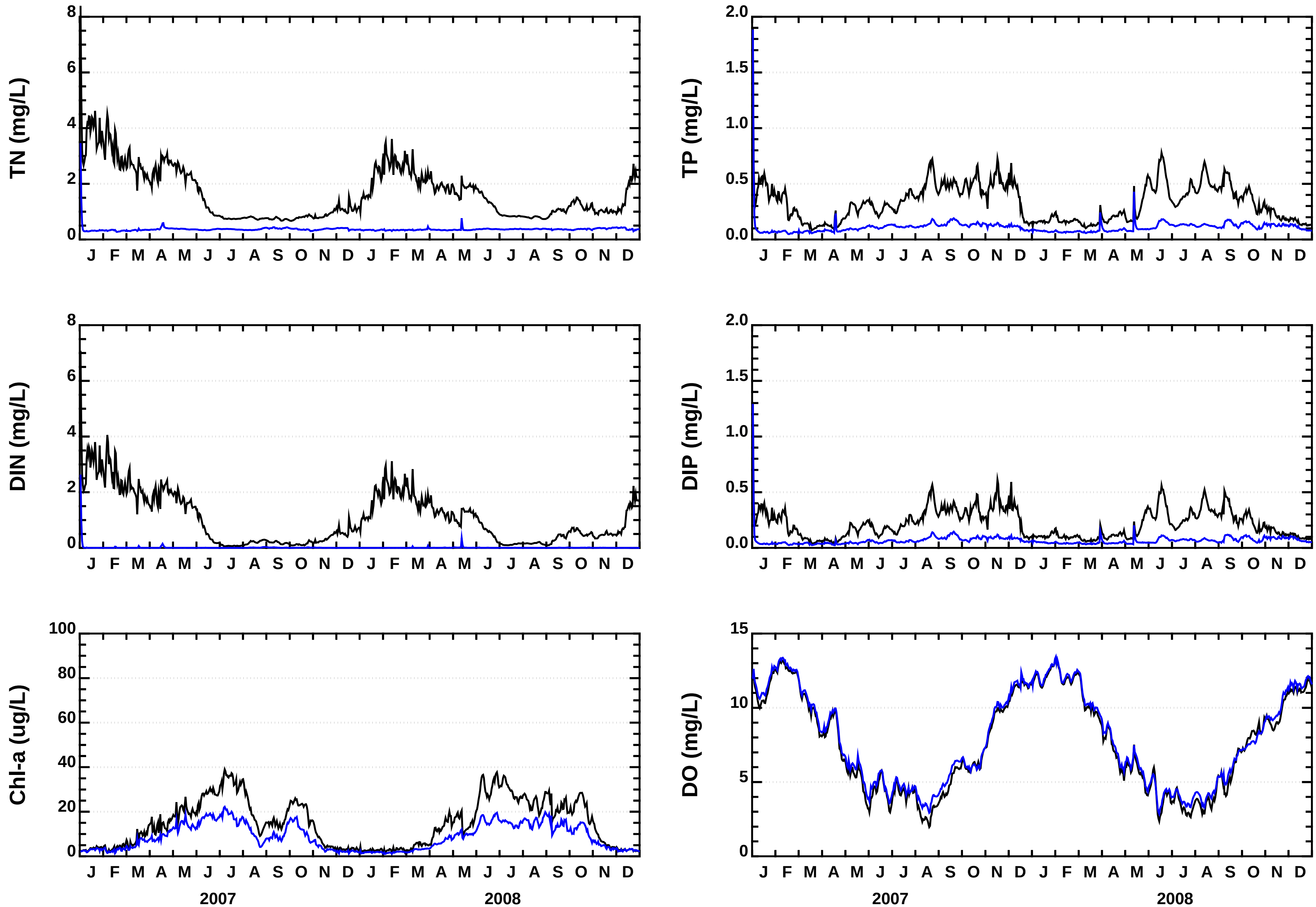


Figure 43. Loading Scenario Results at Milford Neck Wildlife Levee (206141)

(Black - Calibration, Blue - Natural Background)

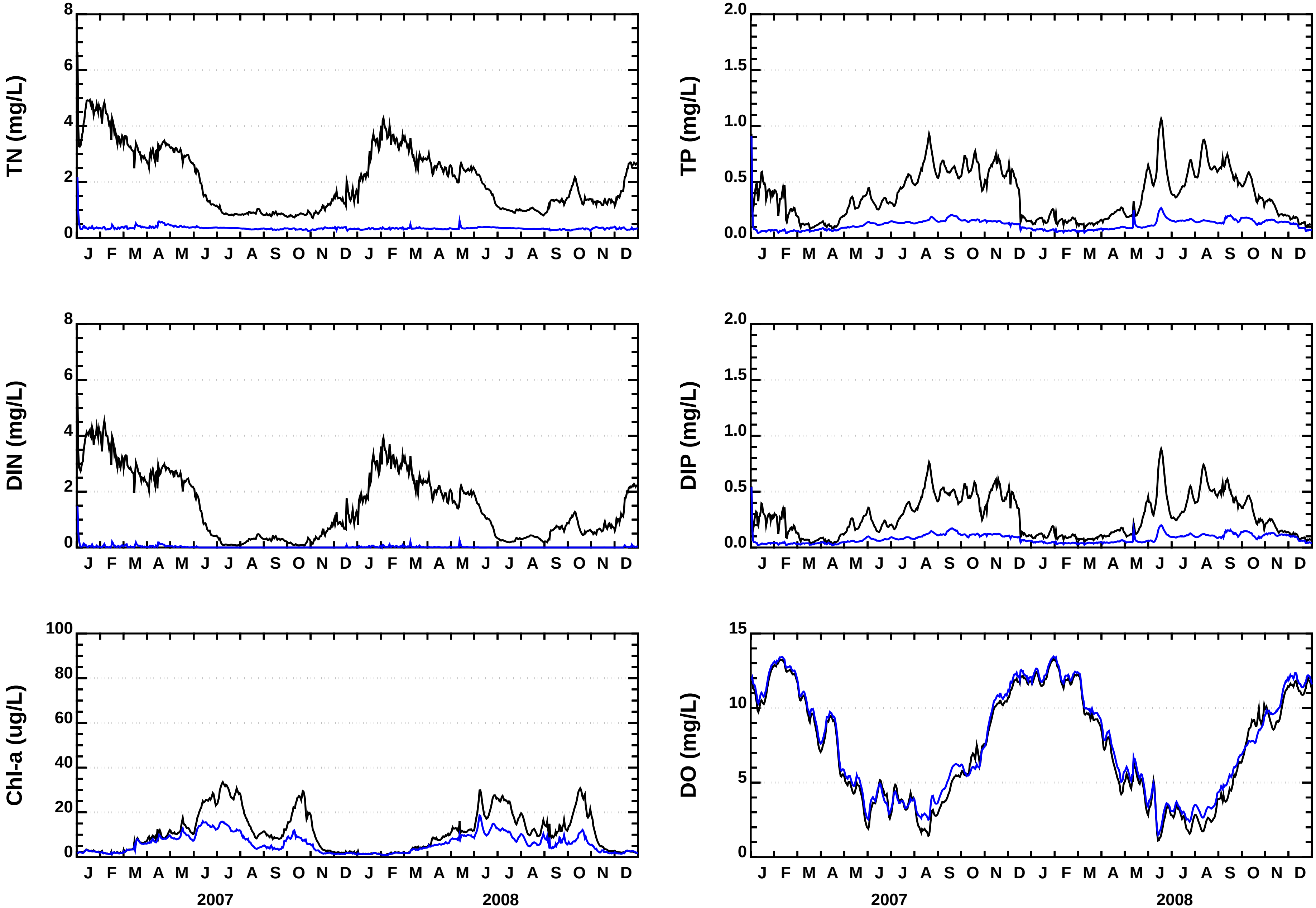


Figure 44. Loading Scenario Results at Kent County Canal (206231)

(Black - Calibration, Blue - Natural Background)

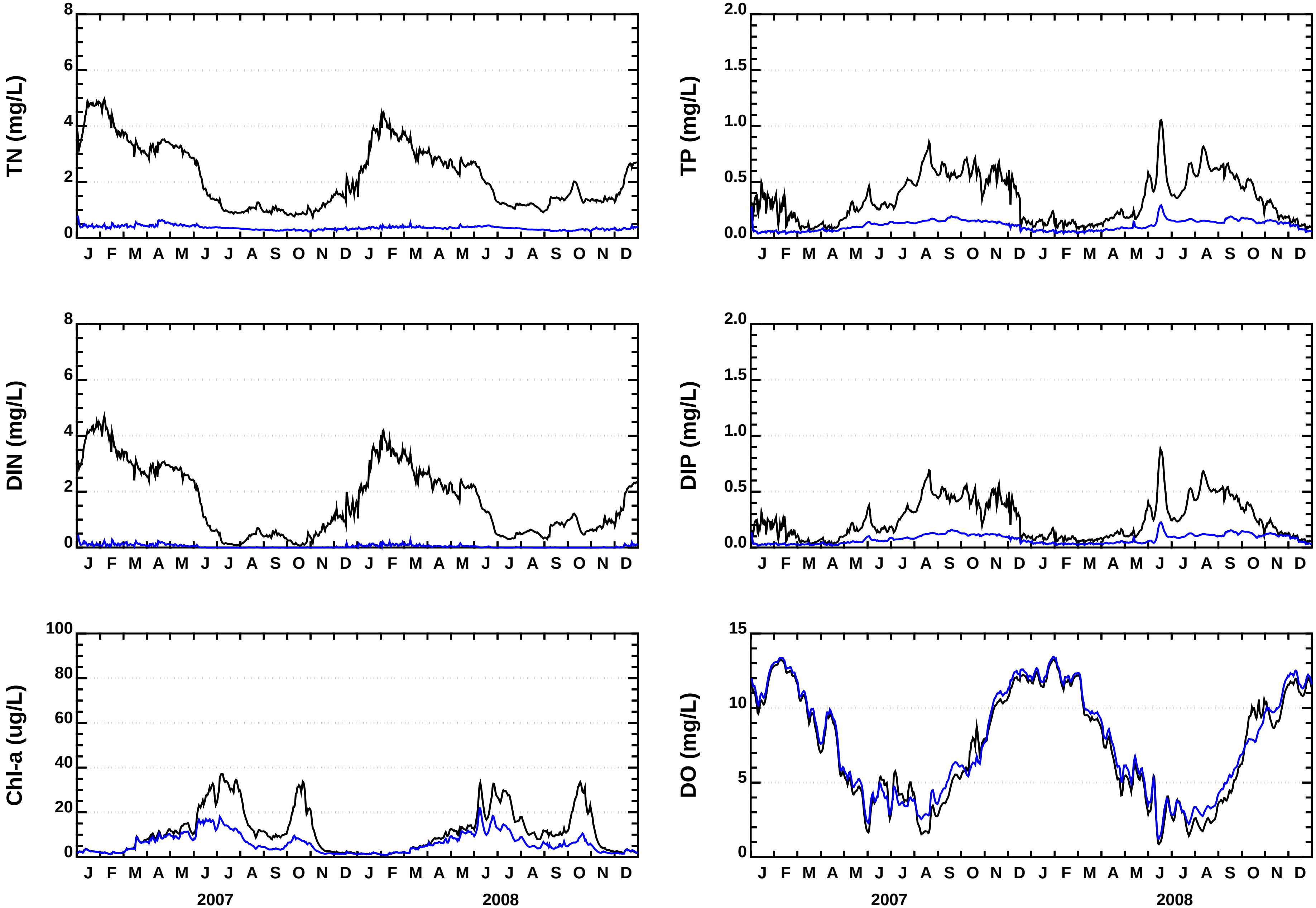


Figure 45. Loading Scenario Results at Bay Road (Frederica) (206091)

(Black - Calibration, Blue - Natural Background)

