TIDAL MURDERKILL RIVER
USE ATTAINABILITY ANALSIS AND
ALTERNATIVE DISSOLVED OXYGEN CRITERIA

Division of Watershed Stewardship
Watershed Assessment and Management Section

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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 the current State water quality standards for dissolved oxygen (DO) of 5 mg/L as a daily average and 4 mg/L as an instantaneous minimum established to protect Delaware's "Fish, Aquatic Life and Wildlife" designated use (defined as "all animal and plant life found in Delaware, either indigenous or migratory, regardless of life stage or economic importance"). 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 requires 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 appealed by Kent County and following extensive negotiations between DNREC and Kent County, the TMDL was amended by DNREC in 2005 (DNREC, 2005).

Since the development of the original Murderkill River Watershed TMDL in 2001, 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. In part, the studies were conducted to determine whether natural processes associated with significant areas of tidal marshes surrounding the Murderkill River and tidal input from Delaware Bay were responsible for the observed low DO in the lower tidal portion of the river. The studies evaluated whether upstream anthropogenic sources, which include the Kent County Regional Wastewater Treatment Facility and agricultural activities, would have a significant impact on the observed low DO, or if the low DO persists even under modeled conditions in which theses sources are eliminated. These studies did not contemplate modifications to the freshwater DO standards applicable to the upstream non-tidal portion of the Murderkill River or the downstream marine DO standards applicable to the Delaware Estuary.

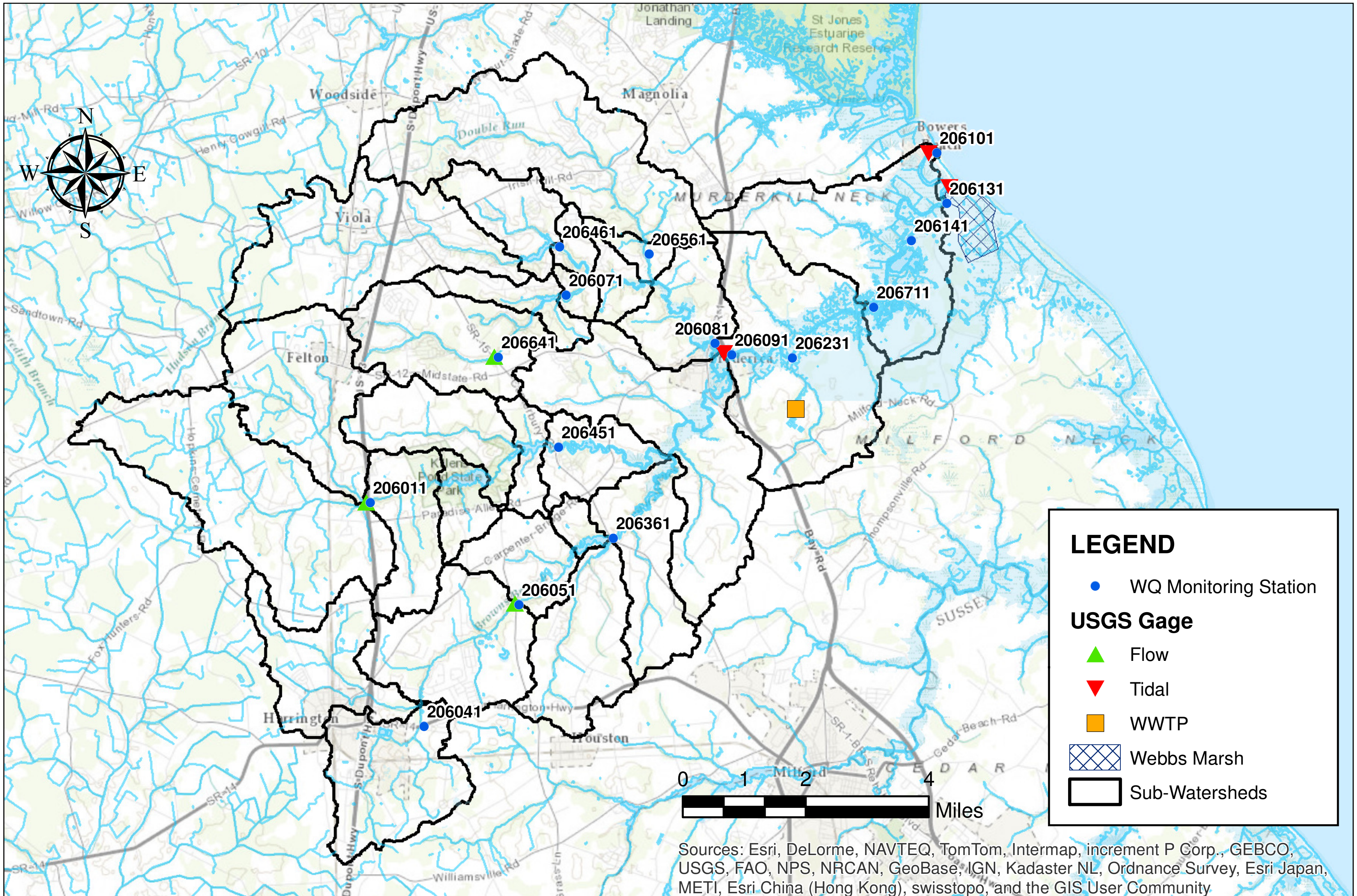

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Figure 1. Murderkill River Watershed Study Area

Federal water quality standards (WQS) regulations at 40 CFR § 131.10: require states to specify appropriate uses to be achieved and protected; require that WQS ensure attainment and maintenance of WQS of downstream waters; allow for sub-categories of uses and seasonal uses; describe when uses are attainable; list six factors of which at least one must be satisfied to justify removal of uses specified in Clean Water Act (CWA) Section 101(a)(2) that are not existing uses; prohibit removal of existing uses; require states to revise WQS to reflect uses that are presently being attained but not designated; and establish when a state is or is not required to conduct a use attainability analysis (UAA).

A state is required to develop a UAA when designating uses that do not include the uses specified in Section 101(a)(2) of the CWA, when removing a designated use specified in Section 101(a)(2) of the Act, or when adopting sub-categories of such uses that require less stringent criteria. The phrase "uses specified in Section 101(a)(2) of the Act" refers to uses that provide for the protection and propagation of fish (including aquatic invertebrates), shellfish, and wildlife, and recreation in and on the water, as well as for the protection of human health when consuming fish, shellfish, and other aquatic life. "Sub-category of a use specified in Section 101(a)(2) of the Act" refers to any use that reflects the subdivision of uses specified in Section 101(a)(2) of the Act into smaller, more homogenous groups of waters with the intent of reducing variability within the group. 40 CFR 131.10(c) provides that states may adopt sub-categories of a use and set the appropriate criteria to reflect varying needs of such sub-categories of uses.

The additional Murderkill River studies conducted since 2001 concluded that it was appropriate to establish a sub-category of Delaware's existing "Fish, Aquatic Life and Wildlife" designated use and to develop alternative criteria for DO for the tidal portion of the Murderkill River and to revise the 2005 TMDL for the tidal Murderkill River in accordance with the alternative DO criteria. Therefore, the remainder of this document, along with other supporting technical reports and references, serve as the UAA in support of proposed revisions to the Delaware water quality standards. This UAA is submitted in support of Delaware's adoption of a "Tidal Marsh Influenced Aquatic Life" use sub-category for the Murderkill River. Consistent with 40 CFR § 131.10(g), Delaware's adoption of the Tidal Marsh Influenced use and associated alternative DO criteria is protective of the existing use that has been attained in the water body since November 28, 1975. The TMDL and associated allocations for the upstream watershed areas will remain the same as determined in the amended 2005 TMDL. Integration of the UAA process with development of TMDLs is supported by EPA Guidance (King, 2006).

Extensive tidal marshes in the lower Murderkill River export nutrients and carbon, and have a considerable impact on DO. Therefore, the Murderkill River studies principally addressed the factor at 40 CFR 131.10(g)(1): "naturally occurring pollutant concentrations prevent the attainment of the use" with respect to the effect of the extensive tidal marshes on DO concentrations in the tidal Murderkill River. To the extent these marshes have been modified over time by human activity, the types of impacts (ditching, etc.) are not expected to have caused the low DO in the tidal river, and could in fact, have mitigated the tidal marsh influence on DO (i.e., the more "natural" the marsh hydrology, the greater the marsh respiration and corresponding impact on DO). Nonetheless, the effects of human-caused hydrologic modification of the marshes were not examined, and it is considered infeasible to restore them to their original condition. To the extent this could be an influence on the extent of hypoxic conditions, and thus reflected in model inputs, this effect would be covered by the factor described at 40 CFR 131.10(g)(4): "…hydrologic modifications preclude the attainment of the use, and it is not feasible to restore the water body to its original condition…in a way that would result in the attainment of the use".

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 main elements of the Murderkill River Study included the following monitoring and modeling components along with how the collected data and modeling was used.

1. Intensive Hydrologic and Water Quality Monitoring – This monitoring was carried out by DNREC and the USGS and included monthly or twice a month water quality sampling at more than 15 fixed stations in the tidal and non-tidal portions of the Murderkill River. In addition, several stream and tide gages, Acoustic Doppler Current Profiler (ADCP) units, and continuous monitors were installed at several locations. Data collected was used to calibrate a watershed and hydrodynamic/water quality model of the Murderkill River. In addition, collected data were used by several researchers in support of their specific studies.

2. Algal Primary Production Study – This study was conducted to determine algal growth and production rates, light limitation on algal growth and the rate of nutrient uptake via photosynthesis processes. Principal Investigator for this study was Dr. Jonathan Sharp of the University of Delaware. The results of the study showed that because of the turbid nature of the Murderkill River, there is no strong correlation between nutrients/DO and primary production in the River. Information obtained during this study was used to assign algal growth rates and calibrate the water quality model of the Murderkill River.

3. Sediment Flux Survey – This study was conducted to measure the nutrient and dissolved oxygen fluxes between the sediment and the water column. Principal Investigators of this study were Drs. Jeff Cornwell and Mike Owens of the University of Maryland. The findings of this survey were used to calibrate the water quality model of the Murderkill River.

4. Study of Tidal Marsh Fluxes of Nutrients, Carbon and DO – This study was conducted to quantify the exchange of nutrients, organic matter and DO between the River and the surrounding tidal marsh. Principal Investigators of this study were Dr. William Ullman of

the University of Delaware and Dr. Anthony Aufdenkampe of the Stroud Water Research Center. This study showed that tidal marshes are significant sources of dissolved organic carbon and low DO water to the Murderkill River. The results of this study were used to assign the marsh loading inputs to the water quality model of the Murderkill River.

5. Study of Tidal Marsh Inundation – This study was conducted to quantify the volume of water that covers tidal marshes during each tidal cycle. This study was conducted by Dr. Tom McKenna of the Delaware Geological Survey and the results were used to calibrate the hydrodynamic model and to assign the marsh loading inputs in the water quality model of the Murderkill River.
6. Study of Sediment Nutrients and Ecological History – This study was conducted to track and date environmental changes in the Murderkill Watershed by studying sediment cores. Principal Investigators of this study were Drs. David Velinski and Don Charles of the Philadelphia Academy of Natural Sciences.
7. Fish Surveys – These surveys were conducted in the summer of 2012 to determine the density and diversity of fishes using the Murderkill River. The surveys were conducted by the DNREC Division of Fish and Wildlife. The survey results showed that the fish population and density in the Murderkill River is very similar to that in the St. Jones River.
8. Watershed and Tidal River Hydrodynamic and Water Quality Modeling – This effort included developing three models: 1) Watershed Model (HSPF); 2) Tidal River Hydrodynamic Model (ECOMSED); and 3) Tidal River Water Quality Model (RCA). These modeling tools were used to analyze various loading scenarios and to quantify the impact of various sources and sinks on water quality in the Murderkill River. HDR|HydroQual was the modeling contractor for this project.

This document presents the use of the calibrated and validated watershed (HSPF), hydrodynamic (ECOMSED) and water quality (RCA) models of the Murderkill River watershed and tidal river for supporting the development of alternative DO criteria for the tidal portion of the river that are protective of a sub-category of Delaware's general aquatic life use. The watershed model characterized watershed processes in the watershed such as rainfall driven runoff and nonpoint source loadings. The hydrodynamic model simulates the tidal movement of water due to tides and freshwater flow, density driven currents, and meteorology 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 marsh interactions were also included as loading functions based on the nutrient balance studies in Webb's Marsh. The models were calibrated and validated with data collected by DNREC and USGS over the 2007-2008 monitoring period and developed with project specific studies focused on supporting model development and investigating important water quality processes in the river (e.g., algal growth production, tidal marsh loading and sediment flux). Section 2 presents a summary of the model development with complete details presented in the *Murderkill River Watershed TMDL Model Development and Calibration Report* (HDR|HydroQual, 2013).

Based on the results from the modeling studies, the Murderkill River models (HSPF, ECOMSED and RCA) are considered to be 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 considered to be appropriate tools to use in supporting alternative DO criteria and in developing TMDLs for the Murderkill River watershed.

This document presents how the calibrated and validated models were used to determine the important factors controlling DO levels in the tidal river and to estimate water quality for a natural background condition (Section 3). In addition, a biological survey was conducted in 2012 to identify the aquatic species present in the river and the nearby St. Jones River along with comparing the results to past surveys (Section 4). Sections 5 and 6 present the aquatic life use sub-category and alternative DO criteria development, and proposed regulations.

SECTION 2

MURDERKILL RIVER MODEL DEVELOPMENT

The Murderkill River modeling framework is comprised of three components: a watershed model; a hydrodynamic model; and a water quality model. 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, temperature and solar radiation information, land use patterns, and land management practices to simulate the quantity and quality of runoff from urban 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 alternative criteria development in the Murderkill River watershed.

2.1 WATERSHED SEGMENTATION & MODEL GRID

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 2). 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 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 3). 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 3 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 3). The extension of the model grid into the bay is aimed at minimizing the bay boundary condition effects on the internal model calculations.

2.2 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 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

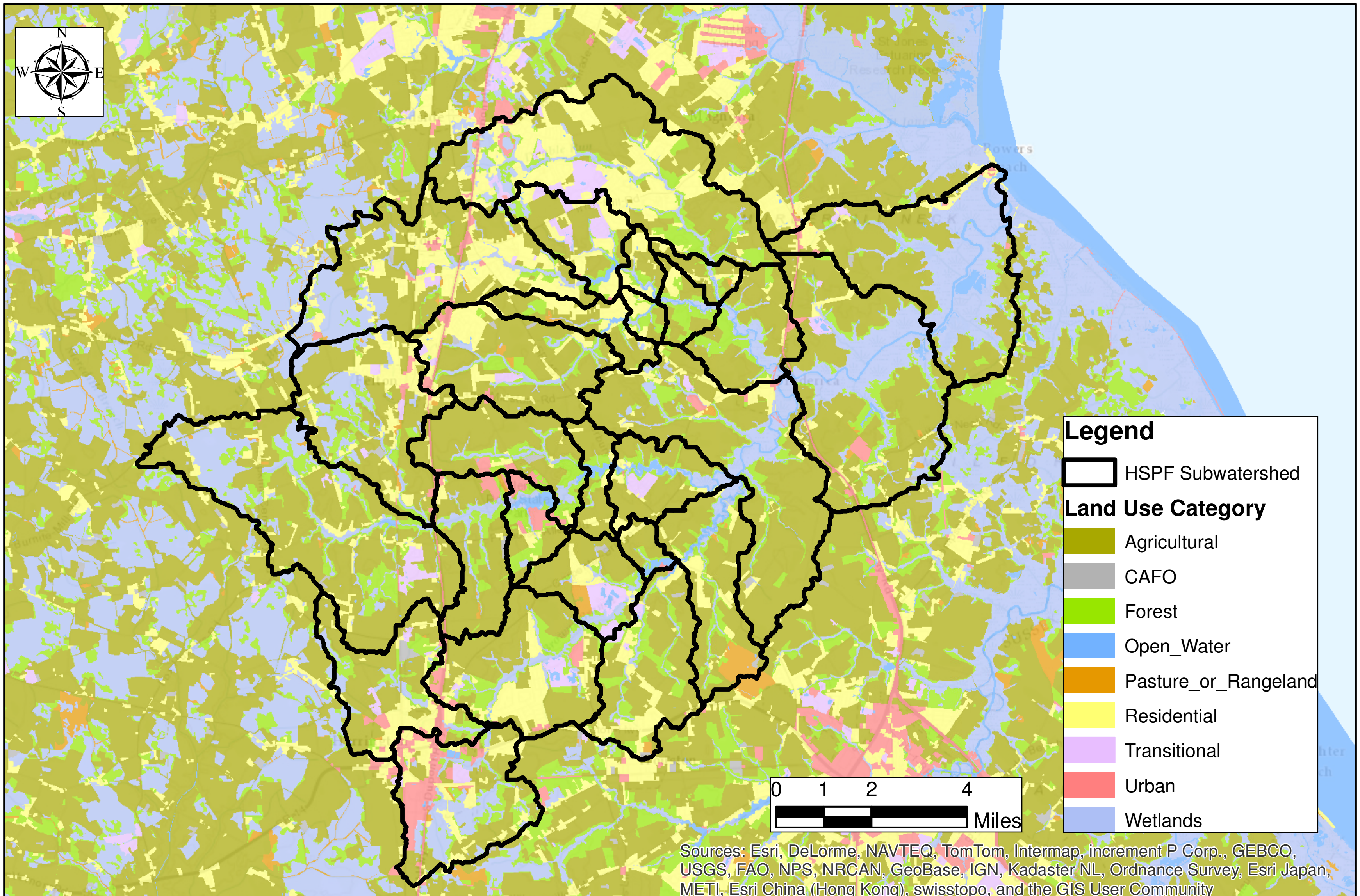

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Figure 2. Murderkill River Watershed HSPF Segmentation

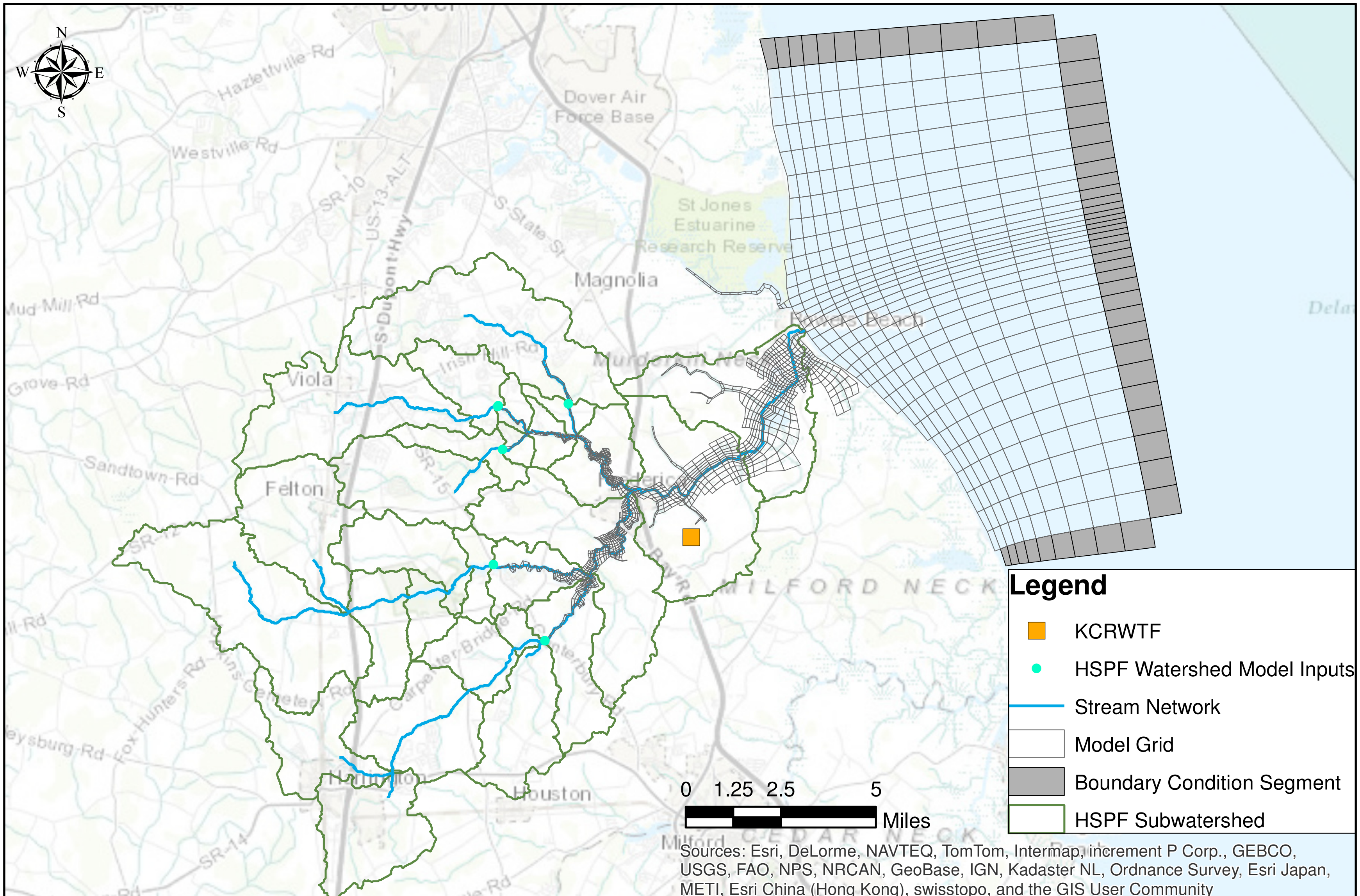

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Figure 3. Murderkill River ECOMSED/RCA Model Grid

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.

2.2.1 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 4 presents the watershed model flow calibration/validation at the three available USGS gages and Figures 5 to 9 present the watershed model water quality calibration/validation at the five main tributaries to the tidal Murderkill River.

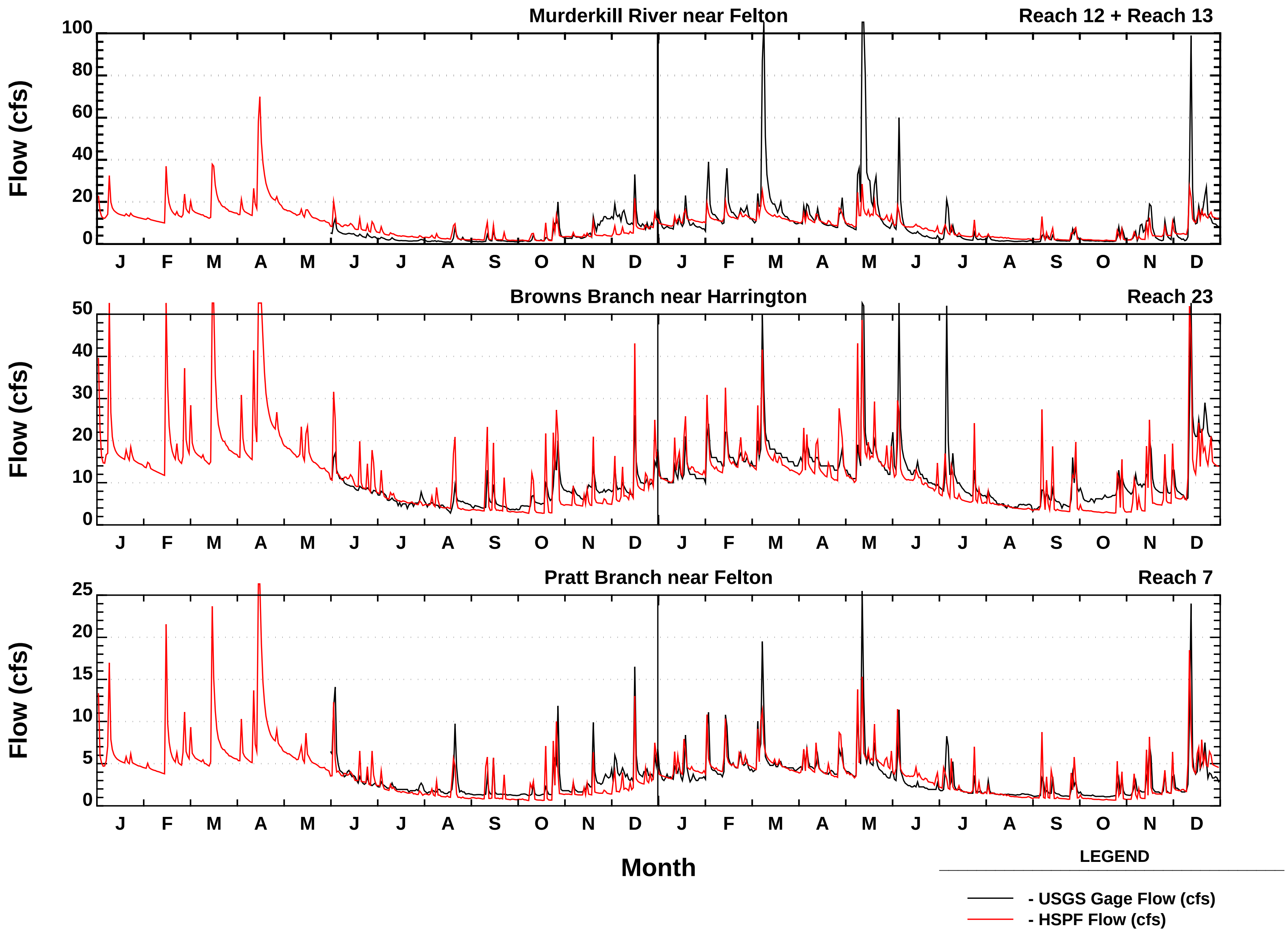

Figure 4. Murderkill River HSPF Flow Calibration/Validation (2007-2008)

