PAWCATUCK RIVER WATERSHED FINAL HSPF MODELING REPORT

REVISION 1 TOPICAL REPORT RSI-3108

PREPARED FOR
Connecticut Department of
Energy and Environmental Protection
79 Elm Street
Hartford, Connecticut 06106

AUGUST 2022

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TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF FIGURES (CONTINUED)

1.0 INTRODUCTION

The Connecticut Department of Energy and Environmental Protection (CTDEEP) is developing a new, watershed-focused approach for identifying and managing nutrient inputs into the coastal embayments to support healthy aquatic communities, restore eelgrass and recreational uses, and manage nutrients in the upland watersheds. This approach employs dynamic watershed models that are calibrated for hydrology and water quality characteristics. These models were chosen to facilitate the analysis of the water quality impacts associated with the current and future conditions within watersheds across the state of Connecticut. Models provide a proven platform for analyzing various implementation scenarios to achieve water quality goals that can then be translated into implementation plans.

CTDEEP selected the Hydrologic Simulation Program-Fortran (HSPF) dynamic watershed model to develop the Connecticut Watershed Model (CTWM) in 2002. HSPF has been widely used throughout the United States to analyze water hydrology and quality to aid in developing implementation plans based on attaining environmental goals [AQUA TERRA Consultants, 2001]. The complex and dynamic HSPF model can address soil, groundwater and surface-water processes, and storm events as well as impacts from point and nonpoint pollution sources. This model has been and continues to be, supported by the U.S. Environmental Protection Agency (EPA) and the U.S. Geological Survey (USGS).

In 2020, CTDEEP (in collaboration with the Rhode Island Department of Environmental Management) contracted with RESPEC to develop multiple HSPF models: one model for the Pawcatuck River Watershed, as shown in Figure 1-1, and a set of models for the remaining watersheds in Connecticut. This report addresses the development of the Pawcatuck River Watershed HSPF model application. The primary water quality parameters that are predicted by the model are nitrogen, phosphorus, suspended sediments, and stream flow. The results of the dynamic watershed models will be used to link with site-specific models of lakes, reservoirs, and tidal waters to conduct assessments of these waterbodies. The models provide nutrient loads, suspended sediment loads, and other freshwater inputs to local site-specific models.

Across southeastern New England, coastal embayments, lakes, and impoundments exhibit the effects of excessive nutrients, such as the loss of (or significantly diminished) eelgrass beds, excessive growth of macroalgae, oxygen-depleted waters, and deteriorated substrates. Eelgrass was once commonly found in many bays and harbors throughout Long Island Sound but are now largely confined to the eastern portion. Harmful algae blooms regularly occur in lakes and reservoirs across the state of Connecticut. Under these conditions, habitats for fish (at all life stages) and other aquatic organisms, along with recreational uses and waterfront property values, suffer.

State and federal regulators have responded to these nutrient-caused impairments by requiring more stringent permit limits for National Pollutant Discharge Elimination System (NPDES) discharges; however, nonpoint sources and stormwater are becoming the largest sources of nutrients. To effectively target these sources and to analyze the loads with the consideration of the point sources, detailed information is needed about the nutrients in the watersheds at fine spatial and temporal scales to identify where and when the bulk of nutrient nonpoint- and stormwater-source nutrient loads are being released to nearby waters. This information is also needed for the inputs to drive site-specific models of lakes, reservoirs, and embayments for determining total maximum daily loads.

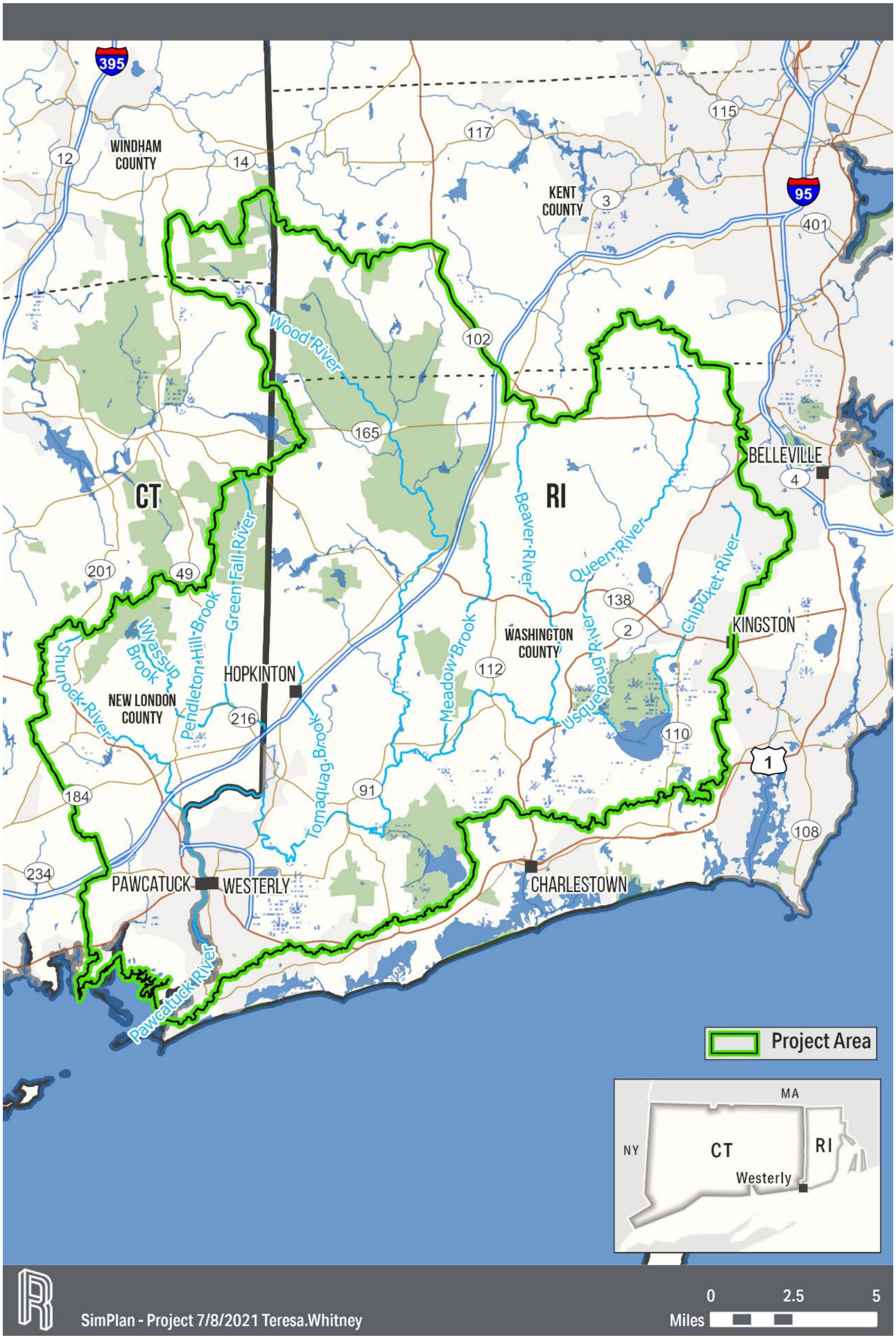

Figure 1-1. Pawcatuck River Project Area.

The Pawcatuck River, Pawcatuck River Estuary (PRE), and Little Narragansett Bay form part of the boundary between Connecticut and Rhode Island. The states have identified water quality impairments within these waters that relate to insufficient oxygen and bacteria. Connecticut has also identified impairments associated with nutrient loading and eutrophic conditions.

A dynamic watershed modeling approach is the most efficient means of obtaining detailed information on nonpoint- and stormwater-source nutrient loads across Connecticut and Rhode Island because directly measuring nutrient loads required at the needed spatial and temporal scales is not possible. While simplified watershed yield models provide annual nutrient loads, the models lack the temporal variability of loads that are important for understanding episodic events or predicting loads under different climatic conditions. The last dynamic watershed model for Connecticut and the freshwater portion of the Anguilla Brook Watershed in Connecticut was completed in 2002, which is an additional limitation in obtaining detailed nonpoint- and stormwater-nutrient information. Dynamic models also provide details necessary for consideration of water quality criteria for dissolved oxygen, which is evaluated on an hourly basis. Note that since the model was calibrated nearly 20 years ago, conditions in the watersheds that drain to Long Island Sound have changed and the capabilities of modeling tools have increased. The 2002 model did not include the Pawcatuck River Watershed; therefore, an HSPF model was developed for the Pawcatuck River Watershed as a collaboration between the State of Rhode Island and the USGS. The model only focused on stream flow, however, and did not address nutrients and other related parameters.

To better understand the water quality within the freshwater portion of the Pawcatuck River Watershed, the States of Connecticut and Rhode Island required information on the nutrient dynamics and stream flow in locations throughout the watershed. The additional, focused data collection (completed in 2019 and 2020) enhanced the development of an HSPF watershed model that was calibrated for nutrients, total suspended solids (TSS), stream flow, and related parameters to assist in assessing and managing nutrients in the Pawcatuck River Watershed. Information on diurnal dissolved oxygen (DO) data at the most downstream calibration site was a critical component of the focused monitoring, as well as additional nitrogen and phosphorus data, all of which were collected in a joint effort by the EPA Region 1 Laboratory and Rhode Island Department of Environmental Management (RIDEM) as input datasets for the watershed-scale hydrology and water quality model.

The HSPF model is a comprehensive watershed model of hydrology and water quality that includes land-surface and subsurface hydrologic and water quality processes that are linked and closely integrated with corresponding stream and reservoir processes [Donigian et al., 2018]. HSPF is considered a premier, high-level model among the models currently available for comprehensive watershed assessments and has experienced widespread usage and acceptance since HSPF was initially released in 1980, as demonstrated through hundreds of applications across the United States and abroad. HSPF is jointly supported and maintained by the EPA and USGS. HSPF is also the primary watershed model in the EPA BASINS modeling system and has been incorporated into the U.S. Army Corps of Engineers (USACE) Watershed Modeling System (WMS). This widespread usage and support has helped to ensure the continued code availability and maintenance for more than 4 decades despite varying federal priorities and budget restrictions.

The main stem of the Pawcatuck River is approximately 36 miles long, and the Hydrologic Unit Code (HUC) 8 watershed (Pawcatuck-Wood, 01090005) drains approximately 383 square miles that includes a 10-square-mile area off the coast of Rhode Island around the independent, terrestrial area of Block Island. Only the areas that drain to the Pawcatuck River and Little Narragansett Bay directly west of the watershed were modeled rather than the entire HUC-8 watershed. The project area for the Pawcatuck River Watershed model is approximately 318 square miles.

The land cover in the modeled Pawcatuck River Watershed project area consists of approximately 74 percent forest; 5 percent wetlands; 12 percent developed land; 4 percent crops (e.g., other hay/non-alfalfa, corn, and sod); and 2 percent classified as grassland, shrubland, or barren land. The average slope in the Pawcatuck River Watershed is approximately 6.5 percent with the minimum at zero and maximum at 121 percent.

This report presents the methods used to develop the Pawcatuck River Watershed hydrology and water quality model using HSPF. The report presents how the model was constructed and calibrated as well as what data were used for the model applications.

The model application development consisted of the following major steps:

1. Collecting and developing time-series data
2. Characterizing and segmenting the watershed
3. Calibrating and validating the model.

These three steps are discussed in detail in the following sections of this simulation plan. This report contains nine chapters, including this introduction. The collection and development of the hydrologic, meteorological, and other data used for the simulation is described in Chapter 2.0. Chapter 3.0 discusses other types of spatial data used for segmentation and characterization of the watershed, and Chapter 4.0 describes the calibration and validation process used as well as the method used to determine the simulation period for the Pawcatuck River Watershed model.

Outputs from the developed, calibrated, and validated model will be used as inputs to the receiving water quality models, and subsequent implementation scenarios will be run and analyzed. Chapter 5.0 discusses the linkage process for the HSPF outputs as inputs to WASP and BATHTUB, and Chapter 6.0 describes several proposed management scenarios. Because of the large amount of data required for watershed modeling, Chapter 7.0 presents the methods used for data management, organization, and transfer. Data sources and cited references are provided in Chapters 8.0 and 9.0, respectively. The land-cover reclassification scheme is provided in Appendix A, and the water quality data summary and calibration are provided in Appendices B and C, respectively.

2.0 DATA COLLECTION AND DEVELOPMENT

Simulating hydrology and water quality within the Pawcatuck River Watershed requires the following types of time-series data:

1. Precipitation
2. Potential evapotranspiration and other meteorological data (e.g., air temperature, wind, solar radiation, dewpoint, and cloud cover)
3. Stream flow
4. Water quality data
5. Point sources
6. Atmospheric deposition
7. Other data (e.g., diversions, withdrawals, and irrigation).

This chapter discusses the availability, selection, and processing methods of the time-series data used in the watershed modeling. The detailed Quality Assurance/Quality Control (QA/QC) and data management procedures are provided in Chapter 7.0. Only meteorological data were required to run the HSPF model; however, stream-flow measurements and water quality observations were also used to calibrate and validate the model. Other data types (e.g., point sources, atmospheric deposition, and diversions) helped to define the inflow, outflow, and water quality in the watershed. All of the input time-series data used to run the model were placed into a Watershed Data Management (WDM) file, which is a binary database format that was originally developed to efficiently store large datasets for use by HSPF and other models.

2.1 PRECIPITATION

The Pawcatuck River Watershed HSPF model required complete precipitation time-series data (i.e., without missing records), at an hourly timestep and with adequate spatial coverage and density across the model domain. Precipitation is the critical forcing function for all watershed models because it drives the hydrologic cycle and provides the foundation for transport mechanisms that move pollutants from the land to the waterbody, where the pollutant impacts are imposed.

The primary sources of long-term precipitation and other meteorological inputs for this watershed model included gridded data from the North American Land Data Assimilation System (NLDAS) and Parameter-elevation Regressions on Independent Slopes Model (PRISM). These data products are complete and available from 1979 to the current year (within the last few weeks of the download date). Because these data are gridded, they allow for easy extraction and aerial averaging over each hydrozone (i.e., an aggregation of subwatersheds that receive the same meteorological inputs) using scripted processes while also providing efficient and consistent time-series extension.

The NLDAS is a 12-kilometer (km) by 12-km dataset that provides hourly meteorological data. PRISM is a 4-km by 4-km dataset that provides daily precipitation totals that are computed by combining a dense network of station data with radar measurement estimates that are interpolated based on a climate-elevation regression for each digital elevation model (DEM). Daily PRISM data were used for the modeling because these data provide a finer spatial resolution and generally have better agreement with the point-precipitation data. The daily values were disaggregated to an hourly timestep using the NLDAS data. The hourly NLDAS precipitation were loaded into the WDM to provide another option to test during calibration. Specific stations are not associated with the gridded meteorological data. The time period needed for modeling (January 1990 through July 2020) was downloaded online (https://ldas.gsfc.nasa.gov/nldas/nldas-get-data).

Snow depth (i.e., snow on the ground) data were used to calibrate the snow accumulation and melt processes when the snow section of the model is active. These data were also used in conjunction with mean and maximum winter-air temperatures to assess if the snow simulation capability within the watershed model was needed and activated. For the Pawcatuck River Watershed and surrounding areas, the snow depth (in inches) and snowfall (in inches) data were available through the National Climatic Data Center (NCDC) Global Historical Climatology Network stations [Menne et al., 2012] (ftp://ftp.ncdc.noaa.gov/pub/data/ghcn/daily/). The snow depth data were used during the hydrology calibration in multiple locations throughout the project area to ensure that snow processes were being accurately represented.

Precipitation data sources included the following:

- NLDAS (https://ldas.gsfc.nasa.gov/nldas/nldas-get-data)
- PRISM (https://prism.oregonstate.edu/).

2.2 EVAPOTRANSPIRATION AND OTHER METEOROLOGICAL DATA

In addition to precipitation, evaporation data are needed to drive the water-balance calculations in HSPF. Other meteorological time series are often required in temperate climates where snow accumulation and melt are a significant component of the hydrologic cycle and water balance. These time series, such as air temperature (ATEM), solar radiation (SOLR), dewpoint temperature (DEWP), wind speed (WIND), and cloud cover (CLOU), are often required if soil and/or water temperatures are simulated. Water temperature is subsequently used to adjust rate coefficients in most water quality processes, and other time series are used in selected calculations (e.g., solar radiation affecting algal growth).

The NLDAS dataset provides hourly ATEM, SOLR, and WIND parameters that were directly applied to the meteorological time series with a conversion to the units needed for HSPF. The remaining meteorological constituents (CLOU, DEWP, and potential evapotranspiration [PEVT]) were not directly available from the NLDAS dataset and required additional computations for this model.

CLOU was estimated by SOLR data for this model provided from the NLDAS database by using a parabolic equation [Thompson, 1976]. Two options for DEWP were computed from a series of calculations that stemmed from the NLDAS specific humidity. The first option used the specific humidity and ATEM to calculate the relative humidity [World Meteorological Organization, 2014]. Relative humidity was then applied with ATEM to the August-Roche-Magnus approximation of the Clausius-Clapeyron equation [Stull, 2017] to calculate DEWP. The second option calculated a mixing ratio using specific humidity and then that mixing ratio was used with atmospheric pressure to estimate vapor pressure. DEWP was then calculated using the Clausius-Clapeyron equation [Stull, 2017]. Both options for DEWP were assessed during calibration, and the August-Roche-Magnus option was chosen because it resulted in a more representative calibration.

Hourly PEVT estimates are included in the NLDAS dataset that are generated using a modified Penman energy-balance method. However, the NLDAS estimates of PEVT are only included for legacy compatibility with input requirements of the Sacramento Soil Moisture Accounting Model (http://hydromad.catchment.org/man/sacramento.html), do not incorporate the subsequent corrections to NLDAS estimates of energy forcing, and were found to overestimate evapotranspiration (ET) in other modeling efforts. Hourly PEVT was represented by a computed Penman pan evaporation based on the Penman [1948] formula and the method of Kohler et al. [1955]. The necessary variables to compute the Penman pan evaporation are daily SOLR, DEWP, ATEM, and wind travel. Because two options for DEWP were calculated, two options for PEVT were also calculated and assessed during calibration.

Evaporation and other meteorological data sources included the following:

- NLDAS (https://ldas.gsfc.nasa.gov/nldas/).

2.3 STREAM FLOW

Flow data were needed for calibrating and validating of the watershed model to ensure that the hydrologic behavior of the Pawcatuck River Watershed as well as the transport of sediment and water quality constituents were reproduced. Continuous, observed stream-flow data were available at 18 gages in the Pawcatuck River Watershed. The stream-flow gages and corresponding record periods to support the model calibration are listed in Table 2-1 along with the percentage of data that were missing during the modeling time period (January 1990 through July 2020). The locations of the flow-monitoring sites are illustrated in Figure 2-1. Flow data were downloaded from the USGS National Water Information System (NWIS) (https://waterdata.usgs.gov/nwis). All continuous, stream-flow data in the watershed were included in the calibration; however, noncontinuous, stream-flow data are not as valuable for calibration purposes. Primary, secondary, and tertiary calibration/validation gages were selected using the following criteria:

- Primary—The flow gage is on the main stem of the Pawcatuck River and had a full dataset for the simulation period (2 sites).
- Secondary—The flow gage is on a tributary to the Pawcatuck River, had a full dataset for the simulation period, and the drainage area was greater than 10 square miles (4 sites).
- Tertiary—Any flow gage that did not meet the primary or secondary criteria (12 sites).

Stream-flow data sources included the following:

- USGS NWIS (https://nwis.waterdata.usgs.gov/nwis).

Table 2-1. List of the U.S. Geological Survey Stations and Data Availability During the Modeling Time Period in the Pawcatuck River Watershed

Station Name	Station I.D.	Start Date	End Date	Missing (%)
CHIPUXET RIVER AT WEST KINGSTON, RI	01117350[a]	01/01/1991	05/04/2020	0.0
QUEEN R 1400 FT UPSTR WM REYNOLDS RD AT EXETER, RI	011173545	10/01/1999	12/14/2004	84.5
QUEEN R AT LIBERTY RD AT LIBERTY, RI	01117370	10/01/1998	05/04/2020	26.2
USQUEPAUG RIVER AT RT 138 AT USQUEPAUG, RI	01117410	07/13/1999	12/15/2004	83.7
USQUEPAUG RIVER NEAR USQUEPAUG, RI	01117420[a]	01/01/1991	05/04/2020	0.0
CHICKASHEEN BROOK AT WEST KINGSTON, RI	01117424	09/26/2002	12/14/2004	92.5
PAWCATUCK RIVER AT KENYON, RI	01117430	01/01/1991	05/04/2020	46.7
BEAVER RIVER NEAR USQUEPAUG, RI	01117468	01/01/1991	05/04/2020	0.0
BEAVER RIVER SHANNOCK HILL RD, NEAR SHANNOCK, RI	01117471	10/01/2002	12/08/2004	92.6
PAWCATUCK RIVER AT WOOD RIVER JUNCTION, RI	01117500[b]	01/01/1991	05/04/2020	0.0
MEADOW BROOK NEAR CAROLINA, RI	01117600	01/01/1991	12/15/2004	92.0
WOOD RIVER NEAR ARCADIA, RI	01117800[a]	01/01/1991	05/04/2020	0.0
WOOD RIVER AT HOPE VALLEY, RI	01118000[a]	01/01/1991	05/04/2020	0.0
PAWCATUCK RIVER AT BURDICKVILLE, RI	01118010	08/06/2002	12/15/2004	92.0
PENDLETON HILL BROOK NEAR CLARKS FALLS, CT	01118300	01/01/1991	05/04/2020	0.0
ASHAWAY RIVER AT ASHAWAY, RI	01118360	08/16/2002	12/15/2004	92.1
SHUNOCK RIVER NEAR NORTH STONINGTON, CT	01118400	10/01/2002	12/15/2004	92.5
PAWCATUCK RIVER AT WESTERLY, RI	01118500[b]	01/01/1991	05/04/2020	0.0

(a) Secondary calibration/validation
(b) Primary calibration/validation.

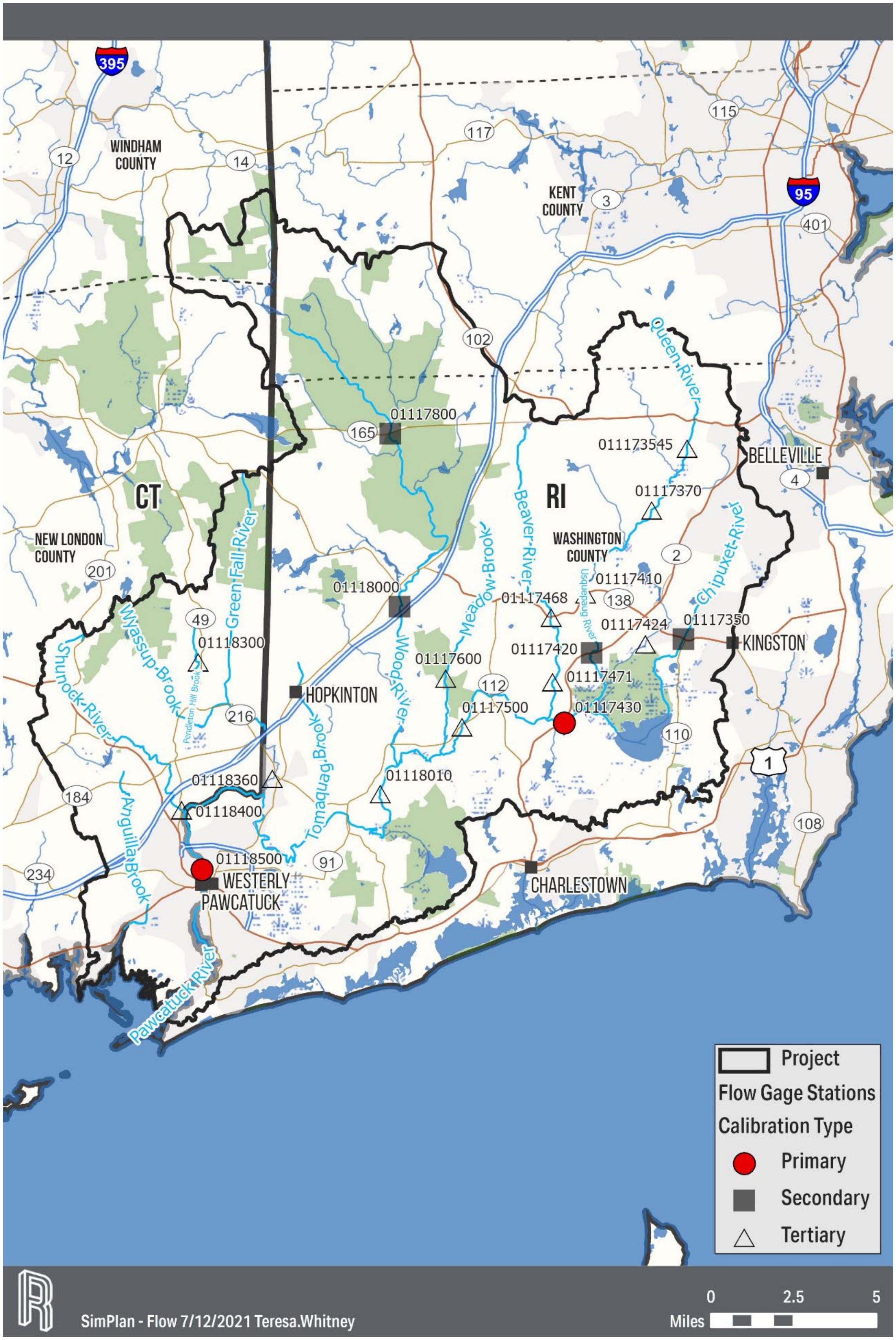

Figure 2-1. Flow Calibration Gages.

2.4 WATER QUALITY DATA

Water quality data were primarily used for model calibration and validation and to also help quantify source contributions and boundary conditions. The specific constituents modeled in this study included all of the constituents needed for modeling nutrients with a specific focus on nitrogen species. The following list shows the conventional constituents that are modeled whenever nutrients are the purpose of a modeling effort:

- TSS
- Water temperature
- DO
- Carbonaceous Biochemical Oxygen Demand ultimate ($CBOD_u$) (i.e., total CBOD)
- Nitrite-Nitrate (NO_2/NO_3)
- Total ammonia (NH_3/NH_4)
- Total nitrogen (TN)
- Orthophosphate (PO_4)
- Total phosphorus (TP)
- Phytoplankton as chlorophyll *a*
- Benthic chlorophyll *a*.

Water quality data were collected from the National Water Quality Monitoring Council Water Quality Portal (https://www.waterqualitydata.us/), which includes data from the USGS, EPA, and National Water Quality Monitoring Council (NWQMC). This portal serves data collected by more than 400 state, federal, tribal, and local agencies. Water quality data were also provided by CTDEEP and RIDEM. Ambient surface-water quality data were used for the water quality calibration. Applicable parameters from all sources (RIDEM, CTDEEP, and the Water Quality Data Portal) were combined into a single dataset. Data gaps were identified as a part of the development of the USGS monitoring plan [USGS, 2019]. A sampling plan review was completed that summarized the existing water quality data and data gaps in the sampling plan. The review of the sampling plan led to the conclusion that the plan was overall well-structured with a good distribution of stations across the watershed and appropriate parameters being monitored [Kenner, 2020]. The sampling plan provides an adequate dataset to represent the recent conditions and identify significant water quality responses within the watershed. The primary data gap identified was the lack of targeted storm sampling that can be critical to effectively estimating the nutrient and sediment loadings during runoff events. This recent sampling effort, in addition to previous sampling efforts, provided a reasonable range of flow conditions and corresponding water quality data to estimate the nutrient and sediment loads and effectively supported the watershed-focused approach for managing nutrient load in the Pawcatuck River Watershed.

The CTDEEP and RIDEM also supplied data from the Municipal Separate Storm Sewer System (MS4) storm drains. These data were compared to the concentrations of developed land as a part of the calibration process. Storm drains were not explicitly represented and were not calibrated.

For tracer modeling, the Scenario Application Manager (SAM) can provide the preferred tracking through the source fate functionality, and a detailed example will be provided during the SAM training workshop. Another option in HSPF called CONS can be used but essentially arrives at the same result that SAM provides. CONS simulates constituents that do not decay with time or leave the Stream Reach or Reservoir (RCHRES) by any mechanism other than advection. Parameter inflows are applied and CONS calls the subroutine ADVECT to perform longitudinal advection of this material and the material already contained in the RCHRES. CONS then calculates the mass of material remaining in the RCHRES after advection and this value, RCON, is necessary for the mass balance checks on conservatives.

Water quality data sources included the following:

- Water Quality Data Portal (https://www.waterqualitydata.us/)
- RIDEM and CTDEEP Uploaded Water Quality Data to Shared Project Folder.

2.5 POINT SOURCES

Point source data for the Pawcatuck River Watershed were provided by CTDEEP and RIDEM and were also downloaded from the EPA ECHO website (https://echo.epa.gov/). Discharging point sources in the Pawcatuck River Watershed are summarized in Table 2-2 and their locations are shown in Figure 2-2. Facilities that were not represented include the Chariho Regional Middle School, Greene Plastics, the Rhode Island Department of Transportation (RIDOT), Westerly and Richmond Mobil Service Stations, Armetta LLC, the Avondale Boat Yard, Washington County Turf Farm, and other facilities with very low flow (average flow less than 0.0001 million gallons per day [mgd]) and/or no data available. If data are provided for the excluded facilities, then they can be represented using monthly averages during their operational periods. Facilities that closed during the model time period include the Ladd School (1993) and Bradford Dying Association (2011).

Table 2-2. Discharging Point Sources

Facility I.D.	Facility Name	Reach
RI0100081	Ladd School Wastewater Treatment Facilities	43
RI0000191	Kenyon Industries	90
RI0001007	RIDEM/Carolina Trout Hatchery	111
RI0022080	Coastal Plastics, Inc.	215
RI0000043	Bradford Dyeing Association	250
RI0020508	The Imperial Home Décor Group	290
RI0021814	Ashaway Line and Twine Manufacturing Company	329
RI0100064	Westerly Wastewater Treatment Facilities	370
CT0101290	Stonington Pawcatuck Water Pollution Control Facility	370

The provided data, which were at a monthly timestep, were transformed into a daily time series following a set of rules and assumptions that are based on the facility type (i.e., mechanical versus controlled), which were determined from permits or by evaluating the dataset.

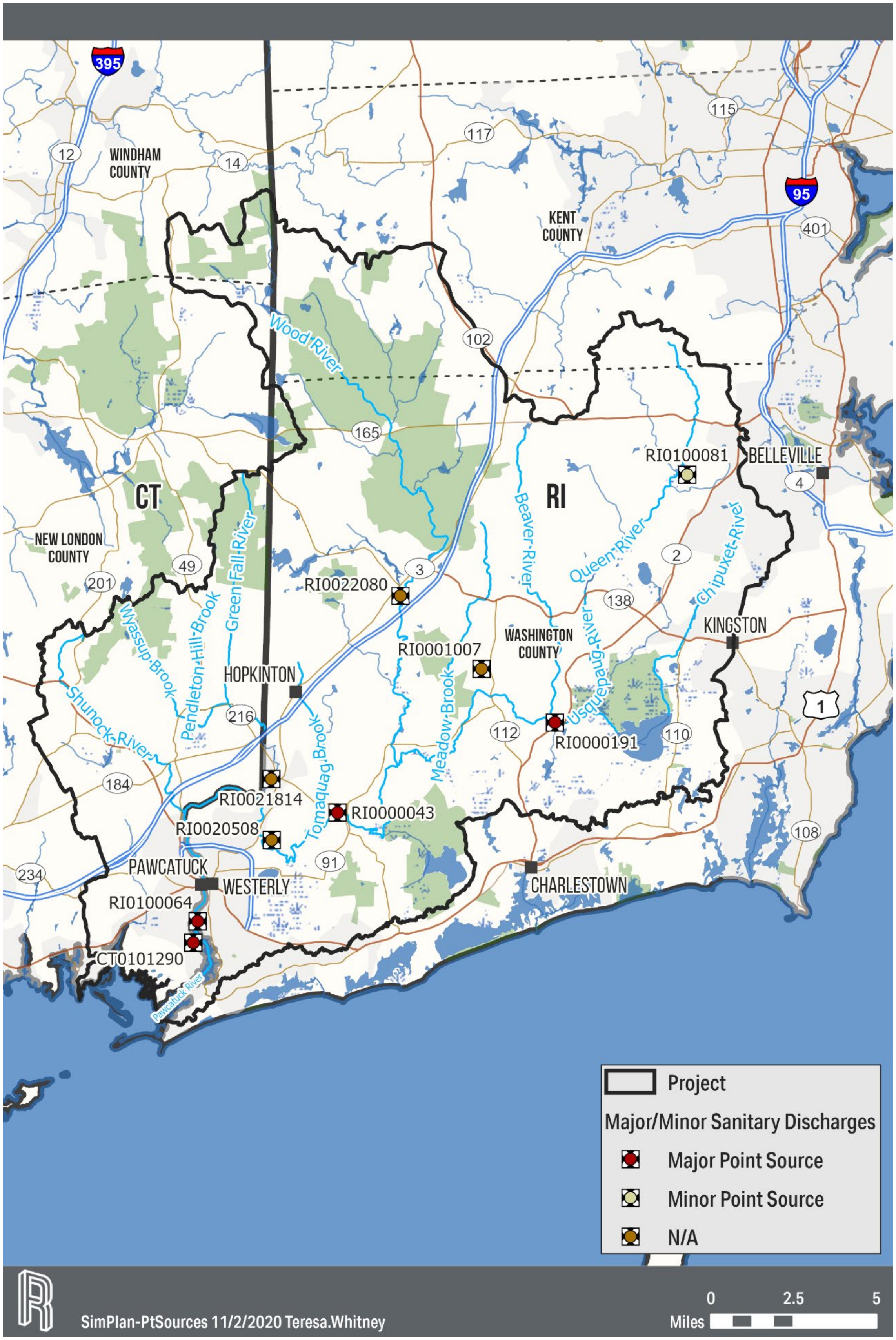

Figure 2-2. Point Source Locations.

Mechanical point sources have continuous flow and are generally industrial facilities or larger municipal wastewater treatment facilities (WWTFs). These facilities were assumed to discharge every day of every month unless otherwise noted. The months with missing data were filled in using the average of similar months (e.g., if January 2015 was missing data, the average of all of the other January data were used to fill the month). If data were missing before or after the full range of values, an assumption was made that the site was not operating at the time and discharge was not represented.

Controlled ponds are lagoons and are usually small facilities that discharge intermittently for variable lengths of time. If a facility had missing monthly data, an assumption was made that the pond did not release effluent during that month. Note that some of the facilities on the Rhode Island side of the watershed are ponds.

Applicable parameters for the discharging facilities generally include carbonaceous 5-day biological oxygen demand ($CBOD_5$), ammonia nitrogen, Kjeldahl nitrogen, nitrate nitrogen, nitrite nitrogen, TP, TSS, DO, and temperature. HSPF requires more input parameters than what are provided in Table 2-3.

Table 2-3. List of Pollutants Calculated From the Point Sources

Pollutant Name	Pollutant Description	Daily Model-Input Units
Flow	Effluent Flow	Acre-Foot
Heat	Heat Energy of the Effluent	BTU
TSS	Total Suspended Solids	Tons
DO	Dissolved Oxygen	Pounds
NO_3-N	Nitrate as Nitrogen	Pounds
NO_2-N	Nitrite as Nitrogen	Pounds
NH_4-N	Total Ammonia as Nitrogen	Pounds
ORN	Refractory Organic Nitrogen	Pounds
PO_4-P	Orthophosphorus as Phosphorus	Pounds
ORP	Refractory Organic Phosphorus	Pounds
$CBOD_u$	Ultimate Carbonaceous Biochemical Oxygen Demand	Pounds
ORC	Organic Carbon	Pounds

BTU = British thermal unit.

Some facilities did not sample or report all of the parameters listed. In these cases, a dataset was derived using either a surrogate facility estimated with nutrient speciation factors or by setting a constant concentration, depending on the missing constituent. A summary of point source discharge, concentration averages, and percent missing of each main constituent is provided in Table 2-4. The assumptions for estimating missing parameters (provided in the following paragraph) have been applied to more than 50 HPSF model applications spanning several states, and have been widely accepted by modelers, watershed managers, and point source permitters.

Table 2-4. Summary of Average Discharge and Concentration for the Available Point Source Parameters

Facility I.D.	Outfall Station	Discharge Rate (mgd)	TSS (mg/L)	$CBOD_5$ (mg/L)	DO (mg/L)	TN (mg/L)	NO_2-N (mg/L)	NO_3-N (mg/L)	NH_4-N (mg/L)	TP (mg/L)	PO_4-P (mg/L)	Water Temperature (°F)
RI0000043	SD002A	0.59	55 (52%)	32 (52%)	—	—	0.18 (72%)	2.7 (72%)	1.2 (58%)	1.3 (54%)	1.3 (82%)	—
RI0000191	SD0031	0.02	—	—	—	—	—	—	—	—	—	62 (44%)
RI0000191	SD001	0.33	132 (1%)	90 (1%)	—	—	1.5 (41%)	16 (25%)	22 (19%)	13 (5%)	5.4 (81%)	—
RI0000191	SD002A	0.049	—	—	—	—	—	—	—	—	—	62 (28%)
RI0100081	SD001A	0.04	11 (5%)	15 (3%)	—	—	—	—	—	—	—	—
RI0020508	SD001A	0.058	1.5 (0%)	3.1 (0%)	—	—	0.061 (0%)	0.67 (0%)	1.5 (0%)	0.26 (0%)	—	—
RI0020508	SD001P	0.011	41 (0%)	1.1 (0%)	17 (99%)	—	0.14 (0%)	1.6 (0%)	5.0 (0%)	1.6 (0%)	—	—
RI0020508	SD001W	0.027	—	—	—	—	—	—	—	—	—	—
RI0020508	SD002A	0.015	—	—	—	—	—	—	—	—	—	—
RI0020508	SD003A	0.069	—	—	—	—	—	—	—	—	—	—
RI0100064	SD001A	2.4	14 (31%)	12 (31%)	—	10 (56%)	1.1 (29%)	2.3 (29%)	4.8 (29%)	—	—	—
RI0001007	SD001A	0.54	7.4 (91%)	2.8 (98%)	6.8 (82%)	1.8 (83%)	—	—	0.33 (85%)	0.15 (85%)	—	55 (82%)
RI0021814	SD001002	0.00012	—	—	—	—	—	—	—	—	—	189 (97%)
RI0022080	SD001	0.0031	25 (87%)	35 (86%)	—	—	—	—	—	—	—	65 (74%)
CT0101290	SD001	0.52	5.0 (29%)	3.7 (35%)	3.3 (87%)	15 (91%)	0.66 (91%)	5.1 (91%)	7.0 (91%)	3.3 (71%)	2.8 (91%)	—

Note: percent missing in parenthesis
°F = Degrees Fahrenheit.

If DO or 5-Day Biochemical Oxygen Demand (BOD_5) data were missing, concentrations of 8 and 1 milligrams per liter (mg/L) were assumed, respectively. If NO_2-N /NO_3-N data were missing, a combined concentration of 2 mg/L was assumed for non-wastewater facilities and a combined concentration of 7 mg/L was assumed for wastewater facilities. The combined NO_2-N /NO_3-N concentration was assumed to be 12 percent NO_2-N and 88 percent NO_3-N based on other facilities with data available in the Pawcatuck River Watershed. If NH_4-N data were missing, a concentration of 2 mg/L was assumed. Facilities without BOD_5 or TP data were assumed to have a TP concentration of 0.1 mg/L, while facilities with BOD_5 and no TP (Coastal Plastics, Westerly WWTF, and Ladd School WWTF) were assumed to have a TP concentration of 0.8 mg/L to prevent PO_4-P calculations from going negative, and 60 to 75 percent of the TP was assumed as PO_4-P. TP that is associated with BOD in HSPF is 0.7 percent, and the remainder of the TP that is not PO_4-P or associated with BOD is assumed to be organic. Similarly, TN that is associated with BOD in HSPF is 4.3 percent and TN that is not NO_2-N, NO_3-N, or NH_4-N is assumed to be organic nitrogen. TSS is split into 40 percent silt and 60 percent clay at each facility. Organic carbon was assumed to be 13 percent of the BOD concentration. The temperature time series from the USGS continuous stream monitoring site (USGS 01194796 Connecticut River at Old Lyme, Connecticut) was used as a surrogate and monthly averages were applied to locations without temperature effluent data. The USGS monitoring site was chosen because of its data availability and central location to the entire modeled area.

Besides temperature, concentrations of all of the available constituents, including BOD as $CBOD_u$ that was converted from $CBOD_5$ by using Equation 2-1 [Chapra, 1997], were converted from mg/L to loads in pounds per day (lb/day) (i.e., concentration × flow × conversion factor; conversion factor = 8.34). Temperature was converted from °F to a heat load in BTUs per day (i.e., temperature × flow × conversion factor; conversion factor = 8,339,145).

$$L_o = \frac{y_5}{1 - e^{-k_1(5)}} \qquad (2\text{-}1)$$

where:

$L_o = CBOD_u$

$y_5 = CBOD_5$

$k_1 = 0.10$ (minimum value after primary treatment).

Estimated daily time series were imported into a WDM file and loads were applied to the corresponding stream in the external sources block of the user control input (UCI) file.

Point source data sources included the following:

- EPA ECHO (https://echo.epa.gov/)
- RIDEM and CTDEEP Uploaded Point Source Data to Shared Project Folder.

2.6 ATMOSPHERIC DEPOSITION

Atmospheric deposition of nutrients is commonly included in watershed modeling efforts that focus on eutrophication issues. Nitrate and ammonium atmospheric depositions were explicitly represented as a daily time series in the Pawcatuck River Watershed HSPF model. Wet atmospheric deposition data were downloaded from the National Atmospheric Deposition Program (NADP) (http://nadp.slh.wisc.edu/) and dry atmospheric deposition data were downloaded from the EPA's Clean Air Status and Trends Network (CASTNet) (https://www.epa.gov/castnet/). The sites, corresponding record periods, and distances to the center of the Pawcatuck River Watershed are shown in Table 2-5, and the locations are shown in Figure 2-3. Site ABT147 is the closest dry deposition site (less than 30 miles from the project area) and has a nearly complete dataset; therefore, this site was the primary dry deposition site. Although Site MA08 has a longer record period and a more complete dataset relative to Site CT15, the CT15 site is closest to the watershed (less than 30 miles) and was the primary wet deposition site. Wet and dry atmospheric depositions were applied directly to the waterbodies and land throughout the watershed.

Table 2-5. Atmospheric Deposition Site Summary

Site I.D.	Name	State	Type	Start Date	End Date	Missing (%)
CT15	Abington	CT	Wet	01/26/1999	10/21/2019	22
MA08	Quabbin Reservoir	MA	Wet	03/05/1982	10/21/2019	19
NY96	Cedar Beach-Southold	NY	Wet	11/25/2003	10/21/2019	22
ABT147	Abington	CT	Dry	12/28/1993	12/30/2019	1

The original dry deposition data were supplied at a weekly time step as a particulate flux kilogram per hectare (kg/ha). To transform the data into a daily time series, the weekly data were divided by 7. The wet deposition was also supplied at a weekly time step but, in rare cases, sampling periods ranged from 1 to 8 days. Because wet deposition was in units of concentration (i.e., mg/L), wet deposition data were not divided by the number of days in the sampling period. The concentration was instead assigned to each day of the sampling period. In the model, the wet deposition data are multiplied by the precipitation amount to calculate the nutrient load. After being transformed to daily time-series data, the missing dry and wet deposition data were filled in using interpolation when less than 14 missing days had occurred between samples and by using monthly mean values when more than 14 missing days occurred between values. The data were converted to elemental concentrations and fluxes using multiplication factors from the UCI (i.e., data are still NO_3 and NH_4, and not NO_3-N and NH_4-N). A summary of the missing data that were filled is shown in Table 2-5. The multiplication factors were used to convert the filled data into the units required by HSPF. The nitrogen deposition was applied as a time series to each segment, and the wash-off rates were mainly driven by precipitation intensity and calibration parameters.

Continuous wet and dry atmospheric phosphorus deposition data were not monitored through the NADP or CASTNet. Because of the lack of temporal data, an annual average value of total phosphorus deposition obtained from regional studies was dispersed using the MONTH-DATA block in HSPF. Values of total phosphorus atmospheric deposition fluxes ranging from 0.037 kilogram per hectare per year (kg/ha/yr) to 0.082 kg/ha/yr [Yang et al., 1996; Hu et al., 1998; Koelliker et al., 2004]. A midpoint value of 0.060 kg/ha/yr was set with higher values occurring in the summer and lower values occurring in the winter [Yang et al., 1996].