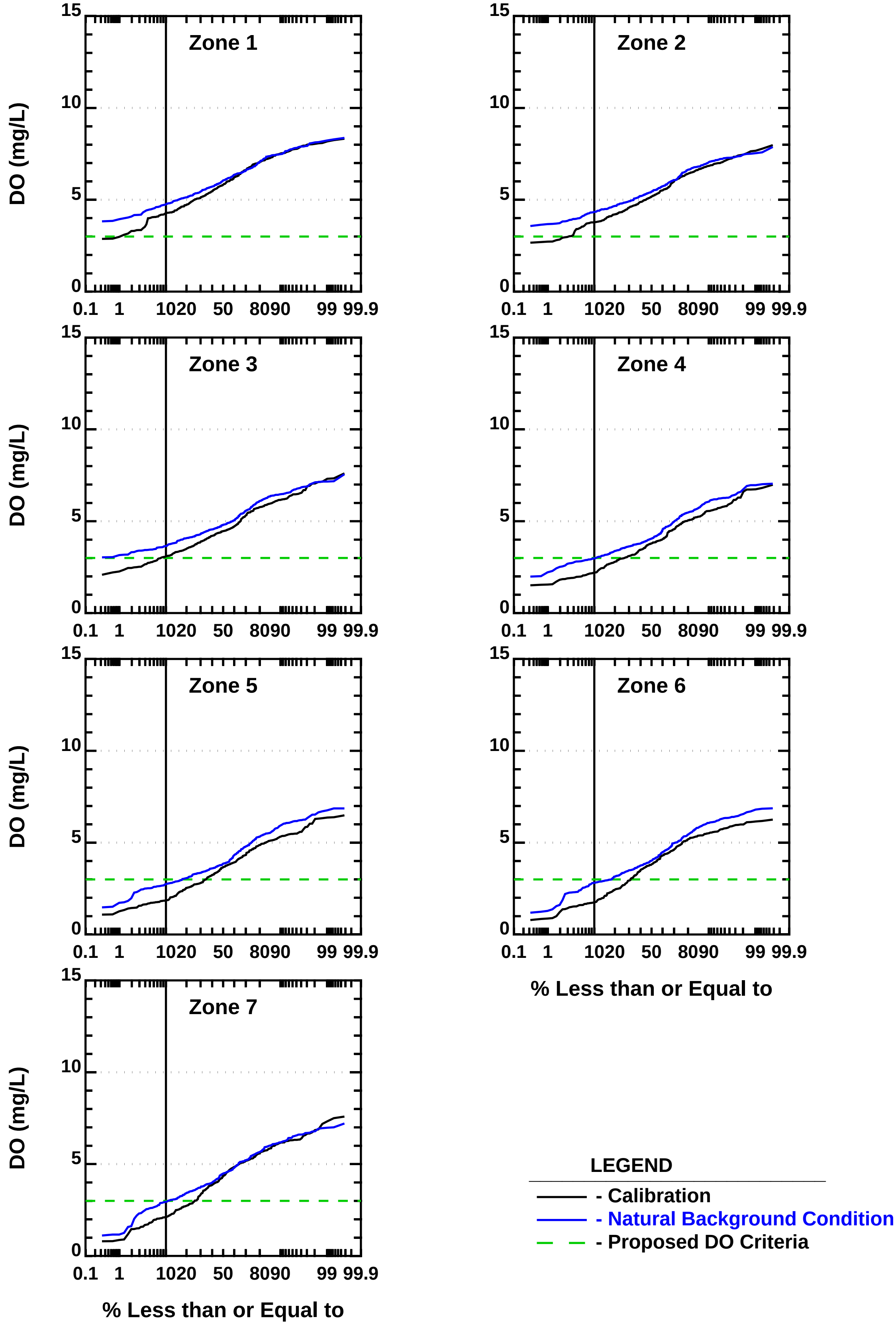


Figure 46. Summer Probability Distributions of Daily Average DO for Natural Background Condition

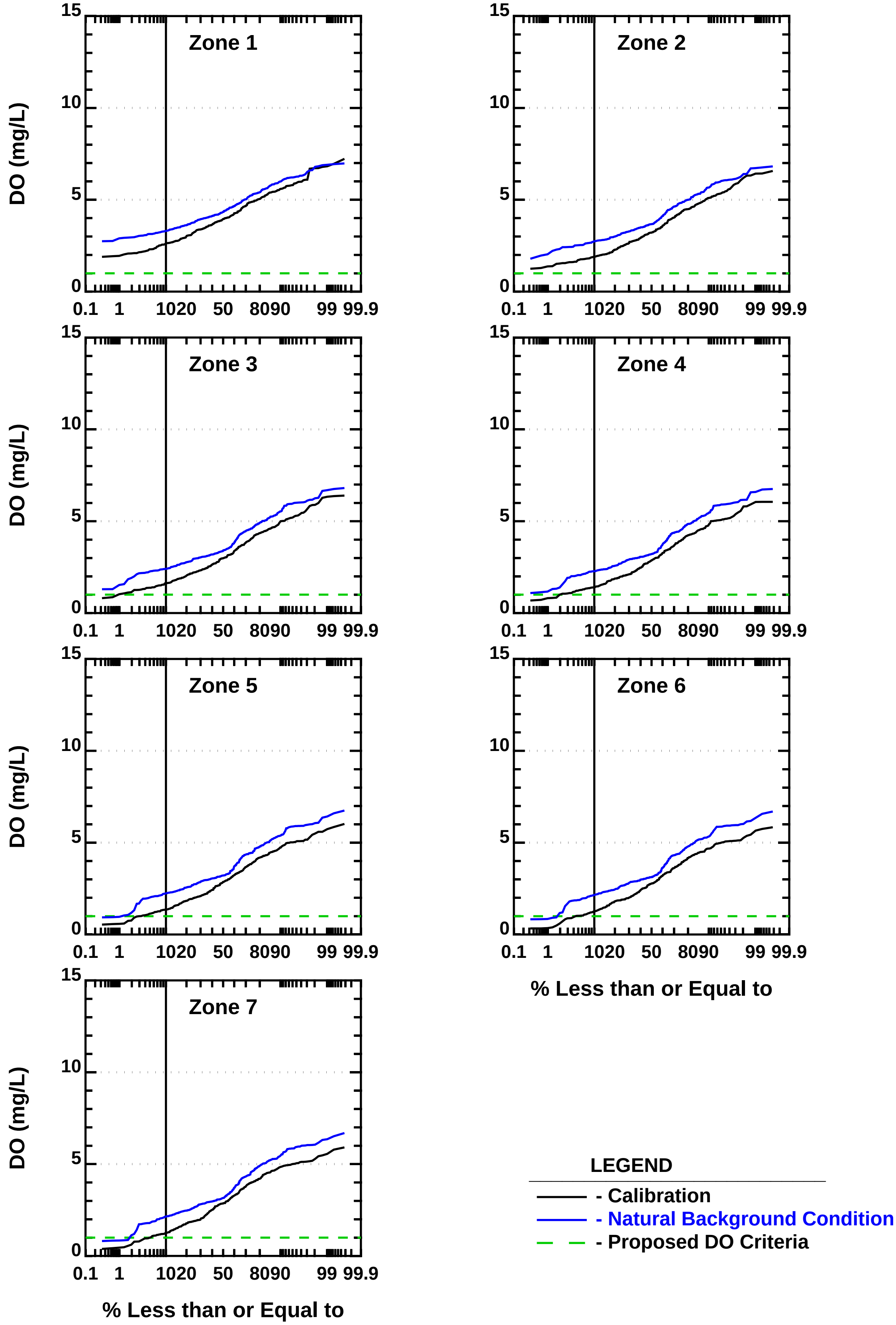


Figure 47. Summer Probability Distributions of Daily Minimum DO for Natural Background Condition

river surface area is about 209 acres as compared to the tidal marsh area of about 2,930 acres, which results in a ratio of 14.0. The large tidal marsh to river area ratio may be a good measure that reflects the importance of tidal marshes in controlling DO levels in the tidal Murderkill River.

Table 7 presents the calculated 10th percentile summer daily average and summer daily minimum DO levels for the "natural background", model calibration/validation, no KCWRTF loads, and no tidal marsh loads for comparison in each of the seven tidal river zones. This table shows that in all river zones for all of the scenarios that the 10th percentile summer daily minimum DO levels are all greater than 1.0 mg/L. On a summer daily average basis, the 10th percentile DO levels are greater than 3.0 mg/L in river zones 1-3 and for the no tidal marsh load scenario that all zones are greater than 3.0 mg/L. In river zones 4-7, the summer daily average 10th percentile DO levels are less than 3.0 mg/L for all scenarios (except for the no tidal marsh load scenario) and even for the "natural background" scenario. These model scenario results will be used to guide development of the site-specific DO criteria for the tidal Murderkill River.

Table 7. Summary of Model Scenario 10th Percentile Summer DO Levels (mg/L)

Model Scenario	Tidal River Zone						
	1	2	3	4	5	6	7
Daily Average							
"Natural Background"	4.77	4.35	3.65	2.98	2.75	2.82	2.95
Calibration/ Validation	4.28	3.78	3.10	2.21	1.87	1.76	2.12
No KCRWTF Loads	5.00	4.43	3.62	2.70	2.28	2.11	2.41
No Tidal Marsh Loads	5.67	5.60	5.37	4.98	4.64	4.17	4.08
Daily Minimum							
"Natural Background"	3.31	2.75	2.41	2.28	2.25	2.16	2.15
Calibration/ Validation	2.63	1.90	1.63	1.40	1.37	1.26	1.26
No KCRWTF Loads	3.17	2.40	2.01	1.79	1.73	1.64	1.63
No Tidal Marsh Loads	4.95	4.67	4.48	4.18	3.75	3.00	3.13

SECTION 6

SITE-SPECIFIC NUTRIENT TARGETS

The assessment of several loading scenarios was in Section 5 and in the *Tidal Murderkill River Site-Specific Dissolved Oxygen Criteria* report (HDR|HydroQual, 2014) that included "natural background" and no KCRWTF discharge scenarios. These loading scenarios have shown that increasing or decreasing nutrient levels in the Murderkill River have very little impact on DO levels. DO was considered an important nutrient endpoint because there is no evidence that harmful algal blooms or an unbalanced population of phytoplankton exist in the tidal Murderkill River. Therefore, it was concluded that nutrient criteria cannot be established based on nutrient effects to aquatic life (as indicated by DO levels) or algal levels (as indicated by the absence of harmful algal blooms or an unbalanced population) and that instead nutrient targets should be developed for the tidal Murderkill River. Considering this, and in order to limit the input of nutrients to the Murderkill River and to minimize the downstream impact of nutrients, it was decided to set nutrient targets at a level that correspond to the maximum nutrient reduction levels from point and nonpoint sources that are practical and achievable. In this respect, the proposed nutrient targets minimize downstream nutrient impacts and prevent any significant increases in river nutrient levels due to anthropogenic sources.

In order to assess nutrient levels in the river, the Murderkill River water quality model was run considering different effluent treatment level scenarios, as discussed below, for the KCRWTF. The different treatment levels for the KCRWTF were considered in order to determine the best combination of TN and TP reduction at the KCRWTF that results in the best water quality improvement in the river. For all of these scenarios, it was assumed that watershed nonpoint source loads are reduced by 50% for phosphorus and 30% for nitrogen load, as required under the 2005 TMDL for the Murderkill River watershed.

6.1 KCRWTF TREATMENT LEVEL SCENARIOS

After assessing the impact of the various loading sources on water quality in the Murderkill River and in order to establish a TMDL for the watershed that meets the site-specific DO criteria for tidal reach of the river, a series of model scenarios were completed to represent a range of effluent treatment levels at the KCRWTF and to determine the subsequent impact on tidal river water quality. These model scenarios were completed along with the watershed load reductions associated with the 2005 TMDL. The 2005 TMDL required watershed load reductions of 30% for TN and 50% for TP. This range in effluent treatment levels for the KCRWTF included the level of technology (LOT) for nutrient removal, minimal nitrogen removal and two cases for enhanced nutrient removal (ENR). Table 8 presents the KCRWTF effluent concentrations used for these scenarios and Table 9 presents the loads for the design flow of 16.3 MGD. These tables also present the existing (2007-2008) effluent concentrations and loads (at a flow of 10.7 MGD) for comparison purposes and show a significant reduction in TP for the four effluent treatment scenarios.

