CHERRY CREEK WATERSHED HSPF NUTRIENT MODELING

TOPICAL REPORT RSI-2847

PREPARED FOR
Cherry Creek Basin Water Quality Authority
c/o CliftonLarsonAllen, LLP
Greenwood, Colorado 80111-4974

NOVEMBER 2018

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Project Number 3152

EXECUTIVE SUMMARY

The Cherry Creek Basin Water Quality Authority (Authority) was established in the early 1980s and aims to improve, protect, and preserve the water quality of the Cherry Creek and Cherry Creek Reservoir and to preserve waters for recreation, fisheries, water supplies, and other beneficial uses. To achieve this goal, the Authority has conducted multiple monitoring and modeling studies and implemented several recommendations for water quality improvements over the last few years [Hawley et al., 2017; US Army Corps of Engineers, 2011; Brown and Caldwell, 2009; Tetra Tech, 2017].

The reservoir exhibits periodic nuisance cyanobacteria (blue-green algae) blooms and high chlorophyll *a* concentrations. The reservoir has failed to consistently meet the current site-specific chlorophyll *a* standard of 18 micrograms per liter (µg/L), which was assessed as a July-September average. Based on the ongoing water quality concerns, the Authority identified a need to develop a water quality model of the reservoir to better understand the causes of the water quality standard exceedances and determine impacts of current and future management strategies.

In 2017, a CE-QUAL-W2 (W2) model of Cherry Creek Reservoir [Hawley et al., 2017] was developed to improve the understanding of the nutrient loading and algal response in the reservoir. One of the major recommendations of the modeling study was to develop the next version of the reservoir model in conjunction with a watershed model to better define and quantify the nutrient loadings, and their seasonal behavior, as inputs to the reservoir.

The Authority awarded a contract to RESPEC in April 2017 to recommend and develop a Watershed Model (model) to use as a tool to prioritize and implement the reservoir modeling study's recommendations for additional water quality controls and management strategies in the watershed. The major goals of the watershed model include predicting appropriate watershed inputs and loads to streams; predicting the fate and transport of the key constituents (such as nutrients) as they travel downstream through Cherry Creek, tributaries to Cherry Creek, and to Cherry Creek Reservoir; and representing alluvial groundwater flows and contributions. This report describes the details watershed model development efforts, including model setup procedures and assumptions, available data to support the model, calibration and validation time periods, constituents to be simulated, model scales and resolution, model performance targets, and a discussion of the results. This the report is provided as a communication tool with the Authority and other stakeholders to ensure that all available data have been identified and acquired to support the model development and calibration efforts.

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1.0 INTRODUCTION

1.1 BACKGROUND AND STUDY OBJECTIVES

Cherry Creek is approximately 40 miles long and flows northward from the Palmer Divide in El Paso County to the Cherry Creek Reservoir, which is located in the Denver Metropolitan area. The Cherry Creek Basin is a high plains watershed in a semiarid environment with a drainage area of approximately 386 square miles. The watershed is primarily located in Douglas County, and the northern portion of the drainage is located in Arapahoe County with smaller portions in Elbert and El Paso Counties (Figure 1-1).

Cherry Creek Reservoir is a 13,000 acre-feet (ac-ft) flood control reservoir near Denver, Colorado. This major watershed feature is the designated downstream limit of the watershed. Cherry Creek State Park is a popular attraction that surrounds the reservoir for approximately 4,000 acres and is important for urban recreation and wildlife habitat. Other major hydrologic features in the Cherry Creek Watershed (CCW) include Cherry Creek and its tributaries. Rueter-Hess Reservoir is a 72,000 acre-foot raw water storage reservoir that is located on Newlin Gulch, which is also a tributary to Cherry Creek. The CCW includes several agricultural/livestock impoundments that were originally constructed in the southern and central parts of the CCW. The southern one-half of the CCW is almost entirely rural or designated open space. In the north, the landscape is increasingly urban with residential as the dominant land use. Predicted growth patterns indicate increasing intensity of urban growth. The alluvial aquifer present in the lower reaches of Cherry Creek is an important source of local water supplies.

The Cherry Creek Basin Water Quality Authority (Authority) was established in the early 1980s and aims to improve, protect, and preserve the water quality of Cherry Creek and Cherry Creek Reservoir and to preserve waters for recreation, fisheries, water supplies, and other beneficial uses. To achieve this goal, the Authority has conducted multiple monitoring and modeling studies and implemented several recommendations for water quality improvements over the last few years [Hawley et al., 2017; US Army Corps of Engineers, 2011; Brown and Caldwell, 2009; Tetra Tech, 2017].

The reservoir exhibits periodic nuisance cyanobacteria (blue-green algae) blooms and high chlorophyll *a* concentrations. The reservoir has failed to consistently meet the current site-specific chlorophyll *a* standard of 18 micrograms per liter (µg/l), which was assessed as a July-September average. The reservoir is also listed as a 303(d) impairment waterbody for dissolved oxygen and chlorophyll *a* (Figure 1-2). Based on ongoing water quality concerns, the Authority identified a need to develop a water quality model of the reservoir to better understand the causes of the water quality standard exceedances, and determine impacts of current and future management strategies [Hawley et al., 2017].

In 2017, a CE-QUAL-W2 (W2) model of Cherry Creek Reservoir [Hawley et al., 2017] was developed to improve the understanding of the nutrient loading and algal response in the reservoir. One of the major recommendations of the modeling study was to develop the next version of reservoir model in conjunction with a watershed model.

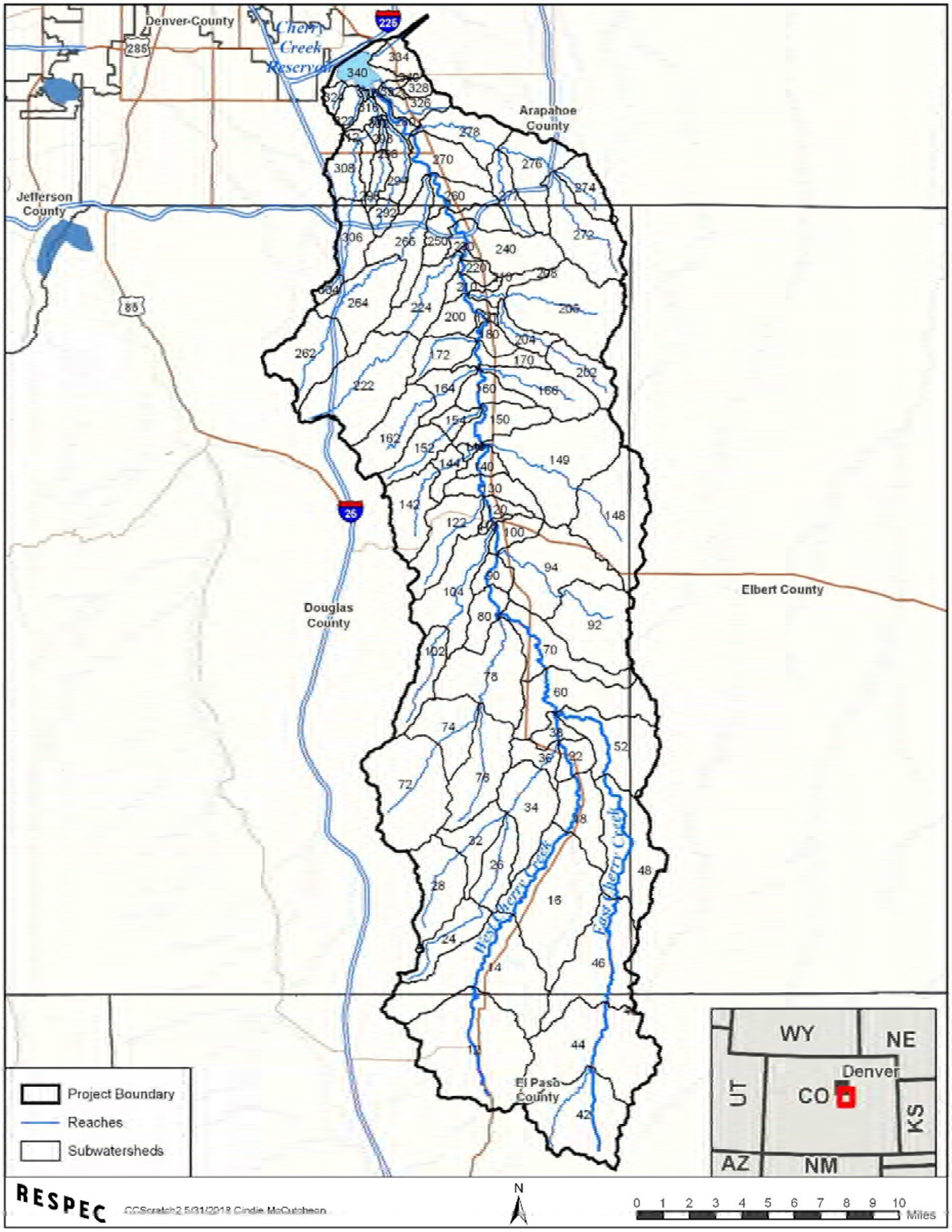


Figure 1-1. Cherry Creek Watershed and General Hydrography.

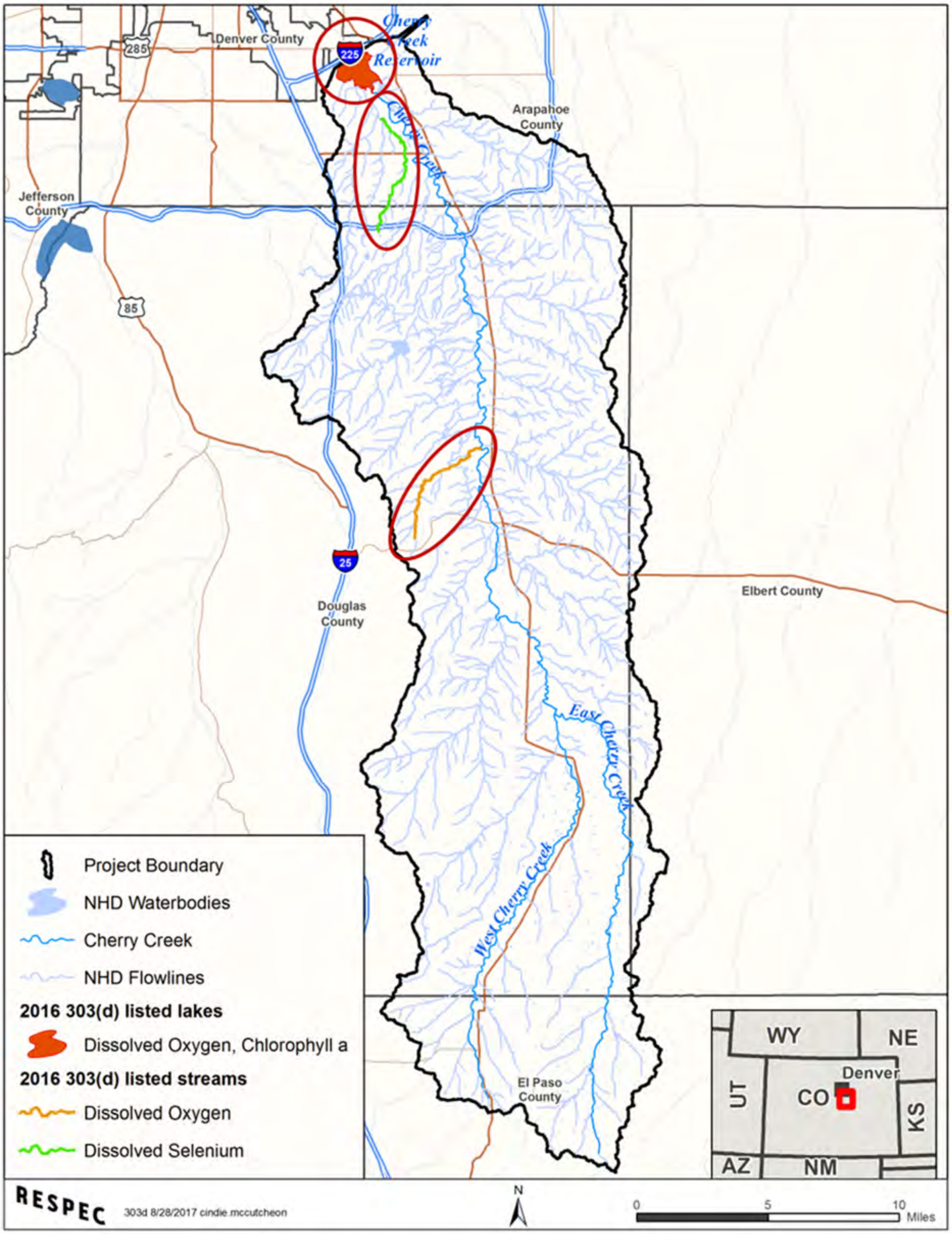


Figure 1-2. 303(d) Listed Waterbodies in the Cherry Creek Watershed.

The Authority awarded a contract to RESPEC in April 2017 to recommend and develop a watershed model to use as a tool to prioritize and implement the reservoir model's recommendations for additional water quality controls and management strategies in the watershed. The major goals of the watershed model include predicting the appropriate watershed inputs and loads to streams; predicting the fate and transport of the key constituents (such as nutrients) as they travel downstream through Cherry Creek, tributaries to Cherry Creek, and to Cherry Creek Reservoir; and representing alluvial groundwater flows that provide input to but does not simulate the reservoir.

The resulting watershed model was also used as a tool to evaluate and prioritize the recommendations from the Authority's current reservoir model for additional water quality controls and management strategies to help meet Colorado Water Quality Control Commission (CWQC) standards, including chlorophyll *a*. RESPEC evaluated different watershed modeling software to suit the overall goal of this project and recommended the HSPF modeling software [Donigian, 2017] for this study.

This report describes the watershed model development, including the model setup procedures and assumptions, calibration and validation time periods, constituents simulated, model scales and resolution, and calibration results.

1.2 MODELING APPROACH

HSPF was selected represent the entire CCW, including the land areas, stream channels, flow through alluvium, diversions, pumping, and point sources [Donigian, 2017].

1.2.1 OVERVIEW OF HSPF AND RATIONALE FOR SELECTION

HSPF was first publicly released in 1980, was developed by Hydrocomp, Inc. [Johanson et al., 1980] under contract with the US Environmental Protection Agency (US EPA). HSPF is a continuous watershed simulation model that produces a time history of the water quantity and quality at any point in a watershed. HSPF is an extension and reformulation of several previously developed models: the Stanford Watershed Model (SWM) [Crawford and Linsley, 1966], the Hydrologic Simulation Program (HSP) including HSP Quality [Hydrocomp, 1977], the Agricultural Runoff Management (ARM) model [Donigian and Davis, 1978], and the Nonpoint Source Runoff (NPS) model [Donigian and Crawford, 1977]. HSPF uses many of the software tools developed by the US Geological Survey (USGS) for providing interactive capabilities on model input, data storage, input-output analyses, and calibration. HSPF has been incorporated into the US EPA's Better Assessment Science Integrating Point and Nonpoint Sources (BASINS), which was developed initially by Tetra Tech, Inc. [Lahlou et al., 1998] under contract with the US EPA, and has been maintained and enhanced by AQUA TERRA Consultants (now RESPEC) since 1998. The main purpose of BASINS is to analyze and develop TMDL standards and guidelines nationwide. The most recent version is BASINS 4 .1 [US EPA, 2013; Duda et al., 2012] and is based on an open-source code concept that incorporates multiple models as plug-in components, including both HSPF and SWAT.

Based on our model review and selection effort that was described in the model selection technical memorandum [Donigian, 2017], previous knowledge of currently available watershed models, and the specific needs for the CCW modeling study, the HSPF model was selected as the preferred framework for the CCW model.

1.2.2 MODEL APPLICATION

HSPF represents a watershed that consists of two primary components: land areas and stream channels or lakes and reservoirs. Each component is represented by a different module(s) within HSPF; the land areas are represented with the PERLND and IMPLND modules for pervious and impervious areas, respectively, and the waterbodies (whether a free-flowing stream or a lake/reservoir) are represented with the RCHRES module.

Figure 1-3 illustrates the various components and capabilities of the PERLND module of HSPF. Each of the boxes in Figure 1-3 identifies a capability used by HSPF to model the corresponding process (or processes) that occur on each category of land. For example, the PWATER subroutine models the water budget, SEDMNT models soil erosion and delivery to the stream, and PSTEMP models the soil temperatures. For runoff loadings of water quality constituents, HSPF provides alternative methods that the user can select to calculate loadings with simple, empirical build-up and wash-off algorithms used in the PQUAL subroutine, or the detailed mass-balance formulations used within the subroutine group within the dashed-line box that is marked as AGCHEM. The PQUAL (and IQUAL for impervious surfaces) are commonly used for urban land uses because the buildup/wash-off formulations have traditionally been applied for urban runoff quality models and for applications that are primarily focused on impacts of urbanization and a general assessment of land-use changes. For watersheds that are dominated by agriculture, agricultural practices and impacts are key elements of the assessment, the AGCHEM module may be required because this allows a more process- and mass balance-based evaluation of land-management practices, including nutrient application practices.

1.3 OVERVIEW OF DATA IDENTIFICATION, ACQUISITION, AND INVESTIGATION EFFORTS

A wide variety of different types of data are required for watershed and waterbody modeling efforts. These categories include meteorological (e.g., precipitation, evapotranspiration, air temperature) data, land characteristics (e.g., topography, land use, soils, and climate variability), hydrography and waterbody characteristics, monitoring data, and other supporting information (e.g., previous studies and source identification).

Since its formation, the Authority has supported multiple efforts to collect various kind of hydrological, hydraulic, water quality, and census data. Meteorological data are available through various Government Agencies (e.g., National Aeronautics and Space Administration [NASA] and National Climatic Data Center [NCDC]).

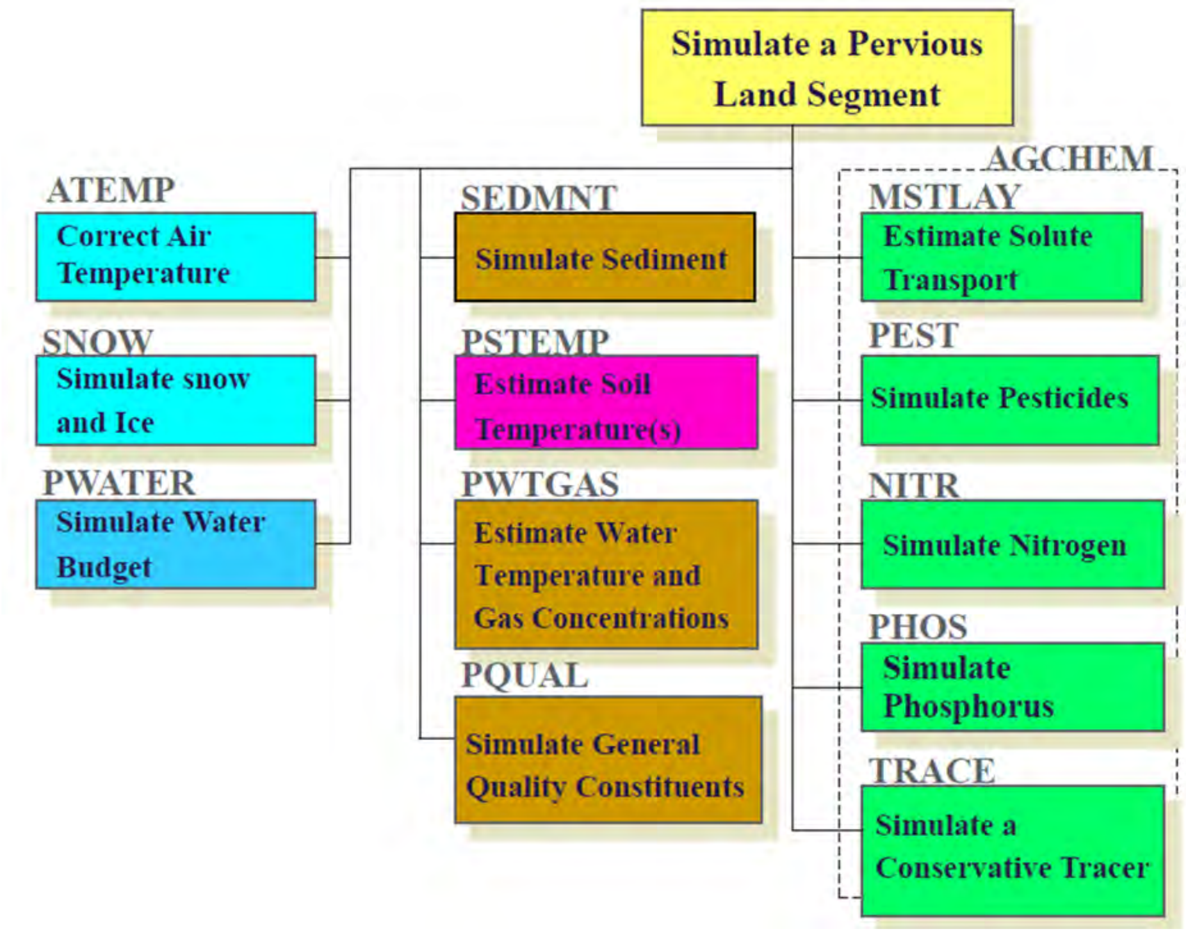


Figure 1-3. Pervious Land Simulation (PERLND) Module in HSPF.

2.0 TIME-SERIES DATA AVAILABILITY FOR THE CHERRY CREEK WATERSHED MODEL

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

1. Precipitation
2. Potential evapotranspiration
3. Other meteorological data (e.g., air temperature, wind, solar radiation, dewpoint, and cloud cover)
4. Streamflow
5. Water quality observations
6. Other data (e.g., points sources, diversions, withdrawals, and atmospheric deposition).

This chapter discusses the availability and selection of these time-series data for use in the watershed modeling. Other data types (e.g., point sources, diversions, and atmospheric deposition) that help to define the inflow, outflow, and quality of water in the watershed, and their uses in the modeling effort are also discussed.

2.1 METEOROLOGICAL DATA

For hydrology simulation, all watershed models require precipitation time series that are complete records (i.e., no missing data) at a daily or shorter time step, depending on the selected model, and with adequate spatial coverage and density across the model domain. Precipitation is the critical forcing function for all watershed models because precipitation drives the hydrologic cycle and provides the foundation for transport mechanisms (for both flow and sediment) that move pollutants from the land to the waterbody where their impacts are imposed.

For this study, long-term precipitation data have been obtained from the following primary sources:

- NLDAS (hourly data) (1979–current year)
- PRISM (daily data) (1979–current year)
- BASINS (hourly data) (1979–2009).

NLDAS and PRISM data are available up to the current year (within the last few weeks of the download date), and these data were used as the primary sources of precipitation and other meteorological inputs for this watershed model (Figure 2-1). The NLDAS is a 12 × 12 kilometer (km) dataset that provides hourly meteorological data. PRISM is a 4 × 4 km dataset that provides the daily precipitation totals, which 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). The resolution of NLDAS grids is about 10.6 km and the resolution of PRISM data are approximately 4 km for the CCW. To use the finer resolution, the PRISM data were used for modeling. The daily precipitation data for PRISM were disaggregated using the NLDAS data.

Watershed models require evaporation data as a companion to precipitation to drive the water-balance calculations that are inherent in the hydrologic algorithms that are contained in these types of models.

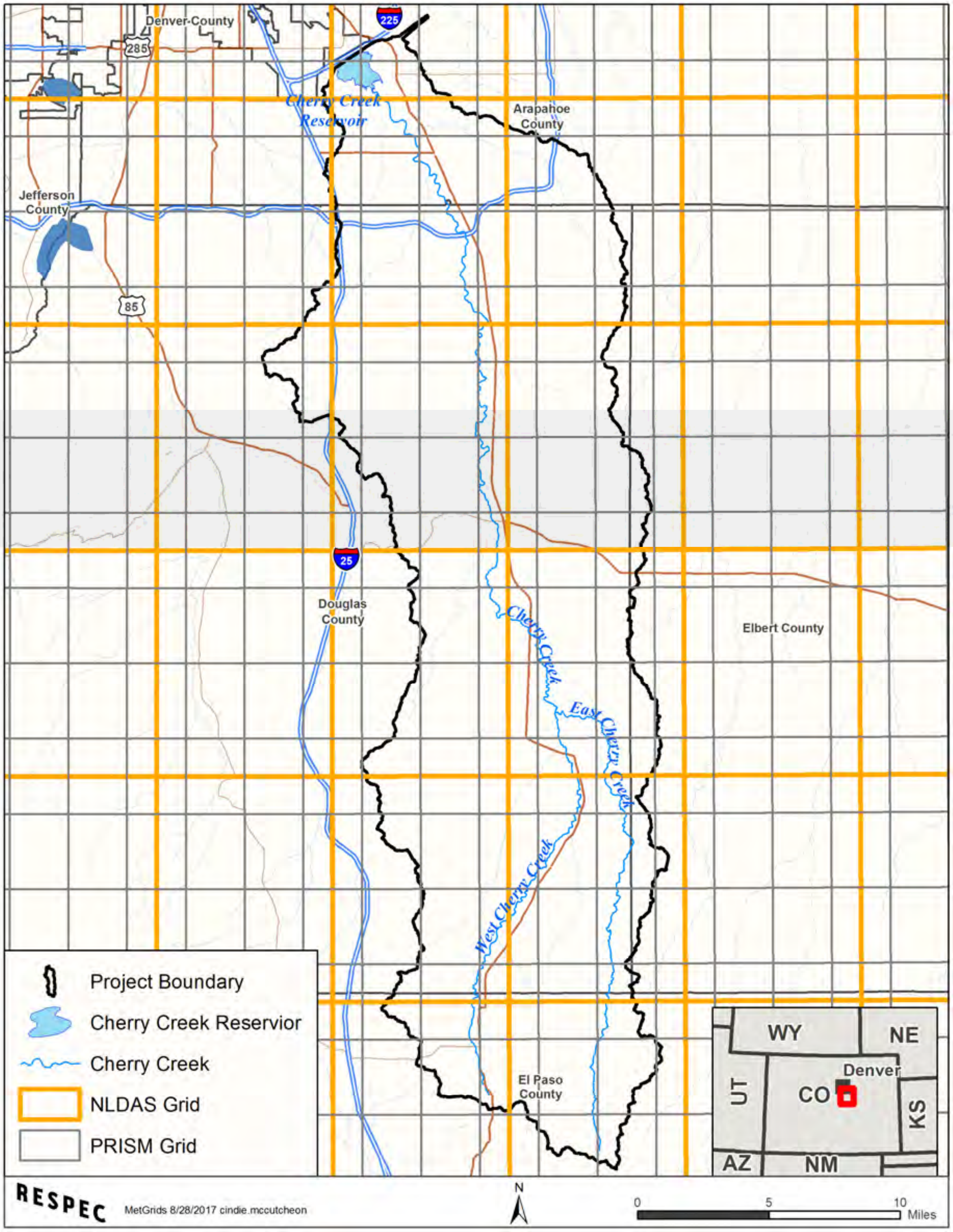


Figure 2-1. NLDAS and PRISM Grid Around the Cherry Creek Watershed.

In addition, other meteorological time series are also often required in temperate climates where snow accumulation and melt are a significant component of the hydrologic cycle and water balance. These time series (e.g., air temperature, solar radiation, dewpoint temperature, wind, and cloud cover) are often required if soil and/or water temperatures are simulated. Water temperature is subsequently used to adjust the rate coefficients in most water quality processes, and other time series are used in selected calculations (e.g., solar radiation affecting algal growth).

NLDAS provides hourly air temperature (ATEM), solar radiation (SOLR), and wind speed (WIND) parameters, which were directly applied to the meteorological time series with a conversion to get them in the units needed for HSPF. The remaining meteorological constituents were not directly available from the NLDAS dataset and required additional computations. Cloud cover (CLOU) was estimated by SOLR data provided from the NLDAS database, using a parabolic equation [Thompson, 1976]. Dew point temperatures (DEWP) were computed from a series of calculations that stemmed from NLDAS-specific humidity. The World Meteorological Organization [2014] uses specific humidity and ATEM to calculate the relative humidity. Relative humidity was then applied with ATEM to the August-Roche-Magnus approximation of the Clausius-Clapeyron equation to calculate DEWP. Hourly potential evaporation (PEVT) was represented by a computed Penman pan evaporation that was based on the Penman [1948] formula and the method from Kohler et al. [1955]. The necessary variables to compute the Penman pan evaporation are daily relative humidity, DEWP, ATEM, and wind travel.