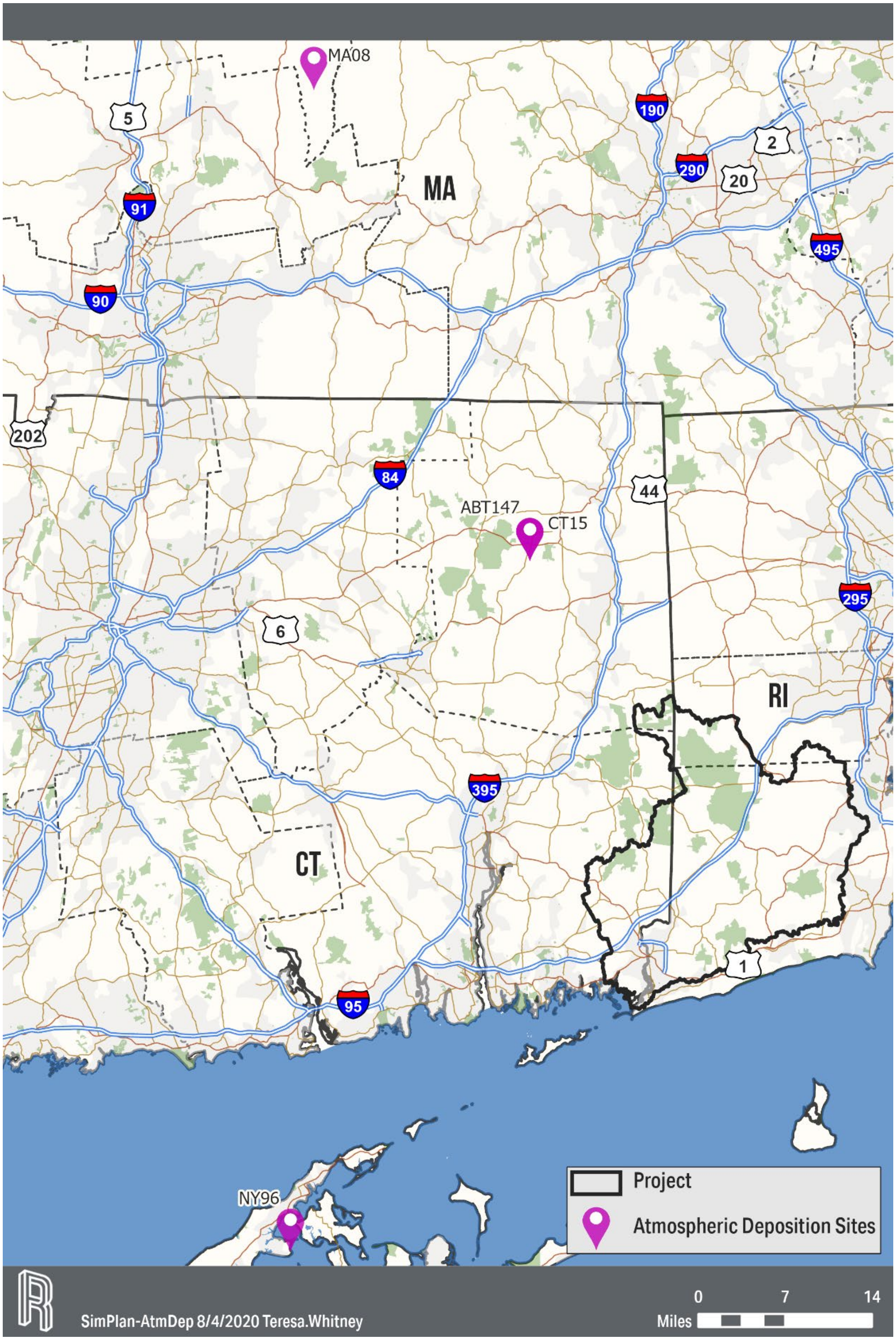

Figure 2-3. Atmospheric Deposition Locations.

2.7 OTHER DATA

Additional items represented in the model application included surface-water diversions, withdrawals, and irrigation represented using time-series data.

2.7.1 DIVERSIONS AND WITHDRAWALS

Wild and Nimiroski [2004] estimated that self-supply withdrawals for domestic, commercial, industrial, and agricultural use averaged approximately 2.3, 0.2, 0.5, and 1.4 mgd, respectively, from 1995 to 1999 in the Pawcatuck River Watershed. According to the Gardner et al. [2011] Pawcatuck modeling report, municipal groundwater withdrawals averaged 7.18 mgd during their study period (2000 to 2004). The report stated that five major municipal water suppliers in the basin operated 16 wells and totaled 7.18 mgd between 2000 and 2004 with 13 minor, nonmunicipal suppliers withdrawing approximately 0.1 mgd each.

Time-series data for the surface and groundwater withdrawals were provided by CTDEEP for the Connecticut portion of the watershed; however, RIDEM did not have surface and groundwater withdrawal time-series data available. Data used in the USGS Pawcatuck River HSPF model application [Gardner et al., 2011] were evaluated and noted to be very consistent in nature, as flow trends were very similar from month to month over each year. Therefore, the day-of-the-year averages from the USGS Pawcatuck River HSPF model were used to generate the water-supply withdrawal time series for the Rhode Island portion of the watershed. During the calibration process, some of the day-of-the-year average withdrawals used were reduced to prevent simulated reach volumes in this exercise from going to zero.

Data sources for diversions and withdrawals included the following:

- Diversions and Withdrawals From USGS Pawcatuck River HSPF Model.
- CTDEEP Uploaded Withdrawals to Shared Project Folder by Subwatershed.

2.7.2 IRRIGATION

Irrigation in the basin is mainly used for turf farms (4.4 square mile [mi^2]), golf courses (0.76 mi^2), vegetable farms (0.41 mi^2), and tree nurseries (0.005 sq mi^2). Because vegetable farms and tree nurseries make up a small portion of the watershed, they were grouped with cropland. The Gardner et al. [2011] Pawcatuck model report developed an equation using a logistic-regression analysis to estimate the probability of turf-farm irrigation on any given day from May 1 to October 31, based on the total PET during the previous 5 days and total precipitation during the previous 2 and 20 days. The report stated that when the probability was greater than 0.40, the assumption was that irrigation had occurred. For the updated model application, the developed equation for turf/sod, shown in Equation 2-2, was used to represent turf and golf courses because golf courses make up a very small fraction of the total land cover. Since precipitation and PET data sources were processed differently for the previous Pawcatuck model, the probability was adjusted to 0.80 so that the average number of irrigation days per year were the same between both studies. The report stated that turf farms applied approximately 3,399 gallons per day per acre (gal/d/acre) and golf courses applied approximately 1,756 gal/d/acre [Gardner et al., 2011]. The ratio of turf farms to golf courses across the watershed were therefore used to determine the irrigation application rate to these areas. The report also states that 40 to 50 percent of turf farms are kept fallow during each year; therefore, the calculated application rate was reduced by 45 percent. On days determined to be irrigation days, the calculated application rate was applied to the model land cover that represents turf farms and golf courses.

$$P = \frac{\left(\exp\left(-2.1149+51.917\left[PET5\right]-0.7777\left[PREC2\right]-0.5877\left[PREC20\right]\right)\right)}{1+\left(\exp\left(-2.1149+51.917\left[PET5\right]-0.7777\left[PREC2\right]-0.5877\left[PREC20\right]\right)\right)} \tag{2-2}$$

where:

P = Probability of turf-farm irrigation on any day from May 1 to October 31

PET5 = Evapotranspiration during the previous 5 days (inches)

PREC2 = Precipitation during the previous 2 days (inches)

PREC20 = Precipitation during the previous 20 days (inches).

Data sources for irrigation included the following:

- Irrigation Application Estimate on Turf and Agricultural Land
- USGS Pawcatuck Model Application Turf Equation With NLDAS Data.

3.0 SEGMENTATION AND CHARACTERIZATION

This chapter describes the methods used to develop the subwatershed, reach, and land-cover segments for the Pawcatuck River Watershed HSPF model application. The segmentation and characterization define water travel from the various land uses within each subwatershed to each reach segment.

3.1 DRAINAGE AREAS

Appropriate resolution for subwatershed areas were defined by the needs of CTDEEP and RIDEM. Subwatersheds were developed to be small enough to represent impaired reaches and lakes as well as monitoring points for calibration. The Connecticut Environmental Conditions Online (CTECO) local subbasins in Connecticut were used as the starting point for all of the subwatersheds in the Connecticut portion of the watershed. In addition to the Connecticut CTECO subwatersheds, The National Hydrography Dataset Plus (NHDPlus) Version 2 was used. NHDPlus Version 2 is a national, geospatial, surface-water framework that includes elevation, flow accumulation, and flow-direction grids. To delineate locations in the Pawcatuck River Watershed that do not have existing CTECO subwatersheds, batch points were created in GIS at desired breakpoints and the ArcHydro platform was used with the NHDPlus Version 2. The two subwatersheds sets (Connecticut CTECO and ArcHydro generated) were integrated into the final subwatersheds that are shown in Figure 3-1.

Data used to develop subwatersheds included the following:

- Connecticut CTECO Local Subbasins (https://cteco.uconn.edu)
- NHDPlus Version 2 (https://www.epa.gov/waterdata/get-nhdplus-national-hydrography-dataset-plus-data).

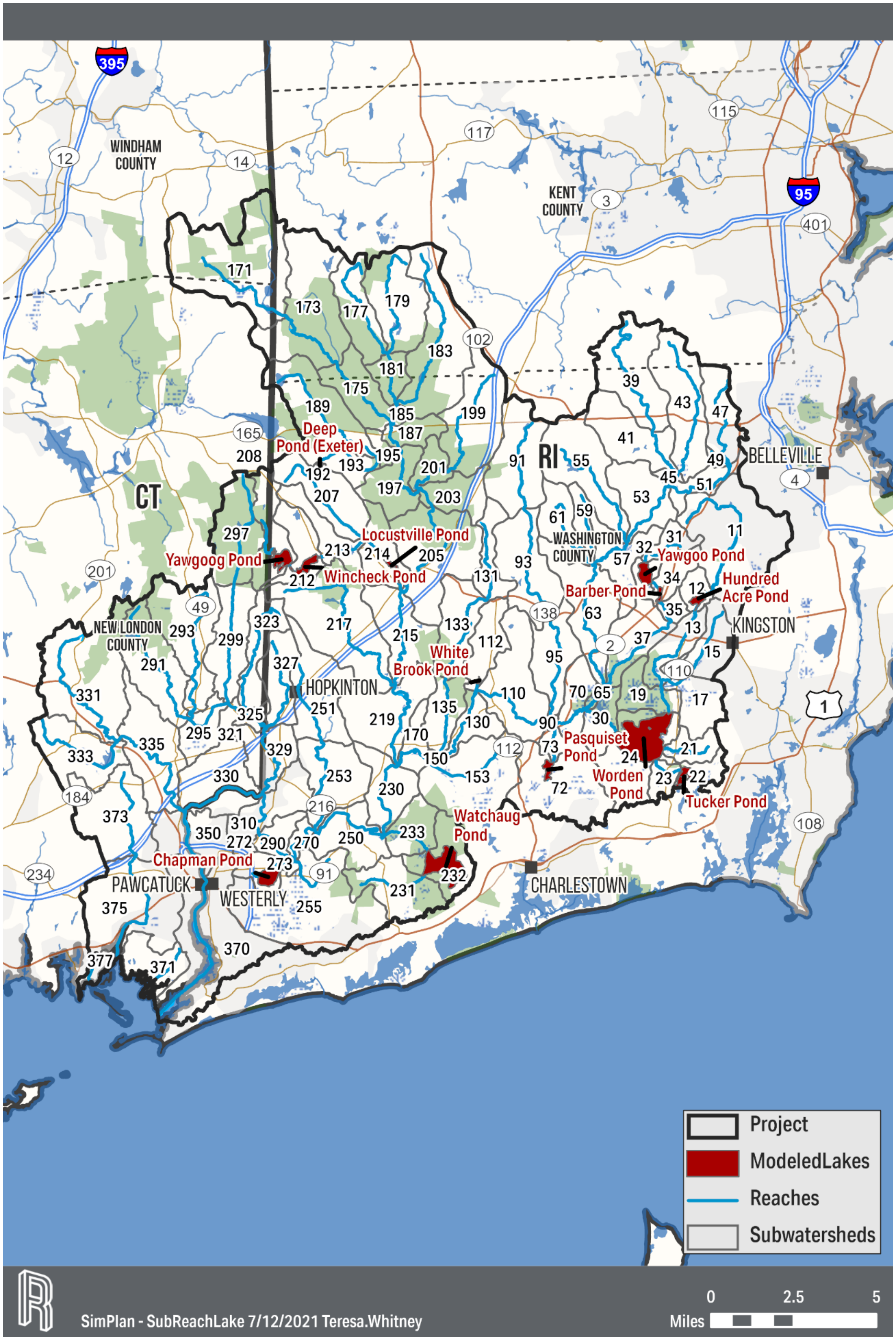

Figure 3-1. Pawcatuck Subwatersheds.

3.2 CHANNEL SEGMENTATION AND CHARACTERIZATION

The river channel network is the major pathway by which sediment and contaminants are transported from the watershed to the Pawcatuck River. Accurately representing or characterizing the channel system in the watershed for the model application is, therefore, important. The river-reach segmentation considers river travel time, riverbed slope continuity, cross-section and morphologic changes, entry points of major tributaries, sampling locations, and impairment status.

The channel characteristics are needed to define routing and stage-discharge behavior, and bed composition for sediment, carbon, and nutrients as well as bed/water-column interactions related to temperature, benthic oxygen demand, nutrient fluxes, and benthic algal mass. Because channel characteristics need to be defined spatially throughout the stream system, information from as many sites as possible were used to define channel characteristics. Some benthic chlorophyll *a* data were available in the Pawcatuck River Watershed and were used during the calibration process.

3.2.1 REACH PROPERTIES AND LAKE SELECTION

The NHDPlus high-resolution flowline layer was used to create the primary reach network. The primary reaches layer was edited as needed by using the DEM and an imagery basemap. The three lakes that are listed in the Request for Proposal (RFP) as needing to be explicitly modeled were Watchaug, Worden, and Hundred Acre. Additional lakes selected to be explicitly modeled were chosen based on the impairment status, lake size, data availability, and location in the watershed. If a lake that was impaired for a modeled parameter was greater than 100 acres, was greater than 50 acres with a substantial dataset (1,000 or more measurements), or was not a headwaters lake and greater than 50 acres, that lake was explicitly modeled. One lake or stream segment was modeled per subwatershed. The significant lakes for the explicit lake analysis were from the assessed lakes and ponds layers from Rhode Island and Connecticut. The final list of ponds to be explicitly modeled included Barber, Chapman, Deep (Exeter), Hundred Acre, Locustville, Pasquiset, Tucker, Watchaug, White Brook, Wincheck, Worden, Yawgoo, and Yawgoog.

Reach length and slope are required to determine physically based parameters in the model application and develop function tables (F-tables). These values were calculated using ArcGIS for all nonlake reaches. Lakes that were modeled explicitly were assumed to have an outflow. Slope was derived from the USGS 10-meter (m) by 10-m three-dimensional (3D) Elevation Program grid.

Data used to develop the reaches included the following:

- NHDPlus High-Resolution Flowlines (https://www.usgs.gov/core-science-systems/ngp/national-hydrography/nhdplus-high-resolution)
- RIDEM and CTDEEP Assessed Streams and Lakes (https://www.rigis.org/ and https://portal.ct.gov/).

3.2.2 NUMBERING SCHEME

This section describes the numbering scheme that was used for the watershed drainage network. Reach I.D.s consist of one to three numerical digits. Main-stem reaches occur along the Pawcatuck River and were given I.D.s that end in zero (i.e., 0) and were assigned an odd-tens digit (i.e., middle number) if they represented a stream segment (e.g., 110, 130, 150, and 190 in the schematic) and an even-tens digit if they represented a lake (e.g., 120 and 160 in the schematic). Tributaries were assigned an odd reach I.D. for the ones digit (i.e., end number) if they represented a reach (e.g., 141, 143, and 153 in the schematic) and an even number if they represented a reservoir (e.g., 142 in the schematic). The tens-digit of the tributary reach I.D.s correspond with the downstream, main-stem reach I.D. (e.g., 111 and 113 flow into 120). Reach I.D.s for subwatersheds and reaches were numbered in order beginning with lower numbers upstream and ending with higher numbers downstream. If the next logical downstream, main-stem reach I.D. was not used, the downstream reach was given the next largest main-stem reach I.D. For example, if a reach downstream of a main-stem reach with a reach I.D. of 170 and five tributary reaches (i.e., 171, 173, 175, 179, and 181) flow into the next downstream, main-stem reach, then that next main-stem reach would need to have a reach I.D. of 190. Each subwatershed typically only contains one waterbody (i.e., reach or lake) and was given the corresponding reach I.D.

3.2.3 F-TABLE DEVELOPMENT

This section describes the development of F-tables, which are required by the HSPF model to route water through each modeled reach (i.e., lake or stream). An F-table summarizes the hydraulic and geometric properties of a reach and is used to specify functional relationships among surface area, volume, and discharge at a given depth.

3.2.3.1 LAKE F-TABLES

Data for lake F-table calculations include surface area and volume at various water elevations (depths) and overflow information. When available, surface area, volume, depth, spillway length, height above sill, and lake runout elevation data were used for F-table development. Because these data are often unavailable, the F-tables were based on the average values where data were missing, which is sufficient for the purposes of this model. The equations that were used to calculate flows from lakes at different water elevations, as well as any assumptions made, are discussed in this section. For simplicity and because of the lack of overflow data, the equation of discharge for overflow spillways was used to calculate discharge from lakes (Equation 3-1). Because of the project scale, coefficient correction factors for overflow calculations were not used and side contractions of the overflow and approach velocity have been disregarded, which allows for using the equation in its simplest form.

$$Q = C \times L_e \times H^{1.5} \qquad (3\text{-}1)$$

where:

Q = Discharge (cubic feet per second [cfs])

H = Water depth above weir (head, feet [ft])

L_e = Effective length of crest (ft)

C = Variable coefficient of discharge.

The total head (H) used in the equation was calculated at variable water levels as the difference between the water-surface and outlet elevations. The outlet was assumed to be at the maximum recorded depth (if available) or the maximum contour depth. An effective length of the crest (L_e) was derived from a spillway length when available from dam data. When a spillway length was not available, the mean length of all of the available sites was assumed. At lake depths below the outlet, L_e was set equal to the spillway length. At lake depths above the outlet, L_e varies as a function of depth and was increased assuming a 0.02 floodplain slope at each end of the crest. The variable coefficient of discharge (C) was calculated using an empirical relationship derived by plotting *x-y* points along a basic discharge coefficient curve for a vertical-faced section with atmospheric pressure on the crest from the U.S. Bureau of Reclamation [1987] (Equation 3-2):

$$C = 0.1528 \times ln\left(\frac{P}{H_d}\right) + 3.8327 \qquad (3\text{-}2)$$

where:

P = Crest height (ft)

H = Head (ft).

The crest height (P) was assumed as the height above the sill (if available). The head (H) varies with the water surface and was calculated as described in the previous paragraph. When the height above the sill is unavailable, the mean value from all of the available sites was assumed.

After the available data were collected and combined, an F-table was developed for each lake by calculating the surface area, volume, and discharge over a range of depths. F-tables for lakes with contour data were created using the depths, surface areas, and volumes calculated with the Bathymetry Volume and Surface Area ArcGIS ModelBuilder tool. This tool creates a separate, triangulated irregular network (TIN) for each lake. The surface volume portion of the tool was used to calculate the area and volume below specified depths. F-tables for the lakes without contour data were developed using the calculated surface area, volume, and depth relations. For these lakes, the volume and surface area at incremental depths was estimated using conical geometry and assuming a flat bottom for an inner circle with one-half of the radius of the maximum surface area. The highest contour (if available) or maximum depth was assumed as the outlet. Depths were added incrementally above the outlet until the F-table discharge exceeds the maximum observed discharge levels. The surface area and volume above the outlet were calculated using conical geometry with an initial floodplain slope of 0.01. The discharge at each height above the outlet was calculated using Equations 3-1 and 3-2. The discharge values of depths at or below the outlet were assumed to be zero. The initial value of the floodplain slope is arbitrary and was adjusted as a part of the calibration process.

Data sources used to develop the lake F-tables included the following:

- CTDEEP (https://portal.ct.gov/DEEP/GIS-and-Maps/Data/GIS-DATA)
- RIDEM (http://www.dem.ri.gov/maps/mapfile/pondbath.pdf)
- National Inventory of Dams (https://nid.sec.usace.army.mil/ords/f?p=105:1)
- CTDEEP Dam Information Uploaded to Shared Folder
- RIDEM Environmental Resource Map (Regulated Facilities – Dam) (https://ridemgis.maps.arcgis.com/apps/webappviewer/index.html?id=87e104c8adb449eb9f905e5f18020de5).

3.2.3.2 STREAM F-TABLES

Data requirements for stream F-table development include cross-section and discharge measurements. Cross-section measurements were obtained from the width, depth, and area measurements provided by CTDEEP and RIDEM; HEC-RAS models, where available; USGS measurements; and Light Detection and Ranging (LiDAR) data, where available. When more than one cross section was available within the same reach, the cross section from the furthest downstream site was assigned to the entire reach. Main-stem reaches for which cross-section data were unavailable were assigned a representative cross section using best engineering judgment. Representative main-stem cross sections were assigned based on the nearest available downstream, main-stem cross section because a cross-section area generally increases from upstream to downstream. Tributary reaches for which cross-section data were unavailable were assigned a representative tributary cross section based the proximity to an available cross-section and similar drainage area. After each reach was assigned the most appropriate cross section based on the location and drainage area, discharge was calculated for each reach by using length, slope, and cross-section data with the Manning's equation shown in Equation 3-3. The channel slope (S) for each reach was calculated by dividing the difference between the maximum and minimum elevations by the reach length.

$$Q = \frac{1.486}{n} \times A \times R^{\frac{2}{3}} \times S^{\frac{1}{2}} \qquad (3\text{-}3)$$

where:

Q = Discharge (cfs)

n = Manning's roughness coefficient

A = Cross-section area (square feet [ft^2])

R = Hydraulic radius (ft)

S = Channel slope.

Manning's roughness coefficients (n) of 0.04 and 0.10 were used for the channel and floodplain, respectively. The values for the floodplain slope, channel slope, Manning's roughness coefficient, and horizontal bank extension length were set based on the local topography and by using best engineering judgment, and the values were adjusted as needed during the calibration process. After the required data were collected and compiled, an F-table was developed for each reach by calculating the surface area, volume, and discharge over a range of depths. To allow the F-table to handle large storm flows, the cross sections were extended 1,000 ft horizontally beyond each bank. The floodplain slope was assumed as 0.05. The volume and surface area were calculated with the cross sections and stream segment lengths. The data used to calculate the elevation and slope for the model included the USGS 3D Elevation Program (https://www.usgs.gov/core-science-systems/ngp/3dep).

Data used to develop the stream F-tables included the following:

- USGS Stream-Gaging Notes Uploaded to Shared Folder
- USGS Stream Measurements (https://waterservices.usgs.gov/nwis/)
- USGS Flood Inundation Maps (https://pubs.er.usgs.gov/publication/sir20185112)

- HEC-RAS Models Provided by Connecticut Department of Transportation (CTDOT) via CTDEEP
- USGS 3D Elevation Program (https://www.usgs.gov/core-science-systems/ngp/3dep).

3.3 LAND SEGMENTATION

Land-use (or land-cover) data are a critical factor in modeling watersheds, because these data provide the detailed characterization of the potential pollutant sources entering the reaches as nonpoint-source contributions. The land-use distribution also has a major determining impact on the hydrologic response of the watershed. The major land use in the Pawcatuck River Watershed is forest, which makes up more than half of the total area.

This section describes how the Pervious Land Segment (PERLND) and Impervious Land Segment (IMPLND) module-use categories were selected for explicit representation in the model application. The PERLND and IMPLND blocks of the UCI file contain most of the parameters that describe the way that water flows over and through the watershed. The objective of this task was, therefore, to separate the watershed into unique land segments by using physical watershed characteristics to effectively represent the variability of hydrologic and water quality responses in the watershed. The primary watershed characteristics selected for the PERLND and IMPLND categorization included drainage patterns, meteorological variability, land-cover, and soil properties. MS4 areas in Connecticut were provided by CTDEEP and RIDEM and are also represented because of their link to permitting and water management. These characteristics were selected based on the significance of their influence on hydrologic processes and water quality constituents of interest as well as the quality and availability of spatial data associated with the characteristics.

3.3.1 ELEVATION

Topography provides the elevation and slope values for a project area, which are important in setting up HSPF because these values are needed for characterizing the landscape and land areas of the watershed. The flow accumulation and direction derived from the elevation raster data were used to delineate the subwatersheds. Average elevations and slopes were also calculated for each model subwatershed.

The delineated subwatershed models were linked to the PERLND or IMPLND that drain to the subwatersheds in the schematic block of the UCI file. The subwatersheds that were aggregated into hydrozones based on meteorological variability provided the initial boundaries for the PERLND and IMPLND and allowed for accurately representing the hydrologic processes while reducing computational demands. The procedures for determining the PERLND and IMPLND categories within each hydrozone are described in the following sections. The 3D Elevation Program from the USGS has 10-m by 10-m elevation data available for download across the United States (https://www.usgs.gov/core-science-systems/ngp/3dep). These 3D Elevation data were used to calculate the slope information for this model application.

3.3.2 LAND USE

Rhode Island has a 2011 land-cover layer (https://www.rigis.org/datasets/land-use-and-land-cover-2011), and Connecticut has a 2015 land-cover layer (https://clear.uconn.edu/projects/landscape/index.htm). Land covers for the two states were aggregated/reclassified into a set of model land covers that were used to develop the PERLND and IMPLND classifications within each hydrozone in the Pawcatuck River Watershed. These data were used to define the movement of water through the system (i.e., infiltration, surface runoff, and water losses from evaporation or transpiration) that was significantly affected by the land cover and its associated characteristics. A hydrologic soil group (HSG) was also represented on the forest land, which makes up a very large portion of the total land cover. The Connecticut land-cover layer does not divide the developed land classifications into different density categories; therefore, the distribution of the National Land-Cover Database (NLCD) 2016 developed density categories from each Connecticut subwatershed of the Pawcatuck River Watershed was applied to the Connecticut-developed land-cover class. The Rhode Island land-cover layer does not include a turf and grass category; therefore, the distribution of the National Agricultural Statistics Service Cropland Data Layer 2019 (https://clear.uconn.edu/projects/landscape/download/Landcover2015_v2-03_ctstp83.zip) (i.e., sod/grass seed versus all of the other cropland categories) was applied to the Rhode Island cropland land-cover class.

3.3.2.1 PERVIOUS AND IMPERVIOUS LAND CLASSIFICATION

The number of operations (e.g., PERLND, IMPLND, RCHRES, PLTGEN, and COPY) allowed in one HSPF model application is limited; therefore, the categories represented in each state land-cover layer were aggregated into relatively homogeneous model categories. Forest is the predominant land-cover class and, therefore, was segmented to represent distinct forest types (e.g., deciduous and coniferous) and HSGs. The Soil Survey Geographic Database (SSURGO) from the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) [2020] was used to determine the HSG (AB versus CD classifications). Figures 3-2 and 3-3 show the general reclassification schemes for converting the Connecticut and Rhode Island land-cover classes to the model land-cover classes. Tables showing more detailed land-cover reclassifications are provided in Appendix A. The HSG distributions by subwatershed were also used as a basis for the model parameterization related to infiltration and soil-moisture capacity values in the model, and the erodibility factor for each PERLND was used to parameterize the HSPF erodibility parameter for the soils in the watershed. The percentage of each HSG in the Pawcatuck River Watershed is shown in Table 3-1.

Lakes and reservoirs that were not explicitly modeled or connected to the reach geometry were modeled with the wetland category. The implications of modeling these waterbodies as wetlands are not significant. Slight differences do exist between lakes and wetlands (in terms of how they are represented in HSPF) but lakes modeled as wetlands are generally very small and likely have similar pan evaporation as wetlands. The main differences between wetlands and small ponds/open water include different amounts of vegetation and groundwater interaction. Lakes and reservoirs that were explicitly modeled were represented with an F-table rather than a modeled land cover.

The Pawcatuck River Watershed has several feedlots. Data were provided by CTDEEP and RIDEM and include the number of dairy cattle in each subwatershed. Feedlot data provided were used for estimating fertilizer application to inform the calibration process throughout the watershed. Manure from the feedlots was assumed to have been spread onto the subwatersheds that the feedlots are located in.

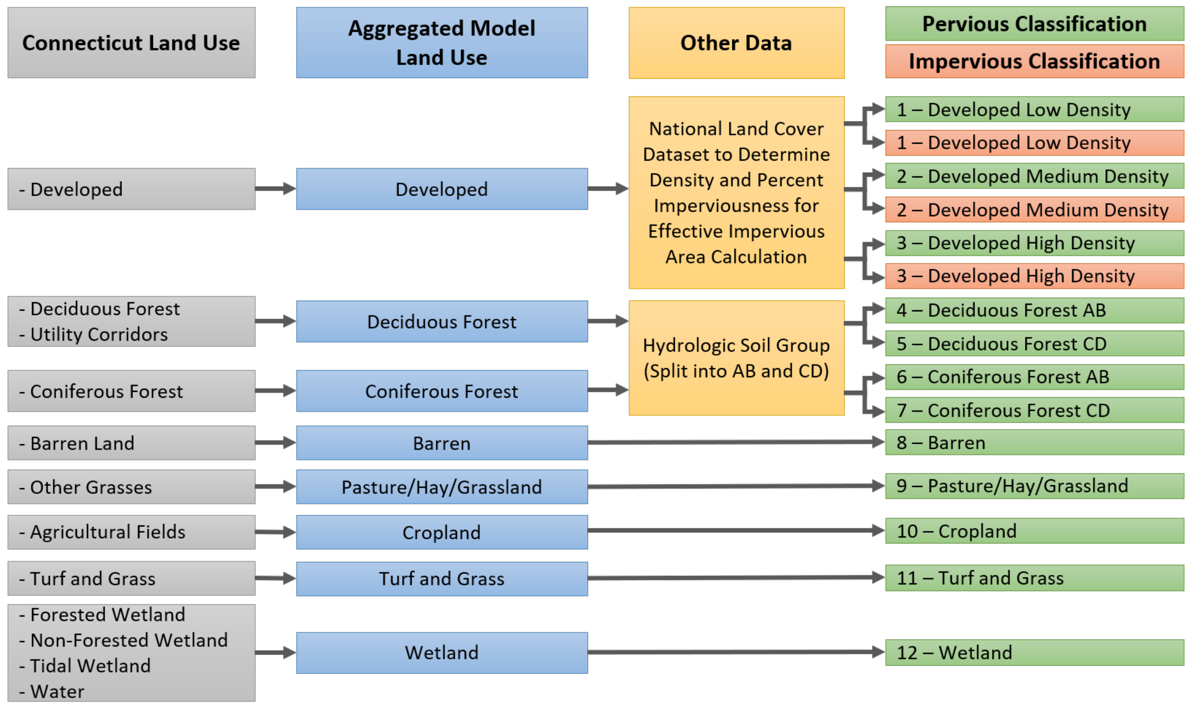

Figure 3-2. Connecticut Land-Use Category Aggregation.

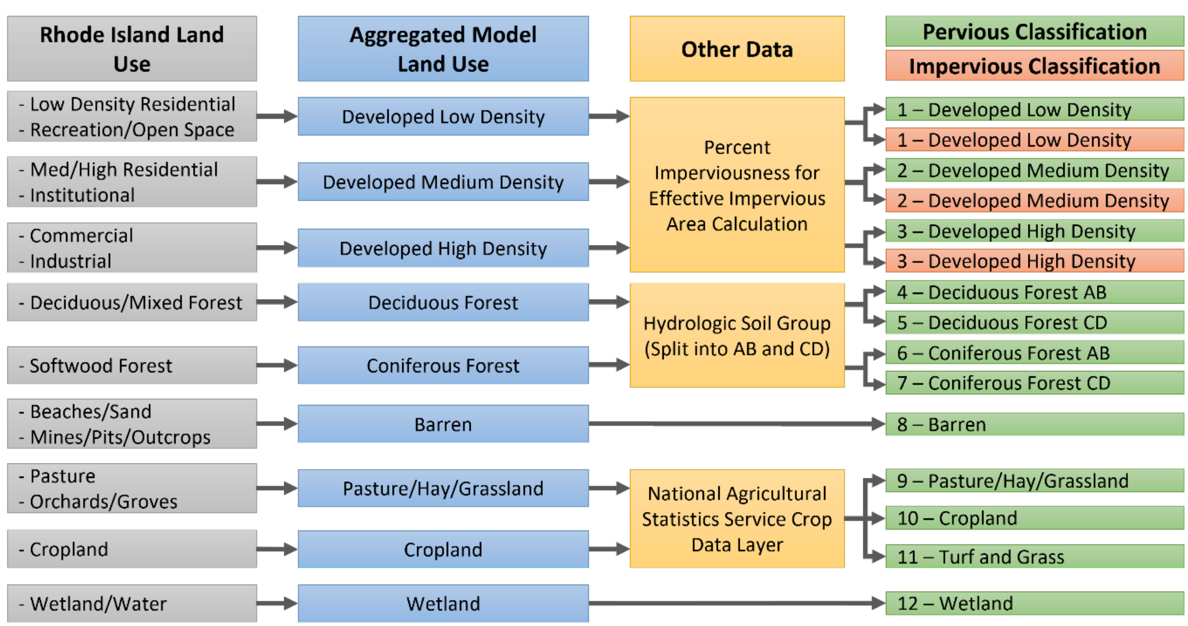

Figure 3-3. Rhode Island Land-Use Category Aggregation.

Table 3-1. General Description of Hydrologic Soil Groups

Hydrologic Soil Group	Abbreviated Description	Project Area (%)
A	Sand; sandy loams with high-infiltration rates; well-drained soils with high transmission	14
AD	A-group soil, if drained	2
B	Silt loam or loam soils, moderate infiltration, moderately drained	47
BD	B-group soil, if drained	13
C	Sandy, clay loams; low-infiltration rates that impede water transmission	6
CD	C-group soil, if drained	6
D	Heavy soils, clay loams, silty, clay; low-infiltration rates that impede water transmission	11
Unclassified	No classification determined	4

Accurately representing the Effective Impervious Area (EIA) in the watershed models is important because of the EIA's impact on the hydrologic processes that occur in urban environments. The term "effective" implies that the impervious region is directly connected to a local hydraulic conveyance system (e.g., gutter, curb drain, storm sewer, open channel, or river) and the resulting overland flow does not run onto pervious areas and, therefore, does not have the opportunity to infiltrate along the respective overland flow path before reaching a stream or waterbody. The average impervious area for each developed model category (low, medium, and high) in each Rhode Island subwatershed was derived from the Rhode Island's impervious layers using the mean impervious area. The Connecticut-developed model categories assigned, based on the NLCD 2016 distribution, were given the percent impervious area from the CLEAR IC data. The data represented the percent total impervious area (TIA), which were used to determine the percent EIA by using Equation 3-4 from Sutherland [2000]. This equation was also referenced as the default equation in Appendix 3 (*Impervious Cover in Connecticut Municipalities*) of the *Connecticut Watershed Response Plan for Impervious Cover* [CTDEEP, 2015] for areas that were mostly storm sewered (with curb and gutter) and with residential rooftops connected to the MS4.

$$EIA = 0.1(TIA)^{1.5}, TIA \geq 1 \quad (3\text{-}4)$$

Data sources used to develop the model land cover included the following:

- Connecticut
  - Connecticut Land Cover 2015 (https://cteco.uconn.edu)
  - Soils, State Soil Geographic (STATSGO) Dataset (https://www.nrcs.usda.gov)
  - Percent Impervious, NLCD 2016, (https://www.mrlc.gov) and CLEAR IC (https://clear.uconn.edu/)
- Rhode Island
  - Rhode Island Land Cover 2011 (http://www.rigis.org)
  - Soils, STATSGO (https://www.nrcs.usda.gov)
  - Percent Impervious, NLCD 2016 (https://www.mrlc.gov) and RIDEM Impervious (http://www.rigis.org).

Data sources that were used to develop an understanding of the manure application on the agricultural land included animal unit information from RIDEM and CTDEEP uploaded to shared project folder and the data were summarized by subwatershed for each state.

3.3.2.2 MUNICIPAL SEPARATE STORM SEWER SYSTEMS

Polluted stormwater runoff is commonly transported through MS4s before being discharged into local waterbodies. Certain MS4s are required to obtain NPDES permits and develop stormwater management programs that describe the stormwater-control practices that were implemented following the permit requirements to minimize the discharge of pollutants from the storm sewer system [National Pollutant Discharge Elimination System, 2020]. Representing regulated MS4s in the watershed in the HSPF model applications is important. GIS layers of the MS4 areas (i.e., polygons) were provided by CTDEEP and RIDEM for Connecticut and Rhode Island, respectively. MS4 areas were represented in the model application schematic by using a separate mass link so that the flow from those areas can be identified as separate from flow that originates in the non-MS4 areas.

Data sources used to develop the modeled MS4 areas included the following:

- Connecticut MS4s, CTDEEP Staff Uploaded MS4 Spatial Data to Shared Project Folder
- Rhode Island MS4s, RIDEM Phase II MS4s (www.dem.ri.gov/maps).

3.3.2.3 SEPTIC SYSTEMS

Septic systems fall under the category of on-site wastewater treatment systems (OWTS). OWTS are used by many households in the Pawcatuck River Watershed. Connecticut and Rhode Island have polygons that represent areas that are sewered. Blockpop points, which provide the populations from the 2010 United States Census, that fall outside of the sewered areas were assumed to be on septic systems. OWTS are generally responsible for some pollutant loads to either the groundwater or tributaries. OWTS were represented in the model application as constant loads and assumed to discharge at 50 gallons per person per day. The loading rates were set at 40.4, 10.58, and 2.5 pounds per person per day for BOD_5, TN, and TP, respectively [EPA,1980 and 1993]. The BOD_5 loads were converted to CBOD by using a factor of 1.2 for untreated waste [Thomann and Mueller, 1987]. Initial attenuation (i.e., pass-through) factors that represent septic-system efficiency were set at 0.60, 0.77, 0.14 for BOD_5, TN, and TP, respectively [EPA,1980 and 1993; Vaudrey, et. al., 2016]. Soil attenuation was represented as a function of simulated groundwater flow with less pass-through of pollutant loads occurring at lower flows; assuming more soil residence time results in greater pollutant degradation and transformation (e.g., denitrification).

The results from Connecticut's Phase II OWTS study [CTDEEP, 2020] and the modeling efforts from the nitrogen loading to Long Island Sound embayments study [Vaudrey, et. al., 2016] were used to inform and compare the OWTS simulation in HSPF. Attenuation estimates/factors were set in the model and calibrated, but the total nitrogen attenuation stayed within the range of the two studies (0.44 to 0.51). This information along with nonpoint source export estimates and point source data, were used to achieve the best possible representation of the source allocation while maintaining a good calibration of instream pollutant concentrations.

Data sources used to develop the modeled septic systems included the following:

- Individuals on Septic Systems
  - CTDEEP Staff Uploaded Connecticut Sewered Area Spatial Data to Shared Project Folder
  - Rhode Island Sewered Areas (http://www.rigis.org)
  - 2010 United States Census Blockpop (https://www.census.gov/programs-surveys/decennial-census/data.html)
- Septic Failure Rates and Loading Estimates
  - CTDEEP Uploaded Septic Study to Shared Project Folder. Data From Study Was Extrapolated to Rhode Island.

4.0 CALIBRATION AND VALIDATION

4.1 CALIBRATION AND VALIDATION TIME PERIODS

Time-period selection for model calibration and validation depends on numerous factors that include the availability of data for model operations, land-use data for model setup, climate variability, and observed data for model-data comparisons. The principal time-series data that were collected for hydrologic and water quality calibration (i.e., meteorological, point source, atmospheric deposition, observed flow, and water quality observations) indicated that long-term simulations (> 20 years) were possible at several of the stream-flow gages within the Pawcatuck River Watershed. Partial record periods, while not ideal, were still used for consistency checks as part of the calibration and validation process.

The continuous meteorological and hydrological data are available for the past 40 years, and discrete water quality sampling data are available for the past 70 years; however, more-intensive water quality sampling occurred after 2006. Based on these considerations, the preliminary hydrology calibration selection was for 2006 to 2020 and the validation period was from 1991 to 2005. The date ranges for the calibration and validation periods included mixed wet and dry periods, as shown in Figure 4-1. The same time periods were selected for water quality calibration and validation. The long-term simulation (1991 to 2020) was also a form of validation.

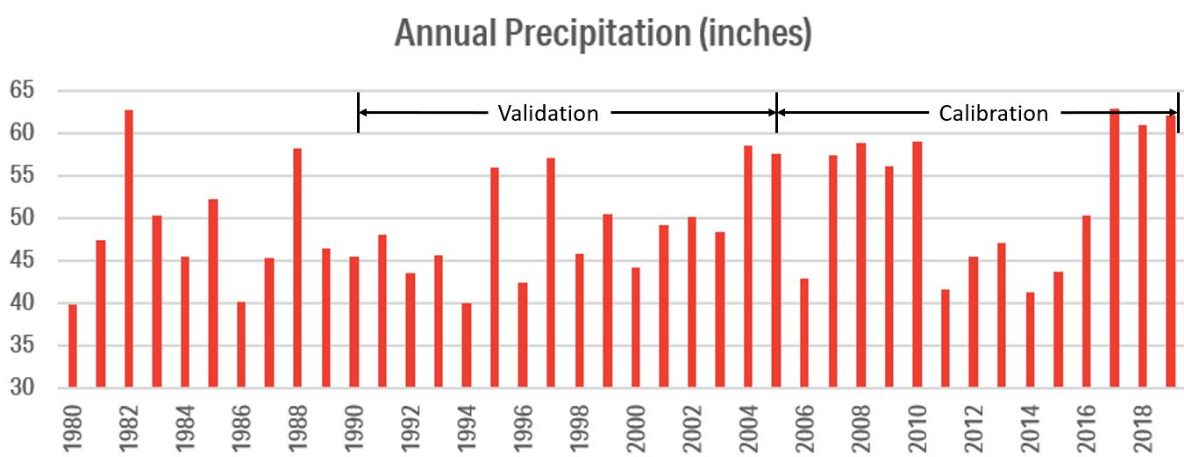

Figure 4-1. Average Annual Precipitation for Modeled Watershed Areas (Connecticut and Rhode Island) From PRISM for Years 1980 to 2019.

4.2 HYDROLOGY CALIBRATION AND VALIDATION PROCEDURES AND COMPARISONS

The Pawcatuck River Watershed model was calibrated through an iterative process of making parameter changes, running the model, producing comparisons of simulated and observed values, and interpreting the results. This process first occurred for the hydrology portions of the model, followed by the water quality portions. The procedures have been well established over the past 35 years, as described in the Application Guide for HSPF [Donigian et al., 1984] and summarized by Donigian [2002]. The hydrology calibration process was facilitated by using scripted processes in MATLAB.

Calibrating HSPF to represent the hydrology of the Pawcatuck River Watershed was an iterative process in which initial parameters were set from the previous USGS Pawcatuck River HSPF model application [Gardner et. al, 2011], and these parameters were adjusted based on the understanding of the datasets and the behavior of different parameters to achieve an acceptable calibration as defined in the Pawcatuck River Quality Assurance Project Plan (QAPP) [Imhoff and McCutcheon, 2020]. Simulated results were compared with recorded data for the entire calibration period, including wet and dry conditions, to observe how well the simulation represents the hydrologic response under various climatic conditions. By iteratively adjusting specific calibration parameter values within accepted and physically based ranges, the simulation results were changed until an acceptable comparison of simulation and recorded data was achieved.