Table 8. KCRWTF Effluent Concentrations

Parameter	Effluent Treatment Scenarios				
	Existing	E3e (LOT)	E3f (Min N Removal)	F1 (ENR1)	F2 (ENR2)
$CBOD_5$ (mg/L)	3.2	3.0	3.0	4.0	4.0
VSS (mg/L)	6.2	5.9	5.9	6.0	6.0
TN (mg/L)	6.2	3.0	20.0	6.6	9.5
NH_3 (mg/L)	1.02	0.06	0.4	0.13	0.19
NO_2+NO_3 (mg/L)	3.7	2.0	13.4	4.4	6.4
TP (mg/L)	1.94	0.125	0.125	0.375	0.375
PO_4 (mg/L)	1.66	0.059	0.059	0.176	0.176

Table 9. KCRWTF Effluent Loads

Parameter	Effluent Treatment Scenarios				
	Existing	E3e (LOT)	E3f (Min N Removal)	F1 (ENR1)	F2 (ENR2)
$CBOD_5$ (lb/d)	283	408	408	544	544
VSS (lb/d)	555	801	801	816	816
TN (lb/d)	556	408	2,719	897	1,291
NH_3 (lb/d)	91	8.2	54.4	17.9	25.8
NO_2+NO_3 (lb/d)	329	273	1,822	601	865
TP (lb/d)	173	17.0	17.0	51.0	51.0
PO_4 (lb/d)	148	8.0	8.0	24.0	24.0

The four treatment level scenarios are compared to the calibration/validation modeling period results for the seven river zones in Figures 48-49 as probability distributions of summer daily average and summer daily minimum DO, annual daily average TN, annual daily average TP, and annual daily average chl-a. In these figures, summer is represented as the months of May through September. As it can be seen from the figures, there is very little difference in DO between the four treatment scenarios but an overall increase in summer median DO levels from the calibration/validation period of 0.65 mg/L on a daily average basis and of 0.51 mg/L on a daily minimum basis. Annual medial TN levels generally decrease for scenarios E3e and F1 with increased TN levels for scenario E3f and small increases associated with scenario F2. Annual median TP levels decrease for all effluent scenarios by about 0.14 mg/L as do the annual 90th percentile chl-a levels by about 4.7 μg/L.

Based on these modeling results and discussions during the water quality standards meetings, the F1 effluent scenario was selected as the KCRWTF discharge condition to use when further analyzing water quality in the tidal river and in developing the site-specific nutrient targets. The F1 effluent scenario was selected because all of the scenarios achieved similar DO improvements in the river and also that the F1 scenario resulted in measurable reductions in TN and TP levels in the river. In addition, the background TN and TP did not increase and the downstream impacts were kept to a minimum under this scenario.

6.2 PROPOSED SITE-SPECIFIC NUTRIENT TARGETS

Site-specific nutrient targets are proposed using the model results from the F1 effluent scenario, other loading scenarios completed and results from the various studies completed in the river. Tables 10, 11 and 12 present annual average TN and TP model results and annual maximum chl-a model results for all river zones for the calibration/validation period, no KCRWTF load scenario and F1 scenario. The no KCRWTF load scenario was included for comparison to show what current nutrient levels in the river would be without the discharge. Again, the 2007-2008 modeling period was considered to be representative of typical to low flow hydrologic conditions in the watershed and, therefore, suitable for supporting site-specific nutrient targets development. For 2007, the annual total rainfall was 40.0 inches and in 2008 was 40.6 inches, which was below the average annual rainfall total of about 45 inches.

The annual average TN results presented in Table 10 show a decrease from the calibration/validation conditions to the F1 scenario with the decreases ranging from 0.07-0.47 mg/L. The largest decreases occur upstream due to the watershed nutrient load reductions associated with the 2005 TMDL. Relatively small differences are calculated between the F1 scenario and the no KCRWTF load scenario (average of 0.13 mg/L). The annual average TP results presented in Table 11 show a decrease from the calibration/validation conditions to the F1 scenario with the decreases ranging from 0.050-0.208 mg/L. The largest decrease occurs near the KCRWTF

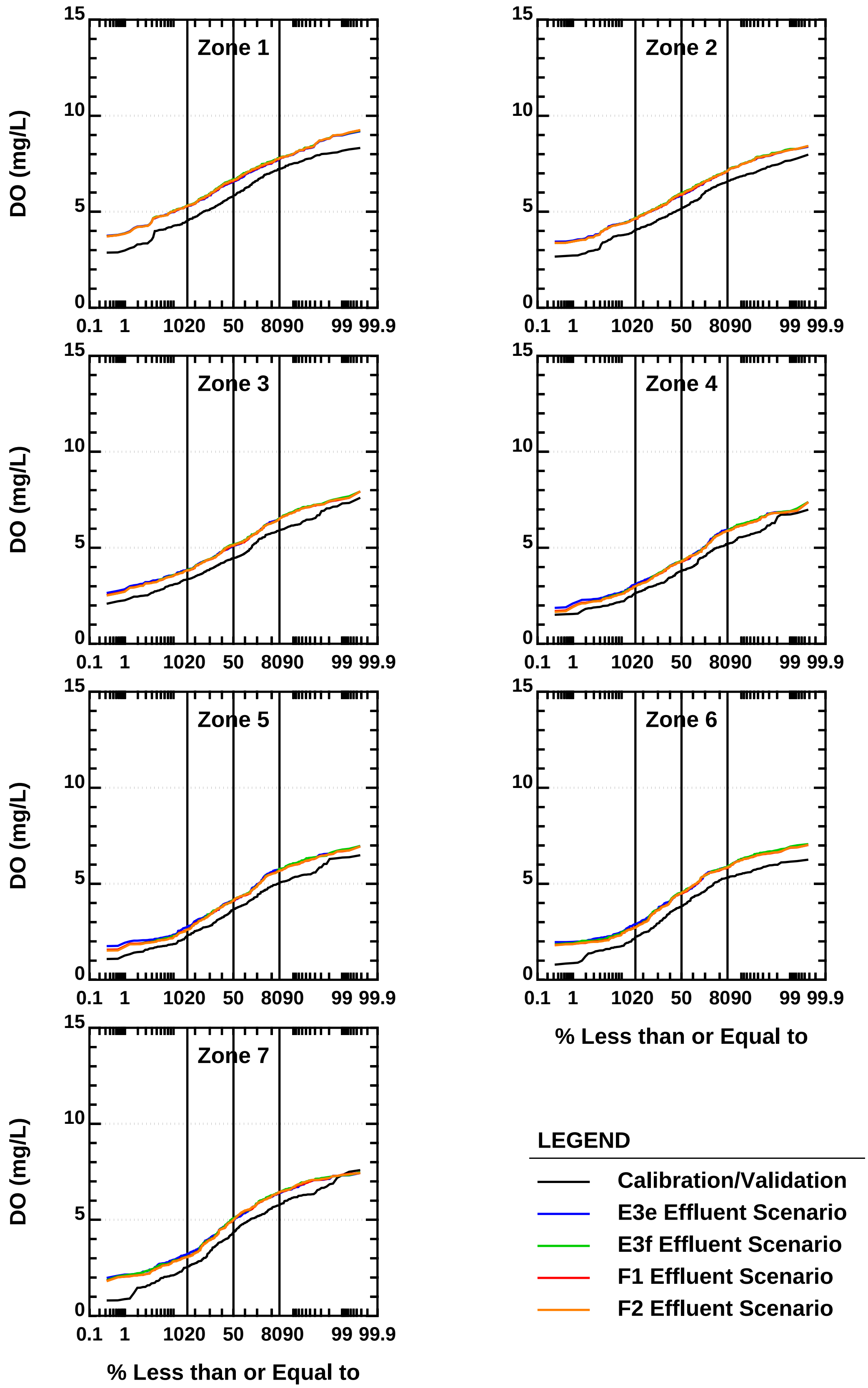


Figure 48. DO Probability Distributions for Effluent Scenarios (Summer Daily Average)

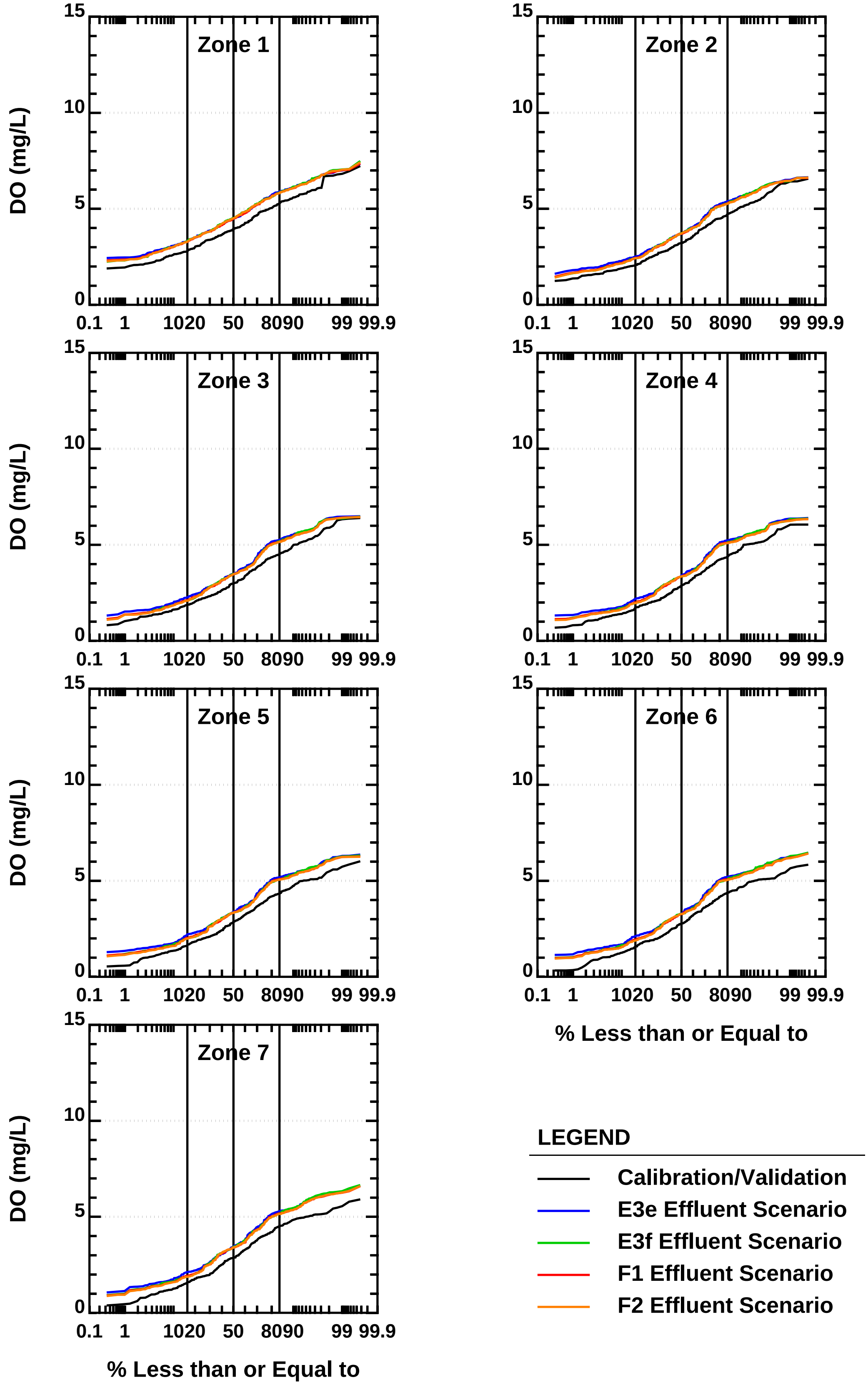


Figure 49. DO Probability Distributions for Effluent Scenarios (Summer Daily Minimum)

canal due to the large reduction in phosphorus from the facility. Relatively small differences are calculated between the F1 scenario and the no KCRWTF load scenario (average of 0.027 mg/L). The annual maximum chl-a results presented in Table 12 show a decrease from the calibration/validation conditions to the F1 scenario with the decreases ranging from 2.7-9.5 μg/L. The largest decreases occur upstream due to the watershed nutrient load reductions associated with the 2005 TMDL and reduction in chl-a levels in the upstream ponds and lakes. Relatively small differences are calculated between the F1 scenario and the no KCRWTF load scenario (average of 2.2 μg/L).

Based on these results and the conclusion that nutrient levels do not substantially affect DO levels (aquatic life) or algal levels, the following site-specific nutrient targets for the tidal Murderkill River are considered for establishing the TMDL:

- Annual average TN less than or equal to 2.0 mg/L; and
- Annual average TP less than or equal to 0.20 mg/L.