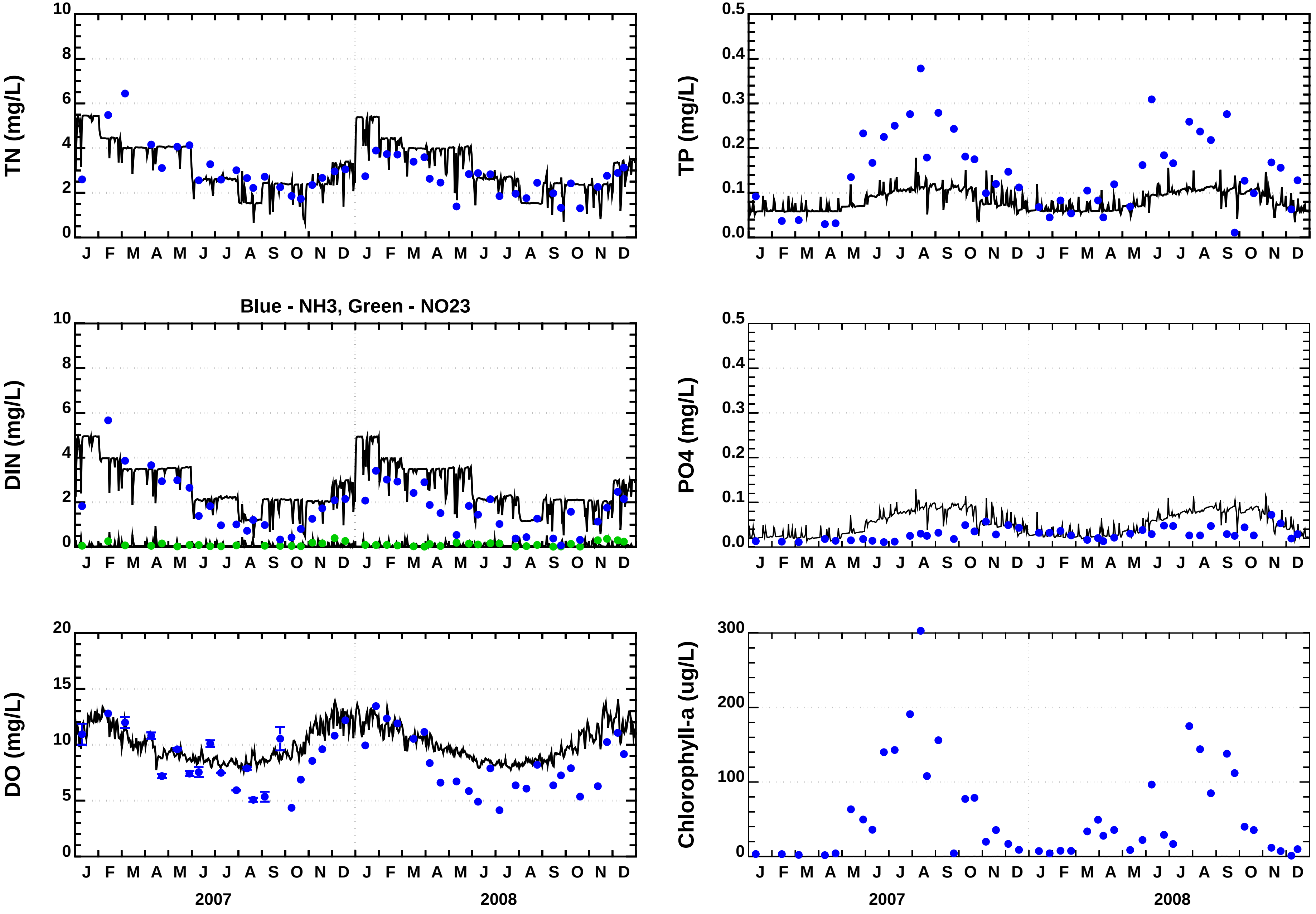

Figure 5. Water Quality Model Calibration at Station 206561, Double Run at Barratts Chapel Rd. (Rd. 371)

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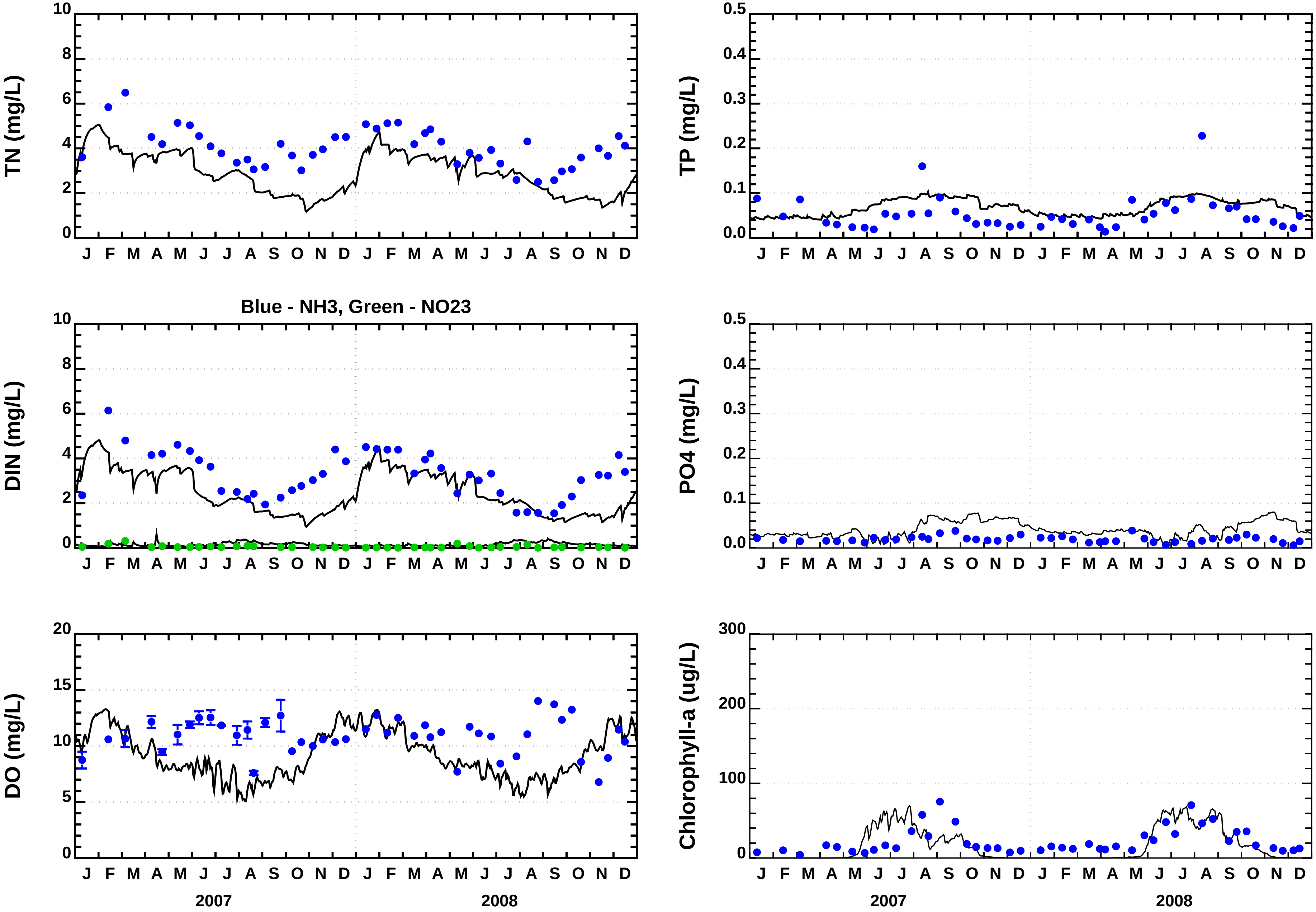

Figure 6. Water Quality Model Calibration at Station 206461, McGinnis Pond at McGinnis Pond Rd. (Rd. 378)

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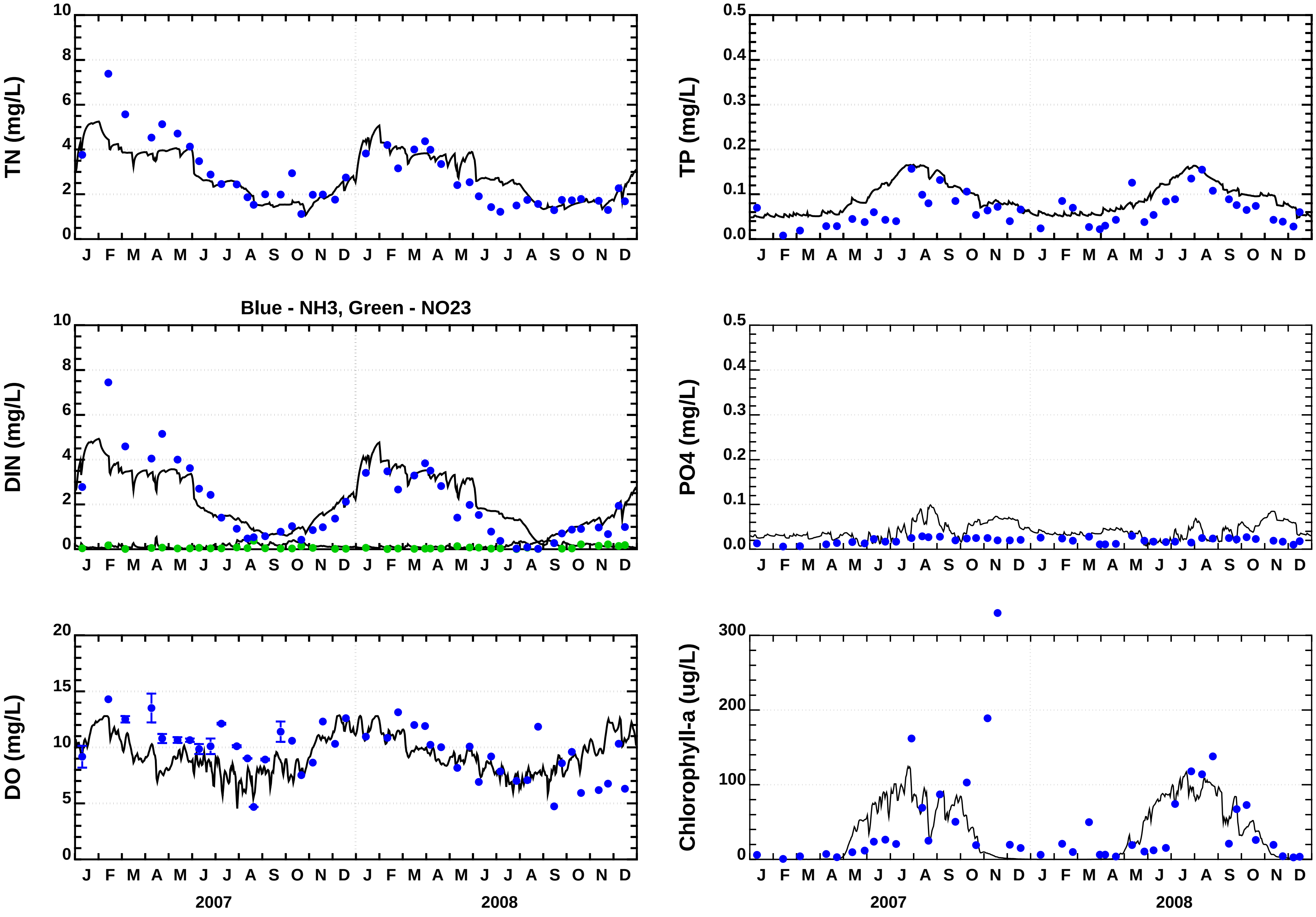

Figure 7. Water Quality Model Calibration at Station 206071, Andrews Lake at Rd. 380 Brdg.

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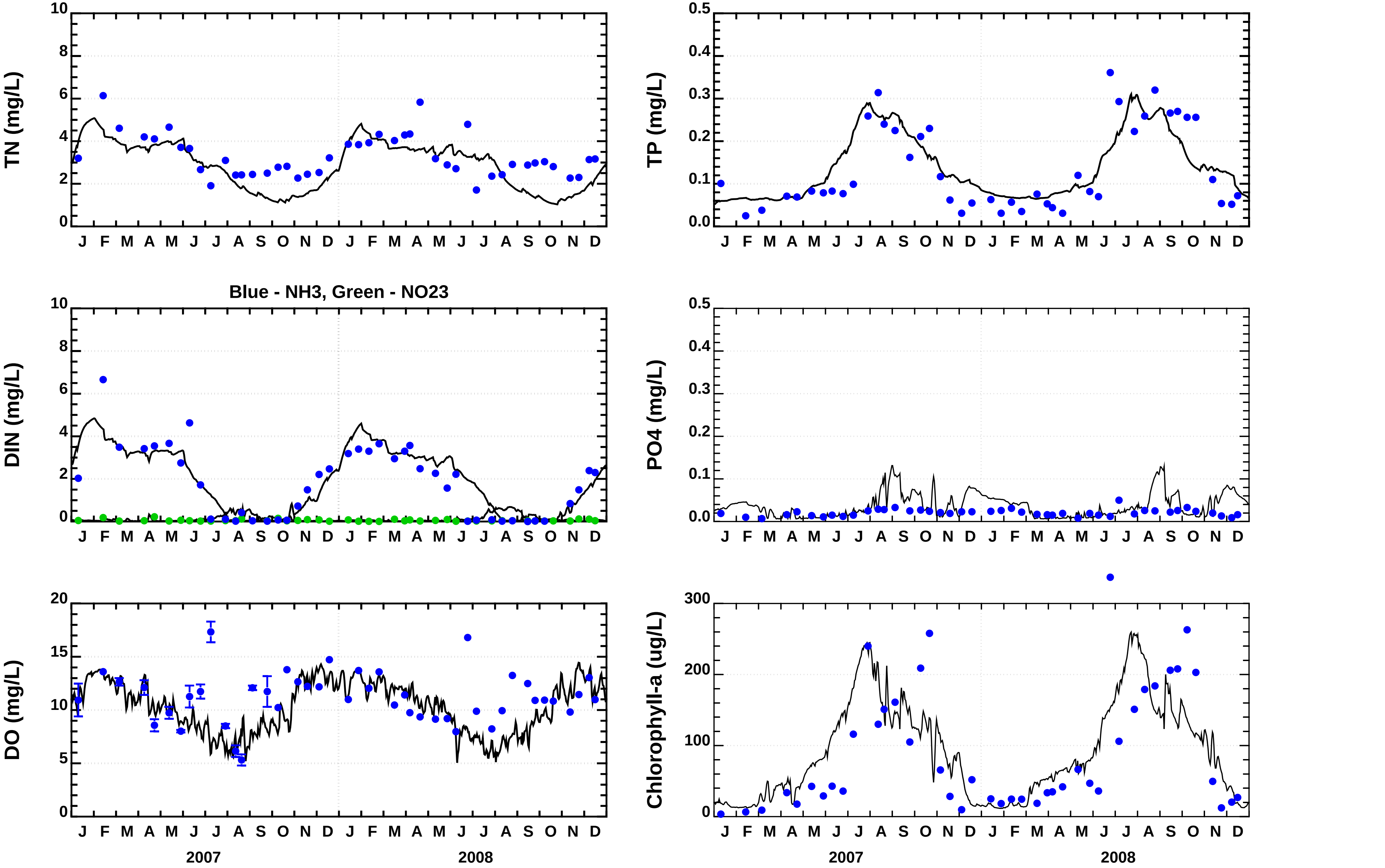

Figure 8. Water Quality Model Calibration at Station 206451, Coursey Pond at Canterbury Rd. (Rt. 15) at Rd. 388 Bridge

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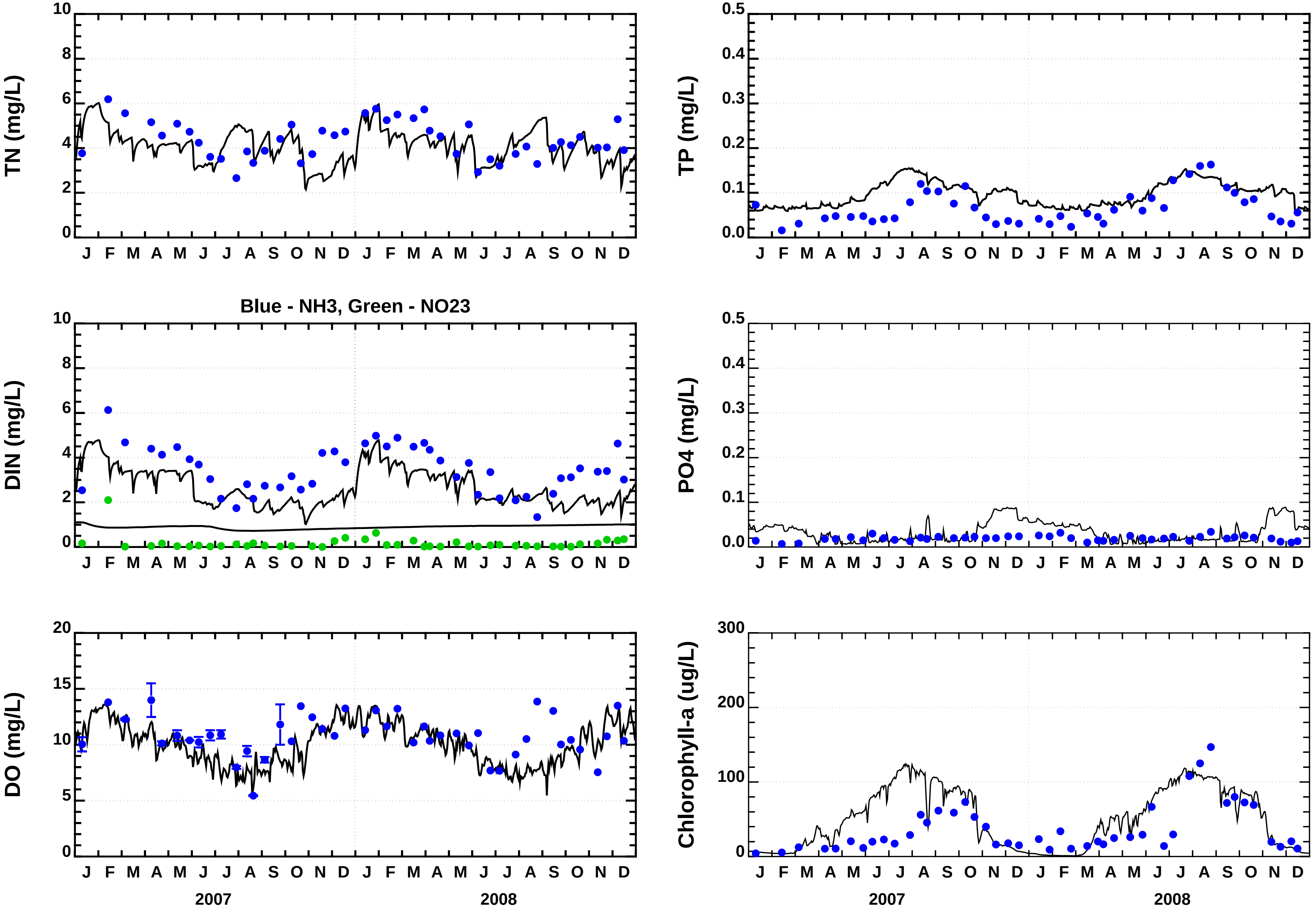

Figure 9. Water Quality Model Calibration at Station 206361, McColley Pond at Canterbury Rd. (Rt. 15) near Spillway

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2.2.2 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 10 and 11 present the hydrodynamic model flux or tidal flow calibration/validation and Figure 12 to 17 present the hydrodynamic model salinity calibration/validation.

2.2.3 TIDAL WATER QUALITY MODEL

The calibrated/validated water quality model reproduces the observed nitrogen data (TN, NH_3 and NO_2+NO_3) and phosphorus data (TP and PO_4) 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,