The standard HSPF hydrologic calibration is divided into four phases:

- **Establish an annual water balance.** This phase consists of comparing the total annual simulated and observed flows (in inches) and is primarily governed by the input of rainfall and evaporation and the parameters for the lower-zone nominal storage (LZSN), lower-zone ET parameter (LZETP), and infiltration index (INFILT).
- **Adjust low-flow/high-flow distribution.** This step is generally performed by adjusting the groundwater or baseflow because the distribution between high and low flow is the easiest to identify in low flow periods. Mean daily flow conditions are used and the primary parameters involved are the INFILT, groundwater recession (AGWRC), and baseflow ET index (BASETP).
- **Adjust storm flow/hydrograph shape.** The storm flow, which is compared in the form of short, timestep (1-hour) hydrographs, is largely composed of surface runoff and interflow. Adjustments are made with the upper-zone storage (UZSN), interflow parameter (INTFW), interflow recession (IRC), and overland flow parameters (i.e., length of the overland flow plane [LSUR], Manning's N [NSUR], and slope of the overland flow plane [SLSUR]). INFILT can also be used for minor adjustments.
- **Make seasonal adjustments.** Differences in the simulated and observed total flow over each month and season are compared to see if runoff needs to be shifted from one month or season to another. These adjustments are generally accomplished by using seasonal (monthly variable) values for the parameters vegetal interception (CEPSC), LZETP, and UZSN. Adjustments to variable groundwater recession (KVARY) and BASETP are also used.

The procedures and parameter adjustments involved in these phases are more completely described in Donigian et al. [1984] and the HSPF hydrologic calibration expert system (HSPEXP) [Lumb et al., 1994; Duda et al., 2019]. The same model-data comparisons were performed for the calibration and validation periods. The specific comparisons of simulated and observed values include:

- Annual and monthly runoff volumes (inches)
- Daily flow time series of flow (cfs)
- Storm-event periods (e.g., hourly values) (cfs)
- Flow frequency (flow-duration) curves (cfs).

In addition to the preceding comparisons, the water-balance components (input and simulated) are reviewed. This effort involves displaying the model results for individual land uses, as well as the entire watershed, for the following water-balance components:

- Precipitation
- Total Runoff (sum of the following components):
  - Overland flow
  - Interflow
  - Baseflow
- PET
- Total Actual ET (sum of following components):
  - Interception ET
  - Upper-zone ET
  - Lower-zone ET
  - Baseflow ET
  - Active-groundwater ET
- Deep-Groundwater Recharge/Losses.

Although observed values are not available for every water-balance component listed above, the average annual values must be consistent with the expected values for the region as impacted by the individual land-use categories. This consistency (or reality) check was separate with data independent of the modeling (except for precipitation) to ensure that land-use categories and overall water balance reflected the local conditions. Additional snow depth/snowfall graphs were also assessed. Snow plots are used to ensure the timing/quantity of snowfall and snowmelt processes.

Figure 4-2 provides the value ranges of the correlation coefficients (R) and coefficient of determination (R^2) for assessing the model performance for daily and monthly flows. The figure shows the range of values that may be appropriate for judging how well the model performs based on the daily and monthly simulation results. As shown in Figure 4-2, the ranges for daily values are lower to reflect the difficulties in duplicating the exact timing of flows given the uncertainties in the timing of model inputs, mainly precipitation. Table 4-1 lists the general calibration and validation tolerances or targets that have been provided to model users as a part of HSPF training workshops over the past 20 years (e.g., Donigian [2000]). The values in the table attempt to provide general guidance in terms of the percent mean errors (or differences between simulated and observed values) so that users can gage what level of agreement or accuracy (i.e., very good, good, or fair) can be expected from the model application. The target level of accuracy for this project corresponded in Table 4-1 to good or very good results at more downstream, main-stem calibration sites and fair at more upstream tributary sites. Accuracy targets are highly dependent on the amount and quality of available data and, consequently, the targets were finalized after the data gaps were analyzed.

The caveats at the bottom of Table 4-1 indicate that the tolerance ranges should be applied to mean values and individual events or observations may show larger differences and still be acceptable. The level of agreement to be expected also depends on numerous site- and application-specific conditions that include the data quality, purpose of the study, available resources, and available alternative assessment procedures that could meet the study objectives.

For any watershed modeling effort, the level of expected agreement is tempered by the complexities of the hydrologic system, quality of the available precipitation and flow data, and available information to characterize the watershed and quantify the human impacts on water-related activities. These tolerances are applied to comparisons of simulated and observed mean flows, annual runoff volumes, mean monthly and seasonal runoff volumes, and daily flow-duration curves. Larger deviations would be expected for individual storm events and flood peaks in both space and time. The values shown in Figure 4-2 were primarily derived from HSPF experience and past efforts on model performance criteria; however, the values do reflect common tolerances accepted by many modeling professionals.

Figure 4-2. *R* and R^2 Value Ranges for Model Performance.

Table 4-1. General Calibration and Validation Targets or Tolerances for HSPF Applications [Donigian, 2000]

Calibration Parameter	Difference Between Simulated and Recorded Values (%)		
	Very Good	Good	Fair
Hydrology/Flow	< 10	10–15	15–25

Stipulations:

Relevant to monthly and annual values; storm peaks may differ more than monthly and annual values

Quality detail of input and calibration data

Purpose of model application

Availability of alternative assessment procedures

Resource availability (i.e., time, money, personnel).

Given the uncertain state-of-the-art in model performance criteria, inherent errors in input and observed data, and the approximate nature of model formulations, absolute criteria for watershed model acceptance or rejection are not generally considered appropriate by most modeling professionals. Most decision-makers, however, want to definitively confirm if the model is good enough for the evaluation. Consequently, for the Pawcatuck River Watershed modeling effort, the targets and tolerance ranges for daily and monthly flows correspond to a very good agreement for both the calibration and validation periods at the primary and secondary flow gages. At a minimum, the tertiary flow gages correspond to a fair agreement with most of sites falling within the good to very good range of tolerances.

The agreement between simulated and observed mean annual flow at the calibration sites is shown in Table 4-2, along with the coefficient of determination (R^2) and model fit efficiency (mfe) for the monthly and daily timesteps. Table 4-3 summarizes storm statistics for the major calibration gages for selected storm events that occurred at each of the respective gages during the calibration period. The water balances for the two primary calibration gages are shown in Table 4-4.

The hydrology results consistently show a good to very good agreement based on the annual and monthly comparisons. The monthly R^2 values are consistently greater than 0.85 and the daily values are greater than 0.70 (as shown in Table 4-2). The annual volumes are usually within the 10 percent target for a very good agreement and always within the 15 percent target for a good agreement. There appears to be a slight bias toward under-simulation during the validation period, but greater importance was assigned to the calibration period because most of the water quality samples were collected during the calibration period.

Daily storm peaks and volumes also show a very good agreement at the primary calibration gages, as shown in Table 4-3 and graphically in the daily time-series plots. Secondary and tertiary gages range from fair to very good with one site performing poorly for storm peaks (HSPF Reach 293). The poorly performing tertiary gage is a headwater stream and has a drainage area of 5.2 square miles. At this small of scale, HSPF has a difficult time representing the upper and lower bounds of the flow because of how the model lumps and routes runoff. Individual storm peaks and volumes are also influenced by attenuation occurring in reservoirs and the overall scale of the model segments. Data characterizing the reach-reservoir properties were minimal and, thus, are partly responsible for some of the discrepancies.

Figures 4-3 through 4-10 present graphical comparisons of the simulated and observed flows for the calibration and validation periods at the main calibration location: Pawcatuck River at Westerly – USGS 01118500. The comparisons include annual and monthly runoff bar graphs, daily flow frequency curves, and daily time series The flow frequency curves in Figures 4-7 and 4-8 demonstrate consistent patterns between the calibration and validation time periods and generally show good agreement. The model base flows are slightly over-simulated during the calibration time period and under-simulated during the validation period, but the differences are quite small. This bias is mainly attributed to the uncertainty in irrigation and water-supply withdrawals, point source discharges, and septic-system estimates, where data limitations and methods (i.e., annual and monthly values being applied to an hourly model timestep) are likely not capturing the daily variability.

The snow simulation results at Kingston, Rhode Island (Station USC00374266) are also shown in Figure 4-11. These results are a representative sample of all of the model results that are included in the deliverables results folder. The snow simulation shows a fair agreement with the snowfall and depth observations. Significant day-to-day differences occur between simulated and observed values, but this is a common occurrence in snow modeling because of the lack of good spatial coverage of meteorologic data, and the tremendous variations in the observed snow measurements within a watershed related to elevation, exposure, and topography. However, the model results are entirely adequate in meeting the study objectives since the primary snow modeling goal was to represent the overall volumes and general timing of the spring melt.

Based on the entire "weight-of-evidence" for the full range of model results presented, the hydrology component is confirmed to be calibrated and validated and provides a sound basis for the water quality and loading purposes of this study.

Table 4-2. Summary of the Hydrologic Calibration and Validation Statistics

HSPF Reach	Gage	Segment	Drainage Area (sq mi)	Type	Calibration (2006–2020)					Validation (1991–2005)				
					Monthly		Daily		Total Volume	Monthly		Daily		Total Volume
					R^2	mfe	R^2	mfe	% Difference	R^2	mfe	R^2	mfe	% Difference
130	01117500	Pawcatuck R	111.1	Primary	0.93	0.92	0.89	0.87	5.38	0.92	0.91	0.88	0.86	2.89
350	01118500	Pawcatuck R	309.4	Primary	0.93	0.93	0.91	0.91	–0.10	0.93	0.93	0.90	0.89	–2.18
13	01117350	Chipuxet R	11.1	Secondary	0.86	0.85	0.83	0.82	–8.15	0.87	0.86	0.82	0.81	–4.86
63	01117420	Usquepaug R	36.5	Secondary	0.91	0.90	0.86	0.84	5.49	0.91	0.91	0.84	0.83	–3.12
187	01117800	Wood R	36.3	Secondary	0.91	0.87	0.85	0.83	6.03	0.92	0.91	0.87	0.86	–6.78
215	01118000	Wood R	77.7	Secondary	0.91	0.89	0.85	0.85	4.52	0.94	0.93	0.88	0.88	–4.99
37	01117424	Chickasheen Br	6.7	Tertiary						0.87	0.86	0.84	0.84	5.62
43	011173545	Queen R	4.9	Tertiary						0.95	0.90	0.82	0.79	–4.57
53	01117370	Queen R	21.1	Tertiary	0.90	0.87	0.83	0.81	12.57	0.94	0.94	0.86	0.86	3.68
63	01117410	Usquepaug R	32.8	Tertiary						0.94	0.93	0.87	0.87	0.70
70	01117430	Pawcatuck R	83.7	Tertiary	0.94	0.93	0.89	0.89	6.88	0.91	0.90	0.88	0.87	–1.35
93	01117468	Beaver R	9.2	Tertiary	0.90	0.9	0.84	0.84	–1.26	0.92	0.89	0.86	0.84	–10.97
95	01117471	Beaver R	12.3	Tertiary						0.90	0.90	0.85	0.84	–0.90
133	01117600	Meadow Br	5.0	Tertiary						0.89	0.82	0.82	0.79	–4.59
230	01118010	Pawcatuck R	217.9	Tertiary						0.93	0.92	0.91	0.91	–2.64
293	01118300	Pendleton Hill Br	5.2	Tertiary	0.85	0.81	0.73	0.67	–11.62	0.89	0.83	0.75	0.69	–11.85
329	01118360	Ashway R	27.7	Tertiary						0.92	0.85	0.80	0.72	–5.72
335	01118400	Shunock R	16.5	Tertiary						0.90	0.85	0.83	0.79	–0.34

Table 4-3. Summary of the Storm-Event Statistics for Calibration Gages

HSPF Reach	Gage	Segment	Drainage Area (sq mi)	Type	Calibration (2006-2020)					
					Storm Volume			Storm Peak		
					Observed (inch)	Simulated (inch)	% Difference	Observed (cfs)	Simulated (cfs)	% Difference
130	01117500	Pawcatuck R	111.1	Primary	15.23	16.31	7.09	503.69	545.90	8.38
350	01118500	Pawcatuck R	309.4	Primary	15.60	15.45	−0.96	1,603.37	1,620.78	1.09
13	01117350	Chipuxet R	11.1	Secondary	15.73	14.84	−5.62	68.35	54.94	−19.63
63	01117420	Usquepaug R	36.5	Secondary	14.69	15.80	7.56	249.35	252.12	1.11
187	01117800	Wood R	36.3	Secondary	13.49	14.65	8.86	233.31	229.95	−1.44
215	01118000	Wood R	77.7	Secondary	14.09	14.81	5.07	541.75	473.58	−12.58
53	01117370	Queen R	21.1	Tertiary	12.29	13.65	11.02	158.82	141.48	−10.91
70	01117430	Pawcatuck R	83.7	Tertiary	15.95	16.67	4.53	364.52	369.33	1.32
93	01117468	Beaver R	9.2	Tertiary	13.59	14.13	3.98	67.66	59.97	−11.37
293	01118300	Pendleton Hill Br	5.2	Tertiary	13.41	10.53	−21.45	49.99	24.86	−50.28

Table 4-4. Weighted Water-Balance Components at Primary Calibration Gages

Water-Balance Component	Water-Balance Component Description	Reach 130 (inch)	Reach 350 (inch)
SUPY	Water supply to soil surface	52.7	51.8
SURO	Surface outflow	1.11	0.936
IFWO	Interflow outflow	5.39	4.93
AGWO	Active-groundwater outflow	21.9	21.6
PERO	Total outflow	28.4	27.5
IGWI	Inflow to inactive groundwater	0.421	0.431
AGWI	Active-groundwater inflow	22.8	22.5
PET	Potential ET	31.2	30.8
CEPE	Evaporation from interception storage	8.64	8.71
UZET	Evapotranspiration from upper zone	3.73	3.57
LZET	Evapotranspiration from lower zone	10.4	10.5
AGWET	Evapotranspiration from active-groundwater storage	0.086	0.136
BASET	Evapotranspiration from baseflow	0.659	0.671
TAET	Total simulated ET	23.6	23.6

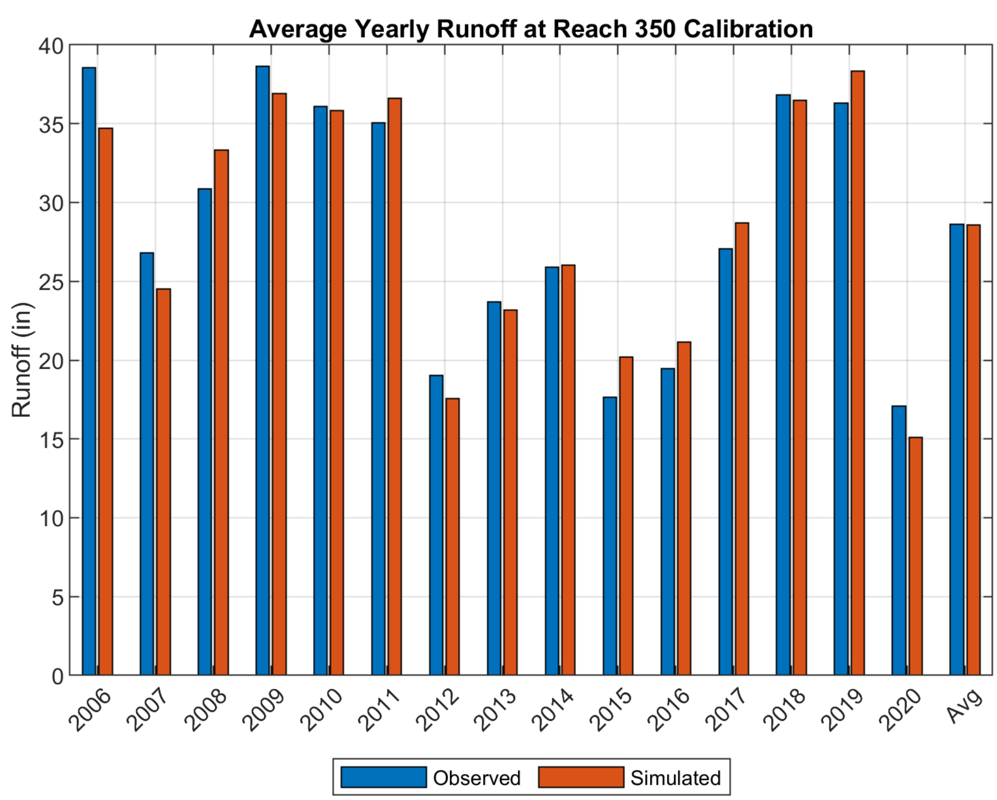

Figure 4-3. Annual Runoff for the Calibration Period at USGS 01118500 (HSPF Reach 350).

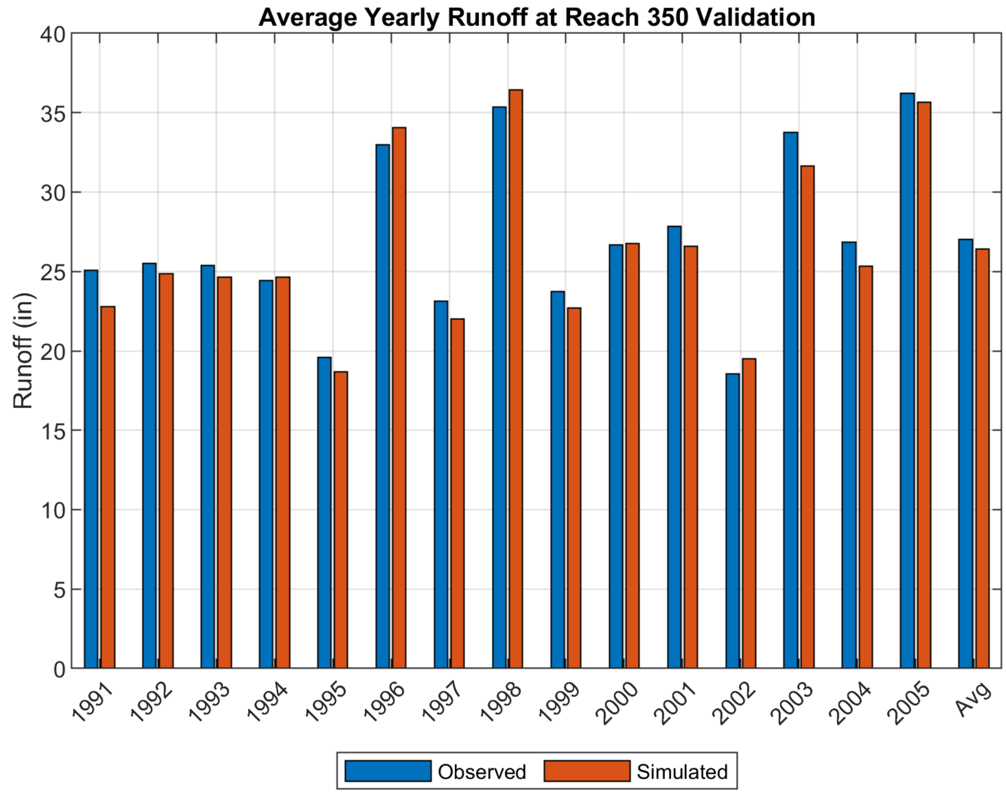

Figure 4-4. Annual Runoff for the Validation Period at USGS 01118500 (HSPF Reach 350).

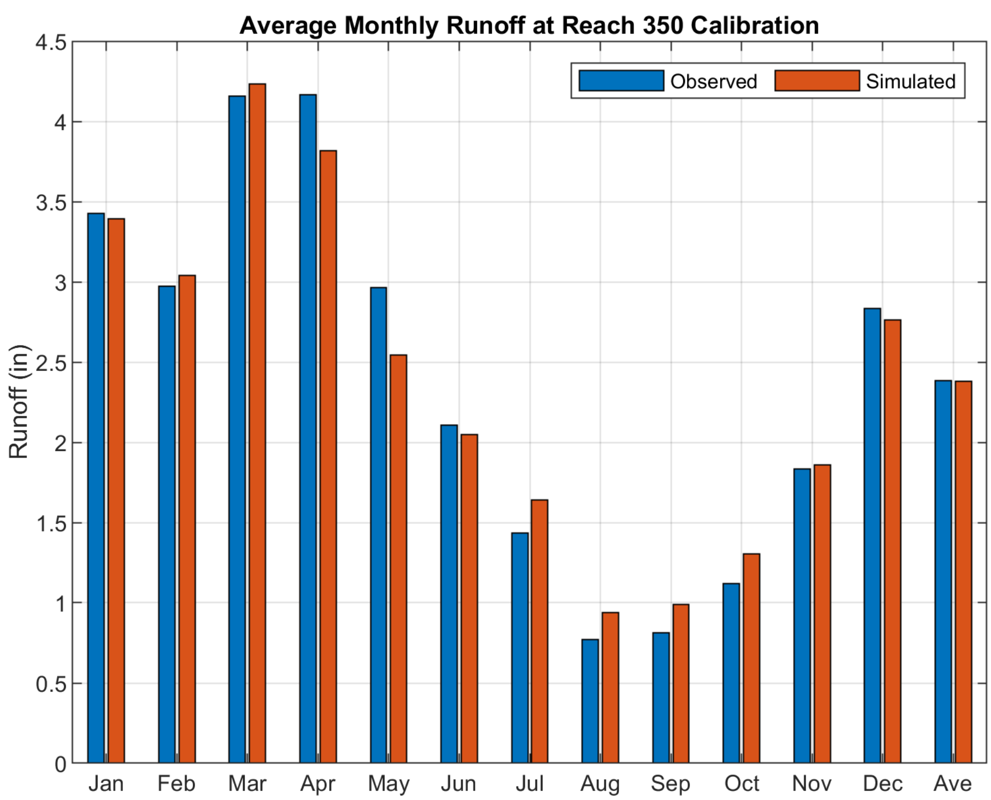

Figure 4-5. Average Monthly Runoff for the Calibration Period at USGS 01118500 (HSPF Reach 350).

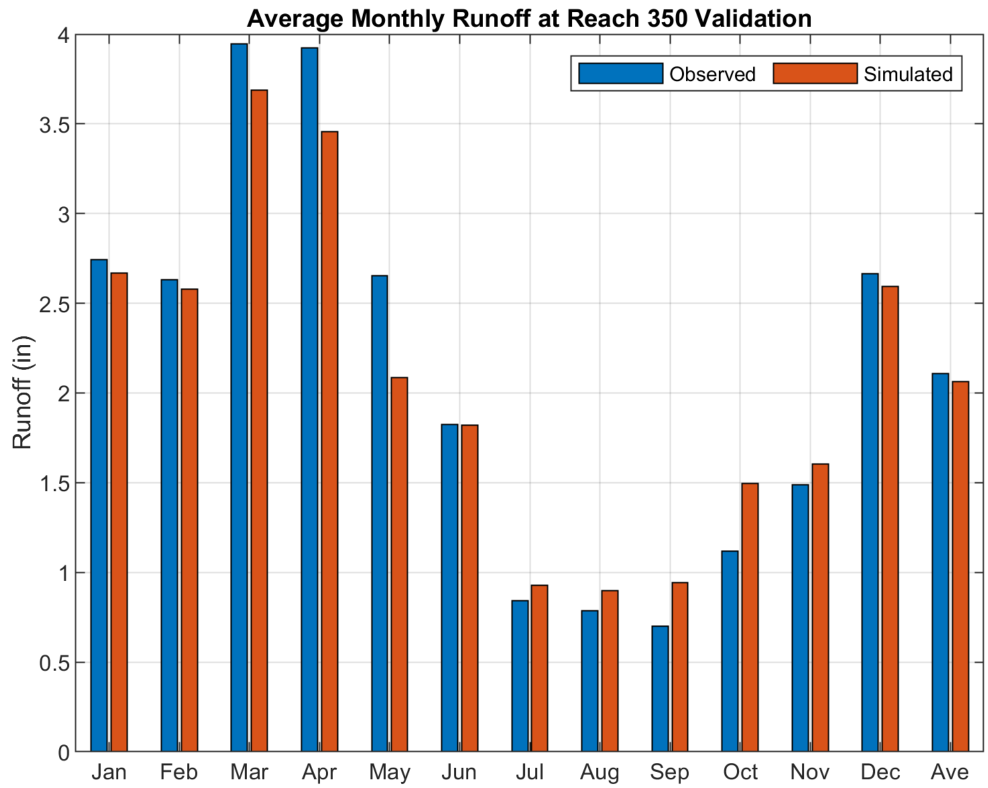

Figure 4-6. Average Monthly Runoff for the Validation Period at USGS 01118500 (HSPF Reach 350).

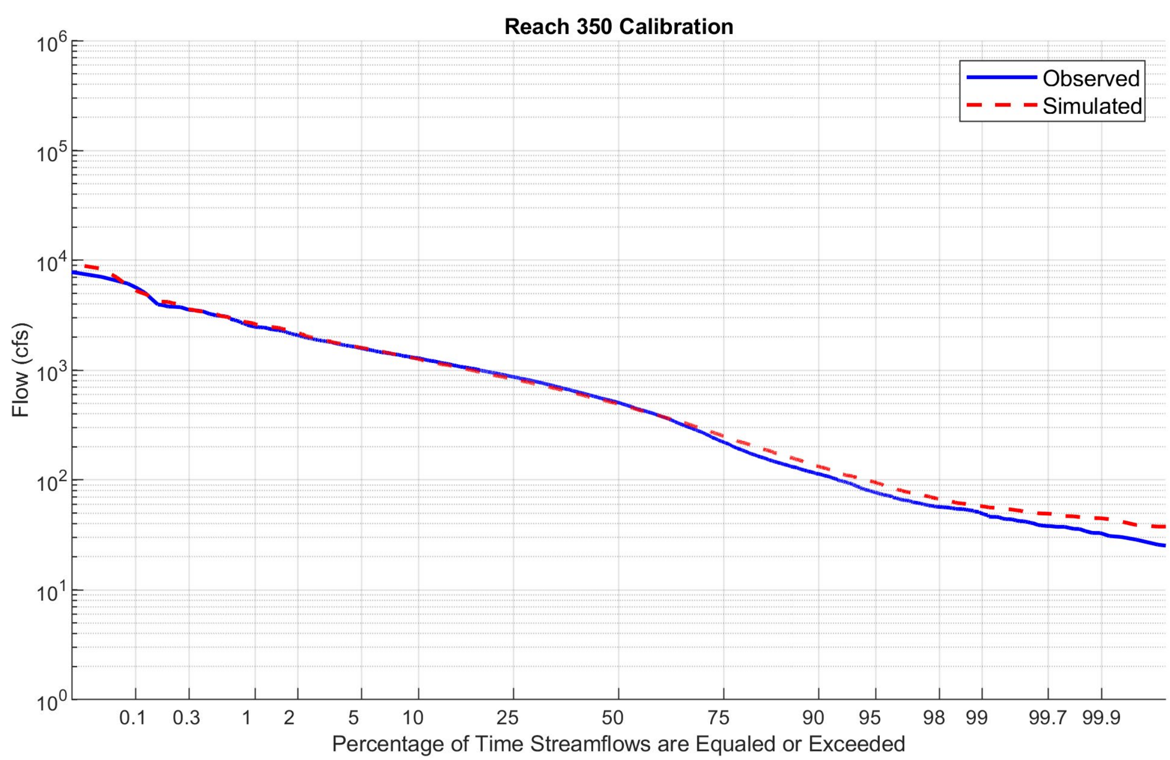

Figure 4-7. Flow Frequency Duration Curve for the Calibration Period at USGS 01118500 (HSPF Reach 350).

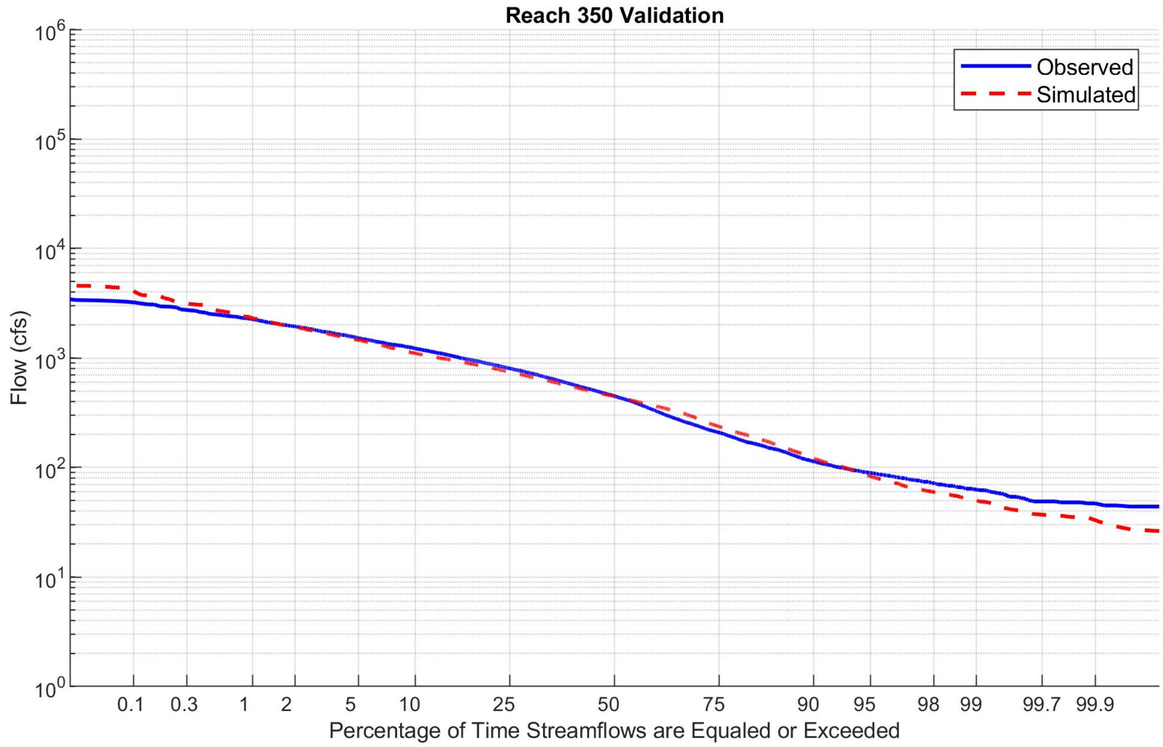

Figure 4-8. Flow Frequency Duration Curve for the Validation Period at USGS 01118500 (HSPF Reach 350).

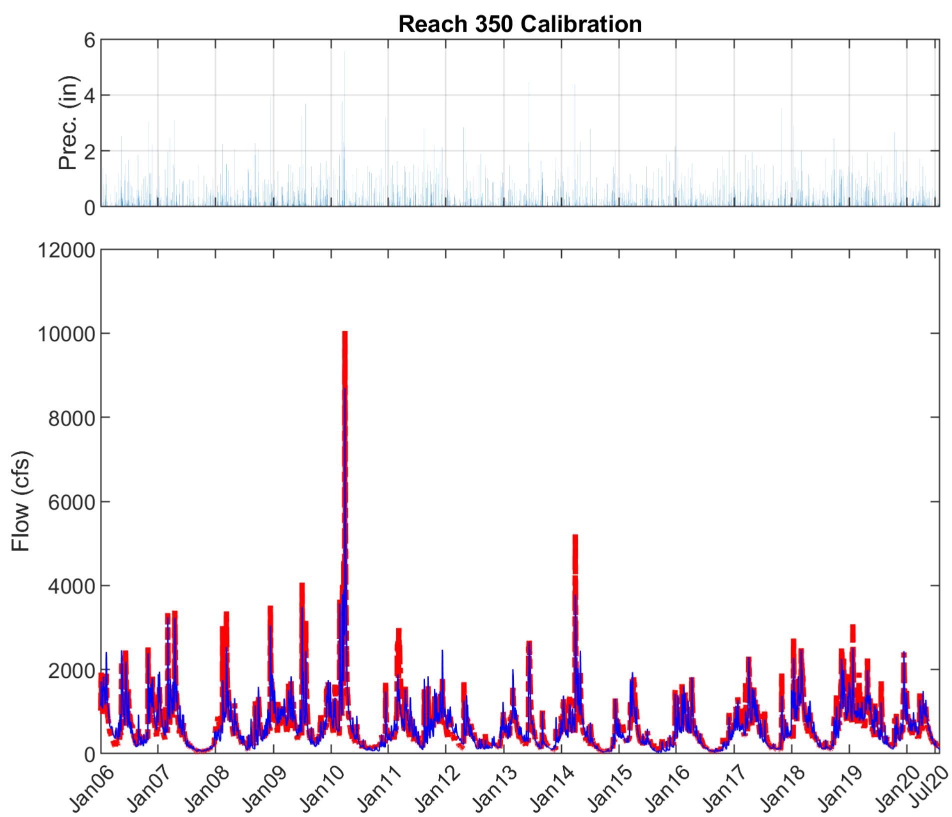

Figure 4-9. Daily Hydrographs for the Calibration Period at USGS 01118500 (HSPF Reach 350).

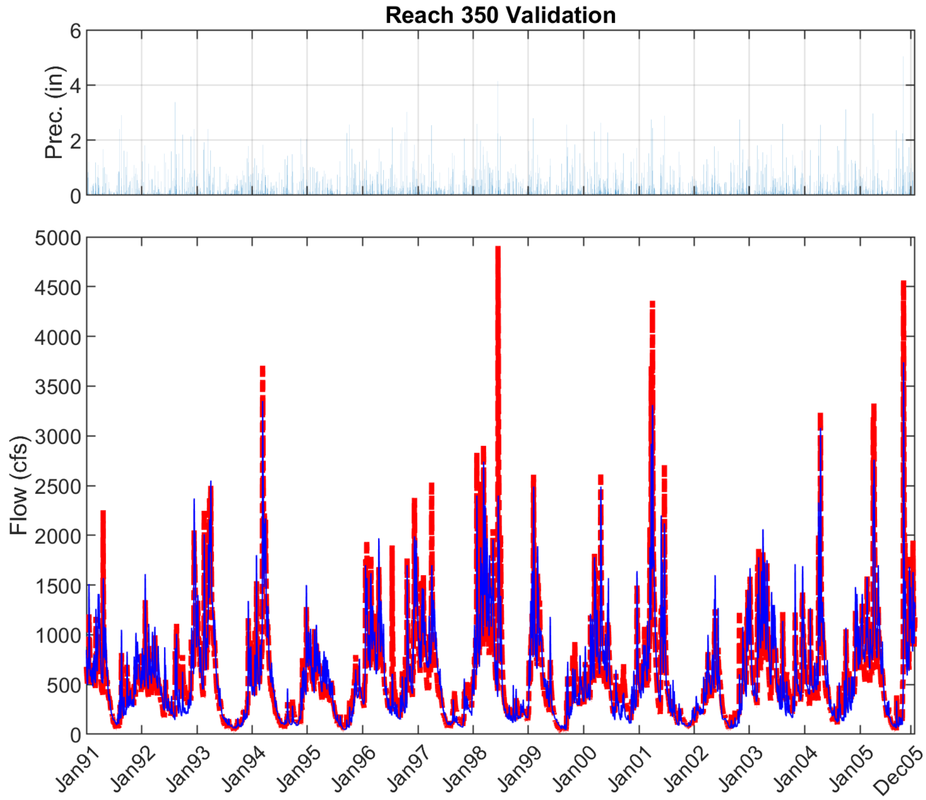

Figure 4-10. Daily Hydrographs for the Validation Period at USGS 01118500 (HSPF Reach 350).

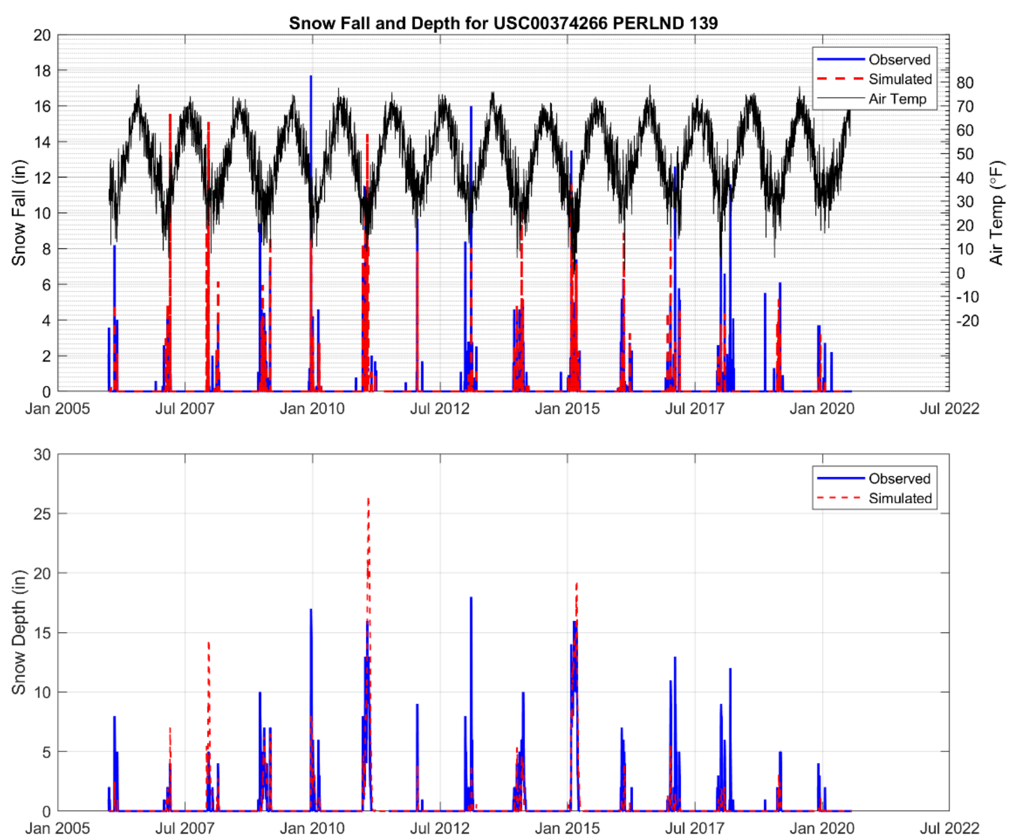

Figure 4-11. Observed and Simulated Snow Fall and Depth at Kingston, Rhode Island (Station USC00374266).

4.3 WATER QUALITY CALIBRATION

Water quality calibration was also completed through an iterative process of parameter adjustments and comparisons of the simulated and observed values and was facilitated by using scripted processes in MATLAB. The model predictions are the integrated result of all of the assumptions used in developing the model input and representing the modeled sources and processes. Differences in the model predictions and observations require the model user to reevaluate these assumptions for the estimated model input and parameters as well as consider the accuracy and uncertainty in the observations.

The water quality monitoring sites applicable for calibration are shown in Figure 4-12 and included in Table B-1 of Appendix B. The simulation plan included more sites than what is now presented as some sites were filtered out because the sampling location was not on a modeled reach segment. The primary calibration site was Pawcatuck River at Westerly, Rhode Island (USGS-01118500) on HSPF Reach 350 because it was the most data-intensive, downstream location and captures most of the watershed's flow and water quality load being transported to the estuary. Three other monitoring sites are located on HSPF Reach 350 and were also considered as primary because they fell on the same model segment. Ten reaches and their respective monitoring sites were designated as secondary calibration locations and were selected to ensure that main tributaries, larger ponds, and upstream portions of the Pawcatuck River were well represented. Eighteen additional reaches and overlapping sites were considered tertiary and were assessed along with the primary and secondary sites to confirm that the entire watershed was properly characterized. Calibration tiers were chosen primarily by location and data availability. All of the available and applicable water quality sites, as well as the calibration types, are summarized in Appendix B.

A calibration goal was to keep the parameterization consistent throughout the project area to avoid curve fitting. Curve fitting is adjusting parameters reach by reach with the intent to force model results to follow the observed data curve without justification as to why two neighboring reaches can exhibit such different behavior. Calibrating this way often causes many inconsistencies when using the model to define protection and restoration goals. The following steps were performed at each of the calibration stations after the hydrologic calibration and validation, as well as completing the input development for the point source, atmospheric, and other contributions:

1. Estimated all of the model parameters, including land-use specific accumulation and depletion/removal rates, wash-off rates, and subsurface concentrations.
2. Tabulated, analyzed, and compared the simulated, annual nonpoint-loading rates with the expected range of nonpoint-loading rates from each land use (and each constituent) and adjusted the loading parameters when necessary.
3. Calibrated instream water temperature, sediment, DO, and nutrients to the observed data.

The primary calibration parameters involved in characterizing the landscape-erosion processes are the coefficients and exponents from three equations that represent different soil detachment and removal processes (detachment from the soil matrix by rainfall, wash-off capacity, and removal). Nonpoint sources of total ammonia and nitrate-nitrite were simulated through accumulation and depletion/removal and a first-order, wash-off rate from the overland flow. Because of the affinity of orthophosphate to bind to sediments, orthophosphate was simulated using a linear relationship with

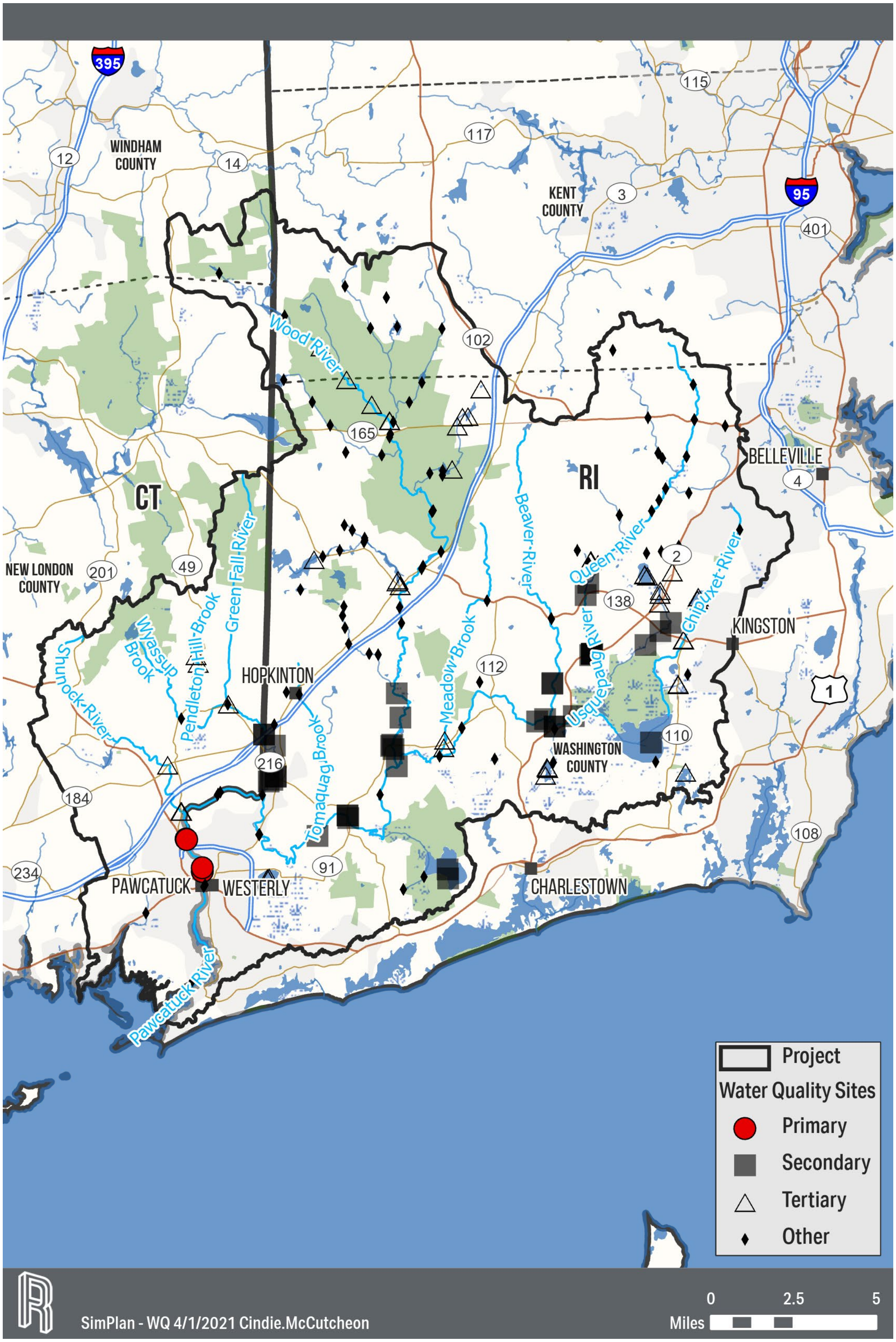

Figure 4-12. Pawcatuck River Water Quality Monitoring Locations.

sediment washing off of the land. BOD was also simulated using the sediment associated wash-off. Subsurface flow concentrations were estimated on a monthly basis. Atmospheric depositions of nitrogen and ammonia were applied to all of the land areas and contributed to the nonpoint source load through the buildup/wash-off process.