Overall, the F1 scenario with ENR at the KCRWTF that includes watershed nutrient load reductions of 50% for phosphorus and 30% for nitrogen results in compliance with the proposed site-specific DO criteria and nutrient targets for the tidal Murderkill River. The difference between the F1 scenario results and the site-specific TN and TP targets provides a compliance safety factor along with consideration of the model bias for TN and TP. These nutrient loading levels represent reductions to the maximum extent reasonably achievable, will not increase current background nutrient levels under reduced watershed nonpoint source loads, have minimal downstream impact, and have a negligible impact on DO levels in the river.

Table 10. Annual TN Model Results (mg/L)

River Zone	Calibration/Validation	No Kent County	F1 Scenario
1	1.06	0.91	0.99
2	1.25	1.00	1.17
3	1.51	1.15	1.39
4	1.84	1.36	1.66
5	2.02	1.53	1.78
6	2.22	1.85	1.84
7	2.32	2.02	1.85
Average	1.75	1.40	1.53

Table 11. Annual TP Model Results (mg/L)

River Zone	Calibration/Validation	No Kent County	F1 Scenario
1	0.139	0.078	0.089
2	0.208	0.092	0.114
3	0.285	0.106	0.139
4	0.355	0.116	0.158
5	0.365	0.116	0.157
6	0.310	0.109	0.134
7	0.265	0.099	0.113
Average	0.275	0.102	0.129

Table 12. Maximum Chl-a Model Results (µg/L)

River Zone	Calibration/Validation	No Kent County	F1 Scenario
1	56.3	53.0	53.2
2	48.1	45.0	44.6
3	40.3	38.3	37.6
4	34.3	32.2	30.2
5	33.5	31.0	29.3
6	39.8	37.5	32.3
7	45.3	41.9	35.8
Average	42.5	39.8	37.6

SECTION 7

REVISED TMDL ANALYSIS

DNREC is revising the 2005 TMDL for TN, TP and DO for the Murderkill River watershed based on additional data collection, new modeling analyses, and to comply with the newly proposed site-specific DO criteria and nutrient targets for the tidal Murderkill River. The revised TMDLs are the result of various load reduction analyses, which were conducted using the Murderkill River Watershed Model as a predictive tool, as presented in Section 4. The revised TMDL is designed such that, when implemented, all segments of the tidal Murderkill River will achieve the site-specific DO criteria and nutrient targets. Monitoring in the watershed should continue to assess the impact of load reductions and to determine the associated water quality improvements. In this manner, an adaptive management approach can be followed in the watershed. In addition, an implicit margin of safety (MOS) was used for the TMDL due to conservative assumptions used in the modeling.

The TMDL revisions were necessary because the waste load allocation (WLA) component changed (elimination of the Harrington WWTP and modification of the Kent County Regional Wastewater Treatment Facility) as did the upstream load allocations (LA) due to use of a different hydrologic baseline period (2007-2008) as compared to the prior TMDL baseline period (1997). In addition, a different watershed loading approach was used for the TMDL revisions (modeling approach) as compared to the prior TMDL that used a simple GIS-data based load calculation approach. Although the new LAs are different than those presented in the 2005 TMDL, the TMDL reductions associated with the LAs are the same.

In order to complete the revisions to the TMDL, and as mentioned earlier, mathematical models of the Murderkill River watershed were developed. These mathematical models include a landside watershed model to calculate nonpoint source (NPS) runoff and quality, a hydrodynamic model to calculate the movement of water in the tidal reaches of the Murderkill River, and a water quality model that is coupled to the hydrodynamic model to calculate water quality in the tidal reaches of the river. Details about the TMDL model and site-specific DO criteria development efforts are presented in the following reports:

- Murderkill River Watershed TMDL Model Development and Calibration (HDR|HydroQual, 2013); and
- Tidal Murderkill River Site-Specific Dissolved Oxygen Criteria (HDR|HydroQual, 2014).

7.1 TOTAL MAXIMUM DAILY LOADS AND THEIR ALLOCATIONS

The calibrated and validated Murderkill River models were used to determine TMDLs for the watershed. This effort involved completing various model load reduction scenarios (as presented in Sections 5 and 6) to ultimately arrive at a load reduction scenario that meets the newly proposed site-specific DO criteria and nutrient targets. As part of the site-specific criteria and targets development effort, a number of model scenarios were completed to assess water quality changes due to: different loading sources; the effect of different KCRWTF treatment levels; and the estimation of a "natural background" condition. Based on the model scenarios that were completed, the following load reductions or watershed conditions were used to develop the TMDL scenario for the Murderkill River watershed.

- The Harrington WWTP load to Browns Branch was removed as a result of this WWTP coming off-line and the wastewater being diverted to the KCRWTF for treatment.
- The KCRWTF load was modified to reflect the enhanced nutrient removal (ENR) treatment upgrade planned at the facility.
- The watershed loads were reduced based on the 2005 TMDL and included a 30% reduction for nitrogen and 50% reduction for phosphorus. These load reductions also included an associated 40% reduction in watershed nonpoint source carbon loads.
- Tidal marsh loads were not changed from the calibration/validation period to represent the existing conditions and the belief that these loads will not change significantly in the future.
- The downstream Delaware Bay boundary conditions assigned in the model were not changed for the TMDL condition.
- Failing septic system loads were removed to reflect properly operating septic systems (i.e., no system failures).

The results of these PS and NPS load reductions were used to establish the proposed nutrient and DO TMDLs for the Murderkill River. In these analyses, meeting the proposed site-specific DO criteria and nutrient targets in the tidal Murderkill River reflect achieving the designated uses in the river.

7.2 TMDL ENDPOINTS

For nutrients, the proposed site-specific nutrient targets were considered as annual averages of 2 mg/L TN and 0.2 mg/L TP, respectively. These targets were considered in the tidal reaches of the watershed. The annual average approach was chosen because nutrient effects on algae are not immediate, that is sufficient time is required for the consumption of nutrients by algae in increasing their biomass. Given the nature of the streams, lakes, ponds, and tidal reaches in the Murderkill River watershed, an annual average time period was considered suitable for assessing nutrient loads for TMDL development.

For DO, the proposed site-specific DO criteria in the tidal river considered were a summer daily average DO greater than or equal to 3.0 mg/L and summer daily minimum (1-hour average)

DO greater than or equal to 1.0 mg/L. During the winter, the existing marine DO standards were considered (daily average of 5.0 mg/L and daily minimum of 4.0 mg/L). The summer "warm" period is defined as May 15 through September 30 and the winter "cool" period as October 1 through May 14. The spring transition from winter "cool" to summer "warm" conditions (May 15) is based on the Chesapeake Bay Ambient DO Criteria (USEPA, 2003) migratory fish spawning and nursery designated use season (February 1 through May 31) but modified slightly to reflect site-specific DO data in the tidal Murderkill River. It should be noted that these site-specific DO criteria do not apply to the upstream freshwater reaches of the watershed (i.e., tidal reach only). Figure 2 presents the tidal reach of the Murderkill River where the site-specific DO criteria will apply.

7.3 TMDL MODEL OUTPUT PRESENTATION

The model output for TN, TP, chlorophyll-a and DO are presented in Figures 50-56 for comparing the TMDL load reduction scenario to the proposed tidal river site-specific summer DO criteria, existing winter DO standards and nutrient targets. These model output figures are developed for the 303(d) listed tidal reach DE 220-001 (lower Murderkill River from the confluence with Spring Creek to the mouth at Delaware Bay) at a number of monitoring locations. In the marine (tidal) reach, the model output are presented at the six tidal monitoring stations (see Table 5) and also in tidal river zones that allowed consideration of model output variability within the zones.

These tidal river zones are centered around tidal DNREC monitoring stations in the river to aid with future water quality compliance assessments. Table 5 and Figure 25 present the tidal river zones and DNREC monitoring stations with these zones used to present the model results. It should be noted that with regard to DO levels, zones 5 and 6 have the lowest DO among all zones and are considered to be the critical segments where the DO sag occurs in the river.

Figures 50 to 56 present the model output for the calibration/validation period and for the TMDL scenario as time-series for TN, dissolved inorganic nitrogen (DIN), TP, dissolved inorganic phosphorus (DIP), chl-a and DO at the seven tidal river stations. The black line in these figures represents the calibration/validation period and the blue line represents the TMDL scenario. These figures show large reductions in TN during the winter/spring period due to watershed nitrogen reductions and large reductions in TP during the summer/fall period due to the KCRWTF phosphorus reductions. Chl-a decreases are minimal because algal growth is limited by light in the river and also that nutrient levels are well above algal growth limiting levels. DO increases are also minimal because DO levels in the tidal river are primarily driven by the influence of the extensive tidal marshes.

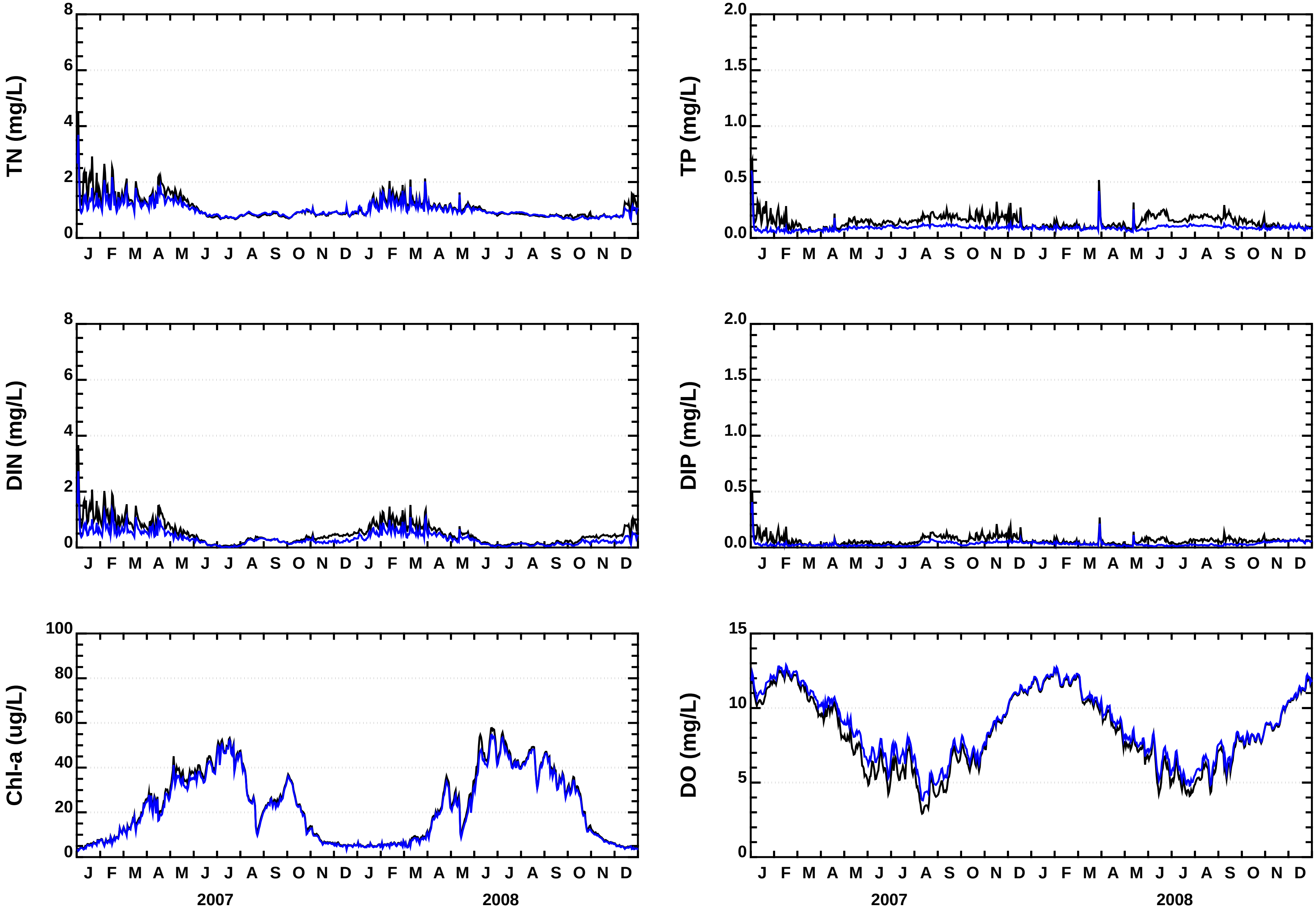


Figure 50. Murderkill River TMDL Loading Scenario Results Bowers Beach (206101)