Snow depth, or snow-on-ground, data were used to calibrate the snow accumulation and melt processes. For the CCW and surrounding areas, the snow depth and snowfall (inches) data are available through NCDC Global Historical Climatology Network stations [Menne et al., 2012]. The snow depth data were used during the hydrology calibration in multiple locations throughout the project area to ensure that the snow processes are being accurately represented.

2.2 STREAMFLOW

Flow data are needed to calibrate and validate the watershed model to ensure that the model is reproducing the CCW's hydrologic behavior, providing proper boundary inflows into the reservoir, and transporting sediment and water quality constituents. The BASINS download capability provided the means to access all of the USGS flow (and water quality) data for sites in the watershed. Data were also available from the Authority where Cherry Creek flows into the Cherry Creek Reservoir (CC-10) and where the Cottonwood Creek flows into Cherry Creek Reservoir.

Figure 2-2 shows the locations of the flow gaging sites within the watershed. Table 2-1 lists the names of the flow gaging sites, USGS identification numbers, periods of record, and missing data. Cherry Creek below the Cherry Creek Lake gage will not be used because the Cherry Creek Reservoir will not be modeled. Cherry Creek near Franktown, CO will also not be used because the data collected at this site are inconsistent with downstream data. Cherry Creek near Melvin, CO will not be used because no records exist from the modeling period.

2.3 WATER QUALITY DATA

Water quality data are used primarily for model calibration and validation and to help quantify source contributions and boundary conditions, such as for point sources, selected agricultural sources, and atmospheric deposition. The specific constituents to be modeled in this study include all of the constituents needed for modeling nutrients with a specific focus on phosphorus species.

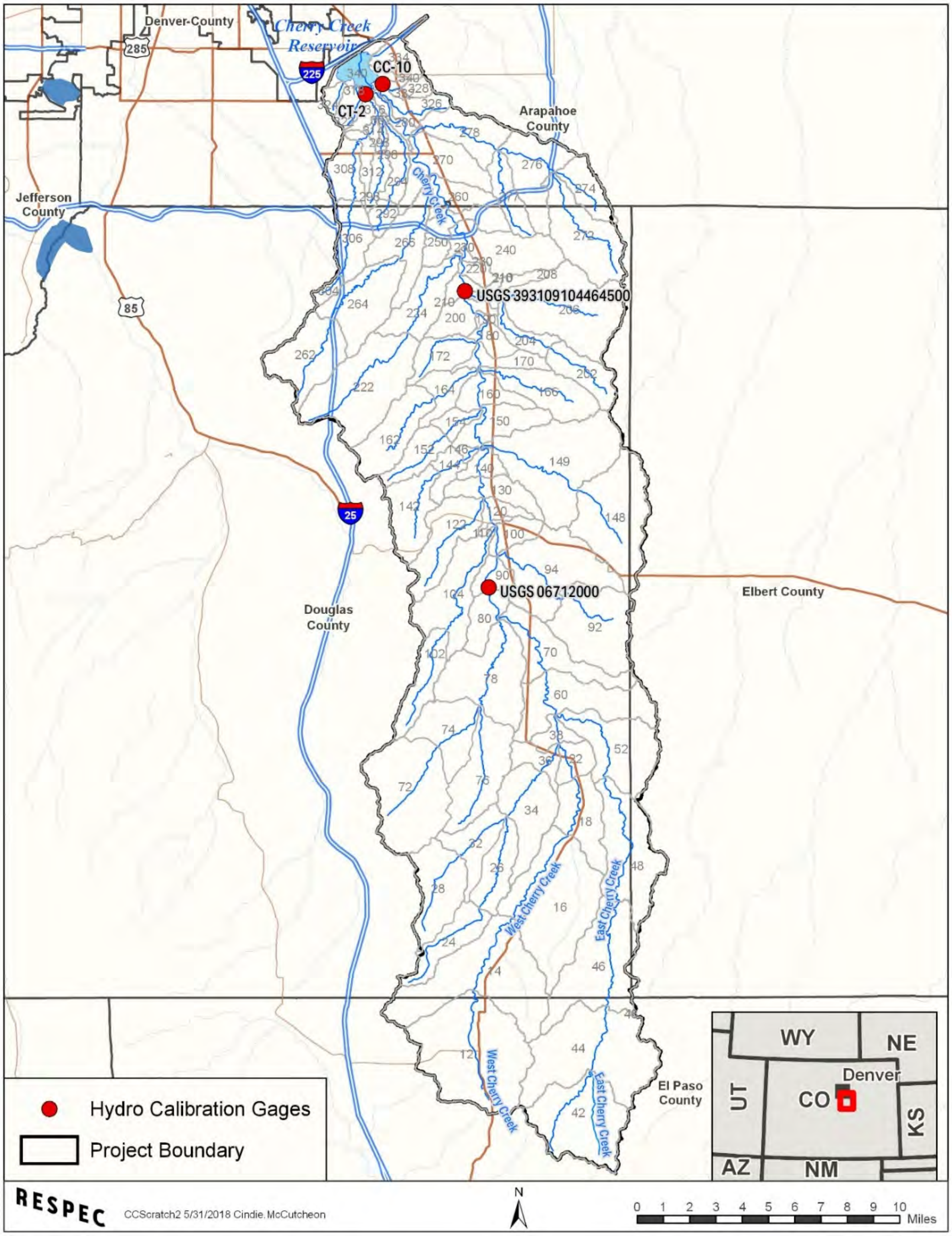


Figure 2-2. US Geological Survey Stream Gage Locations in the Cherry Creek Watershed.

Table 2-1. List of US Geological Survey Stations and Their Data Availability in the Cherry Creek Watershed

Station Name	Station I.D.	Start Date	End Date	Count Missing	Hydrology Calibration Site, Type
Cherry Creek Near Franktown, CO	USGS 6712000	11/21/1939	6/23/2017	1	No. Data are inconsistent with the downstream sites.
Cherry Creek Near Melvin, CO	USGS 6712500	10/01/1939	10/01/1985	5,362	No. Out of modeling period.
Cherry Creek Below Cherry Creek Lake, CO	USGS 6713000	6/30/1950	6/23/2017	3,323	No. Below modeling area.
Cherry Creek Near Parker, CO	USGS 393109104464500	10/01/1991	06/23/2017	0	Yes, Secondary
Cherry Creek at Cherry Creek Reservoir	CC-10	1/1/2003	12/31/2013	0	Yes, Primary
Cottonwood Creek at Cherry Creek Reservoir	CT-2	1/1/2003	12/31/2013	0	Yes, Primary

The following list shows the conventional constituents that are modeled whenever nutrients are the purpose of a modeling effort:

1. Total Suspended Solids (TSS)
2. Water temperature
3. Dissolved Oxygen (DO)
4. Biological Oxygen Demand ultimate (BODu), or total BOD
5. Nitrite-Nitrate (NO2/NO3)
6. Total Ammonia (NH3/NH4)
7. Total Nitrogen (N)
8. Orthophosphate (PO4)
9. Total Phosphorus (P)
10. Phytoplankton as chlorophyll *a*
11. Benthic algae (as biomass).

Water quality data were collected from the Cherry Creek Basin Water Quality Data Portal and from the National Water Quality Monitoring Council. National Water Quality Monitoring Council data include data from the USGS, Colorado Department of Public Health & Environment (CDPHE), The Rivers of Colorado Water Watch Network, and US EPA. Ambient surface water and groundwater data were collected. The surface water quality data are available throughout the watershed from the mid-1990s through 2017. In general, the data availability are greater in the recent years. The ambient surface water data were calibrated in HSPF, and groundwater concentrations were used to guide calibration concentrations. For the watersheds where surface and groundwater streams are simulated, groundwater concentrations were evaluated to understand their similarities to observed data. Figure 2-3 shows ambient surface water monitoring sites with applicable parameters, and Figure 2-4 shows groundwater monitoring wells with applicable parameters. Data collected within the Cherry Creek Reservoir are not used in this HSPF model and are not included in Figure 2-3.

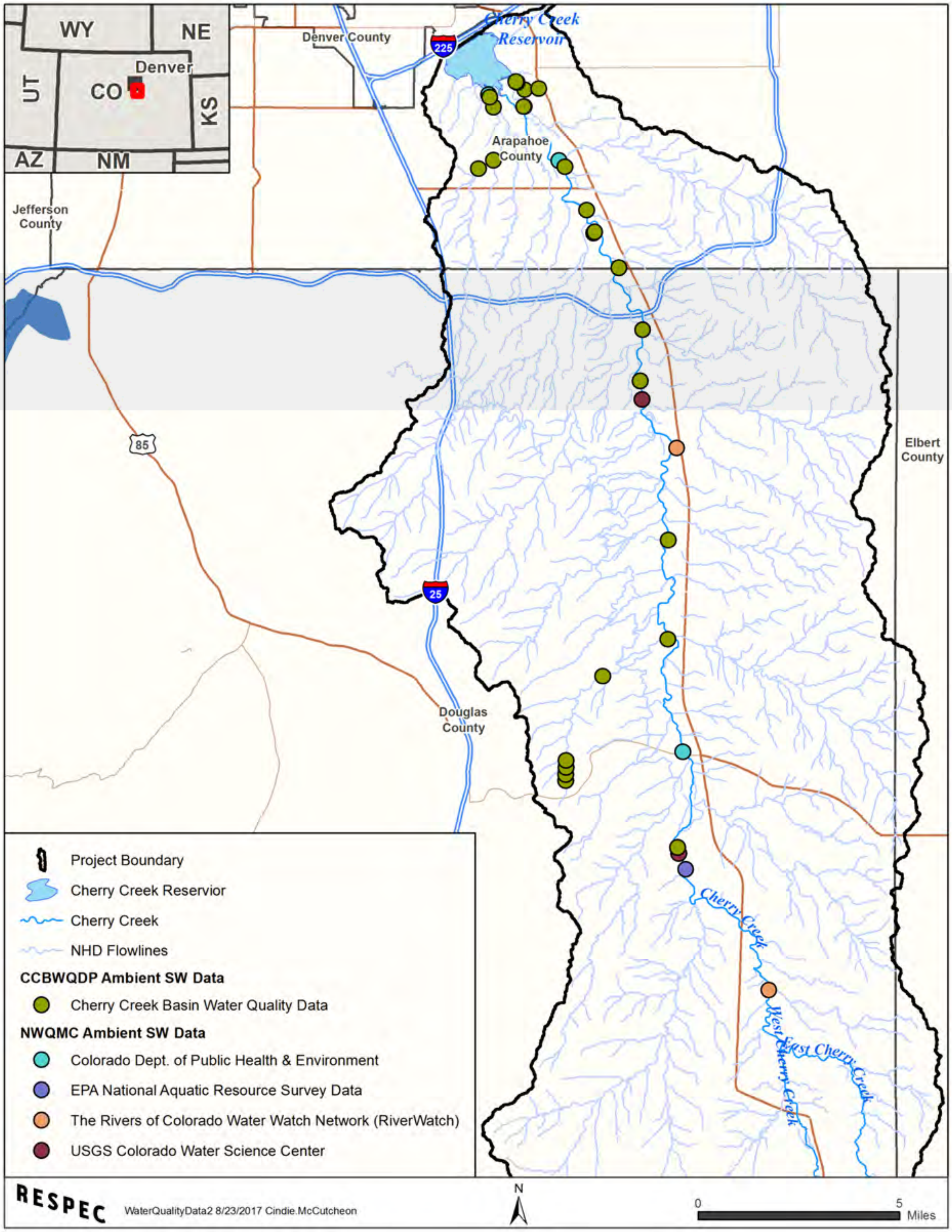


Figure 2-3. Ambient Surface Water Monitoring Sites With Applicable Data.

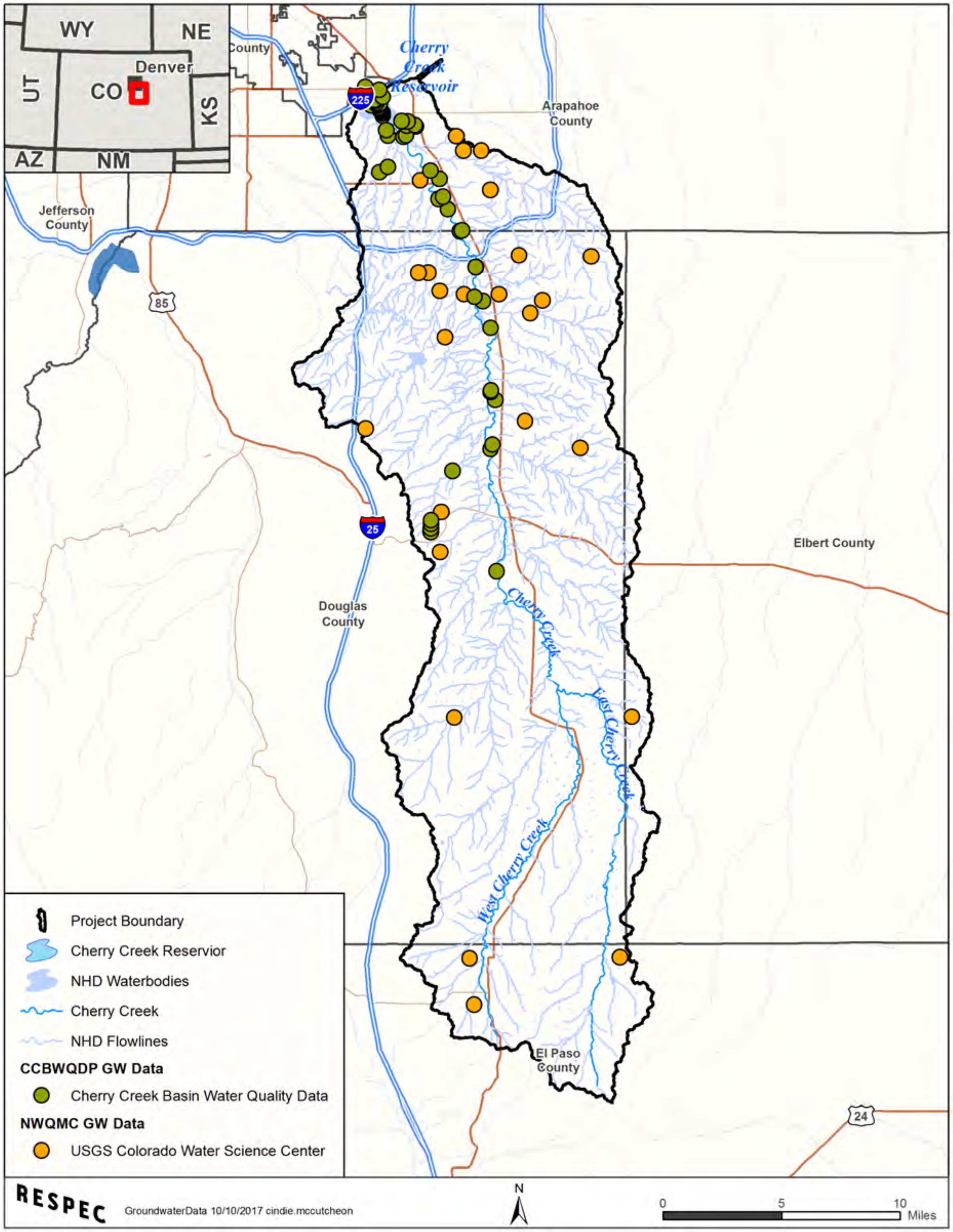


Figure 2-4. Groundwater Monitoring Wells With Applicable Data.

2.4 POINT SOURCES

Point sources displayed in Figure 2-5 and Table 2-2 were located using BASINS data and the Annual Reports [Cherry Creek Basin Water Quality Authority, 2016]. The CDPHE maintains a data warehouse of Daily Monitoring Reports (DMR), permits, and any other modifications of the point sources in Colorado. However, the DMR are available as PDFs of scanned documents that are resource intensive to extract any useful data. The US EPA also maintains the Enforcement and Compliance History Online (ECHO) database that contains the monitoring data in an easy-to-process, comma-separated values (csv) format. However, these data are generally available only from 2012 and later. Because of its usability, the ECHO data were chosen and used in the model application. Parameters that need to be represented from point sources in HSPF include flow, heat, sediment, dissolved oxygen, nitrate/nitrite, ammonia, organic nitrogen, orthophosphate, organic phosphorus, ultimate carbonaceous biochemical oxygen demand, and organic carbon. Actual flow values were used when available, and when unavailable, monthly average flows were used to fill missing data. The Arapahoe County Water and Wastewater Authority (ACWWA) facility used a rapid infiltration basin through 1999 when they began directly discharging directly. From 1999 through 2014, tap sales were used at ACWWA to represent the increase in discharge over time. The Stonegate facility discharges began in 1993 and were linearly increased to the full discharge in 2003. The Pinery facility began operating in 1991, and had an average discharge of 0.54 mgd that was used to linearly interpret flows between 1991 and 2012 when flow data were available. No “ramp-up” period was represented at the Parker facility, which has been discharging since before 1994. Monthly averages were used for the concentration data. Flows and concentrations were used to calculate loads.

For parameters with data at one or more of the represented sites, an average was used to estimate the sites missing that parameter for all but missing BOD. Missing DO was assumed to be 6 milligrams per liter (mg/L), missing NO2+NO3 was assumed to be 2.8 mg/L, and missing TSS was assumed to be 3.2 mg/L. Missing BOD was calculated using a derived formula of 0.25 times the TP load divided by a factor of 0.0073 that represents the portion of CBODu that is organic phosphorus. Parameters that were not available at any represented sites included dissolved oxygen, organic nitrogen, orthophosphate, organic phosphorus, and organic carbon. To estimate labile organic phosphorus, the factor of 0.0073, which represents the portion of CBOD5 that is labile organic phosphorus in HSPF, was multiplied by the CBOD5. Similarly, to estimate labile organic nitrogen, the factor of 0.0529 representing the portion of CBOD5 that is labile organic nitrogen in HSPF was multiplied by CBOD5. Refractory organic phosphorus was estimated as the remaining phosphorus not allocated as labile phosphorus or orthophosphate. Refractory organic nitrogen was estimated to occur at the same ratio as refractory organic phosphorus to labile organic phosphorus. Organic carbon was assumed to be 12.79 percent of CBOD5. The TSS were divided to be 40 percent silt and 60 percent clay, and the orthophosphate was assumed to be 67 percent of total phosphorus [Leonard Rice Engineers, Inc. and Lynker Technologies LLC, 2016]. NO2+NO3 was divided up to be 95 percent NO3 and 5 percent NO2 [Leonard Rice Engineers and Lynker Technologies, 2016].

2.5 ATMOSPHERIC DEPOSITION

The atmospheric deposition of nutrients is commonly included in watershed modeling efforts that focus on nutrient issues. The atmospheric deposition of nitrate and ammonia were explicitly represented as a daily time series in the Cherry Creek HSPF Model. Wet atmospheric deposition data were downloaded from the National Atmospheric Deposition Program (NADP).

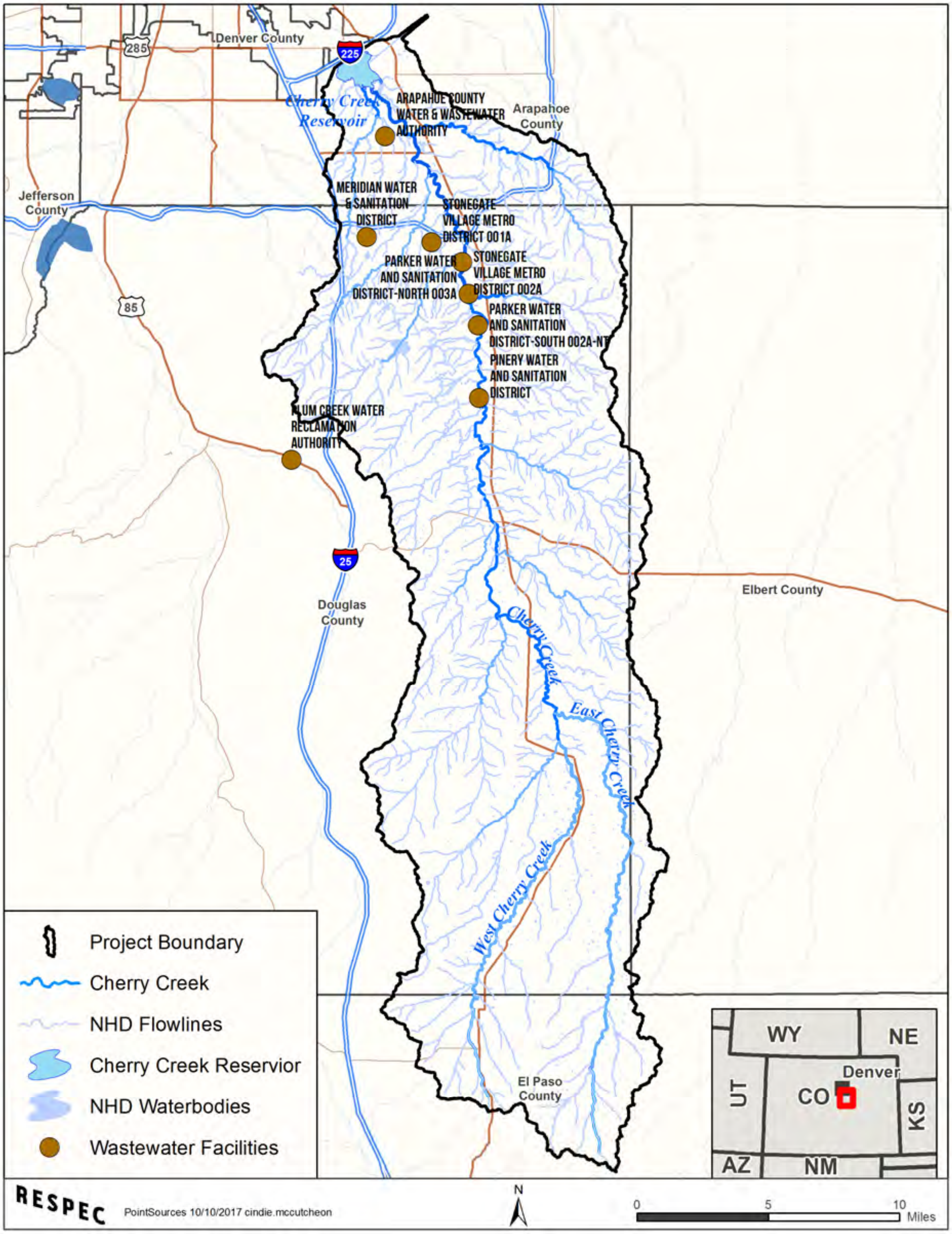


Figure 2-5. Location of Point-Source Dischargers in the Cherry Creek Watershed.

Table 2-2. Wastewater Facilities in the Cherry Creek River Watershed

NPDES Permit	Facility Name	Outfall Represented	Reach	Waterbody	Available Data	Notes
CO0041092	Pinery Water and Sanitation District	002A	160	Cherry Creek	Flow, BOD, Ammonia, Nitrate/Nitrite, Total Phosphorus, Sediment, Temperature	001A discharges to rapid infiltration basins, not modeled
CO0046507	Parker Water and Sanitation District	003A	208	Sulphur Gulch	Flow, Ammonia, Nitrate/Nitrite, Total Phosphorus, Sediment, Temperature	001N and 001S discharge to 002A to Regional Reservoir, not modeled
CO0040291	Stonegate Village Metro District	002	220	Cherry Creek	Flow, BOD, Ammonia, Nitrate/Nitrite, Total Phosphorus, Temperature	001A discharges to storage, not modeled
CO0040681	Arapahoe County Water & Wastewater Authority	001	298	Lone Tree Creek	Flow, BOD, Ammonia, Total Phosphorus, Sediment	All effluent discharges modeled
CO0038547	Plum Creek Water Reclamation Authority	NA	NA	NA	NA	001 and 005 discharges outside watershed, 007 discharges in watershed to Rueter Hess with no flow data, none modeled
CO0038679	Inverness Water & Sanitation District	NA	NA	NA	NA	Land application, not modeled
CO0039110	Meridian Water & Sanitation District	NA	NA	NA	NA	Land application, not modeled

Dry atmospheric deposition data were downloaded from the EPA's Clean Air Status and Trends Network (CASTNet). A summary of these stations is shown in Table 2-3 and displayed in Figure 2-6. Of the wet deposition sites, CO21 is closer to the CCW. Of the dry deposition sites, ROM406 and its collocated 206 site are the closest to the CCW. The closest sites were used to input atmospheric deposition into the model application.

Table 2-3. Atmospheric Deposition Site Summary

Site I.D.	Name	State	Elevation (feet)	Type	Available Parameters	Start Date	End Date
Rain Gage	Cherry Creek Rain Gage	CO	5,605	Wet	TN, DN, NH4, NO2+NO3, TP, DP, SRP	2001	2016
CO21	Manitou	CO	7,747	Wet	NH4, NO2+NO3	10/17/1978	Active
CO94	Sugarloaf	CO	8,279	Wet	NH4, NO2+NO3	11/04/1986	Active
GTH161	Gothic	CO	9,561	Dry	NH4, NO2+NO3	05/13/1989	Active
ROM206	Rocky Mtn NP Collocated	CO	8,994	Dry	NH4, NO2+NO3	06/26/2001	Active
ROM406	Rocky Mtn NP	CO	8,997	Dry	NH4, NO2+NO3	10/01/1994	Active

Some wet atmospheric deposition concentrations were available from a rain gage site within the CCW. Wet deposition data from this gage are not continuous like the NADP data and have fewer than 50 sample dates for each parameter between 2001 and 2016. Because of the NADP data's proximity to the watershed, effective quality assurance/quality control (QA/QC), and continuous data. CO21 data was used to input atmospheric NH4-N and NO2+NO3-N. Monthly average phosphorus data from the Cherry Creek Rain Gage were used in the HSPF model (Figure 2-7). Data for the months with no available data (October through March) were estimated using interpolation between September and April.

The original dry deposition data were supplied at a weekly time-step as a particulate flux (kilograms per hectare [kg/ha]). To transform the data into a daily time series, the weekly data were divided by seven. Similarly, the wet deposition was obtained at a weekly time-step, but in rare cases, sampling periods ranged from one to eight days. Because the wet deposition data were in units of concentration (mg/L), the wet deposition did not need to be divided by the number of days in the sampling period. Instead, the concentration was 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. Once transformed to daily time-series data, missing dry and wet deposition data were filled using interpolation when fewer than 7 missing days occurred between samples and by using monthly mean values when more than 7 missing days occurred between values. The raw data filling period was from 1990 through 2017. The data are converted to elemental concentrations and fluxes using multiplication factors in the UCI (i.e., data are still as NO3 and NH4, not NO3-N and NH4-N). A summary of the missing data that were filled and the approximate distance to the center of CCW are shown in Table 2-4.