The model simulates the instream and lake processes that contribute to sediment transport, algal growth, nutrient consumption, and DO dynamics. The sediment behavior for each size class was investigated to ensure that the sediment dynamics reflected the field observations. Although HSPF does not explicitly simulate stream-bank contribution dynamics, these processes were implicitly included by allowing the streambed to contribute those loads. All of the required instream parameters were specified for total ammonia, inorganic nitrogen, orthophosphate, and BOD. The processes in the instream portion of the model included BOD accumulation, storage, decay rates, benthic algal oxygen demand, settling rates, and reaeration rates. Atmospheric deposition onto water surfaces was represented in the model as a direct input to the lakes and river systems. Biochemical reactions that affect DO were also represented in the model application. The overall sources considered for BOD and DO included point sources such as WWTFs, nonpoint sources from the watershed, interflow, and active-groundwater flow.

The instream calibration began with temperature and sediment and then to DO and nutrients. The DO and nutrient calibrations were conducted in tandem because these components depend on each other. The calibration required developing time-series graphs to compare the simulated and observed water quality data. Instream water quality calibration also included generating monthly boxplots, concentration-duration curves, and scatterplots of concentrations and corresponding flows. To assess the diurnal variability, hourly boxplots were generated for temperature and DO. Sediment scour and deposition in the streambed for each reach over the simulation period and nutrient budget were evaluated.

Lake and impoundment water quality calibrations are often difficult in HSPF because the model simulates a completely mixed system (homogeneous water body with no vertical stratification). Large, deep headwater lakes with little inflow/outflow can produce an overestimation/accumulation of nitrogen or phosphorus and low chlorophyll *a* concentrations. The inherent variability in depth, surface area, volume, and residence time between lakes in a model application causes each lake to behave differently, which makes developing a standard approach or solution difficult. To address these issues and achieve a dynamic, steady-states system, instream parameters for lakes/ponds are generally very different compared to reaches [AQUA TERRA Consultants, 2015]. Bias as a result of lake stratification is reduced by calibrating to the observed values taken from the surface to 1 meter in depth.

The essence of watershed water quality calibration is to obtain acceptable agreement of observed and simulated concentrations (i.e., within defined criteria or targets) while keeping the instream water quality parameters within physically realistic bounds and the nonpoint-loading rates within the expected ranges from the literature. The general water quality calibration targets or tolerances for HSPF applications are shown in Table 4-5.

The calibration was accomplished while maintaining consistent parameters in each of the land-use categories throughout the Pawcatuck River Watershed and was attained by prioritizing the calibration at the primary calibration site. Twenty-eight additional gage sites (as listed in Appendix B) were also examined during the calibration efforts to ensure that the model results were consistent throughout the watershed.

Table 4-5. General Calibration Targets or Tolerances for HSPF Applications [Donigian, 2000]

Calibration Parameter	Difference Between Simulated and Recorded Values (%)		
	Very Good	Good	Fair
Sediment	< 20	20–30	30–45
Water Temperature	< 7	8–12	13–18
Water Quality/Nutrients	< 15	15–25	25–35
Pesticides/Toxics	< 20	20–30	30–40

Stipulations:

Relevant to monthly and annual values; storm peaks may differ more than monthly and annual values

Quality detail of input and calibration data

Purpose of model application

Availability of alternative assessment procedures

Resource availability (i.e., time, money, and personnel).

HSPF uses nonpoint-loading rates (sometimes referred to as export coefficients) are highly variable with values ranging occasionally to an order of magnitude depending on local and site conditions of soils, slopes, topography, climate, and disturbance. Although several studies on export coefficients have been completed for Connecticut, the values developed by Frink [1991] and the previous CTWM modeling efforts [AQUA TERRA Consultants, 2001; 2002; 2015] were used to compare the main nutrient variable (TN and TP) results because of their relevance to the current modeling effort. The averages for the two studies are shown in Table 4-6 along with a standard error term for Frink's results and a range for the CTWM results.

Experience with HSPF applications is generally consistent with the above values. The above loading rates were used for general guidance (to supplement our past experience) in evaluating the loading rates and imposing relative magnitudes by land-use type. No attempt was made to specifically calibrate the loading rates to duplicate the export coefficients previously noted. The Pawcatuck River Watershed Model land-use specific average annual nonpoint-loading rates (pounds per acre per year [lb/acre/year]) for TN and TP during the calibration period are provided in Table 4-7. A summary of the export coefficients for all of the modeled constituents is provided in Appendix C.

The mean simulated values for TN and TP are fairly comparable to the two previous studies when considering the reported ranges. The only land classes that fall outside the reported ranges are the agricultural classes for TN and wetland class for TP; however, considering that each study used data from a different time period and that the model segments account for some degree of local conditions, the values are generally consistent.

Table 4-6. Summary of Export Coefficients From Past Studies

Land-use	Frink's Export Coefficients (lb/ac/yr)		CTWM Export Coefficients (lb/ac/yr)	
	Total Nitrogen	Total Phosphorus	Total Nitrogen	Total Phosphorus
General Urban	12.0 ± 2.3	1.5 ± 0.2	NA	NA
Pervious Urban	NA	NA	8.5 (5.6–15.7)	0.26 (0.20–0.41)
Impervious Urban	NA	NA	4.9 (3.7–6.6)	0.32 (0.18–0.36)
Agriculture	6.8 ± 2.0	0.5 ± 0.13	5.9 (3.4–11.6)	0.30 (0.23–0.44)
Forest	2.1 ± 0.4	0.1 ± 0.03	2.4 (1.4–4.3)	0.04 (0.03–0.08)
Wetland	NA	NA	2.2 (1.4–3.5)	0.03 (0.02–0.05)

Table 4-7. Pawcatuck Watershed Model Export Coefficients for Total Nitrogen and Total Phosphorus

Land Cover	Loading Rates (lb/ac/yr)	
	Total Nitrogen Mean (range)	Total Phosphorus Mean (range)
Developed Low Intensity	8.1 (7.5–9.0)	0.38 (0.35–0.42)
Developed Low Intensity EIA	5.8 (5.5–6.0)	0.41 (0.4–0.42)
Developed Medium Intensity	8.1 (7.6–9.1)	0.39 (0.36–0.43)
Developed Med Intensity EIA	5.8 (5.6–6.1)	0.42 (0.41–0.43)
Developed High Intensity	8.2 (7.7–9.3)	0.41 (0.39–0.46)
Developed High Intensity EIA	5.9 (5.6–6.1)	0.42 (0.41–0.43)
Coniferous Forest AB	2.4 (2.0–2.5)	0.093 (0.080–0.098)
Coniferous Forest CD	2.4 (2.1–2.6)	0.093 (0.081–0.10)
Deciduous Forest AB	2.3 (2.1–2.5)	0.091 (0.081–0.098)
Deciduous Forest CD	2.4 (2.1–2.6)	0.093 (0.082–0.10)
Wetlands	2.0 (1.8–2.2)	0.074 (0.067–0.083)
Pasture	4.9 (4.4–5.3)	0.18 (0.16–0.19)
Turf and Grass	11.8 (10.3–14.0)	0.55 (0.49–0.66)
Cropland	12.6 (11.0–14.9)	0.60 (0.54–0.73)
Barren	6.0 (5.5–6.5)	0.39 (0.35–0.46)

Approximately 800 storm drain samples that span 5 calibration parameters were collected from 21 industrial and 1 MS4 permitted locations from 2005 through 2019 and were compared to the simulated average pollutant concentrations from developed land classes. Results are summarized in Table 4-8. No attempt was made to calibrate specific events because storm drains were not explicitly represented and the model scale of developed areas was much larger than the drainage areas of individual sampling locations (i.e., HSPF lumps runoff from all of the developed areas in a subwatershed and applies it to the entire reach segment). The sampling data were used solely to ensure that generalized concentration results fell within the expected ranges.

Table 4-8. Summary of Stormwater Results

Constituent	Stormwater Concentration (mg/L)	
	MS4 Sample Data	HSPF
	Median (5th–95th Percentile)	Annual Mean
Total Suspended Sediment	41 (2.5–480)	65
Total Kjeldahl Nitrogen	1.3 (0.25–13)	1.9
Ammonia as N	0.34 (0.13–1.7)	0.20
Nitrite-Nitrate as N	0.42 (0.05–2.7)	1.4
Total Phosphorus	0.25 (0.03–3.5)	0.16

Runoff and pollutant loads generated from the land surface as well as point sources, septic systems, and atmospheric deposition were summarized by source for the Pawcatuck Watershed. The percent contribution of runoff, TSS, TN, and TP are shown in Figures 4-13 through 4-16, respectively. Runoff is displayed to help visualize the relative impacts from each source. The land-cover sources were also aggregated for these outputs to aid in the review.

Relative to the runoff contributions, the TN and TP source allocation is heavily dominated by point sources and septic systems. Septic systems account for 21 and 14 percent of the TN and TP load, respectively. Calibration tests indicated that simulated instream nitrogen concentrations were very sensitive to septic-system attenuation estimates; consequently, a large portion of the calibration focused on their representation. A summary of the input annual septic loads, attenuation factors (the product of initial septic-system pass-through and soil attenuation), and simulated annual septic loads of TN, TP, and BOD for the calibration period are shown in Table 4-9.

The simulated septic-system TN load was 8.5 percent higher than the Vaudrey et al. [2016] estimate of 234,432 pounds per year (lb/yr) (not factoring in the 0.50 attenuation factor used to represent pond/stream cycling) and 47 percent higher than the CTDEEP's estimate of 30,686 lb/yr, which included only a small portion of the watershed (HSPF simulated 45,224 lb/yr for the overlapping area in Connecticut). Although the total loads may vary because of differences in the population estimates, study areas, and loading assumptions, the simulated TN attenuation was within the range of 0.44 – 0.51 that was determined by the two previous OWTS studies [Vaudrey, et al., 2016; CTDEEP, 2020]. The attenuation factor for TP is relatively low when compared to BOD and TN, which indicates very little of the TP load made it into a simulated reach or pond. The small amount of TP pass-through can be attributed to orthophosphate's affinity to adsorb to soil particles, and pass-through factors as low as 0.01 have been reported [Efroymson et al., 2007; Lowe and Siegrist, 2008].

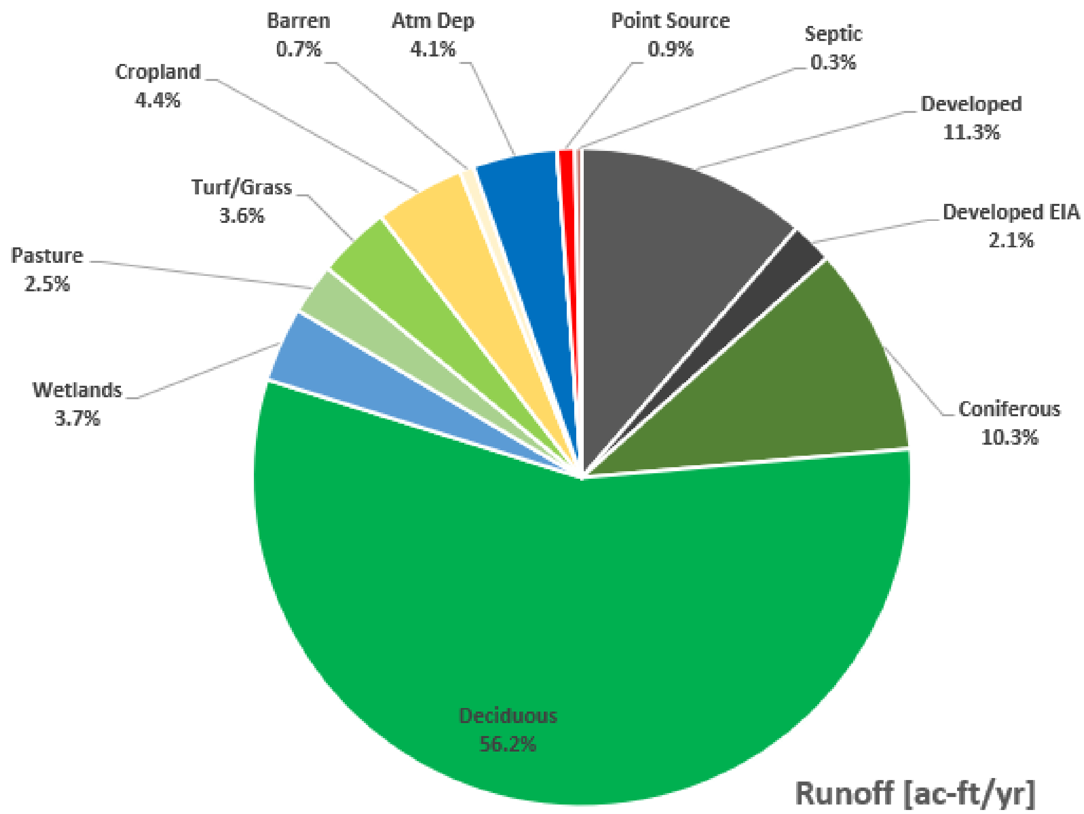

Figure 4-13. Percent Runoff Contribution for the Pawcatuck River Watershed.

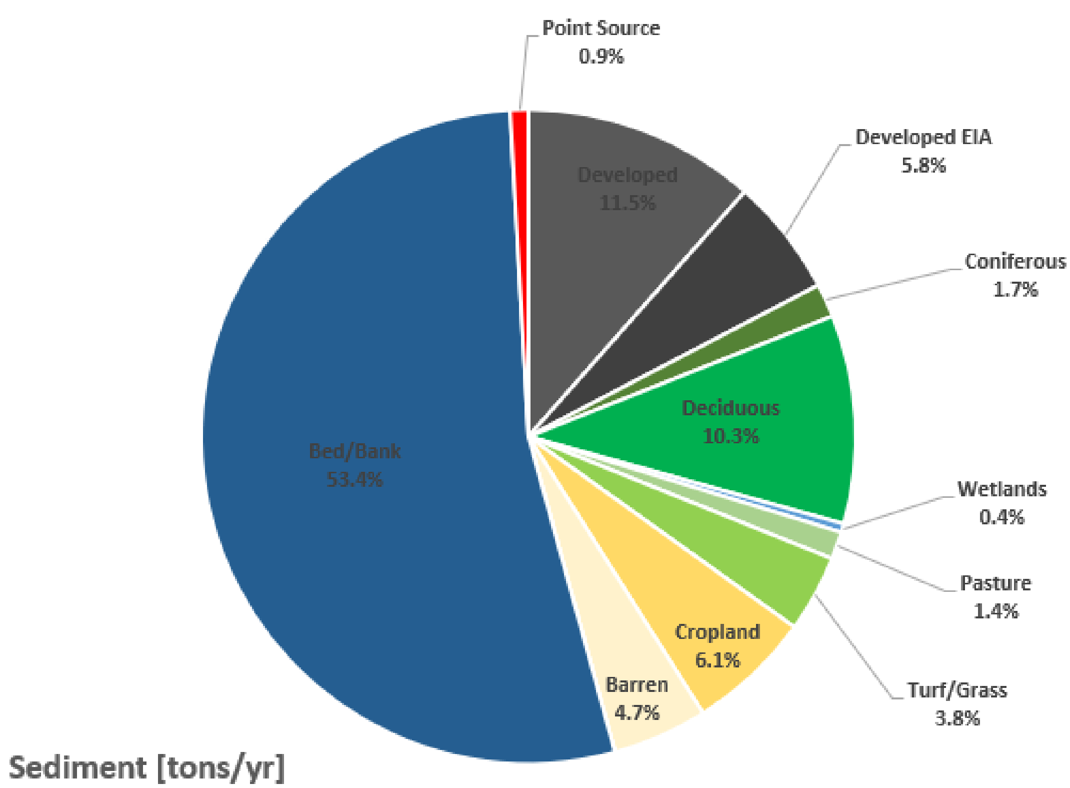

Figure 4-14. Percent Total Suspended Solids Load Contribution for the Pawcatuck River Watershed.

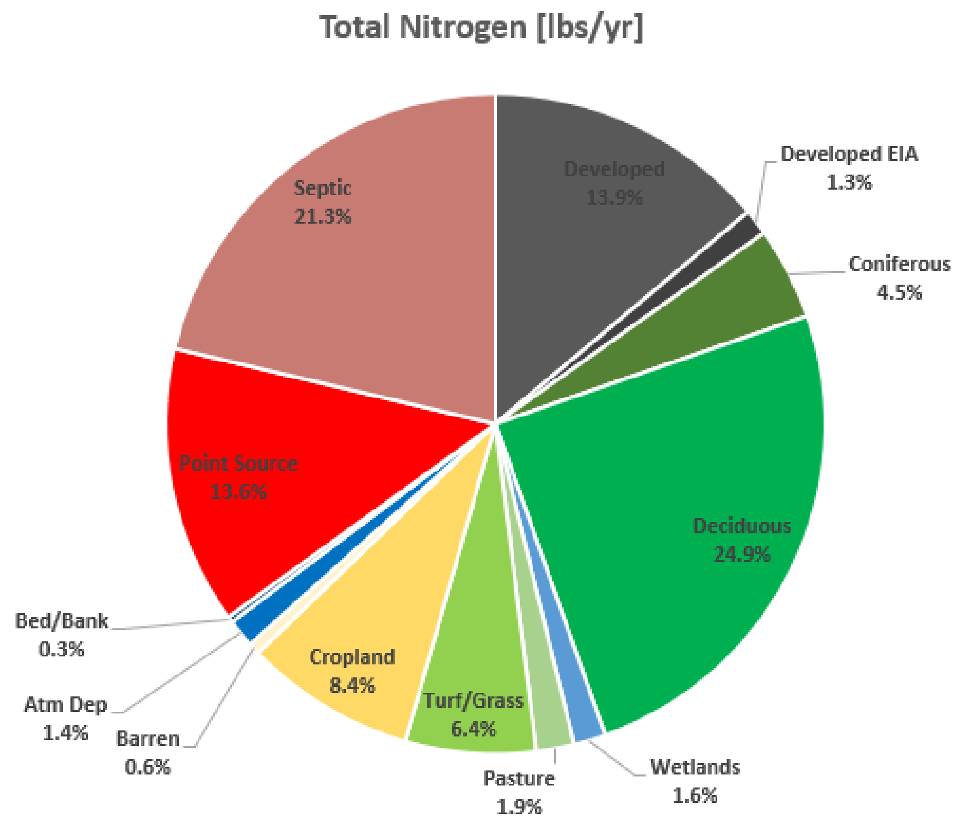

Figure 4-15. Percent Total Nitrogen Load Contribution for the Pawcatuck River Watershed.

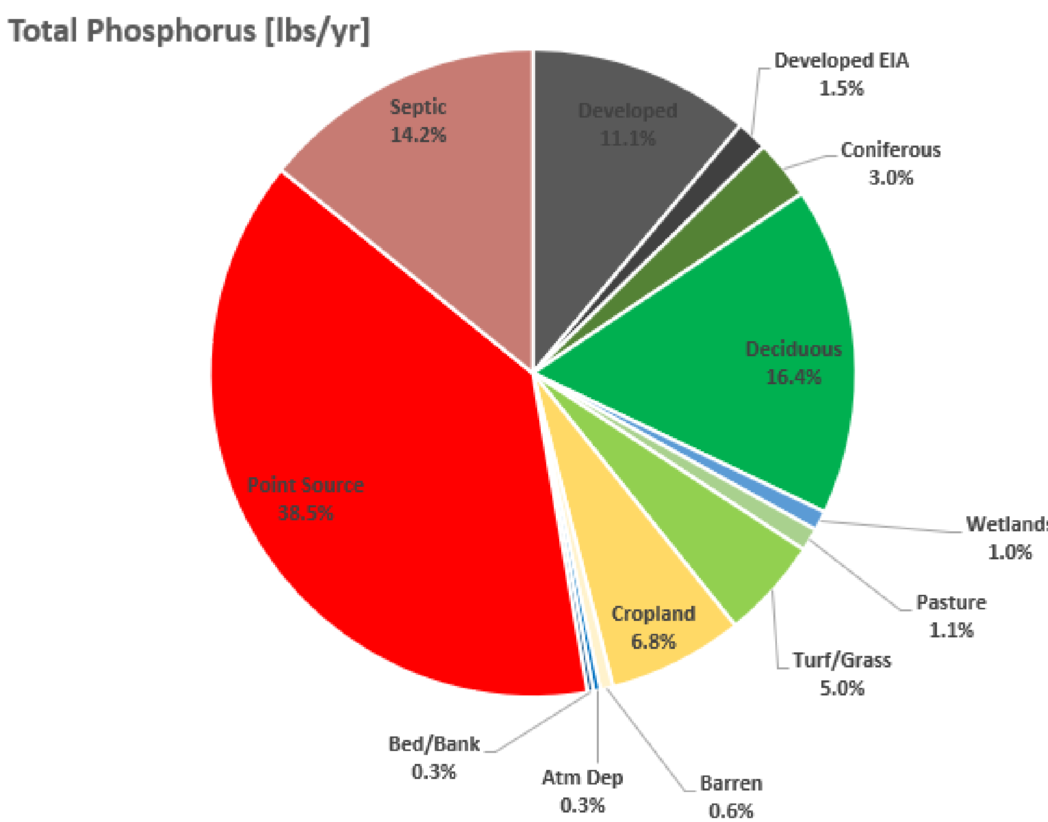

Figure 4-16. Percent Total Phosphorus Load Contribution for the Pawcatuck River Watershed.

Table 4-9. Septic-System Load and Attenuation Factor Summary

Constituent	Input Unattenuated Load (lb/yr)	Model Attenuation Factor	Output Model Load (lb/yr)
Total Nitrogen	533,323	0.48	254,424
Total Phosphorus	126,930	0.08	10,038
Biochemical Oxygen Demand	1,569,113	0.53	832,851

Point sources account for approximately 14 and 39 percent of the TN and TP load in the entire modeled area, respectively. Given the high effluent concentrations/loads of TN and TP at Kenyon Industries, Inc. (annual average concentrations are consistently greater than 40 and 10 mg/L for TN and TP, respectively, thus significantly increasing relative loads) and good correlation of septic estimates and export coefficients relative to the previous studies, the simulated nutrient source allocations are reasonable.

Table 4-10 provides the mean simulated and observed concentrations for all of the water quality stations and the primary location where calibration was performed for the full simulation period (1991 to 2020). The full simulation period was used for the instream concentration calibration so that the largest dataset could be used and all of the non-detect values were removed from the analysis. More weight was inherently placed on the calibration period because this timeframe was when most of the data collection occurred. The time-series water quality calibration plots at the primary calibration location (Reach 350) are shown in Figures 4-17 through 4-30. Depending on the number of samples for each constituent, either the full simulation period or calibration period is shown and the option is noted in the figure caption. The concentration-duration curves, monthly average boxplots, and scatter plots at the primary calibration location for the full simulation period are shown in Appendix C. The same outputs for the secondary calibration locations are included in the results folder supplied with this report.

The comparison of mean concentrations, and the percent differences of simulated to observed (as shown in Table 4-10), demonstrate that simulated values are generally within 25 percent of observed data and often within 15 percent at the main calibration location as well as secondary and tertiary locations. The only variables not passing the fair calibration criteria shown in Table 4-2 are total ammonia for the primary location (56 percent higher than the observed average), and TSS for all of the 28 calibration locations (61 percent lower than the observed average). Detailed explanations for each variable and shortcomings of the instream calibration are provided in the following paragraphs.

Approximately 75 percent of all of the TSS samples taken on the 28 calibration reaches were labeled as non-detect and after those data were excluded, only three calibration reaches had more than 15 samples during the simulation period. Two of the reaches were tertiary, headwater locations with less than 8 square miles of total drainage area and the third reach were the primary location. Because of insufficient data, the TSS calibration focused primarily on HSPF Reach 350 where a very good calibration was achieved.

The water temperature and DO simulations show an inverse relationship and are usually well simulated in terms of both the range of values and seasonal patterns. Low values of DO during the summer months and high values during the winter months are occasionally missed by the model, but the overall simulations are very good. The continuous DO data indicate a larger diurnal pattern than what the model is simulating and differences can be partially explained by how HSPF represents reach segments (i.e., each RCHRES is modeled as a completely mixed system and may not represent a single sonde location). Efforts were made to match the diurnal pattern but these efforts resulted in a gross overestimation of the algae growth (i.e., chlorophyll *a*) and the simulated inorganic nutrient concentrations displayed an opposite season trend when compared to the observed data. Therefore, the continuous DO data calibration focused on the minimum daily concentrations during the growing season because the minimum DO values are the main concern with regard to water quality impairments.

The simulation of total nitrogen and components is considered very good except for the total ammonia at the primary location, which is 56 percent higher than the observed average. The over-simulation only occurs in the cooler months and is primarily driven by the elevated ammonia concentrations from Kenyon Industries, Inc. during the same months and septic-system estimates. HSPF is likely not capturing the expected seasonal variability in the septic-system annual estimate or daily variability in the point source average monthly estimates. Because the main pathways for ammonia transformation (i.e., nitrification and algae growth) are heavily governed by water temperature, the model is unable to convert or cycle the higher concentrations in late fall and winter; however, when total ammonia and nitrite-nitrate are grouped into total inorganic nitrogen, the difference is only 5 percent at the primary calibration reach (average nitrite-nitrate concentrations are nearly an order of magnitude higher than ammonia). Total nitrogen is better simulated than the individual species, but all components generally represent the range of observed data, seasonal variability, and negative correlation with stream flow (i.e., higher concentrations at lower flows). Total phosphorus and orthophosphate meet the very good criteria at the primary calibration location and the “good” criteria for the 28 calibration reaches. Both variables tracked very well in terms of concentration ranges and seasonal variability.

The chlorophyll *a* and BOD mean concentration comparisons range from fair to good with chlorophyll *a* being over-simulated and BOD being under-simulated. Relative to more eutrophic freshwater systems, the magnitude of average concentrations is very low; therefore, the simulation of these variables is generally quite good (i.e., the true differences in chlorophyll *a* and BOD mean concentrations at the primary reach are only 1.2 µg/L and 0.4 mg/L, respectively). The data used for the BOD calibration were all 5-day tests (BOD_5), so a factor of 0.4 was applied to the total CBOD results from the HSPF results to convert to BOD_5 [Chapra, 1997]. This factor can be highly variable and could have been adjusted to improve calibration statistics, but the end result of total CBOD being passed to the receiving model would remain the same.

The total organic carbon (TOC) state variable includes the carbon components of both dead and living organic materials and, like nitrogen and phosphorus, HSPF does not bifurcate dissolved and particulate forms of organics. The sample size of TOC and other constituents that influence TOC concentrations (BOD and chlorophyll *a*) are relatively small compared to the sample size of other nutrient data, and only two samples were taken at the primary reach during the calibration period. Similar to the analysis reported by Fulwiler et al. [2003], the available data do not show as strong of correlation to flow or seasonal variability when compared to the other nutrient data. The potential also exists for a large portion of the TOC to be refractory. This form of TOC can be highly variable and limited information or studies that quantify this portion exist because the TOC has little impact on the nutrient cycling and DO processes. The combination of data and model limitations coupled with a largely very good calibration of other primary nutrients, no scientific justification was found to force (i.e., curve fit) the simulated TOC concentrations to match the observed values; therefore, a multiplication factor of 1.75 was applied to the simulated TOC results to perform statistical and graphical analysis. Using this correction factor, the dynamic pattern of simulated TOC generally mimics the range of observations.

Based on the weight-of-evidence from the full range of model results presented, which include loading rates, source allocations, mean concentration differences, and the various calibration plot comparisons of observed and simulated values, we conclude that the model is an acceptable representation of the Pawcatuck Watershed.

Table 4-10. Average Annual Simulated and Observed Concentrations for the Simulation Period

Constituent	All 28 Calibration Reaches				Pawcatuck at Westerly, Rhode Island (HSPF Reach 350)			
	Observed (mg/L)	Simulated (mg/L)	Difference[a] %	Sample Size	Observed (mg/L)	Simulated (mg/L)	Difference[a] %	Sample Size
Total Suspended Sediment	25	10	–61	67	8.1	8.7	7.5	19
Temperature	68	64	–4.9	3,640	54.7	52.2	–4.6	322
Dissolved Oxygen	7.7	7.2	–7.1	1,309	10.5	9.5	–8.9	321
Total Nitrogen	0.77	0.78	2.1	1,784	0.81	0.79	–2.3	330
Total Inorganic Nitrogen	0.46	0.51	10	1,127	0.47	0.49	4.9	207
Total Kjeldahl Nitrogen	0.37	0.35	–7.3	411	0.37	0.34	–6.1	233
Ammonia as N	0.060	0.051	–14	1,172	0.033	0.051	56	207
Nitrite-Nitrate as N	0.40	0.46	14	1,127	0.44	0.44	2.0	280
Total Phosphorus	0.046	0.038	–17	1,733	0.042	0.045	8.3	282
Orthophosphate as P	0.019	0.016	–15	340	0.020	0.017	–14	244
Chorlophyll *a* [b]	4.7	6.1	29	1,805	5.2	6.4	23	36
Biochemical Oxygen Demand	1.1	0.78	–30	86	1.2	0.80	–31	73
Total Organic Carbon	6.5	6.9	6.1	93	7.0	6.2	–12	65

(a) Calculations were performed before rounding of concentrations

(b) Concentrations are in micrograms per liter (µg/L)

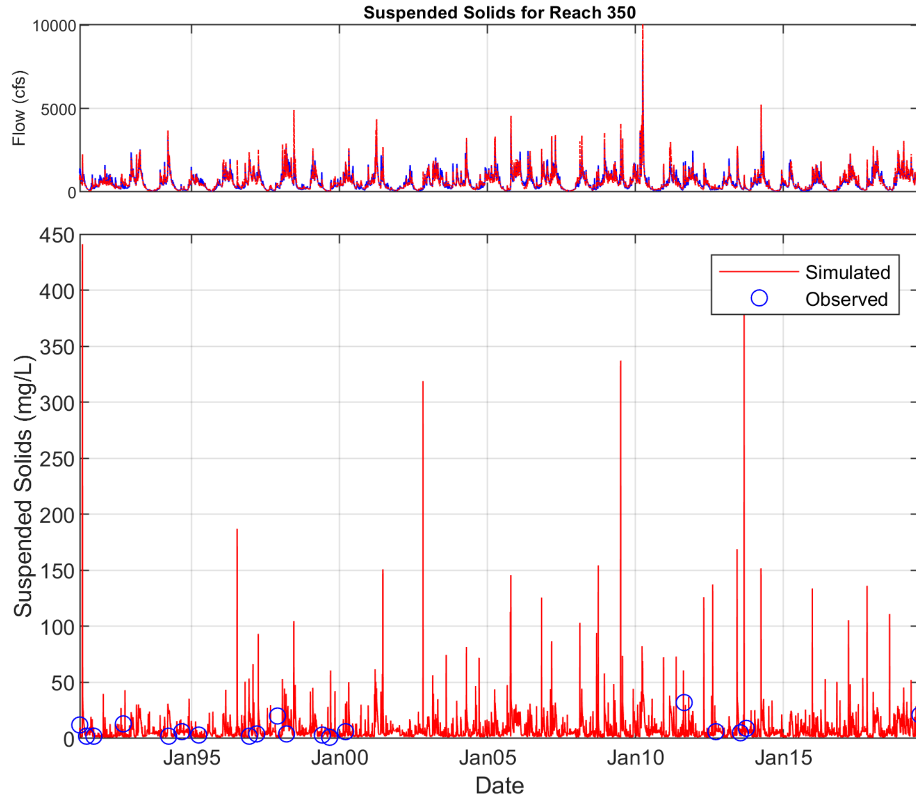

Figure 4-17. Total Suspended Solids Time-Series Calibration Plot for HSPF Reach 350 (Full Period).

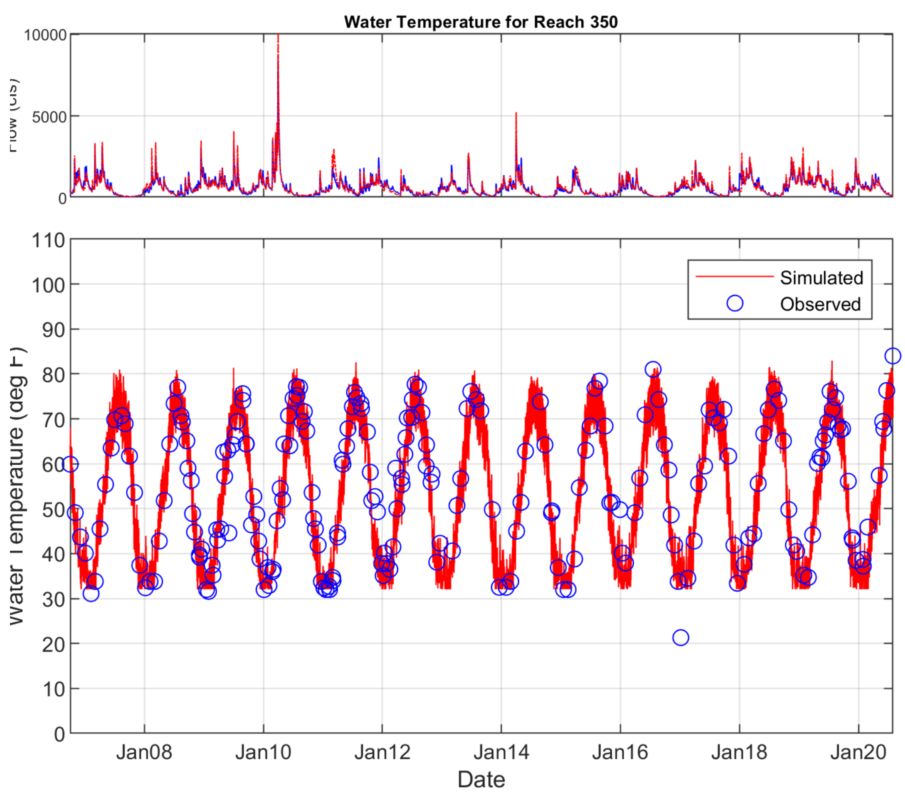

Figure 4-18. Instantaneous Temperature Time-Series Calibration Plot for HSPF Reach 350 (Calibration Period).

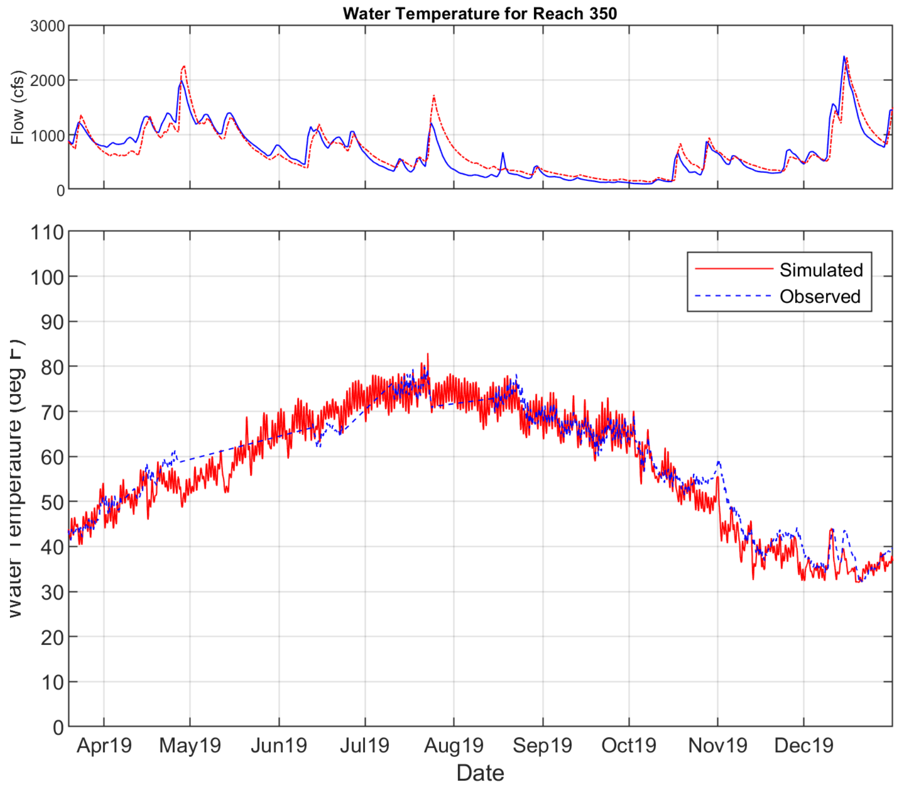

Figure 4-19. Continuous Temperature Time-Series Calibration Plot for HSPF Reach 350 (Calibration Period).

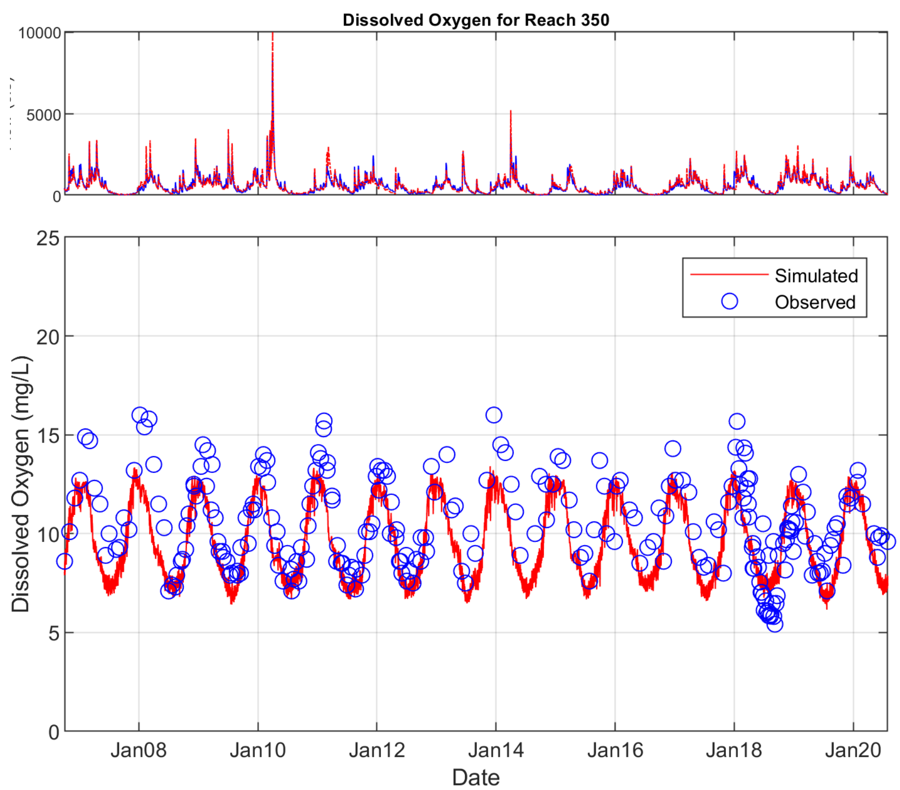

Figure 4-20. Instantaneous Dissolved Oxygen Time-Series Calibration Plot for HSPF Reach 350 (Calibration Period).

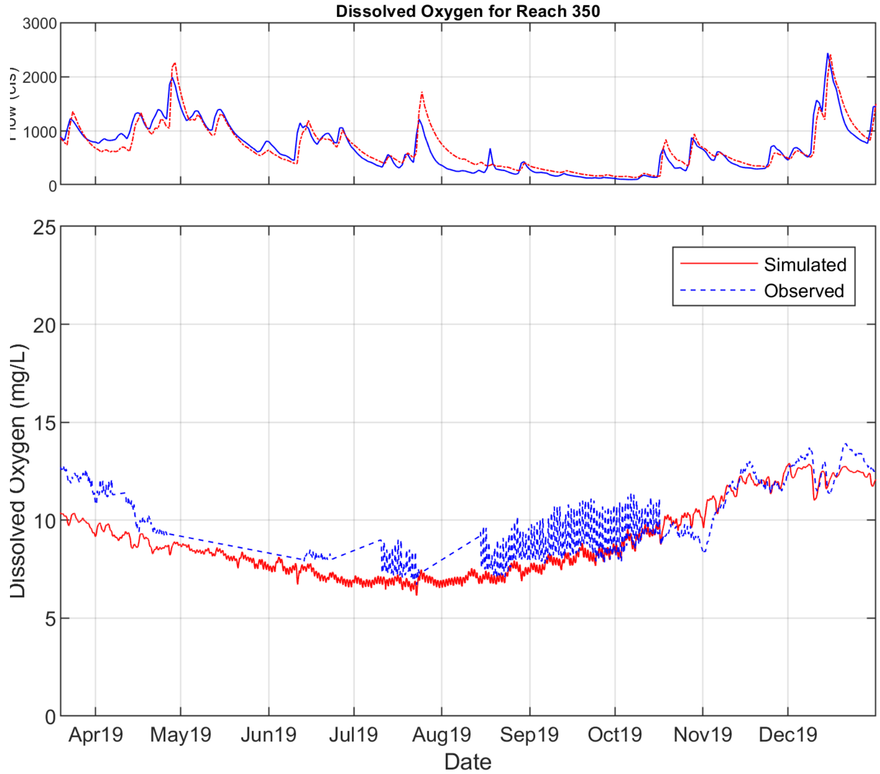

Figure 4-21. Continuous Dissolved Oxygen Time-Series Calibration Plot for HSPF Reach 350 (Calibration Period).

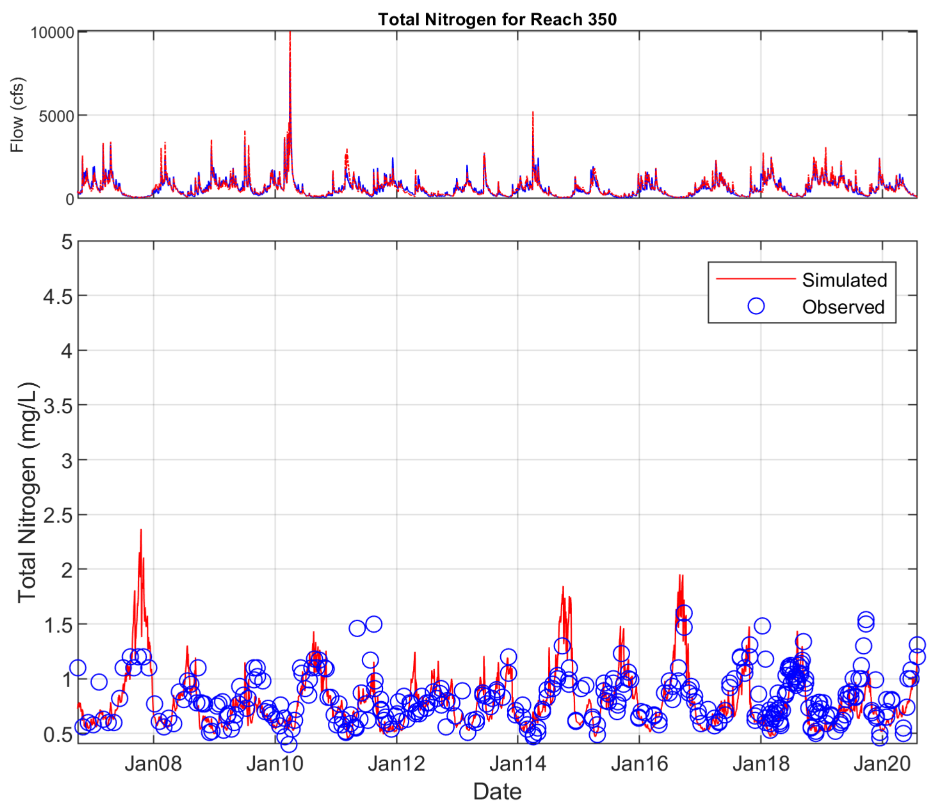

Figure 4-22. Total Nitrogen Time-Series Calibration Plot for HSPF Reach 350 (Calibration Period).