(Black - Calibration, Blue - TMDL (F1) Scenario)

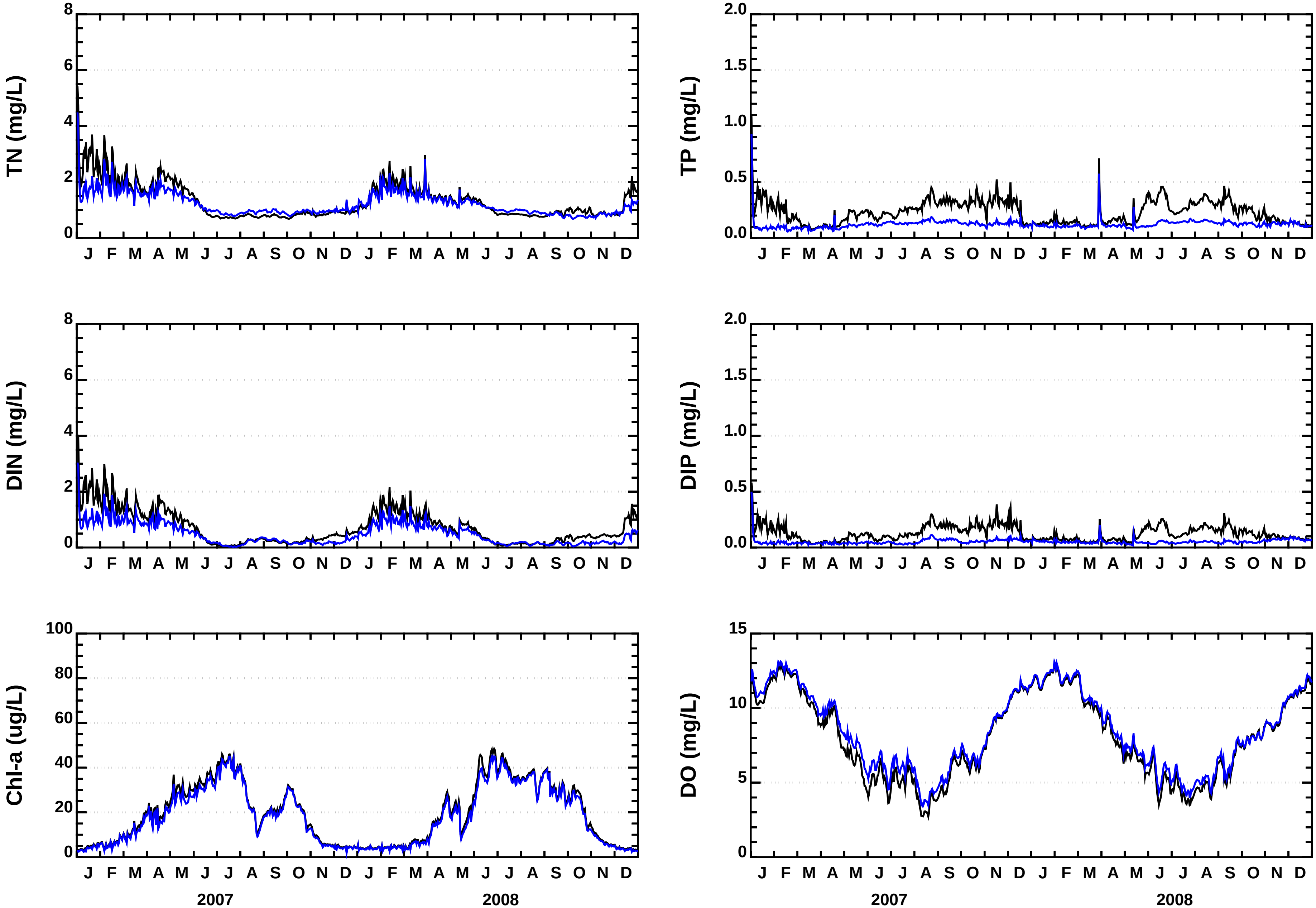


Figure 51. Murderkill River TMDL Loading Scenario Results Murderkill River at Webb Landing (206131)

(Black - Calibration, Blue - TMDL (F1) Scenario)

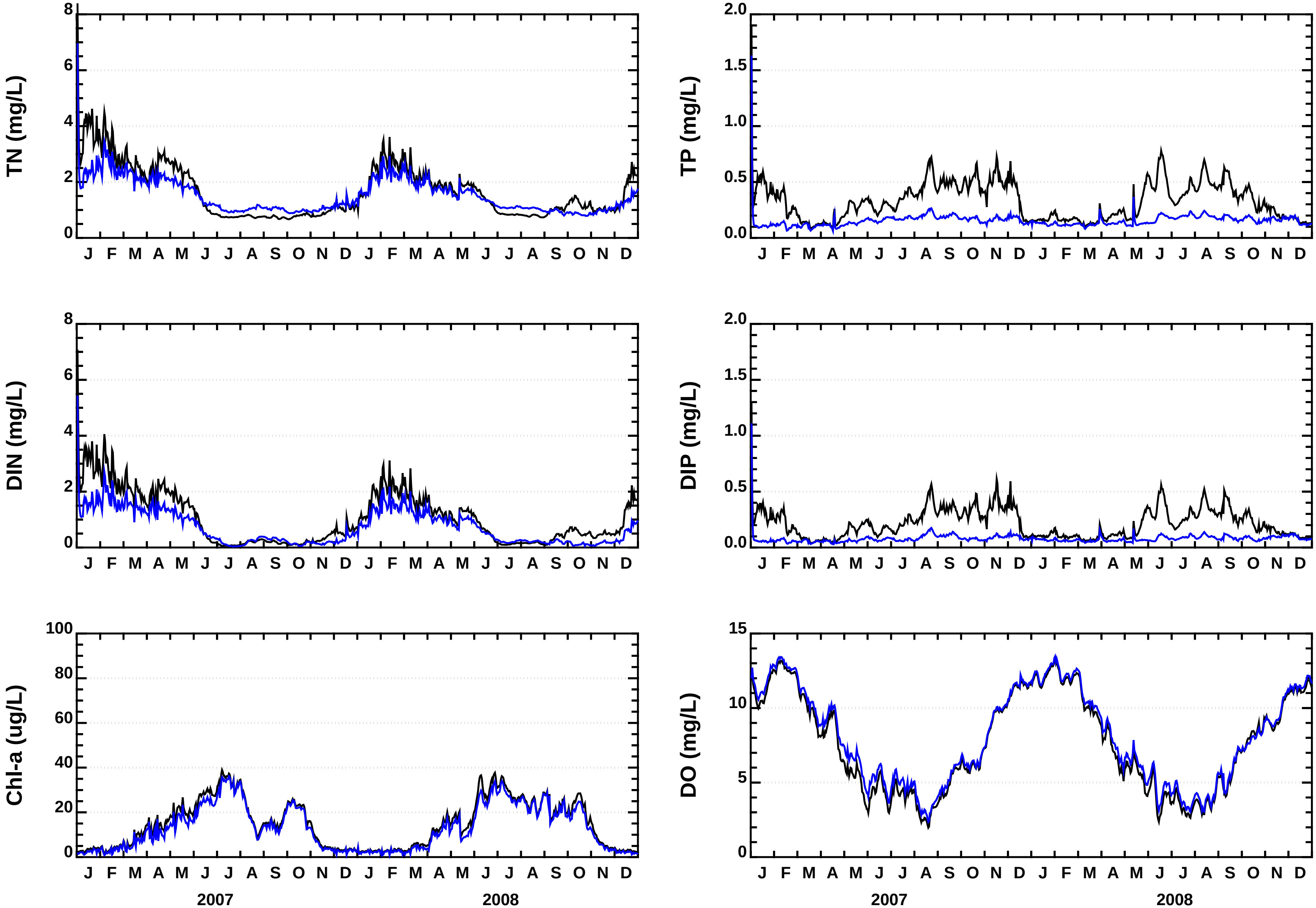


Figure 52. Murderkill River TMDL Loading Scenario Results Milford Neck Wildlife Levee (206141)

(Black - Calibration, Blue - TMDL (F1) Scenario)

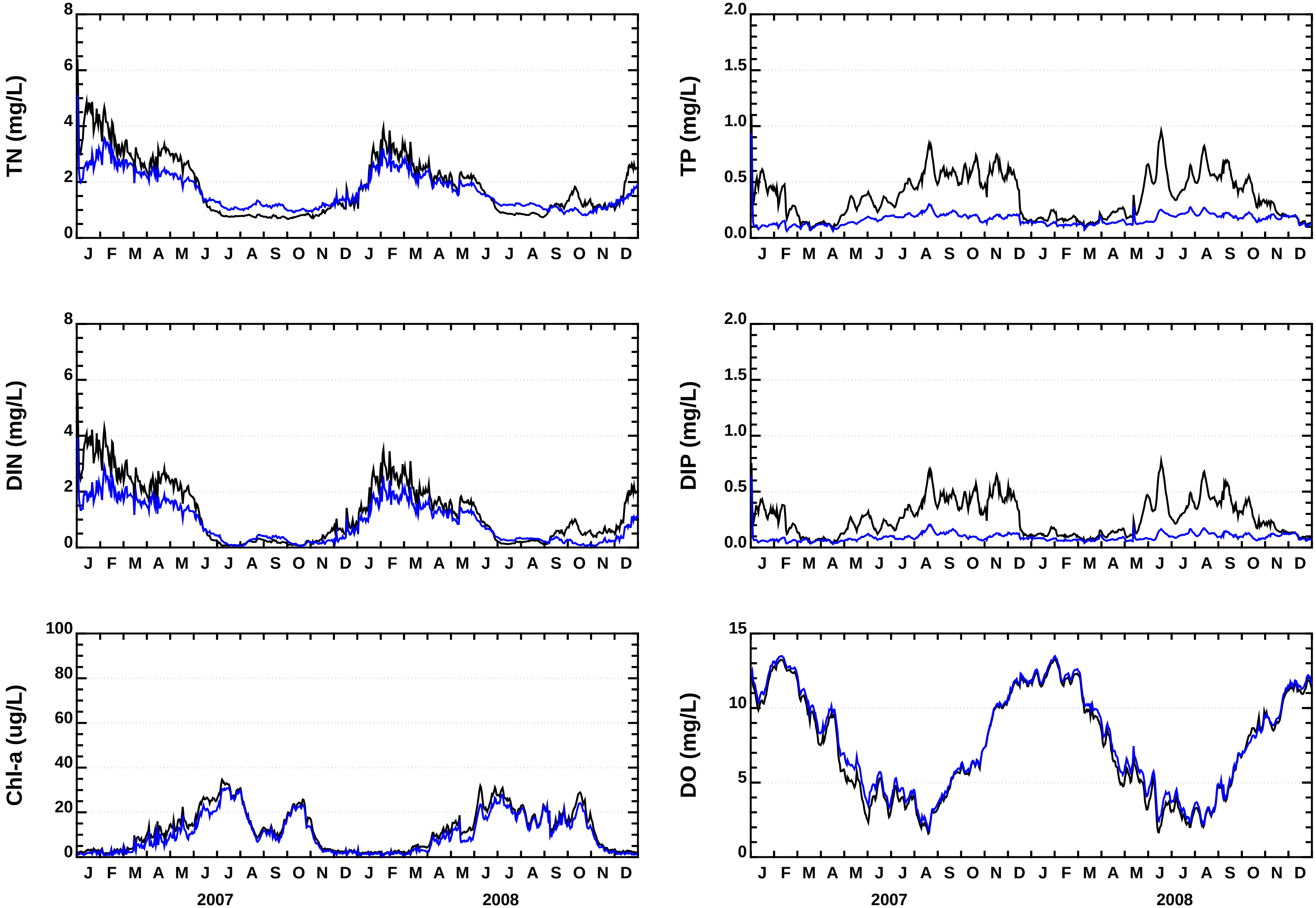


Figure 53. Murderkill River TMDL Loading Scenario Results Murderkill River near Power Lines (206711)

(Black - Calibration, Blue - TMDL (F1) Scenario)