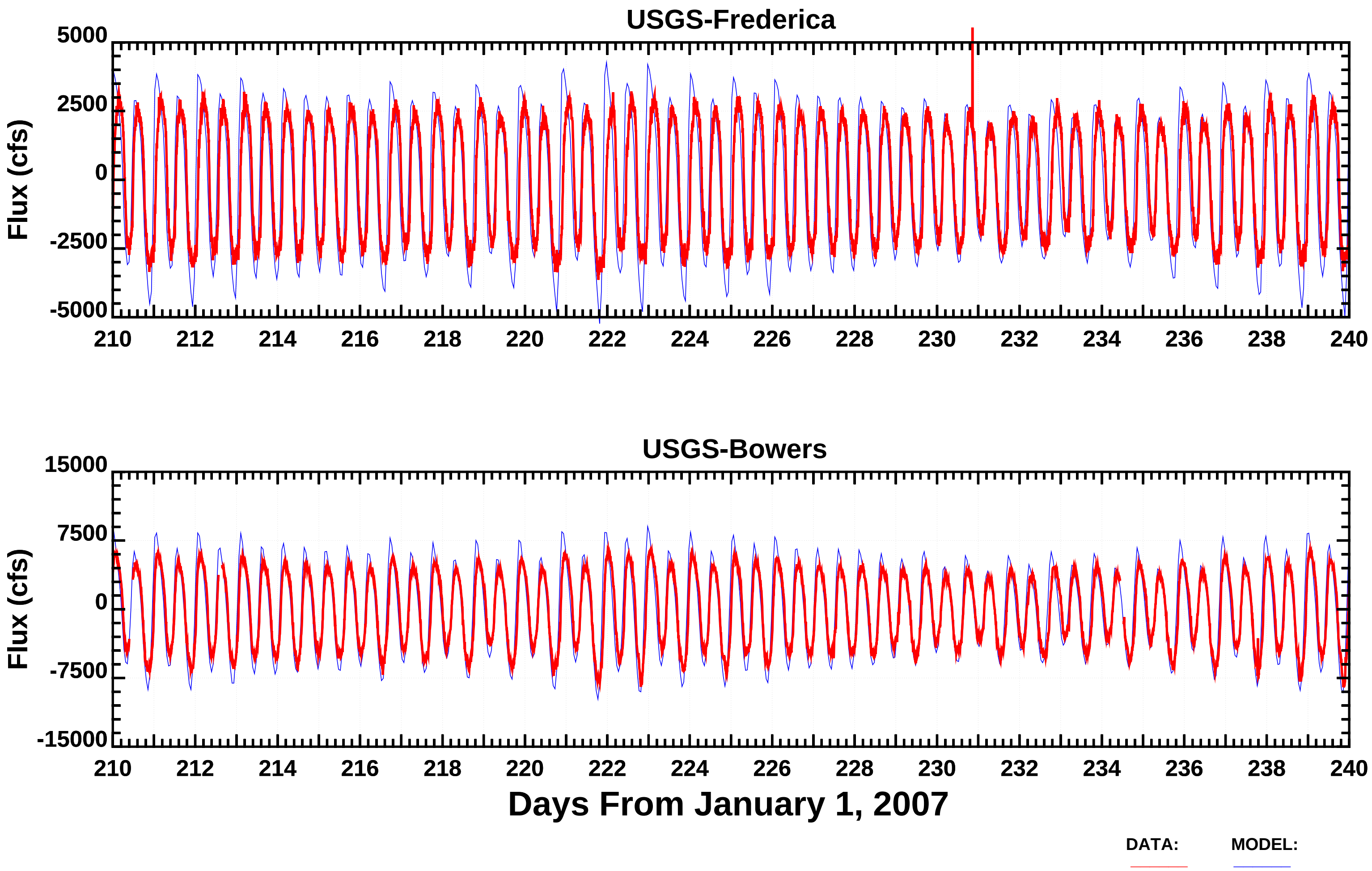


Figure 10. Hydrodynamic Model Flux Calibration for August 2007

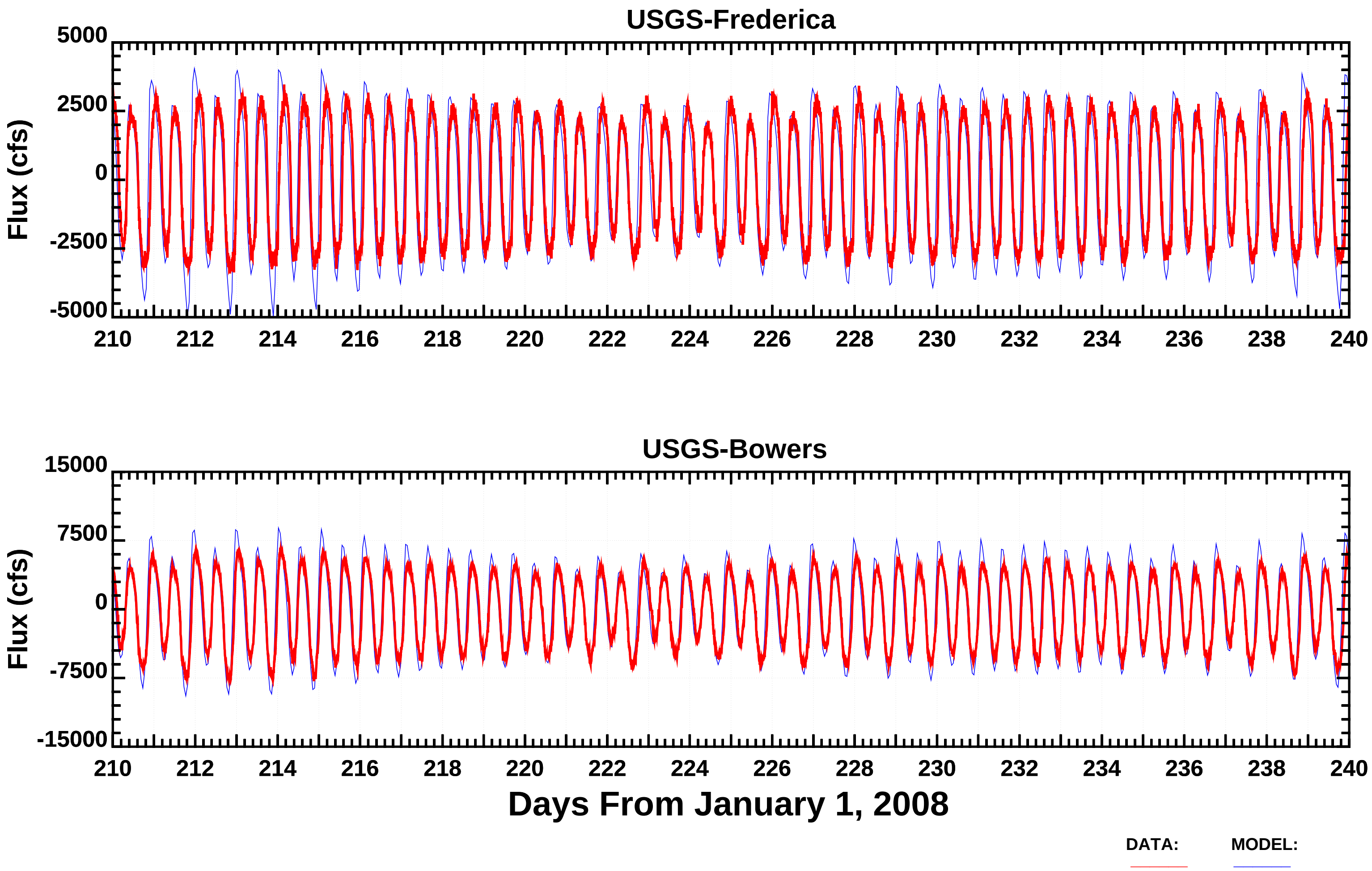


Figure 11. Hydrodynamic Model Flux Validation for August 2008

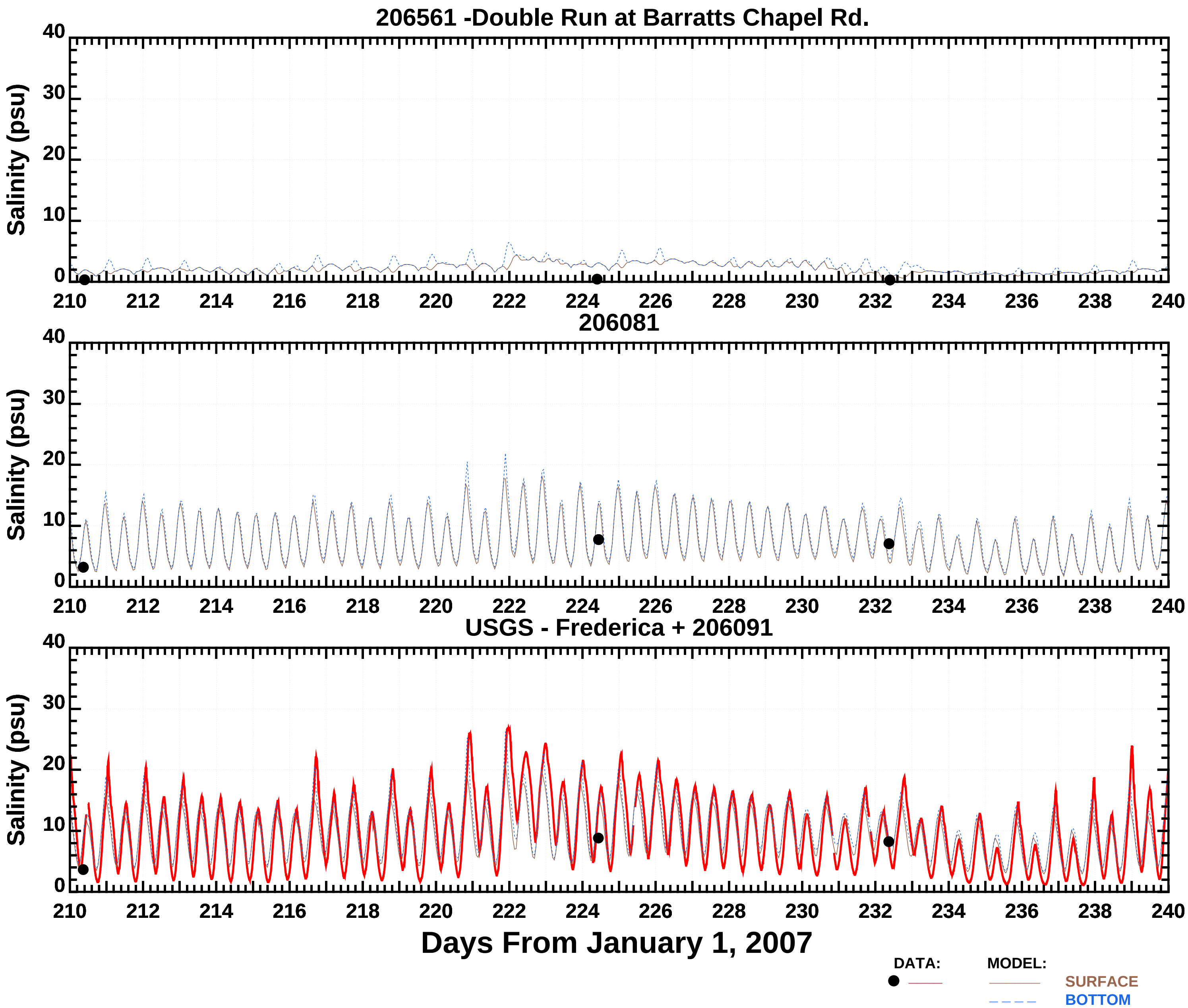


Figure 12. Hydrodynamic Model Salinity Calibration for August 2007

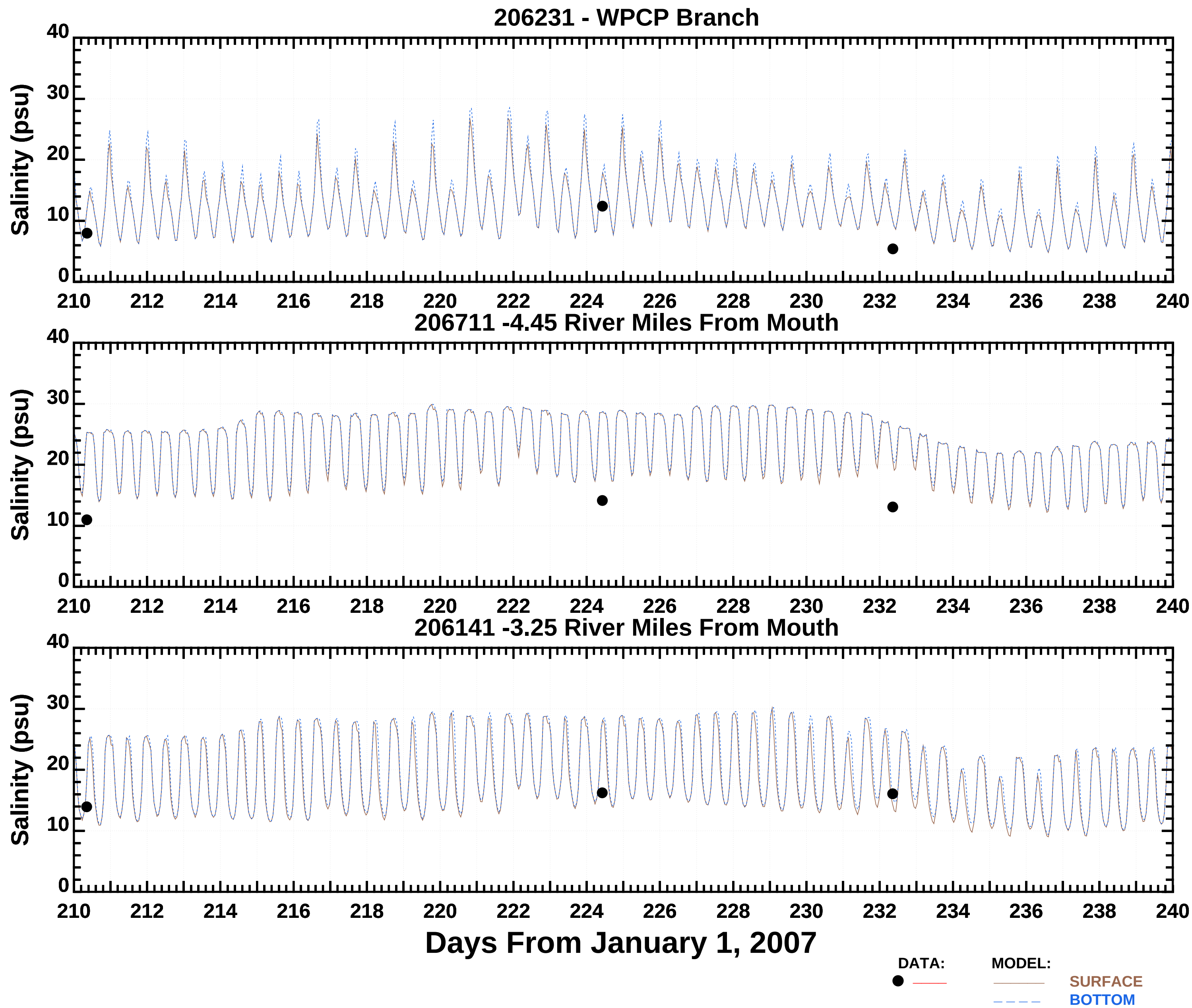


Figure 13. Hydrodynamic Model Salinity Calibration for August 2007

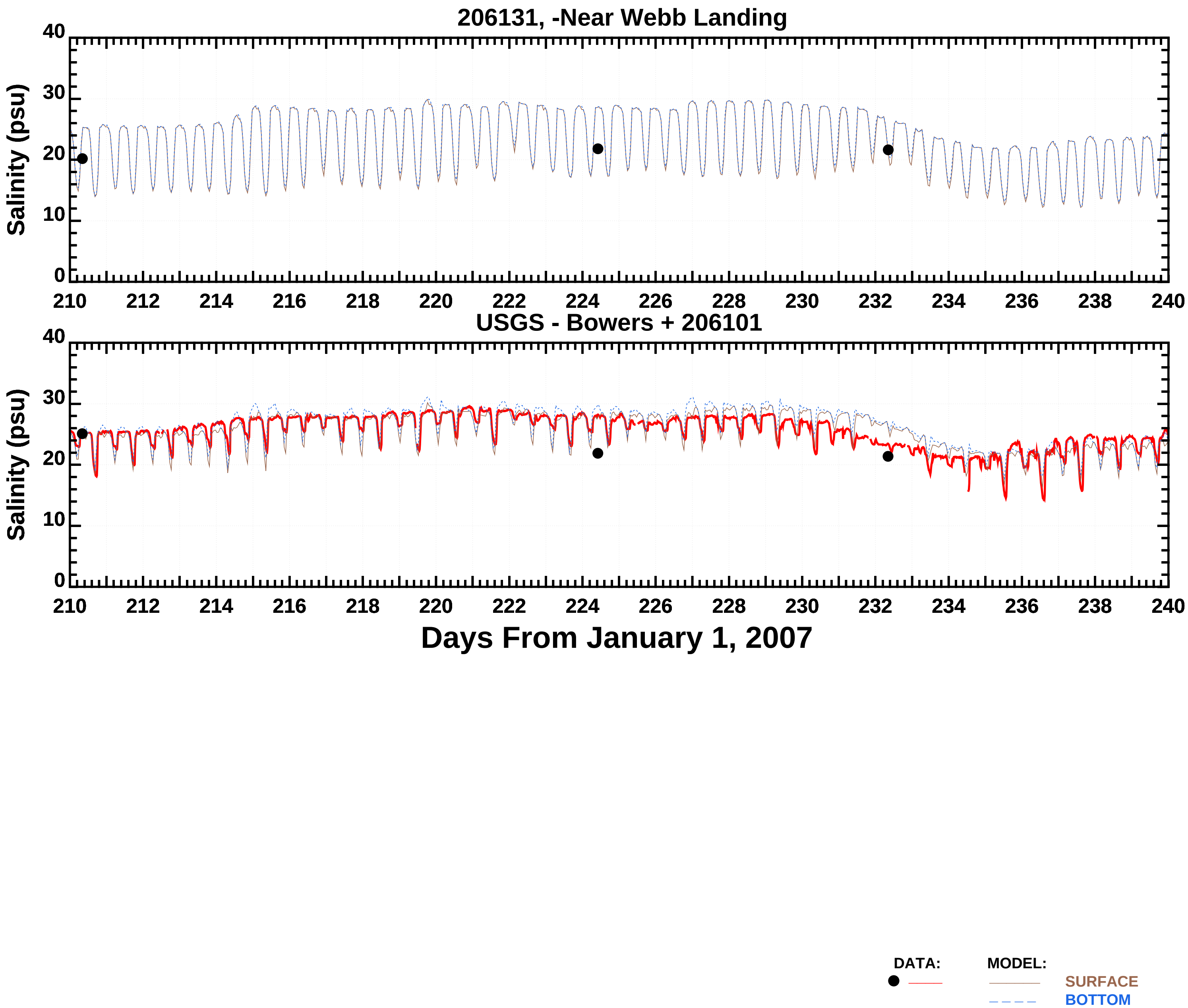


Figure 14. Hydrodynamic Model Salinity Calibration for August 2007

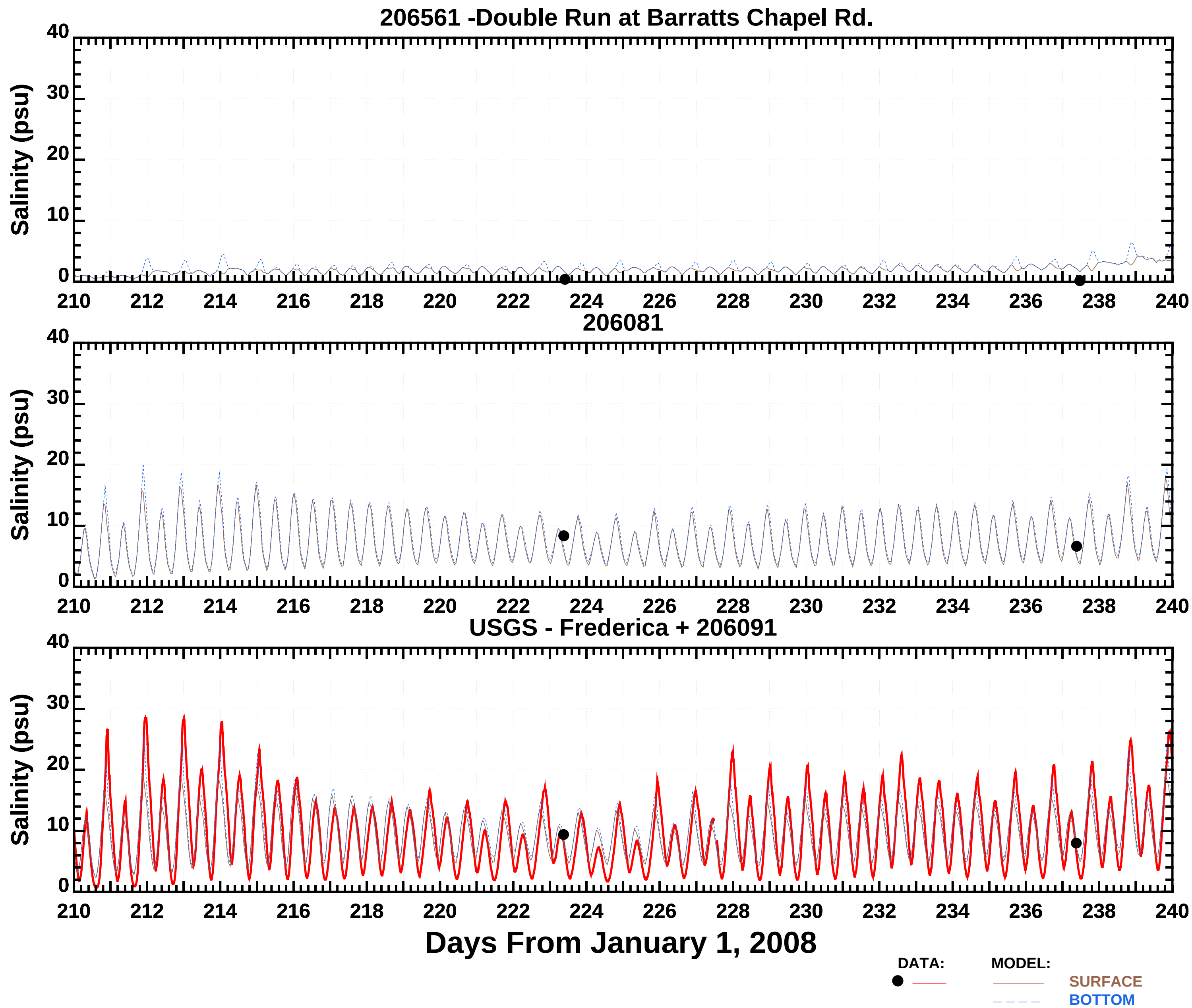


Figure 15. Hydrodynamic Model Salinity Validation for August 2008

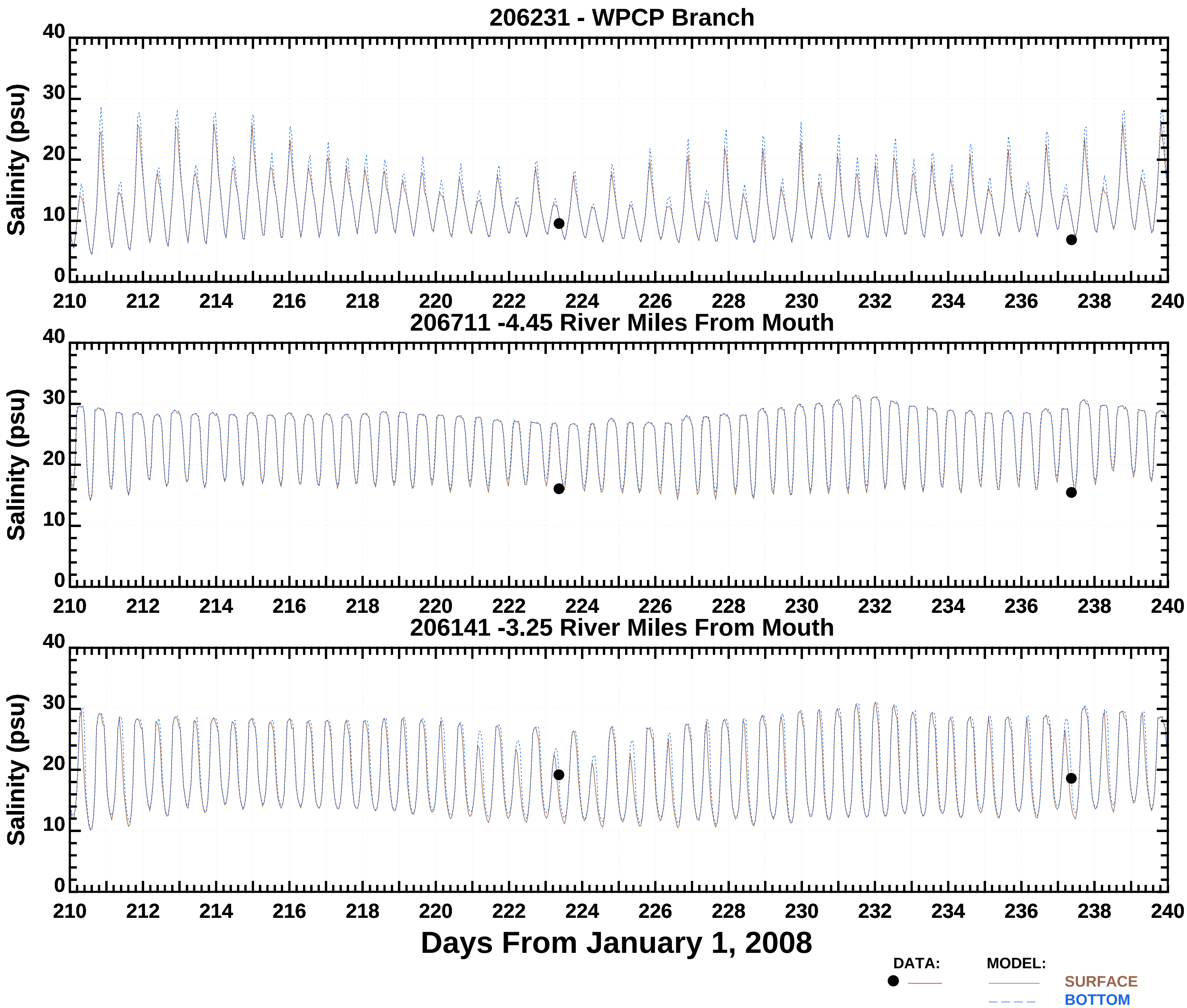


Figure 16. Hydrodynamic Model Salinity Validation for August 2008

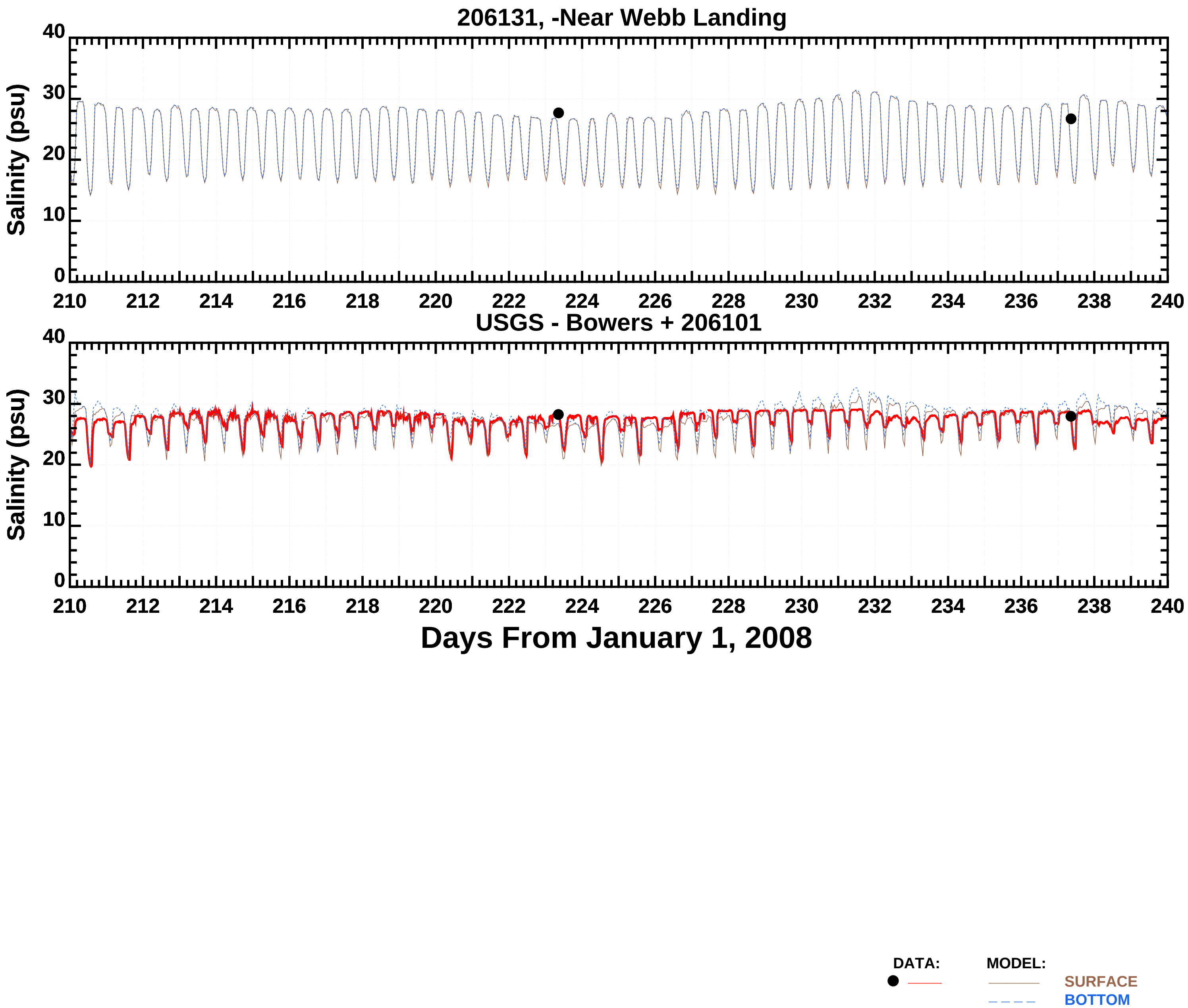


Figure 17. Hydrodynamic Model Salinity Validation for August 2008

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 BOD_5 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.

Figures 18 through 21 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 PO_4, 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.