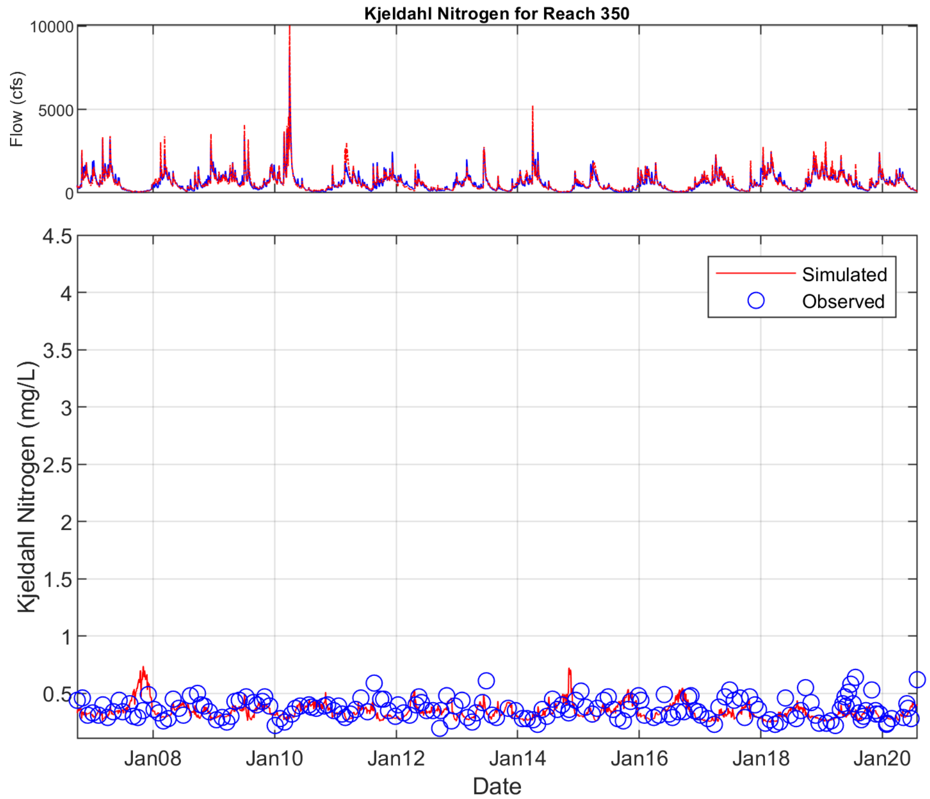

Figure 4-23. Total Kjeldahl Nitrogen Time-Series Calibration Plot for HSPF Reach 350 (Calibration Period).

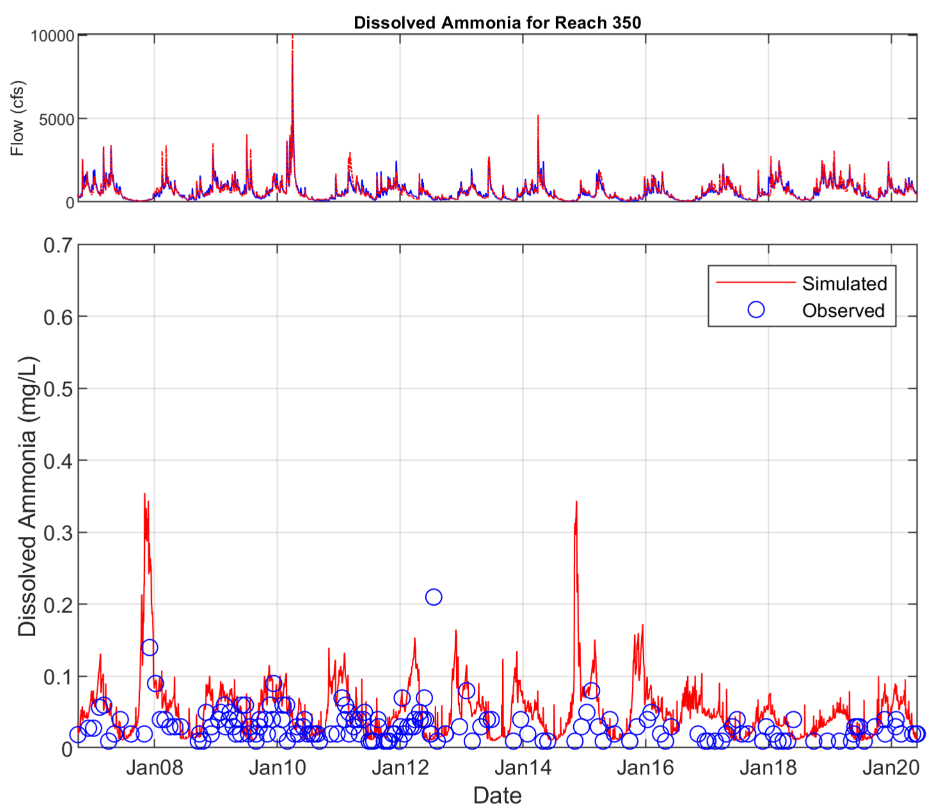

Figure 4-24. Total Dissolved Ammonia as Nitrogen Time-Series Calibration Plot for HSPF Reach 350 (Calibration Period).

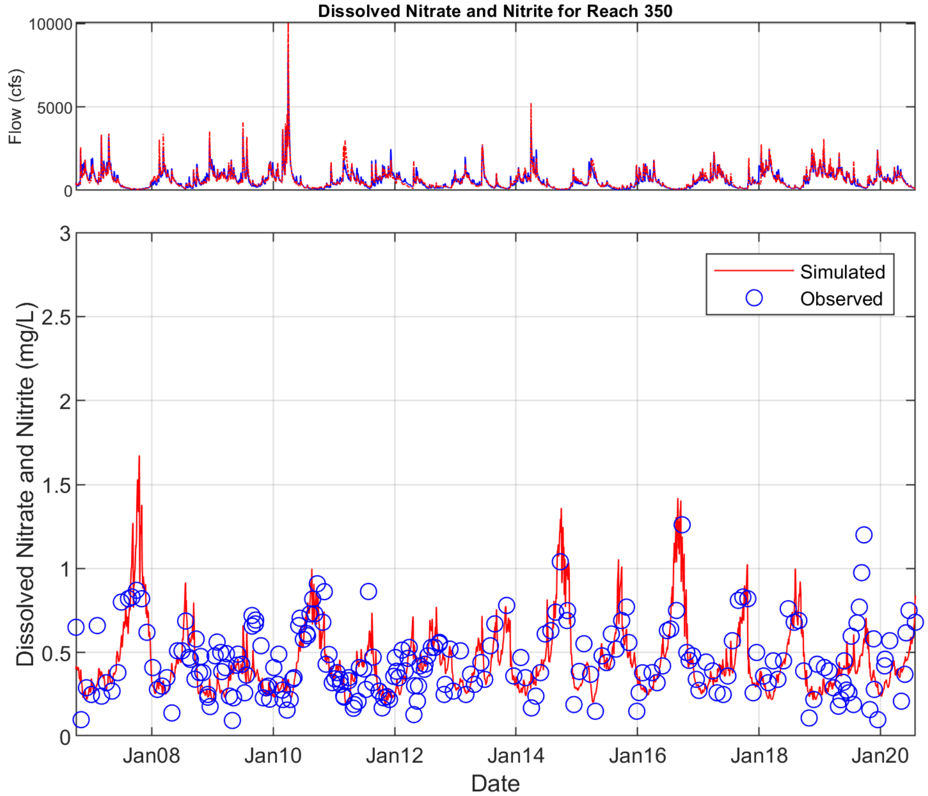

Figure 4-25. Total Dissolved Nitrite-Nitrate as Nitrogen Time-Series Calibration Plot for HSPF Reach 350 (Calibration Period).

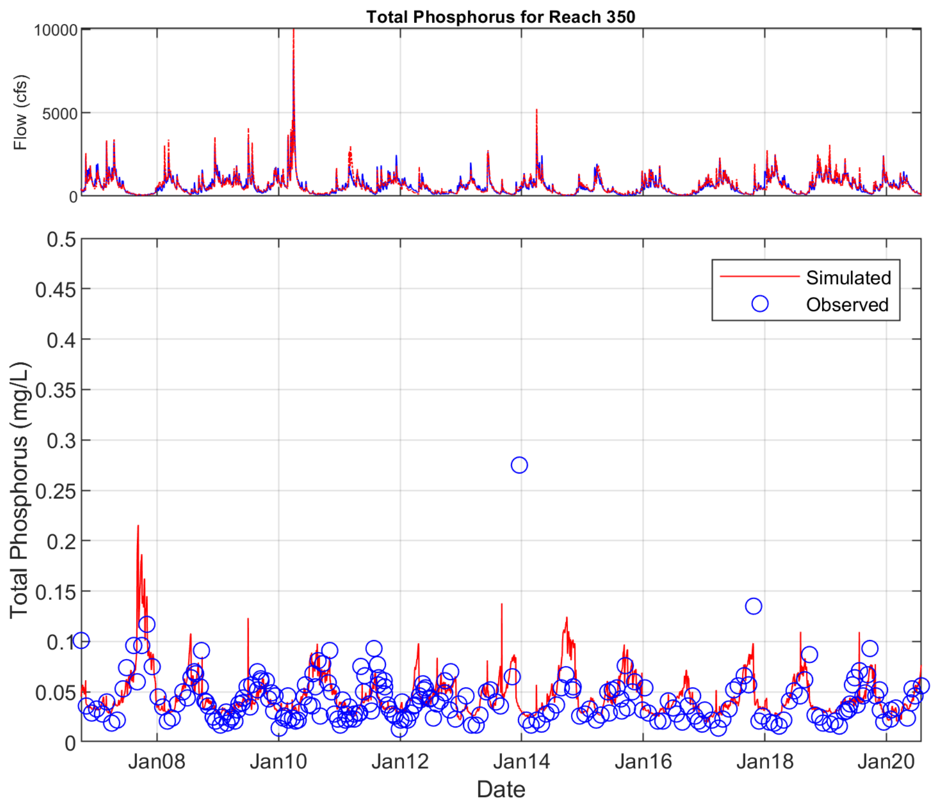

Figure 4-26. Total Phosphorus Time-Series Calibration Plot for HSPF Reach 350 (Calibration Period).

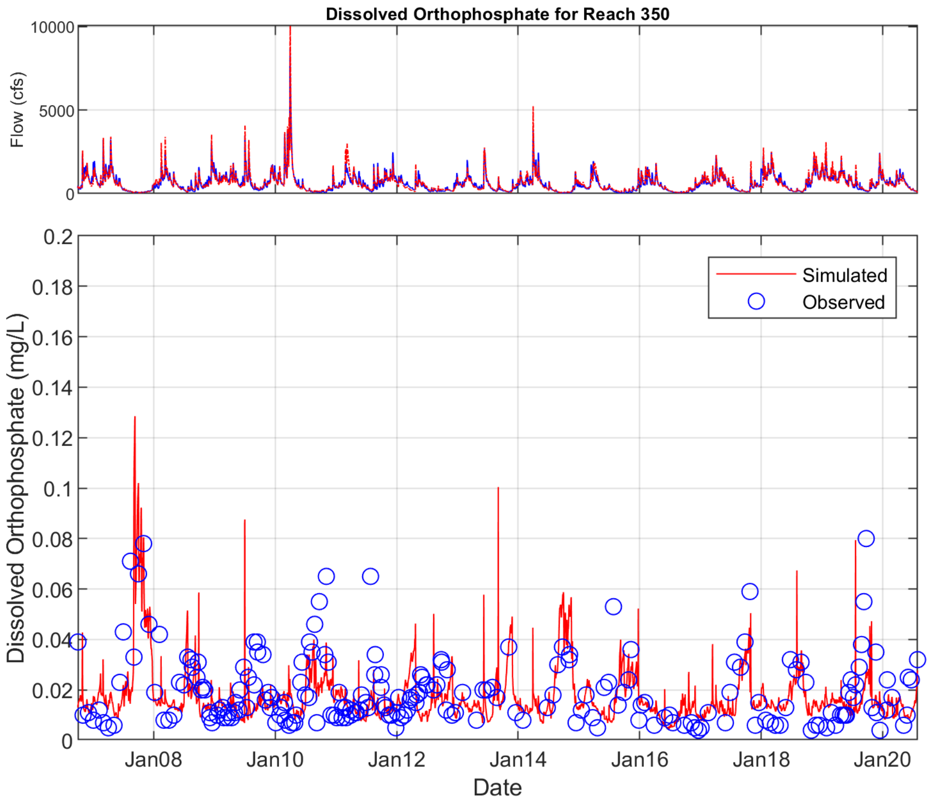

Figure 4-27. Total Dissolved Orthophosphate as Phosphorus Time-Series Calibration Plot for HSPF Reach 350 (Calibration Period).

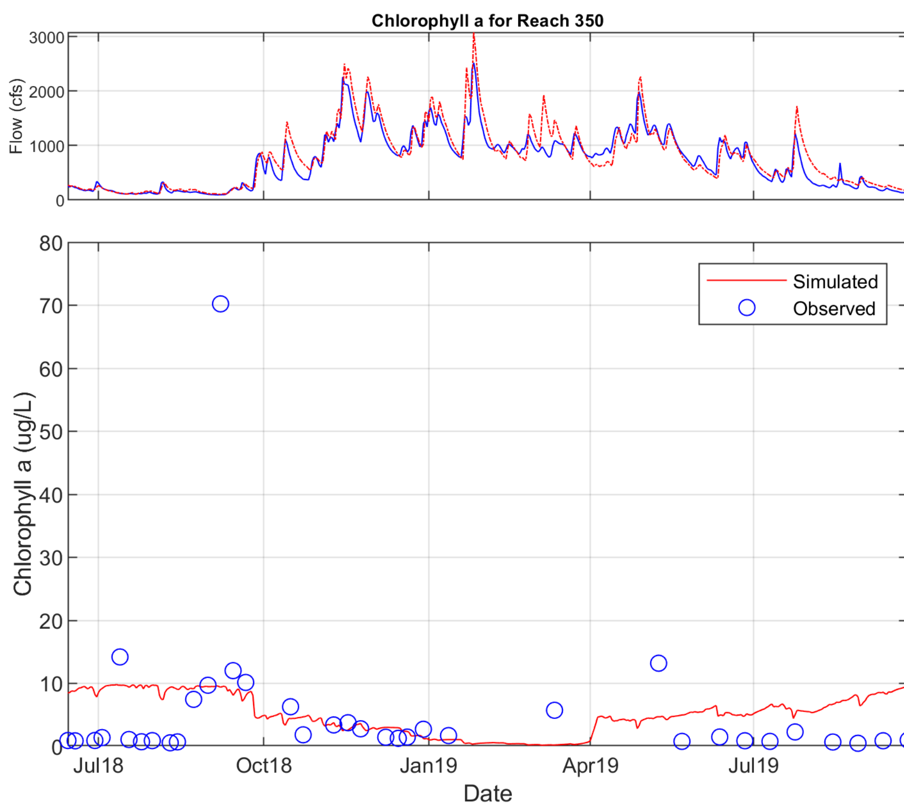

Figure 4-28. Chlorophyll *a* Time-Series Calibration Plot for HSPF Reach 350 (Calibration Period).

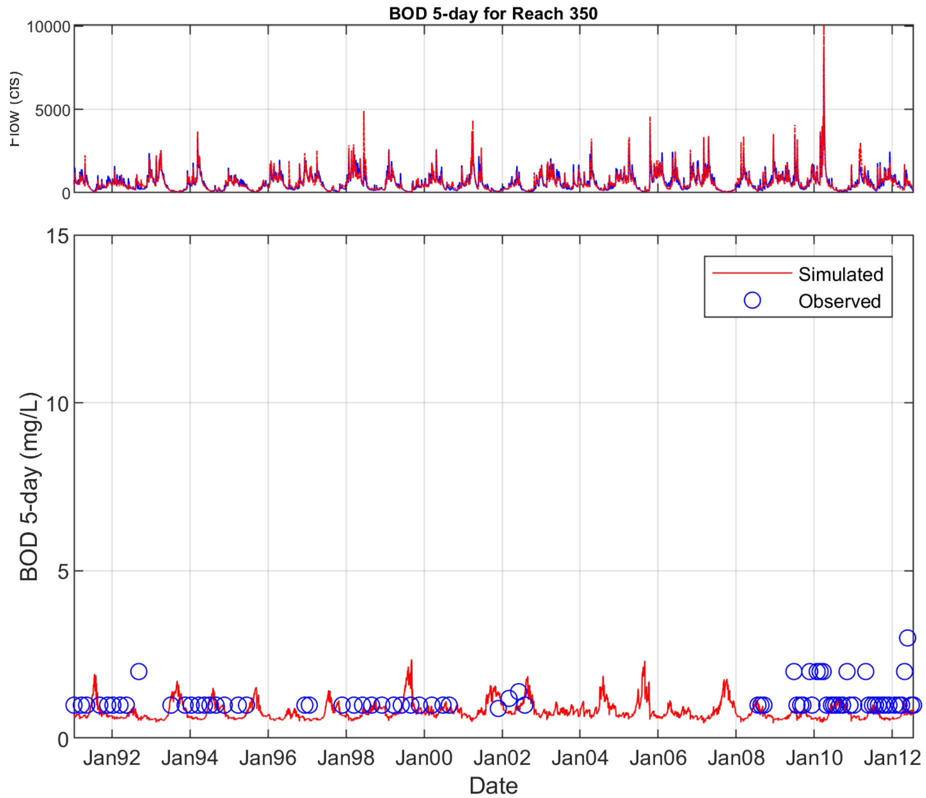

Figure 4-29. Biological Oxygen Demand (5-Day) Time-Series Calibration Plot for HSPF Reach 350 (Full Period).

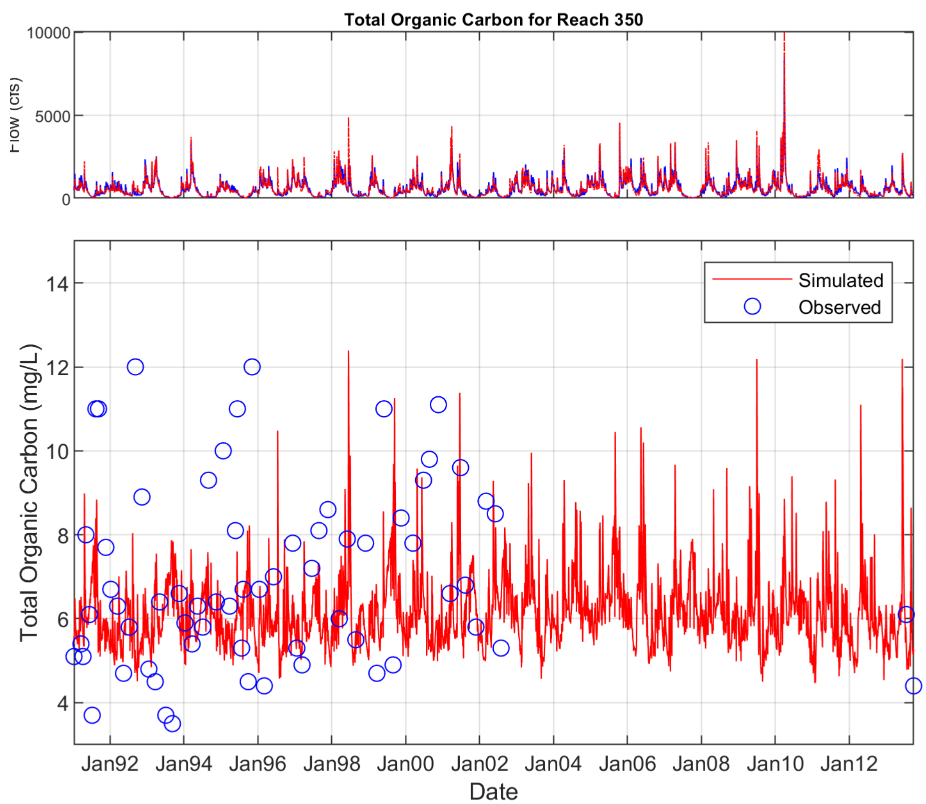

Figure 4-30. Total Organic Carbon Time-Series Calibration Plot for HSPF Reach 350 (Full Period).

5.0 HSPF LINKAGE TO RECEIVING MODELS

The HSPF model can be used to provide nutrient loads, suspended sediment loads, and freshwater inputs for other site-specific models (e.g., BATHTUB, WASP, and EcoGEM), as well as the 3D linked hydrodynamic water quality model that is being developed for Long Island Sound. The HSPF output will be used with a future WASP model for the associated estuarine embayment as well as BATHTUB models of Hundred Acre, Worden, and Watchaug Ponds in Rhode Island. The HSPF model was developed at an hourly time step from 1991 through 2020 and, therefore, as long as receiving model time periods fall within this time period, the models can be used together. The Pawcatuck River HSPF model application will be extended through 2022 when the Connecticut Statewide models are extended. The reach calibration ends at USGS gage 0118500, but all of the land segments were modeled to provide further boundaries for the WASP model.

Three main components must be considered when linking watershed models to receiving water quality models: spatial resolution, temporal resolution, and state variable mapping. RESPEC will work closely with the receiving model developers during the watershed delineation to ensure that the HSPF model provides results at the correct spatial resolutions. HSPF provides results at an hourly timestep but can be aggregated or averaged to any timestep, therefore, the temporal resolution can easily be adjusted to fit the receiving model's requirements. Each receiving model will have state variables that are slightly different than HSPF and will need to be mapped using assumptions (e.g., factors for partitioning dissolved and particulate organic matter).

Some lakes are represented explicitly in HSPF, as discussed in Section 3.2.1. HSPF does well at representing in-lake water quality, especially for lakes that do not stratify. The primary reason for representing these larger, more data-intensive lakes in HSPF is because in-lake processes can lead to substantial changes in water quality, such as settling of sediment. When these are represented in the model and data are available in the lakes, the next downstream reach is more accurately represented in HSPF. BATHTUB models are often used for Total Maximum Daily Loads (TMDLs) because they are widely accepted by the EPA. RESPEC has a method scripted in MATLAB to develop inputs for BATHTUB from HSPF outputs for lakes and/or impoundments. This method can be easily accomplished in SAM, or MATLAB tools can be complied so that the model users can also prepare BATHTUB inputs. If the lake or impoundment needing to be modeled in BATHTUB was not delineated with its own subwatershed at the outlet, unit-land use loads may need to be calculated for the local area loads. SAM can provide most of the HSPF model outputs needed for model linkage; however, the San Antonio River Authority (SARA) Time-Series Utility can be used to extract more advanced outputs if needed. RESPEC is also developing a specialized tool to extract and process HSPF data to link the embayment models.

The HSPF to WASP state variable linkage map is shown in Table 5-1, and the linkage process was scripted in MATLAB to ensure consistency and repeatability in the method. The HSPF subwatersheds were segmented before the final WASP model was segmented. The WASP segmentation is at a finer resolution than the HSPF segmentation and WASP segments fall in three separate HSPF subwatersheds (330 – WASP segments 1-4, 350 – WASP segments 5-7, and 370 – WASP segments 8-16). NHDPlus Version 2 was used to delineate areas of the three HSPF subwatersheds by creating batch points in GIS at desired breakpoints using the ArcGIS watershed toolset. Then the existing model subwatersheds were split along delineation lines. The tabulate area tool in GIS was used with the HSPF model land-cover raster to estimate the area of modeled land use in each WASP segment. The developed distribution percentages used for the modeled land cover in each subwatershed were applied to the Connecticut-developed land and the percent of turf used for the modeled land cover in each subwatershed was applied to the cropland in Rhode Island. To provide inputs to the WASP model for each segment, the unit loadings from each model land cover were applied to the corresponding land cover in each segment for each desired parameter. In addition, meteorological, atmospheric deposition, point source, and tributary time-series data were provided.

Table 5-1. Linkage Between HSPF Model Outflow Constituents and WASP System Constituents

HSPF Outflow Constituent	Constituents Included in the WASP Eutrophication Model	WASP System Type	Notes
ROVOL	Flow	N/A	—
TAM-OUTTOT	Total Ammonia	NH-34	—
NO3-OUTTOT	Nitrate-Nitrite	NO3O2	Add HSPF NO_3 and NO_2 for WASP system NO3O2
NO2-OUTTOT			
PO4-OUTTOT	Dissolved Inorganic Phosphorus	D-DIP	—
N-TOTORG-OUT	Dissolved Organic Nitrogen	ORG-N	Assumed factor to disperse dissolved and detrital nitrogen
	Detrital Nitrogen	DET-N	
P-TOTORG-OUT	Dissolved Organic Phosphorus	ORG-P	Assumed factor to disperse dissolved and detrital phosphorus
	Detrital Phosphorus	DET-P	
C-TOTORG-OUT	Detrital Carbon	DET-C	—
NA	Total Detritus	TOTDE	Calculated by WASP
BODOUTTOT	$CBOD_u$ – Watershed	CBODU	—
NA	$CBOD_u$ – Point Source	CBODU	Obtained from WDM
NA	$CBOD_u$ – Biological	CBODU	Calculated by WASP
DOXOUTTOT	DO	DISOX	—
ROSED-SAND	Sand	SOLID	—
ROSED-SILT	Silt	SOLID	—
ROSED-CLAY	Clay	SOLID	—
PHYTO-OUT	Phytoplankton	PHYTO	—
NA	Benthic Algae	MALGA	Calculated by WASP
NA	Benthic Algae Nitrogen	MALGN	
NA	Benthic Algae Phosphorus	MALGP	
ROHEAT	Water Temperature	WTEMP	—

N/A = Not Applicable

6.0 PROPOSED MANAGEMENT SCENARIOS

The Pawcatuck River Watershed HSPF RFP states that the model simulations must be able to represent the predicted future precipitation and various management scenarios involving discharge limits and land-use changes. The development of the HSPF model described in this report allows for flexibility in creating management scenarios, such as land-use conversion, development, meteorological variations, climate change, and best management practices (BMPs). CTDEEP and RIDEM have accounted for a minimum of five management scenarios and included climate change and population projections for the year of 2050 as a part of these scenarios. Detailed descriptions of the climate change, land-cover change, and BMP scenario methods will be included in a future report.

7.0 DATA MANAGEMENT

Two data types were used to support the Pawcatuck HSPF modeling project: GIS and time-series data. The format of the data types must be changed as they are integrated into an HSPF model and are thus subject to possible errors. As with the case of electronic data acquisition, RESPEC adhered to protocols that we have developed while performing abundant previous HSPF applications to ensure that we properly address quality assurance considerations related to preventing, detecting, and correcting electronic data manipulation errors. RESPEC also adhered to protocols for data acceptance criteria described in the Pawcatuck River Watershed Modeling QAPP [Imhoff and McCutcheon, 2020]. RESPEC will maintain a copy of the project files on our network for a minimum of 5 years after the project is completed.

Consistent data management procedures were used during the preprocessing, model calibration, and postprocessing stages of the project. All of the data and information collected and generated during this project are stored in a project folder on RESPEC's network. Data processing was completed using a combination of ArcGIS, MATLAB, Python, and the SARA Time-Series Utility. RESPEC modelers will be responsible for adhering to and documenting data management practices that ensure the quality of data that are downloaded and/or manipulated. Original data sources were documented to identify the website or contact person that provided the data, data query parameters, and data request correspondence. Original (unaltered) copies of all of the data sources used in the project are be retained in the project folder on RESPEC's network. Metadata are included with spatial datasets. The SARA Time-Series Utility can be used to access the WDM files that were used to store model-input data, such as meteorological, point source, atmospheric deposition, and other time-series data.

GIS data were used in a geodatabase feature-class format. The projection of all of the GIS data is consistent. When new GIS data are added to a feature class, ArcPro automatically projects the data to match the projection of the feature class. Rhode Island has developed metadata standards that are summarized for any data submissions to the Rhode Island Geographic Information System (RIGIS) (https://info.rigis.org/data-resources/metadata-resources/). A sample metadataset (https://portal.ct.gov/DOT/Engineering-Applications/Sample-Metadata) is provided by Connecticut.

Model inputs that include meteorological data, point- source data, and surface-water withdrawals were stored in a .wdm file during the calibration process. The size of the .wdm files for the Pawcatuck River Watershed Model is approximately 140 megabytes (mb). Model outputs at calibration gages were stored in a set of binary (.hbn) files. The size of the .hbn files for the Pawcatuck River Watershed Model varies depending on the number of parameters and reaches that are included. During calibration, the observed water quality and hydrology data will be stored in Excel files associated with the calibration reach numbers. The size of these files for the Pawcatuck River Watershed Model is approximately 6 mb. The .hbn and .wdm files can be accessed by using the SARA Time-Series Utility, which can be downloaded online (https://www.respec.com/product/modeling-optimization/sara-timeseries-utility). SAM project files will also be used as storage and the SAM program has the capability to allow the user to extract a wide-range model data. SAM can provide most of the HSPF model outputs; however, the SARA Time-Series Utility can be used to extract more advanced inputs and outputs as needed.

Static SAM project files are currently downloaded to the user's local drive and responsibility for downloading the new versions is placed on the end user. RESPEC's Data and Technology Services and Water and Natural Resources business units have proposed working together as a part of the Connecticut Statewide modeling to move the SAM projects into the cloud and enhance the existing SAM functionality to bring data distribution, with a download option, and versioning into model files. A version-controlled repository could be included with SAM to allow the application to verify input data for a model, inform the user if updated model datasets or new versions of scenarios exist, and ensure that decisions are based on the best available data. If the system does not move the SAM projects to the cloud, SharePoint will be used for file sharing.

8.0 DATA SOURCES

The following outline shows the data sources that were used for each modeling component. All of the data were collected for the entire modeling period (i.e., January 1991 through July 2020), when available. QA/QC documents were not collected for federal or state data, because these datasets were assumed to have robust QA/QC.

- Meteorological
  - Precipitation, NLDAS (https://ldas.gsfc.nasa.gov/nldas/nldas-get-data), and PRISM (https://prism.oregonstate.edu/)
  - Evaporation, Temperature, Wind, Solar Radiation, Dewpoint, Cloud Cover, and Humidity, NLDAS (https://ldas.gsfc.nasa.gov/nldas/)
  - Snowfall and Snow Depth, NOAA Global Historical Climatology Network (GHCN) (https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/global-historical-climatology-network-ghcn)
- Discharge for Calibration
  - USGS NWIS (https://nwis.waterdata.usgs.gov/nwis)
- Water Quality for Calibration
  - Water Quality Data Portal (https://www.waterqualitydata.us/)
  - RIDEM and CTDEEP Uploaded Water Quality Data to Shared Project Folder
- Point Source Data
  - EPA Echo (https://echo.epa.gov/)
  - RIDEM and CTDEEP Uploaded Point Source Data to Shared Project Folder
- Atmospheric Deposition
  - Dry Nitrogen, CASTNet (https://www.epa.gov/castnet/)
  - Wet Nitrogen, NADP (http://nadp.slh.wisc.edu/)
  - TP, Regional Studies Cited in the Atmospheric Deposition Section 2.6
    - (https://link.springer.com/article/10.1023/A:1004954923033)
    - (https://www.sciencedirect.com/science/article/abs/pii/1352231096000945?via%3Dihub)
    - (https://link.springer.com/article/10.1023%2FB%3AWATE.0000022952.12577.c5)
- Subwatersheds
  - Connecticut Local Subwatersheds (https://cteco.uconn.edu)
  - NHDPlus Version 2 (https://www.epa.gov/waterdata/get-nhdplus-national-hydrography-dataset-plus-data)
  - ArcPro Arc Hydro and Editing Tools
- Reaches and Lakes
  - NHDPlus Version 2 High-Resolution Flowlines (https://www.usgs.gov/core-science-systems/ngp/national-hydrography/nhdplus-high-resolution)
  - RIDEM and CTDEEP Assessed Streams and Lakes (https://www.rigis.org/ and https://portal.ct.gov/)

- Cross Sections for F-Tables
  - USGS Stream-Gaging Notes Uploaded to Shared Folder
  - USGS Stream Measurements (https://waterservices.usgs.gov/nwis/)
  - USGS Flood Inundation Maps (https://pubs.er.usgs.gov/publication/sir20185112)
  - HEC-HMS Models Provided by Connecticut Department of Transportation (CTDOT) via CTDEEP
  - USGS 3D Elevation Program (https://www.usgs.gov/core-science-systems/ngp/3dep)
- Bathymetry for F-Tables
  - CTDEEP (https://portal.ct.gov/DEEP/GIS-and-Maps/Data/GIS-DATA)
  - RIDEM (http://www.dem.ri.gov/maps/mapfile/pondbath.pdf)
- Dam Information for F-Tables
  - National Inventory of Dams (https://nid.sec.usace.army.mil/ords/f?p=105:1)
  - CTDEEP Uploaded Dam Information to Shared Folder
  - RIDEM Environmental Resource Map (Regulated Facilities – Dam) (https://ridemgis.maps.arcgis.com/apps/webappviewer/index.html?id=87e104c8adb449eb9f905e5f18020de5)
- Elevation and Slope
  - USGS 3D Elevation Program (https://www.usgs.gov/core-science-systems/ngp/3dep)
- Model Land Cover
  - Connecticut
    - Connecticut Land Cover 2015 (https://cteco.uconn.edu)
    - MS4, CTDEEP Staff Uploaded to Shared Project Folder
    - Soils, State Soil Geographic (STATSGO) Dataset (https://www.nrcs.usda.gov)
    - Percent Impervious, NLCD 2016 (https://www.mrlc.gov), and CLEAR IC (http://cteco.uconn.edu/)
  - Rhode Island
    - Rhode Island Land Cover 2011 (http://www.rigis.org)
    - MS4, RIDEM Phase II MS4s (www.dem.ri.gov/maps)
    - Soils, STATSGO (https://www.nrcs.usda.gov)
    - Percent Impervious, NLCD 2016 (https://www.mrlc.gov), and RIDEM IC (https://www.rigis.org/)
- Individuals on Septic Systems
  - Connecticut Sewered Areas, CTDEEP Staff Uploaded to Shared Project Folder
  - Rhode Island Sewered Areas (http://www.rigis.org)
  - 2010 United States Census Blockpop (https://www.census.gov/programs-surveys/decennial-census/data.html)
- Septic Failure Rates and Loading Estimates
  - CTDEEP Uploaded to *A Report on Septic Failure Rates and Loading Estimates* to Shared Project Folder. Data from the study were extrapolated to Rhode Island.
- Groundwater Transfers/Losses
  - LIS Groundwater Model Results and Inputs Provided by USGS When Approved to Share

- Irrigation Application Estimate on Turf and Agricultural Land
  - USGS Pawcatuck Model Application Turf Equation with NLDAS Data
- Diversions and Withdrawals From Surface Water
  - CTDEEP uploaded withdrawals to shared project folder by subwatershed.
- Animal Units
  - RIDEM and CTDEEP Uploaded to Shared Project Folder; Data Summarized by Subwatershed for Each State.

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APPENDIX A

LAND-COVER RECLASSIFICATION SCHEME FOR THE PAWCATUCK RIVER WATERSHED HSPF MODEL

Table A-1. Rhode Island Land-Use Classification (Page 1 of 2)

Rhode Island Versus NLCD Land-Use Classes – Pawcatuck	Model Class
High-Density Residential (< ⅛-acre lots)	Developed Medium Density
Medium-High-Density Residential (¼- to ⅛- acre lots)	Developed Medium Density
Medium-Density Residential (1- to ¼- acre lots)	Developed Medium Density
Medium-Low-Density Residential (1- to 2- acre lots)	Developed Medium Density
Low-Density Residential (>2- acre lots)	Developed Low Density
Commercial (sale of products and services)	Developed High Density
Industrial (e.g., manufacturing, design, assembly)	Developed High Density
Roads (divided highways > 200 feet plus related facilities)	Developed High Density
Airports (and associated facilities)	Developed Low Density
Railroads (and associated facilities)	Developed High Density
Water and Sewage Treatment	Developed Low Density
Waste Disposal (e.g., landfills, junkyards)	Developed Low Density
Power Lines (100 feet or more width)	Deciduous Forest
Other Transportation (e.g., terminals, docks)	Developed High Density
Commercial/Residential Mixed	Developed High Density
Commercial/Industrial Mixed	Developed High Density
Developed Recreation (all recreation)	Turf and Grass
Vacant Land	Deciduous Forest
Cemeteries	Developed Low Density
Institutional (e.g., schools, hospitals, churches)	Developed Medium Density

Table A-1. Rhode Island Land-Use Classification (Page 2 of 2)

Rhode Island Versus NLCD Land-Use Classes – Pawcatuck	Model Class
Pasture (agricultural not suitable for tillage)	Pasture/Hay/Grassland
Cropland (tillable)	Rhode Island Cropland to Split With Cropland Data-Layer Sod/Grass Seed Percentages
Orchards, Groves, Nurseries	Pasture/Hay/Grassland
Confined Feeding Operations	Pasture/Hay/Grassland
Idle Agriculture (abandoned fields and orchards)	Deciduous Forest
Brushland (shrub and brush areas, reforestation)	Deciduous Forest
Deciduous Forest (> 80% hardwood)	Deciduous Forest
Softwood Forest (> 80% softwood)	Coniferous Forest
Mixed Forest	Deciduous Forest
Water	Wetlands
Wetland	Wetlands
Beaches	Barren
Sandy Areas (not beaches)	Barren
Rock Outcrops	Barren
Mines, Quarries, and Gravel Pits	Barren
Transitional Areas (urban open)	Developed Low Density
Mixed Barren Areas	Barren

NLCD = National Land Cover Database

Table A-2. Connecticut Land-Use Classification

Connecticut Versus NLCD Land-Use Classes – Pawcatuck	Model Class
Developed	Connecticut Developed to Split With NLCD Developed Percentages
Turf and Grass	Turf and Grass
Other Grasses	Pasture/Hay/Grassland
Agricultural Fields	Cropland
Deciduous Forest	Deciduous Forest
Coniferous Forest	Coniferous Forest
Water	Wetlands
Non-Forested Wetland	Wetlands
Forested Wetland	Wetlands
Tidal Wetland	Wetlands
Barren Land	Barren
Utility Corridors	Deciduous Forest

APPENDIX B
WATER QUALITY DATA SUMMARY

Table B-1. Summary of the Water Quality Data Available for Calibration (Page 1 of 10)

Provider	Station I.D.	Description	Type	Sample Count	HSPF Reach	Calibration Type
RIDEM	PAW05	Chipuxet River at Wolf Roack Trail/Road in Exeter (north of Hundred Acre Pond)	Stream/River	36	11	N/A
RIDEM	PAW36	Chipuxet River at Yawgoo Valley Road, Exeter	Stream/River	18		
RIDEM	PAW37	Chipuxet River at Liberty Road, Slocum	Stream/River	18		
RIDEM	WW17	Hundred Acre Pond	Reservoir	1,185	12	Tertiary
STORET	NALMS-5621	Hundred Acre	Lake/Pond	2		
RIDEM	WW245	Chipuxet River @ Rte 138	Stream/River	445	13	Tertiary
NWIS	USGS-01117350	CHIPUXET RIVER AT WEST KINGSTON, RI	Stream/River	350		
RIDEM	PAW35	Chipuxet River off Route 138 at the USGS Gage #1117350	Stream/River	37		
RIDEM	WW435	White Horn Brook @ Bike Trail	Stream/River	470	15	N/A
RIDEM	WW412	White Horn Brook @ Ministerial Rd.	Stream/River	600	17	Tertiary
NWIS	USGS-01117351	WHITE HORN BRK AT MINISTERIAL RD NR W KINGSTON, RI	Stream/River	306		
RIDEM	WW56	Tucker Pond	Lake/Pond	1,779	22	Tertiary
STORET	NALMS-5666	Tucker Pond	Lake/Pond	1		
RIDEM	PAW34	Alewife Brook at Wordens Pond Road, South Kingstown	Stream/River	24	23	N/A
RIDEM	WW66	Worden Pond	Lake/Pond	924	24	Secondary
RIDEM	WW120	Chickasheen Brook @ Miskiania	Stream/River	640	31	N/A
RIDEM	WW119	Chickasheen Brook @ Rte 2	Stream/River	407		
RIDEM	WW223	Chickasheen @ Potter Road (Skagg's old dam)	Stream/River	46		
RIDEM	WW68	Yawgoo Pond	Lake/Pond	2,903	32	Tertiary
STORET	NARS_WQX-NLA06608-2162	Yawgoo Pond	Lake/Pond	31		

Table B-1. Summary of the Water Quality Data Available for Calibration (Page 2 of 10)

Provider	Station I.D.	Description	Type	Sample Count	HSPF Reach	Calibration Type
STORET	NALMS-5682	Yawgoo Pond	Lake/Pond	2	32	Tertiary
RIDEM	WW02	Barber Pond	Lake/Pond	2,068	34	Tertiary
RIDEM	WW104	Barber Pond-Mud Brook	Stream/River	646		
RIDEM	WW121	Chickasheen Brook @ Barber Outlet	Stream/River	646		
STORET	NALMS-5595	Barber Pond	Lake/Pond	1		
RIDEM	WW122	Chickasheen Brook @ Rte 138	Stream/River	652	37	Secondary
RIDEM	WW225	Shickasheen Brook @ Liberty Lane	Stream/River	483		
RIDEM	PAW09	Chickasheen Brook at Waites Corner Road, South Kingstown	Stream/River	19		
NWIS	USGS-011173555	FISHERVILLE BROOK AT HENRY BROWN ROAD	Stream/River	3	39	N/A
NWIS	USGS-01117356	FISHERVILLE BROOK AT STATE HIGHWAY 102	Stream/River	3		
RIDEM	WW195	Queen River #3/Fisherville Brook	Stream/River	56	41	N/A
RIDEM	QN08	Sodom/Fisherville Brook At bend in Liberty Church Rd & William Reynolds road	Stream/River	37		
NWIS	USGS-01117360	FISHERVILLE BK AT LIBERTY CHURCH RD NR EXETER RI	Stream/River	3		
RIDEM	WW253	Queen River @ Rte 102	Stream/River	324	43	N/A
RIDEM	WW101	Queens River (Brownells - Wm Reynolds Rd)	Stream/River	285		
RIDEM	QN09	Queens River & Tribs On William Reynolds Road	Stream/River	37		
RIDEM	QN11	On Rte 102 near Exeter Country Club	Stream/River	18		
NWIS	USGS-01117345	QUEEN RIVER AT STONY LANE	Stream/River	3		
NWIS	USGS-01117355	QUEEN RIVER AT REYNOLDS RD NR EXETER RI	Stream/River	3		
NWIS	USGS-01117354	QUEEN RIVER AT STATE HIGHWAY 102 AT EXETER, RI	Stream/River	2		
RIDEM	QN20	Queens For Brook @ Rte 102	Stream/River	18	47	N/A

Table B-1. Summary of the Water Quality Data Available for Calibration (Page 3 of 10)

Provider	Station I.D.	Description	Type	Sample Count	HSPF Reach	Calibration Type
RIDEM	QN10a	Off School Landwoods Road, south of King Phillip Circle, 1100 feet downstream of QN10	Stream/River	31	51	N/A
RIDEM	WW103	Queens River (Mail Rd) #06b	Stream/River	453	53	N/A
RIDEM	WW102	Queens River #5 (Sand Bridge)	Stream/River	279		
RIDEM	QNAB	On Mail Rd/Liberty Rd USGS gage	Stream/River	37		
NWIS	USGS-01117368	QUEEN RIVER AT DAWLEY ROAD	Stream/River	3		
NWIS	USGS-01117370	QUEEN R AT LIBERTY RD AT LIBERTY RI	Stream/River	3		
RIDEM	WW207	Queen River @ Locke Brook	Stream/River	288	55	N/A
RIDEM	QN06	Locke Brook Mail Road	Stream/River	35		
NWIS	USGS-01117380	LOCKE BROOK AT MAIL RD AT LIBERTY RI	Stream/River	3		
RIDEM	QN21	Queens River at Dugway Bridge Road	Stream/River	36	57	N/A
NWIS	USGS-01117387	QUEEN RIVER AT DUGWAY ROAD	Stream/River	3		
RIDEM	WW100	Queens River (Sherman Brook)	Stream/River	619	59	Tertiary
RIDEM	QN04	Sherman Brook Before bend on Glen Rock Rd	Stream/River	37		
NWIS	USGS-01117400	SHERMAN BK AT GLEN ROCK RD AT GLEN ROCK RI	Stream/River	3		
RIDEM	WW246	Glen Rock Brook	Stream/River	333	61	N/A
RIDEM	QN03	Glen Rock Brook on Gardner Rd.	Stream/River	36		
NWIS	USGS-01117390	GLEN ROCK BK AT GLEN ROCK RD AT GLEN ROCK RI	Stream/River	3		
RIDEM	WW34	Queen River @ Usquepaugh (Glen Rock Reservoir)	Reservoir	1,165	63	Secondary
RIDEM	WW256	Usquepaugh River @ Rte 2	Stream/River	391		
NWIS	USGS-01117420	USQUEPAUG RIVER NEAR USQUEPAUG, RI	Stream/River	355		
RIDEM	QN01	Usquepaug River On Rte 2/ South County Trail	Stream/River	18		

Table B-1. Summary of the Water Quality Data Available for Calibration (Page 4 of 10)