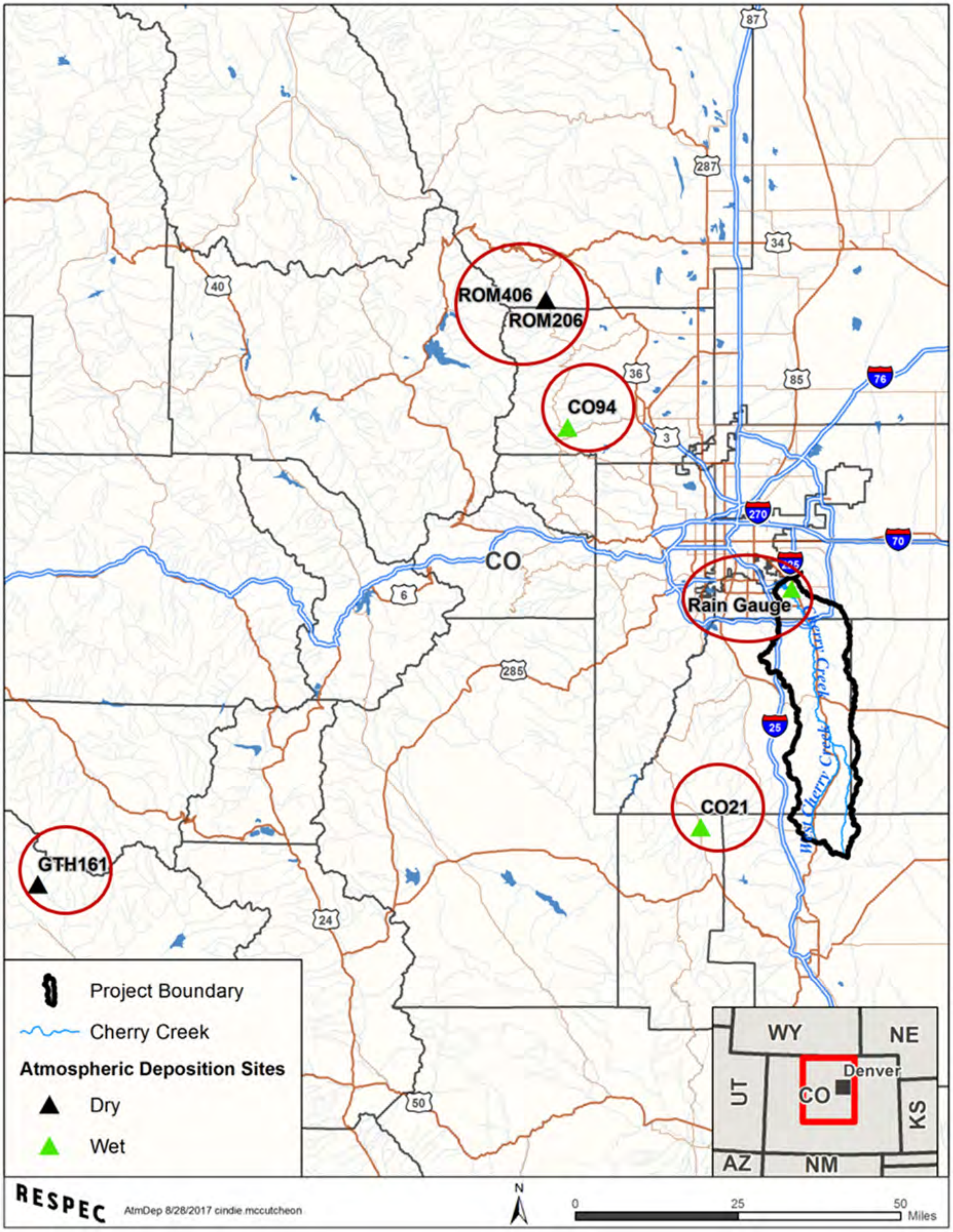


Figure 2-6. Locations of Wet and Dry Atmospheric Deposition Sites.

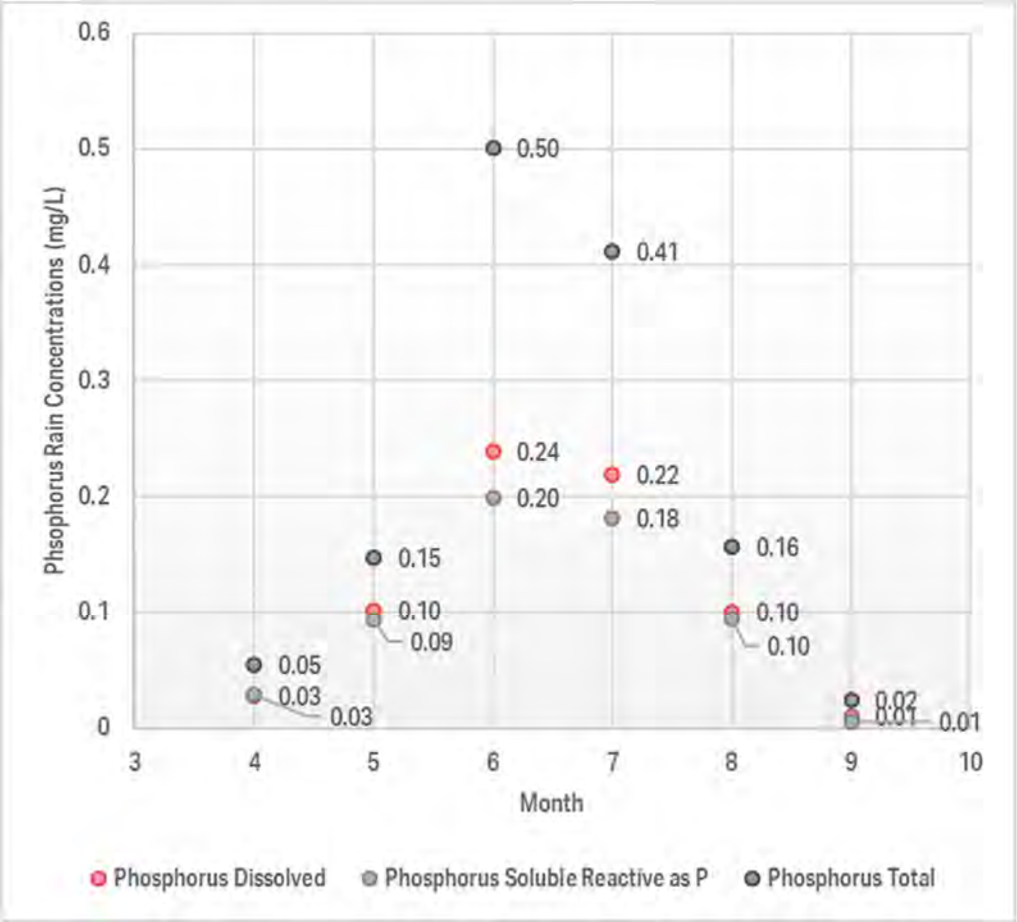


Figure 2-7. Monthly Average Phosphorus Concentration (Wet Deposition) at the Cherry Creek Rain Gage.

2.6 WELL PUMPING AND DIVERSION DATA

Wells are located throughout the alluvial area for municipal and irrigation use. Alluvial wells have time-series data available (some monthly and some weekly intervals) and are represented in the model application by pulling water from alluvial reaches. A monthly time series of data exists beginning in 2011 for a pumping station along Cherry Creek that diverts water to the Rueter-Hess Reservoir for storage, which is represented in the HSPF model application.

Table 2-4. Missing Data Summary and Proximity to the Cherry Creek Watershed

Site I.D.	Percent Missing	Distance (mi)
CO21	35	27
CO94	29	57
GTH161	4	123
ROM206	45	74
ROM406	22	74

mi = miles.

3.0 SEGMENTATION AND CHARACTERIZATION OF THE CHERRY CREEK WATERSHED MODEL

Whenever any watershed model is set up and applied to a watershed, the entire study area must undergo a segmentation process. The watershed segmentation divides the study area into individual land and channel segments (or pieces) that are assumed to demonstrate relatively homogenous hydrologic and hydraulic and water quality behavior. This segmentation provides the basis for assigning similar or identical input and/or parameter values or functions to where they can be applied logically to all of the portions of a land area or channel length that is contained within a model segment. Because most watershed models differentiate between the land and channel portions of a watershed and each portion is modeled separately, each portion undergoes a segmentation process to produce separate land and channel segments that are linked together to represent the entire watershed area.

Watershed segmentation is based on individual spatial characteristics of the watershed, including topography, drainage patterns, land uses and distribution, meteorological variability, and soils conditions. The process is essentially an iterative procedure of overlaying these data layers and identifying portions of the watershed with similar groupings of these characteristics. The results of the land-segmentation process are a series of model segments (sometimes call hydrologic response units [HRUs]) that demonstrate similar hydrologic and water quality behavior. Over the past few decades, geographic information systems (GIS), and associated software tools have become critical tools for watershed segmentation. Combined with advances in computing power, these tools have allowed for the development of automated capabilities to efficiently perform the data-overlay process.

GIS data (i.e., coverages) are used to spatially quantify the characteristics of the watershed landscape to develop the model input that informs the model regarding how the watershed characteristics change across the study area. GIS data that are used in the segmentation process affect the hydrologic and water quality response of a watershed are: topography and elevation, hydrography/drainage patterns, land use and land cover, soils information, and other various types of spatial data.

The primary sources for GIS data obtained for the CCW were those accessed through using the BASINS data download capability, and the data provided by the Authority. Through the BASINS interface, a wide range of GIS data layers were downloaded and displayed. BASINS accesses GIS data from various sources, such as The National Land Cover Database (NLCD), National Hydrography Dataset (NHD), and the USGS seamless data server.

3.1 TOPOGRAPHY AND ELEVATION

GIS layers of topography are important when setting up HSPF because the GIS layers provide elevation and slope values for the project area and are needed for characterizing the landscape and the land areas of the watershed. These elevation values are used to delineate subbasins, determine average elevations for each model subbasin, and/or compute average slopes for model subbasins and land uses within a subbasin. A very detailed topographic layer (e.g., Light Detection and Ranging [LiDAR] data) can also be useful in determining stream cross sections that are used to define the hydraulic characteristics of the streams. The National Elevation Dataset (NED) available through BASINS 4.2 is a 30-meter DEM grid, with vertical units in meters (Figure 3-1).

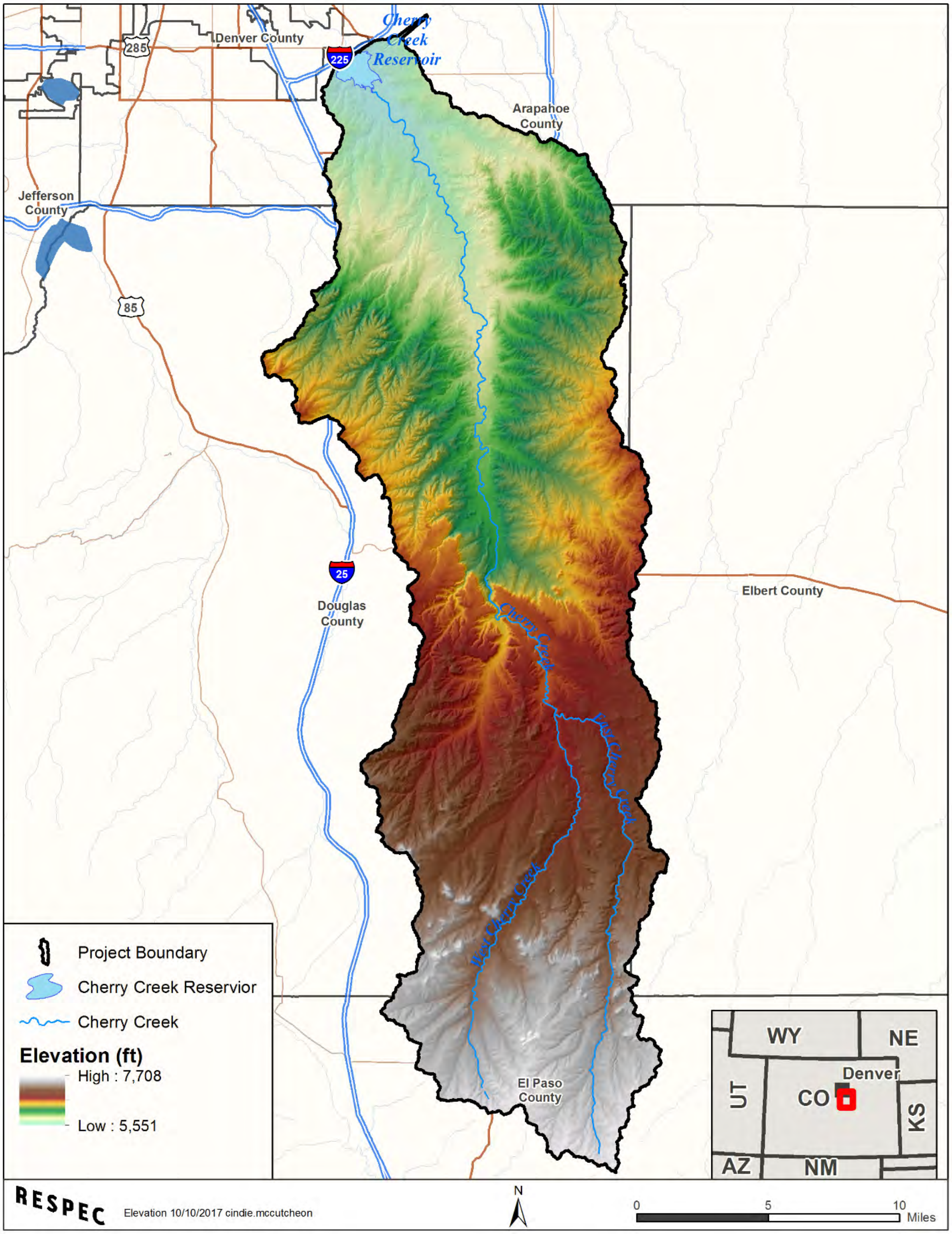


Figure 3-1. Elevation Map of the Cherry Creek Watershed (30-Meter Digital Elevation Model).

3.2 HYDROGRAPHY/DRAINAGE PATTERNS

Hydrography includes GIS layers of stream segments with varying levels of detail and subbasins, drainage boundaries, and waterbodies. A set of coverages that is commonly used in watershed modeling is the NHDPlus dataset. NHDPlus is an integrated suite of geospatial data sets that incorporates many of the best features of the NHD, the NED, the NLDC, and the Watershed Boundary Dataset (WBD).

The NHDPlus dataset includes elevation, elevation-derived catchments and stream network. The NHDPlus catchments were produced using the New-England Method [McKay et al., 2017]. These grids are the most hydrologically accurate 30-meter DEMs available to the water-resources community. Figure 3-2 shows the subwatersheds delineated for the model application. NHDPlus layers developed with a hydrologically conditioned DEM include the flow-accumulation stream grid were downloaded. ArcHydro was used to generate batchpoints at locations of interest, including changes in slope/terrain, outlets of tributaries, monitoring locations, and upstream and downstream of Pollutant Reduction Facilities (PRFs). Each model subwatershed and corresponding river reach is assigned a unique identification number (Reach I.D.) in ascending order from upstream to downstream. The subwatersheds with the same meteorological stations, similar soils, and slopes are grouped into hydrozones. The pervious (PERLND) and impervious (IMPLND) land areas in the same hydrozones receive the same meteorological input and have same parameters.

3.3 LAND USE

Land-use, or land-cover, data are a critical factor in modeling complex multiland-use watersheds because it provides the detailed characterization of the potential sources of pollutants that enter the reaches as nonpoint-source contributions. In addition, the land-use distribution has a major determining impact on the hydrologic response of the watershed.

The latest available land-use data for the Cherry Creek Watershed is NLCD 2011 [Homer et al., 2015]. Major land uses in the watershed include grassland/herbaceous, shrub/scrub, and urban areas, which are shown in Tables 3-1 [Fry et al., 2011] and 3-2 [Homer et al., 2015]. The urban areas are concentrated toward the downstream end of the watershed near the reservoir (Figure 3-3). The land-use data from the NLCD [Fry et al., 2006; Homer et al., 2015] were also downloaded to quantify the changes in the land uses from 2006 to 2011. The major changes occurred in the developed land uses, where high-intensity developed land use increased by as much as 32 percent and medium intensity increased by 15 percent. To model the effect of primary land uses, and future conditions, some land uses may need to be aggregated. A draft aggregation of land uses is presented in Tables 3-1 and 3-2.

3.3.1 EFFECTIVE IMPERVIOUS AREA

The Effective Impervious Area (EIA) is important to accurately represent in watershed models because of its impact on the hydrologic processes occurring 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 will not run onto pervious areas and, therefore, will not have the opportunity to infiltrate along its respective overland flow path before reaching a stream or waterbody.

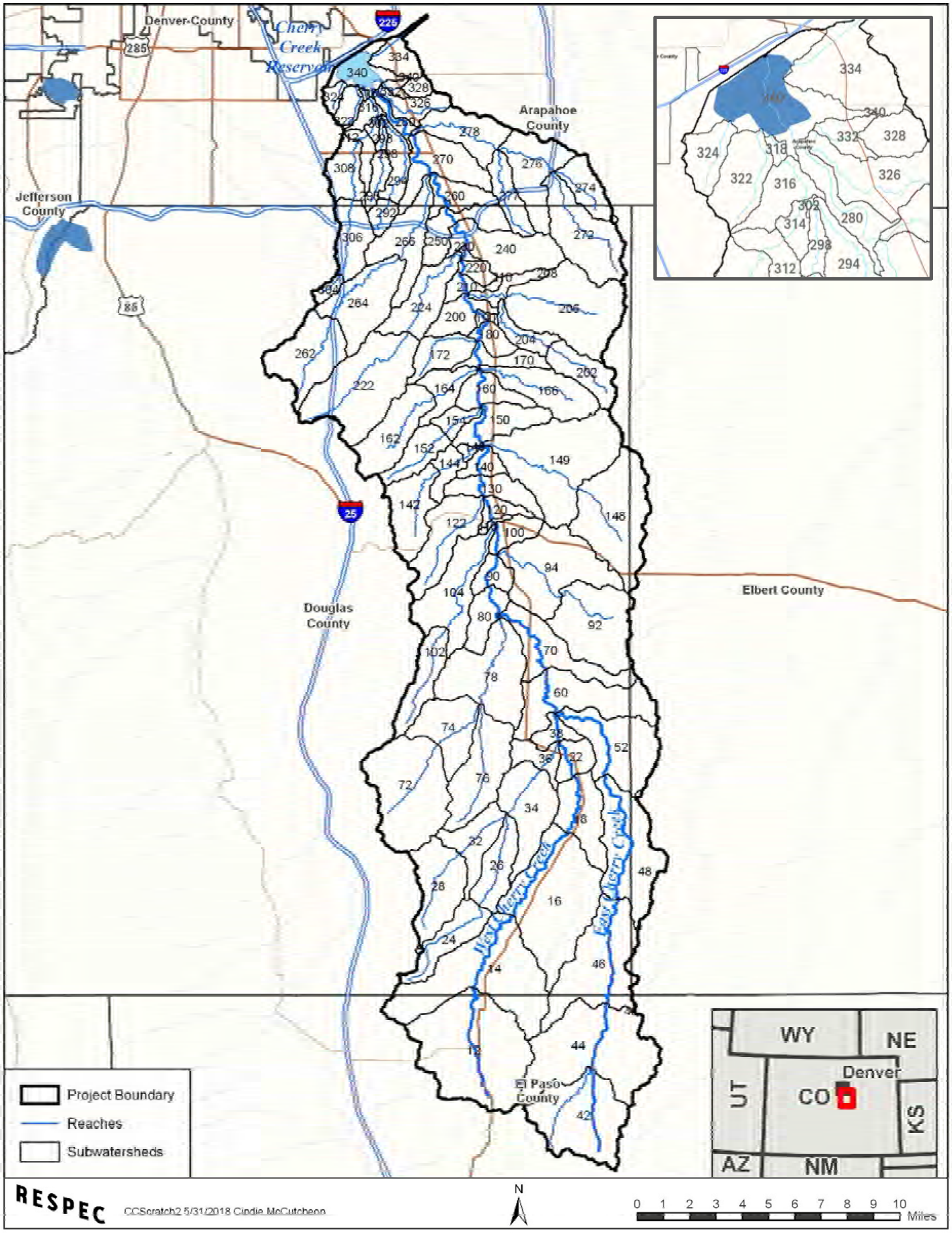


Figure 3-2. Subwatershed Delineation.

Table 3-1. National Land Cover Database 2006 Land-Use Distribution and Aggregated Categories

National Land Cover Database Class	Area (ac)	Percent (%)	Aggregated Model Categories	Percent (%)
Deciduous Forest	1,627.5	0.7	Forest	7.9
Evergreen Forest	17,782.7	7.2		
Pasture/Hay	50.5	0.0	Pasture/Hay	0.0
Grasslands/Herbaceous	139,458.8	56.5	Grass/Shrub/Barren	71.7
Shrub/Scrub	37,277.8	15.1		
Barren Land (rock/sand/clay)	232.6	0.1		
Developed, Open Space	19,550.5	7.9	Developed, Open Space	7.9
Developed, Low Intensity	12,346.9	5.0	Developed, Low Intensity	5.0
Developed, Medium Intensity	8,861.1	3.6	Developed, Medium/High Intensity (includes Commercial/Industrial	4.2
Developed, High Intensity	1,385.3	0.6		
Woody Wetlands	2,829.1	1.1	Wetlands	2.3
Emergent Herbaceous Wetlands	2,863.6	1.2		
Cultivated Crops	1,331.9	0.5	Cultivated crops	0.5
Open Water	1,121.8	0.5	Open Water[a]	0.5
Totals	246720.0	100	Totals	100

Table 3-2. National Land Cover Database 2011 Land-Use Distribution and Aggregated Categories

National Land Cover Database Class	Area (ac)	Percent (%)	Change From 2006 (%)	Aggregated Model Categories	Percent (%)	Change From 2006 (%)
Deciduous Forest	1,624.8	0.7	–0.2	Forest	7.8	–0.4
Evergreen Forest	17,705.3	7.2	–0.4			
Pasture/Hay	56.9	0.0	12.7	Pasture/Hay	0.0	12.8
Grasslands/Herbaceous	137,812.8	55.9	–1.2	Grass/Shrub/Barren	71.1	–0.9
Shrub/Scrub	37,082.1	15.0	–0.5			
Barren Land (rock/sand/clay)	481.7	0.2	107.1			
Developed, Open Space	19,294.3	7.8	–1.3	Developed, Open Space	7.8	–0.4
Developed, Low Intensity	12,614.0	5.1	2.2	Developed, Low Intensity	5.1	0.8
Developed, Medium Intensity	10,227.3	4.1	15.4	Developed, Medium/High Intensity (includes Commercial/Industrial	4.9	17.6
Developed, High Intensity	1,826.7	0.7	31.9			
Woody Wetlands	2,793.1	1.1	–1.3	Wetlands	2.3	–1.2
Emergent Herbaceous Wetlands	2,829.5	1.1	–1.2			
Cultivated Crops	1,213.2	0.5	–8.9	Cultivated crops	0.5	–8.9
Open Water	1,158.2	0.5	3.2	Open Water[a]	0.5	3.3
Totals	246,720.0	100	0.0	Totals	100	0

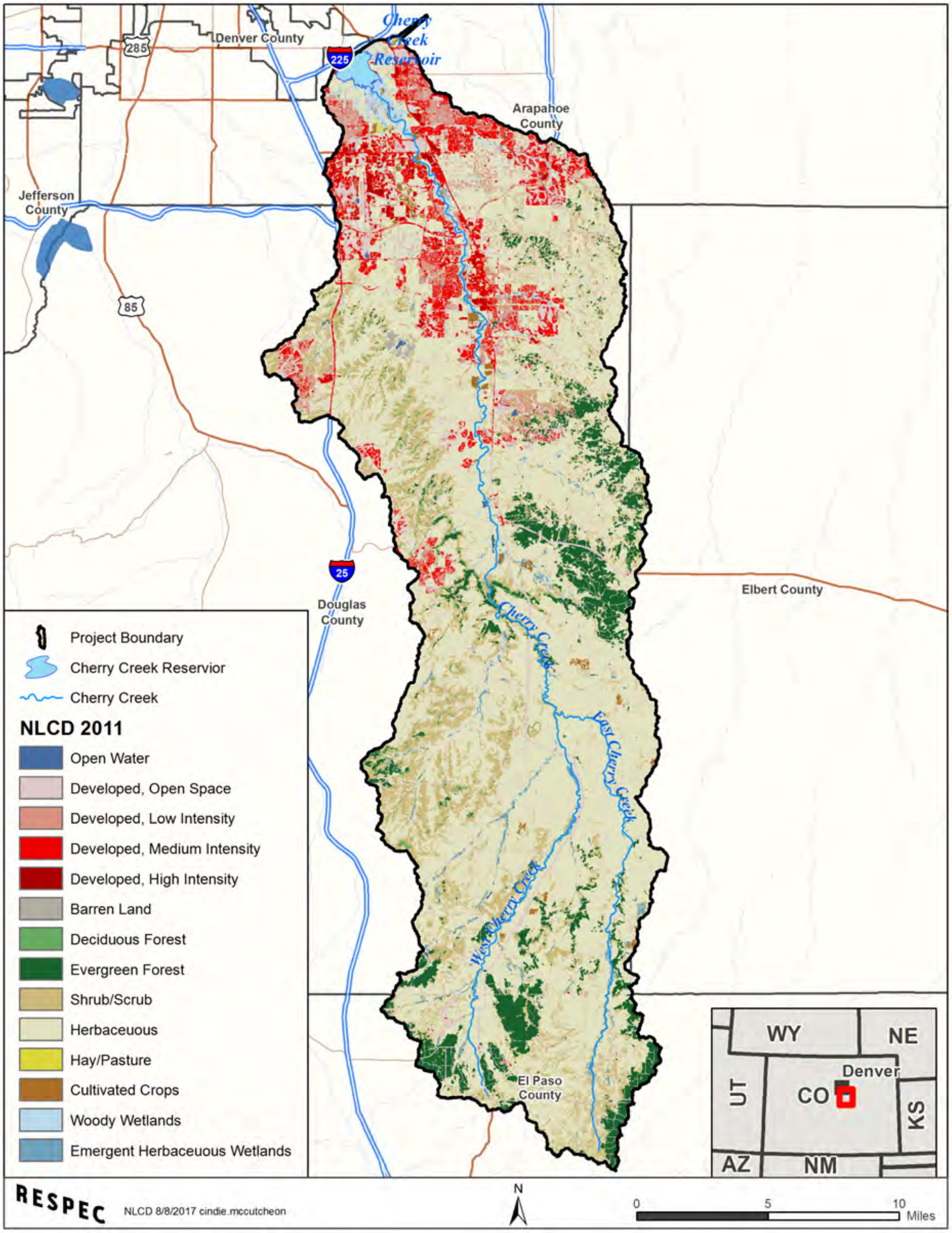


Figure 3-3. National Land Cover Data of the Cherry Creek Watershed for 2011.

The EIA for the CCW was represented using NLCD 2011 [Homer et al., 2015] but with specific focus on the Percent Imperviousness grid layers from those coverages. However, the NLCD percent imperviousness grids represent total impervious area (TIA), and addressing the distinction and difference between TIA and EIA is important. The EIA is always less than or equal to the TIA. To convert the TIA values to the EIA values needed for use in the HSPF model, the conversion percentages for each land-cover type specified in Table 3-3 were used.

Table 3-3. Total Impervious Areas and Percent Imperviousness of Each Urban Land Use for National Land Cover Database [2011] and Calculation of the Effective Impervious Area Based on Equations Proposed by Sutherland [2000]

Land-Use Category	Total Area (ac)	Impervious Area (ac)	TIA (%)	EIA (%)
Developed, Open Space	19,585.2	1,195.9	6.2	0.75
Developed, Low Intensity	12,368.5	4,363.8	34.5	15
Developed, Medium Intensity	8,870.7	6,241.9	61.0	30
Developed, High Intensity	1,388.9	1,551.6	84.8	60
Total	44,035.7	13,353.3	30.3	

3.3.2 POLLUTANT REDUCTION FACILITIES

As reported in the 2015 Annual report of the CCW, the Authority has added 23 PRFs in the CCW since 1989 to reduce the pollutant loadings in the watershed. Some PRFs have been added around the reservoir and one destratification system has been added in the reservoir. The Cherry Creek Annual Reports show approximately 43 PRFs in the CCW, some of which are planned for the future. These PRFs include stream reclamation, stream stabilization, floodplain preservation/conservation easements. The installation date for some of the PRFs was not available. If information could not be found on when a PRF began operation, an attempt was made to identify a shift in the observed data (if available). If the date when the operation began could not be determined, that PRF was not represented in the model application. Stream reclamation, stream stabilization, and settling pond PRFs are represented in the model application by increasing settling and reducing scour at each PRF location to ensure that a representative reduction occurs with simulated matching the observed data after PRF installation. This requires multiple model runs with and without the PRF, but the end-model application will have PRFs represented. As a shapefile of the PRF is not available, the approximate location of these PRFs were digitized by RESPEC and have been presented in Figure 3-4.