2.3 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 alternative 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

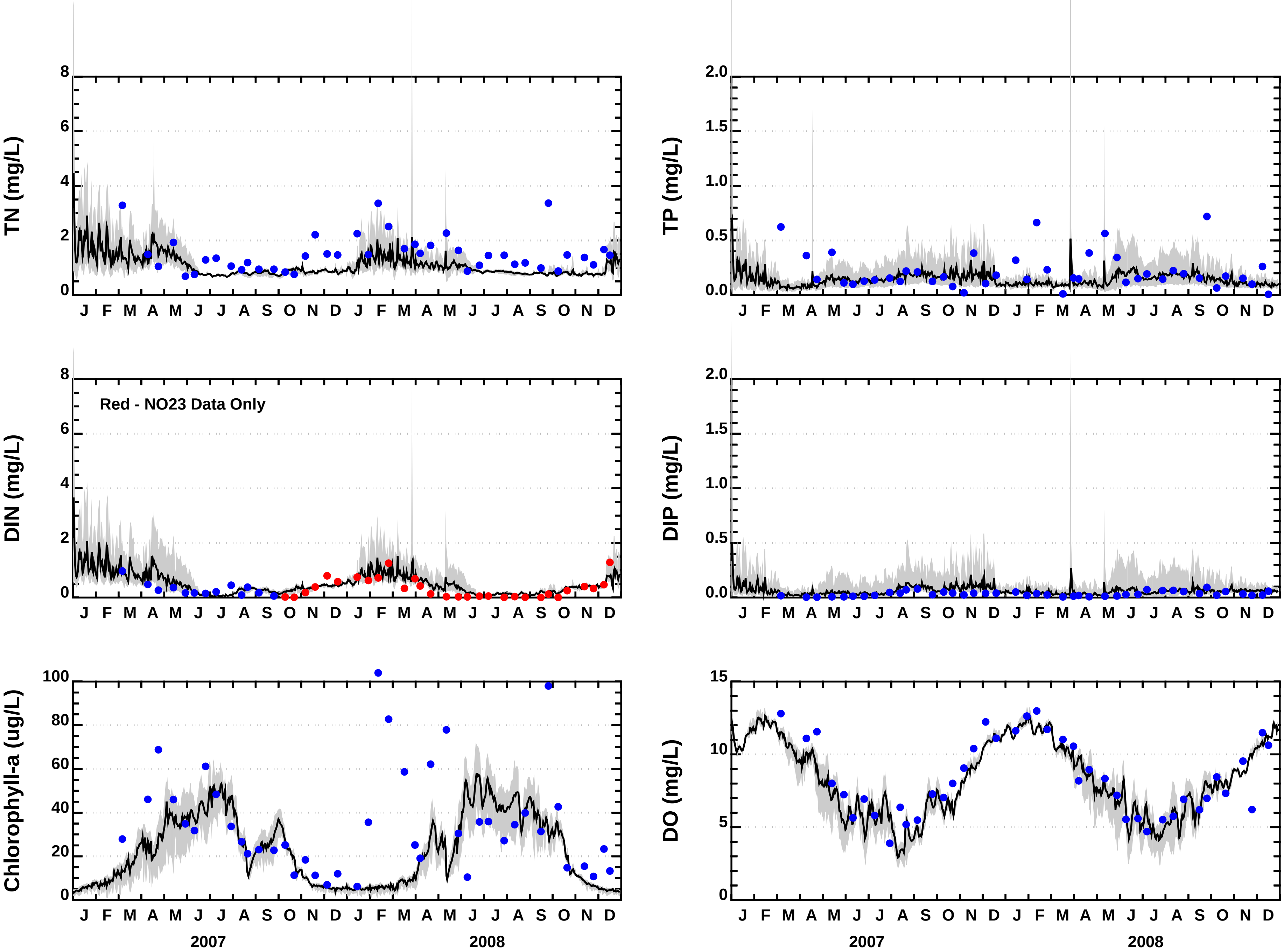


Figure 18. Water Quality Model Calibration/Validation (2007-2008)
Station 206101, Murderkill River at Bowers Beach Warf (Mouth), (74,41)

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

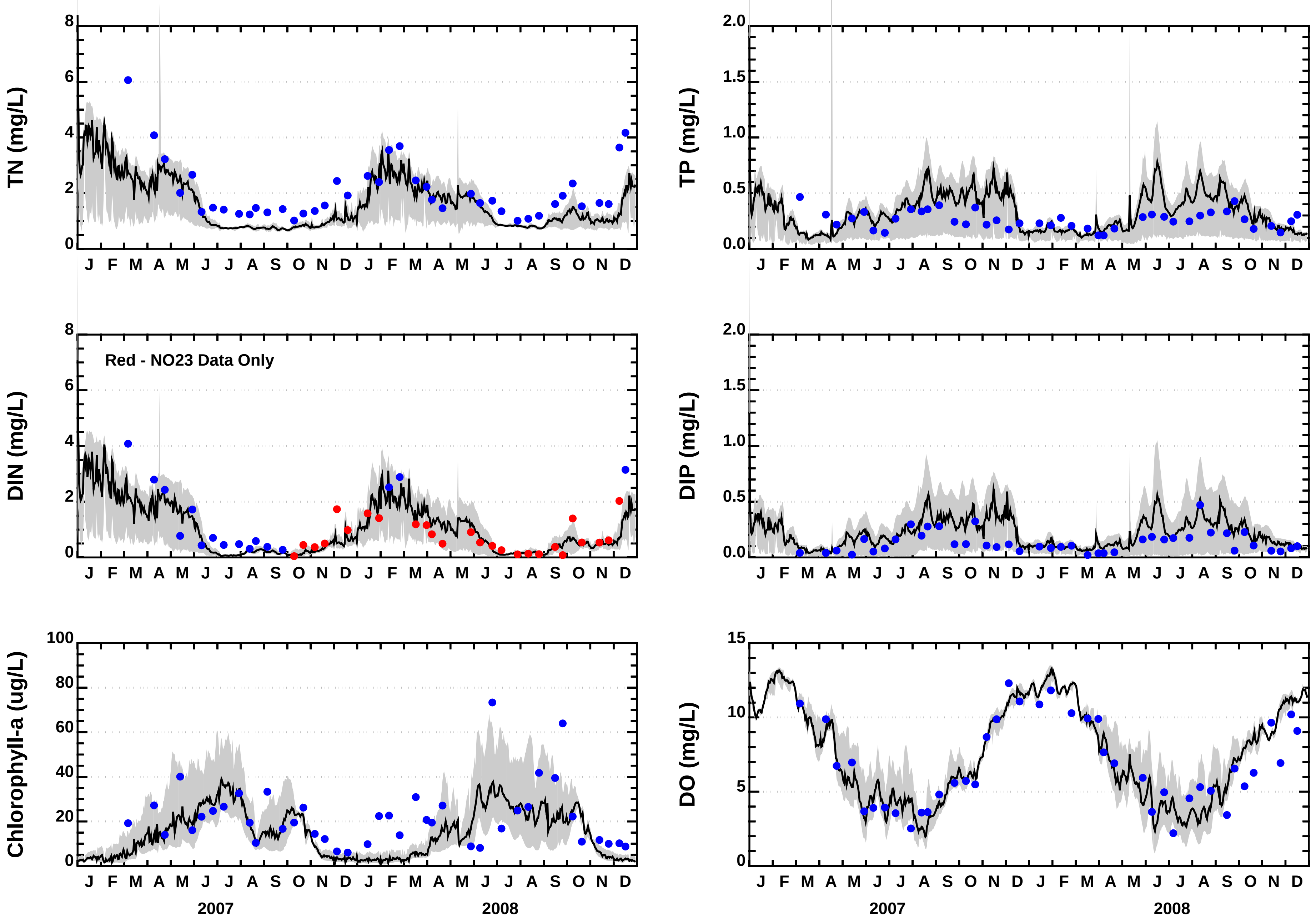


Figure 19. Water Quality Model Calibration/Validation (2007-2008)
Station 206141, Murderkill River near Levee at Milford Neck Wildlife, (54,32)

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

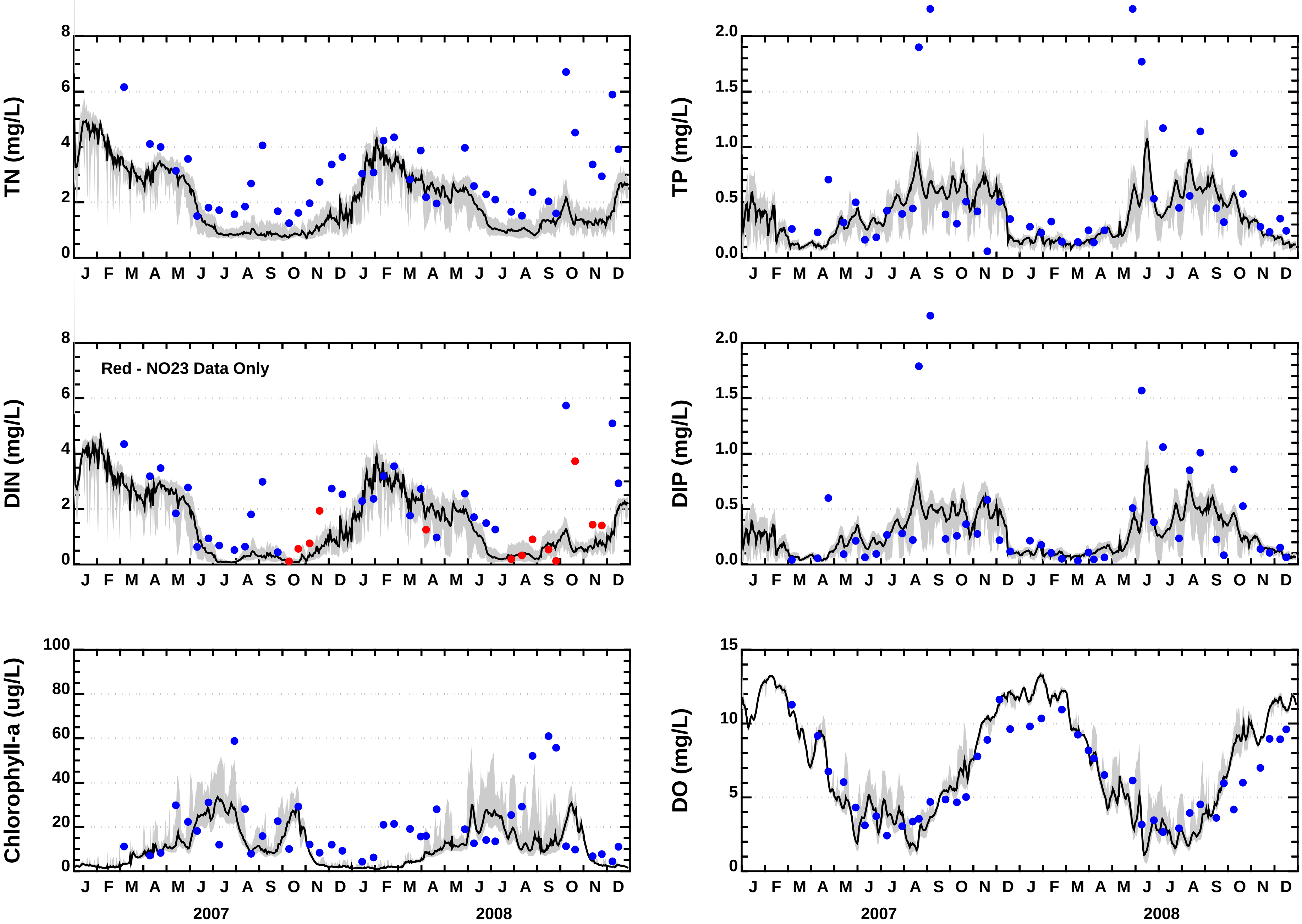


Figure 20. Water Quality Model Calibration/Validation (2007-2008)
Station 206231, Murderkill River at Confluence of Kent County WWTF, (36,33)

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

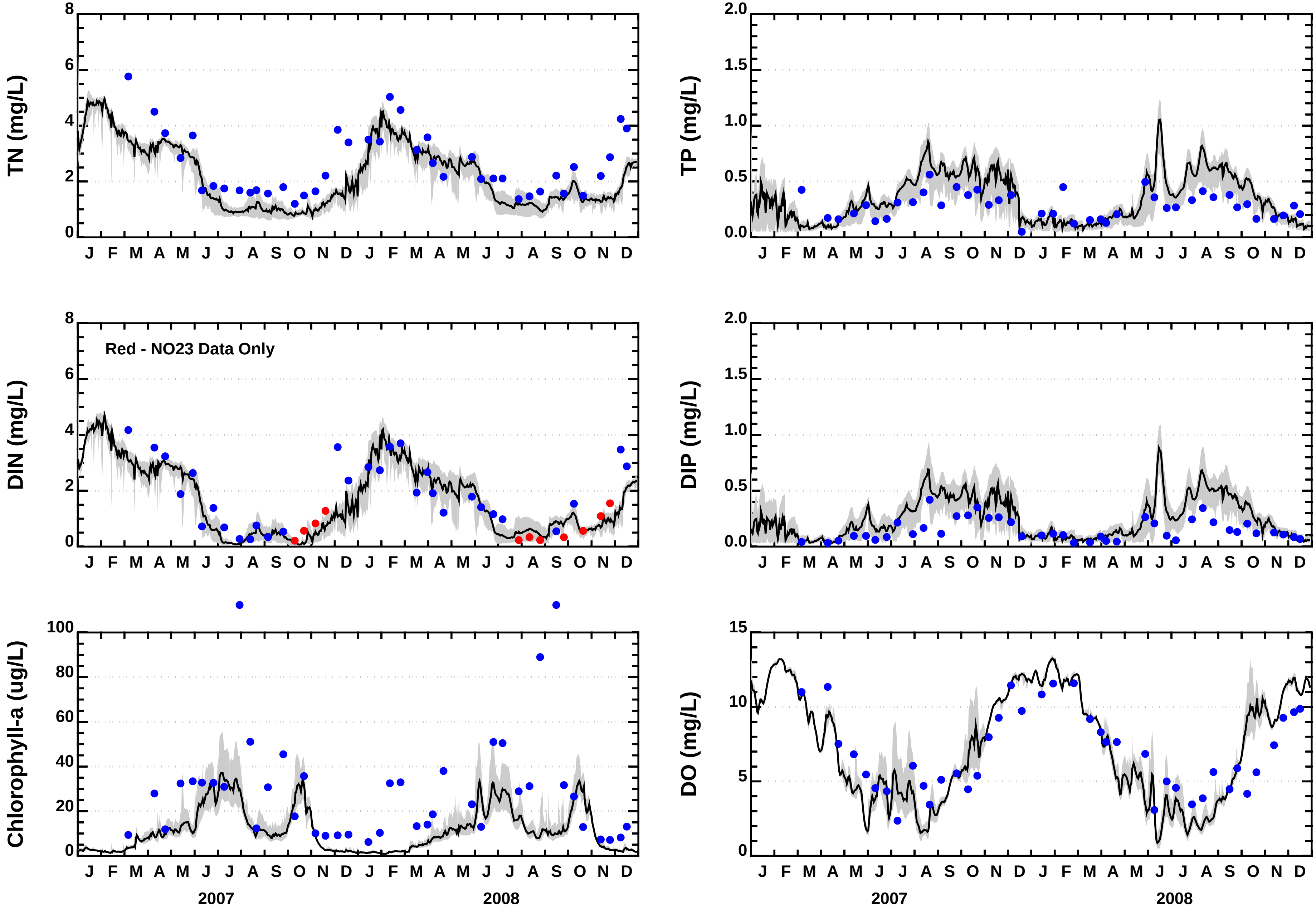


Figure 21. Water Quality Model Calibration/Validation (2007-2008)
Station 206091, Murderkill River at Bay Road (Rt 1/113), (27,39)

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

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 alternative DO criteria and in developing TMDLs for the Murderkill River watershed.

SECTION 3

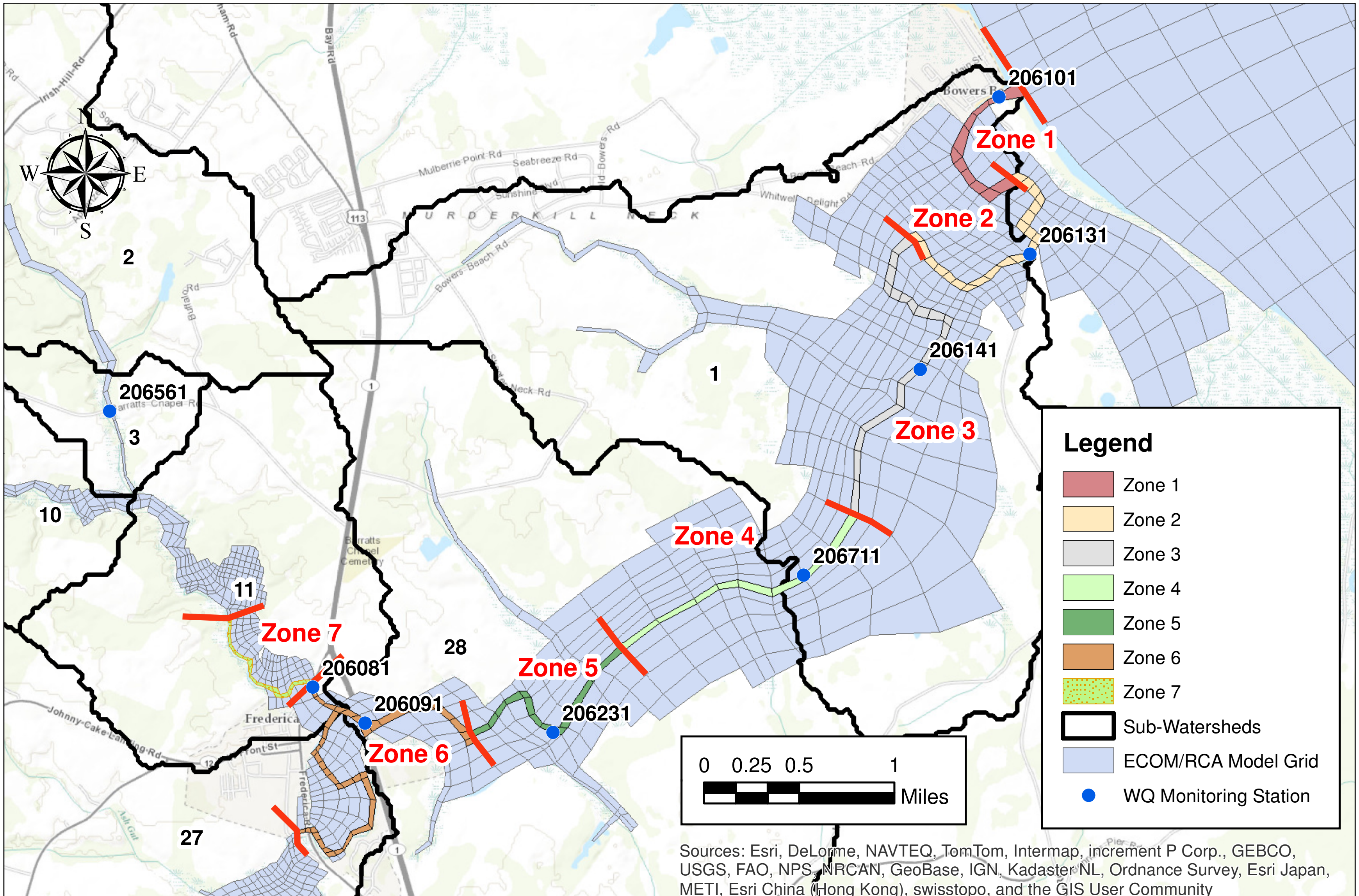
LOADING SCENARIO ASSESSMENT AND DO IMPACT

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.

As part of the alternative criteria development, a water quality standards working group was formed that included representatives from DNREC, KCDPW, University of Delaware, Stroud Water Research Center and HDR|HydroQual. This group held numerous meetings and reviewed the various modeling scenarios completed, biological data collected and other studies completed in the tidal Murderkill River. One outcome of this process was the development of tidal river zones for assessing model output that allowed consideration of model variability within the 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 1 and Figure 22 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.

Table 1. 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 22. Tidal Murderkill River Zones

3.1 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 23 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 24-27) and as summer daily average and daily minimum probability distributions in the seven tidal river zones (Figures 28-29). 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 28-29 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

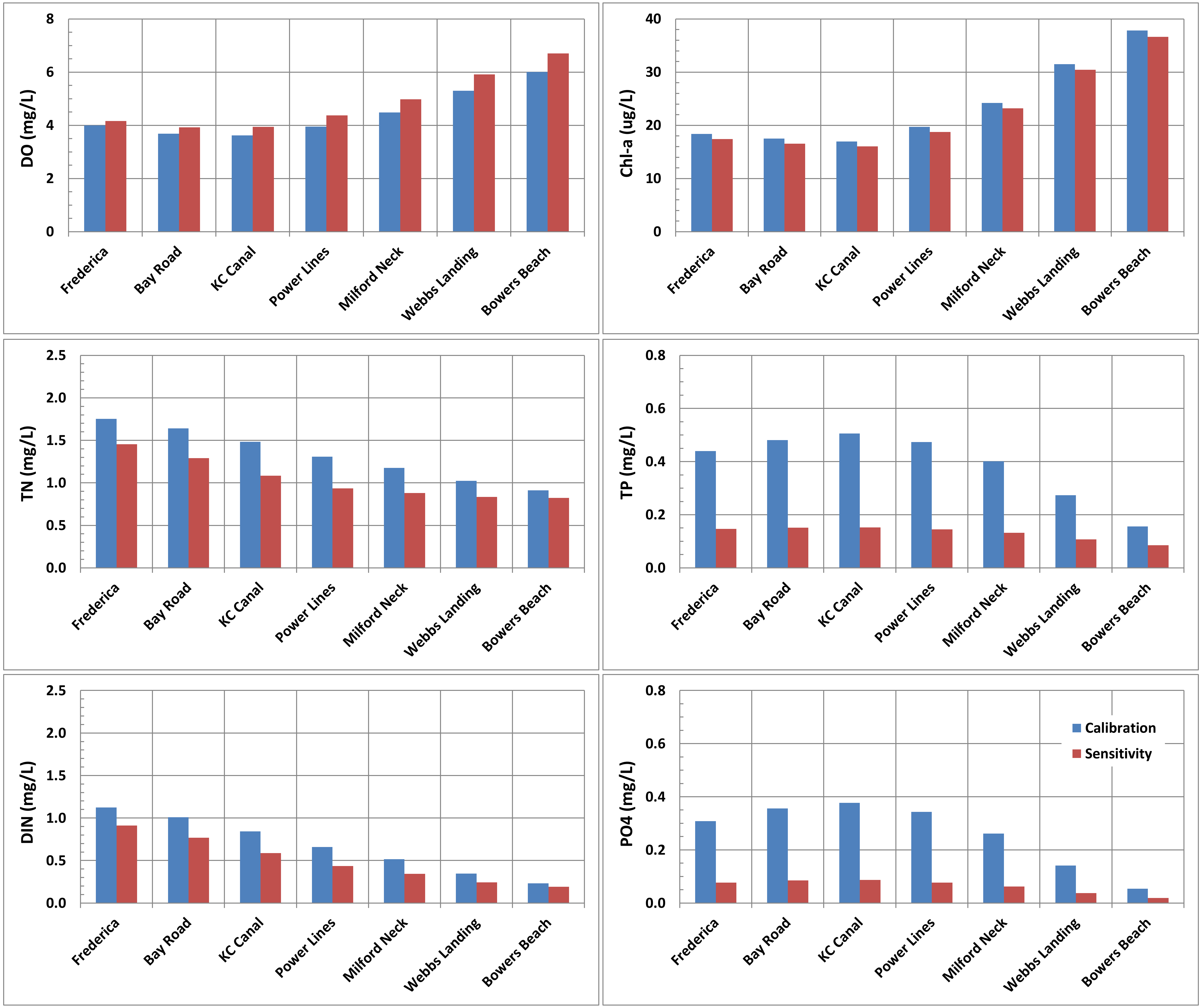


Figure 23. Model Sensitivity Run for No KCRWTF Loads (Summer Average Results)

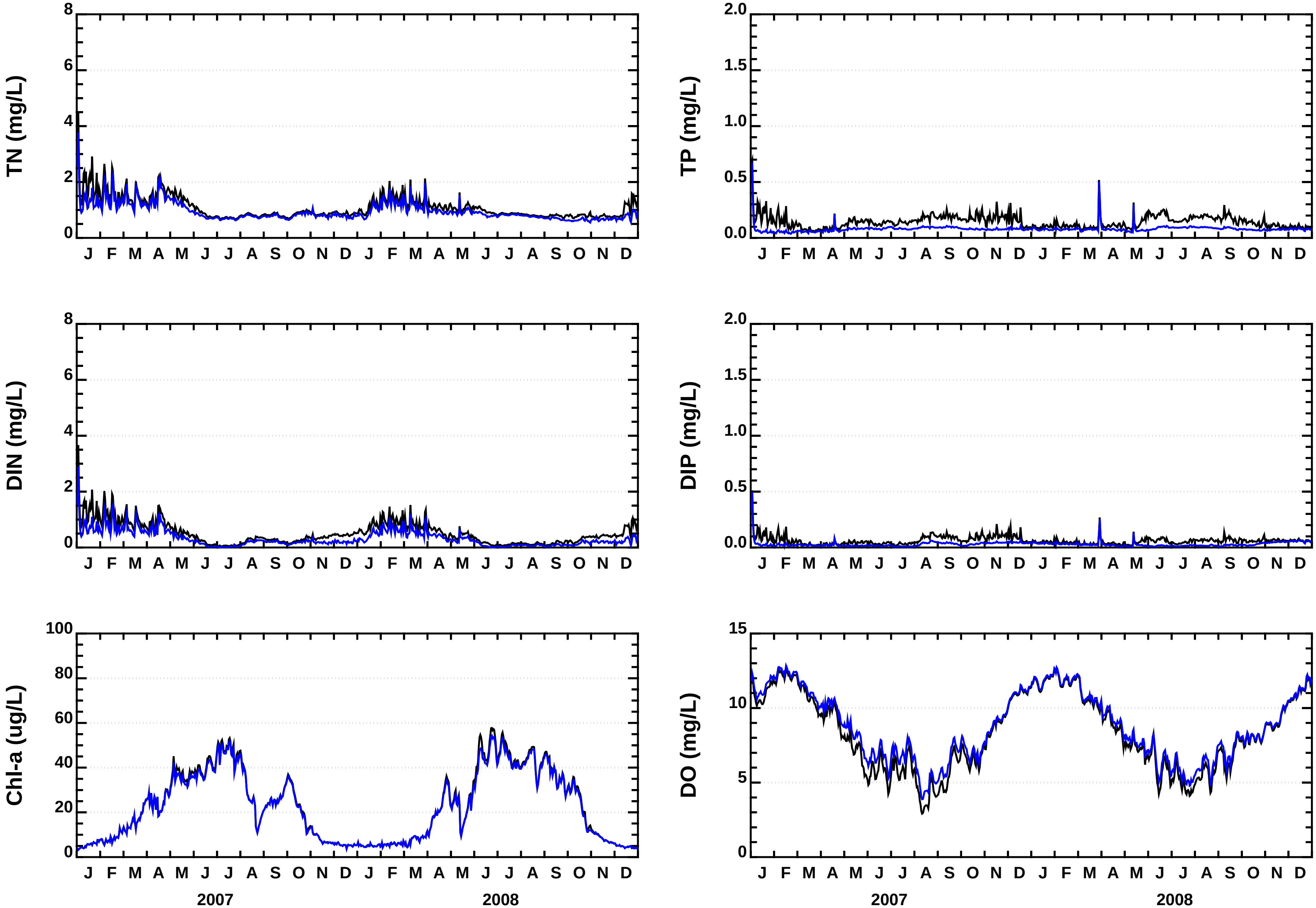


Figure 24. Loading Scenario Results at Bowers Beach (206101)