Provider	Station I.D.	Description	Type	Sample Count	HSPF Reach	Calibration Type
RIDEM	QN01a	Usquepaug River at South County Trail (Rt. 2)	Stream/River	18	63	Secondary
NWIS	USGS-01117410	USQUEPAUG RIVER AT RT 138 AT USQUEPAUG, RI	Stream/River	3		
RIDEM	WW244	Pawcatuck River @ Biscuit City Rd (Charlestown, Richmond)	Stream/River	345	70	Secondary
NWIS	USGS-01117455	PAWCATUCK R AT SHERMAN AVE AT KENYON, RI	Stream/River	306		
RIDEM	PAW40	Pawcatuck River upstream of Kenyon at Sherman Road, Charlestown	Stream/River	18		
RIDEM	WW30	Pasquiset Pond	Lake/Pond	1912	72	Tertiary
STORET	NALMS-7392	Pasquiset Pond	Lake/Pond	36		
RIDEM	WW544	Pasquisett Pond (Ferrio Dock)	Lake/Pond	17		
RIDEM	WW115	Pasquiset Tributary/Pasquisett Brook	Stream/River	198	73	N/A
RIDEM	PAW26	Pasquiset Brook at the USGS Gage #1117450 on Route 2, Charlestown	Stream/River	36		
RIDEM	WW617	Pasquisett Brook @ Rte 2	Stream/River	28		
RIDEM	WW70	Beaver River #3 (Rte 138)	Stream/River	86	93	N/A
NWIS	USGS-01117468	BEAVER RIVER NEAR USQUEPAUG, RI	Stream/River	49		
RIDEM	PAW29	Beaver River at the USGS Gage #1117468 on Route 138, Richmond	Stream/River	36		
NWIS	USGS-01117471	BEAVER RIVER SHANNOCK HILL RD, NEAR SHANNOCK, RI	Stream/River	302	95	Secondary
RIDEM	PAW28	Mouth of Beaver River at the USGS Gage #1117471 on Shannock Hill Road, Richmond	Stream/River	36		
RIDEM	WW251	Pawcatuck River below Kenyon Ind. (Charlestown, Richmond)	Stream/River	389	110	Secondary
RIDEM	PAW41	Pawcatuck River at Shannock Road (Horseshoe Falls dam) Charlestown/Richmond	Stream/River	35		
RIDEM	WW314	White Brook Pond	Lake/Pond	49	112	N/A

Table B-1. Summary of the Water Quality Data Available for Calibration (Page 5 of 10)

Provider	Station I.D.	Description	Type	Sample Count	HSPF Reach	Calibration Type
RIDEM	WW252	Pawcatuck River @ Rte 91	Stream/River	403	130	N/A
NWIS	USGS-01117500	PAWCATUCK RIVER AT WOOD RIVER JUNCTION, RI	Stream/River	62		
RIDEM	PAW22	Meadow Brook at Rt 138 (near Meadow Brook Golf Club), Richmond	Stream/River	24	131	N/A
RIDEM	PAW20	Meadow Brook at USGS Gage #1117600 on Pine Hill Road, Richmond	Stream/River	37	133	N/A
RIDEM	WW26	Meadowbrook Pond (Sandy Pond)	Reservoir	1,112	135	Tertiary
STORET	NALMS-5634	Meadowbrook Pond	Lake/Pond	1		
RIDEM	PAW43	Pawcatuck River on Kings Factory Rd/Narragansett Trail in Richmond/Charlestown	Stream/River	36	150	N/A
RIDEM	WW580	Saw Mill Pond	Lake/Pond	61	153	N/A
RIDEM	WRB32	Falls River (Wood River) -Outlet of Hazard Pond on Hazard Rd	Stream/River	21	171	N/A
CTDEEP	CTDEEP14514	Porter Pond 50 meters north of pond outlet dam at southern end	Lake/Pond	11		
RIDEM	WW75	Falls River D - Stepstone Falls	Stream/River	547	173	Tertiary
RIDEM	WW74	Falls River C - Austin Farm Rd	Stream/River	550	175	Tertiary
RIDEM	WW72	Falls River A - Twin Bridges	Stream/River	546		
RIDEM	WW73	Falls River B - Sand Bank	Stream/River	401		
RIDEM	WRB22	Falls River (Wood River)- Baseline Station BL12	Stream/River	57		
RIDEM	WRB27	Phillips Brook on Dirt Road through Alton Jones Campus map required	Stream/River	39	177	N/A
RIDEM	WRB29	Phillips Brook-Plains Meeting House Rd	Stream/River	21		
RIDEM	WRB28	Acid Factory Brook-Plains Meeting House Rd	Stream/River	39	179	N/A
RIDEM	WW160	Eisenhower Lake	Lake/Pond	35		

Table B-1. Summary of the Water Quality Data Available for Calibration (Page 6 of 10)

Provider	Station I.D.	Description	Type	Sample Count	HSPF Reach	Calibration Type
RIDEM	WW136	Breakheart Pond	Reservoir	79		
RIDEM	WRB23	Breakheart Brook- Frosty Hollow Rd USGS 1117780	Stream/River	58	183	N/A
RIDEM	WRB26	Breakheart Brook-Raccoon Hill Trail	Stream/River	21		
RIDEM	WRB22a	Flat River at Midway Trail. Exeter	Stream/River	6	185	N/A
NWIS	USGS-01117800	WOOD RIVER NEAR ARCADIA, RI	Stream/River	89		
RIDEM	WRB17	Wood River-USGS 1117800 in Arcadia Management Area	Stream/River	39	187	N/A
RIDEM	WRB17a	Wood River at Ten Rod Rd. (Rt. 165)	Stream/River	18		
RIDEM	WRB20	Parris Brook-Escoheag Rd	Stream/River	21		
RIDEM	WRB21	Parris Brook-Old Voluntown Rd	Stream/River	21	189	N/A
RIDEM	WW181	Tippencansett Pond	Lake/Pond	10		
RIDEM	WRB19	Woody Hill Brook-Woody Hill Rd	Stream/River	21	193	N/A
RIDEM	WRB18	Parris Brook-Baseline Station BL19 at USGS 1117830 in Arcadia Management Area	Stream/River	57	195	N/A
RIDEM	WW06	Boone Lake	Lake/Pond	1,469		
RIDEM	WRB24	Roaring Brook-Outlet of Boon Lake on East Shore Drive	Stream/River	21		
RIDEM	WRB25	Roaring Brook-Inlet of Boon Lake on Austin Farm Rd	Stream/River	21	199	Tertiary
RIDEM	WRB40	Roaring Brook at Ten Rod Rd. (Rt. 165)	Stream/River	18		
NWIS	USGS-413330071410701	Roaring Brook at KG Ranch Road, Arcadia, RI	Stream/River	1		
RIDEM	WW298	Browning Mill Pond	Lake/Pond	41		
STORET	NALMS-5602	Browning Mill Pond	Lake/Pond	2	201	N/A
NWIS	USGS-01117870	ROARING BROOK AT BALD HILL RD AT ARCADIA, RI	Stream/River	1		
RIDEM	WW67	Wyoming Pond	Reservoir	389	205	N/A

Table B-1. Summary of the Water Quality Data Available for Calibration (Page 7 of 10)

Provider	Station I.D.	Description	Type	Sample Count	HSPF Reach	Calibration Type
RIDEM	WRB14	Wood River-above Wyoming Pond on Dye Hill Rd	Stream/River	39	205	N/A
RIDEM	WRB15	Wood River-Barbersville Baseline Station BL25-Old Nooseneck Rd	Stream/River	39		
RIDEM	WRB15a	Wood River at Old Nooseneck Rd.	Stream/River	18		
STORET	NALMS-5681	Wyoming Pond	Lake/Pond	1		
RIDEM	WW77	Locustv. Brushy Brook at Woody Hill	Stream/River	185	207	N/A
RIDEM	WW78	Locustv. Brushy Brook at Saw Mill	Stream/River	185		
RIDEM	WRB12	Brushy Brook-Dye Hill Rd	Stream/River	33		
RIDEM	WRB36	Brushy Brook at Sawmill Rd.	Stream/River	18		
RIDEM	WW214	Wincheck Pond	Lake/Pond	1,324	212	Tertiary
RIDEM	WRB11	Moscow Brook-Dye Hill Rd	Stream/River	58	213	N/A
RIDEM	WW79	Locustv. Moscow Brook at Saw Mill	Stream/River	37		
RIDEM	WRB10	Moscow Brook-Rockville off Wincheck Pond Rd	Stream/River	21		
RIDEM	WW21	Locustville Pond	Reservoir	746	214	Tertiary
RIDEM	WRB09	Brushy Brook-Outlet of Locustville Pond on Rte 3	Stream/River	57		
STORET	NALMS-5628	Locustville Pond	Lake/Pond	5		
RIDEM	WW391	Wood River @ Switch Rd.	Stream/River	131	215	N/A
RIDEM	WRB08	Wood River-USGS 1118000	Stream/River	57		
NWIS	USGS-01118000	WOOD RIVER AT HOPE VALLEY, RI	Stream/River	48		
RIDEM	WW22	Long Pond (Hopkinton)	Lake/Pond	72	217	N/A
RIDEM	WRB05	Canochet Brook-Palmer Circle	Stream/River	57		
RIDEM	WRB07	Canochet Brook - Outlet of Ashville Pond on Marshall Drifting Rd	Stream/River	39		
RIDEM	WRB06	Canochet Brook - Route 3 crossing - USGS 1118005	Stream/River	39		

Table B-1. Summary of the Water Quality Data Available for Calibration (Page 8 of 10)

Provider	Station I.D.	Description	Type	Sample Count	HSPF Reach	Calibration Type
RIDEM	WRB04	Canochet Bk.-Baseline Station BL08-Woodville-Alton Rd	Stream/River	21	217	N/A
RIDEM	WRB37	Canonchet Brook at Canonchet Rd. (U.S.)	Stream/River	18		
RIDEM	WRB38	Canonchet Brook at Canonchet Rd. DS of Lawton Foster Rd N.	Stream/River	18		
RIDEM	WW01	Alton Pond	Reservoir	1,221	219	Secondary
NWIS	USGS-01118009	WOOD RIVER NEAR ALTON, RI	Stream/River	306		
RIDEM	WRB02	Wood River-Rte 91 in Alton	Stream/River	57		
RIDEM	WRB03	Wood River-Woodville Rd in Woodville	Stream/River	57		
RIDEM	WRB01	Wood River-Confluence with Pawcatuck River	Stream/River	21		
STORET	NALMS-5594	Alton Pnd	Lake/Pond	2		
RIDEM	WW249	Pawcatuck River @ Burdickville Rd (Hopkinton, Chalestown)	Stream/River	391	230	N/A
RIDEM	WW133	Watchaug Pond-Perry Healy Brook	Stream/River	244	231	N/A
RIDEM	PAW17	Perry Healy Brook at Klondike Road, Charlestown	Stream/River	37		
RIDEM	WW60	Watchaug Pond	Lake/Pond	1,939	232	Secondary
STORET	NALMS-5673	Watchaug Pond	Lake/Pond	4		
RIDEM	WW31	Pawcatuck River @ Bradford. (Westerly/Hopkinton)	Stream/River	757	250	Secondary
NWIS	USGS-01118030	PAWCATUCK R AT ALTON-BRADFORD RD AT BRADFORD, RI	Stream/River	306		
RIDEM	PAW38	Pawcatuck River upstream of Bradford Dyeing on route 91 (Alton-Bradford Road)	Stream/River	36		
RIDEM	WW248	Pawcatuck River below Bradford Dyeing Assoc.	Stream/River	20		
RIDEM	WW255	Tomaquag Brk @ Woodville Rd.	Stream/River	106	251	N/A
RIDEM	PAW52	Tomaquag Brook	Stream/River	18		
NWIS	USGS-01118055	TOMAQUAG BROOK, AT RT. 216, AT BRADFORD, RI	Stream/River	306	253	N/A

Table B-1. Summary of the Water Quality Data Available for Calibration (Page 9 of 10)

Provider	Station I.D.	Description	Type	Sample Count	HSPF Reach	Calibration Type
RIDEM	WW310	Tomaquag Brook @ Chase Hill	Stream/River	234	253	N/A
RIDEM	PAW54	Tomaquag Brook at Diamond Hill Rd.	Stream/River	18		
RIDEM	WW200	Chapman Pond	Lake/Pond	506	272	Tertiary
STORET	NARS_WQX-NLA06608-2566	Chapman Pond	Lake/Pond	5		
STORET	NALMS-5608	Chapman Pond	Lake/Pond	1		
NWIS	USGS-01118100	PAWCATUCK RIVER NEAR SOUTH HOPKINTON, RI	Stream/River	306	290	N/A
RIDEM	WW250	Pawcatuck River @ Chase Hill Rd.	Stream/River	43		
RIDEM	PAW39	Pawcatuck River on Nooseneck Hill Road (Rte 3), Hopkinton	Stream/River	36		
CTDEEP	CTDEEP17211	Wyassup Brook under and above Route 49	Stream/River	19	291	N/A
CTDEEP	CTDEEP15796	Pendleton Hill Brook adjacent to Route 49 on state property upstream of USGS gage, pole #257 and house # 567	Stream/River	170	293	Tertiary
CTDEEP	CTDEEP16079	Pendleton Hill Brook Upstream Grindstone Hill Road Pendleton Hill Brook Near Clarks Falls	Stream/River	18		
CTDEEP	CTDEEP14719	Wyassup Brook at mouth upstream of Clarks Falls Road	Stream/River	27	295	N/A
CTDEEP	CTDEEP14720	Green Fall River upstream confluence with Wyassup Bk US Clarks Fall Rd.	Stream/River	172	299	Tertiary
RIDEM	WW411	Parmentier Brk @ Clark Falls Rd.	Stream/River	60	327	N/A
RIDEM	PAW13	Parmenter Brook at USGS gage #1118355 on Wich Way, Hopkinton	Stream/River	37		
NWIS	USGS-01118356	ASHWAY RIVER AT EXTENSION 184 NEAR ASHWAY, RI	Stream/River	306	329	Secondary
NWIS	USGS-01118360	ASHAWAY RIVER AT ASHAWAY, RI	Stream/River	306		
RIDEM	WW242	Ashaway River @ Rte 216	Stream/River	240		
RIDEM	WW243	Ashaway River @ Wellstown Rd.	Stream/River	222		

Table B-1. Summary of the Water Quality Data Available for Calibration (Page 10 of 10)

Provider	Station I.D.	Description	Type	Sample Count	HSPF Reach	Calibration Type
RIDEM	WW304	Green Falls - Rte 184	Stream/River	203	329	Secondary
RIDEM	PAW12a	Ashaway River at Ashaway Rd. (Rte 216)	Stream/River	18		
RIDEM	PAW50	Ashaway River at Ashaway Line and Twine	Stream/River	18		
RIDEM	WW141	Pawcatuck River @ Potter Hill	Stream/River	161	330	N/A
RIDEM	WW479	Pawcatuck River - Upstream of Boom Bridge	Stream/River	160		
RIDEM	PAW49	Pawcatuck River at Boom Bridge Road	Stream/River	36		
RIDEM	WW480	Pawcatuck River - At Boom Bridge	Stream/River	20		
RIDEM	WW481	Pawcatuck River - Downstream of Boom Bridge	Stream/River	20		
NWIS	USGS-01118400	SHUNOCK RIVER NEAR NORTH STONINGTON, CT	Stream/River	306	335	Tertiary
CTDEEP	CTDEEP14721	Shunock River upstream Route 49	Stream/River	55		
CTDEEP	CTDEEP14859	Shunock River upstream Route 184	Stream/River	9		
NWIS	USGS-01118500	PAWCATUCK RIVER AT WESTERLY, RI	Stream/River	5,162	350	Primary
CTDEEP	S011018	Stillman Bridge	Stream/River	277		
RIDEM	PAW01	Mouth of Pawcatuck River Basin located at Bridge Street (White Rock Bridge) Westerly	Stream/River	36		
CTDEEP	CTDEEP14379	Pawcatuck River under White Rock Road Bridge at state line	Stream/River	27		
CTDEEP	CTDEEP17746	Anguilla Brook at Route 1	Stream/River	9	375	N/A

APPENDIX C
WATER QUALITY CALIBRATION

Table C-1. Average Annual Nonpoint-Loading Rates (Pound/Acre/Year) for the Calibration Period

Land Cover	Constituents (Average lb/acre/yr loadings)							
	Total Suspended Sediment	Total Nitrogen	Ammonia as N	Nitrate-Nitrite as N	Total Kjeldahl Nitrogen	Total Phosphorus	Orthophosphate as P	Biochemical Oxygen Demand
Developed Low Intensity	93.6	8.11	0.441	3.48	4.63	0.377	0.175	23.7
Developed Low Intensity EIA	528	5.75	1.34	3.05	2.70	0.412	0.336	8.77
Developed Medium Intensity	140	8.13	0.453	3.51	4.61	0.386	0.185	23.5
Developed Med Intensity EIA	533	5.80	1.35	3.08	2.72	0.416	0.340	8.87
Developed High Intensity	232	8.19	0.477	3.57	4.62	0.406	0.206	23.4
Developed High Intensity EIA	535	5.88	1.37	3.11	2.76	0.422	0.345	9.01
Coniferous Forest AB	14.6	2.38	0.062	0.774	1.60	0.0931	0.0192	8.77
Coniferous Forest CD	26.4	2.40	0.070	0.824	1.58	0.0930	0.0208	8.56
Deciduous Forest AB	13.9	2.33	0.061	0.756	1.58	0.0915	0.0188	8.63
Deciduous Forest CD	26.8	2.39	0.069	0.819	1.57	0.0929	0.0208	8.55
Wetlands	11.0	1.99	0.056	0.660	1.33	0.0744	0.0134	7.24
Pasture	72.1	4.92	0.178	2.10	2.81	0.178	0.051	15.0
Turf and Grass	141	11.7	0.604	4.76	6.99	0.550	0.242	36.2
Cropland	185	12.6	0.750	5.41	7.14	0.601	0.293	36.3
Barren	979	5.97	0.319	2.72	3.25	0.394	0.251	16.7

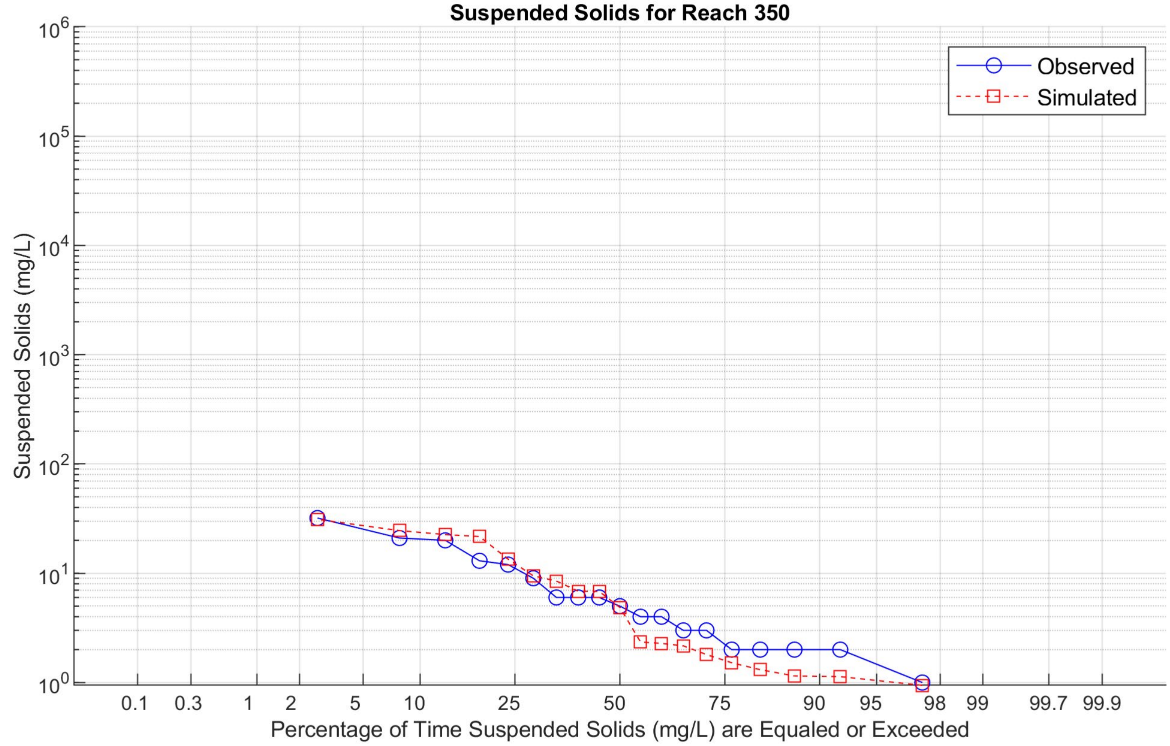

Figure C-1. Total Suspended Sediment Duration Plot for HSPF Reach 350 (Log Scale).

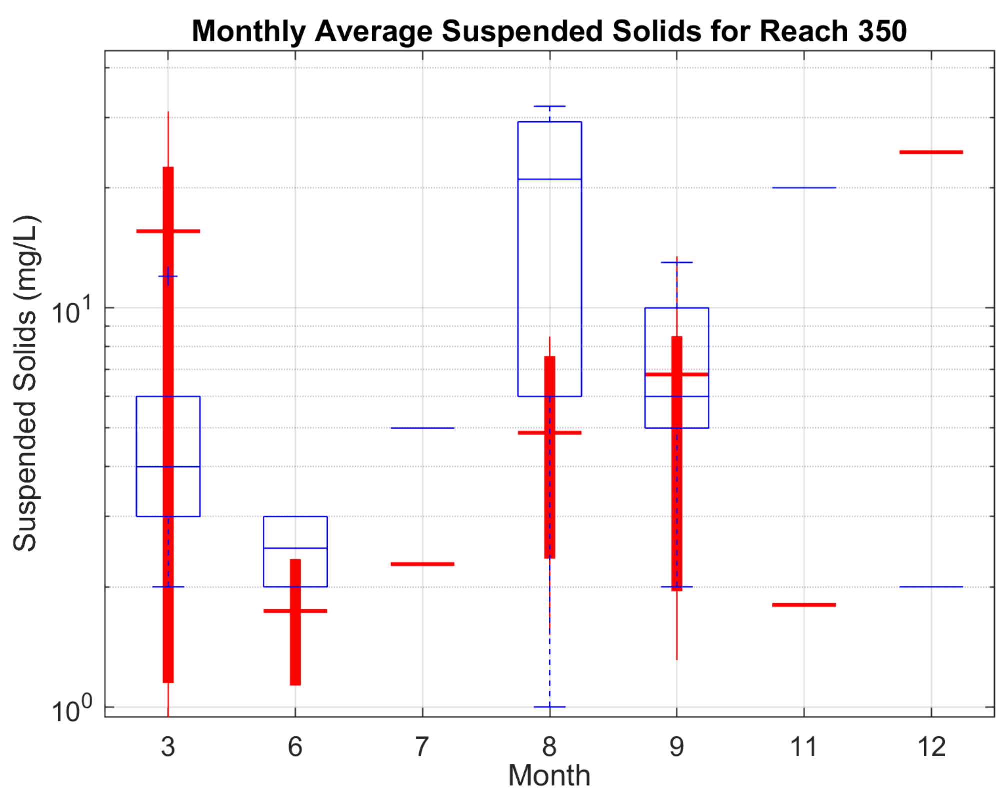

Figure C-2. Total Suspended Sediment Monthly Average Boxplot for HSPF Reach 350 (Log Scale).

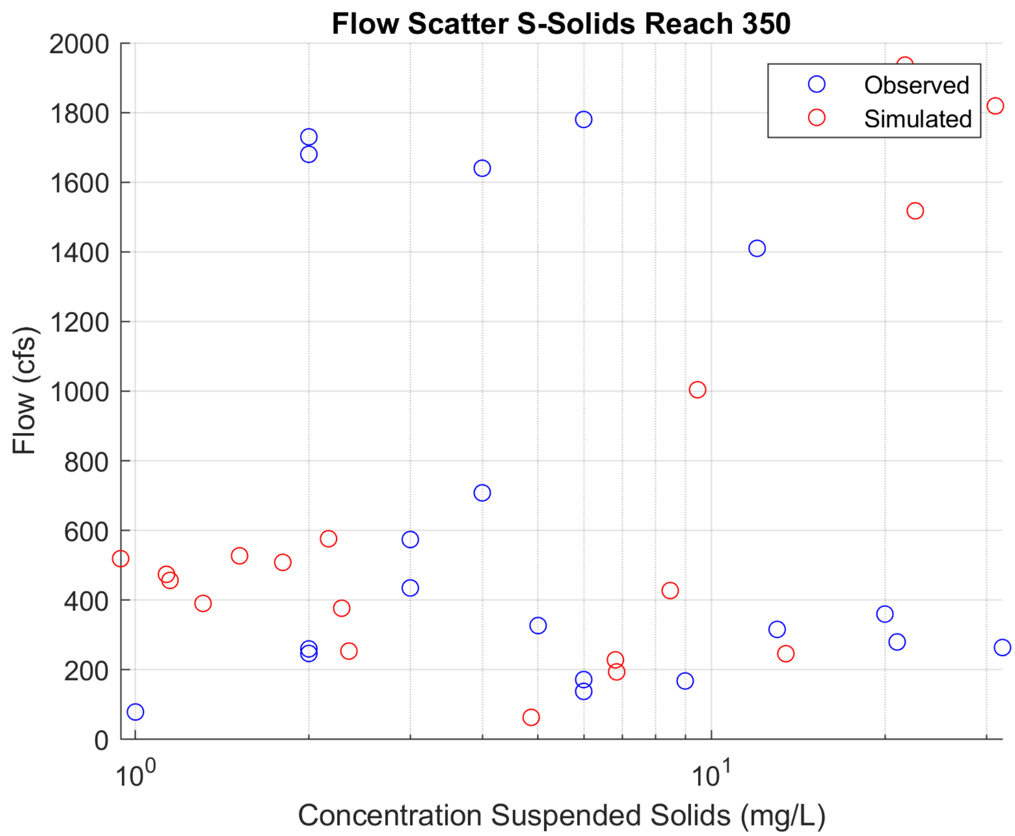

Figure C-3. Total Suspended Sediment Scatter Plot for HSPF Reach 350 (Log Scale).

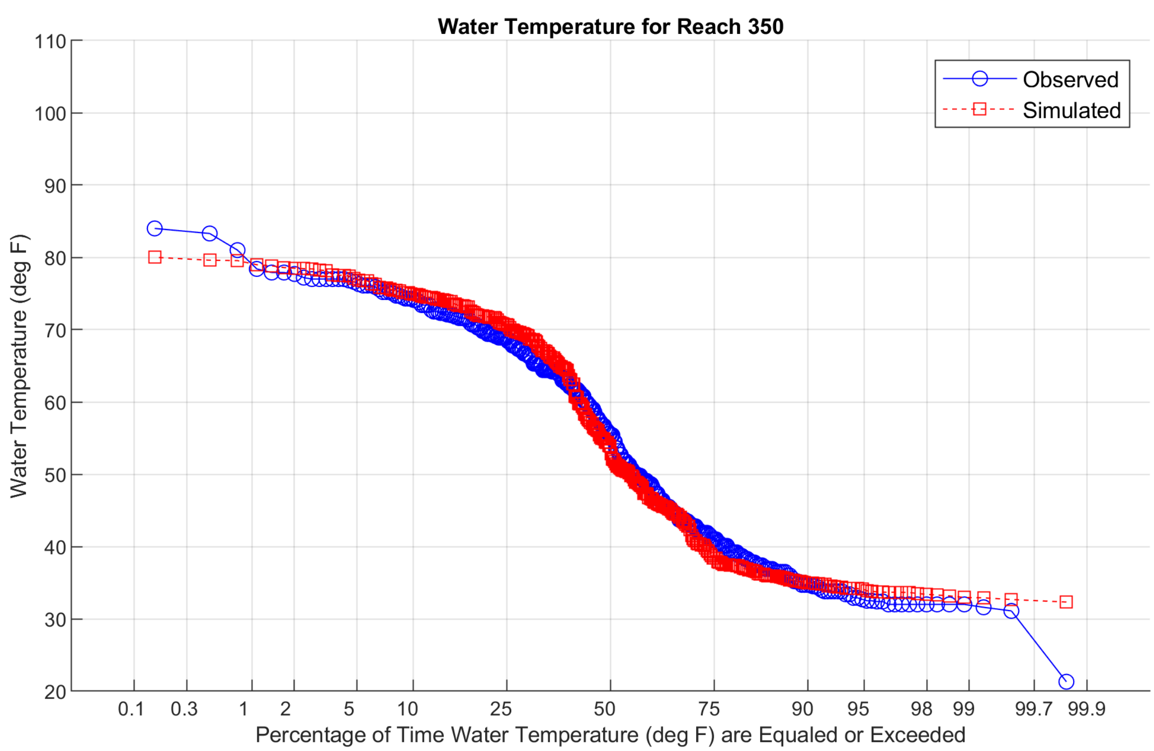

Figure C-4. Instantaneous Temperature Duration Plot for HSPF Reach 350.

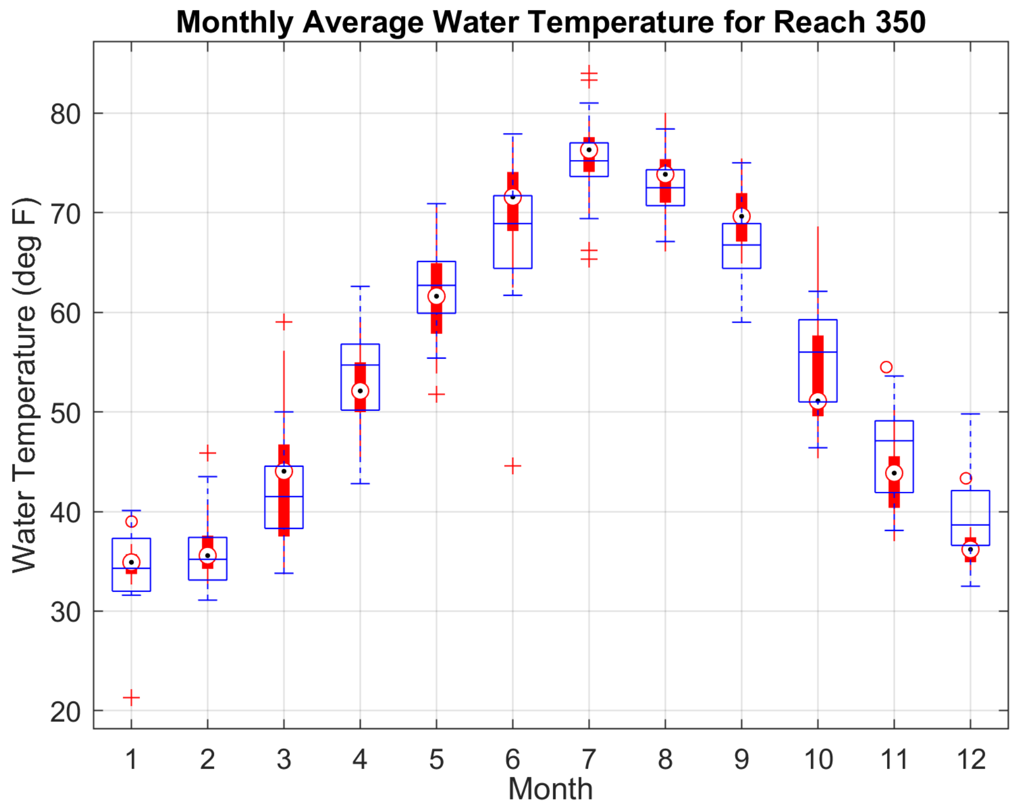

Figure C-5. Instantaneous Temperature Monthly Average Boxplot for HSPF Reach 350.

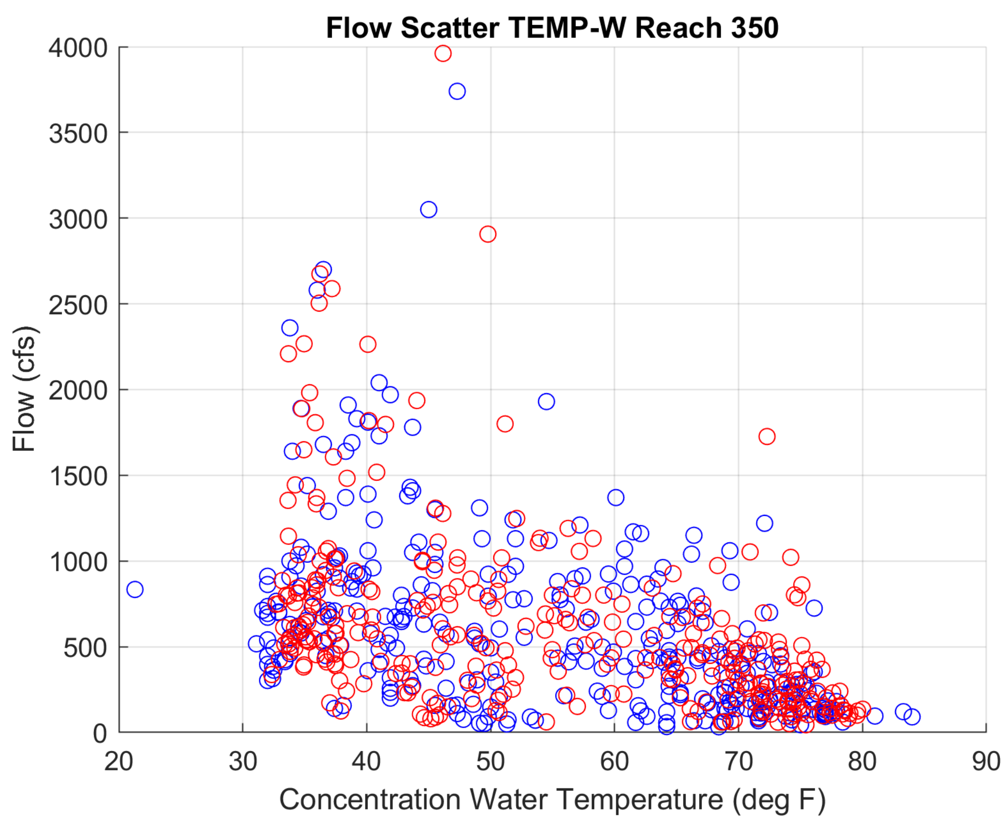

Figure C-6. Instantaneous Temperature Scatter Plot for HSPF Reach 350.

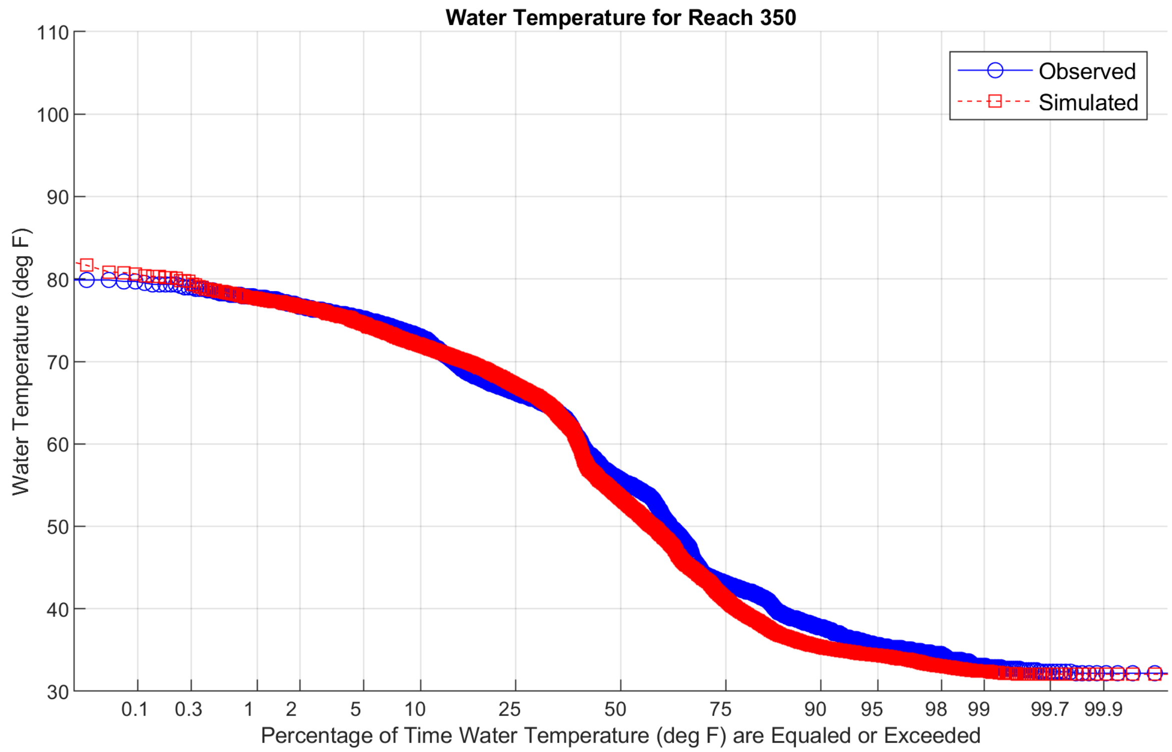

Figure C-7. Continuous Temperature Duration Plot for HSPF Reach 350.

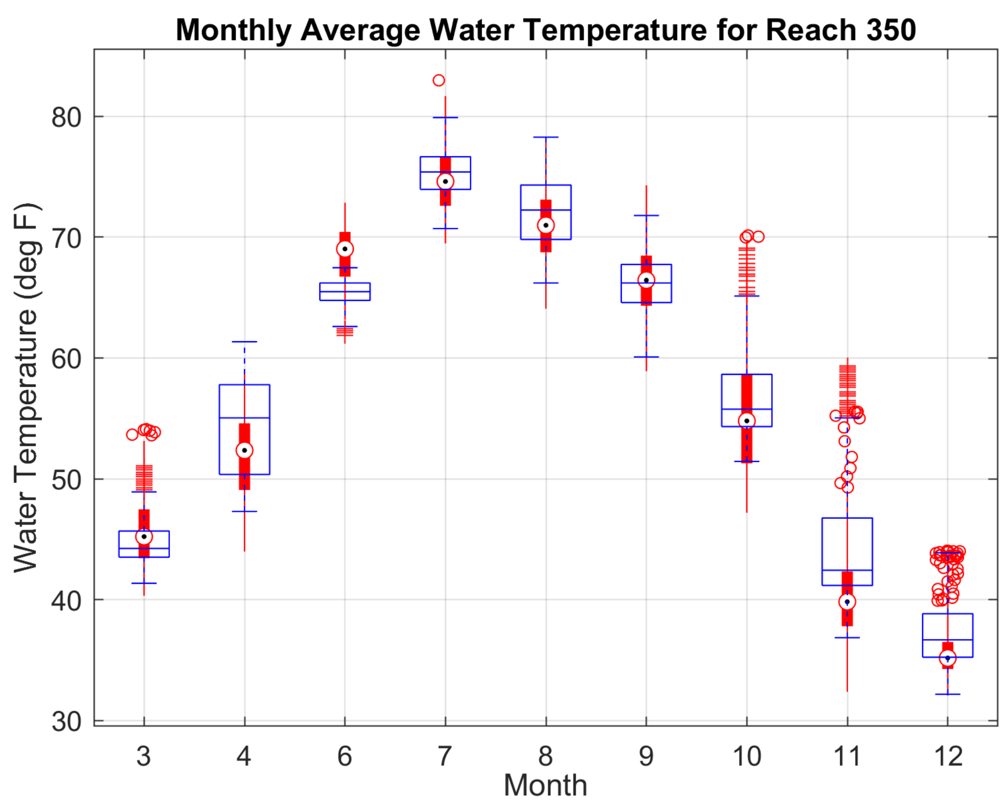

Figure C-8. Continuous Temperature Monthly Average Boxplot for HSPF Reach 350.

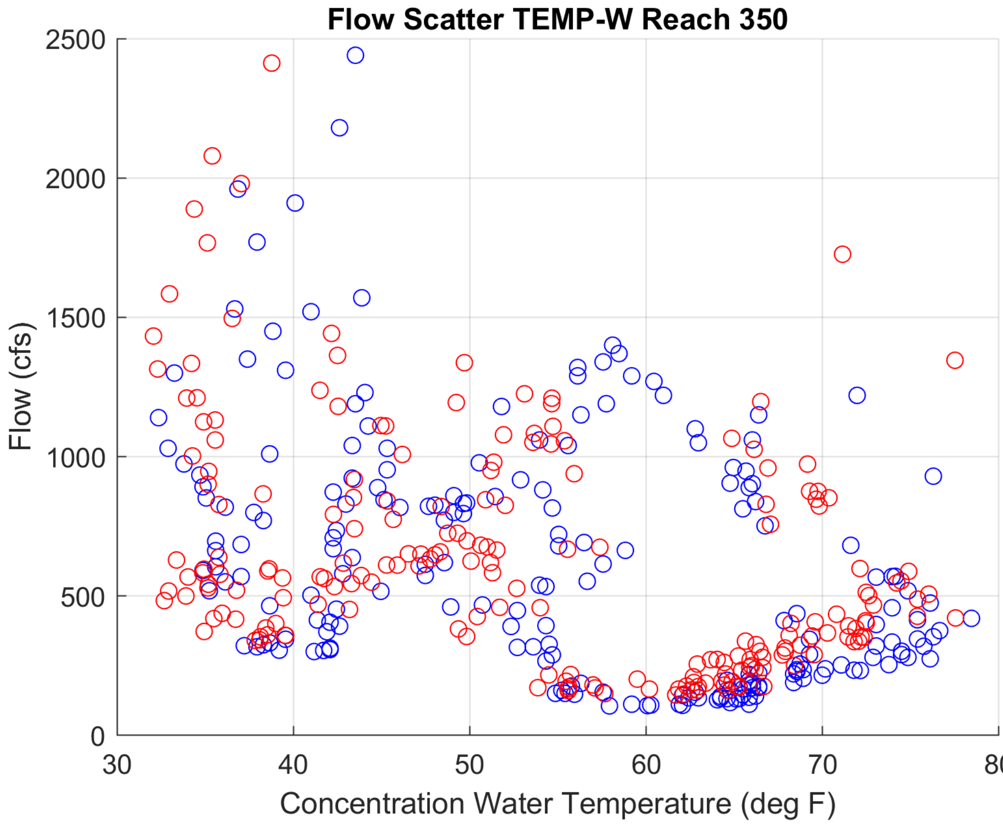

Figure C-9. Continuous Temperature Scatter Plot for HSPF Reach 350.

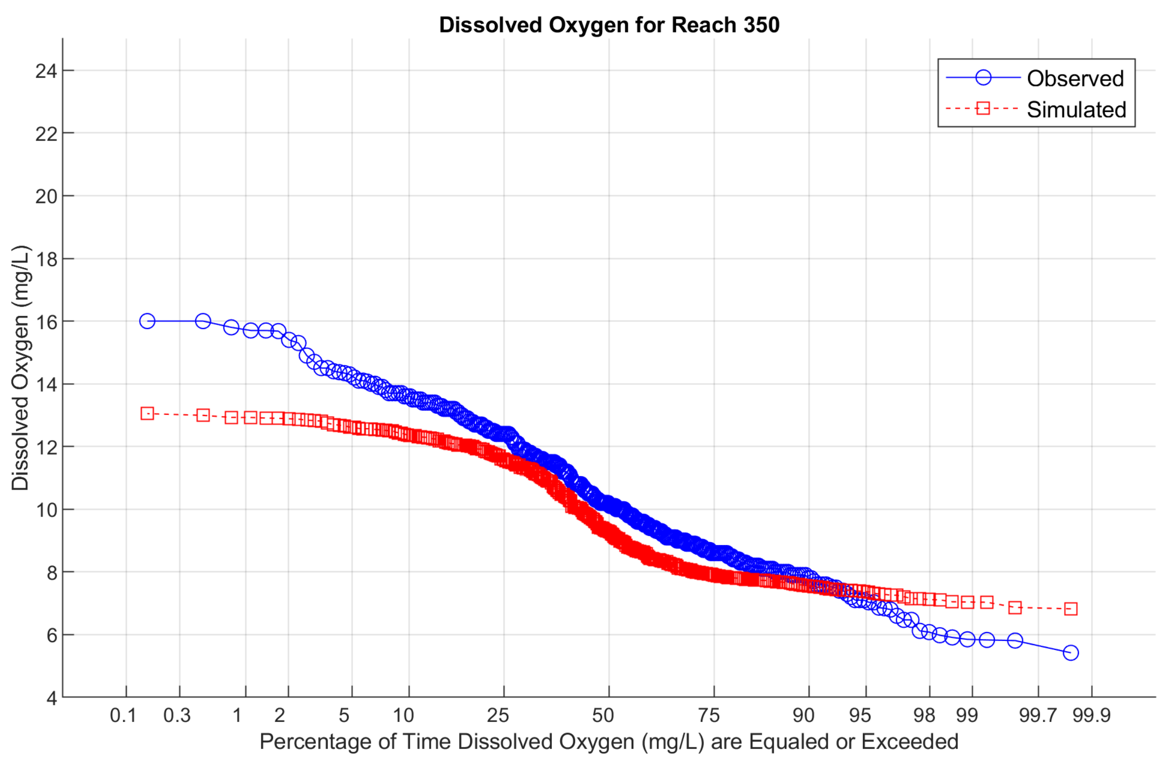

Figure C-10. Instantaneous Dissolved Oxygen Duration Plot for HSPF Reach 350.