3.3.3 ON-SITE WASTEWATER TREATMENT SYSTEMS OR INDEPENDENT SEWAGE DISPOSAL SYSTEMS

On-Site Wastewater Treatment Systems (OWTS) or Independent Sewage Disposal Systems (ISDS) are used by many households in the CCW. These OWTS are responsible for pollutant loadings [Cherry Creek Basin Water Quality Authority, 2009; URS Corporation, 2003] either to the groundwater, or directly to the tributaries. Some of the studies have noted an increase in groundwater concentrations of PO4 and NO3 near the areas with OWTS.

The TriCounty Health department maintains a GIS database of OWTS in the area. Approximately 9,000 OWTS are listed in the GIS shapefile provided by the Authority and approximately 9 percent were

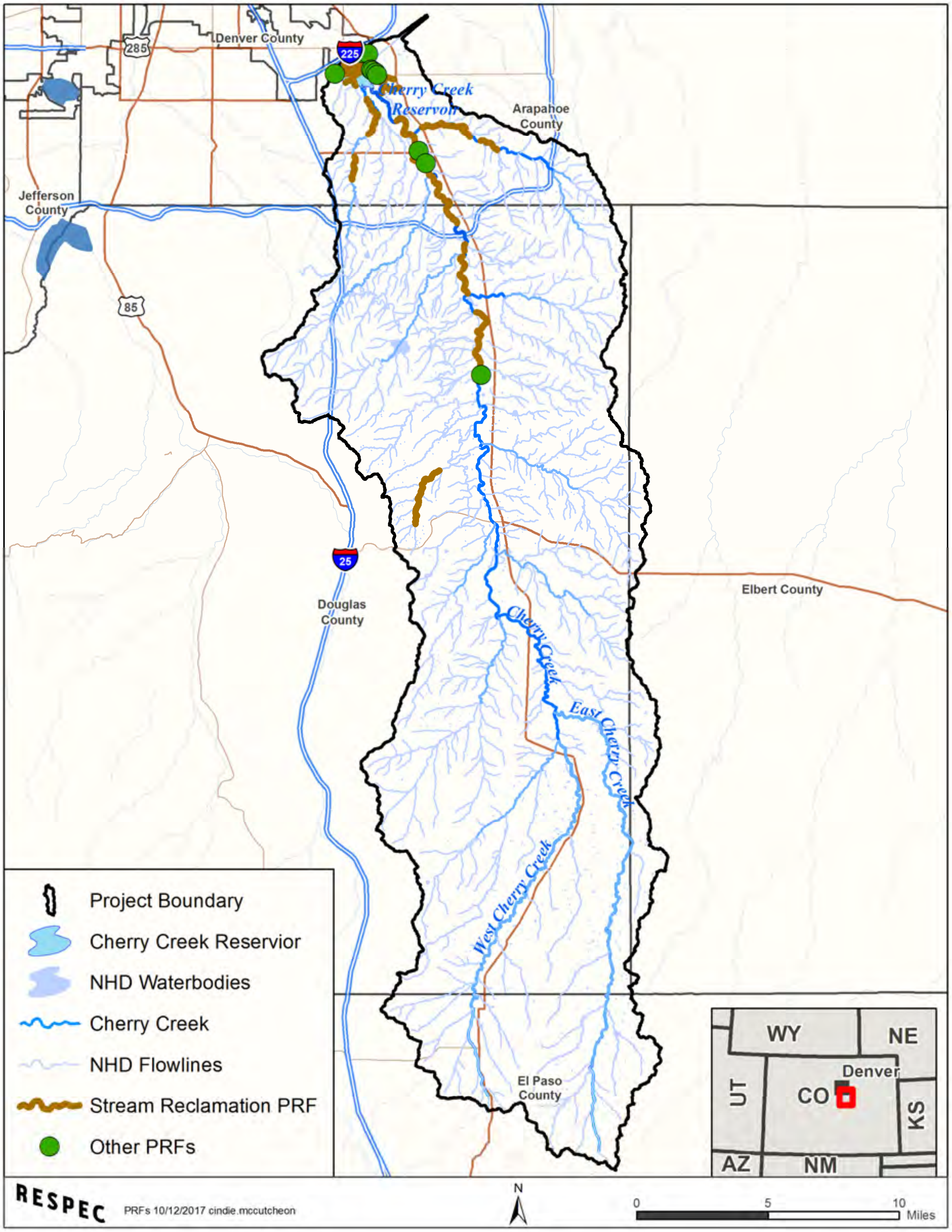


Figure 3-4. Location of Pollutant Reduction Facility in the Cherry Creek Watershed.

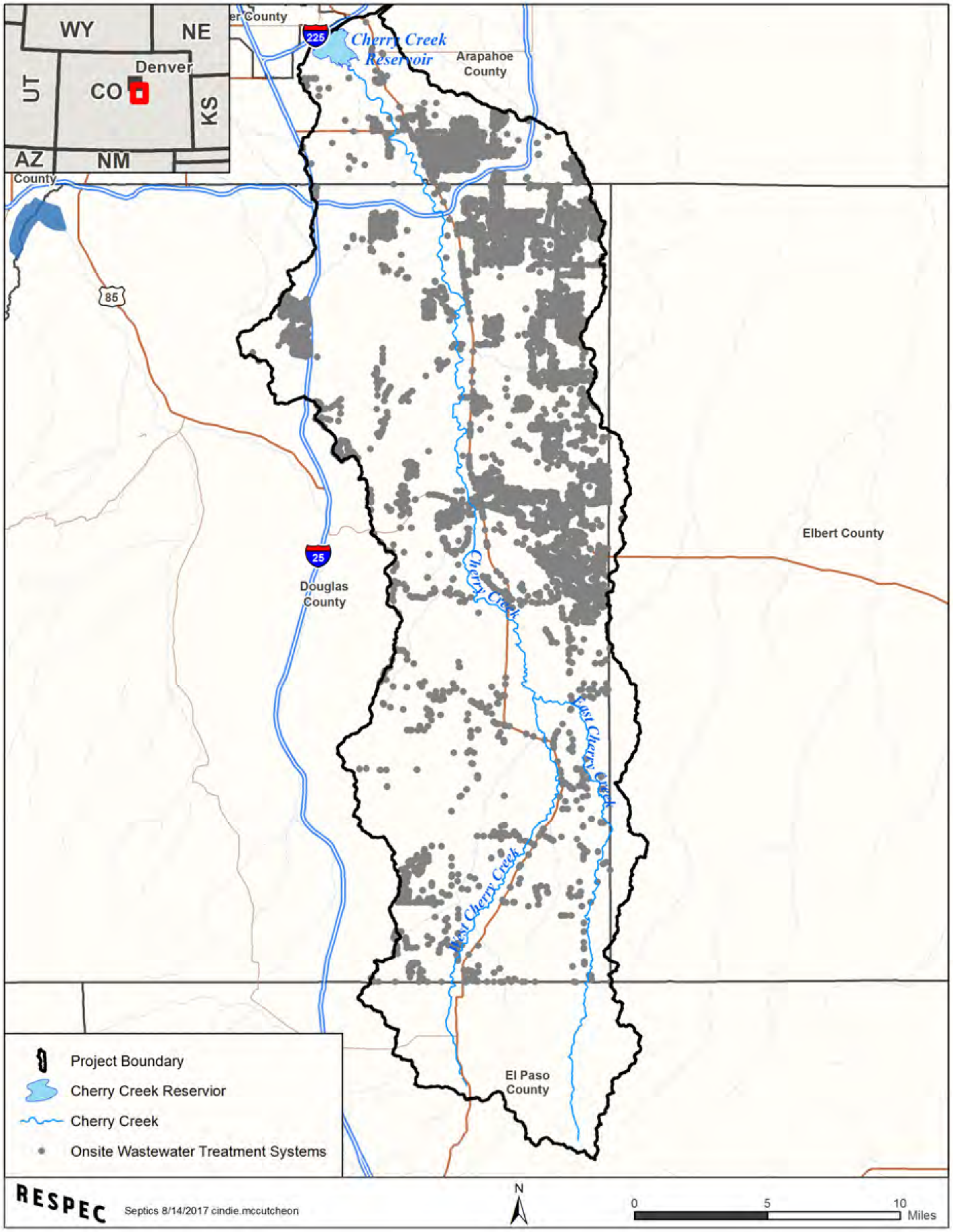


Figure 3-5. Location of the On-Site Wastewater Treatment Systems in the Cherry Creek Watershed.

estimated to be underreported (Figure 3-5). Individuals using OWTS were estimated using the available GIS data and the number of individuals per household from the 2010 US Census Data. In subwatersheds that overlap El Paso County (which did not have GIS OWTS data), the density from the nearest subwatershed that does not overlap El Paso County was used. Loads from OWTS were represented as a constant point source. Loads from a 2013 study by Leonard Rice and Engineers that estimate N and P loadings from the ISDS in the Cherry Creek Watershed were used for each individual using septic tanks by subwatershed.

3.3.4 MUNICIPAL SEPARATE STORM SEWER SYSTEM

The Authority has provided a GIS layer of Municipal Separate Storm Sewer System (MS4) areas (Figure 3-6). Some MS4 polygons cover an entire county, such as Douglas County. The CCW is further regulated under Cherry Creek Reservoir Control Regulation 5 CCR 1002-721, Section 72.7 (CR-72.7), *Stormwater Permit Requirements*. CR-72.7, which sets forth the additional measures for MS4s within the Cherry Creek Reservoir Watershed to protect the water quality of Cherry Creek Reservoir and Cherry Creek. For this study, we will consider all of the urban areas in the CCW under a CR72.7 permit (similar to the MS4).

3.3.5 RANCHES AND FEEDLOTS

As noted in multiple annual report documents, several ranches, dairies, and stables are located in the CCW. However, no information about Concentrated Animal Feeding Operations (CAFOs) in the area. Grassland and herbaceous land uses in the CCW were assumed to be occupied intermittently by pasture animals and wildlife. The nutrient loading rate for these land uses was generally calibrated with the target loading rate from other studies.

3.3.6 IRRIGATION

Approximately 2,458 acres of the 247,012 total acres (less than 1 percent) are irrigated (not including lawn irrigation). Irrigation water is generally pumped from the alluvium or applied along waterways. Although the pumping of irrigation water from the alluvium was represented with the time-series data, the reapplication of irrigation water was not represented in this model application. In developed areas, lawn irrigation also occurs but uses municipal water. In the model, lawn irrigation was implicitly represented through calibration because of the limited data.

3.4 SOILS DATA

Soils data are used to characterize the infiltration and soil-moisture capacity characteristics of the watershed soils, along with the erodibility parameters for soil erosion. The Gridded Soil Survey Geographic (gSSURGO) Database available from the Natural Resources Conservation Service [2017] was used as primary soils data for the CCW.

The gSSURGO dataset provides information about the soil hydrologic group, drainage class, soil type, and erodibility factor. Spatial data on the SCS Hydrologic Soil Groups (HSG) were obtained and used to generate a map of the spatial distribution of these properties (Table 3-4 and Figure 3-7).

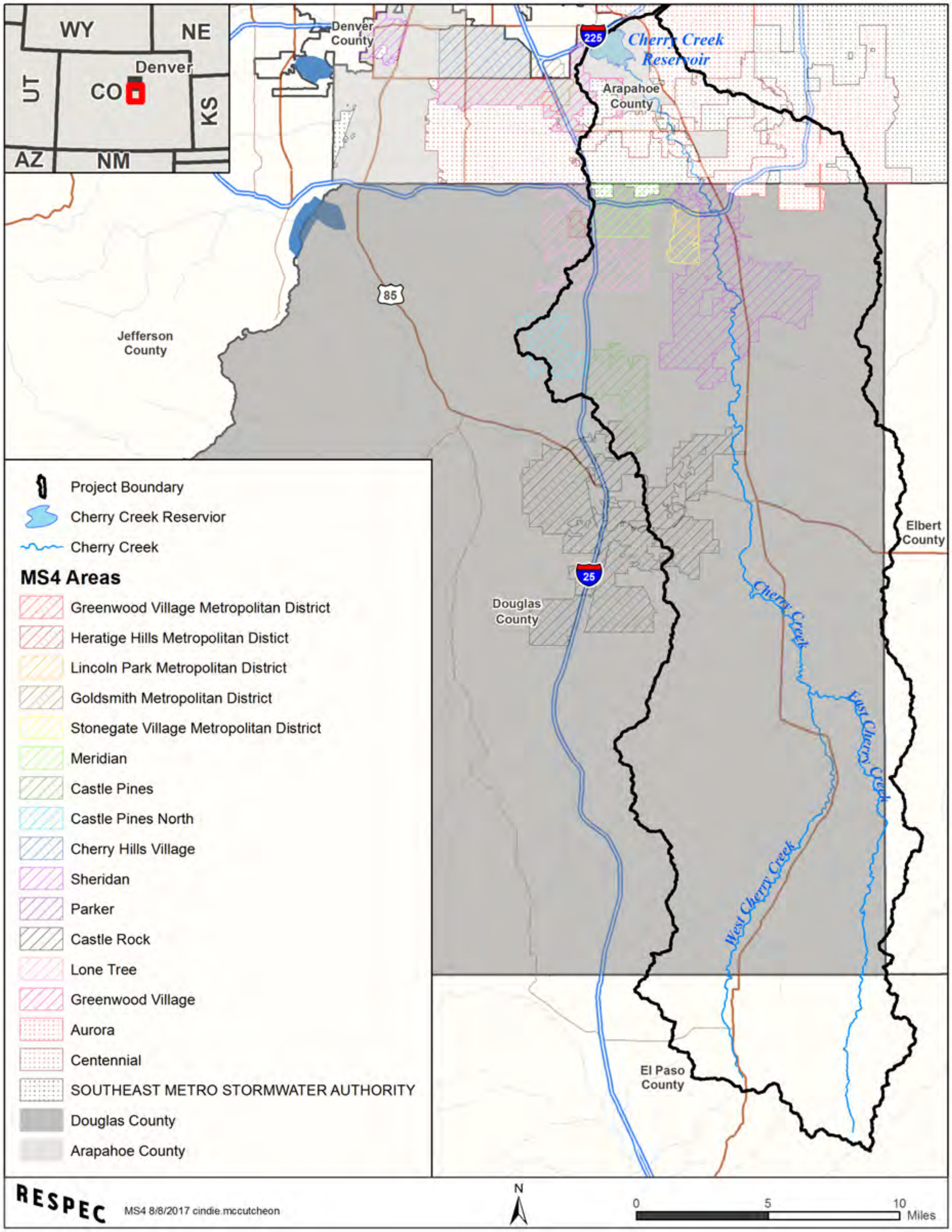


Figure 3-6. Municipal Separate Storm Sewer System Areas in the Cherry Creek Watershed.

Table 3-4. General Description of Hydrologic Soil Groups

Hydrologic Soil Group	Abbreviated Description	Percent of Project Area
A	Sand, sandy loams with high infiltration rates. Well-drained soils with high transmission	12
B	Silt loam or loam soils. Moderate infiltration, moderately drained	34
C	Sandy clay loams. Low infiltration rates, impedes water transmission	34
D	Heavy soils, clay loams, silty, clay. Low infiltration rates that impedes water transmission	19
Unclassified	No classification determined	1

The HSG distributions by subwatershed were evaluated and were fairly evenly distributed (46 percent AB soils, 43 percent CD soils, and 1 percent unclassified soils) throughout the watershed and was not represented in the segmentation. The erodibility factor for each PERLND was used to parameterize the erodibility factor of soils in the watershed.

Multiple studies have been completed to quantify the geomorphology in the project area and the nutrient concentrations in the sediment. One study showed that soil phosphorus measurements ranged from 0 to 3.9 mg/kg [John C. Halepaska and Associates, Inc, 1999] while another by Colorado State University (CSU) extension showed the range much higher from 1 to 60 mg/kg. When looking at streambank-phosphorus measurements, the phosphorus content was much higher and ranged from 310 to 580 mg/kg [John C. Halepaska and Associates, Inc, 1999] and 950 mg/kg [CH2M Hill, 2009]. Based on these studies, the PO4 streambank concentrations were set at 500 mg/kg and were adjusted as needed during the calibration process. A sediment budget [GK Cotton Consulting, Inc, 2011] showed that the transport capacity steadily decreased in the downstream direction and that only one area below the confluence with Happy Canyon Creek had the potential for scour.

3.5 CHANNEL CHARACTERISTICS

The river channel network is the major pathway by which flow, sediment, and contaminants are transported from the watershed to the Cherry Creek Reservoir. Accurately representing or characterizing the channel system in the HSPF model of the watershed is important. The river reach segmentation considers the river travel time, riverbed slope continuity, cross-section and morphologic changes, and entry points of major tributaries.

The channel characteristics help to define the routing and stage-discharge behavior, bed composition for sediment, carbon, and nutrients, and bed/water column interactions related to temperature, benthic oxygen demand, nutrient fluxes, and benthic algal mass. Because they need to be defined spatially throughout the stream system, information from as many sites as possible was used to define their characteristics.

3.5.1 HYDRAULIC CHARACTERIZATION OF RIVER AND RESERVOIR SEGMENTS

As part of the stream segmentation, the stream segments were analyzed to define their hydraulic behavior and characteristics, along with the tributary areas of the land-use categories that drain to them. Within the channel module (RCHRES) of HSPF, the stream hydraulic behavior of each waterbody

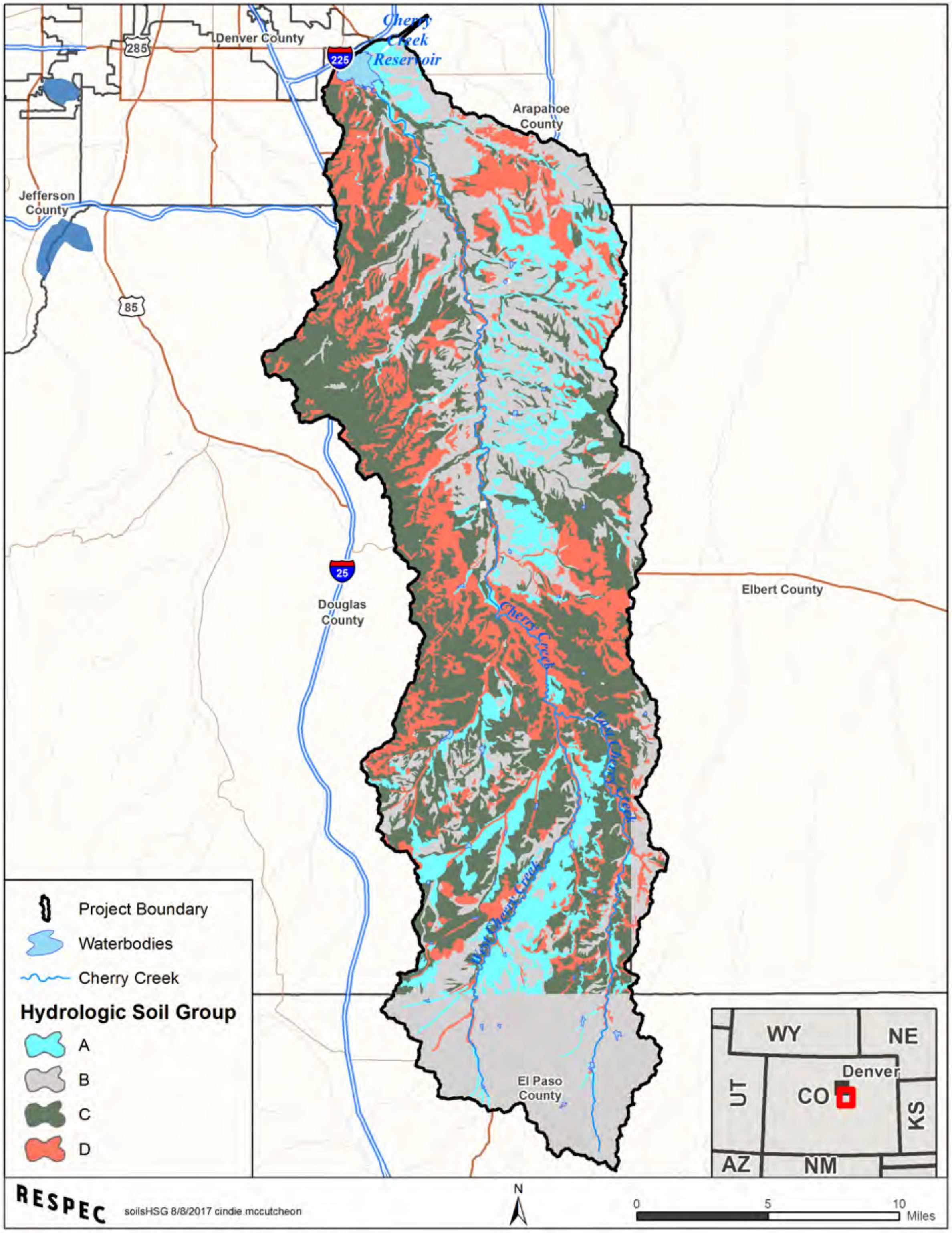


Figure 3-7. Distribution of the Natural Resources Conservation Service's Hydrologic Soil Groups for the Cherry Creek Watershed.

(e.g., stream/river or reservoir) is represented by a hydraulic function table (FTABLE), which defines the flow rate, surface area, and volume as a function of the water depth. To develop an FTABLE, the waterbody geometric and hydraulic properties (e.g., slope, cross-section, and Manning's *n*) must be defined using data or estimated values. After the geometry and hydraulic properties have been defined, developing the FTABLE as a function of the depth of water (i.e., stage) at the outlet is possible. For some reaches, the HEC-RAS model files are available. Cross sections from the HEC-RAS model files were used to develop the hydraulic characteristics of these reaches. These cross sections were assigned to other reaches based on the drainage area and other hydraulic characteristics.

The Reuter-Hess Reservoir is a major reservoir that supplies municipal water for the Parker Water and Sanitation District. The construction of this reservoir began in 2004 and finished in 2012. The storage capacity of this dam is approximately 72,000 ac-ft when filled completely. As of June 10, 2018, the reservoir contained about 26,500 acre-feet of water and is still in the process of filling. To represent the reservoir, Newlin Gulch stream that feeds the reservoir was assumed to be diverted directly downstream until the filling process began in the spring of 2012. In April 2012, flows above Reach 222 in the Newlin Gulch stream were not routed beyond the reservoir in the model. A portion of the flow from Cherry Creek was also diverted to the reservoir from Reach 160 based on a provided time series.

3.5.2 ALLUVIAL INTERACTION BETWEEN SURFACE WATER AND GROUNDWATER

Lewis and Sanders [2001] reviewed the alluvial flow through the CCW and provided the basis for estimating the total flow and flow components into and through the Cherry Creek Reservoir. Lewis and Sanders [2001] suggested that the Franktown gage (Figure 2-2) about half way through the watershed, probably reflects the total water yield from the basin above because of its proximity to bed rock. However, the downstream gages are underlain by thick alluvium, which probably conveys a significant amount of water that cannot be detected by a gage.

To represent flow through the alluvium model, the main stem of Cherry Creek downstream of the Franktown gage on the main stem were represented by a pair of reaches (i.e., a surface reach and an underground reach). Runoff was routed to the surface reach and the surface reach was routed to the underground reach. The network of surface reaches and underground reaches eventually flows into the Cherry Creek Reservoir. The groundwater reaches are subjected to less evaporation and a similar temperature and dewpoint as the surface reaches. No solar radiation or wind are applied to the groundwater reaches. The alluvial space under each reach was estimated using GIS information from the Cherry Creek Aquifer Modeling Project (CCAMP) model. Reaches with the alluvial interaction represented include Mainstem Reaches 90–280 and Sulpher Gulch Reach 208. Each associated groundwater reach was given the surface water reach number plus 500. Water from the surface water reach is transferred to the next down surface water reach using the methods discussed in Section 3.5.1 and to the corresponding alluvial reach through transmission loss. Water from the alluvial reach can either flow to the next down groundwater reach or to the next down surface water reach as springs flow. Monthly pumping data are also available, and the flow from the groundwater reaches was represented. A small fraction (0.01) of the Penman Pan evaporation was applied to the surface reaches and alluvial reaches.

An FTABLE for Reach 270 was developed using the most representative HEC-RAS cross section in the reach and properties calculated from GIS (Table 3-5). Discharge in the reach was calculated using length, slope, and cross-section data with the Manning's equation shown in Equation 1. The channel slope (S) for each reach was calculated by dividing the difference between the maximum and minimum bed elevations by each reach length.

Table 3-5. Properties of Reach 270 Calculated From GIS Data

Property	Value
Length (mi)	2.2
Area of alluvium in Subbasin 270 (ac)	787.9
Percent Area of Subbasin 270 that contains alluvium	25.2
Average Saturated thickness of alluvium (ft)	53.2
Average hydraulic conductivity (ft/day)	289

$$Q = \frac{1.486}{n} \times R^{2/3} \times S^{1/2} \tag{3-1}$$

where:

$Q =$ discharge (cubic feet per second)

$n =$ Manning's roughness coefficient

$A =$ cross section area (square feet)

$R =$ hydraulic radius (feet)

$S =$ channel slope.

Manning's roughness coefficients (n) of 0.03 and 0.25 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 using local topography and best engineering judgment. The FTABLE was developed by calculating the surface area, volume, and discharge over a range of depths. To allow the FTABLE to handle large storm flows, the cross sections were extended 1,000 feet horizontally beyond each bank, and the floodplain slope was assumed to be 0.02. The volume and surface area were calculated with the cross sections and stream segment lengths. The cross-sectional area at each depth (not part of standard FTABLE) was also calculated for transmission loss calculations.

The channel loss in cubic feet per second (cfs) per mile (S) was calculated using the Moritz formula [US Bureau of Reclamation, 1967].

$$S = 0.2C\left(\frac{Q}{V}\right)^{0.5} \tag{3-2}$$

where:

$C =$ cubic feet of water lost in 24 hours through each square foot of wetted area of canal prism

$Q =$ discharge of canal (cfs)

$V =$ mean velocity of flow (fps)

$Q/V =$ cross-sectional area of flow (ft^2).

The transmission loss from each reach was calculated as:

$$O = S \times L \tag{3-3}$$

where:

$O =$ transmission loss from the channel (cfs)

$L =$ channel length (miles)

$S =$ channel loss in cfs per mile of the channel.

The US Bureau of Reclamation [1967] also provided various values of C for different types of channel bed material. The value of C can vary from 0.34 for cemented gravel and hardpan with sandy loam to 2.20 for sandy and gravelly soil. The channel material was assumed to be "sandy and gravelly soil" with a C value of 2.20. Additionally, C was treated as a calibration parameter and adjusted during the calibration process to ensure reasonable inflow/transmission loss to the underlying alluvium reach. The Reach 270 FTABLE when the transmission loss was calculated at a higher C and lower C value is shown in Table 3-6. At each time step, the water will flow to the downstream reach according to the discharge rate (column 4) and to the corresponding alluvium reach according to the transmission loss (Column 5 using a C of 2 or 6 using a C of 0.2). Whether Column 5 or 6 is used is based on a seasonal COLIND time series, with higher transmission loss occurring during summer months (July through September), lower transmission loss occurring during winter months (December through April), a transition from low to high in May and June, and a transition from high to low in October and November.

To calculate the FTABLE for the alluvium reach, the cross-sectional area of the alluvium was calculated at different depths. The cross-sectional area was a product of average alluvium width for Reach 270 (4,725 ft) and the depth of alluvium (varying from 0 to 15.95 ft). The depth of water in alluvium was calculated as a factor of alluvium depth and the porosity. Robson [1987] reported mean porosity of alluvium in the Denver Basins. The mean porosity of alluvium in the Cherry Creek was reported as 30 percent. The surface area of the alluvium reach was calculated as 787.9 acres (based on the GIS map) and assumed to be constant for the entire depth of alluvium. To calculate the discharge rate at each depth Darcy's equation was used. The FTABLE for the alluvium reach corresponding to Reach 270 (numbered as Reach 770) is presented in Table 3-7.

When the alluvium reach was full, the excess water was routed to the downstream surface reach to emerge as spring flow. To model the spring flow of the excess water, additional rows were added with depth greater than the water depth in the alluvium. An additional exit column that discharges only when water depth increases beyond the maximum water depth of 15.95 ft was also added. The regular stream discharge rates were applied to this column to ensure that the excess water will flow out as a spring. This discharge rate was evaluated during calibration process. Figure 3-8 shows a diagram of interaction between surface and alluvial reaches.