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

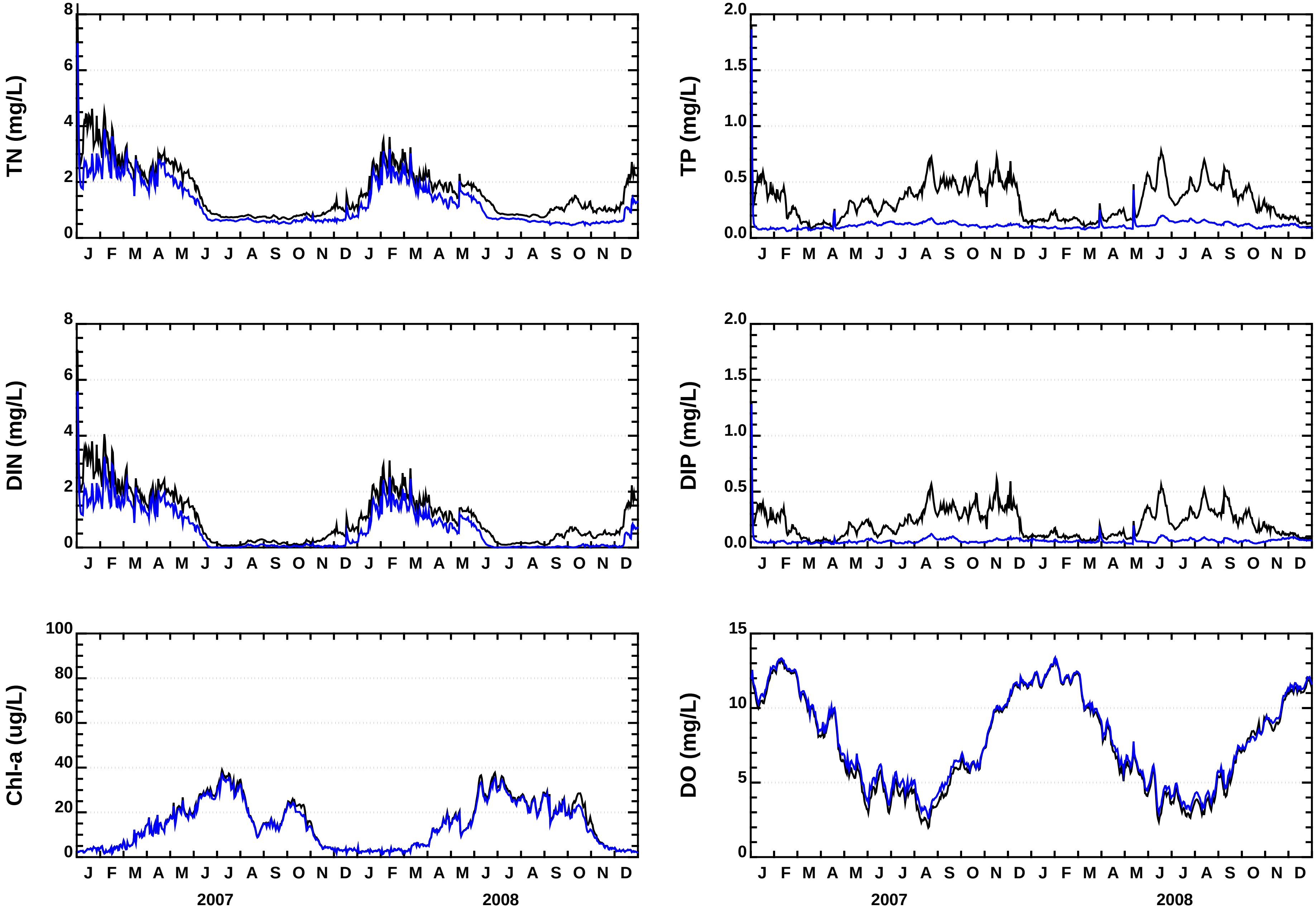


Figure 25. Loading Scenario Results at Milford Neck Wildlife Levee (206141)

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

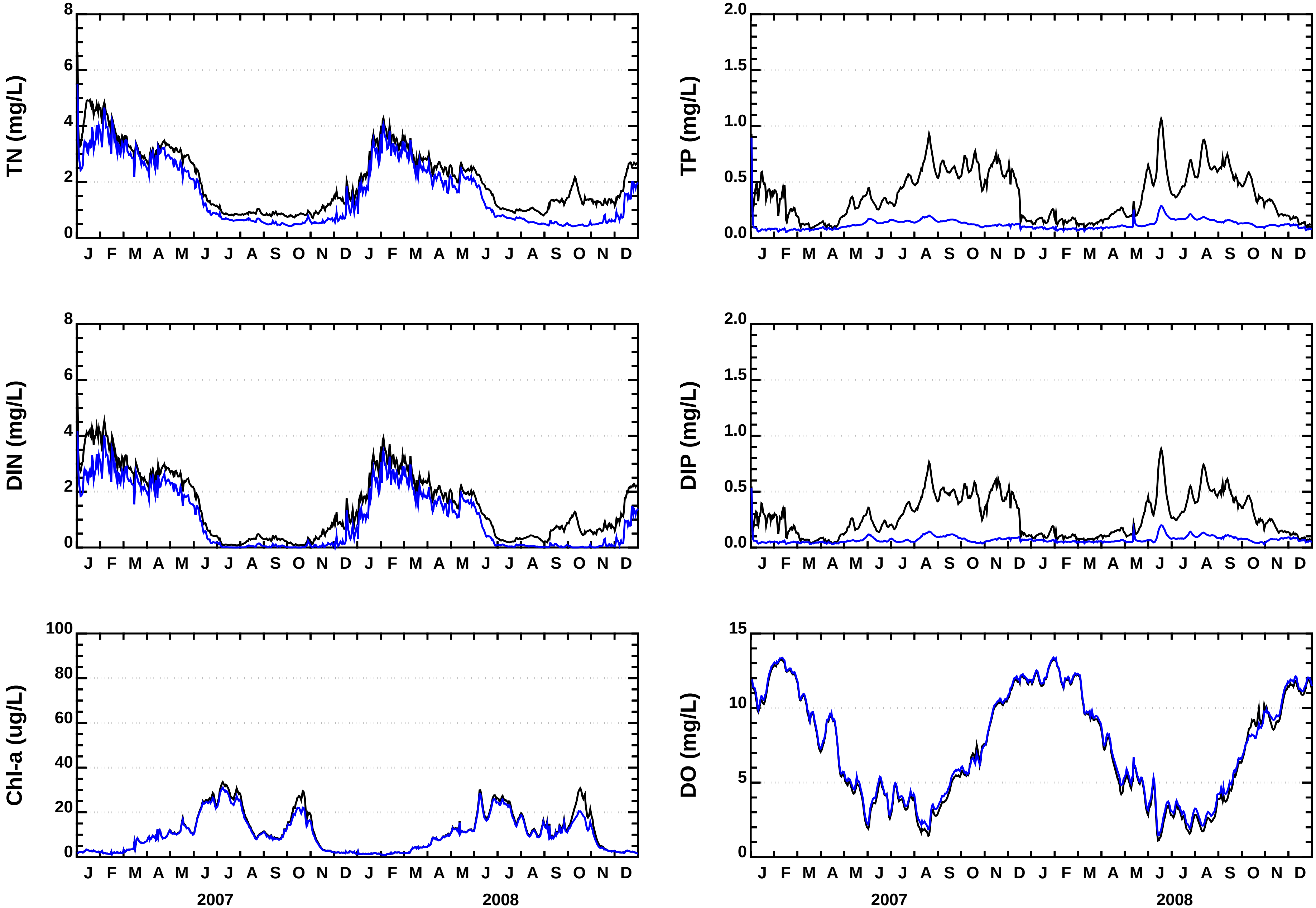


Figure 26. Loading Scenario Results at Kent County Canal (206231)

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

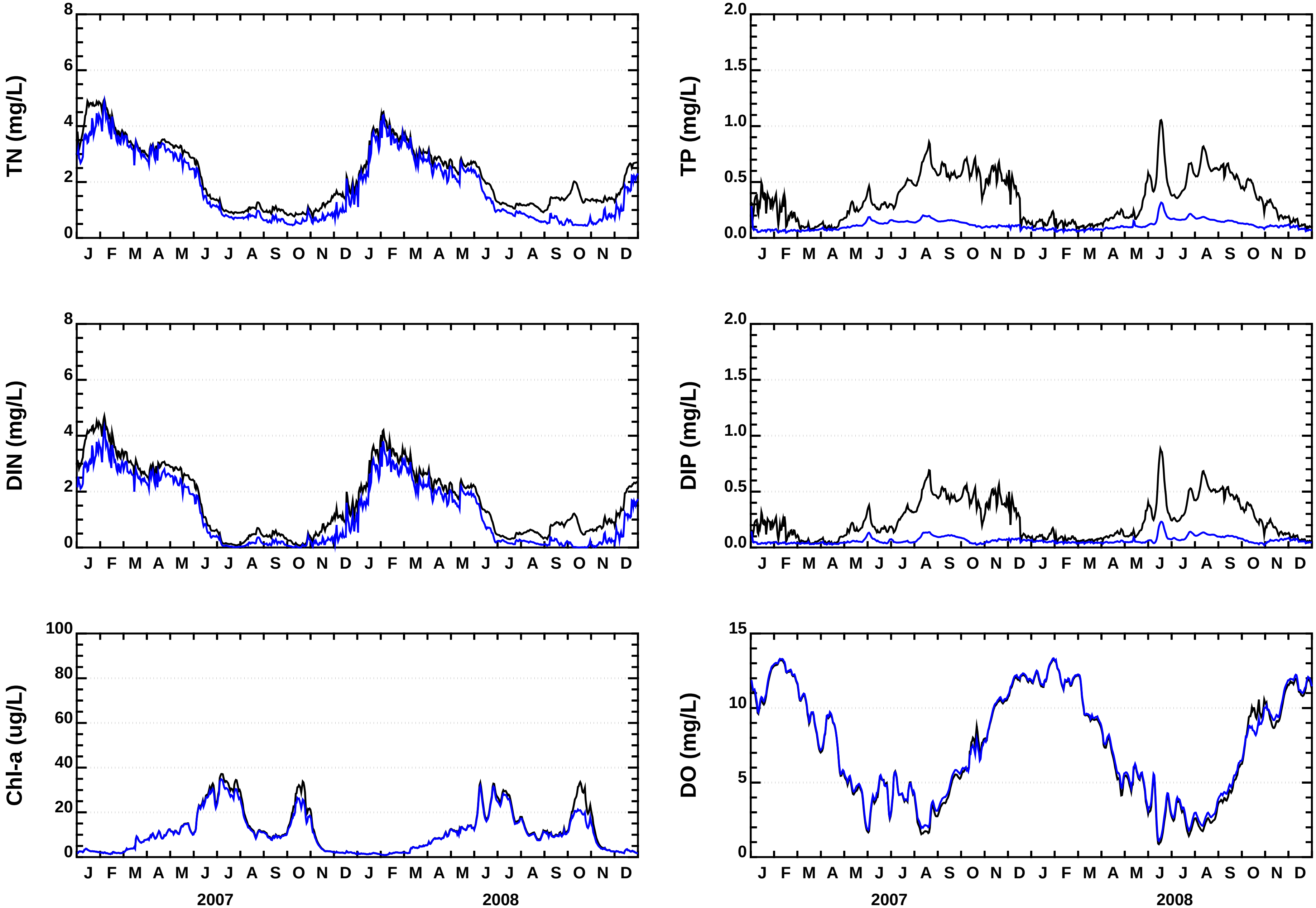


Figure 27. Loading Scenario Results at Bay Road (Frederica) (206091)

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

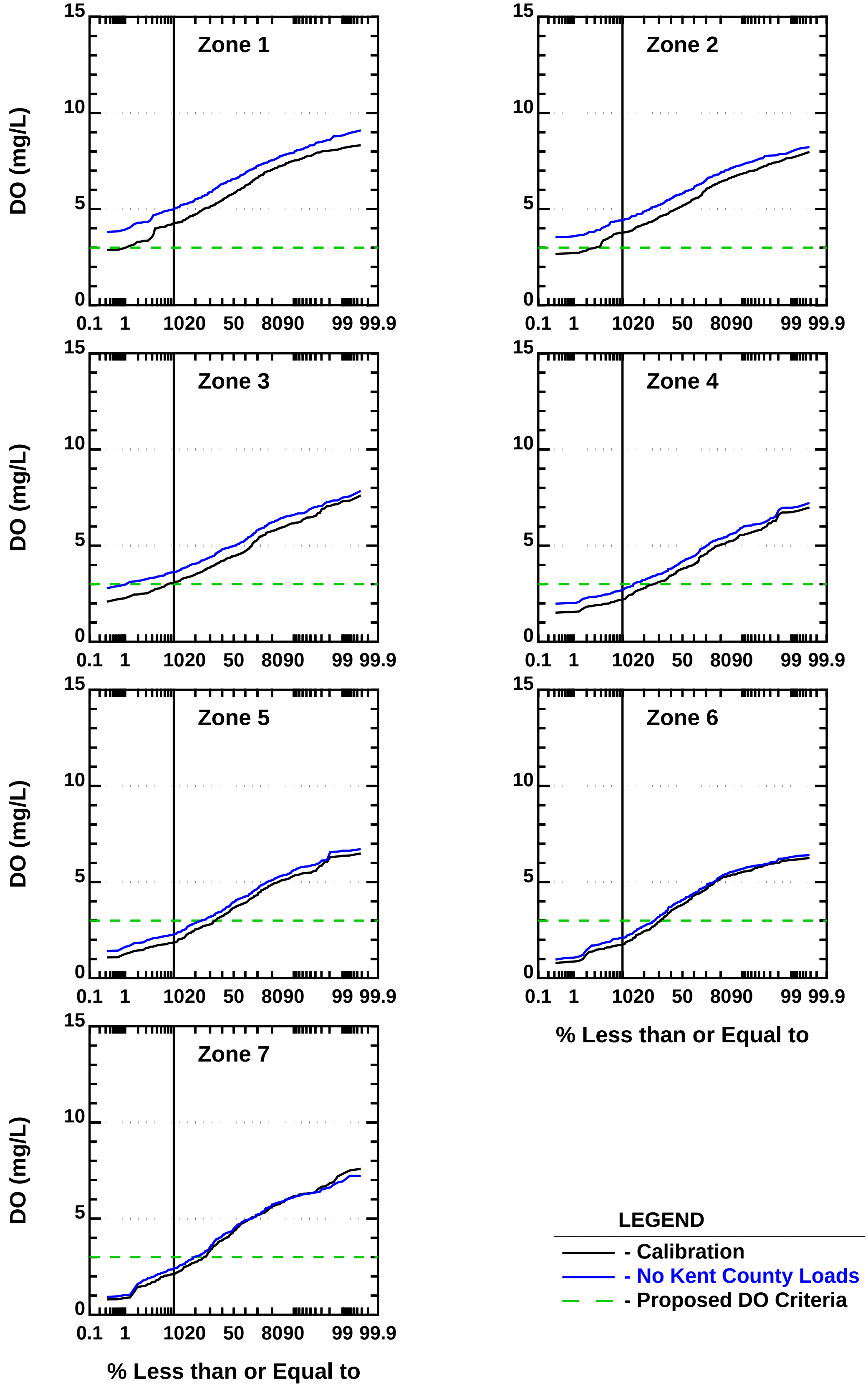


Figure 28. Summer Probability Distributions of Daily Average DO for No Kent County Loads

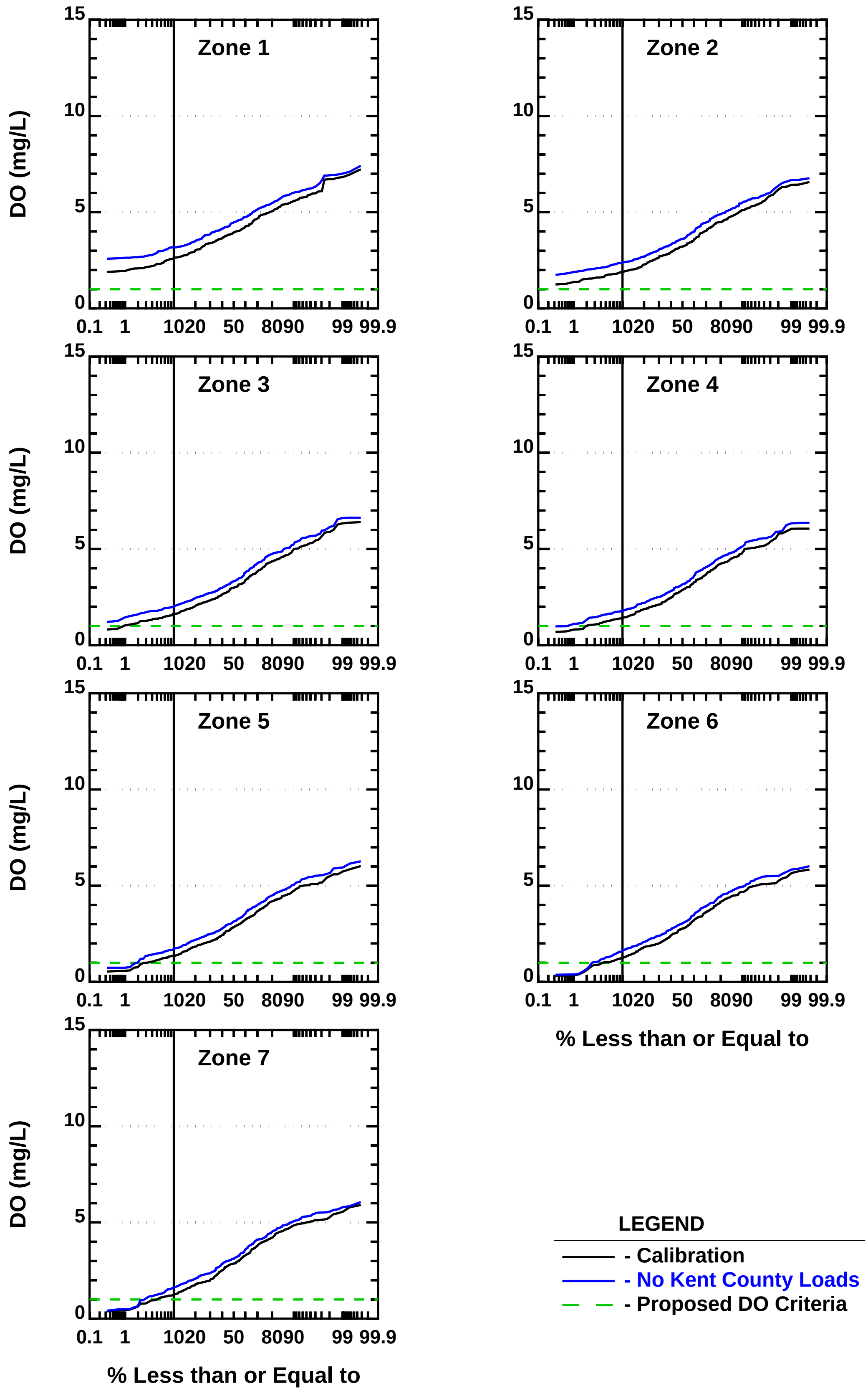


Figure 29. Summer Probability Distributions of Daily Minimum DO for No Kent County Loads

(location of maximum DO decrease). In Zones 4-7, the summer daily average 10th percentile DO levels are less than 3.0 mg/L for both the calibration and no KCRWTF load conditions. The summer daily minimum 10th percentile DO levels are all greater than 1.0 mg/L for both conditions.

3.2 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 30 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 2.

The time-variable marsh loading data presented in Table 2 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 2 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 31 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.

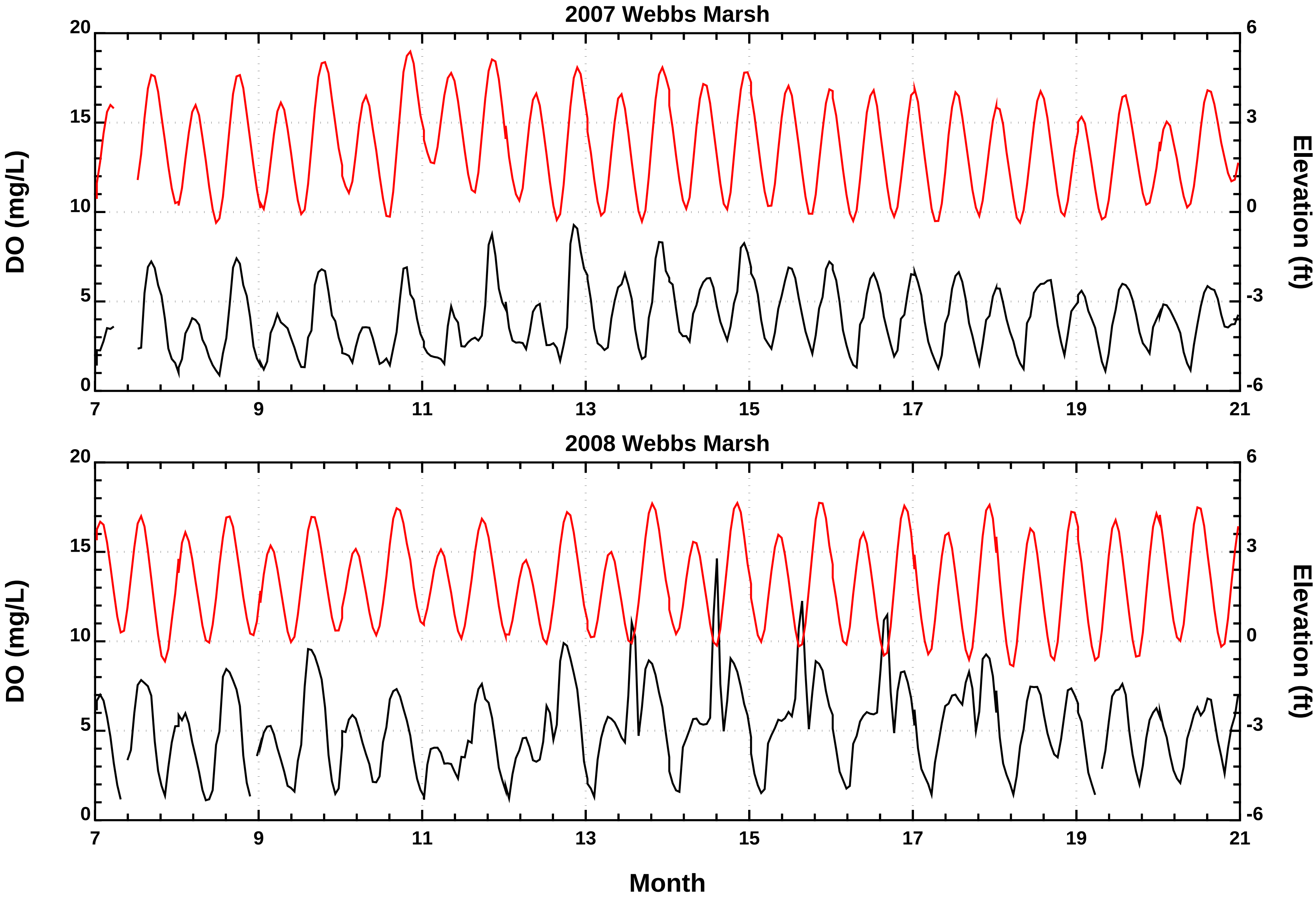


Figure 30. USGS Webbs Marsh Continuous DO Data (2007-2008) - August
(Black - DO, Red - Elevation)

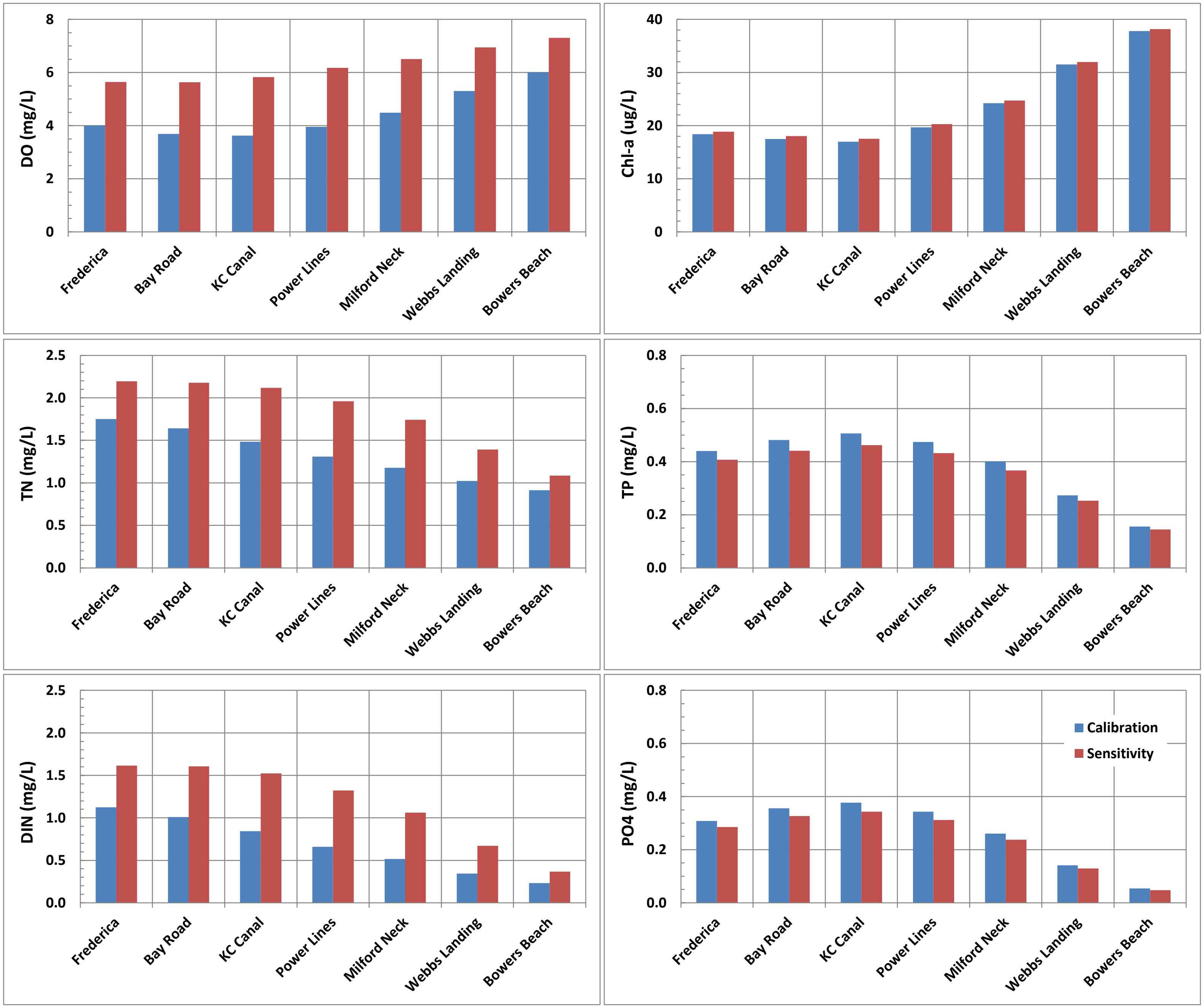


Figure 31. Model Sensitivity Run for No Tidal Marsh Loads (Summer Average Results)