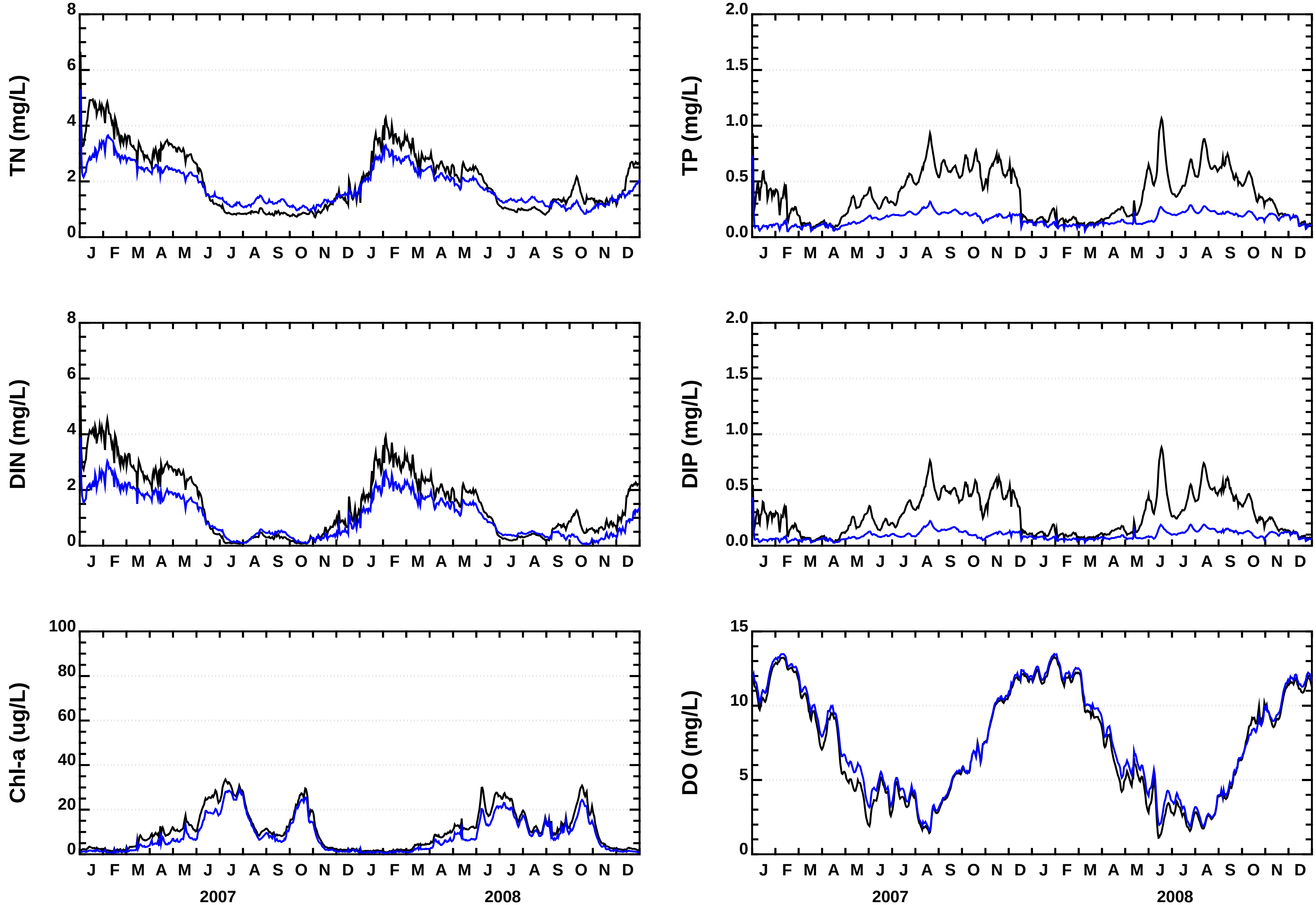


Figure 54. Murderkill River TMDL Loading Scenario Results Kent County Canal (206231)

(Black - Calibration, Blue - TMDL (F1) Scenario)

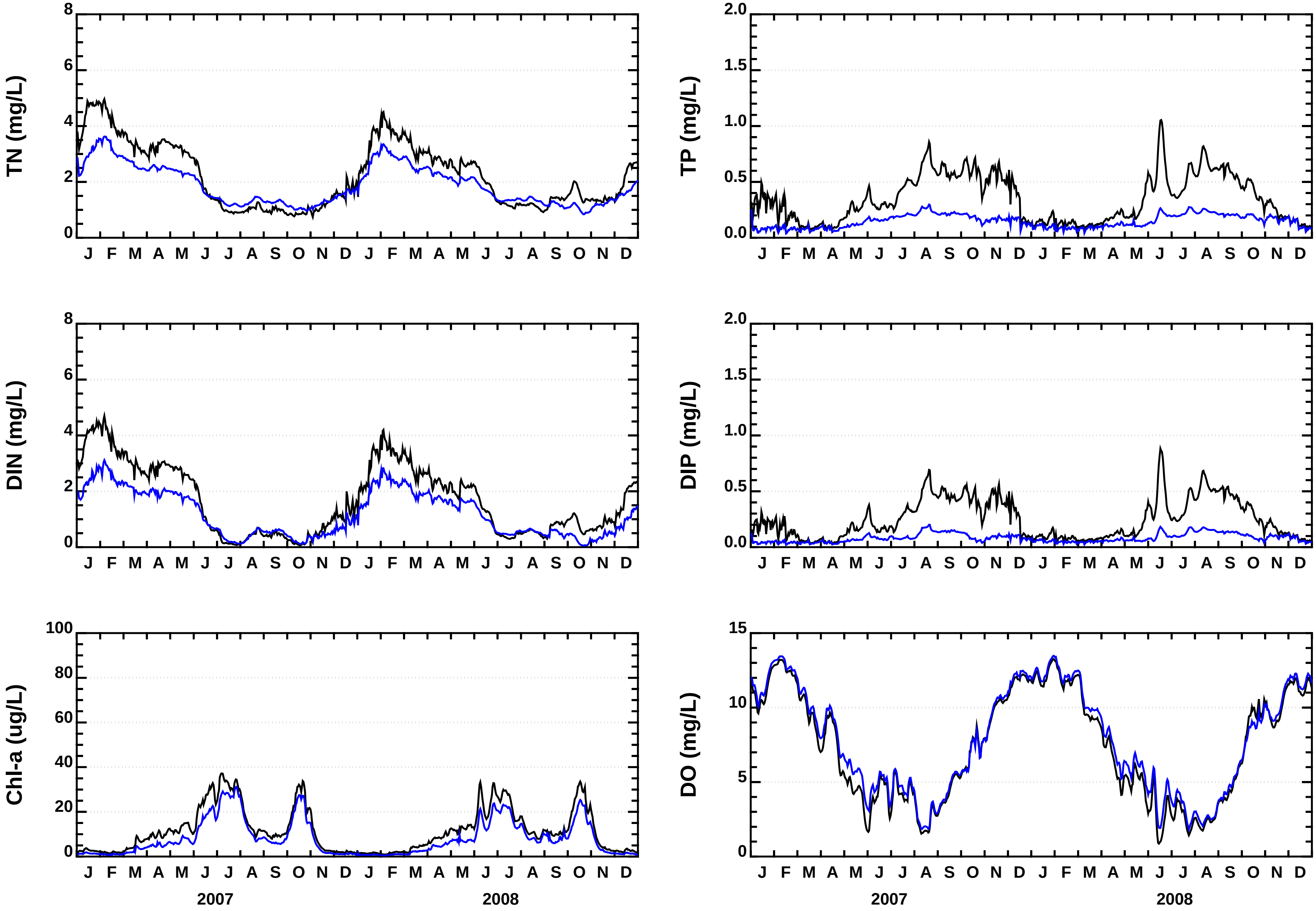


Figure 55. Murderkill River TMDL Loading Scenario Results Bay Road (Frederica) (206091)

(Black - Calibration, Blue - TMDL (F1) Scenario)

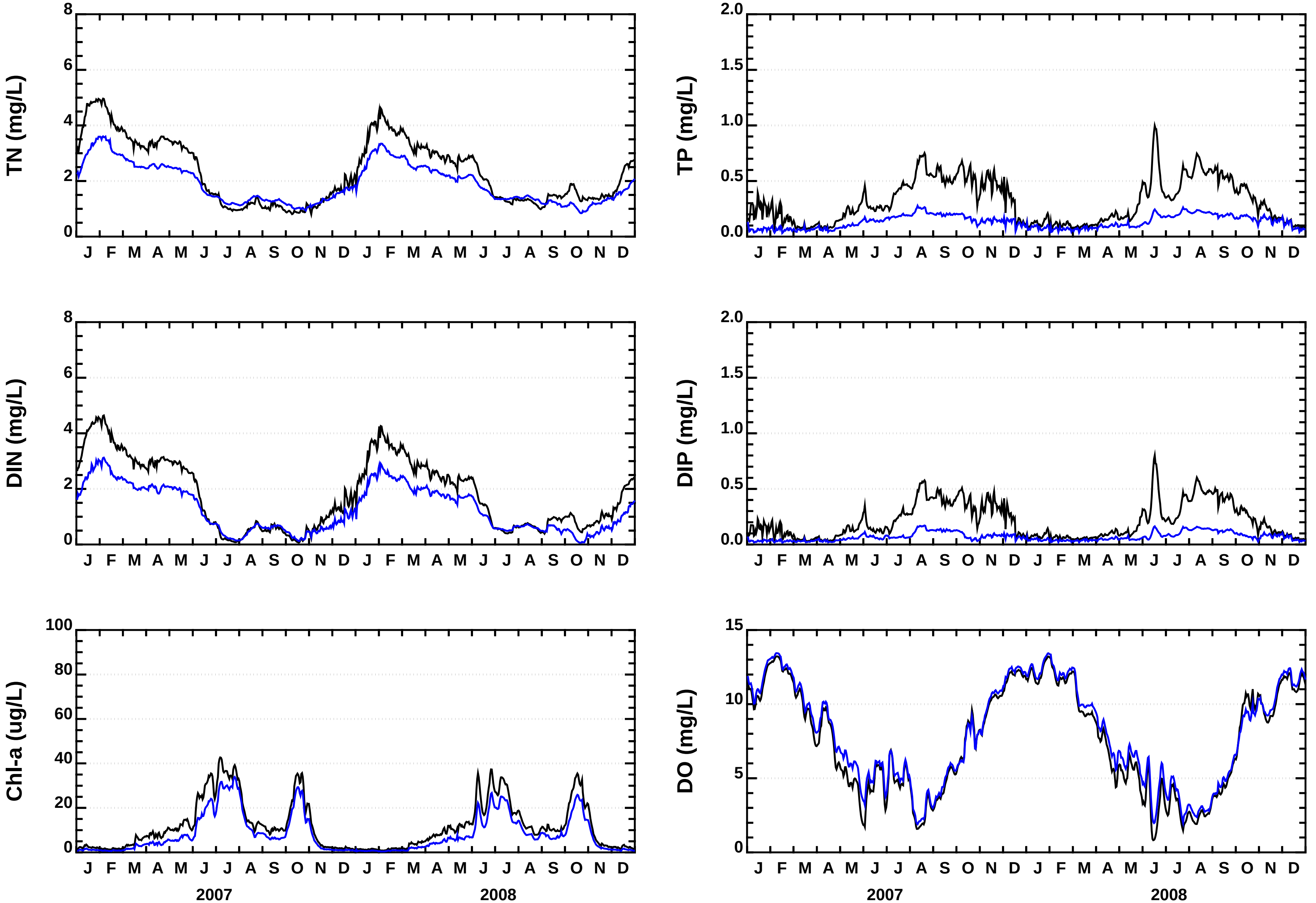


Figure 56. Murderkill River TMDL Loading Scenario Results Spring Creek at Rt. 12 Bridge at Frederica (206081)

(Black - Calibration, Blue - TMDL (F1) Scenario)

7.4 INTERPRETATION OF RESULTS

The load reduction scenarios were based on the 2005 TMDL update and numerous model scenarios analyzed during the development of the proposed site-specific DO criteria and nutrient targets for the tidal Murderkill River. The watershed and point source load reductions along with the other conditions used for the TMDL scenario are discussed in Section 6.1.