3.6 ALLUVIAL WATER QUALITY REPRESENTATION

Alluvial water quality was represented using a series of GENERS in the HSPF model. The first set of GENERs avoided the surface flow values of zero by making a minimum surface flow of 0.01 ac-ft/hr in alluvial reaches. The second set of GENERs generated an alluvial flow fraction by dividing the alluvial flow in a reach to its corresponding surface flow. The remaining sets of GENERs then applied a load to the alluvium that represented the surface reach concentrations by multiplying the alluvial flow fraction by the corresponding surface reach loads for each parameter. Parameters represented included DO, BOD, temperature, sand, silt, clay, nitrate, nitrite, ammonia, orthophosphate, particulate ammonia, particulate PO4 on sand, silt, and clay, phytoplankton, organic nitrogen, organic phosphorus, and organic carbon.

Table 3-6. Reach 270 FTABLE With the Seasonal (High and Low) Transmission Loss

Depth (ft)	Surface Area (ac)	Volume (ac-ft)	Discharge (cfs)	Transmission Loss High (cfs)	Transmission Loss Low (cfs)
0.0	0.0	0.0	0.0	0.0	0.0
0.20	0.90	1.50	3.93	2.08	0.21
1.29	62.07	46.52	372.57	11.61	1.16
2.38	172.62	173.88	1,695.87	22.44	2.24
3.47	253.80	400.89	5,277.41	34.08	3.41
4.56	292.66	691.52	11,905.01	44.75	4.48
5.64	346.84	1,036.35	20,862.08	54.79	5.48
6.73	360.79	1,394.84	34,496.35	63.56	6.36
7.82	363.66	1,759.13	51,596.55	71.38	7.14
8.91	368.05	2,126.13	71,166.45	78.47	7.85
10.00	409.72	2,546.93	88,502.75	85.89	8.59
11.54	471.74	3,158.20	130,953.01	95.64	9.56
13.08	486.29	3,831.42	174,538.97	105.34	10.53
14.63	529.07	4,546.36	222,763.55	114.75	11.48
16.17	549.12	5,401.14	276,209.65	125.07	12.51
17.71	557.87	6,171.93	334,315.28	133.70	13.37
19.71	626.38	7,236.06	416,085.60	144.77	14.48
21.71	719.31	8,471.96	506,850.17	156.64	15.66
23.71	812.24	9,893.72	608,193.42	169.28	16.93
27.71	998.10	13,294.80	844,060.30	196.23	19.62

3.7 DEVELOPED LANDS WATER QUALITY REPRESENTATION

Two methods were attempted to represent the water quality on developed lands. The Colorado Regulation 85 Nutrient Data Gap Analysis Report included TN and TP event mean concentrations (EMCs) for commercial land, highways, industrial land, developed open space, and residential areas. These EMCs were applied to flows from applicable lands as percentages of TN and TP derived from observed data. Parameters initially represented with EMCs included nitrate (45.3 percent of TN), nitrite (3.9 percent of TN), ammonia (11.3 percent of TN), and organic nitrogen (39.5 percent of TN), orthophosphate (52.7 percent of TP), and organic phosphorus (47.3 percent of TP). When calibrating areas with a higher percentage of developed land, obtaining the variation needed was difficult. Therefore, the PQUAL method was tried (the same method as is used on all other, undeveloped land covers) and resulted in the variation needed to attain an acceptable water quality calibration.

Table 3-7. FTABLE for the Alluvium Reach 770 (Corresponding to Reach 270)

Depth (ft)	Surface Area (ac)	Volume (ac-ft)	Discharge to Next Down Alluvial Reach (cfs)	Discharge as Spring to Downstream Surface Reach (cfs)
0.00	787.94	0.00	0.00	0.00
1.99	787.94	1,570.82	0.12	0.00
3.99	787.94	3,141.64	0.23	0.00
5.98	787.94	4,712.45	0.35	0.00
7.97	787.94	6,283.27	0.46	0.00
9.97	787.94	7,854.09	0.58	0.00
11.96	787.94	9,424.91	0.70	0.00
13.95	787.94	10,995.73	0.81	0.00
15.95	787.94	12,566.54	0.93	0.00
16.15	788.84	12,568.04	0.93	3.93
17.24	850.01	12,613.06	0.93	372.57
18.33	960.56	12,740.42	0.93	1,695.87
19.42	1,041.74	12,967.43	0.93	5,277.41
20.50	1,080.60	13,258.06	0.93	11,905.01
21.59	1,134.78	13,602.89	0.93	20,862.08
22.68	1,148.73	13,961.38	0.93	34,496.35
23.77	1,151.60	14,325.67	0.93	51,596.55
24.86	1,155.99	14,692.67	0.93	71,166.45
25.95	1,197.66	15,113.47	0.93	88,502.75
27.49	1,259.68	15,724.74	0.93	130,953.01
29.03	1,274.23	16,397.96	0.93	174,538.97
30.58	1,317.01	17,112.90	0.93	222,763.55
32.12	1,337.06	17,967.68	0.93	276,209.65
33.66	1,345.81	18,738.47	0.93	334,315.28

35.66	1,414.32	19,802.60	0.93	416,085.60
37.66	1,507.25	21,038.50	0.93	506,850.17
39.66	1,600.18	22,460.26	0.93	608,193.42
41.66	1,693.11	24,067.87	0.93	720,450.02
43.66	1,786.04	25,861.34	0.93	844,060.30

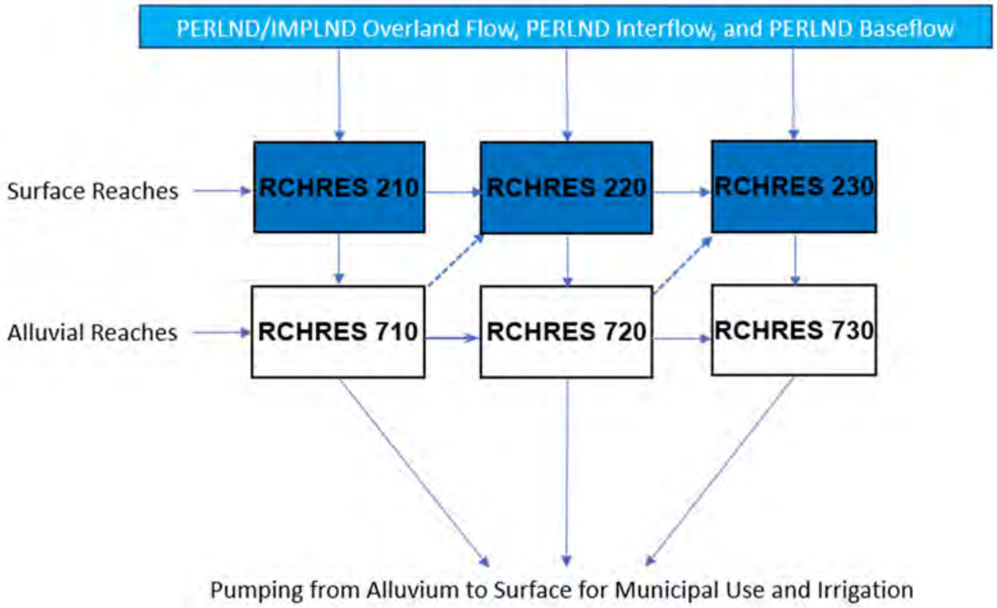


Figure 3-8. Diagram of Surface Reach and Alluvial Reach Interaction.

4.0 CALIBRATION AND VALIDATION OF THE CHERRY CREEK WATERSHED MODEL

4.1 CALIBRATION AND VALIDATION TIME PERIODS

Selecting time periods for model calibration and validation depends on several factors, including 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 needed for hydrologic and water quality calibration (e.g., rainfall, evaporation, ATEM, WIND, DEWP, CLOU, SOLR, observed flow, and water quality observations) indicate that long-term simulations are possible at several the USGS gages within the IRW. The observed flow data and meteorological data are available for at least the last 25 years. The CE-QUAL-W2 model runs from 2003 through 2013 and, therefore, the HSPF model should also cover these periods and beyond to meet the boundary condition need of the CE-QUAL-W2 model. Point-source and atmospheric deposition data were available during this time period, and PRF installation data is also the most detailed after 2003. Water quality data are also very thorough after 2003.

Precipitation and meteorological data are a fundamental necessity for model execution, and these data must span the entire simulation period and cover the calibration and validation periods. Partial periods of record, while not ideal, can still be used for consistency checks as part of the calibration and validation process. Land-use data are available as snapshots in time and partially control the selection process because having the land-use data at the approximate midpoint of each period, calibration, and validation is preferable. These data provide a reasonable representation of conditions throughout each period.

Climate variability is considered once the potential time periods are identified, so that both calibration and validation are performed over a range of climate conditions, including a reasonable balance of wet and dry periods. To assess the variation in precipitation, average annual precipitation for the CCW was calculated by averaging the rainfall recorded in the 14 grids encompassing the CCW. The yearly precipitation graph (Figure 4-1) shows that the annual precipitation varied from 10.5 inches (in) to 23.9 in in this 27-year period, with a mean of 17.04 in and a standard deviation of 2.85 in. A calibration period from 2003 to 2016 includes high rainfall years (e.g., 2009 and 2015) and drier years (e.g., 2008 and 2012) and demonstrates the hydrologic variability. Therefore, this period is a good candidate for watershed model calibration. In general, more recent time periods are more suitable for watershed model calibration because the recent data are assumed to be more readily available and of higher quality. For validation, the model runs will be split into two time periods (2003–2009 and 2010–2016) and statistics will be evaluated. For water quality calibration and validation, the same time periods were selected. The land-use data for 2011 was used for the calibration and validation period.

4.2 HYDROLOGY CALIBRATION/VALIDATION PROCEDURES AND COMPARISONS

Calibrating the CCW model was an iterative process of making parameter changes, running the model, producing comparisons of simulated and observed values, and interpreting the results. This process occurs first for the hydrology portions of the model and then for the water quality portions. The procedures have been well established over the past 30 years and are described in the HSPF Application Guide [Donigian et al., 1984] and summarized by Donigian [2002]. Calibrating HSPF to represent the hydrology of the CCW is an iterative trial-and-error process. The simulated results are compared with recorded data for the entire calibration period, including both wet and dry conditions, to see how well the simulation represents the hydrologic response observed under a range of climatic conditions. By iteratively adjusting specific calibration parameter values within accepted and physically based ranges the simulation results are changed until an acceptable comparison of the simulated and recorded data are achieved.

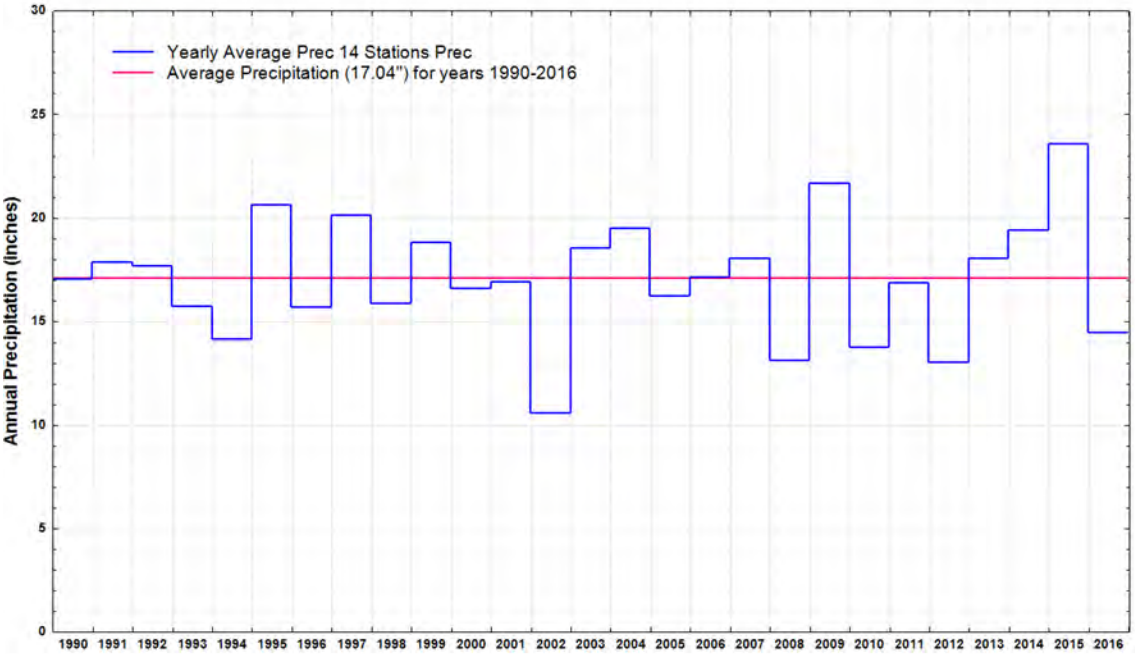


Figure 4-1. Annual Precipitation for the Cherry Creek Watershed From the NLDAS Data for Years 1990–2016.

The standard HSPF hydrologic calibration is divided into the following phases:

- **Establish an annual water balance.** This phase consists of comparing the total annual simulated and observed flow (in) and is governed primarily by the input rainfall and evaporation and the parameters for the lower zone nominal storage (LZSN), lower zone evapotranspiration parameter (LZETP), and infiltration index (INFILT).
- **Adjust low-flow and high-flow distribution.** This phase is generally completed by adjusting the groundwater or baseflow because identifying the groundwater or baseflow is easiest in low-flow periods. Comparisons of mean daily flow are used, and the primary parameters involved are INFILT, AGWRC (groundwater recession), and BASETP (baseflow ET index).
- **Adjust the stormflow and hydrograph shape.** The stormflow, which is compared in the form of short (1 hour) time-step 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 the overland flow parameters (LSUR, NSUR, and SLSUR). INFILT also can be used for minor adjustments.
- **Make seasonal adjustments.** The differences in the simulated and observed total flow over the summer and winter are compared to see if the runoff needs to be shifted from one season to another. These adjustments are generally accomplished by using seasonal (monthly variable) values for the parameters CEPSC (vegetal interception), LZETP, UZSN. Adjustments to KVARY (variable groundwater recession) 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].

The same model-data comparisons were performed for both the calibration and validation periods. The specific comparisons of simulated and observed values include:

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

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

- Precipitation
- Total Runoff (sum of following components)
    - Overland flow
    - Interflow
    - Baseflow
- Potential Evapotranspiration (ET)
- 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 each of the water-balance components listed above, the average annual values must be consistent with the expected values for the region, which are impacted by the individual land-use categories. This is a separate consistency check with data that are independent of the modeling (except for precipitation) to ensure that land-use categories and overall water balance reflect the local conditions. For CCW, Lewis and Sanders [2001] provided some estimates of the distribution of flow among surface reaches and flow though alluvium. These estimates were compared with the water balance for Cherry Creek during the calibration and showed lower total evaporation, similar surface runoff, and higher alluvial flow. The study does mention that the alluvial flow estimate may be high because of several factors, including slope, transmissivity estimates, and cross-sectional estimates at the site evaluated.

Table 4-1 lists the general calibration/validation tolerances or targets that have been provided to model users as part of HSPF training workshops over the past 10 years (e.g., Donigian [2000]). The values in the table attempt to provide some general guidance, in terms of the percent mean errors or differences between simulated and observed values, so that users can gage the level of agreement or accuracy (e.g., very good, good, and fair) that may be expected from the model application.

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

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

CAVEATS:
Relevant to monthly and annual values; storm peaks may differ more
Quality detail of input and calibration data
Purpose of model application
Availability of alternative assessment procedures
Resource availability (i.e., time, money, personnel)

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 but can still be acceptable. The level of agreement to be expected depends on many site- and application-specific conditions, including the data quality, purpose of the study, available resources, and available alternative assessment procedures, that could meet the study objectives.

Figure 4-2 provides value ranges for the correlation coefficients $\left(R\right)$ and coefficient of determination $\left(R^2\right)$ for assessing model performance for both daily and monthly flows. The figure shows the range of values that may be appropriate for judging how well the model is performing based on the daily and monthly simulation results. As shown, the ranges for daily values are lower to reflect the difficulties in exactly duplicating the timing of flows, given the uncertainties in the timing of model inputs (mainly precipitation).

CRITERIA
R ← 0.75 — 0.80 — 0.85 — 0.90 — 0.95 →
R^2 ← 0.6 — 0.7 — 0.8 — 0.9 →
DAILY FLOWS: POOR FAIR GOOD VERY GOOD
MONTHLY FLOWS: POOR | FAIR | GOOD | VERY GOOD

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

For any watershed modeling effort, the level of expected agreement is tempered by the complexities of the hydrologic system, the quality of the available precipitation and flow data, and the available information to help characterize the watershed and quantify the human impacts on water-related activities. The values shown above have been derived primarily from HSPF experience and selected past efforts on model performance criteria; however, the values reflect common tolerances accepted by many modeling professionals.

4.3 HYDROLOGY CALIBRATION AND VALIDATION RESULTS

The hydrologic calibration focused on the two most downstream, primary gages (CC-10 and CT-2) which contribute directly to Cherry Creek Reservoir. These two gages ensured that the water routing across the land, through interflow, and the groundwater was correctly represented. The hydrology calibration results at these calibration locations are provided in Appendix A. An example of a calibration snow plot is shown in Figure 4-3, and an example of a duration curve from the hydrology calibration is shown in Figure 4-4. The weighted water-balance components in the watersheds for primary gages CC-10 and CT-2 are provided in Table 4-2, and Table 4-3 shows calibration statistics and volume percent error for the two primary gages. The more upstream gage (Cherry Creek near Parker, Colorado) was a secondary calibration gage which was used to calibrate flows from the land-segment categories more prevalent upstream such as grassland. Hydrology calibration figures at Cherry Creek near Parker, Colorado, are also included in Table 4-2, Table 4-3, and Appendix A. At CC-10, the simulated and observed very low flows do not appear to match the flow duration curve; however, the difference along the flow duration curve between the observed and simulated flow is generally less than 1 cfs. This 1 cfs difference in the wide channel above the reservoir inlet is considered negligible and the calibration is acceptable at this location. Similarly, at CT-2, a 1 cfs difference occurs during the lowest flows. A difference of 1 cfs in this location is negligible and the calibration is acceptable at this location.

4.4 WATER QUALITY CALIBRATION PROCEDURES AND COMPARISONS

Water quality calibration is an iterative process; the model predictions are the integrated result of all the assumptions used in developing the model input and representing the modeled sources and processes. Differences in model predictions and observations require the model user to reevaluate these assumptions for the estimated model input and parameters and consider the accuracy and uncertainty in the observations.

The following steps were performed at each of the calibration stations after the hydrologic calibration and validation and after completing the input development for the point-source, atmospheric, and other contributions:

1. Estimate all model parameters, including land use-specific accumulation and depletion/removal rates, wash-off rates, and subsurface concentrations
2. Tabulate, analyze, and compare the simulated annual nonpoint loading rates with the expected range of nonpoint loadings from each land use (and each constituent) and adjust the loading parameters when necessary
3. Calibrate instream water temperature, sediment, dissolved oxygen, and nutrients to the observed data.

The essence of the watershed water quality calibration is to obtain acceptable agreement of observed and simulated concentrations (i.e., within defined criteria or targets), while maintaining the instream water quality parameters within physically realistic bounds and maintaining the nonpoint loading rates within the expected ranges from the literature. The nonpoint loading rates, which are sometimes referred to as export coefficients, are highly variable with values that vary in magnitude, depending on local and site conditions of the soils, slopes, topography, and climate.

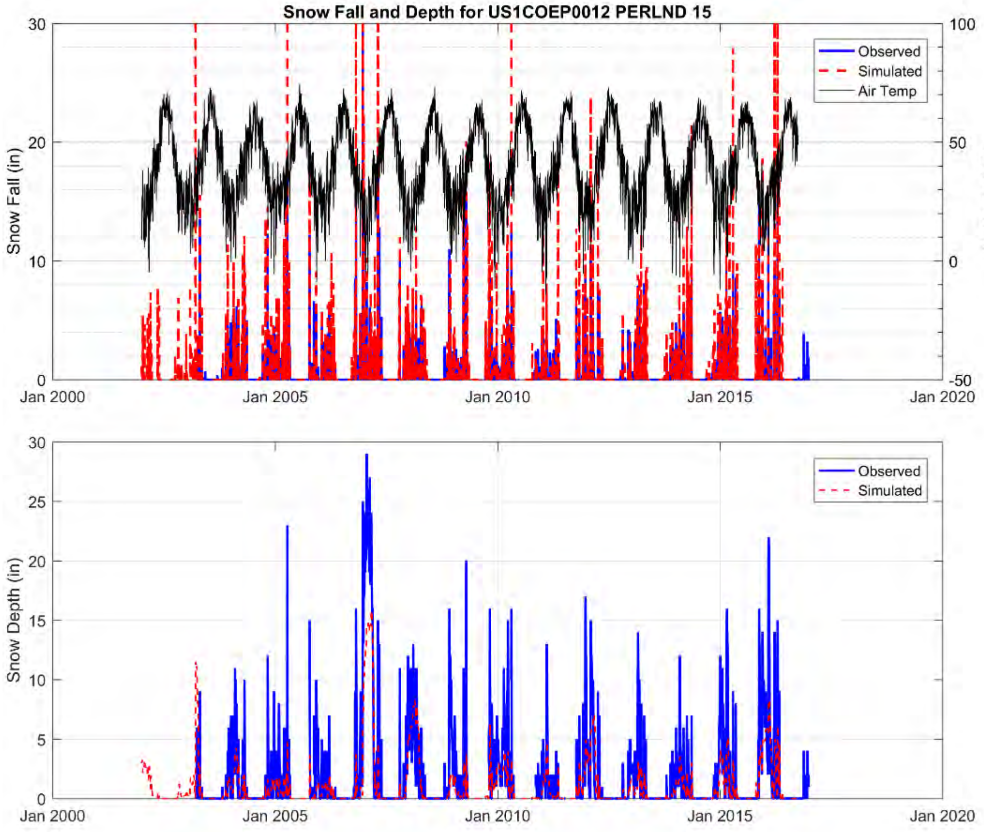


Figure 4-3. Calibration Figure to Evaluate Snowfall and Snow Depth Simulation.

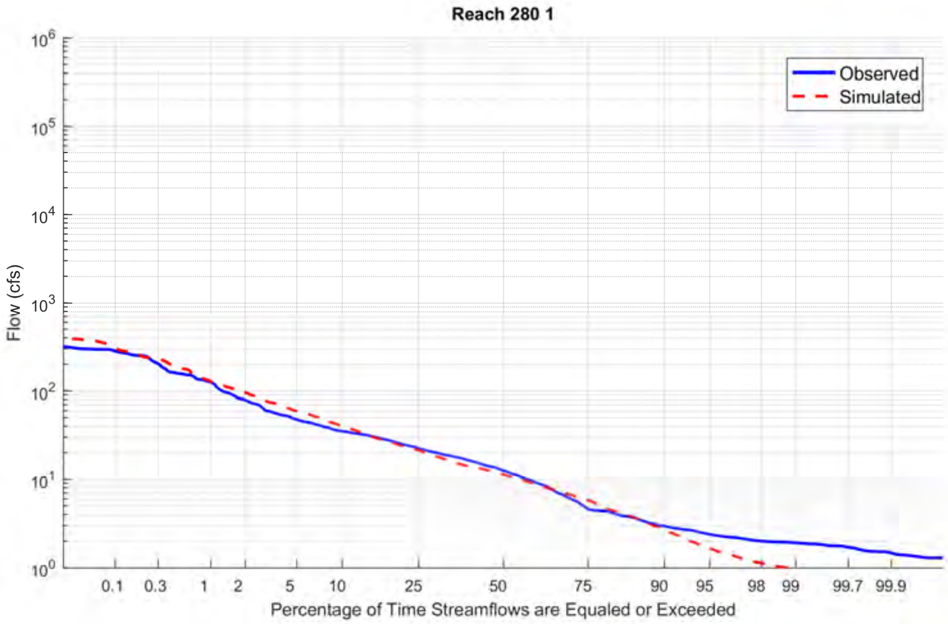


Figure 4-4. Flow Duration Curve Calibration Plot at CC-10.

Table 4-2. Summary of Water Balance at Primary Calibration Reaches

Water-Balance Component	Water-Balance Component Description	Reach 210 (in)	Reach 280 (in)	Reach 318 (in)
SUPY	Water supply to soil surface	19.283	19.192	18.593
SURO	Surface outflow	0.248	0.498	2.749
IFWO	Interflow outflow	0.054	0.051	0.047
AGWO	Active groundwater outflow	0.413	0.425	0.690
PERO	Total outflow from PLS	0.469	0.479	0.738
IGWI	Inflow to inactive groundwater	0.122	0.123	0.154
AGWI	Active groundwater inflow	1.097	1.106	1.386
PET	Potential ET	52.078	52.814	56.212
CEPE	Evaporation from interception storage	6.076	5.874	4.076
UZET	Evapotranspiration from upper zone	2.483	2.463	2.395
LZET	Evapotranspiration from lower zone	9.069	8.813	6.337
AGWET	Evapotranspiration from active groundwater storage	0.394	0.393	0.366
BASET	Evapotranspiration from baseflow	0.241	0.239	0.278
TAET	Total simulated ET	18.388	18.033	14.839

Table 4-3. Hydrology Calibration Results for the Primary Gages

Observed Flow Gage, Calibration Gage Type	HSPF Reach	Total Runoff Volume			Monthly			Daily			Storm Percent Error (%)	
		Observed (in)	Simulated (in)	% Δ	R	R^2	MFE	R	R^2	MFE	Volume	Peak
USGS 393109104464500, Secondary	210	0.54	0.56	3.25	0.85	0.73	0.68	0.69	0.47	0.41	0.94	−15.65
CC-10, Primary	280	0.68	0.70	3.85	0.87	0.76	0.74	0.78	0.61	0.47	6.21	2.49
CT-2, Primary	318	8.70	8.49	−2.44	0.82	0.68	0.67	0.72	0.51	0.51	−10.90	−18.21

MFE = Model-Fit-Efficiency

The nonpoint source-loading rates from different land uses were compared against the nonpoint source-loading rates summarized in previous studies [AQUA TERRA Consultants, 2002; 2015]. Multiple local studies include estimates of nonpoint loading rates. The Tri-Lakes sedimentation study conducted by US Army Corps of Engineers [2011] calculated the sediment loading into the Cherry Creek Reservoir based on the current data and historical studies. The Cherry Creek Basin Watershed Phosphorus Model by Brown and Caldwell [2009] calculated P loads generated in the CCW. The geomorphic analysis by Simons [2011] was also considered.

The instream calibration began with temperature, sediment, and then to DO and nutrients. The DO and nutrients calibration was 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 scatter plots of concentrations and corresponding flows. Boxplot components used for monthly calibrations is shown in Figure 4-5. Sediment scour and deposition in the stream bed for each reach over the period of simulation and the nutrient budget were also evaluated.

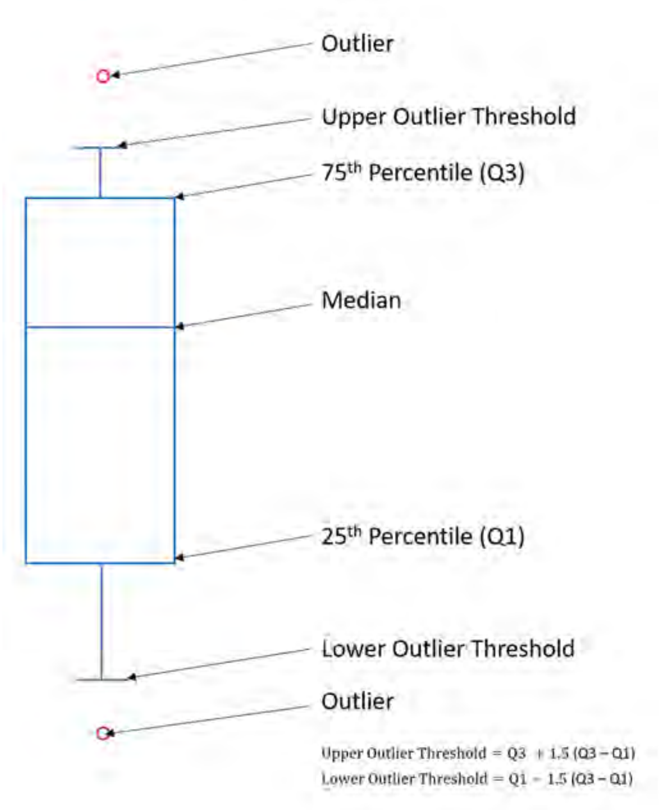


Figure 4-5. Components of a Monthly Boxplot.