Table 2. 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 32-35) and as summer daily average and daily minimum probability distributions in the seven tidal river zones (Figures 36-37). The time-series figures highlight the spatial variation in the river (i.e., larger impacts in the middle of

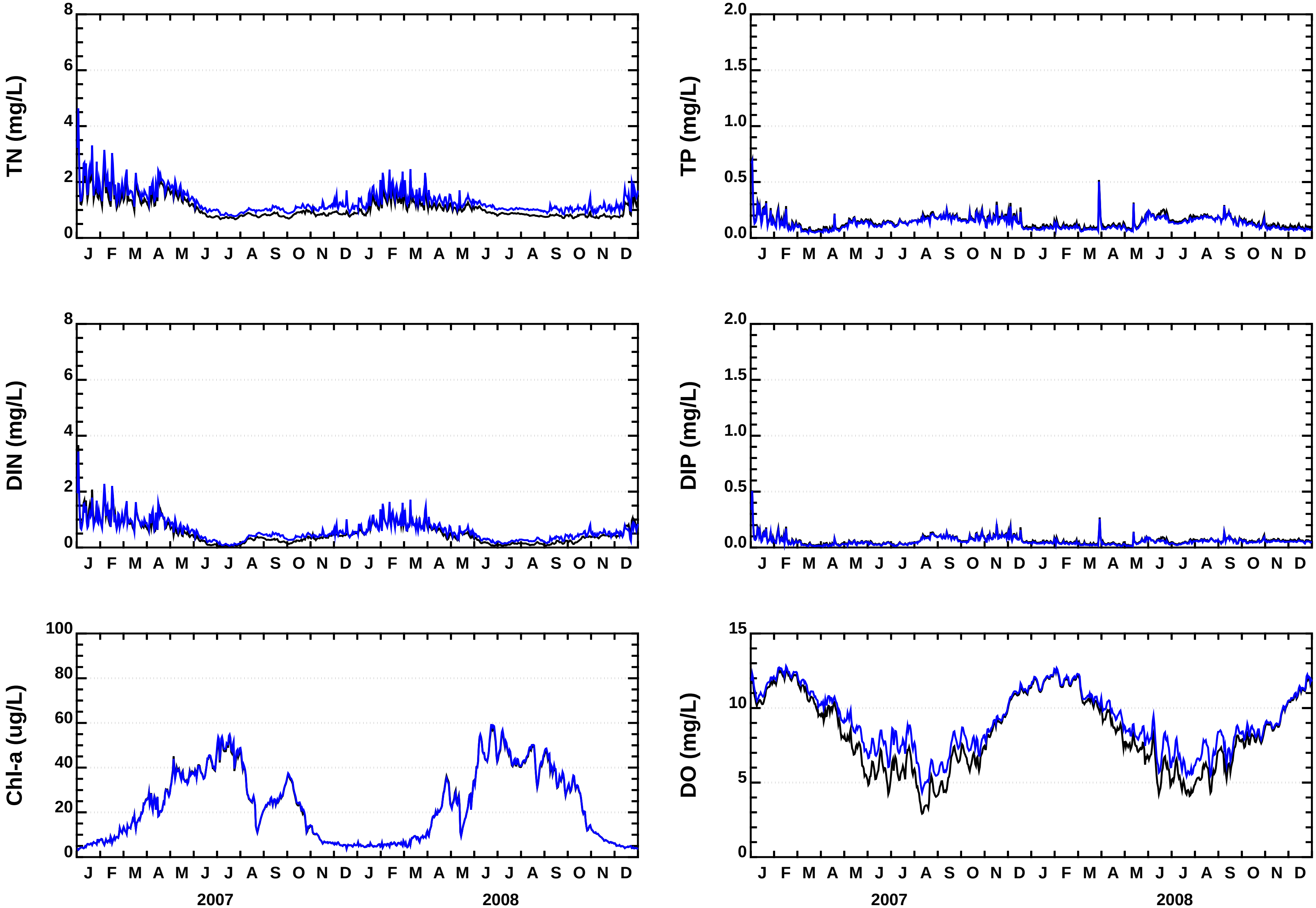


Figure 32. Loading Scenario Results at Bowers Beach (206101)

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

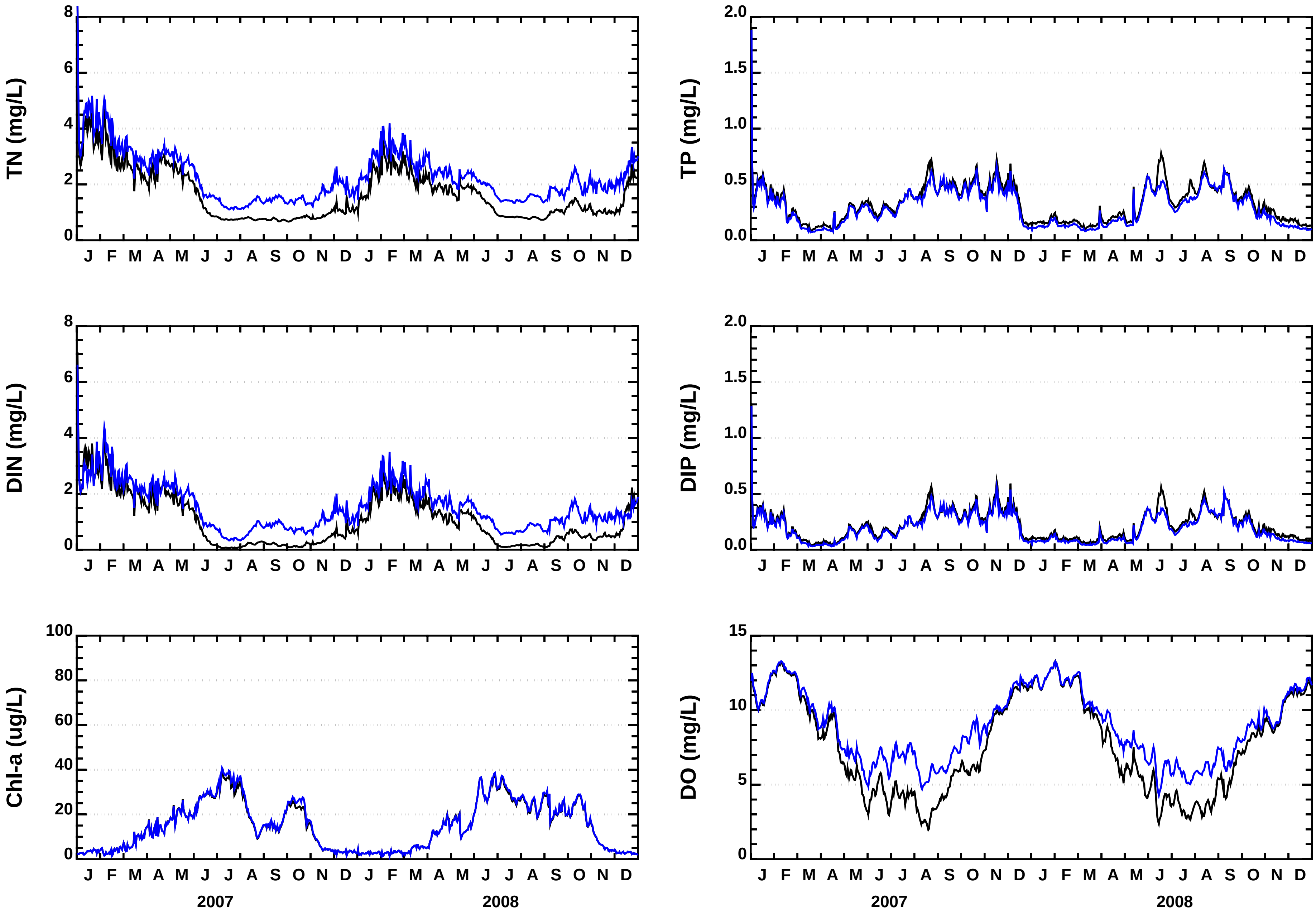


Figure 33. Loading Scenario Results at Milford Neck Wildlife Levee (206141)

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

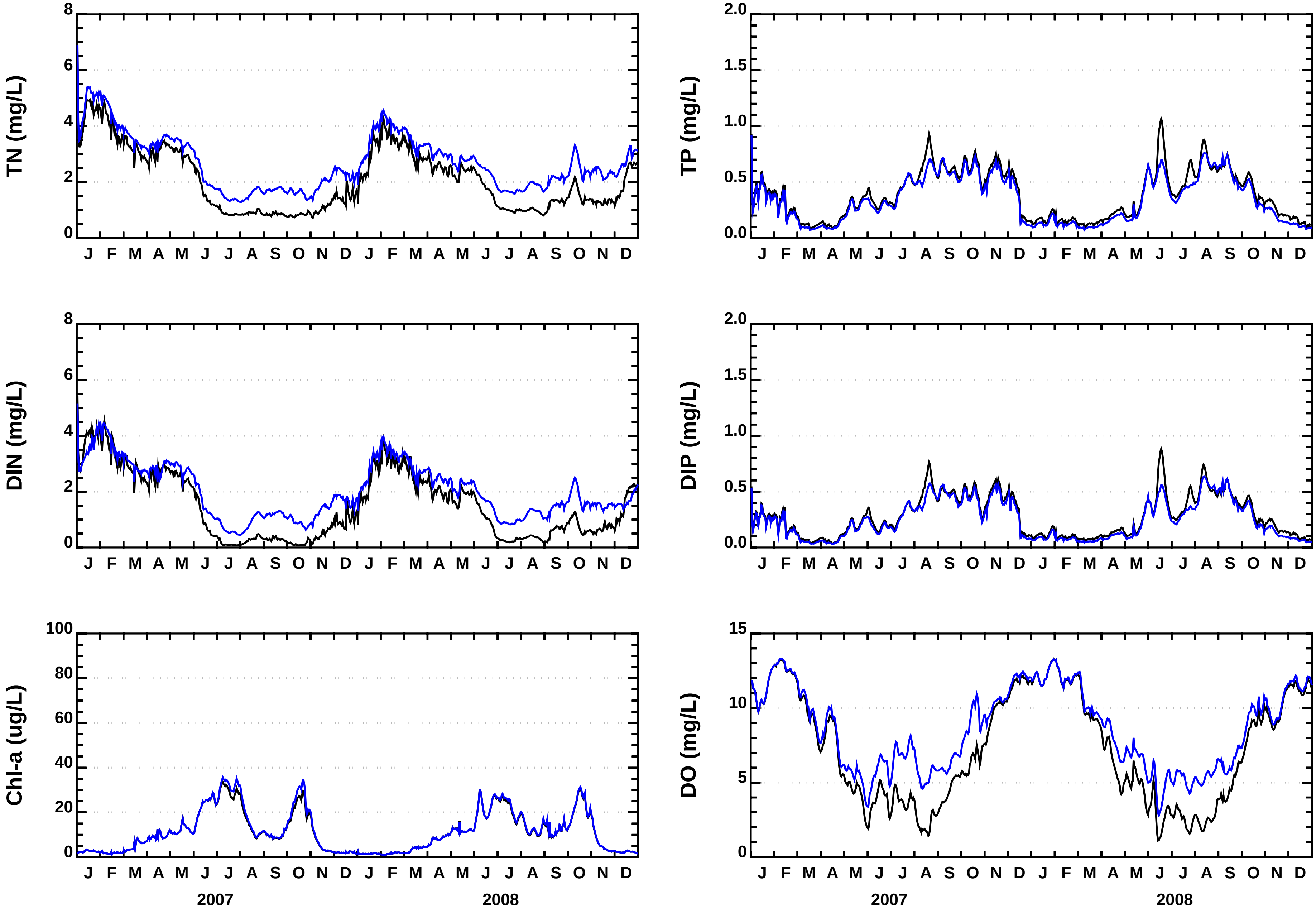


Figure 34. Loading Scenario Results at Kent County Canal (206231)

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

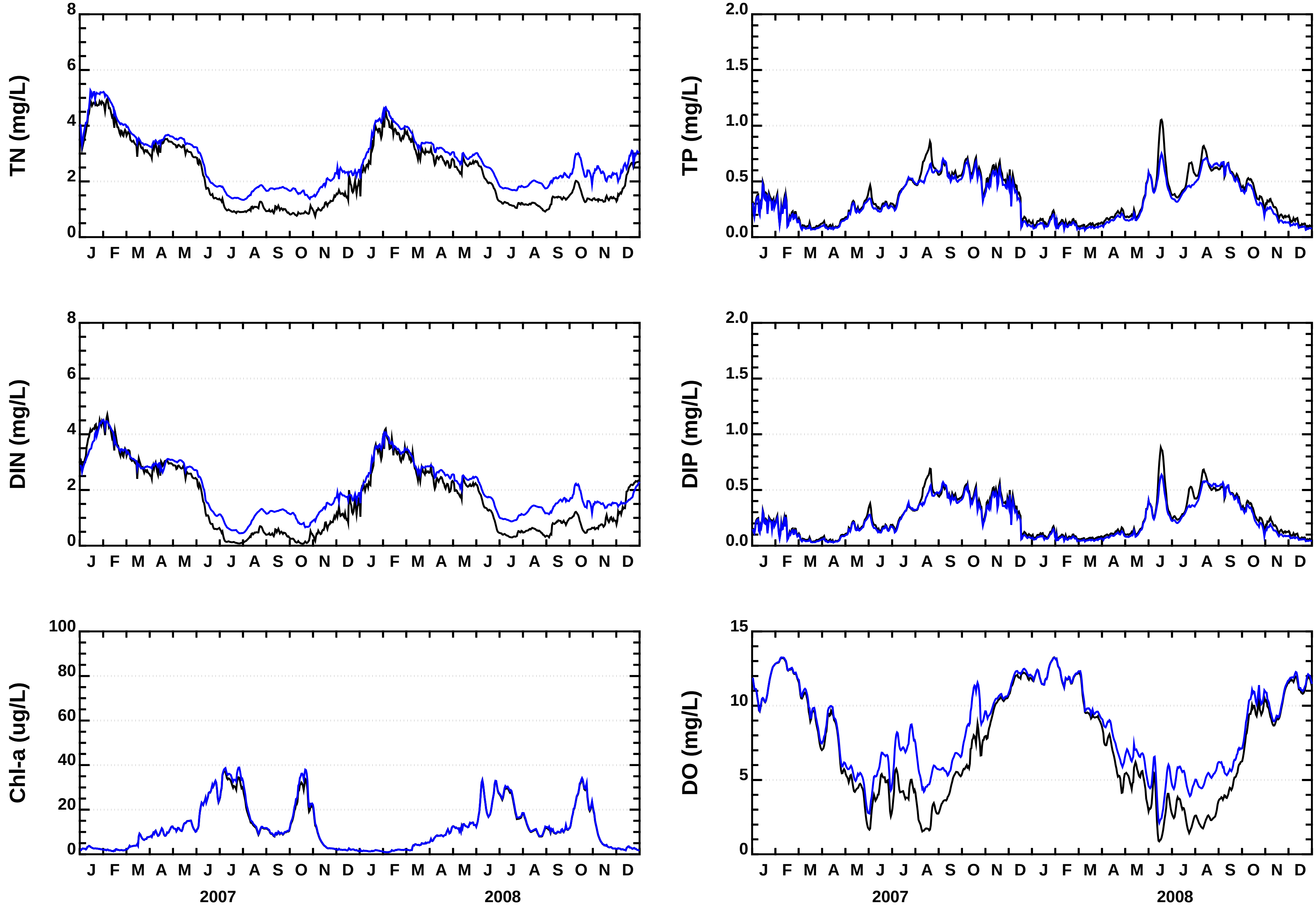


Figure 35. Loading Scenario Results at Bay Road (Frederica) (206091)

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

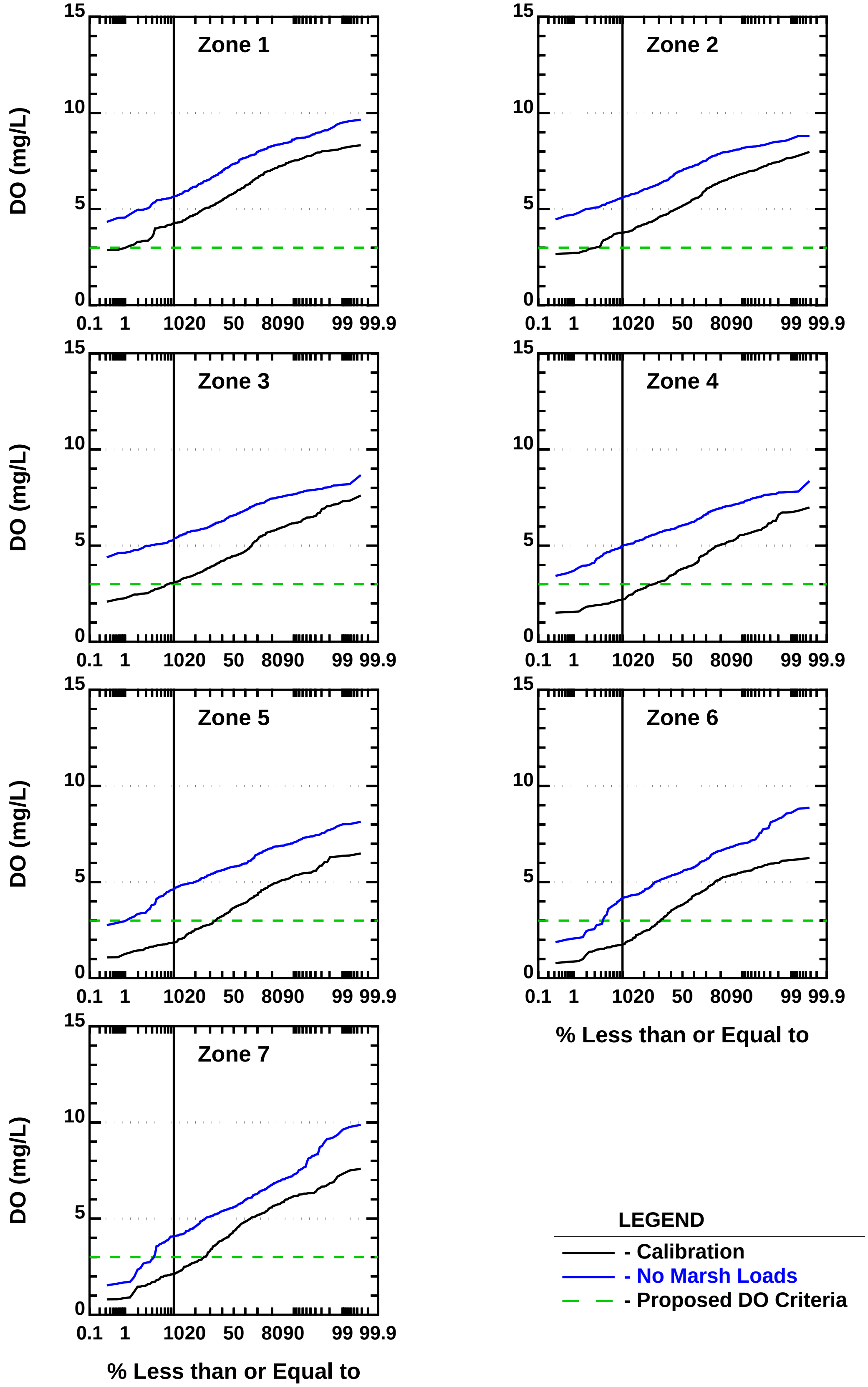


Figure 36. Summer Probability Distributions of Daily Average DO for No Marsh Loads

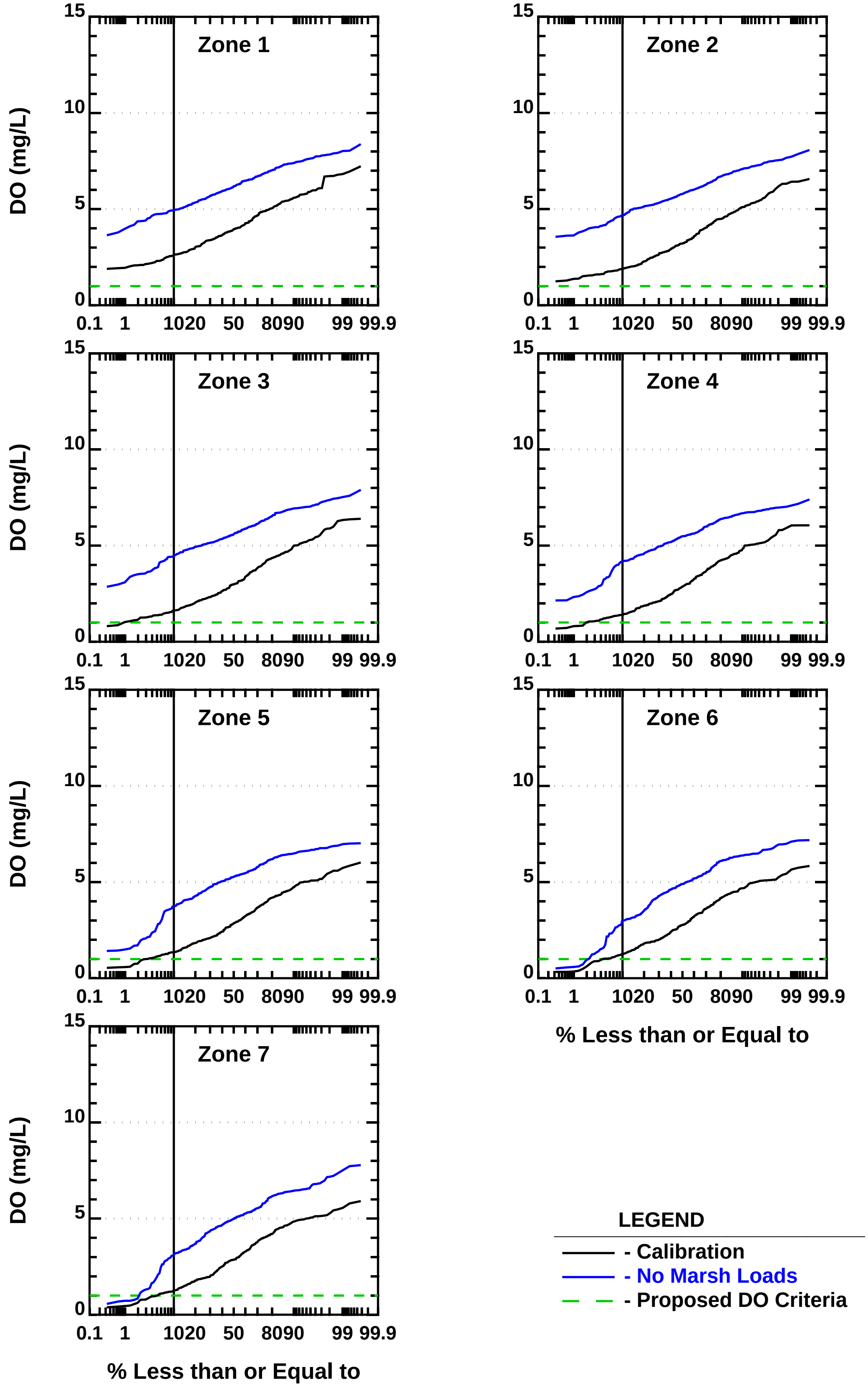


Figure 37. Summer Probability Distributions of Daily Minimum DO for No Marsh Loads

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 36-37 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.