The TMDL model scenario results were processed to develop annual average TN and TP concentrations for each tidal river zone. These results are presented in Tables 13 and 14 and show that both the site-specific TN (2 mg/L) and TP (0.2 mg/L) targets are attained in the river. The annual average TN levels ranged from 0.99-1.85 mg/L with the lower levels calculated near the mouth of the river. The TMDL resulted in TN reductions of 7-20% as compared to the 2007-2008 conditions. The annual average TP levels ranged from 0.089-0.158 mg/L with the lower levels calculated near the mouth of the river and in the upstream reach above the KCRWTF discharge canal. The TMDL resulted in TP reductions of 36-57% as compared to the 2007-2008 conditions.

Figure 57 presents the model DO results for the TMDL scenario as probability distributions by river zone (colored circles) for the site-specific summer daily average and daily minimum DO criteria and the existing winter DO standards. It should be noted that overall the model under-calculates summer DO levels by 0.8 mg/L in the calibration/validation near the middle of the river and, therefore, this model bias is considered when assessing compliance with the proposed site-specific DO criteria. This figure presents the proposed site-specific DO criteria and standards as the horizontal dashed lines, and the 10^{th} percentile as the vertical solid line.

Compliance with the proposed site-specific DO criteria was based on the 10^{th} percentile of the model results. Use of the 10^{th} percentile model results was considered appropriate because of the highly variable nature of the tidal Murderkill River due to tidal interactions between the river and tidal marshes, along with meteorological events that can inundate the marshes for extended periods of time causing increased marsh loadings and subsequent effects on river DO levels. For example, the May 2008 storm that was captured by the marsh monitoring experienced tidal water levels that were about 0.5 meters greater than typical high tides and persisted continuously for about 2-3 days. This prolonged period of tidal marsh inundation resulted in much greater than normal marsh loads of nitrogen, phosphorus, carbon and DO deficit. Based on the marsh monitoring from May 14-15, 2008, the total organic nitrogen loads were about 13 times greater than the other four monitoring events, for total organic phosphorus about 10 times greater, and for total organic carbon about 30 times greater. Given the natural variability in the tidal Murderkill River, compliance with the proposed site-specific DO criteria will be based on the 10^{th} percentile model results.

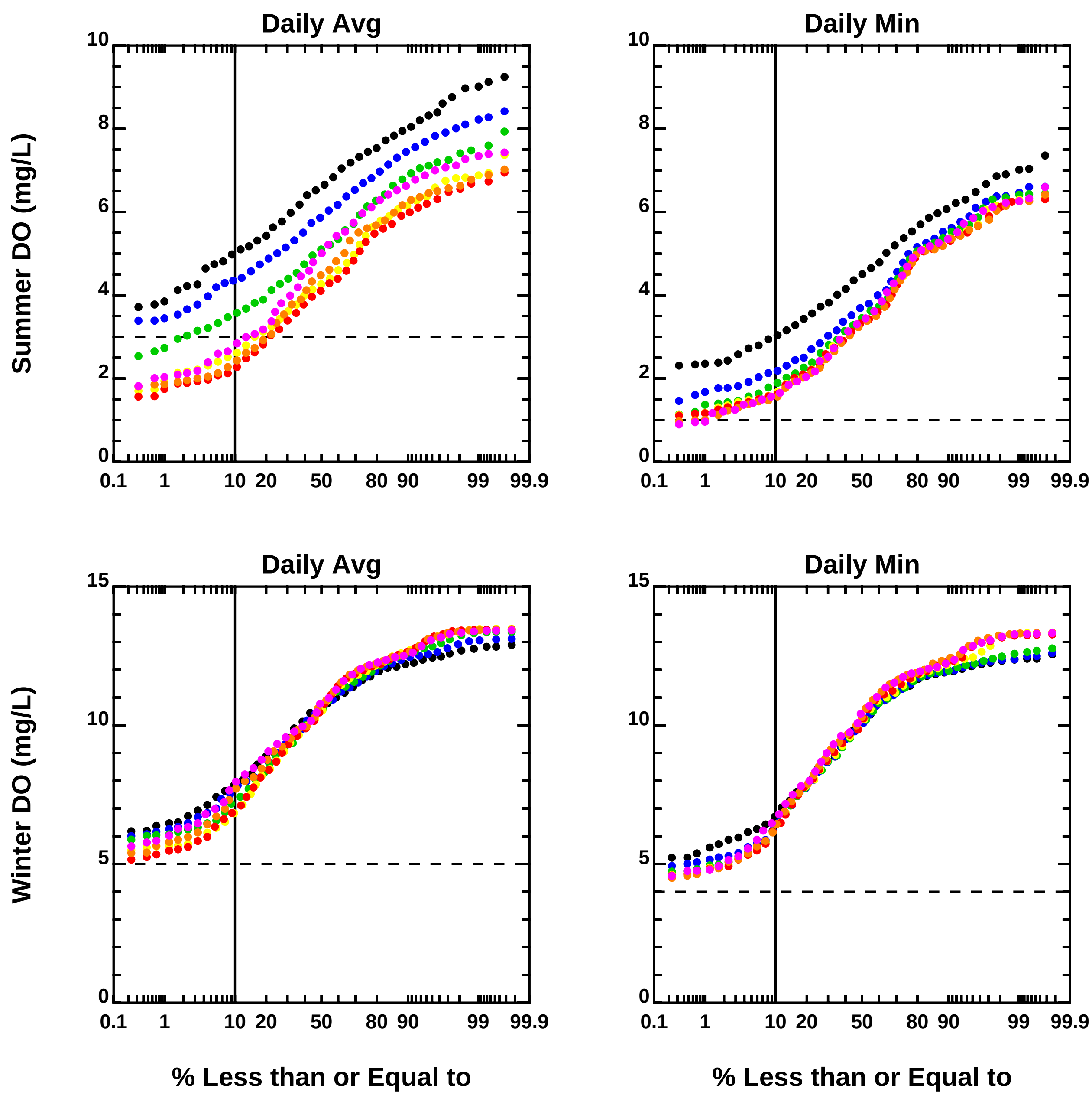


Figure 57. Murderkill River DO Probability Distributions for the TMDL Scenario
(Black - Zone 1, Blue - Zone 2, Green - Zone 3, Yellow - Zone 4, Red - Zone 5, Orange - Zone 6, Purple - Zone 7)

The model results show that the existing winter DO standards (daily average of 5 mg/L and daily minimum of 4 mg/L) will be achieved in the river at all times in all tidal river zones. During the summer period, 10^{th} percentile model results indicate that the proposed daily minimum DO criteria of 1 mg/L will be met in all zones. Based on the 10^{th} percentile model results, the proposed summer daily average DO criteria of 3.0 mg/L is met in all zones except zones 4 to 7 when considering the model bias of 0.8 mg/L.

Based on these results, the TMDL scenario that includes watershed nutrient TMDL reductions, repair of failing septic systems, removal of the Harrington STP, and implementation of ENR at the KCRWTF indicates compliance with the proposed site-specific summer daily average and daily minimum DO criteria, existing DO standards in the winter, and the proposed site-specific nutrient targets for the tidal Murderkill River.

Table 13. Annual TN Model Results (mg/L)

River Zone	Calibration/ Validation	TMDL (F1) Scenario
1	1.06	0.99
2	1.25	1.17
3	1.51	1.39
4	1.84	1.66
5	2.02	1.78
6	2.22	1.84
7	2.32	1.85
Average	1.75	1.53

Table 14. Annual TP Model Results (mg/L)

River Zone	Calibration/ Validation	TMDL (F1) Scenario
1	0.139	0.089
2	0.208	0.114
3	0.285	0.139
4	0.355	0.158
5	0.365	0.157
6	0.310	0.134
7	0.265	0.113
Average	0.275	0.129

SECTION 8

THE REVISED MURDERKILL TMDL

As stated, the revised TMDL load reduction scenario is a 30% NPS reduction of nitrogen and 50% reduction of phosphorus in NPS watershed sources, as called for by the promulgated 2005 TMDL Regulation for the Murderkill River Watershed. These NPS load reductions are coupled with the revised point source Waste Load Allocations (WLA) and are presented in Tables 15 and 16 along with repair of failing septic systems. Table 17 presents the WLAs, LAs and TMDLs for the revised Murderkill River watershed TMDL. Figure 58 presents the location of the major sub-watersheds in the Murderkill River and Table 18 presents the associated sub-watershed TMDL loads. In the tidal Murderkill River, the site-specific nutrient targets and DO criteria are attained at these revised TMDL loading levels.

These load reduction scenarios are meant as a guide in improving water quality in the Murderkill River watershed and should be periodically revisited to determine whether they are still applicable. In addition, water quality monitoring should continue throughout the watershed to quantify the instream effects of the proposed load reductions and to monitor the calculated water quality improvement in the river.

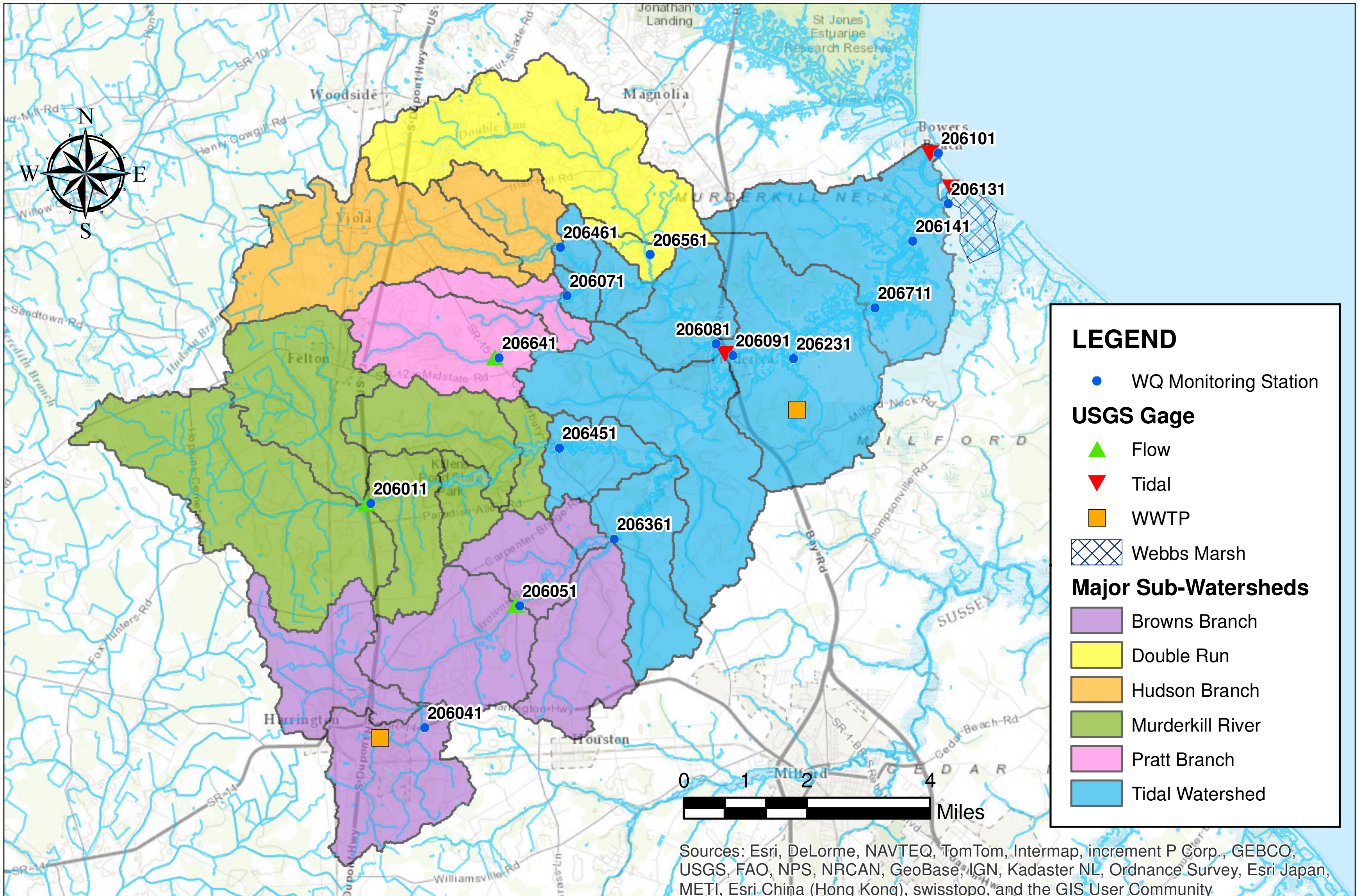
Table 15. Proposed Murderkill River WLA (Concentration)