During calibration, some of the instream parameters were adjusted by stream order for temperature, sediment scour, and algae growth/death/settling. The instream parameterization of PRF sites is described in Section 3.3.2. Instream parameterization was consistent by stream order and PRF type for all reaches, except Reaches 270 (CC-8) and 280 (CC-10). The benthic release of PO4 (BRPO4 parameter) at Reaches 270 and 280 was set to 0.4 and 0.9, respectively, to represent alluvial interactions with surface water and the mobilization of dissolved phosphorus from pore water in areas where sediments are dried and reflooded [Kinsman-Costello et al., 2016]. These phenomena are expected to be occurring on Cherry Creek in the reach closest to the Cherry Creek Reservoir because the observed average PO4 concentration at CC-10 increased by factors of 1.2 and 1.9 when compared to the observed data at Reaches 270 and 260, respectively. Average PO4 concentration in the alluvium at Reach 280 (MW-9) also increased by factors of 2.3 and 2.9 when compared to observed alluvium data at Reach 270 (MW-8) and Reach 260 (MW-7), respectively. The overland refractory nitrogen and carbon that are associated with the BOD from the land were reduced from what is typically used to ensure that the TKN component of nitrogen (and, therefore, the total nitrogen) and organic carbon were simulated accurately.

4.5 WATER QUALITY CALIBRATION RESULTS

The most downstream gages contributing to the Cherry Creek Reservoir include CC-10 and CT-2. Examples of results (e.g., concentration duration curves, monthly average boxplots, flow scatter plots, and time-series plots) from CC-10 for sediment are shown in Figures 4-6 through 4-8. For these figures, the observed data are depicted in blue and the model simulations are shown in red. In the concentration duration curves, each observed sample is represented by a blue circle; the paired simulated values from the same dates are used for the red squares. The x-axis of the duration plots are weighted to show a very small percentage of concentrations equaled or exceeded ateach end of the x-axis for accuracy in the calibration process; however, these concentrations are likely data outliers and do not make up the average condition at the calibration location. Concentration duration curves and monthly average boxplots only show the model simulation results when observed data were available, while the time series show the entire model simulation period. The remainder of the results for these locations are included in Appendix B, and Appendix C has water quality calibration figures for Cherry Creek near Parker and Cherry Creek near Franktown.

For the suspended solids plots at CC-10, large differences occur twice above 400 mg/L (less than 1 percent of the time). Similarly, at CT-2, large differences occur three times above 200 mg/L (less than 2 percent of the time). These differences are likely caused by bank erosion during the flashy flows; however, similar events occur at these locations without the spikes in suspended sediment. Therefore, the model is calibrated to the typical expected concentrations during the events for sediment and all other parameters. Parameters and locations where the observed data shifts over time include ammonia and nitrate/nitrite in Cottonwood Creek at CT-2, nitrate/nitrite in Cherry Creek at CC-10, and total phosphorus in Cottonwood Creek at CT-2. Shifts are apparent in time-series calibration plots. These shifts can occur because of water-treatment improvements and best management practices implementation. When a shift occurs in observed concentrations over time, the model is calibrated to the most recent condition. The goal of the temperature and dissolved oxygen calibration was to simulate the range of temperatures occurring in the stream. Reach bed heat can be overstimulated occasionally causing higher than observed simulated water temperature. At an altitude of 5000 ft at 32 degrees Fahrenheit, 100 percent oxygen saturation is approximately 12 mg/L, and at the median temperature of 60 degrees Fahrenheit, 100 percent oxygen saturation is approximately 8 mg/L. Therefore, the observed values in the summer above 8 mg/L indicate super-saturated conditions and may be erroneous.

4.6 SOURCE ALLOCATION/MODEL SENSITIVITY

Total phosphorus, total nitrogen, and total suspended solids pollutant loads generated from land surfaces as well as alluvium, point sources, and septic systems were summarized by source and by modeled subwatershed. Figures 4-9 through 4-11 show total phosphorus, total nitrogen, and total suspended solids loads by subwatershed, respectively. These maps also show major sources such as wastewater facilities and can help pinpoint the best locations for PRFs in the watershed. Figures 4-12 through 4-14 show the show total phosphorus, total nitrogen, and total suspended solids loads overall by source in the project area, respectively. These pie charts will help to understand the land types that will be most sensitive to PRFs to improve the source of nutrients to Cherry Creek. The figures also give an understanding of what areas in the model would be the most sensitive for calibration adjustments at the outlets to the Cherry Creek Reservoir Model.

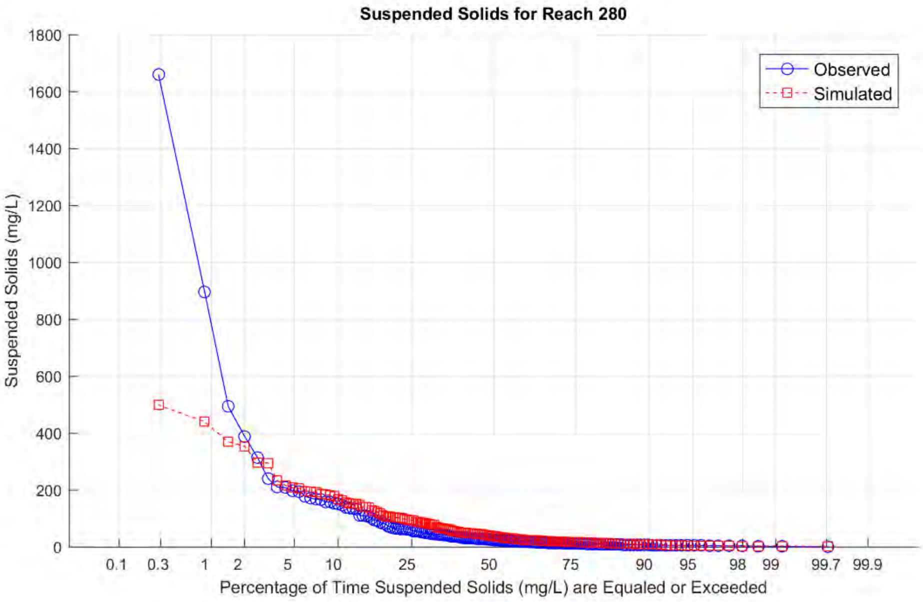


Figure 4-6. Sediment Concentration Duration Calibration Plot at CC-10.

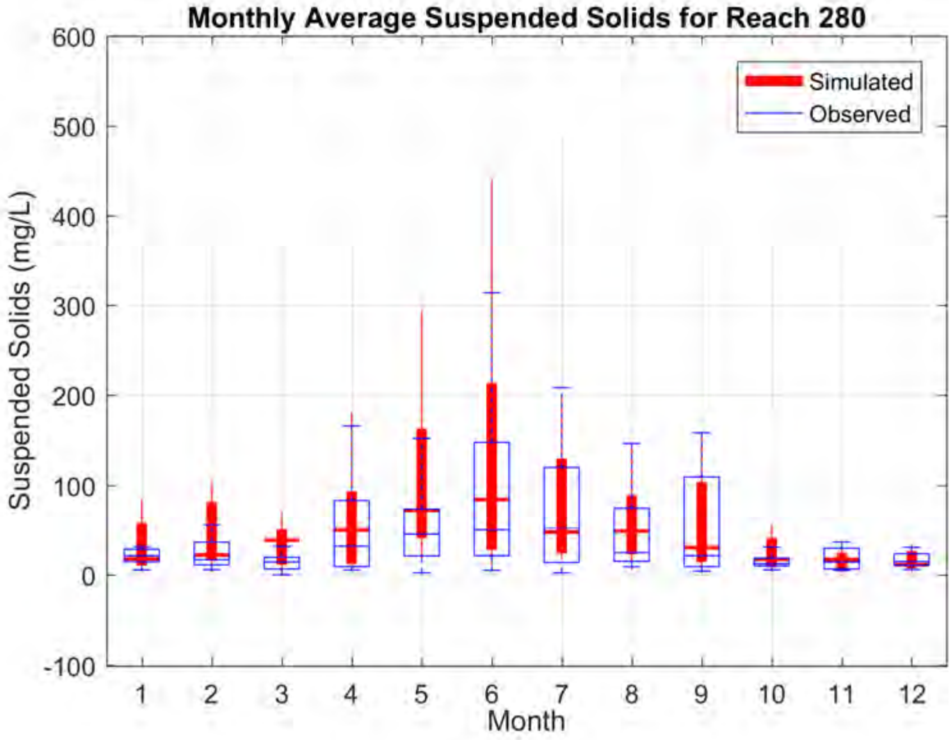


Figure 4-7. Sediment Monthly Average Calibration Boxplots at CC-10 (Outliers Removed).

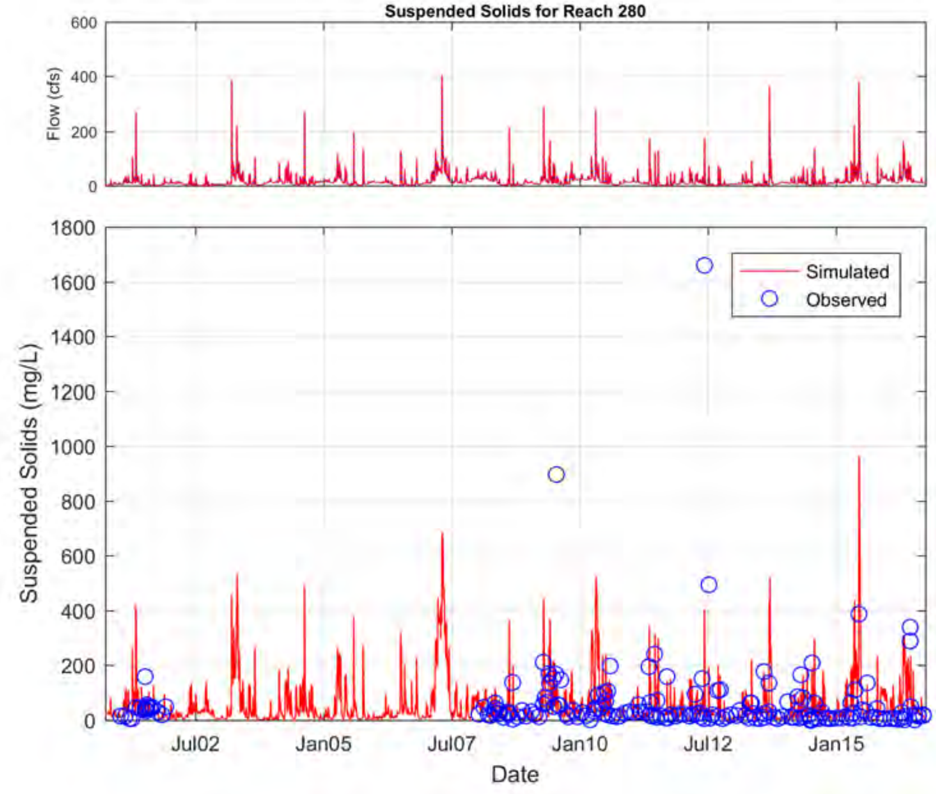


Figure 4-8. Sediment Time-Series Calibration Plot at CC-10.

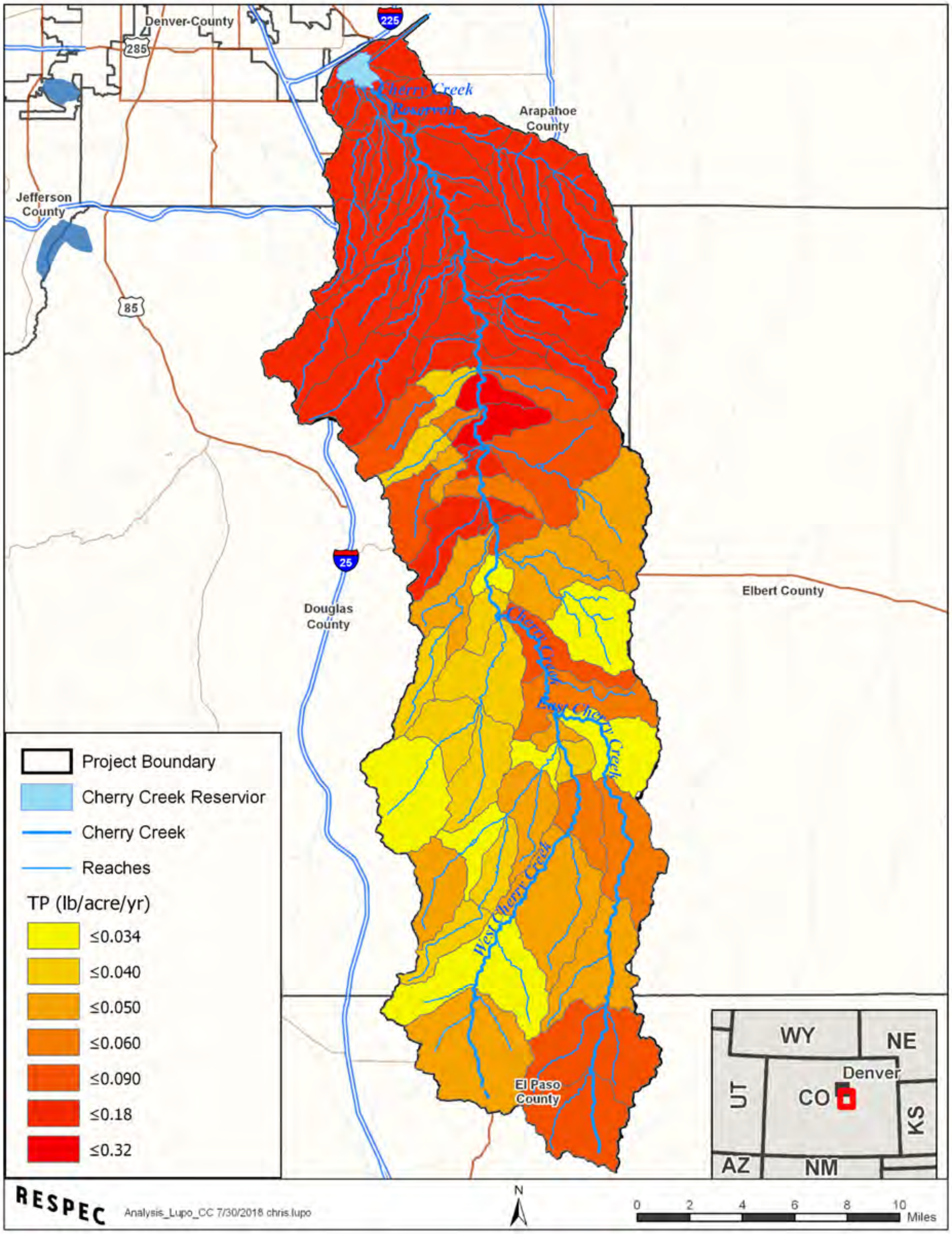


Figure 4-9. Average Simulated Total Phosphorus Loading Rates by Subwatershed.

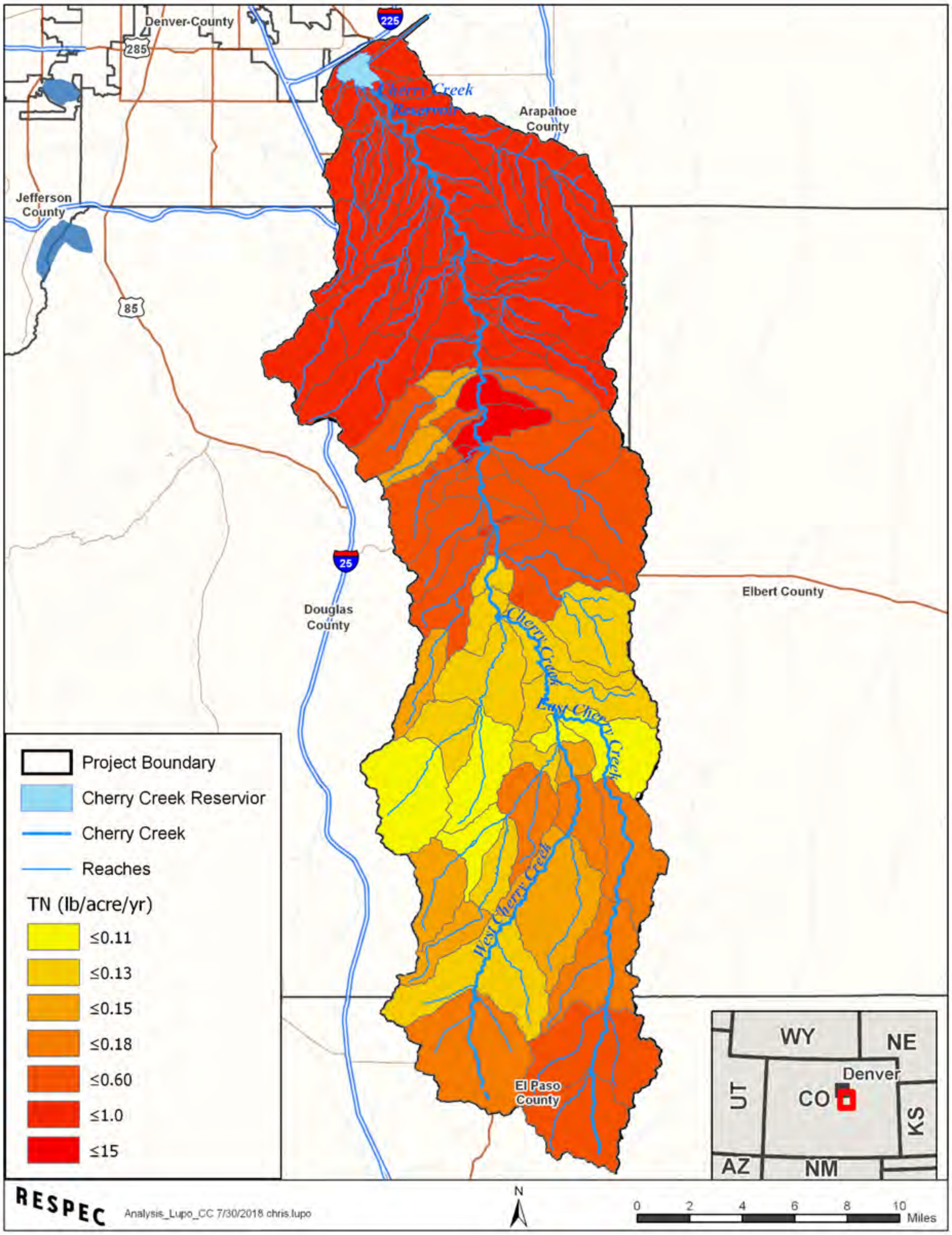


Figure 4-10. Average Simulated Total Nitrogen Loading Rates by Subwatershed.

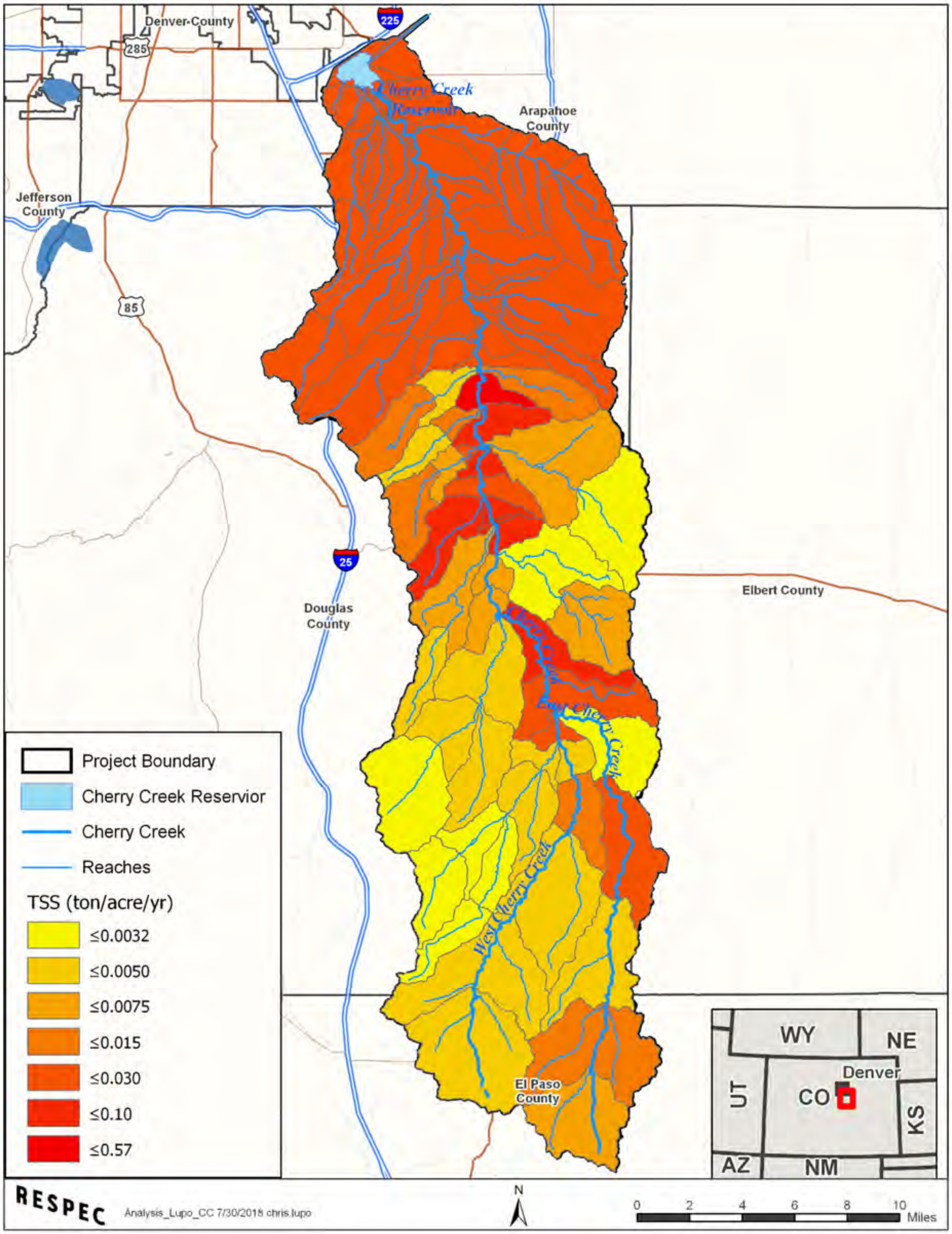


Figure 4-11. Average Simulated Total Suspended Solids Loading Rates by Subwatershed.

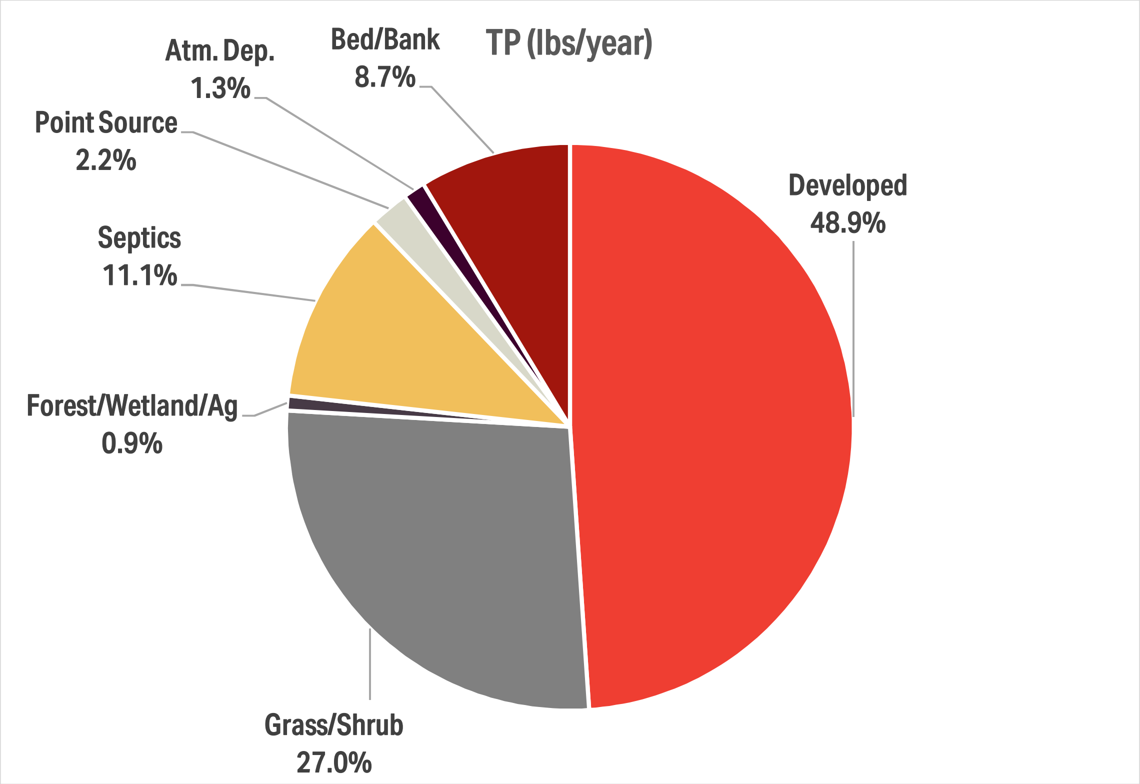


Figure 4-12. Percent Phosphorus Load Contribution From the Calibrated HSPF Model Application.

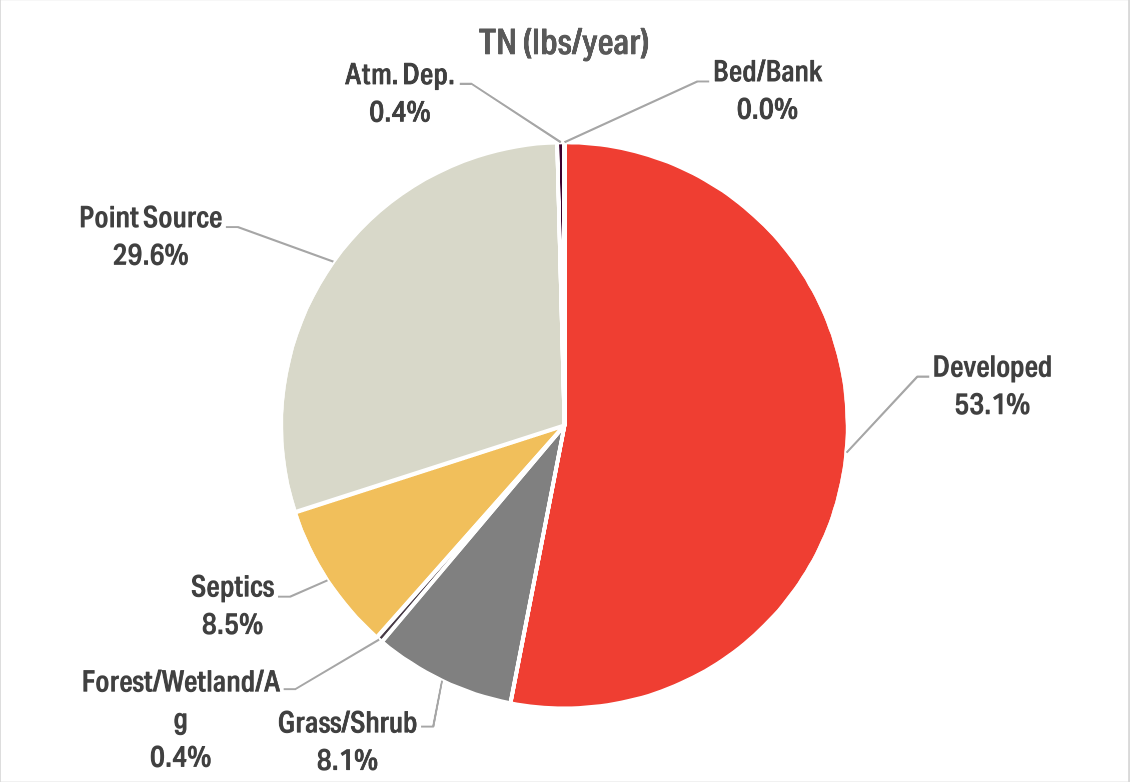


Figure 4-13. Percent Nitrogen Load Contribution From the Calibrated HSPF Model Application.