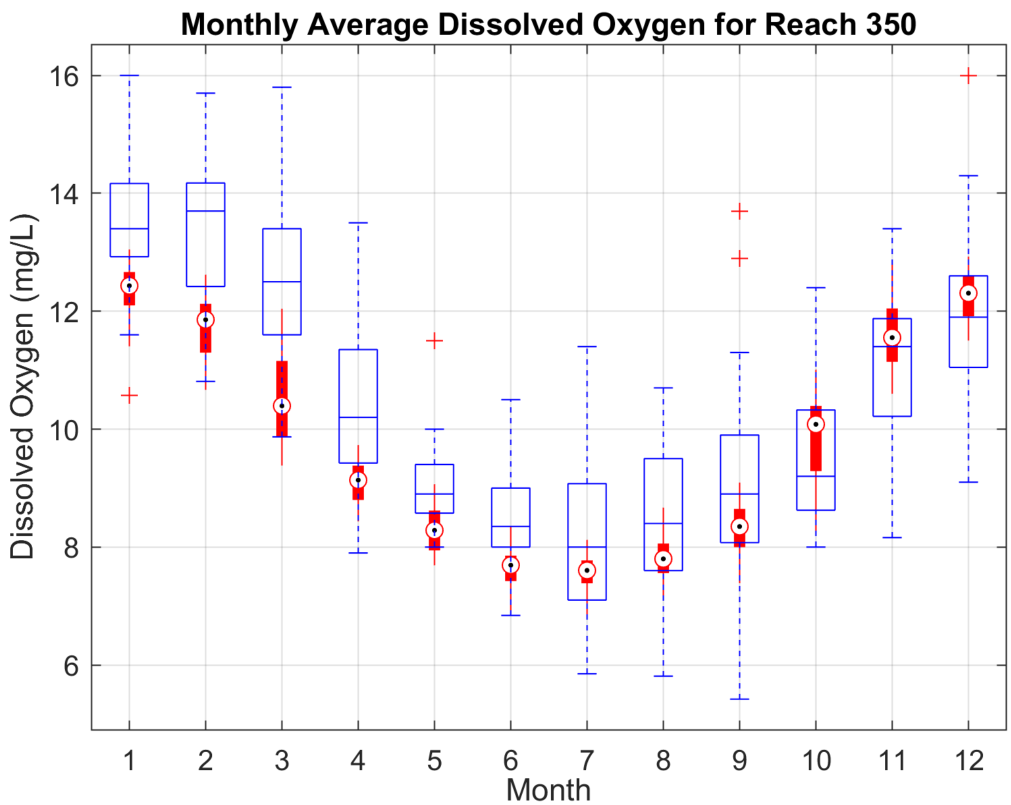

Figure C-11. Instantaneous Dissolved Oxygen Monthly Average Boxplot for HSPF Reach 350.

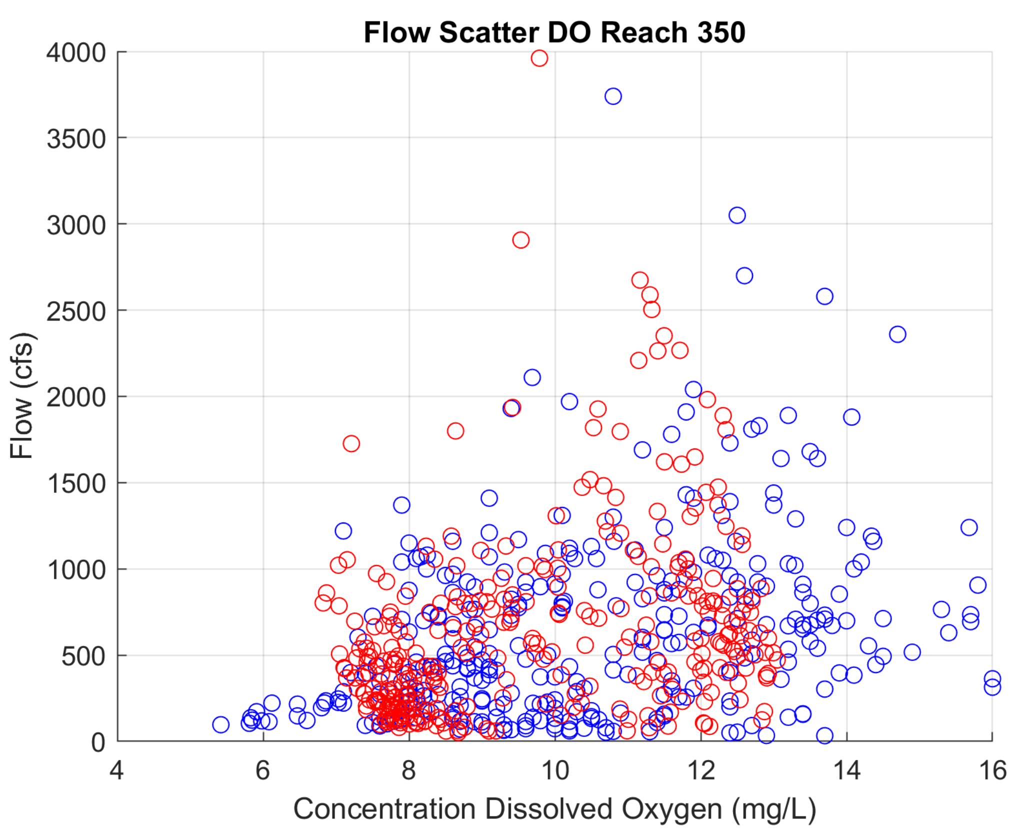

Figure C-12. Instantaneous Dissolved Oxygen Scatter Plot for HSPF Reach 350.

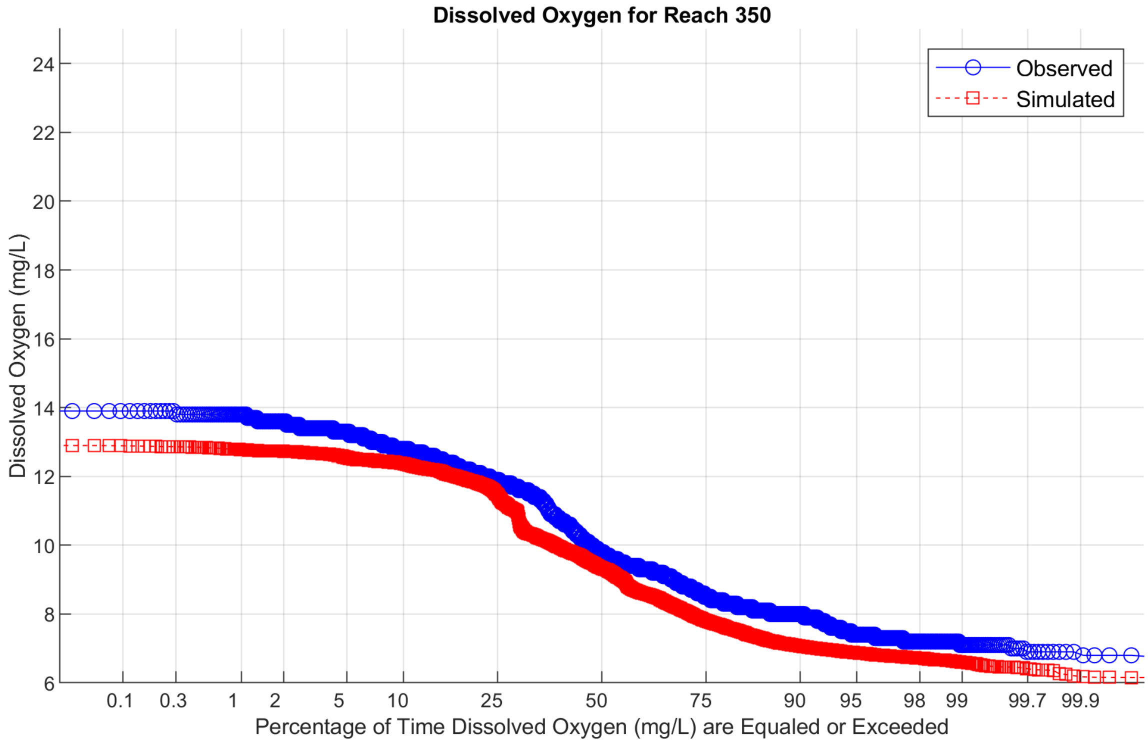

Figure C-13. Continuous Dissolved Oxygen Duration Plot for HSPF Reach 350.

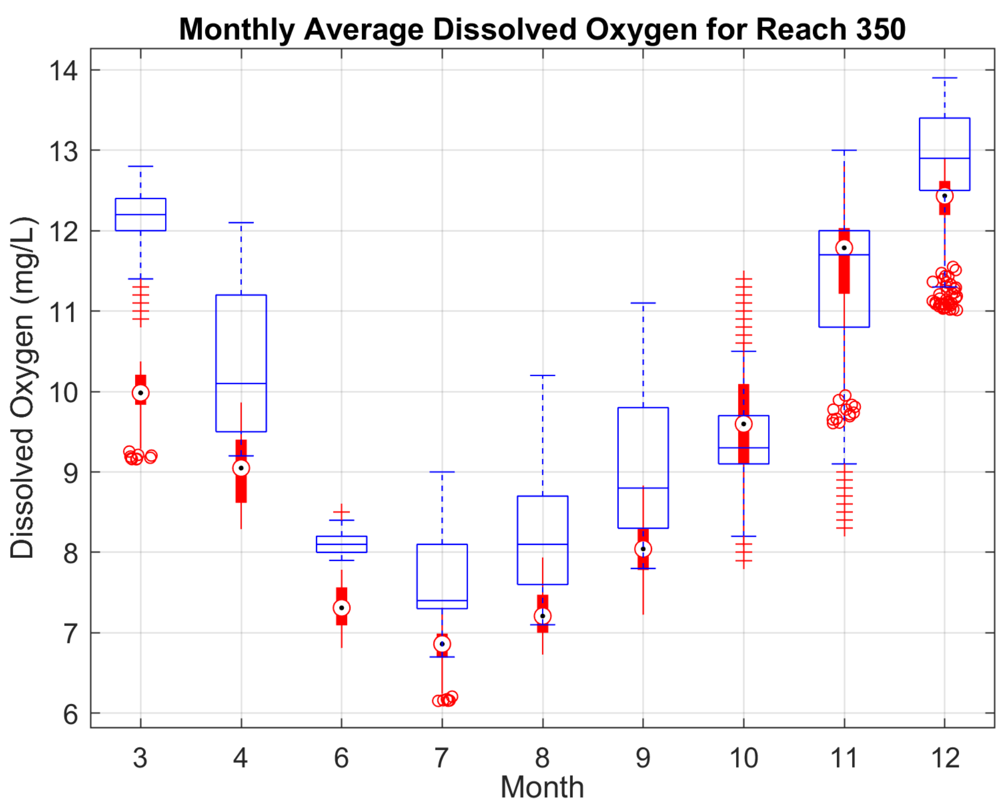

Figure C-14. Continuous Dissolved Oxygen Monthly Average Boxplot for HSPF Reach 350.

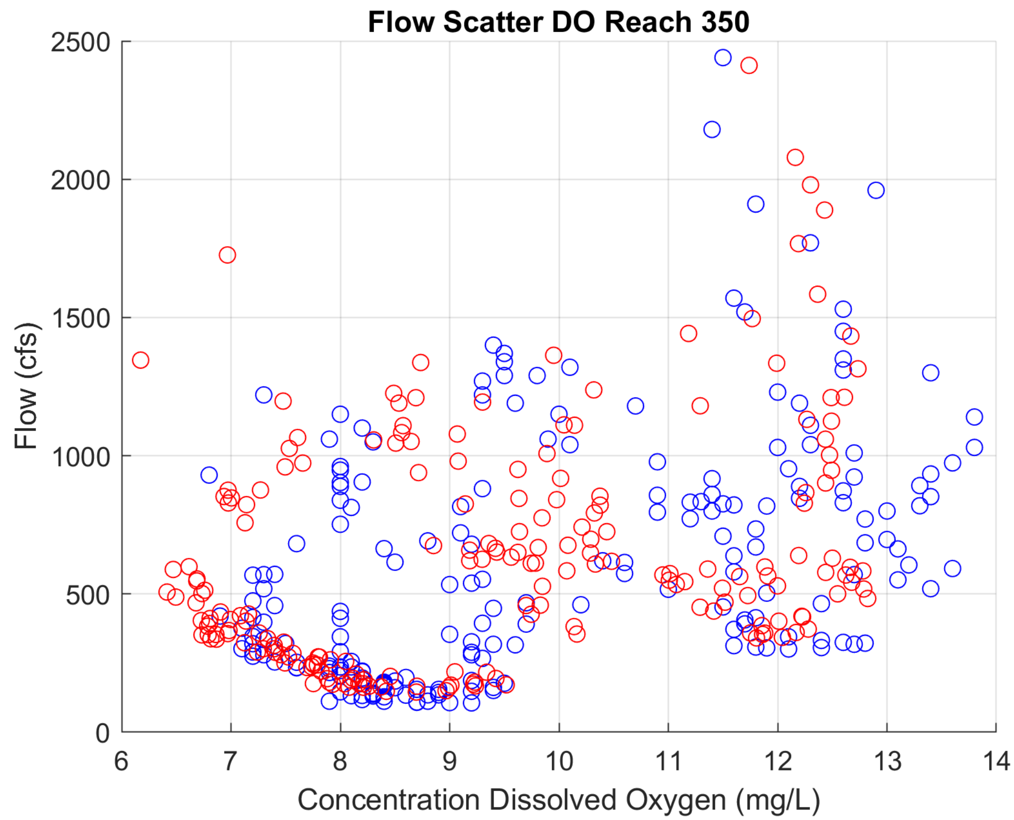

Figure C-15. Continuous Dissolved Oxygen Scatter Plot for HSPF Reach 350.

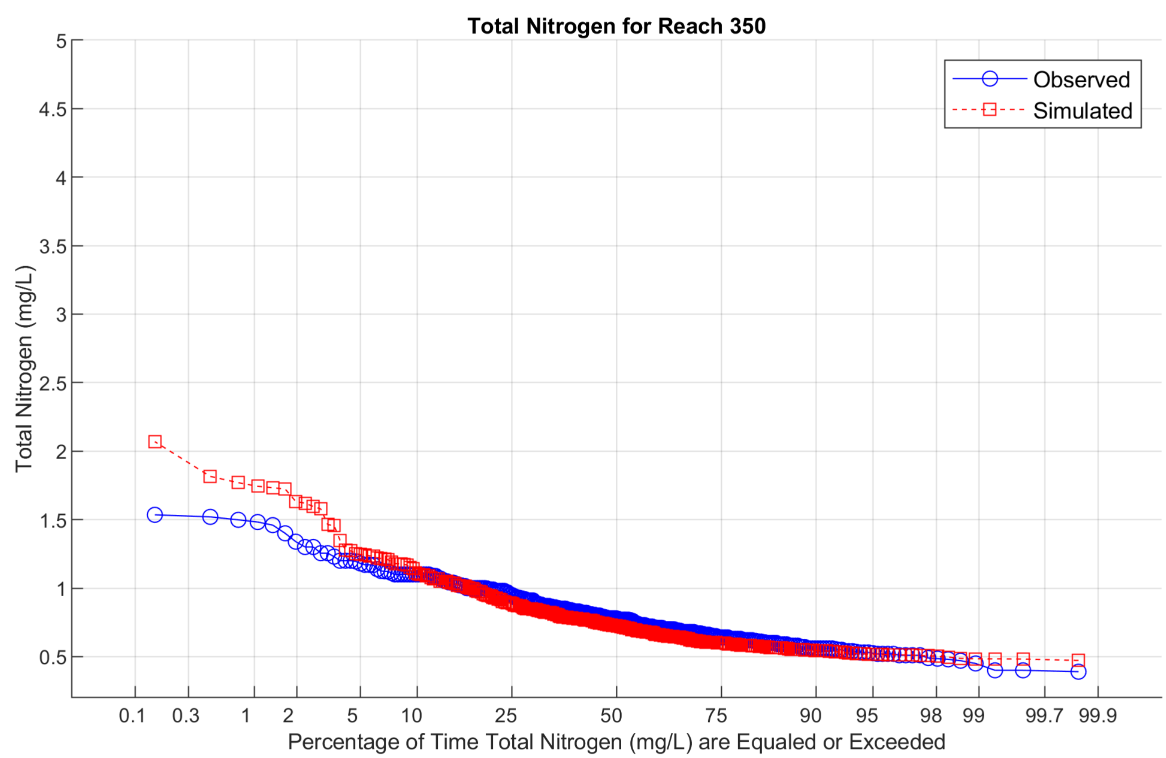

Figure C-16. Total Nitrogen Duration Plot for HSPF Reach 350.

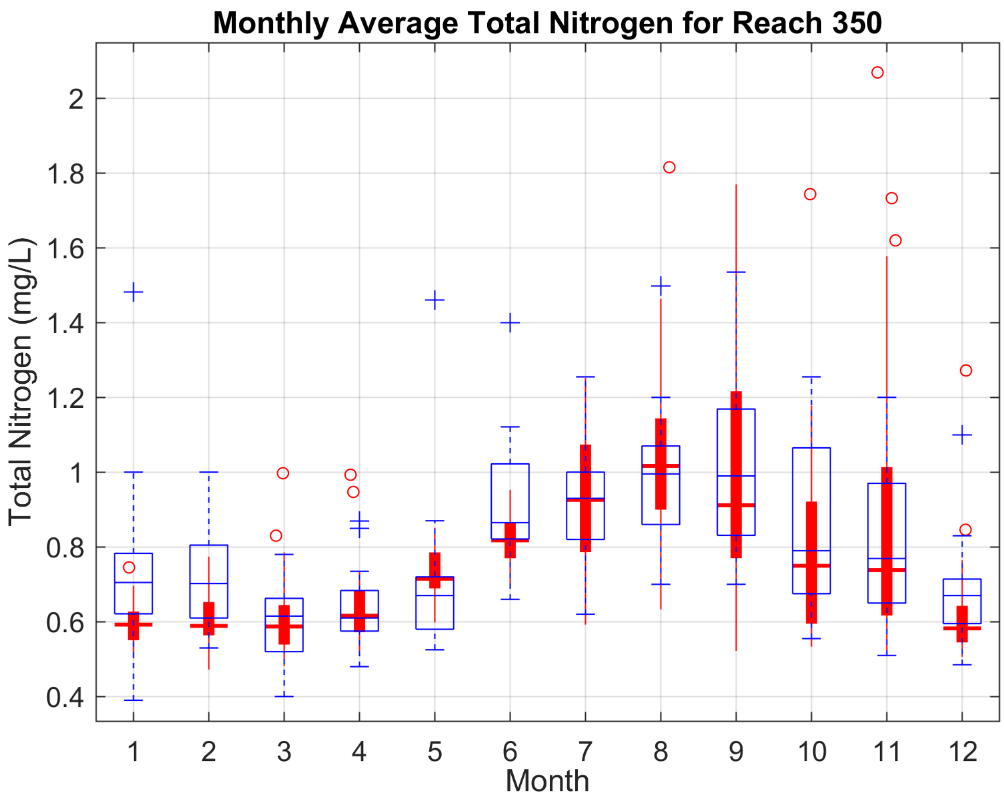

Figure C-17. Total Nitrogen Monthly Average Boxplot for HSPF Reach 350.

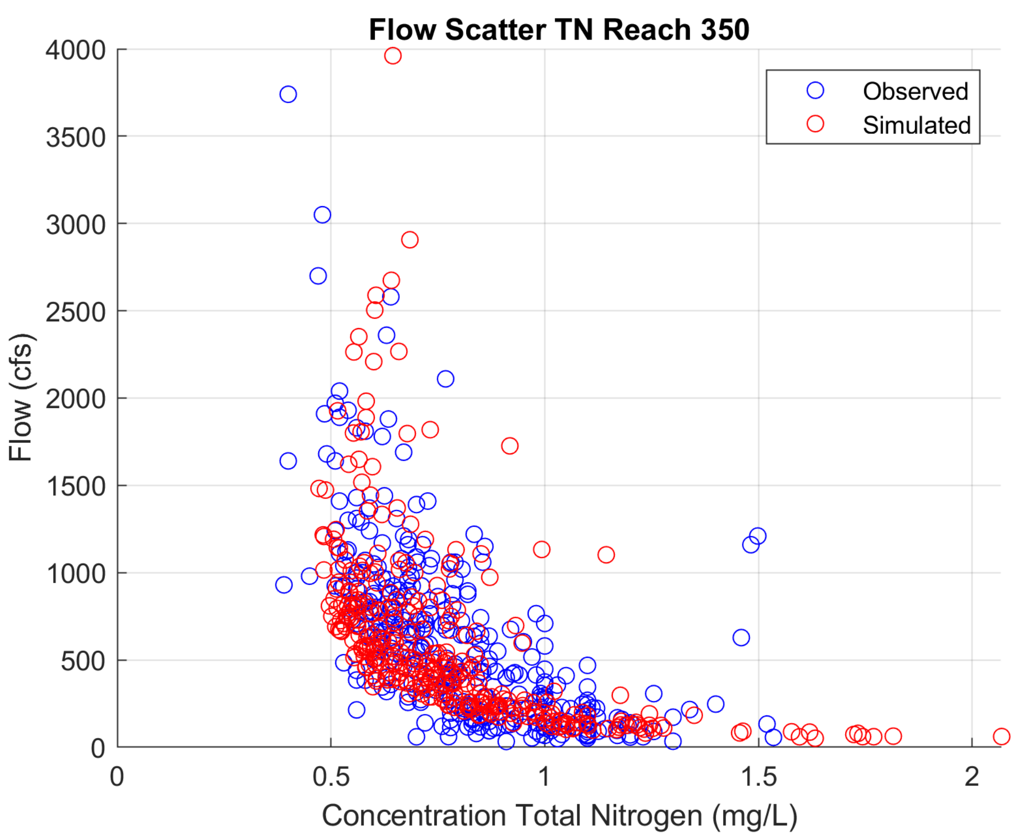

Figure C-18. Total Nitrogen Scatter Plot for HSPF Reach 350.

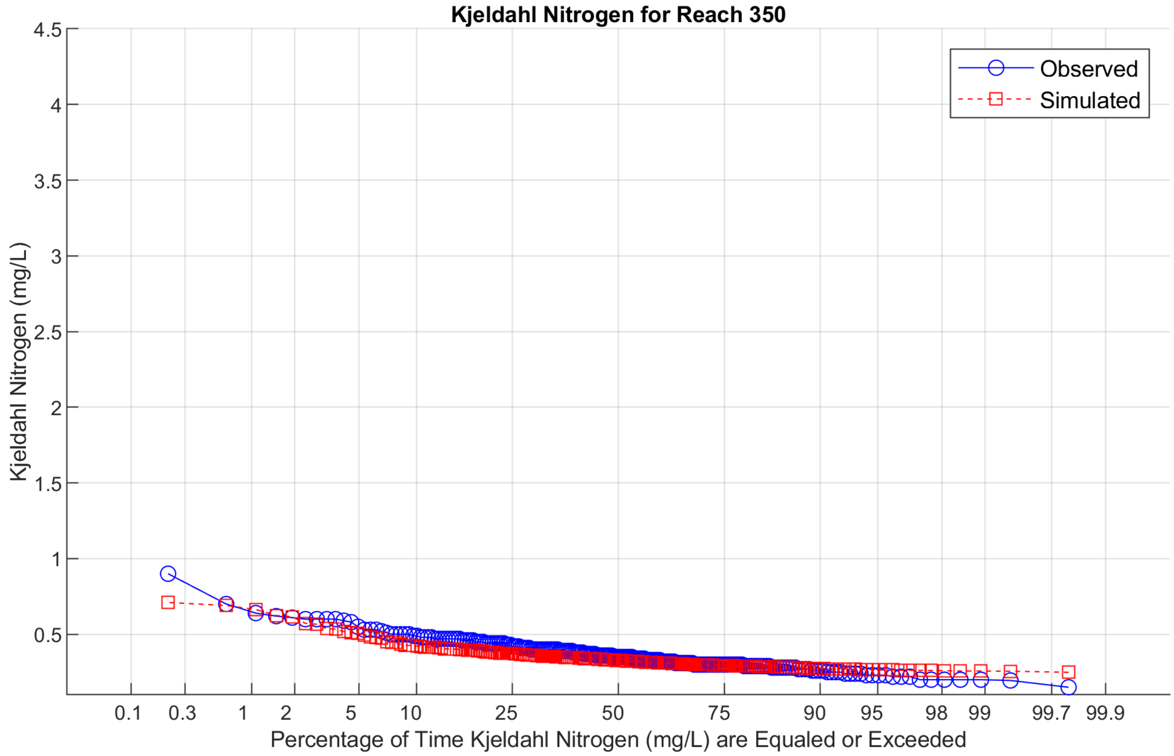

Figure C-19. Total Kjeldahl Nitrogen Duration Plot for HSPF Reach 350.

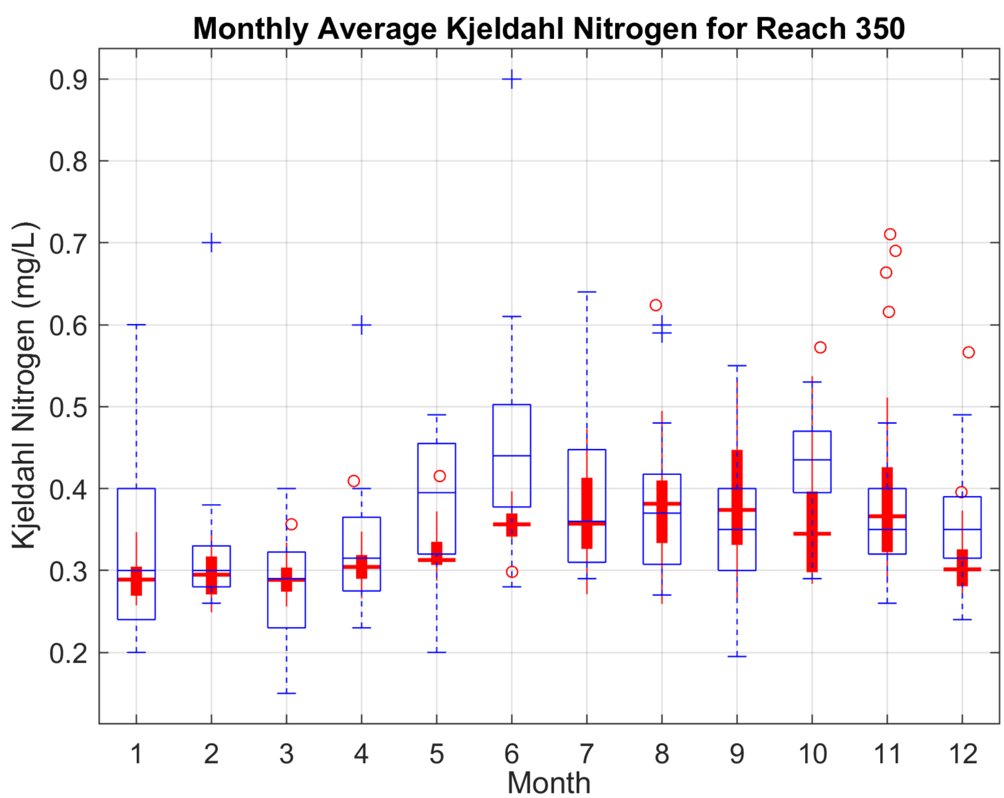

Figure C-20. Total Kjeldahl Nitrogen Monthly Average Boxplot for HSPF Reach 350.

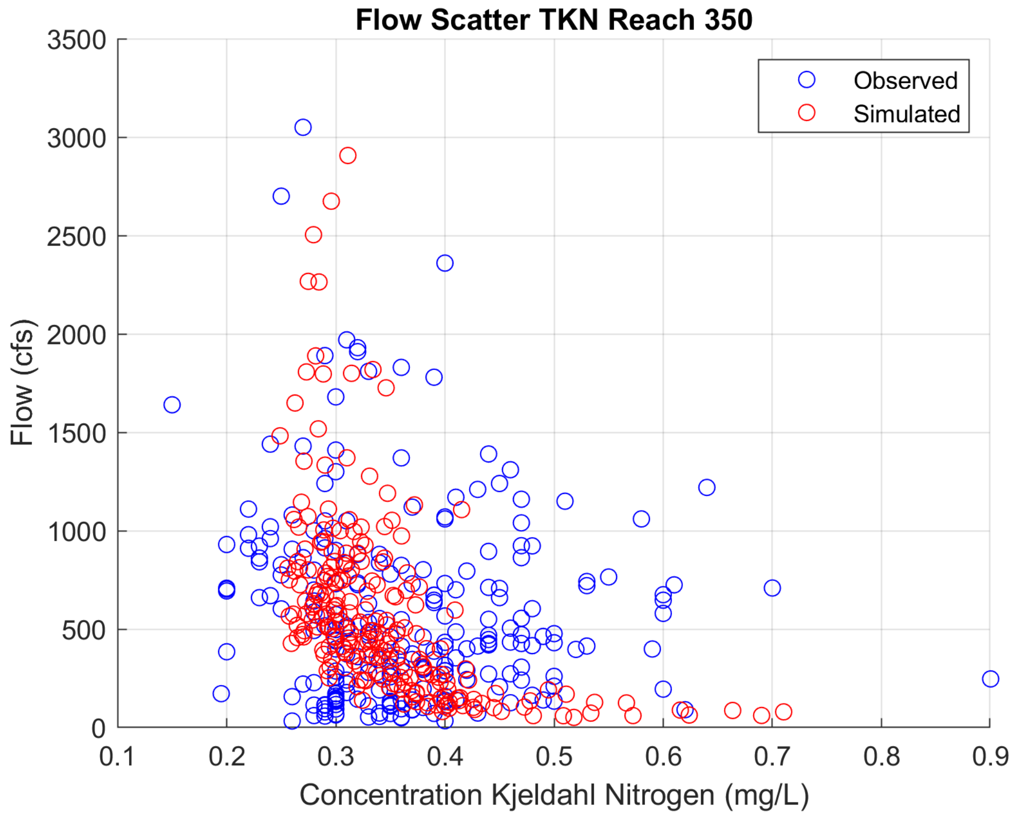

Figure C-21. Total Kjeldahl Nitrogen Scatter Plot for HSPF Reach 350.

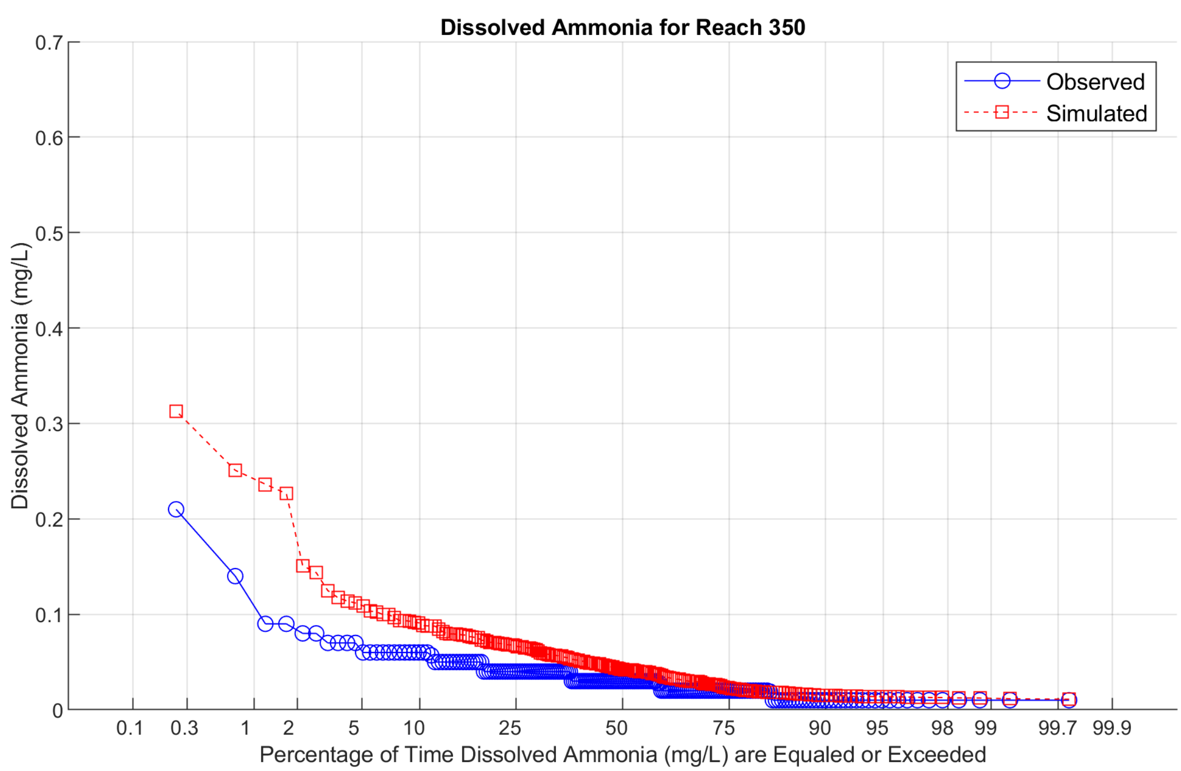

Figure C-22. Total Dissolved Ammonia as Nitrogen Duration Plot for HSPF Reach 350.

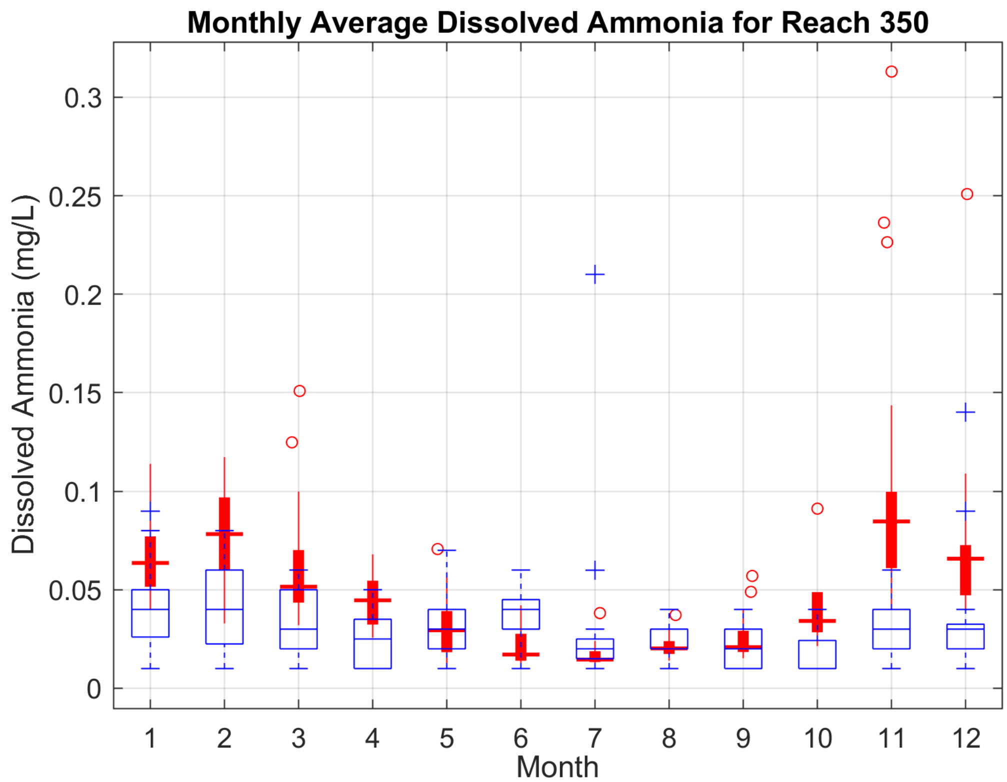

Figure C-23. Total Dissolved Ammonia as Nitrogen Monthly Average Boxplot for HSPF Reach 350.

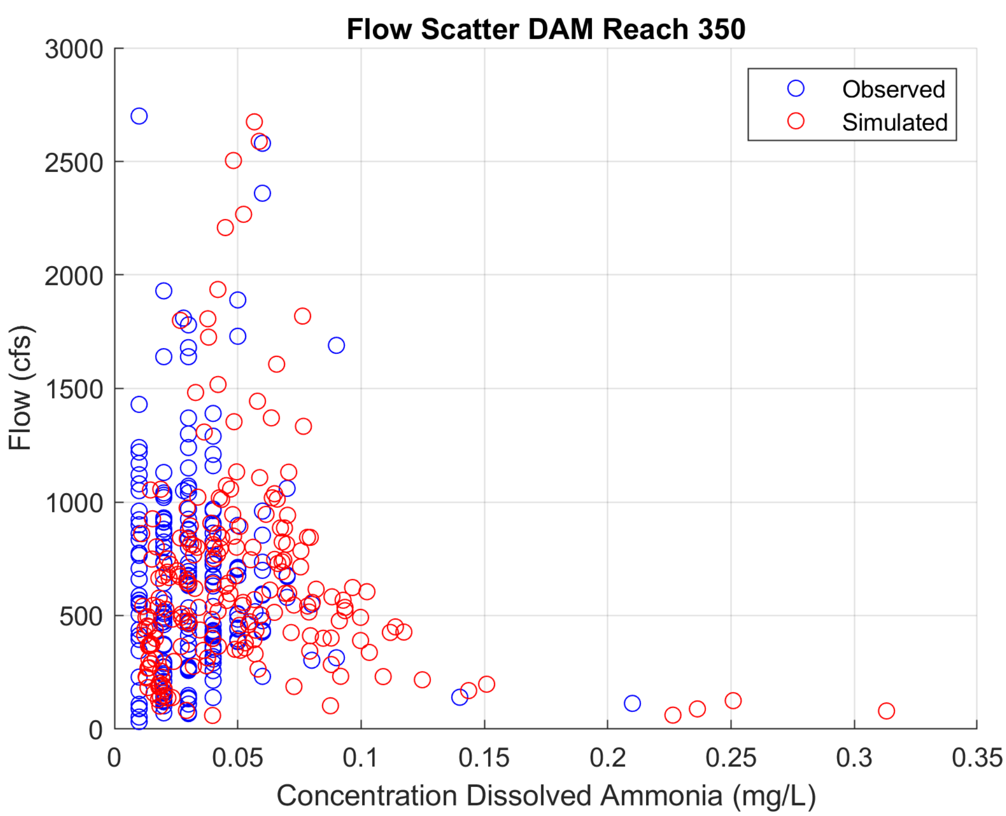

Figure C-24. Total Dissolved Ammonia as Nitrogen Scatter Plot for HSPF Reach 350.

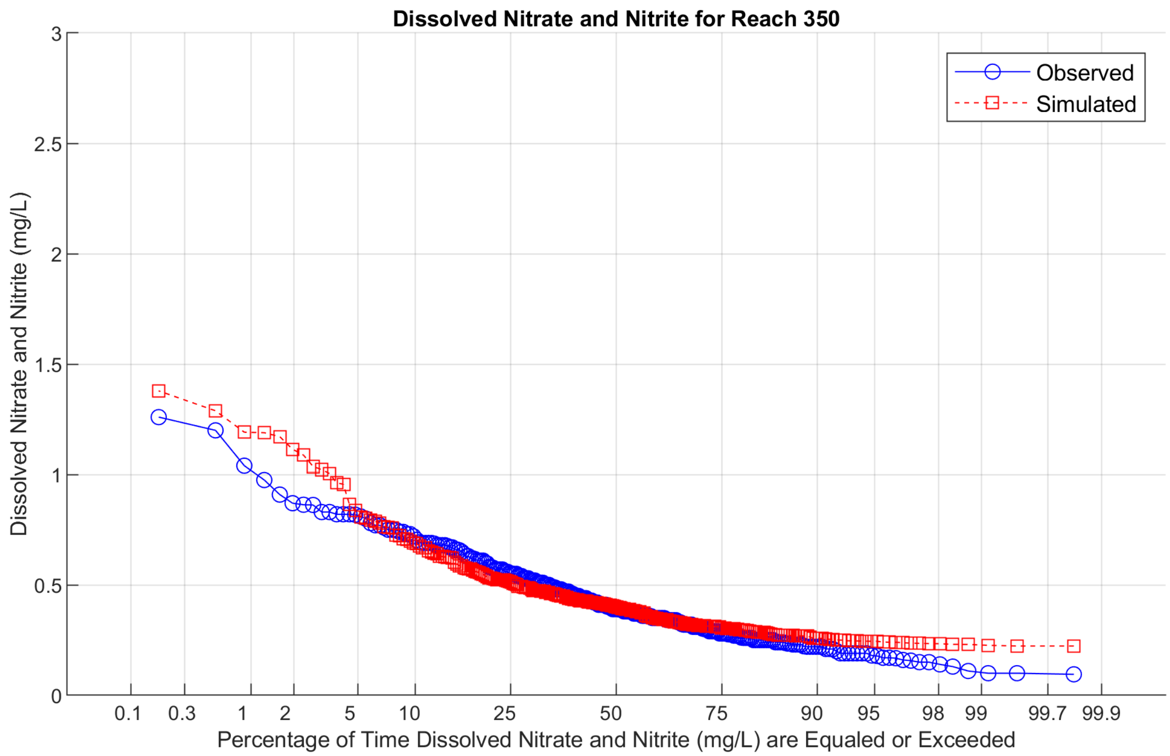

Figure C-25. Total Dissolved Nitrite-Nitrate as Nitrogen Duration Plot for HSPF Reach 350.

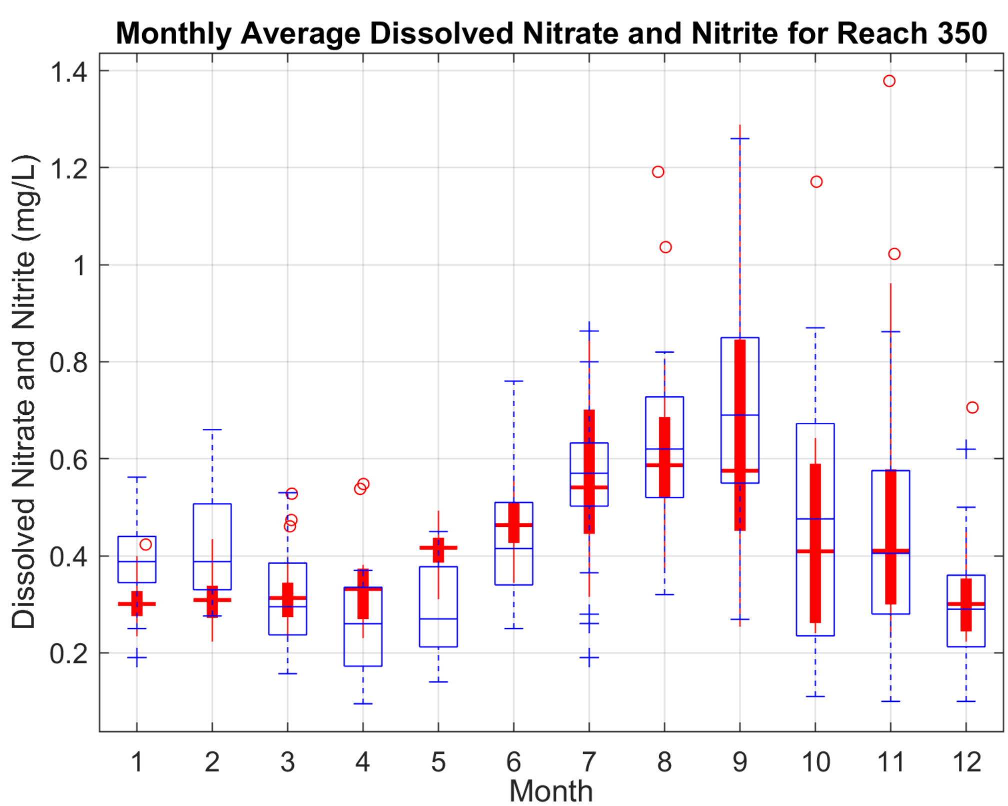

Figure C-26. Total Dissolved Nitrite-Nitrate as Nitrogen Monthly Average Boxplot for HSPF Reach 350.