Parameter	Harrington WWTP	KCRWTF
NPDES #	DE0020036	DE0020338
Effluent Type	Treated Municipal Wastewater	Treated Municipal Wastewater
Flow (MGD)	0.0	16.3
$CBOD_5$ (mg/L)	0.0	4.0
TN (mg/L)	0.0	6.6
NH_3 (mg/L)	0.0	0.13
NO_2+NO_3 (mg/L)	0.0	4.4
TP (mg/L)	0.0	0.375
PO_4 (mg/L)	0.0	0.176

Table 16. Proposed Murderkill River WLA (Loads)		
Parameter	**Harrington WWTP**	**KCRWTF**
NPDES #	DE0020036	DE0020338
Effluent Type	Treated Municipal Wastewater	Treated Municipal Wastewater
Flow (MGD)	0.0	16.3
$CBOD_5$ (lb/d)	0.0	544.0
TN (lb/d)	0.0	897.0
NH_3 (lb/d)	0.0	17.9
NO_2+NO_3 (lb/d)	0.0	601.0
TP (lb/d)	0.0	51.0
PO_4 (lb/d)	0.0	24.0

Table 17. Revised TMDLs for the Murderkill River Watershed			
Parameter	**WLA (lb/d)**	**LA (lb/d)**	**TMDL (lb/d)**
TN	897.0	972.6	1,869.6
TP	51.0	12.1	63.1

Table 18. Revised Murderkill River Sub-Watershed TMDL Load Allocations		
Sub-Watershed	**TN (lb/d)**	**TP (lb/d)**
Double Run	101.4	1.2
McGinnis Pond	86.0	1.0
Andrews Lake	63.3	0.9
McColley Pond	218.3	2.1
Coursey Pond	186.2	2.9
Tidal River	317.3	3.9
Total	972.6	12.1



HDR HydroQual

Figure 58. Major Subwatersheds in the Murderkill River

8.1 CONSIDERATION OF THE IMPACT OF BACKGROUND POLLUTANTS

The Murderkill River watershed TMDLs for nutrients and DO were estimated using the results of calibrated/validated models (watershed, hydrodynamic and water quality). The models were developed using data collected in the field to represent model inputs and for calibration/validation of the models. The data collected in the field also reflected background pollutant conditions and Delaware Bay water quality in addition to tidal marsh loadings in the model. Therefore, the impact of background pollutants is accounted for in the model.

The impact of pollutant sources varies significantly according to location in the watershed. The major sources of nutrients are the watershed NPSs, the KCRWTF, the downstream boundary condition with Delaware Bay and the tidal marsh contribution of organic matter. The Delaware Bay impacts DO and nutrient levels closer to the mouth of the Murderkill River. Tidal marshes have an influence on DO and nutrient levels in the middle of the river as does the KCRWTF load. And the upstream watershed NPS loads affect DO and nutrient levels near the upstream reaches of the tidal river. These sources are the major causes of varying levels of background pollutants throughout the watershed and impact the model differently according to location.

8.2 CONSIDERATION OF CRITICAL ENVIRONMENTAL CONDITIONS

Low river flows during summer months coupled with high water temperatures represent critical conditions for point sources and also for nutrient related algal growth and DO impacts. High flow or wet weather conditions are also important for assessing nonpoint sources, which are present during the winter/spring season. The calibration/validation time period of 2007 and 2008 experienced annual total rainfalls amounts of 40.0 and 40.6 inches, respectively, which is below the average annual rainfall total of about 45 inches. Although the 2007-2008 modeling time period was below average, the watershed experienced a wide range of wet and dry flow conditions. Flow data were available at the following three freshwater USGS gages: Murderkill River near Felton (#01484000); Browns Branch near Harrington (#01484018); and Pratt Branch near Felton (#01484050). These gaged flows were extrapolated to the entire Murderkill River watershed area using a drainage area ratio and resulted in an average freshwater flow during the 2007-2008 modeling time period of 72 cfs (ranging from 14 to 940 cfs). The Murderkill River near Felton gage had historical records available for a number of periods (1931-1933, 1960-1985, 1996-1999, and 2007-2008). Based on these data a 7Q10 low flow of 1.7 cfs was calculated. During 2007 and 2008 the minimum 7-day average flow at this gage was 1.0 and 1.2 cfs, respectively. While the 2007-2008 modeling time period was representative of low-flow years there were periods of high flow and, therefore, the 2007-2008 time period represented a wide range of hydrologic conditions, and critical dry and wet weather conditions are included in the analysis.

8.3 CONSIDERATION OF SEASONAL VARIATIONS

Seasonal variations are considered in the Murderkill River models since the models were calibrated/validated in a time-variable mode for the years 2007-2008. This time period reflects flow and watershed conditions during all four seasons over a wide range of hydrologic conditions. Therefore, seasonal variations have been considered for this analysis.

8.4 CONSIDERATION OF MARGIN OF SAFETY

USEPAs technical guidance allows consideration for the margin of safety as implicit or explicit. The margin of safety can account for uncertainty about the relationships between pollutant loads and receiving water quality in addition to uncertainty in the analysis (USEPA, 2001). An implicit margin of safety is when conservative assumptions are contained in model development and TMDL establishment. An explicit margin of safety is a specified percentage of assimilative capacity that is kept unassigned to account for uncertainties, lack of sufficient data or future growth. An implicit margin of safety has been considered for the Murderkill River TMDL analysis.

The Murderkill River nutrient and DO models were constructed with several implicit, conservative assumptions built into the models. In addition, the models represented the complex watershed dynamics and tidal nature of the river as opposed to analyzing with a simple model framework not accounting for these complex processes that would include more uncertainty. As stated in the *Protocol for Developing Pathogen TMDLs* (USEPA, 2001), "trade-offs associated with using simpler approaches include a potential decrease in predictive accuracy and often an inability to predict water quality at fine geographic and time scales and the advantages of more detailed approaches are presumably an increase in predictive accuracy and greater spatial and temporal resolution". The Murderkill River models were also developed from a comprehensive water quality database that was collected over several years (as described in the TMDL Modeling and Site-Specific DO Criteria Reports). This also reduces the uncertainty in the analysis based on a good understanding of water quality dynamics as determined from the available observed field data.

Furthermore for the TMDL scenarios, the reductions were applied to the entire watershed to satisfy the applicable water quality standards at the most critical location rather than to specific reaches upstream of the critical location (i.e., downstream impacts were considered). This results in an implicit margin of safety in upstream areas since load reductions are applied to meet the standards at the critical downstream locations. In the case of point sources, the WLAs were assigned as constant loads for the TMDL scenarios at the proposed effluent permit limits. Typical operating conditions at WWTPs are to not exceed permit limits and, therefore, discharge loadings are generally less than the effluent permit limits. Therefore, actual point source loadings will be less than the WLA used in the analysis. This will add an additional implicit margin of safety to this TMDL analysis.

It was also assumed that the load reductions required are to be achieved by solely altering practices within the Murderkill River watershed. In the nutrient model this means that the downstream Delaware Bay boundary condition loadings are not reduced due to upstream Delaware River controls in the States of Delaware, Pennsylvania, New York and New Jersey not to mention coastal water quality. Since there is intrusion of water from Delaware Bay into the river and water quality of Delaware Bay will undoubtedly improve in the future, this adds an additional level of conservatism to the analysis since the boundary conditions were not changed for the TMDL analysis.

Finally, critical stream conditions were considered in the TMDL analysis. That is, low-flow and high temperature conditions were part of the period that controlled the establishment of the TMDL loads. The nutrient loads, although based on annual average conditions, reflect the critical conditions that occur within this period. Particularly for point sources, the combination of low-flow, high temperature and permit loading conditions represent a rare occurrence and, therefore, provide an additional level of conservatism and implicit margin of safety. For nonpoint sources, critical conditions are more driven by high-flow runoff events and these conditions are also represented in this TMDL analysis.

Overall, the implicit margin of safety chosen reflects the complex modeling developed for the TMDL analysis, comprehensive database available for model development, conservative modeling assumptions chosen and the overall objective of DNREC to implement TMDLs in a phased, adaptive implementation strategy. The use of an implicit margin of safety allows water quality improvements to be realized within the adaptive management framework while not imposing unnecessary source reduction costs on local stakeholders until real world water quality improvements can be better correlated to economically feasible source controls.

8.5 CONSIDERATION OF MODEL CAPABILITIES AND LIMITATIONS

The Murderkill River watershed model is a valuable tool for the assessment and prediction of water quality parameters (including DO and nutrients) in the tidal and nontidal portions of the river. However, just like any model, the Murderkill River watershed model has limitations to go along with its capabilities. In the upstream nontidal reaches, the HSPF model has the ability to calculate instream concentrations at selected points in the river near water quality monitoring stations, lake inflows and outflows, confluences of reaches and other strategically selected locations. The driving functions for the model are the accumulation of pollutants on land uses and the delivery of pollutants to reaches through overland and groundwater flow. Moreover, HSPF is a lumped parameter and land use generalized model that is calibrated for whole watershed analyses and, therefore, HSPF's loading functions should not be used to assess the affects of a specific site on downstream water quality without further research and verification of accumulation rates and runoff concentrations at the site.

For the tidal reaches of the Murderkill River watershed, the coupled, three-dimensional ECOMSED (hydrodynamic) and RCA (eutrophication, sediment flux) models account for the factors that influence water quality in a tidal system. Given the increased complexity of a tidal water body, the ECOMSED and RCA models are well suited to simulate flow and water quality because of their capabilities. It should be noted that the coupled model is loaded with flows and pollutant loads from the HSPF model and is, therefore, influenced by the same factors that limit HSPF. ECOMSED tracks flow and transport according to freshwater flow, density driven currents, wind driven currents and other meteorological influences and can calculate flow, velocity, salinity and temperature at any three-dimensional point in the tidal water body.

The RCA eutrophication model can calculate DO, nutrients, carbon and chlorophyll-a concentrations at any three-dimensional point in the water body based on sediment interactions, upstream sources of pollution, tidal flow and chemical interactions. The model also incorporates an annual average net flux of nutrients, and monthly average net flux of carbon and DO deficit from the tidal marshes. That is, nutrient, carbon and DO uptake and export from wetlands on a tidal basis was not considered in the marsh load but rather represented as an annual or monthly average net flux to or from the river. In general, the influence of nonpoint sources, point sources and boundary conditions from Delaware Bay on the water quality in the tidal water bodies of the Murderkill River can be assessed using the RCA eutrophication model.

8.6 REASONABLE ASSURANCE

Reasonable assurance that the Murderkill River TMDL will be implemented and can be met is required as part of the regulatory process. The revised Murderkill River TMDL considers reduction of nutrients and oxygen consuming pollutants from point and nonpoint sources within the watershed. The magnitude of load reductions suggested by the revised TMDL is technically feasible and financially affordable. In fact, the KCRWTD is already in the process of designing and implementing many wastewater treatment upgrades that are required for meeting the proposed WLA for the facility.

Furthermore, the Murderkill River Tributary Action Team (TAT) is in place and has already assisted DNREC in developing a Draft Pollution Control Strategy for implementation of the 2005 Murderkill River TMDL. Following adoption of this revised TMDL, DNREC will reconvene the Tributary Action Team to assist DNREC in modifying the Pollution Control Strategy, as needed.

In addition to the above watershed specific activities which provide reasonable assurance that requirements of the Murderkill River TMDL will be implemented, DNREC has several state-wide programs and regulations that will result in significant reduction of nonpoint source loads in the Murderkill River Watershed. These programs and regulations include nutrient management programs, sediment and storm water management programs, and on-site wastewater treatment and disposal system programs. Collectively, these state-wide programs and regulations along with the planned watershed specific activities provide reasonable assurance that requirements of the revised Murderkill River TMDL will be implemented.

8.7 TMDL IMPLEMENTATION / PUBLIC PARTICIPATION

The proposed revisions to the Murderkill River Watershed nutrient and DO TMDL will be presented during a Public Hearing to be held on April 29, 2014 at the DNREC main office in Dover. All comments received before and during the Public Hearing process will be considered by DNREC. Based on the comments received, the report may be modified accordingly.

SECTION 9

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