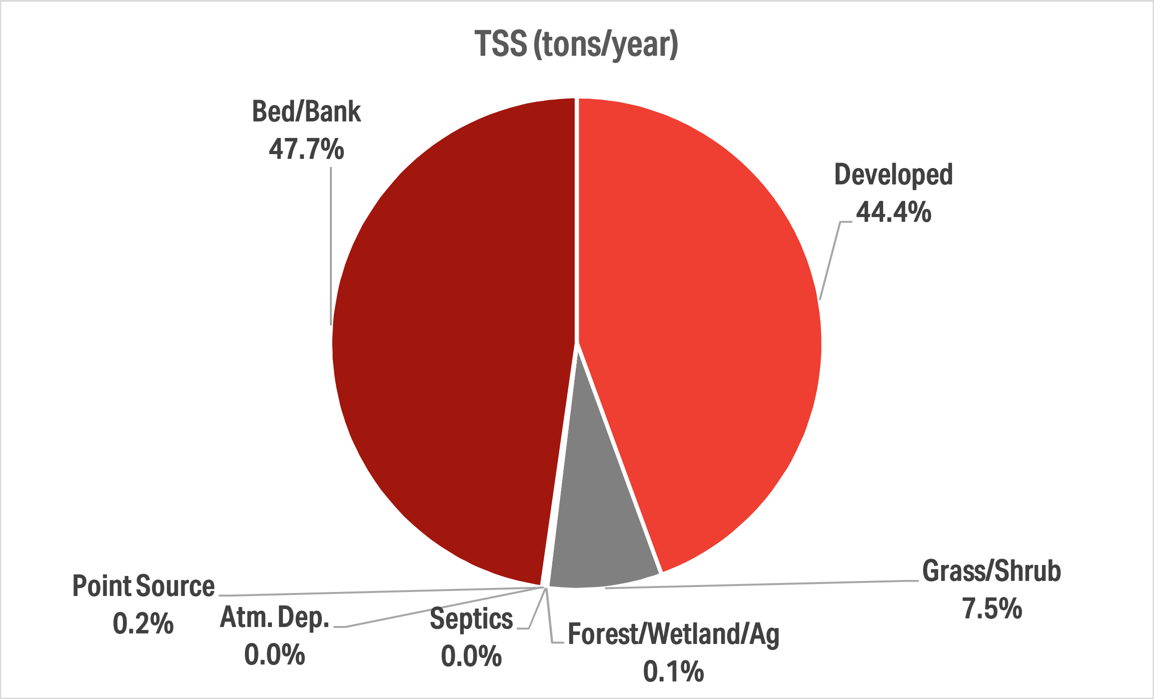
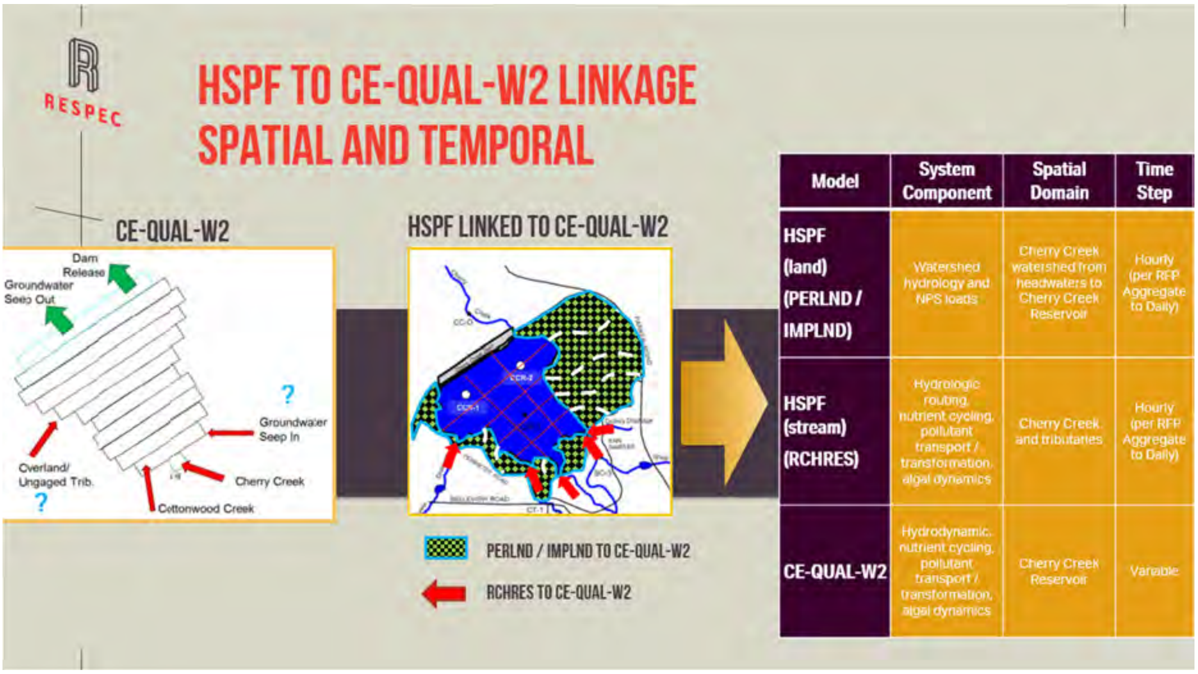


Figure 4-14. Percent Total Suspended Solids Load Contribution From the Calibrated HSPF Model Application.

5.0 HSPF TO CE-QUAL-W2 LINKAGE

The major goal of the watershed model is to predict appropriate watershed inputs and loads to streams and predict the fate and transport of the key constituents (such as nutrients) as they travel downstream through the Cherry Creek, tributaries to Cherry Creek through alluvial groundwater flows, and into Cherry Creek Reservoir.

The loading to the reservoir occurs through multiple tributaries and local adjacent drainage to the reservoir. To accurately model the loadings, the surface grid of the reservoir model was obtained, and the time series of flow and water quality constituent to each grid cell were identified. A schematic of the HSPF to CE-QUAL-W2 linkage has been presented in Figure 5-1. The constituents modeled with HSPF that are needed for CE-QUAL-W2 include total phosphorus, orthophosphate, total nitrogen, ammonia, nitrate+nitrite, total organic carbon, dissolved oxygen, temperature, and total suspended solids. The one constituent that was not modeled with HSPF but needed in CE-QUAL-W2 is dissolved organic carbon (DOC). Ratios of DOC and TOC were developed using observed data for the most downstream monitoring locations. For Cherry Creek (CC-10), the DOC:TOC was 0.879; for Cottonwood Creek (CT-2), which can be used to represent other local tributaries), the DOC:TOC was 0.826; and for the alluvium (MW-9), the DOC:TOC was 0.912. HSPF has the flexibility to output the modeling results in simple text formats or variety of alternative formats.



HSPF TO CE-QUAL-W2 LINKAGE
SPATIAL AND TEMPORAL

Model	System Component	Spatial Domain	Time Step
HSPF (land) (PERLND / IMPLND)	Watershed hydrology and NPS loads	Cherry Creek watershed from headwaters to Cherry Creek Reservoir	Hourly (per RFP Aggregate to Daily)
HSPF (stream) (RCHRES)	Hydrologic routing, nutrient cycling, pollutant transport / transformation, algal dynamics	Cherry Creek and tributaries	Hourly (per RFP Aggregate to Daily)
CE-QUAL-W2	Hydrodynamic, nutrient cycling, pollutant transport / transformation, algal dynamics	Cherry Creek Reservoir	Variable

Figure 5-1. Schematic of the HSPF to CE-QUAL-W2 Linkage.

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APPENDIX A

HYDROLOGY CALIBRATION RESULTS FOR CHERRY CREEK AT CHERRY CREEK RESERVOIR (CC-10 IN MODEL REACH 280) AND COTTONWOOD CREEK NEAR CHERRY CREEK RESERVOIR (CT-2 IN MODEL REACH 318)

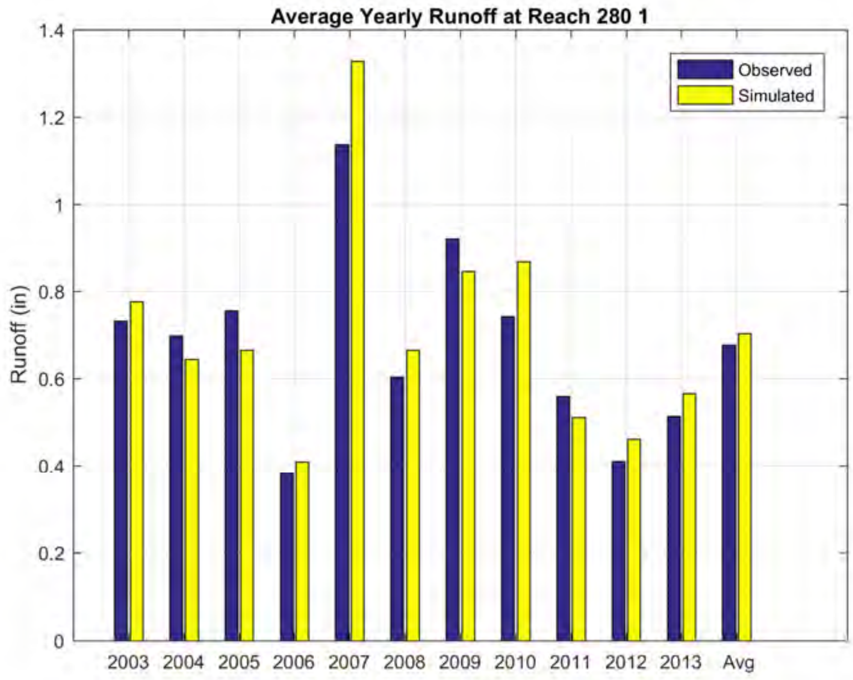
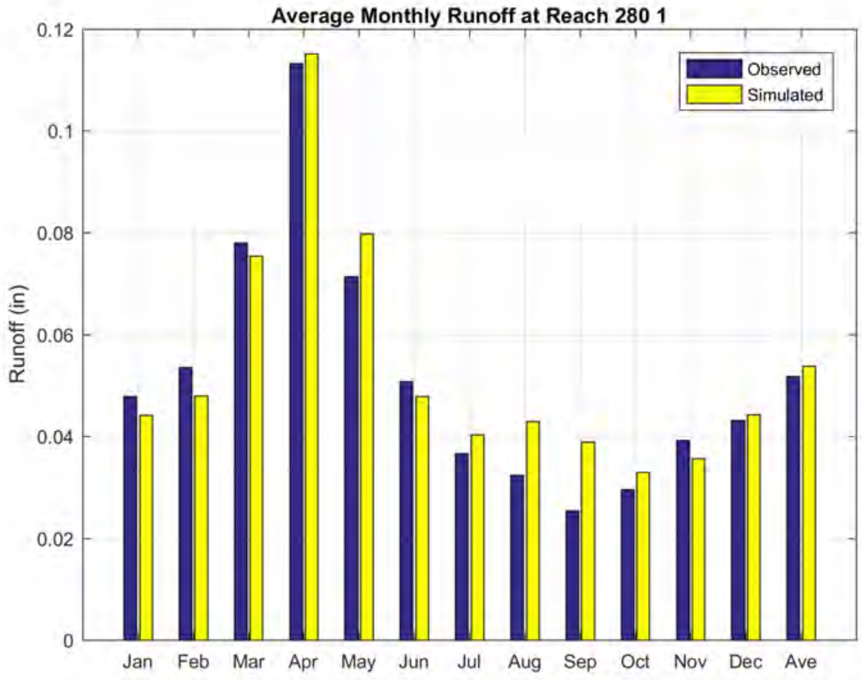


Figure A-1. Average Yearly Runoff at Reach 280 (CC-10).



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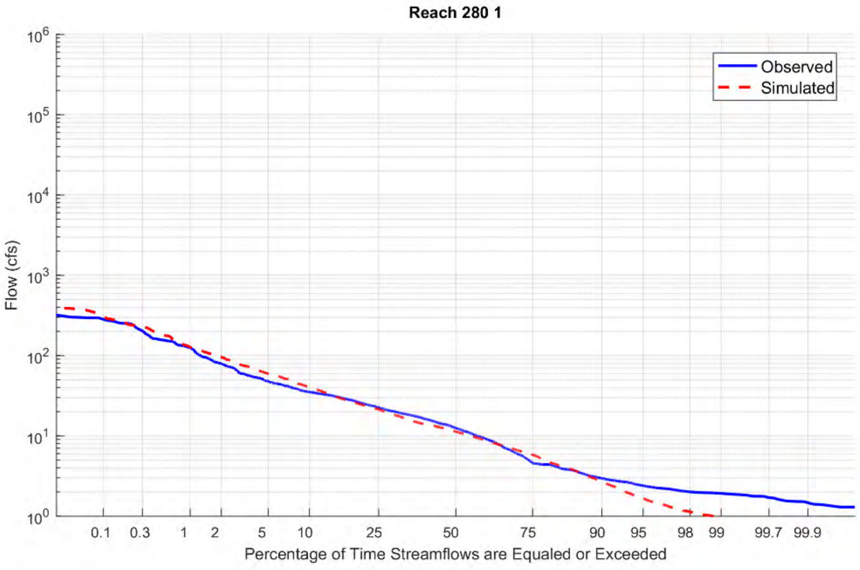


Figure A-3. Flow Duration Plot for Reach 280 (CC-10).

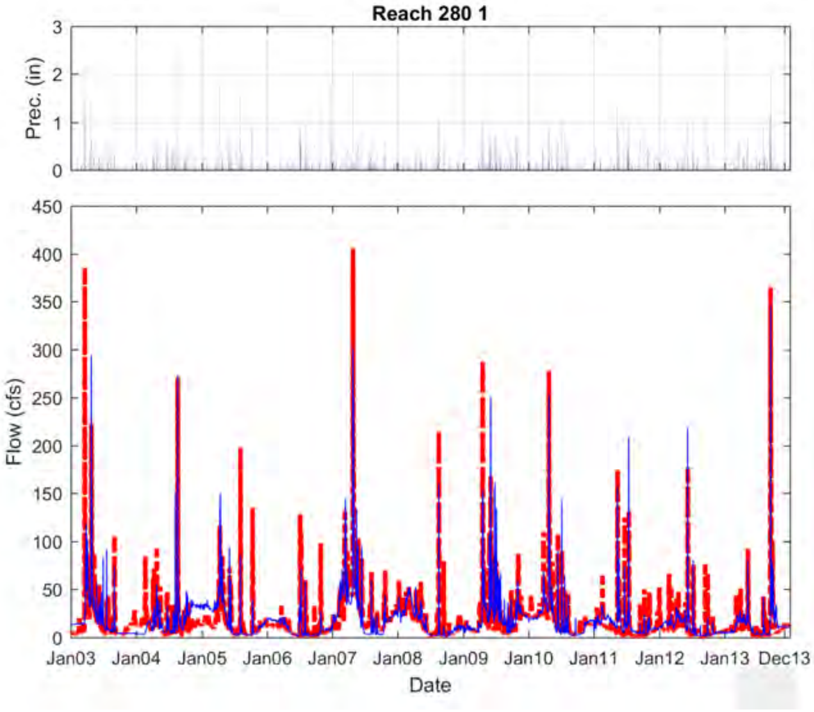


Figure A-4. Daily Hydrographs for Reach 280 (CC-10).

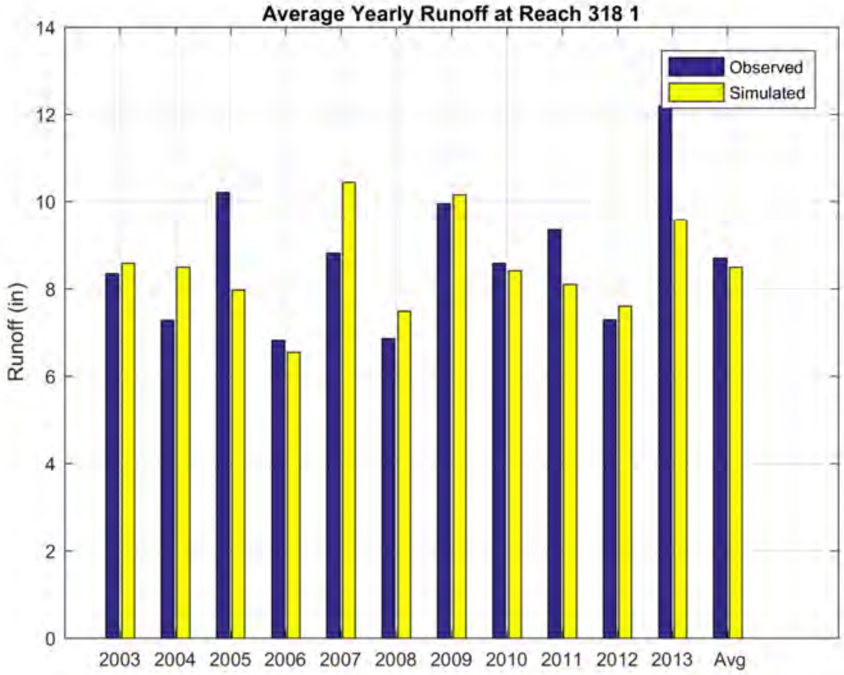
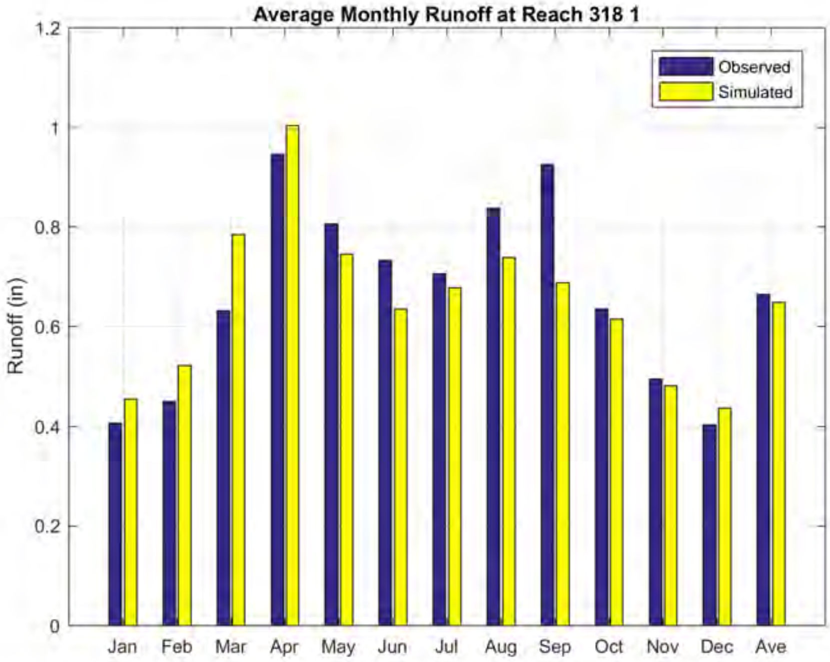


Figure A-5. Average Yearly Runoff at Reach 318 (CT-2).



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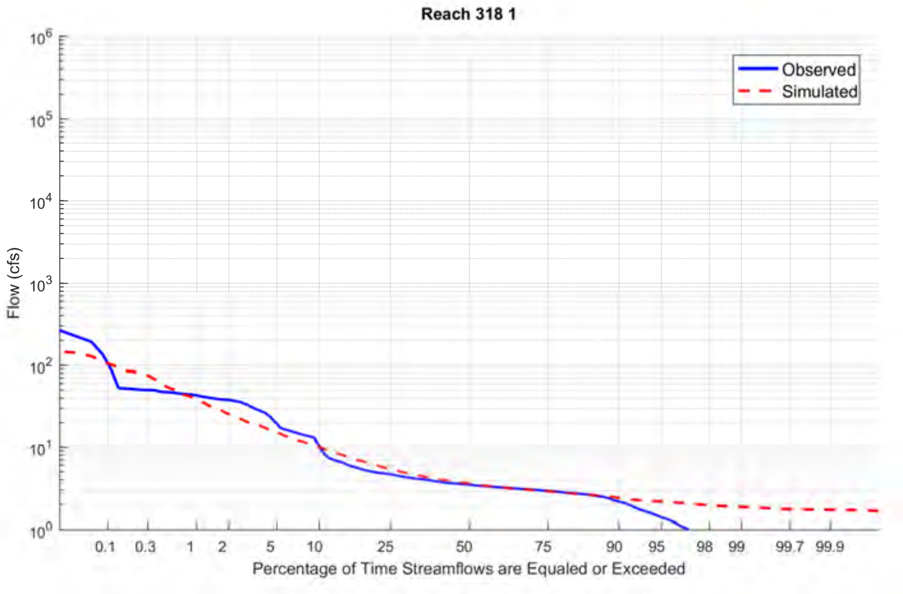


Figure A-7. Flow Duration Plot for Reach 318 (CT-2).

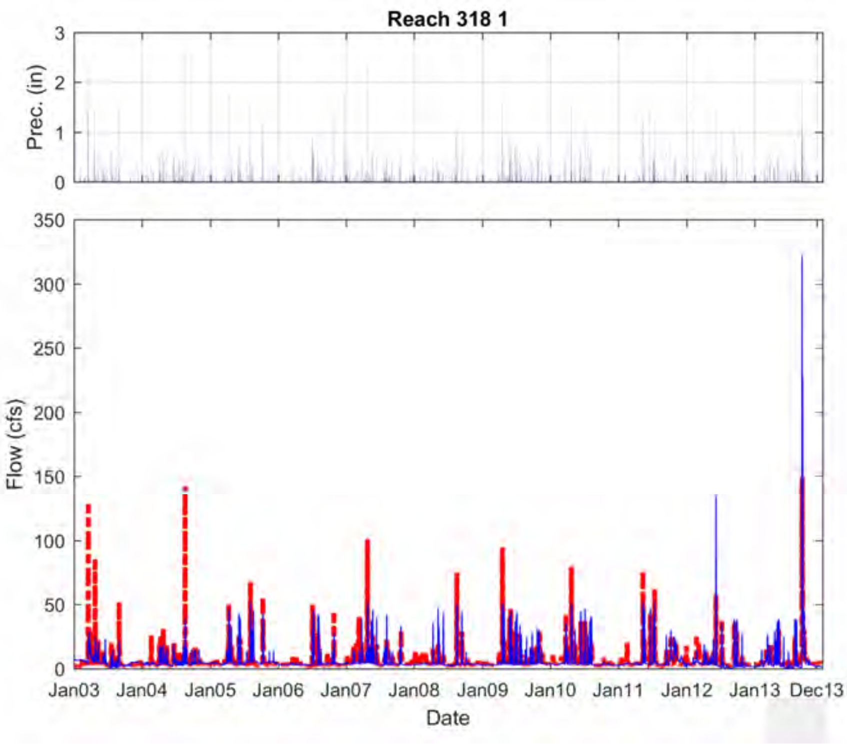


Figure A-8. Daily Hydrographs for Reach 318 (CT-2).

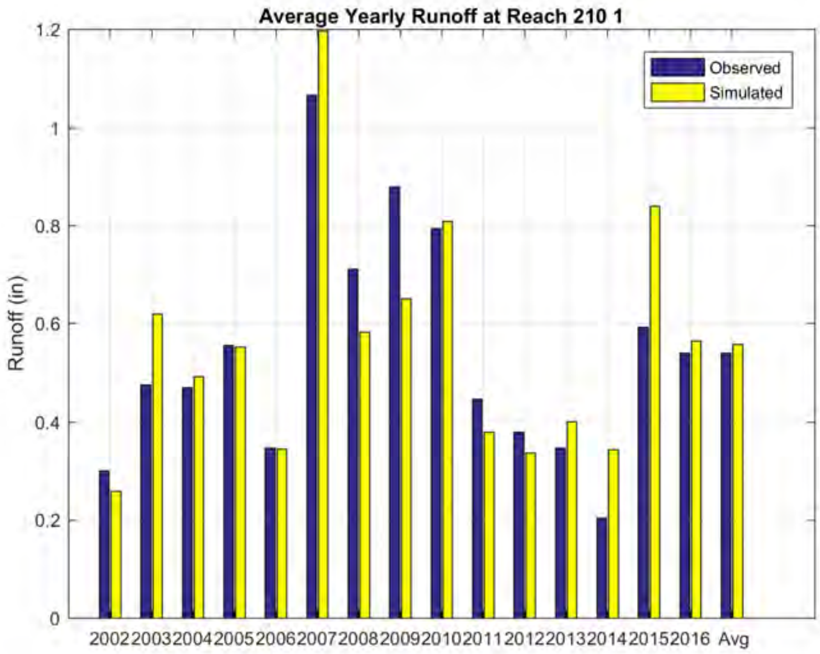


Figure A-9. Average Yearly Runoff at Reach 210 (USGS 393109104464500).

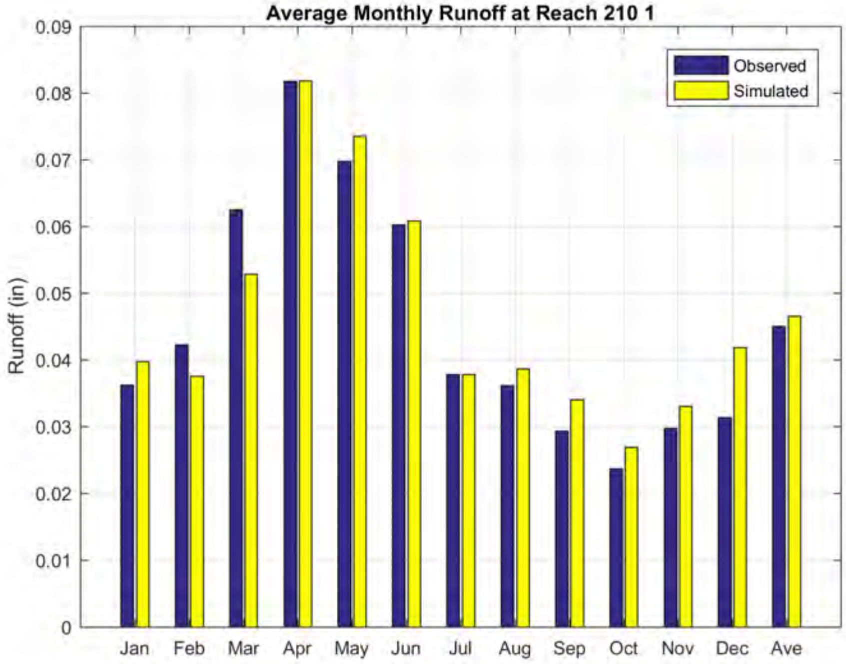


Figure A-10. Average Monthly Runoff at Reach 210 (USGS 393109104464500).

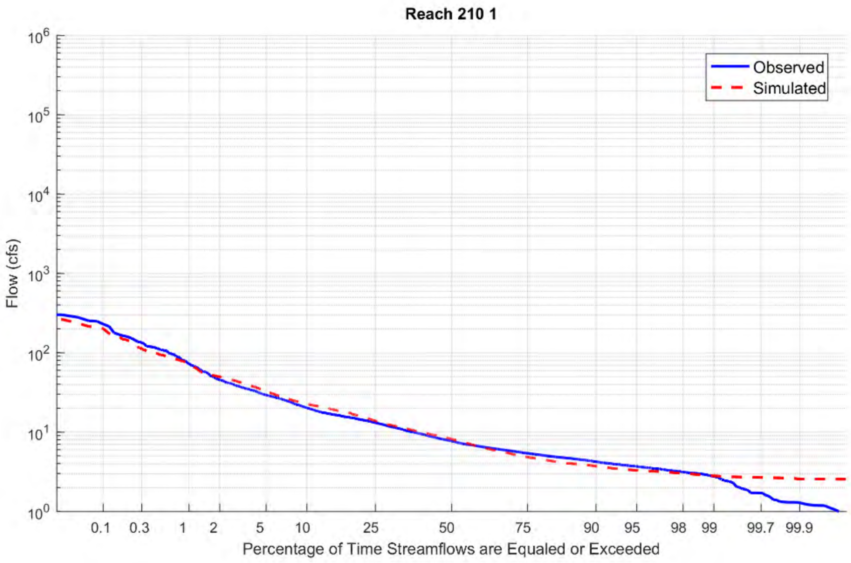


Figure A-11. Flow Duration Plot for Reach 210 (USGS 393109104464500).