3.3 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 38 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 39-42) and as summer daily average and daily minimum probability distributions in the seven tidal river zones (Figures 43-44). 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 43-44 show that the median DO levels do not increase as much as the 10th 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 10th percentile DO levels are less than 3.0 mg/L for the "natural background" condition with the summer daily minimum 10th 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

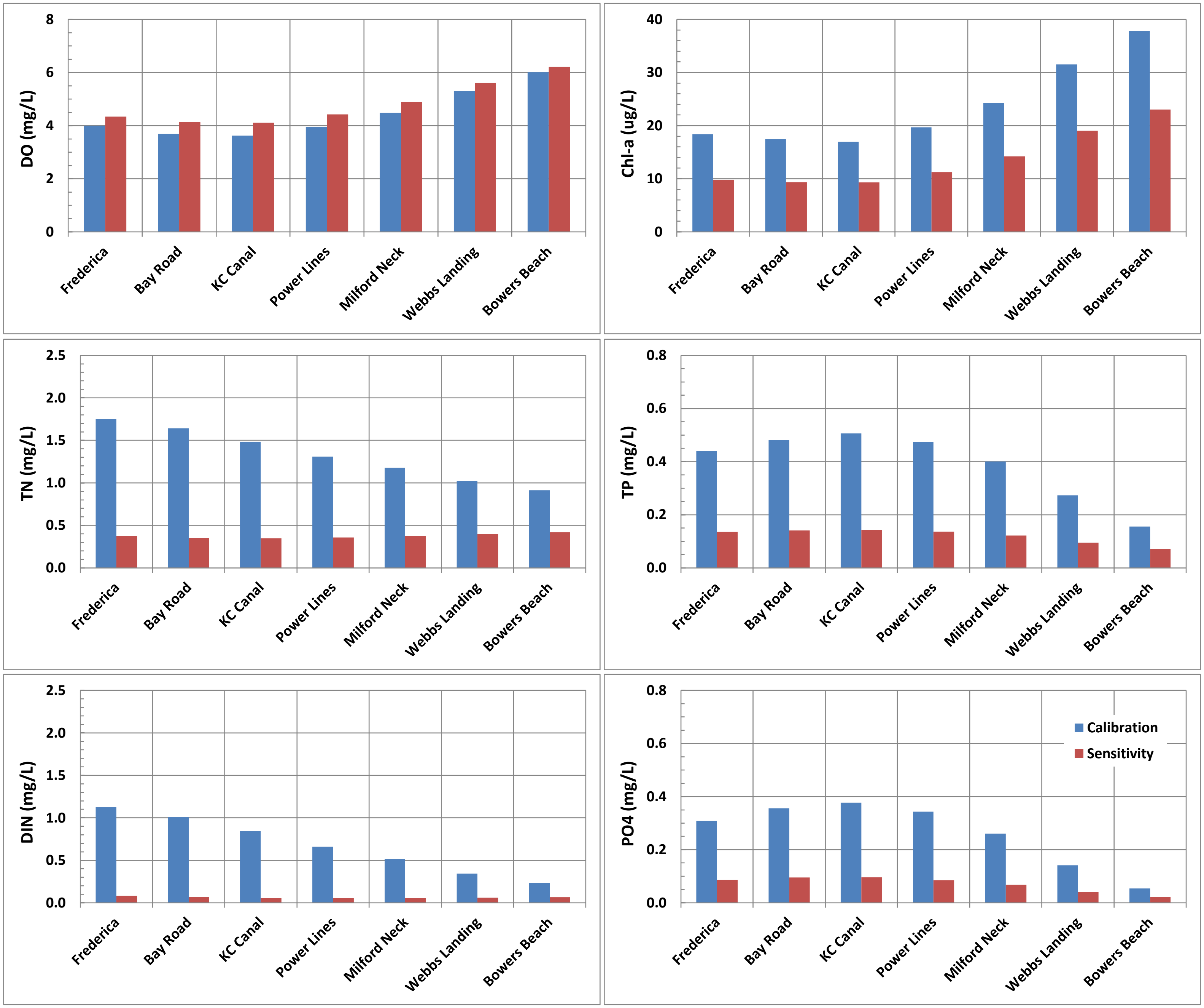


Figure 38. Model Sensitivity Run for "Natural Background" Scenario (Summer Average Results)

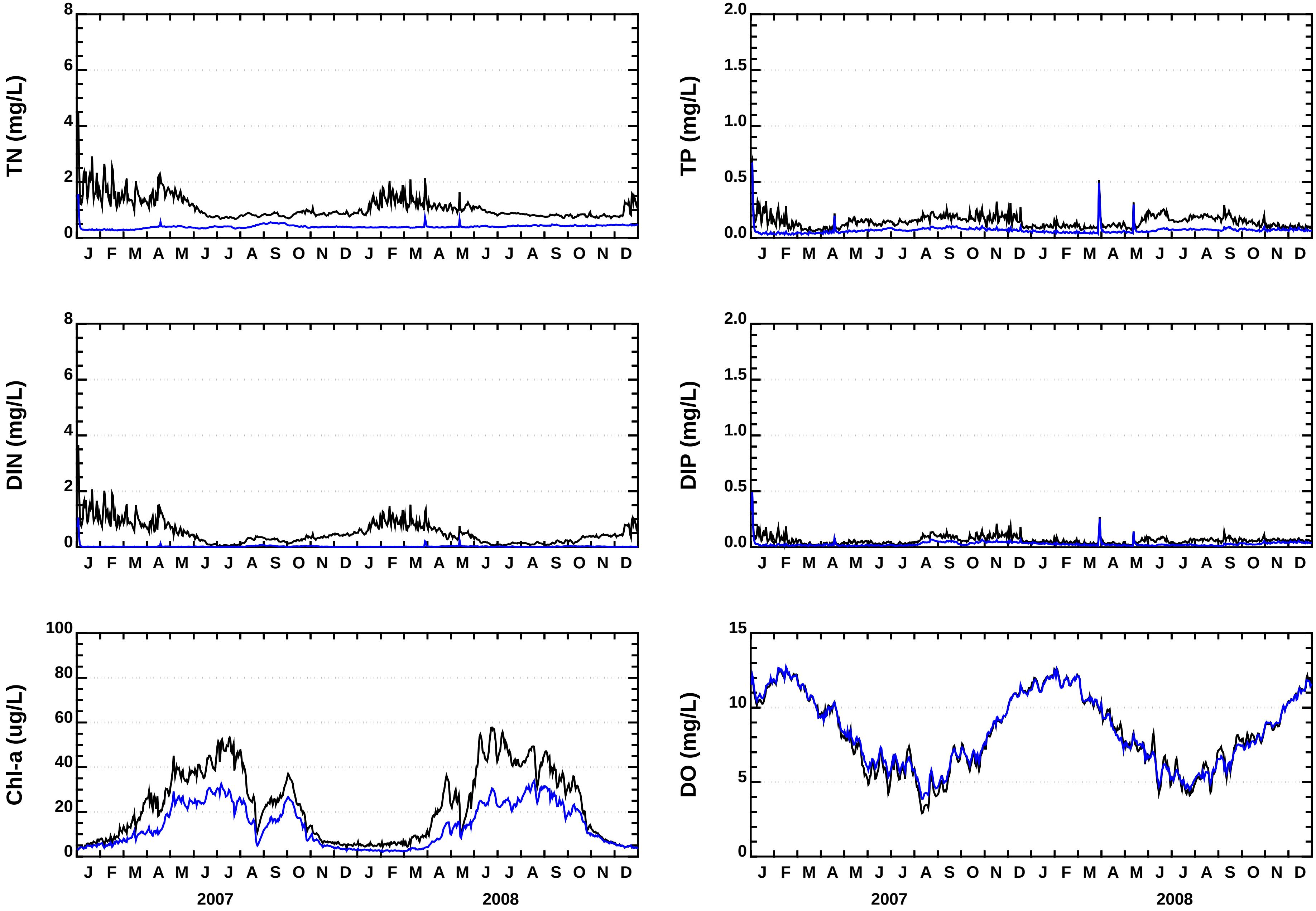


Figure 39. Loading Scenario Results at Bowers Beach (206101)

(Black - Calibration, Blue - Natural Background Condition)

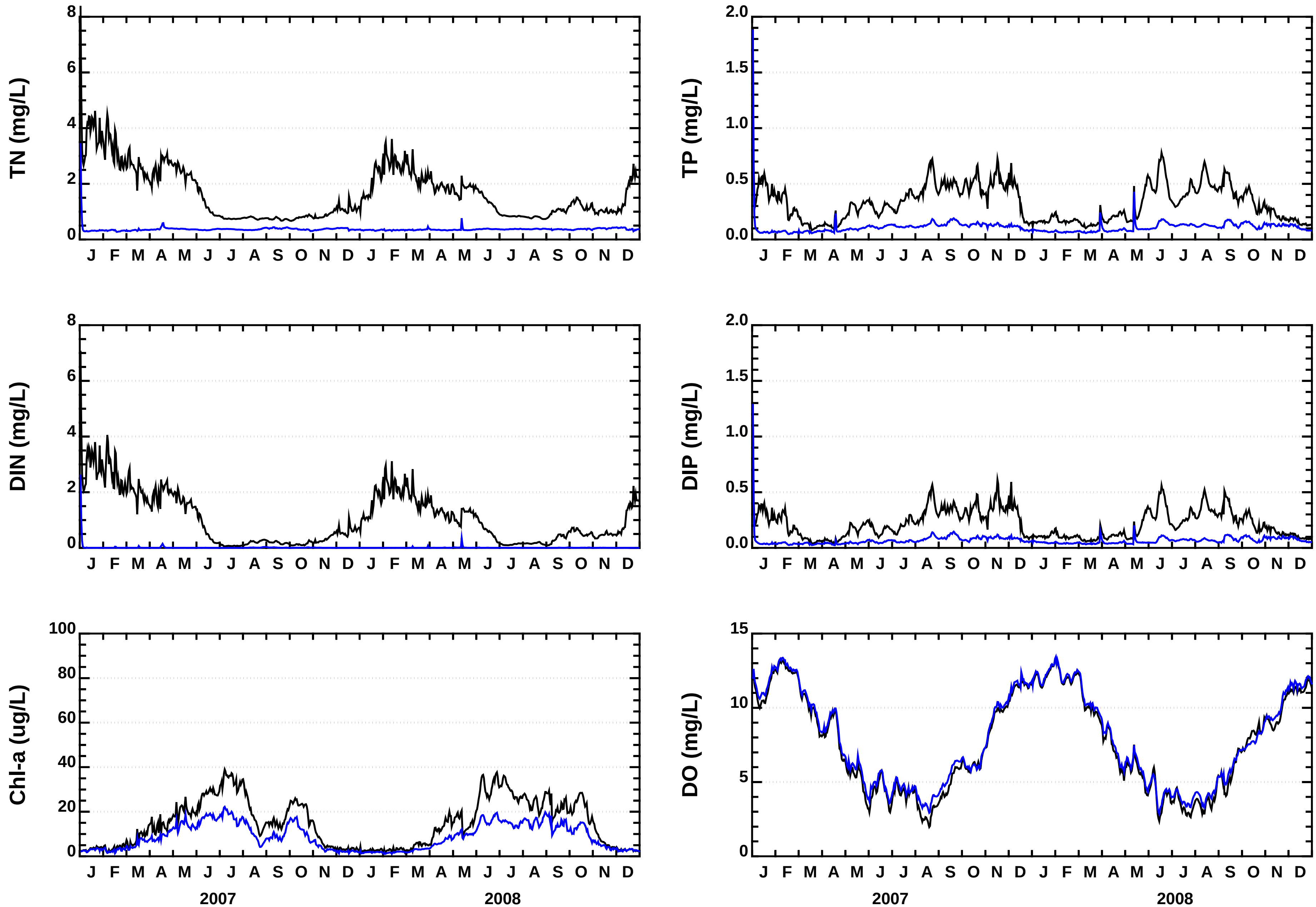


Figure 40. Loading Scenario Results at Milford Neck Wildlife Levee (206141)

(Black - Calibration, Blue - Natural Background Condition)

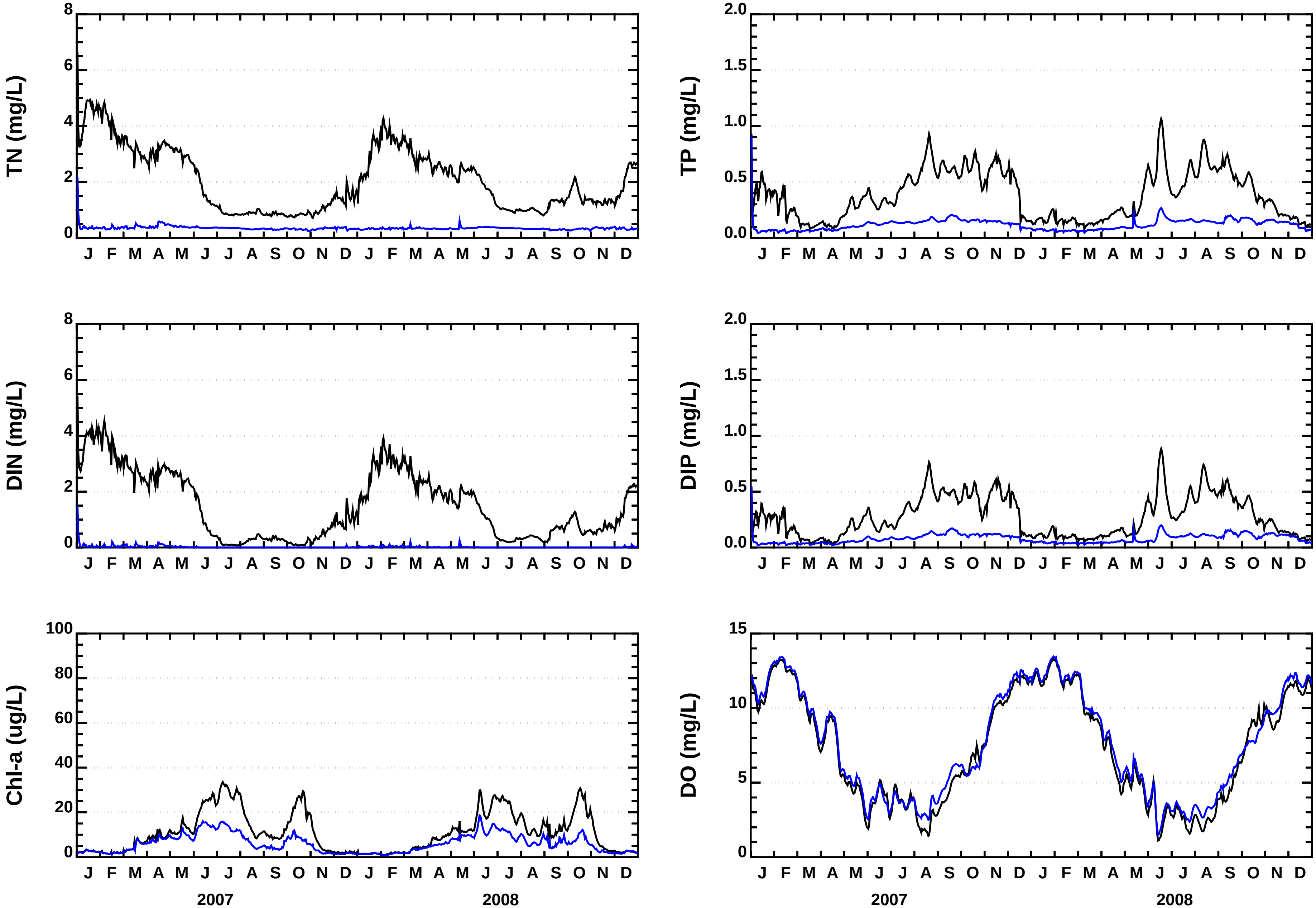


Figure 41. Loading Scenario Results at Kent County Canal (206231)

(Black - Calibration, Blue - Natural Background Condition)

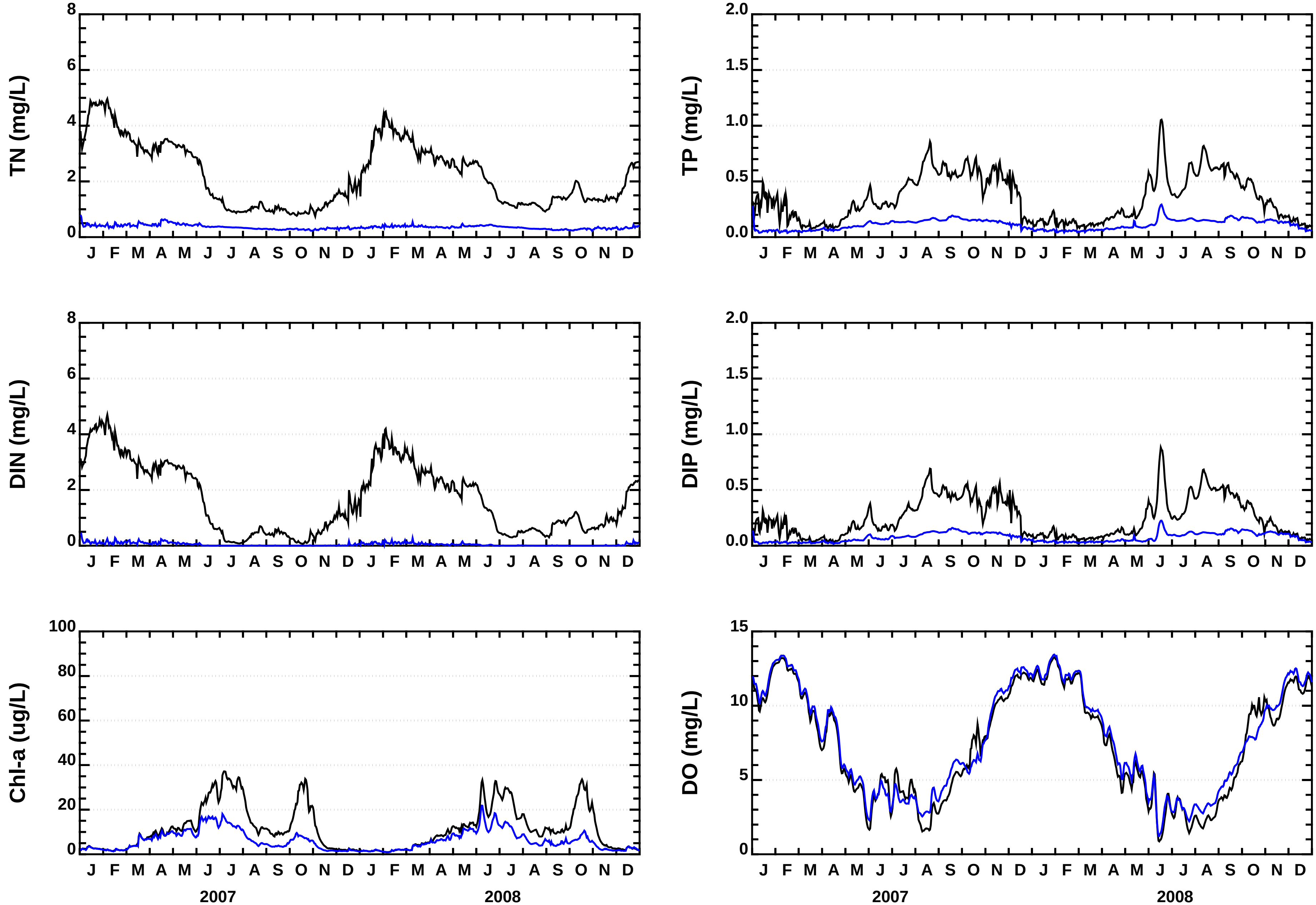


Figure 42. Loading Scenario Results at Bay Road (Frederica) (206091)

(Black - Calibration, Blue - Natural Background Condition)

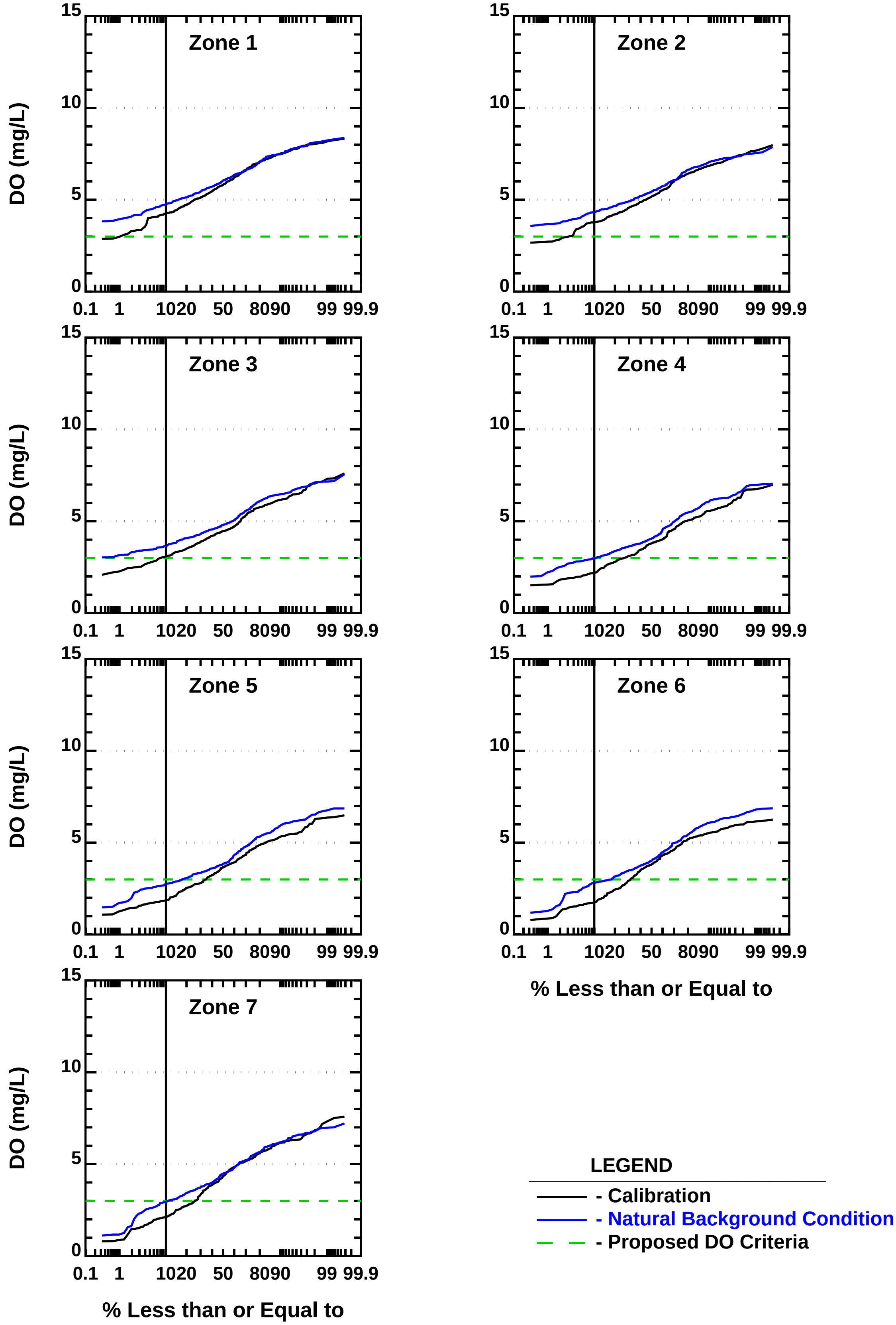


Figure 43. Summer Probability Distributions of Daily Average DO for Natural Background Condition

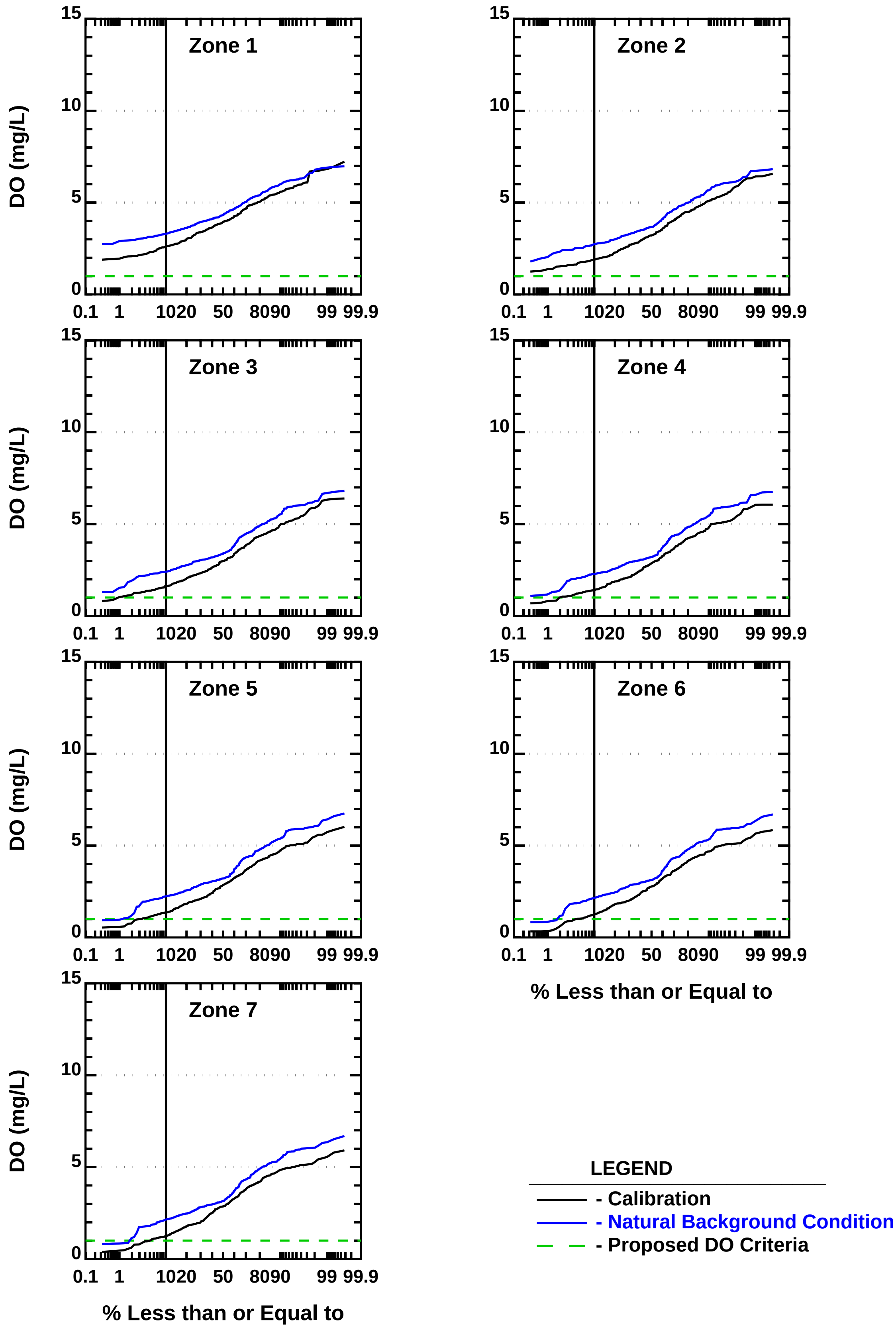


Figure 44. Summer Probability Distributions of Daily Minimum DO for Natural Background Condition

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 3 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 alternative DO criteria for the tidal Murderkill River.

Table 3. 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 4

FISH SURVEYS

In order to determine if the existing low DO levels in the Murderkill River has adversely impacted the fish population and diversity of the River and to ensure that the proposed alternative DO criteria for tidal Murderkill River will not cause any negative impacts on fish populations, the Delaware Division of Fish and Wildlife (DDFW) conducted a biological survey of the fish assemblages in the Murderkill River from July to October 2012 to determine the presence of different fish species in the river (DDFW, 2013). The fish assemblage data collected was used to assess whether a biologically diverse fish population is present under existing conditions in the river that represent summer time low DO levels.

4.1 2012 FISH SURVEY SUMMARY

The Murderkill River and St. Jones River were both sampled so that a comparison of fish assemblages between the two rivers could be completed. As noted above, the St. Jones River has similar summer time low DO levels, watershed land use and hydrologic conditions as the Murderkill River but is absent a direct point source discharge. In this respect, the St. Jones River represents a reference water body that does not include a point source discharge. Sampling in the Murderkill River was focused on the tidal river from Bowers Beach to Frederica with data collected at four stations. Three sampling locations were monitored in the St. Jones River. Figure 45 presents the sampling locations in both rivers. Fish collection was completed using semi-balloon trawls and with a fyke net for a shallow location near the KCDPW discharge canal in the Murderkill River. Salinity, temperature and DO were also measured during the surveys. Six surveys were completed from July to October 2012. During the six surveys, temperature ranged from 20-28°C, salinity ranged from 6-30 ppt, and DO ranged from 2.7-7.7 mg/L in both rivers.