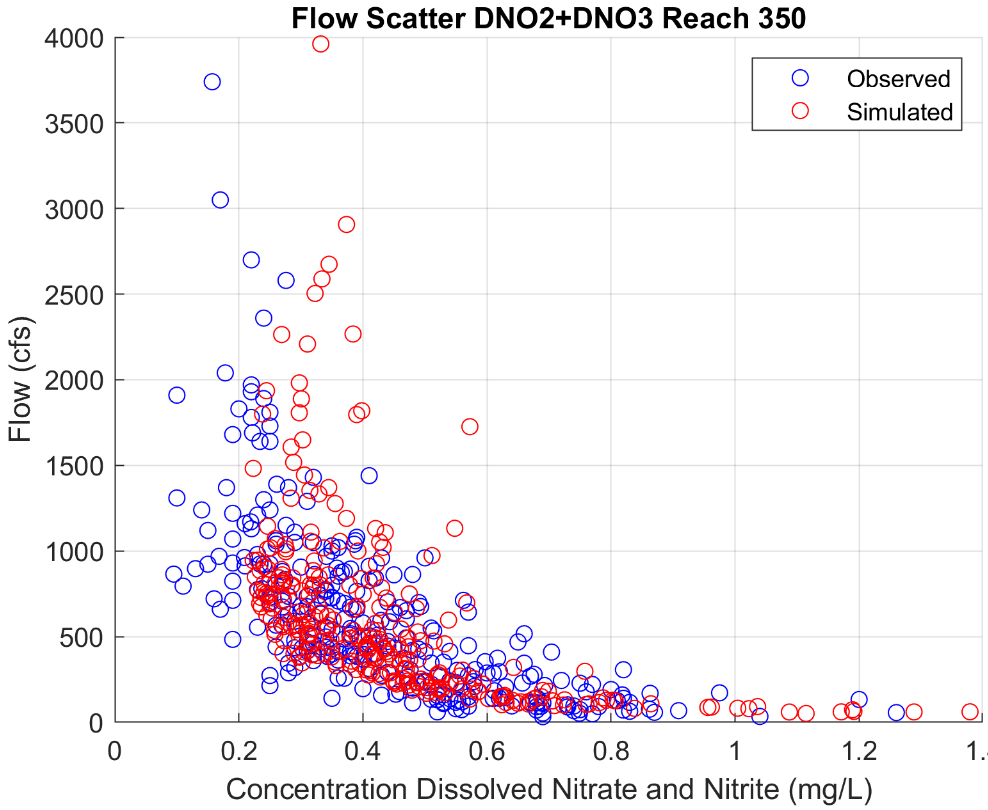

Figure C-27. Total Dissolved Nitrite-Nitrate as Nitrogen Scatter Plot for HSPF Reach 350.

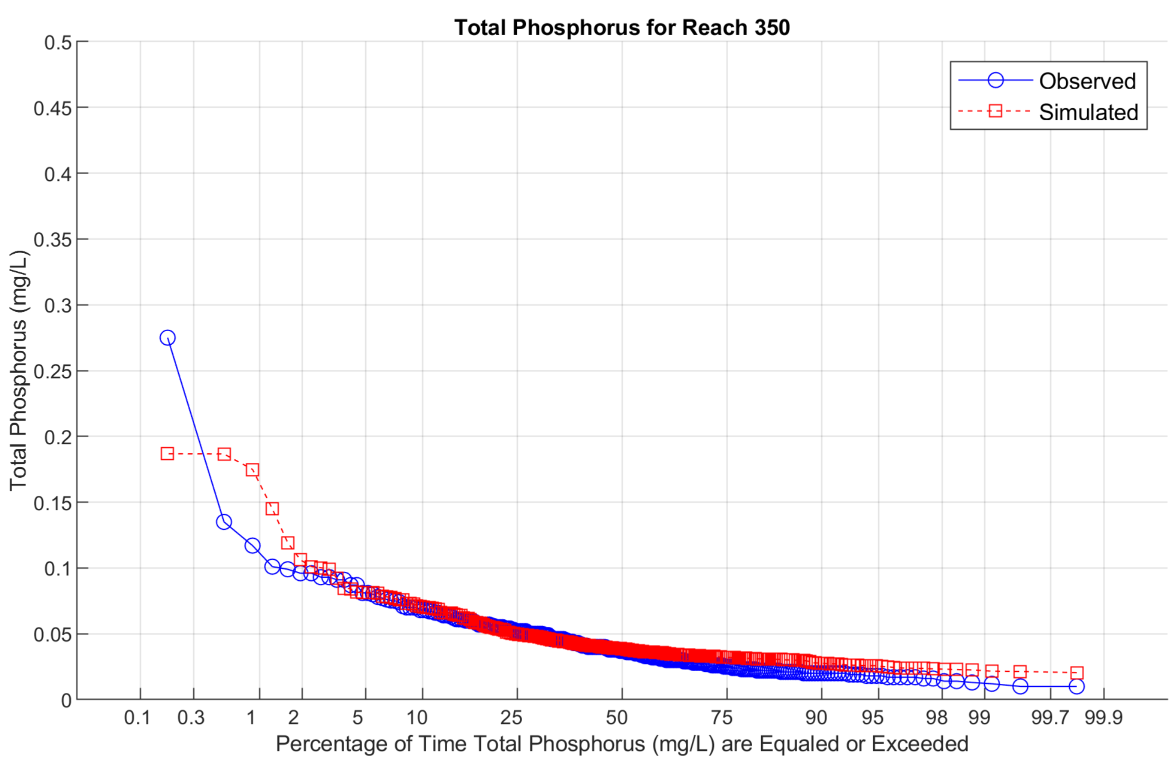

Figure C-28. Total Phosphorus Duration Plot for HSPF Reach 350.

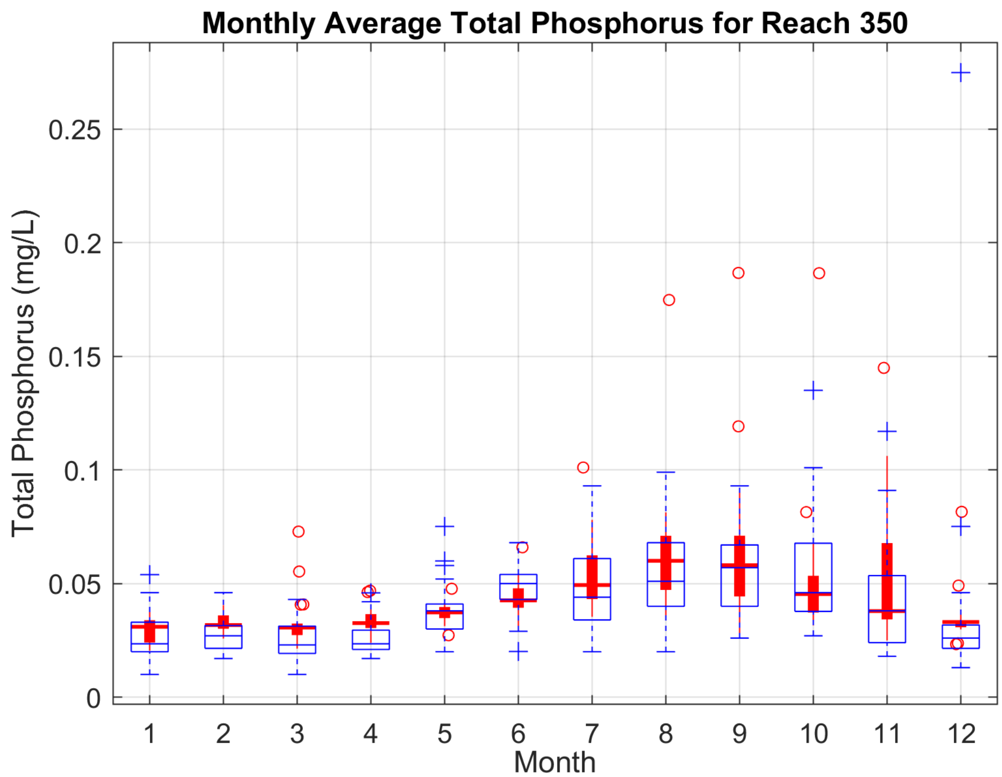

Figure C-29. Total Phosphorus Monthly Average Boxplot for HSPF Reach 350.

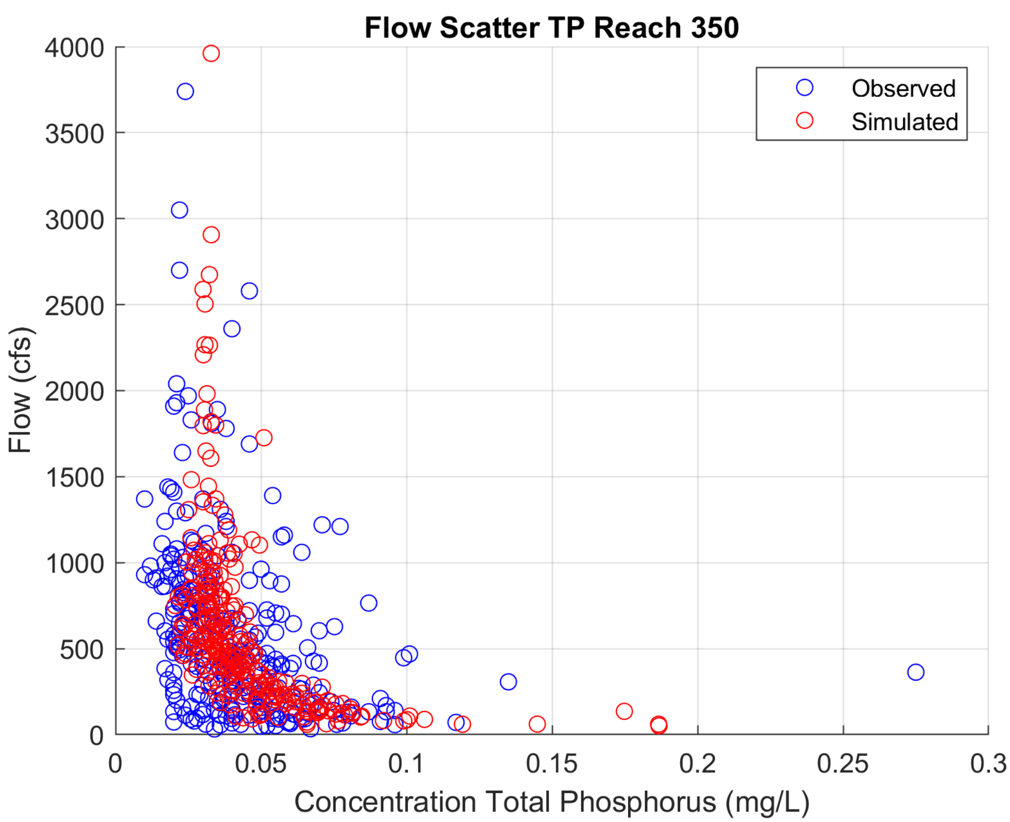

Figure C-30. Total Phosphorus Scatter Plot for HSPF Reach 350.

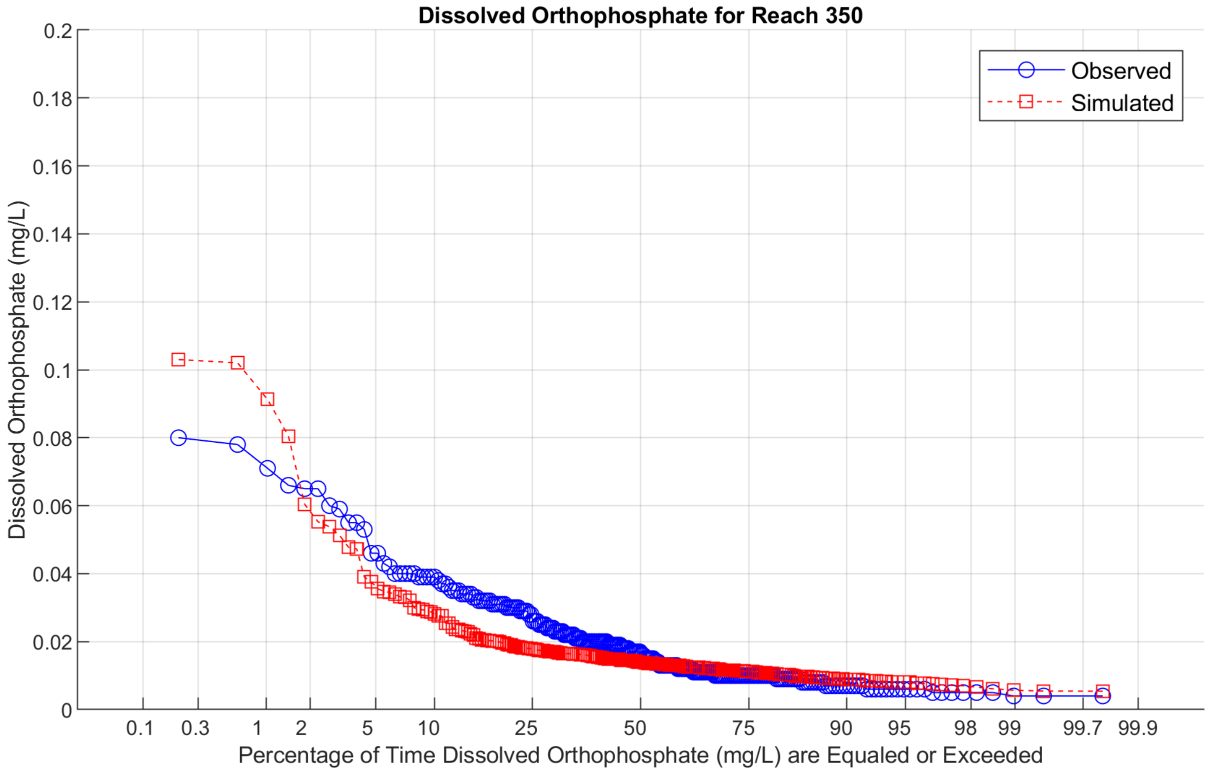

Figure C-31. Total Dissolved Orthophosphate as Phosphorus Duration Plot for HSPF Reach 350.

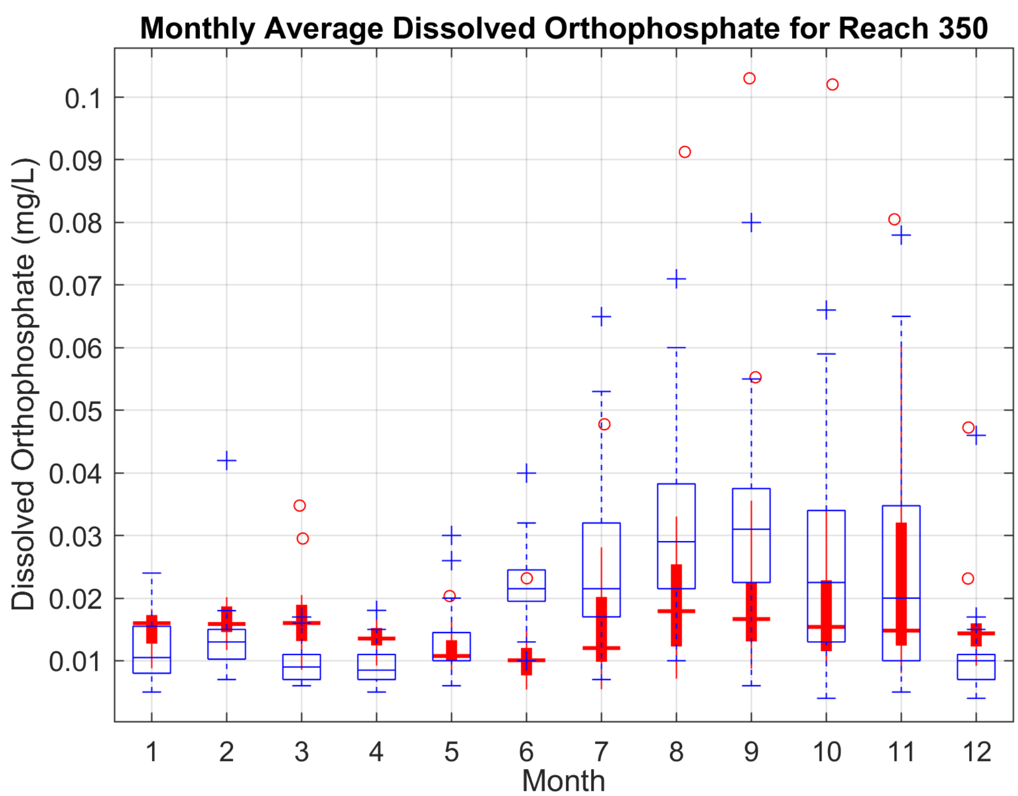

Figure C-32. Total Dissolved Orthophosphate as Phosphorus Monthly Average Boxplot for HSPF Reach 350.

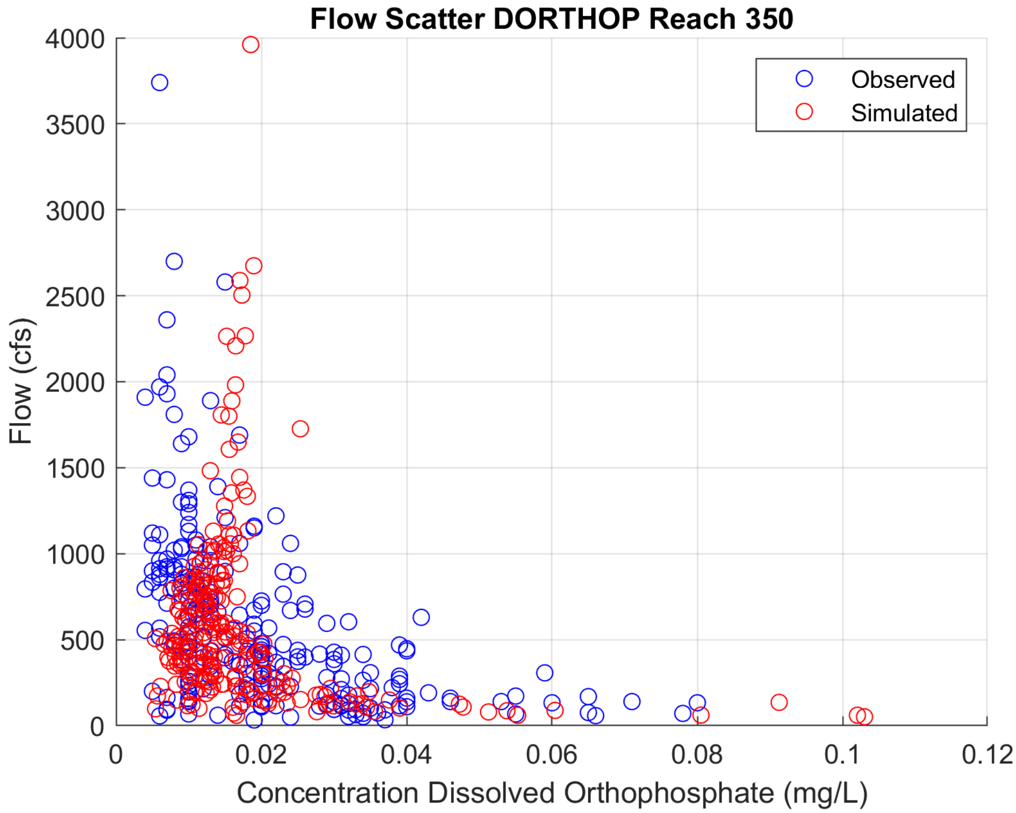

Figure C-33. Total Dissolved Orthophosphate as Phosphorus Scatter Plot for HSPF Reach 350.

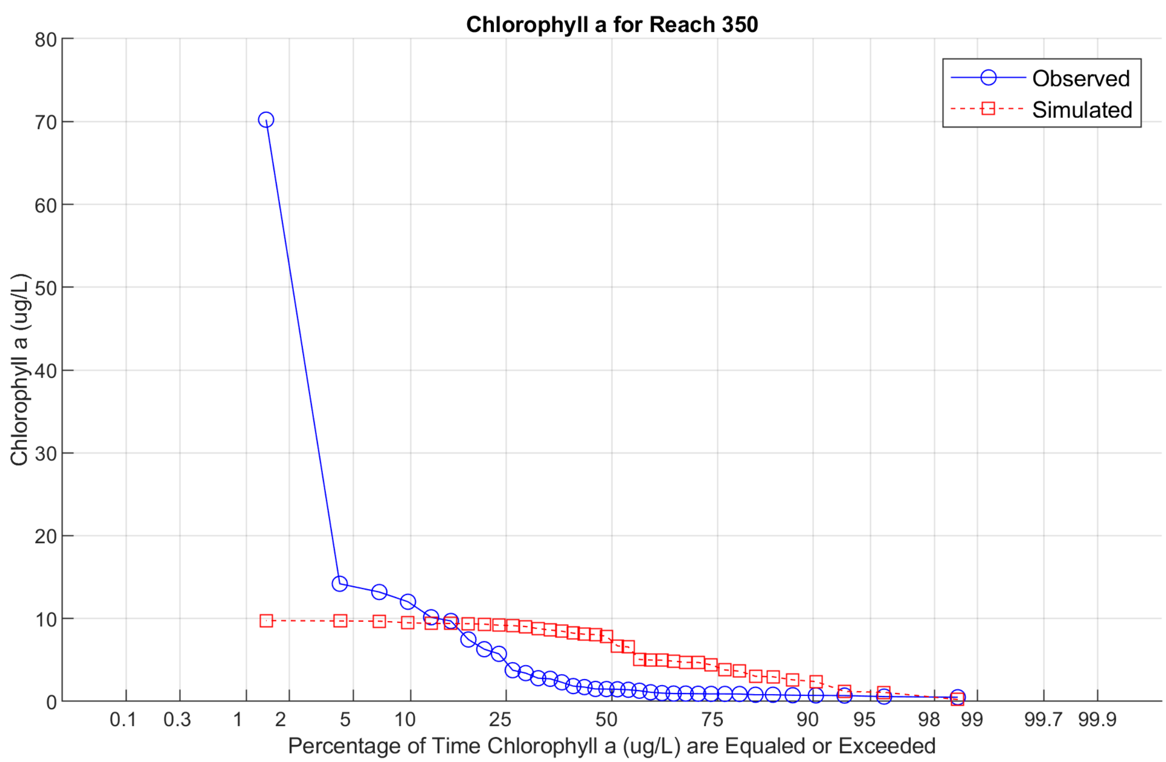

Figure C-34. Chlorophyll *a* Duration Plot for HSPF Reach 350.

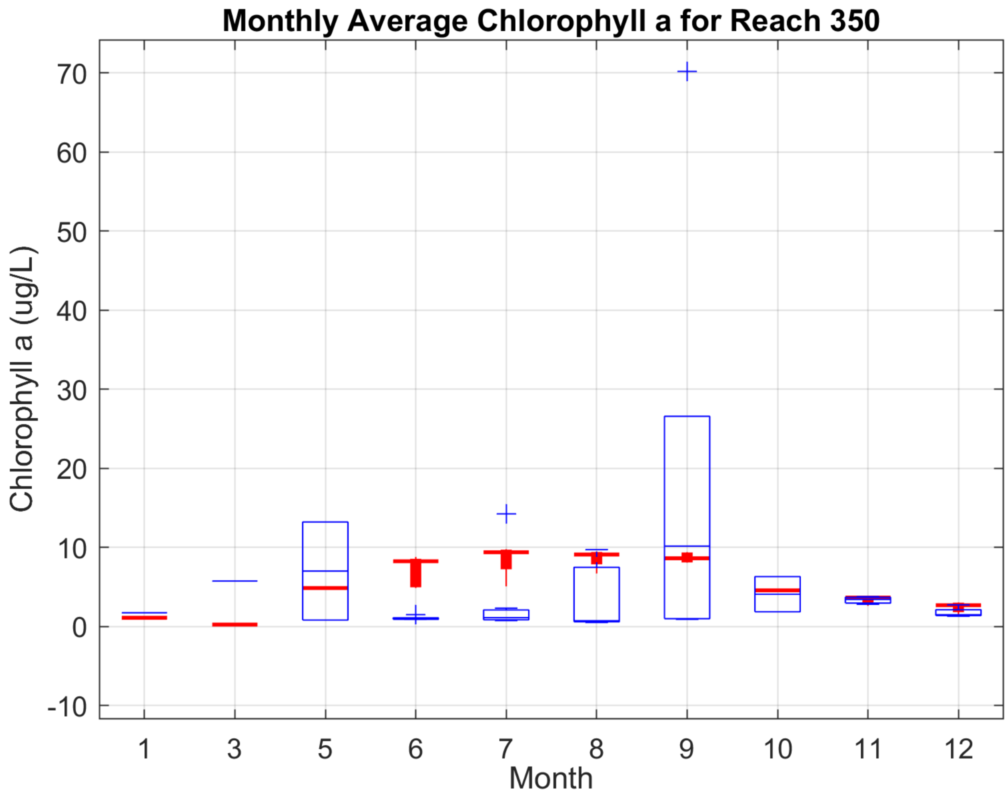

Figure C-35. Chlorophyll *a* Monthly Average Boxplot for HSPF Reach 350.

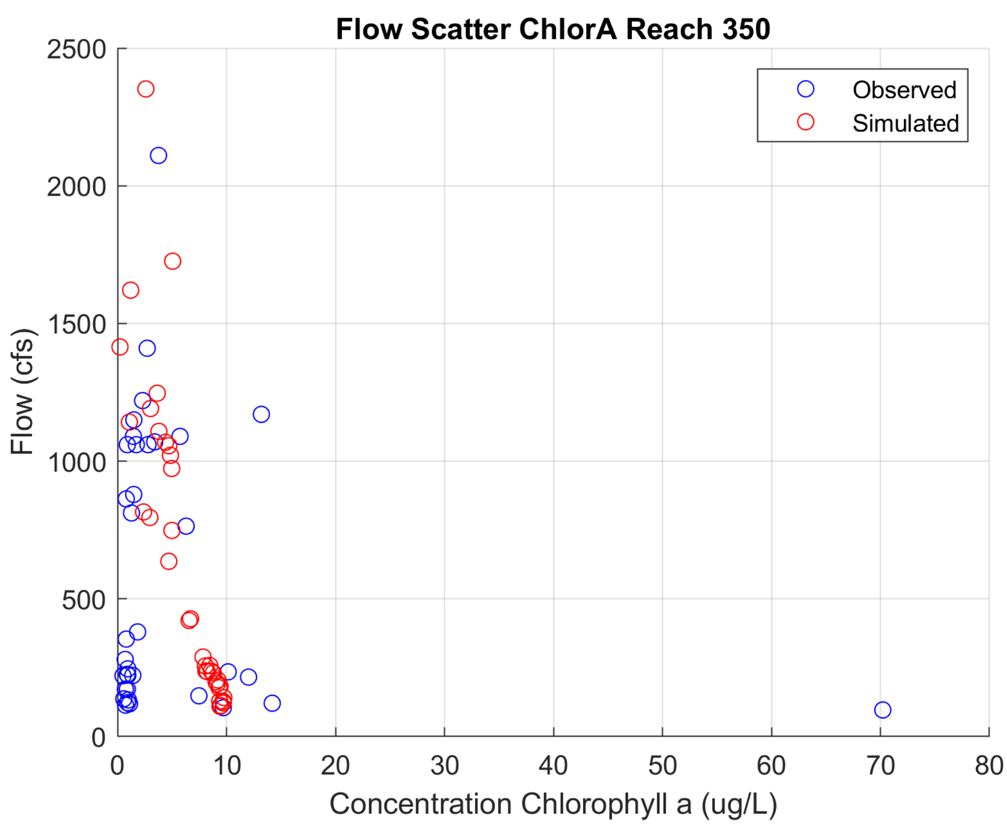

Figure C-36. Chlorophyll *a* Scatter Plot for HSPF Reach 350.

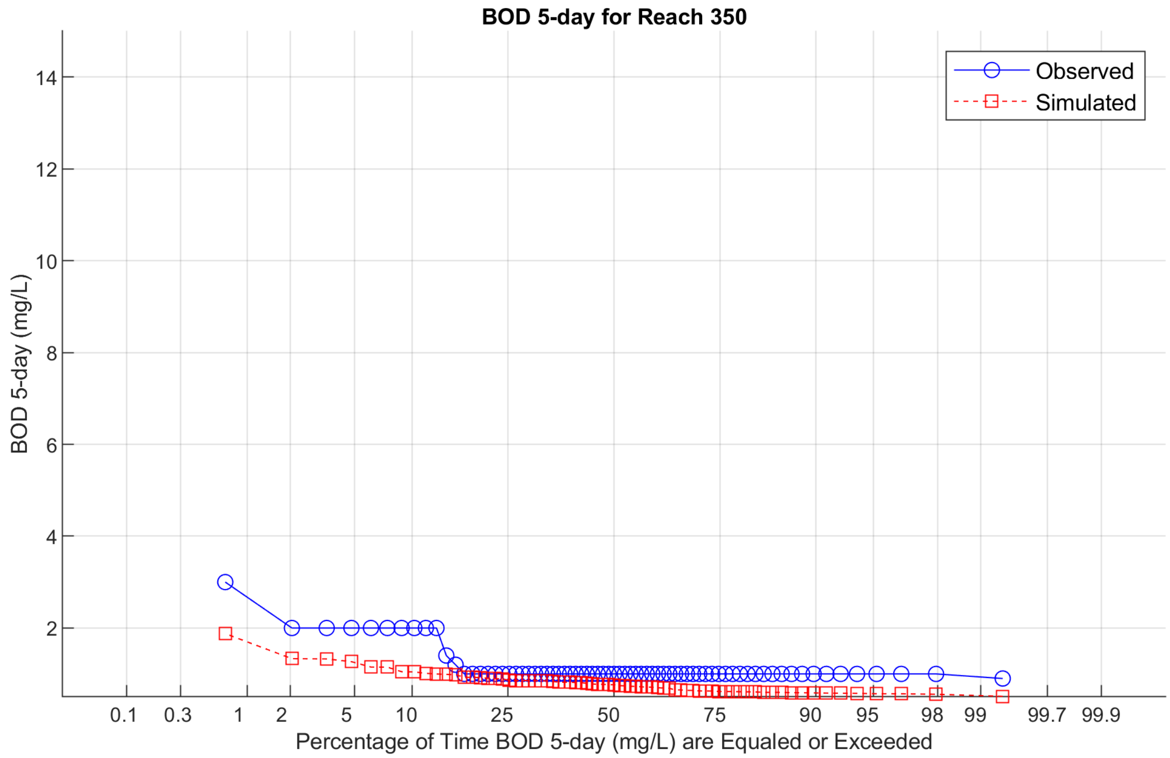

Figure C-37. Biological Oxygen Demand (5-Day) Duration Plot for HSPF Reach 350.

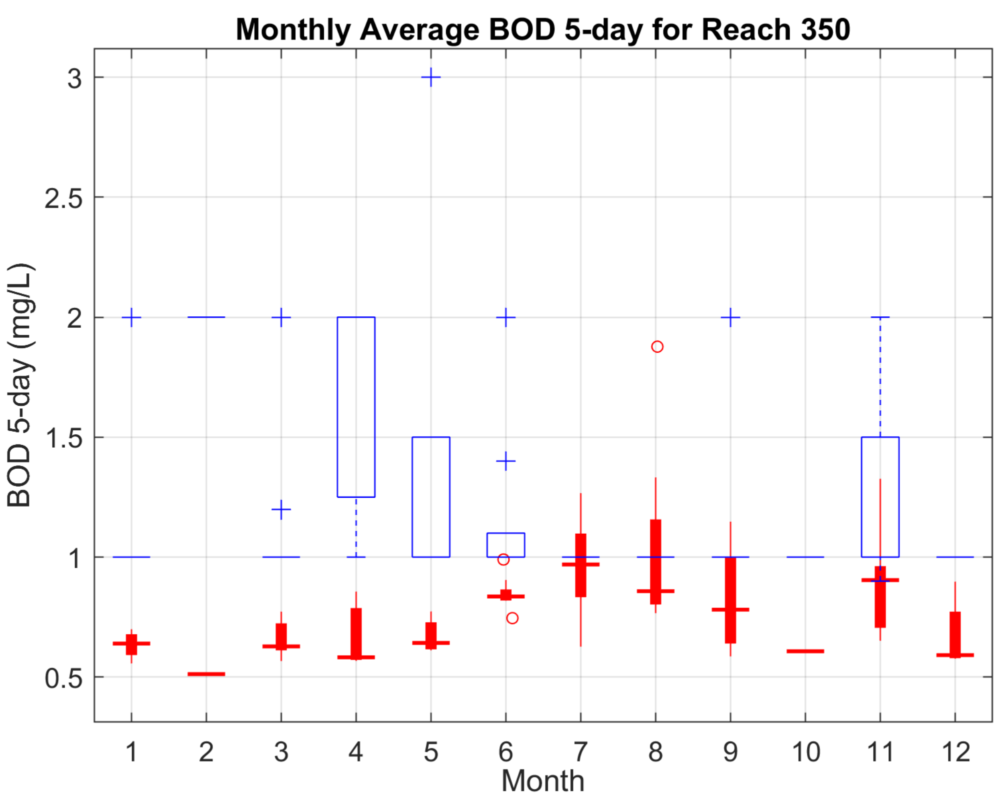

Figure C-38. Biological Oxygen Demand (5-Day) Monthly Average Boxplot for HSPF Reach 350.

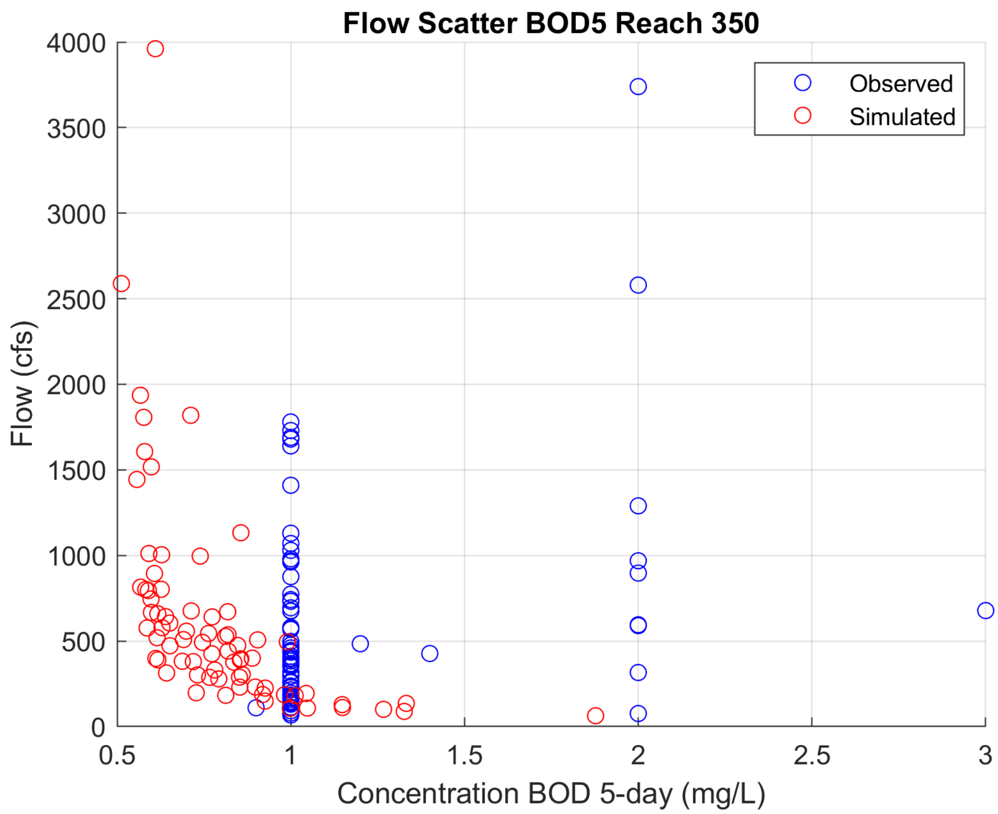

Figure C-39. Biological Oxygen Demand (5-Day) Scatter Plot for HSPF Reach 350.

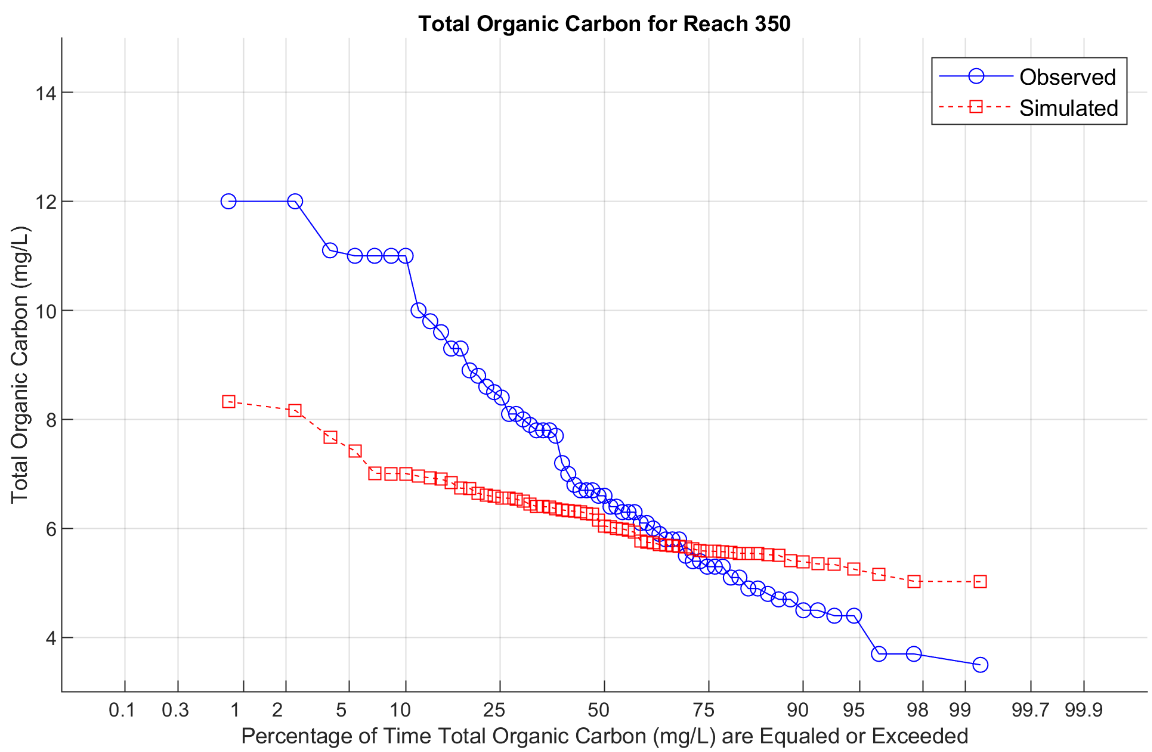

Figure C-40. Total Organic Carbon Duration Plot for HSPF Reach 350.

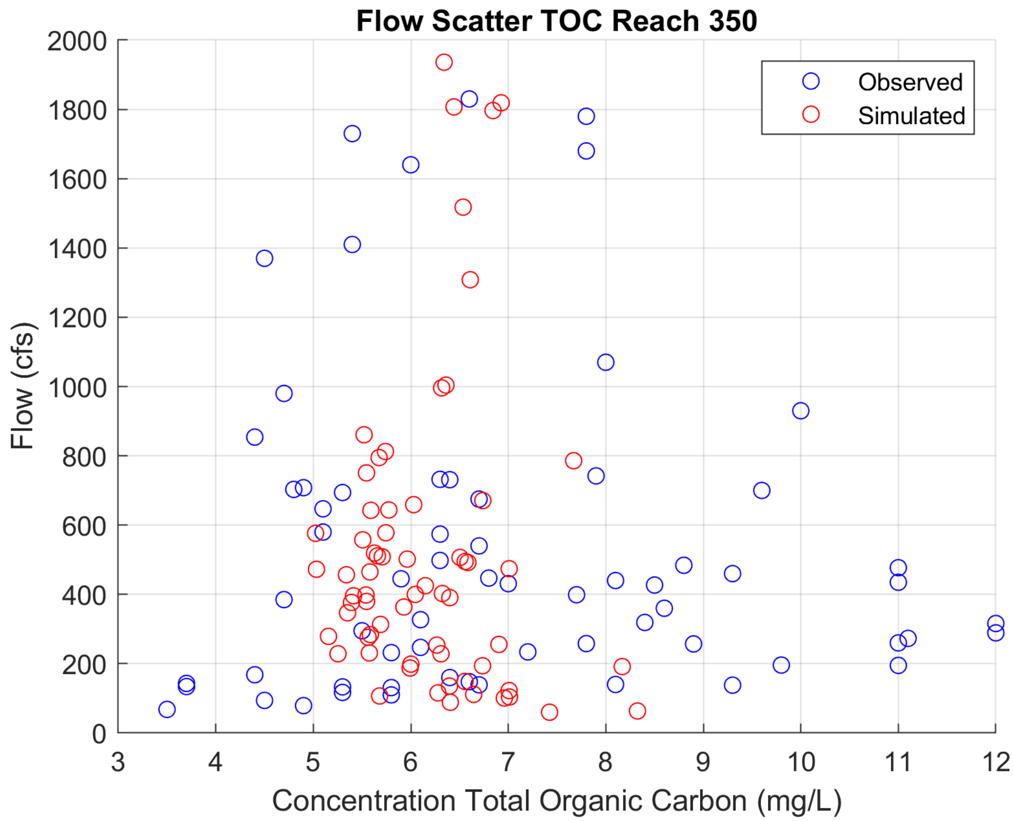

Figure C-41. Total Organic Carbon Monthly Average Boxplot for HSPF Reach 350.

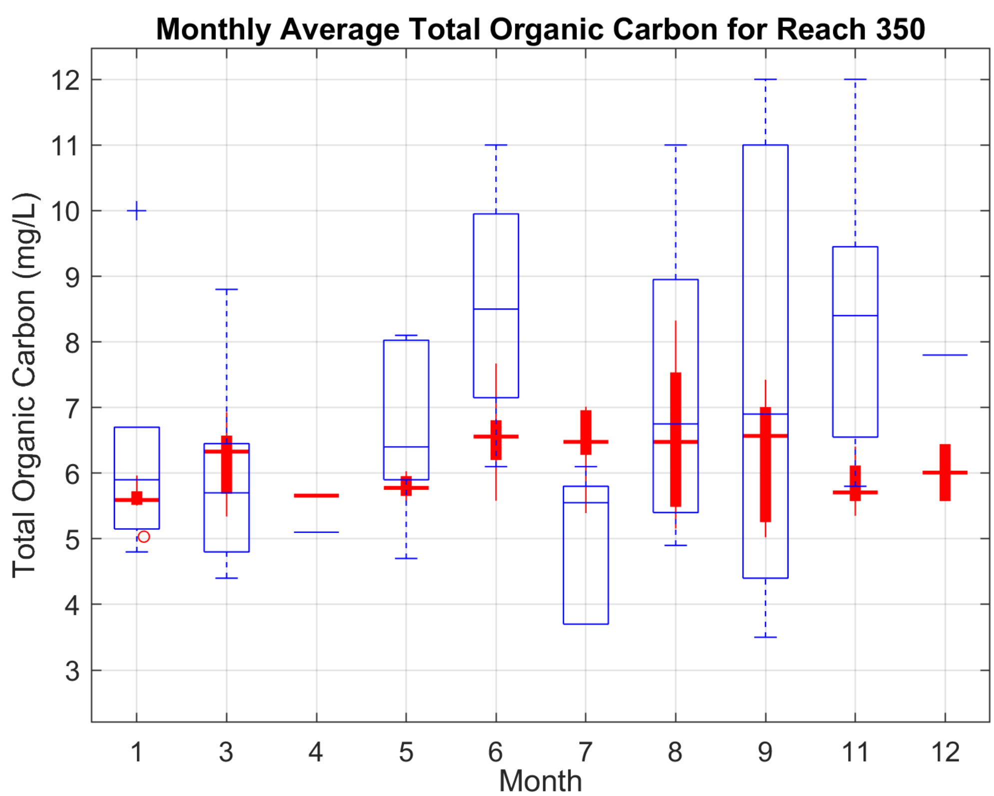

Figure C-42. Total Organic Carbon Scatter Plot for HSPF Reach 350.