A total of 16 species of finfish and 3 species of invertebrates were recorded in both rivers. Finfish species diversity was slightly higher in the Murderkill River as compared to the St. Jones River and species caught solely in the Murderkill River were Atlantic menhaden, northern kingfish, channel catfish and white catfish. Five species constituted over 74% of the total finfish catch and included: hogchoker; white perch; Atlantic croaker; spot; and blue crab. The species collected during the 2012 surveys were also compared to historical data collected in 1986. A summary of the fish species caught and percent of total catch is presented in Table 4. Prior studies have shown that most species managed under fishery management plan inhabit tidal tributaries and that tidal tributaries are important nursery areas for these species. The size distribution of the fish species collected indicated the presence of young of the year and juveniles for several managed species in both rivers. In addition, fish species collected near the KCDPW discharge canal were similar in composition and numbers to other sites in the Murderkill and St. Jones River.

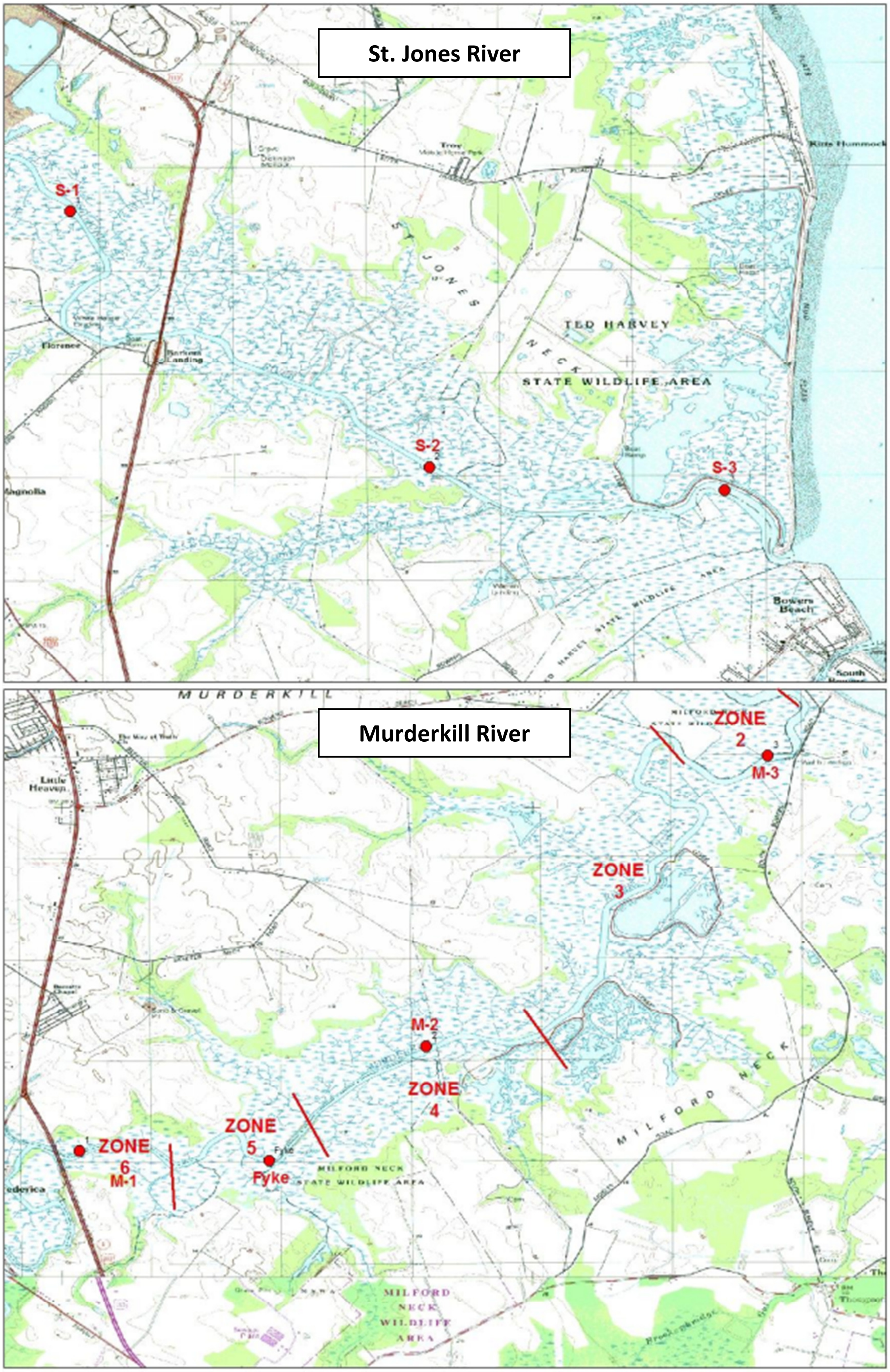


Figure 45. Fish Sampling Locations in the St. Jones and Murderkill Rivers

Table 4. Summary of Fish Surveys

Species	Percentage	Species	Percentage
Murderkill (2012)		**Murderkill (1986)**	
Hogchoker	45	White perch	49
Atlantic croaker	13	Hogchoker	11
White perch	7	White catfish	11
Spot	6	Mummichog	6
Weakfish	5	Atlantic menhaden	4
St. Jones (2012)		**St. Jones (1986)**	
White perch	32	Atlantic silverside	50
Spot	16	White perch	14
Hogchoker	11	Spot	10
Atlantic croaker	9	Hogchoker	7
Weakfish	6	Striped cusk eel	5

Based on the similar species collected in both the Murderkill and St. Jones River in 2012, and similar comparisons to the species collected in 1986, it is concluded that the fish population in the Murderkill River represents a typical population and diversity of fish species for a tidal tributary system that is used as a nursery area along Delaware Bay.

In addition, for similar juvenile fishes as those found in the Murderkill River, Tyler and Targett (2007) observed repeatedly that under various environmental conditions finfish were very scarce to absent where the DO concentration was below 2.0 mg/L and returned within minutes to hours of the time that the concentration rose above 2.0 mg/L. These observations indicated that the fish avoided concentrations less than 2.0 mg/L and the authors also referenced multiple studies that reported a similar, very temporally dynamic response among fishes.

Considering the results of this survey, it is concluded that the existing low DO levels in the Murderkill River, which are primarily caused by the extensive tidal marshes surrounding the river, has not caused any measurable negative impact on the river's fish diversity and population as compared to other tidal rivers in the area. Furthermore, it is concluded that the proposed alternative DO criteria for the Murderkill River will not cause any adverse impact on the river's fish population and diversity.

SECTION 5

PROPOSED DESIGNATED USE SUB-CATEGORY AND ALTERNATIVE DO CRITERIA

Section 3 presented model sensitivity results for three scenarios including no discharge from the KCRWTF, no tidal marsh load, and the "natural background" water quality condition. The modeling scenarios were completed to help develop a sub-category of the aquatic life designated use and alternative DO criteria for the tidal Murderkill River that accounted for natural processes controlling water quality and considering the dominant factors controlling DO levels in the river. As noted above, federal regulations at 40 CFR 131.10(g) allow states to establish sub-categories of a use if it can be demonstrated that attaining the designated use is not feasible because of one or more of the six factors from 40 CFR 131.10(g).

As the results from the modeling scenarios in Section 3 showed, the extensive tidal marshes surrounding the Murderkill River result in summer average DO levels that are naturally low and are about 3.8 mg/L, especially in the middle of the river (Frederica to the Power Lines). In addition, results from the model scenarios showed that the impact of anthropogenic point and nonpoint sources on river DO levels is minimal. For example, under the "natural background" scenario when all anthropogenic sources are removed from the watershed, DO levels in the middle of the river are not significantly greater and are about 4.2 mg/L. In contrast, when the tidal marsh load is removed from the model, summer average DO concentrations in the middle of the river are about 5.8 mg/L (an increase of about 2.0 mg/L) and summer average DO values were above 5.0 mg/L in all zones of the river.

Considering the above, it is concluded that the extensive tidal marshes surrounding the river cause DO levels in the river during summer months to decrease by about 2.0 mg/L and are the dominant factor controlling DO levels in the tidal Murderkill River. This is consistent with the factor at 40 CFR 131.10(g)(1) that "naturally occurring pollutant concentrations prevent the attainment of the use" and in addition, to a lesser extent the factor described at 40 CFR 131.10(g)(4): "…hydrologic modifications preclude the attainment of the use, and it is not feasible to restore the water body to its original condition…in a way that would result in the attainment of the use". Therefore, the following aquatic life use sub-category and alternative DO criteria for the tidal Murderkill River are proposed.

5.1 PROPOSED AQUATIC LIFE USE SUB-CATEGORY

Based on aquatic life surveys (described in Section 4 of this document), it is concluded that the fish population in the Murderkill River represents a typical population and diversity of fish species for a tidal tributary system that is used as a nursery area along Delaware Bay.

In addition, for similar juvenile fishes as those found in the Murderkill River, Tyler and Targett (2007) observed repeatedly that under various environmental conditions finfish were very scarce to absent where the DO concentration was below 2.0 mg/L and returned within minutes to hours of the time that the concentration rose above 2.0 mg/L. These observations indicated that the fish avoided concentrations less than 2.0 mg/L and the authors also referenced multiple studies that reported a similar, temporally dynamic response among fishes.

Considering the results of this survey, it is concluded that the existing naturally-occurring low DO levels in the Murderkill River, which are primarily caused by the extensive tidal marshes surrounding the river, have not caused any measurable negative impact on the river's fish diversity and population as compared to other tidal rivers in the area. Furthermore, it is concluded that the proposed alternative DO criteria for the Murderkill River will not cause any adverse impact on the river's fish population and diversity. Therefore, the tidal Murderkill River can be considered to support a sub-category of Delaware's "Fish, Aquatic Life and Wildlife" designated use (defined as "all animal and plant life found in Delaware, either indigenous or migratory, regardless of life stage or economic importance") in that it shall support all animal and plant life expected to be found in rivers influenced by tidal marshes in Delaware, either indigenous or migratory, regardless of life stage or economic importance.

In light of these conclusions, the proposed aquatic life use sub-category is "Tidal Marsh Influenced Aquatic Life" based on a 40 CFR 131.10(g)(1) and 40 CFR 131.10(g)(4) demonstration.

5.2 PROPOSED ALTERNATIVE DO CRITERIA

Based on the model scenario assessments discussed in Section 3 and the conclusion that the tidal marshes cause summer average DO concentrations in critical zones of the river to decrease by about 2.0 mg/L, the following alternative DO criteria are proposed for the tidal Murderkill River:

- 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 apply during winter months (daily average of 5.0 mg/L and daily minimum of 4.0 mg/L).

In order to interpret the model results for the various loading scenarios presented in Section 3, the 10^{th} percentile DO results by river zone are compared to the proposed alternative DO criteria for the summer and winter periods. 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 alternative DO criteria 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.

Use of the 10th percentile model results was also 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, 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, the proposed alternative DO criteria are based on the 10th percentile model results.

In addition to the 2 mg/L DO deficit attributable to the tidal marsh impacts described above, the model results presented in Table 3 show that under the modeled "natural background" scenario that the 10th percentile daily average DO concentrations are approximately 3 mg/L in zones 4 through 7 of the river. These model results provide additional support for the alternative daily average DO criterion. The daily minimum (1-hour average) DO criterion is supported by EPA's Virginian Province Saltwater Dissolved Oxygen Criteria document (EPA, 2000). This document includes a limit for episodic and cyclic exposure (less than 24-hour duration of low DO conditions) based on the hourly duration of exposure curve ($DO = 0.370 \times \ln(t) + 1.095$; where: DO is the allowable concentration (mg/L) and t is the exposure duration in hours). For a one hour exposure period, the resulting allowable DO concentration is 1.095 mg/L, or approximately 1 mg/L. The daily minimum (1-hour average) DO criterion is further supported by continuous DO monitoring data from the nearby St. Jones River (Figure 47) where DO levels fall below 1.0 mg/L in the summer. The St. Jones River also has tidal marshes but does not have a point source discharge, and thus offers a comparison to supplement the modeling scenarios.

The summer "warm" period is defined as May 16 through September 30 and the winter "cool" period as October 1 through May 15. The spring transition from winter "cool" to summer "warm" conditions (May 16) 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. Continuous DO monitoring data from the Frederica gage on the tidal Murderkill River (Figure 46) and from the Scotton Landing gage in the nearby similar St. Jones River (Figure 47) clearly show that DO conditions related to the expression of the alternative DO criteria change in mid-May as opposed to late May or early June. It should be noted that these alternative DO criteria do not apply to the upstream freshwater reaches of the watershed (i.e., tidal reach only). Figure 48 presents the tidal reach of the Murderkill River where the alternative DO criteria will apply.

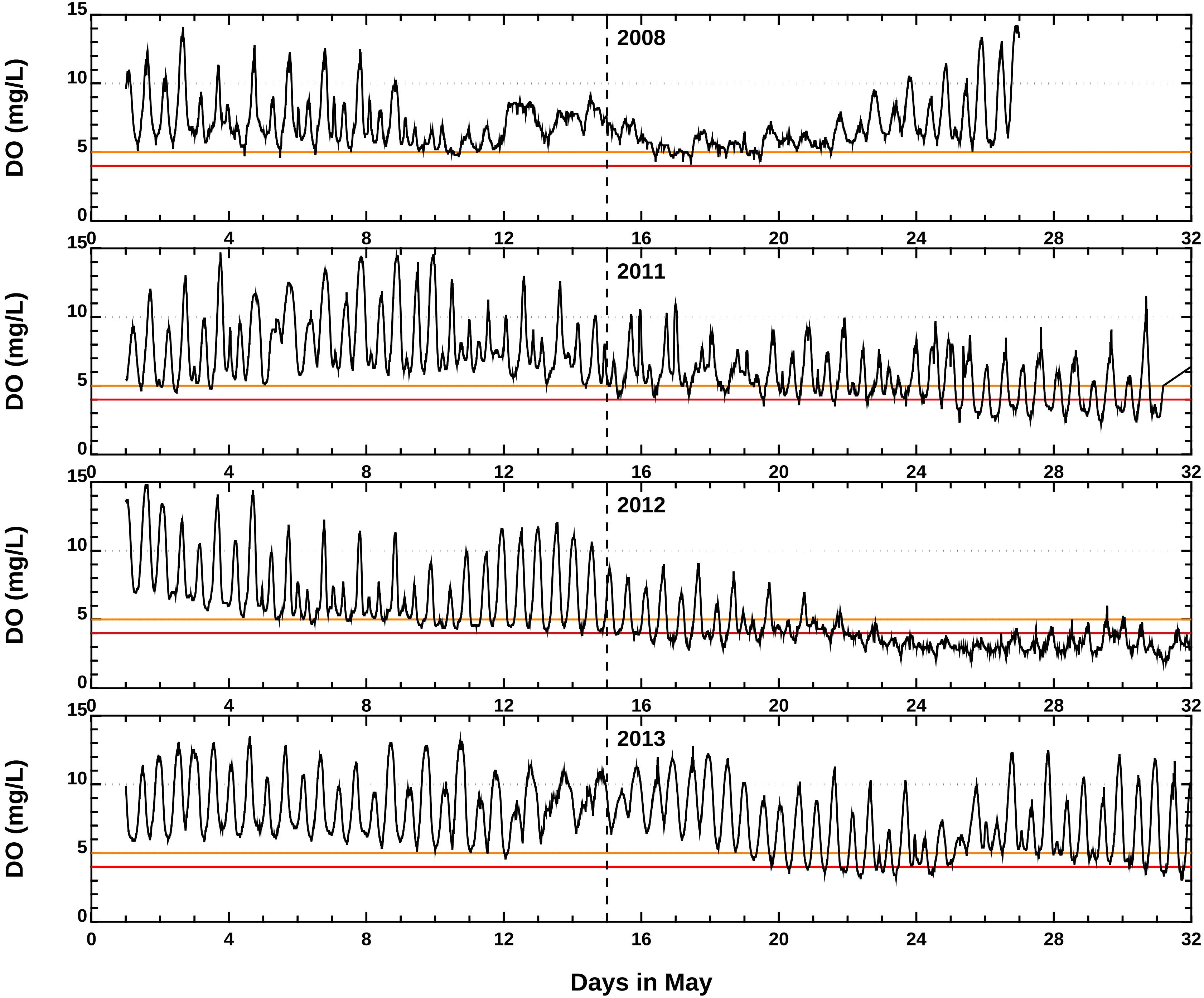


Figure 46. Murderkill River Continuous DO at Frederica

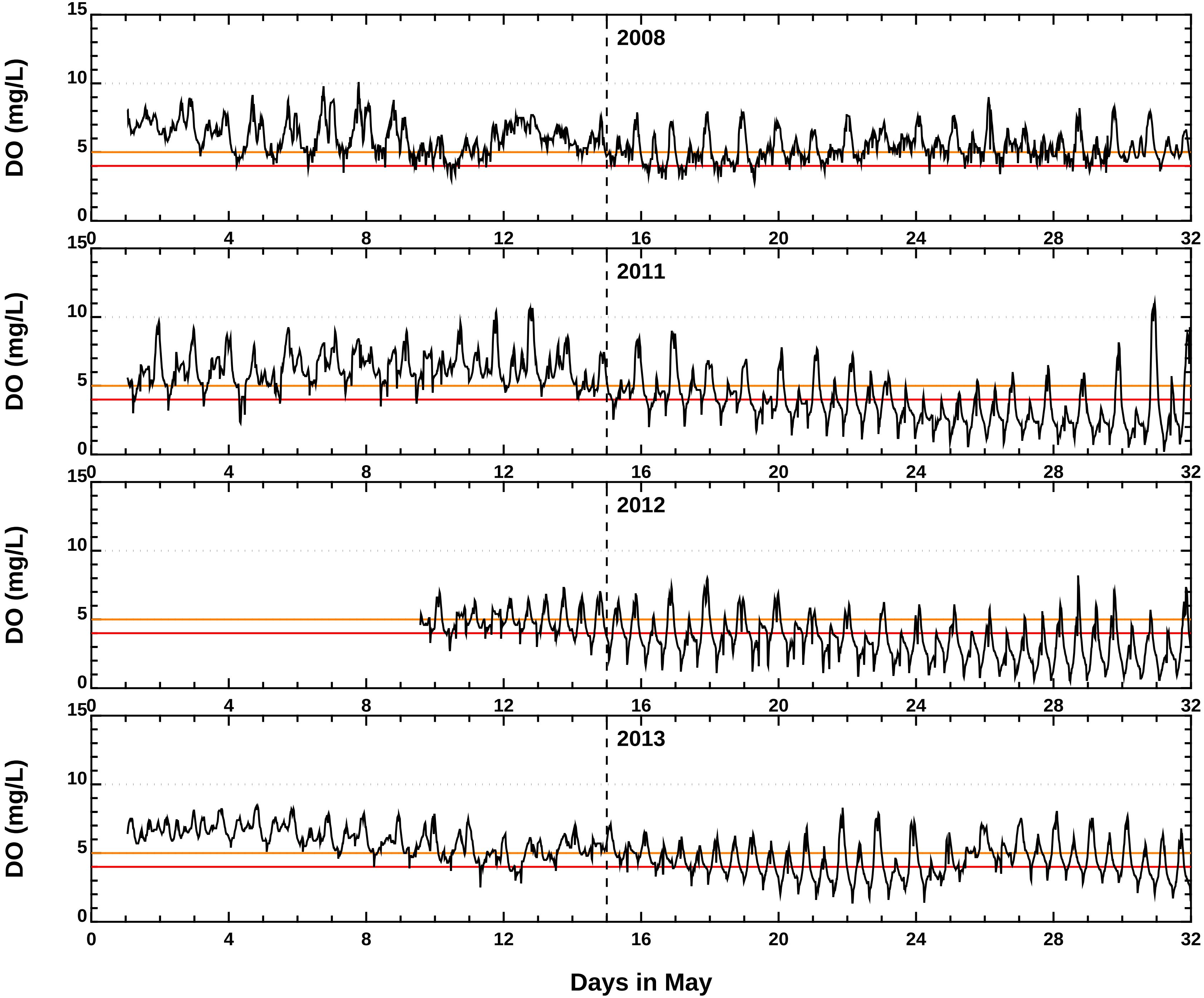


Figure 47. St. Jones River Continuous DO at Scotton Landing

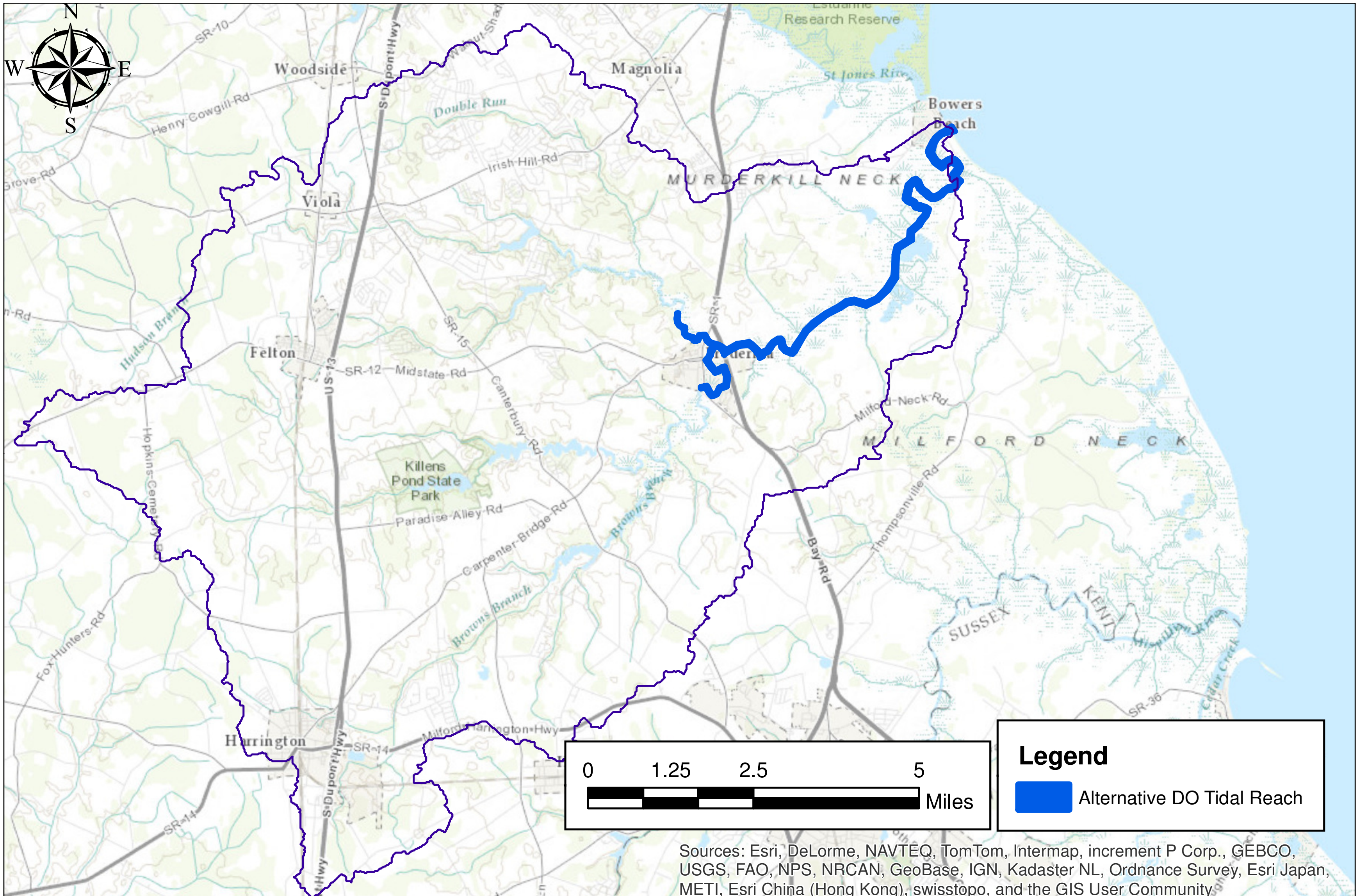


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Figure 48. Murderkill River Tidal Reaches where Alternative DO Criteria Apply

SECTION 6

PROPOSED REGULATIONS

The proposed DNREC regulations for the aquatic life use sub-category and alternative DO criteria in the tidal Murderkill River are presented below. These proposed regulations were developed by DNREC and included extensive discussion and review of the models developed and studies completed by the Murderkill River Workgroup and Water Quality Standards committee. Members of the workgroup and committee included DNREC and EPA regulatory staff, KCDPW, academic institutions and private consultants. Consensus was obtained in the use of the models and in the development of the proposed alternative DO criteria for the tidal Murderkill River.

6.1 PROPOSED DNREC REGULATIONS

The existing DO standards for marine waters are a daily average not less than 5.0 mg/L and an instantaneous minimum not less than 4.0 mg/L. Below are proposed new Sections to the State of Delaware Surface Water Quality Standards for the new aquatic life use sub-category (Tidal Marsh Influenced Aquatic Life) and alternative DO criteria for the tidal Murderkill River:

4.1.2.5 The Murderkill River from the Route 1 Bridge to the mouth at Bowers Beach

4.1.2.5.1 Tidal Marsh Influenced Aquatic Life use DO standards for the period from May 16 to September 30:

4.1.2.5.1.1 Daily average shall not be lower than 3.0 mg/L

4.5.2.5.1.2 Minimum one hour average shall not be less than 1.0 mg/L

4.5.2.5.2 For the period from October 1 to May 15 applicable criteria for all waters of the state shall apply

In addition, DNREC is also proposing the following DO assessment methodology for the tidal Murderkill River.

- The tidal portion of the Murderkill River has criteria for a daily averages and a one hour average minimum criteria. Where continuous data are available, it will be assessed as rolling averages for the one hour minimum criteria and simple arithmetic averages for the daily average.
- For the one hour calculations, events less than 24 hours apart will be considered a single event. Two or more events more than 24 hours apart in one season will be considered not supporting of the use.
- Daily average criteria will be simple daily averages of the continuous data for each day in the period. Because of the hydrodynamics of the system, violations can occur over multiple day periods caused solely by tide and weather events. Violations less than 3

days apart will be considered a single event. Two or more violations in a single year, of the daily average will be considered as not supporting the use.

SECTION 7

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