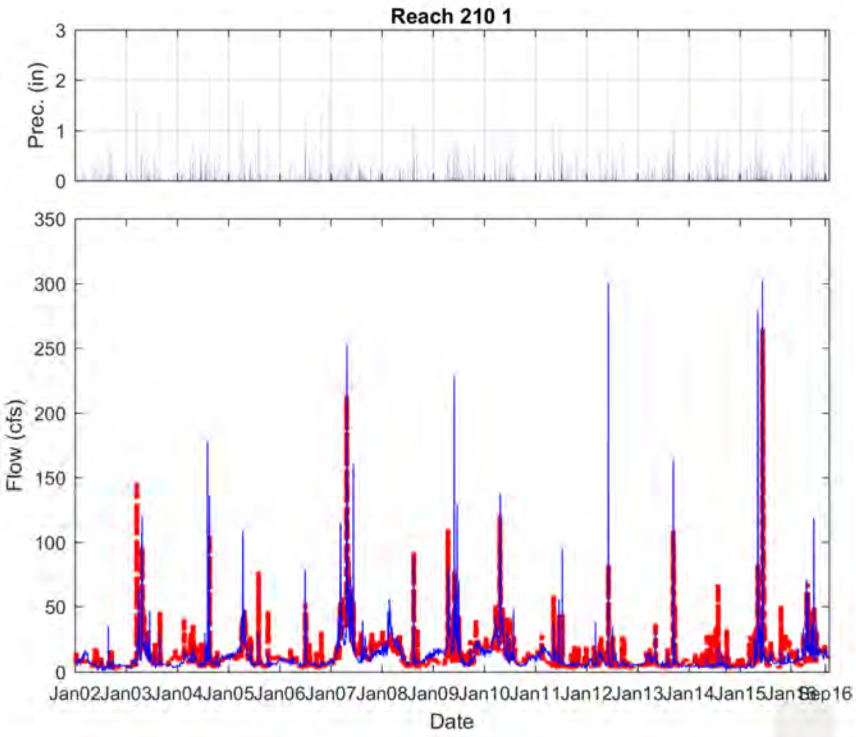


Figure A-12. Daily Hydrographs for Reach 210 (USGS 393109104464500).

APPENDIX B

WATER QUALITY CALIBRATION RESULTS FOR CHERRY CREEK AT CHERRY CREEK RESERVOIR (CC-10 IN MODEL REACH 280) AND COTTONWOOD CREEK NEAR CHERRY CREEK RESERVOIR (CT-2 IN MODEL REACH 318)

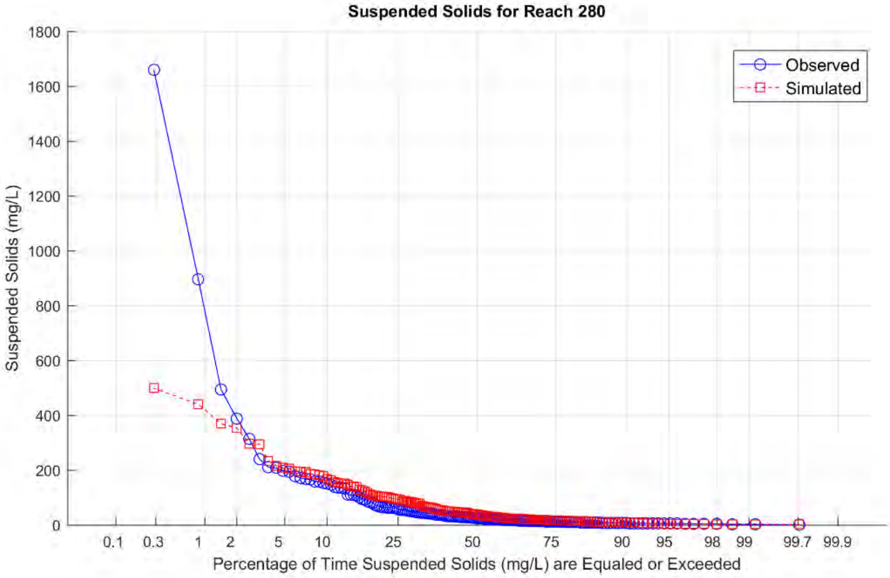


Figure B-1. Sediment Concentration Duration Calibration Plot at CC-10.

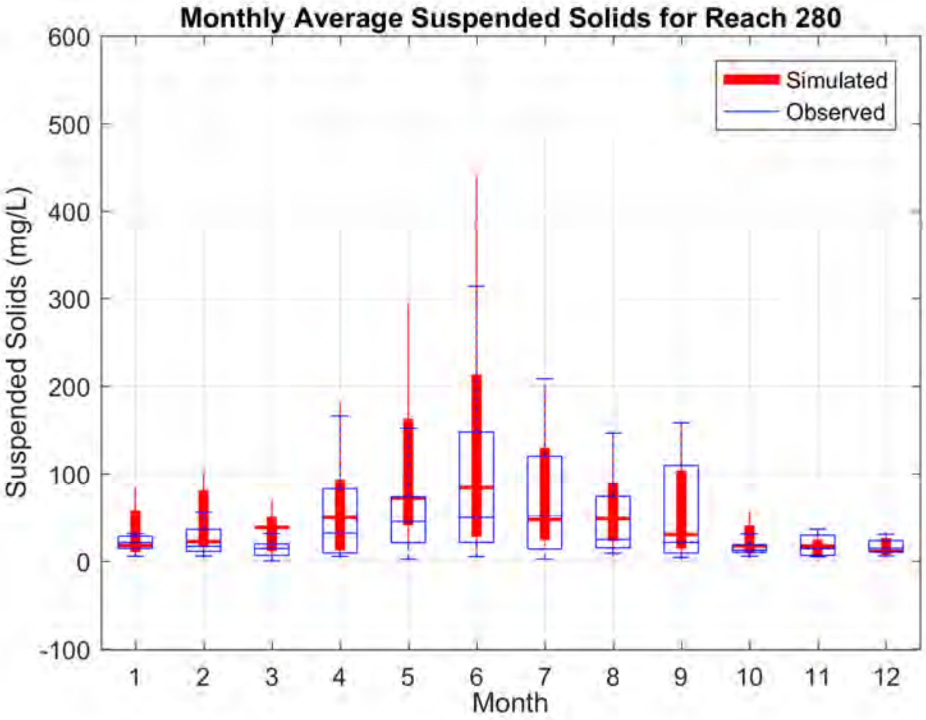


Figure B-2. Sediment Monthly Average Calibration Boxplots at CC-10 (Outliers Removed).

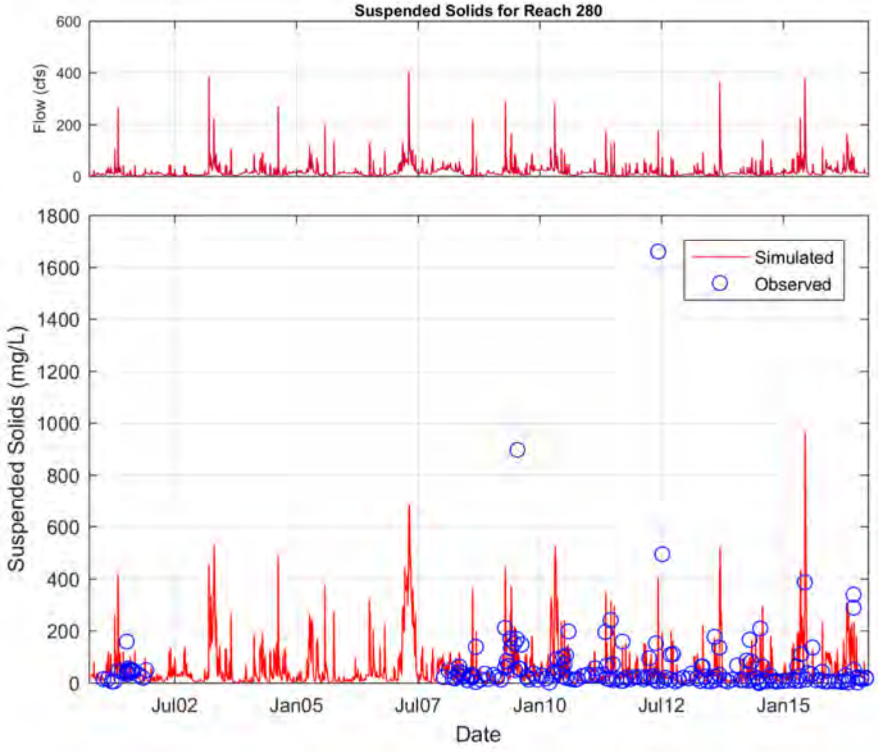


Figure B-3. Sediment Time-Series Calibration Plot at CC-10.

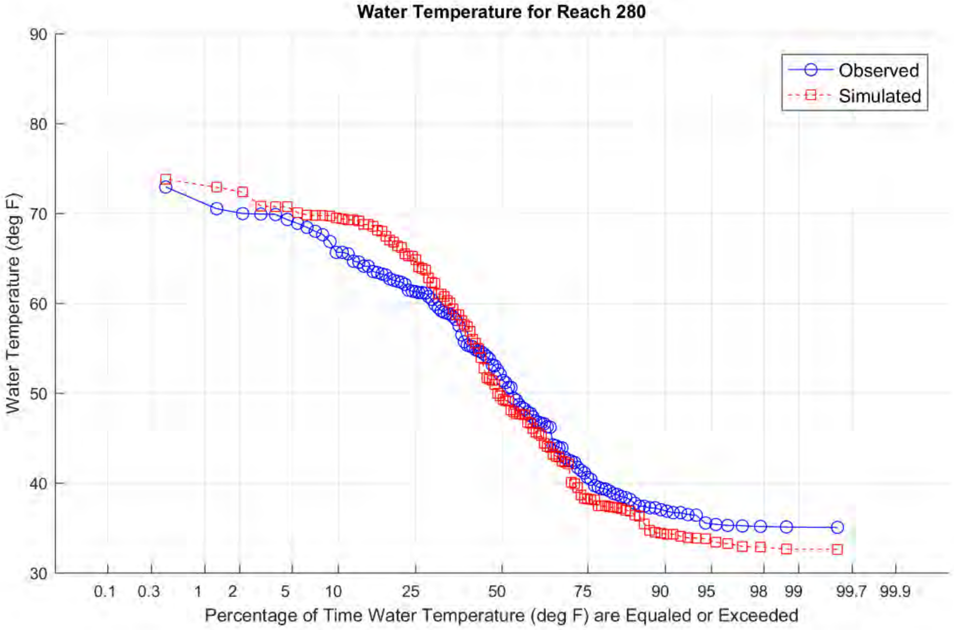


Figure B-4. Temperature Duration Calibration Plot at CC-10.

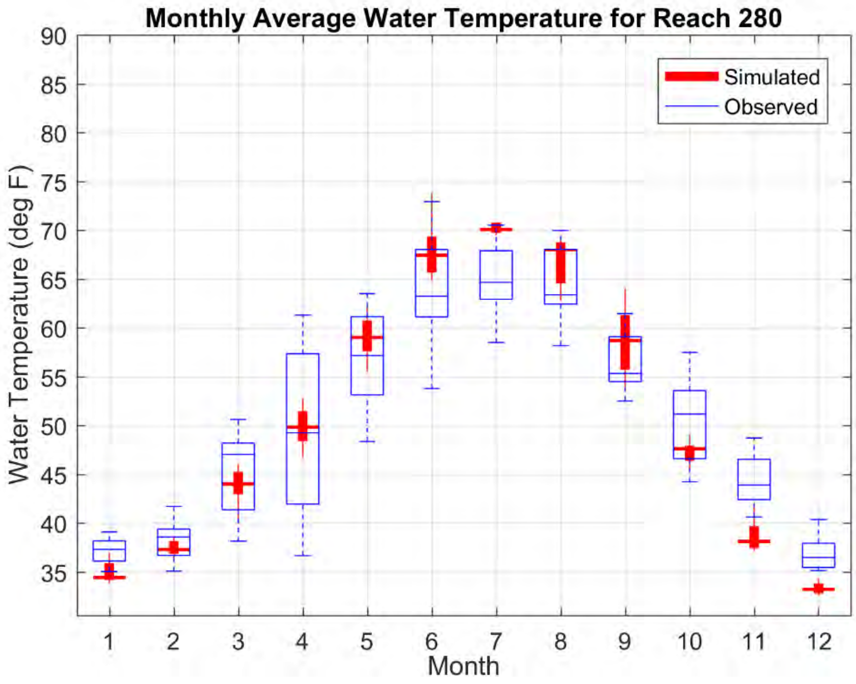


Figure B-5. Temperature Monthly Average Boxplots at CC-10 (Outliers Removed).

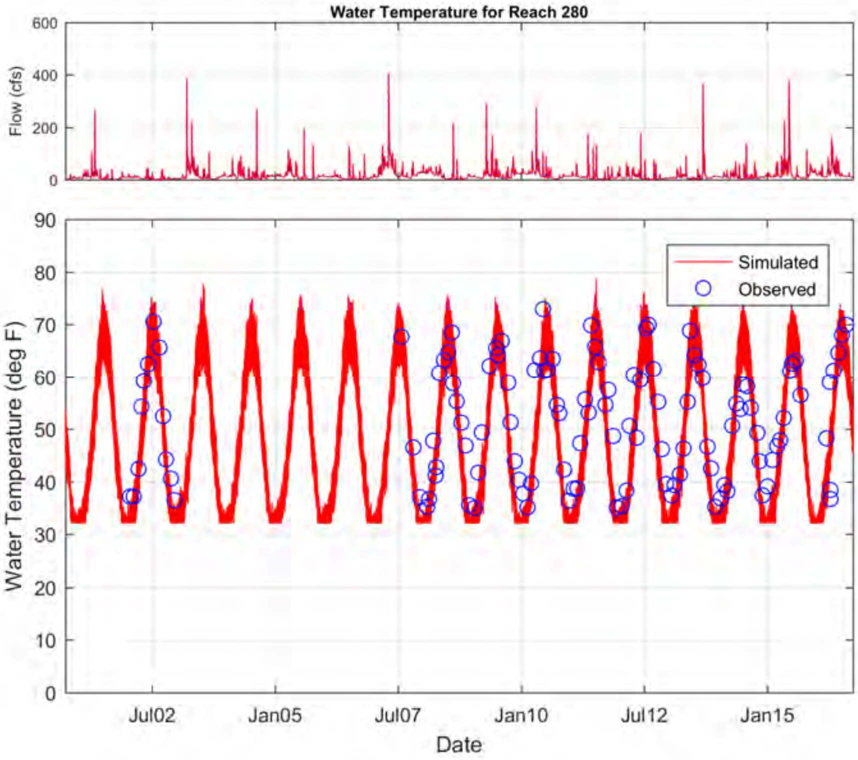


Figure B-6. Temperature Time-Series Calibration Plot at CC-10.

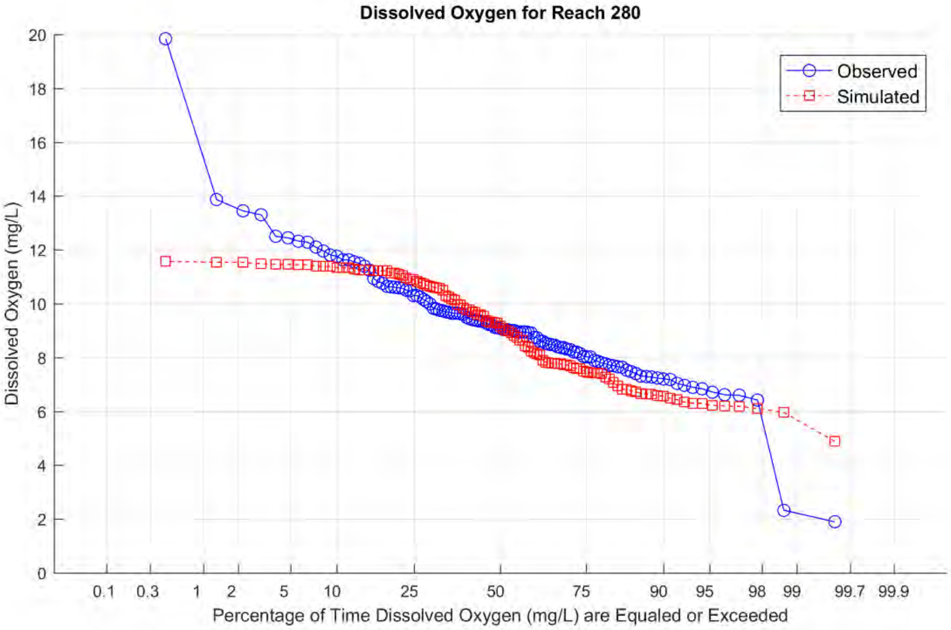


Figure B-7. Dissolved Oxygen Concentration Duration Calibration Plot at CC-10.

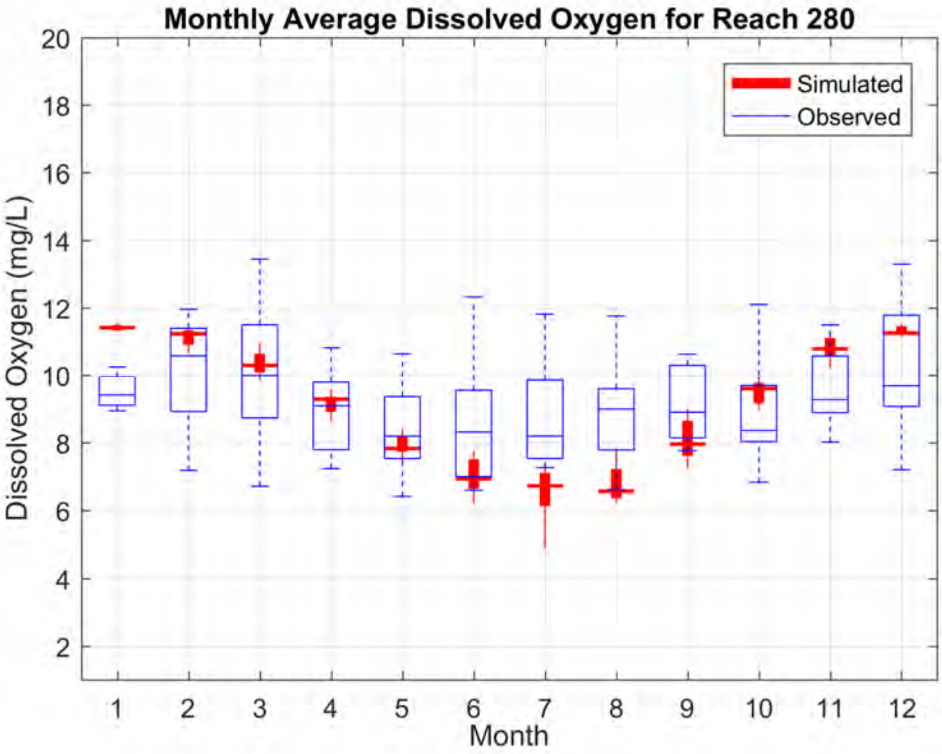


Figure B-8. Dissolved Oxygen Monthly Average Calibration Boxplots at CC-10 (Outliers Removed).

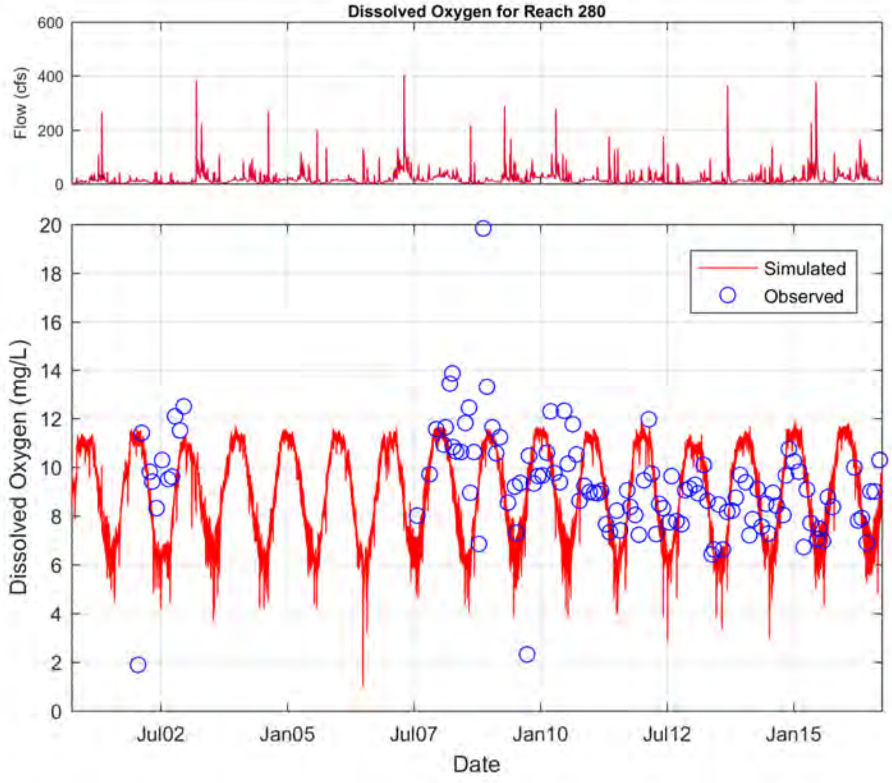


Figure B-9. Dissolved Oxygen Time-Series Calibration Plot at CC-10.

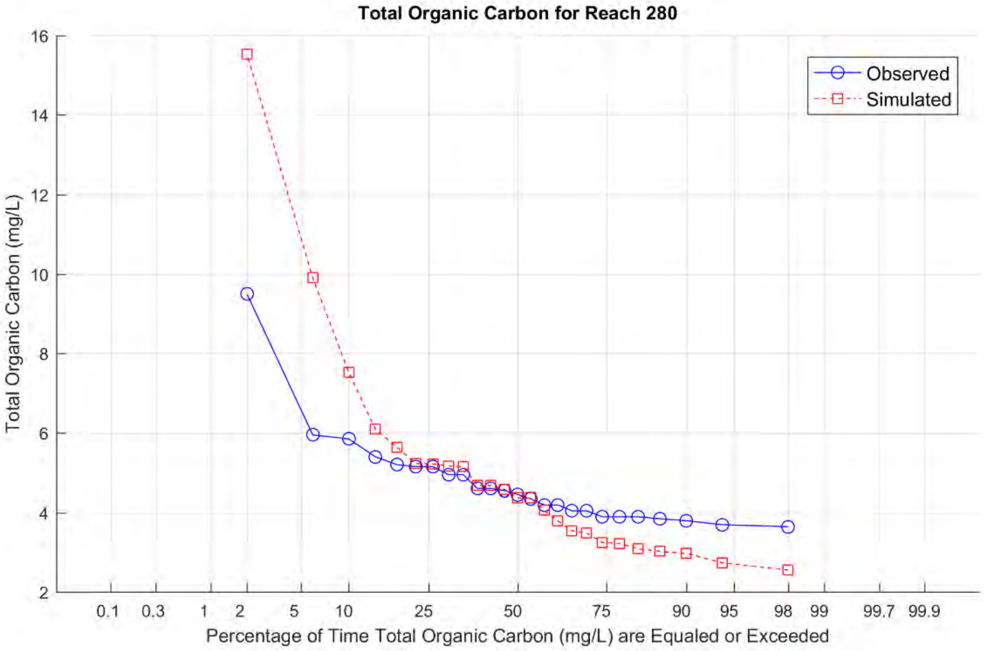


Figure B-10. Total Organic Carbon Concentration Duration Calibration Plot at CC-10.

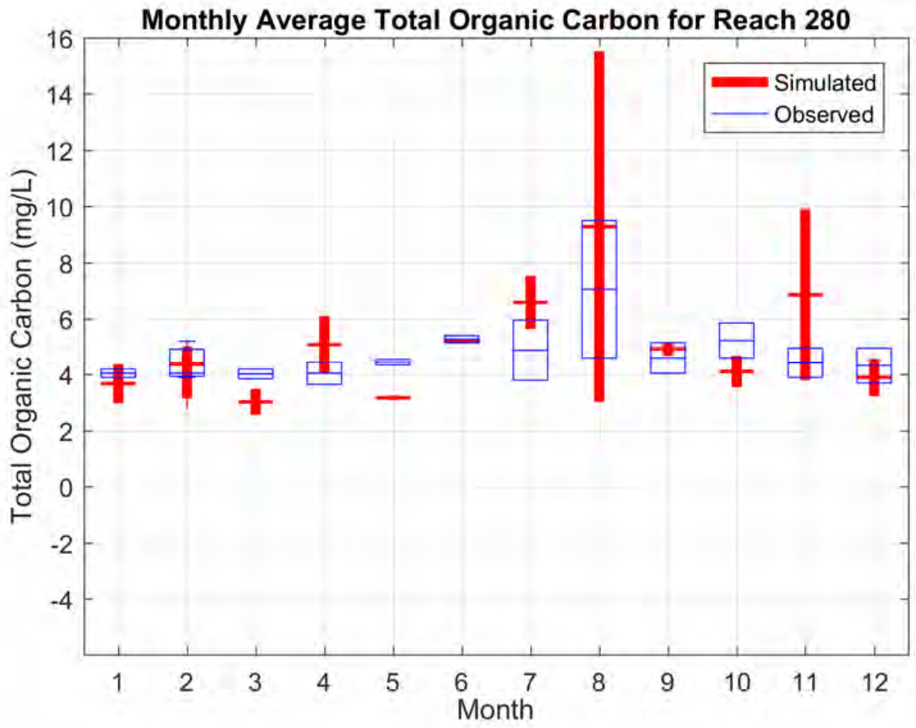
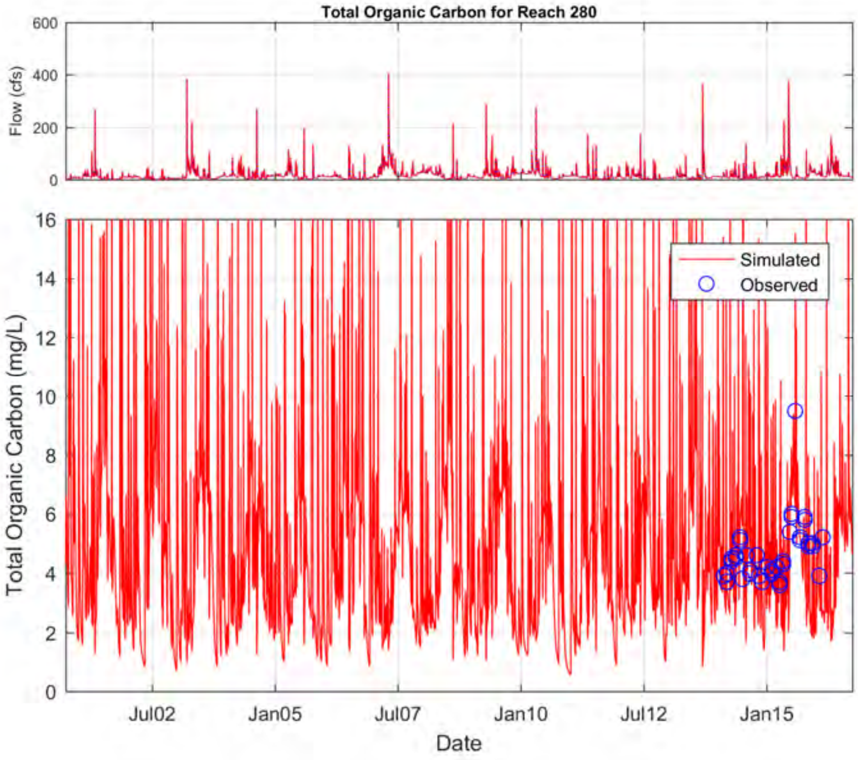


Figure B-11. Total Organic Carbon Monthly Average Calibration Boxplots at CC-10 (Outliers Removed).



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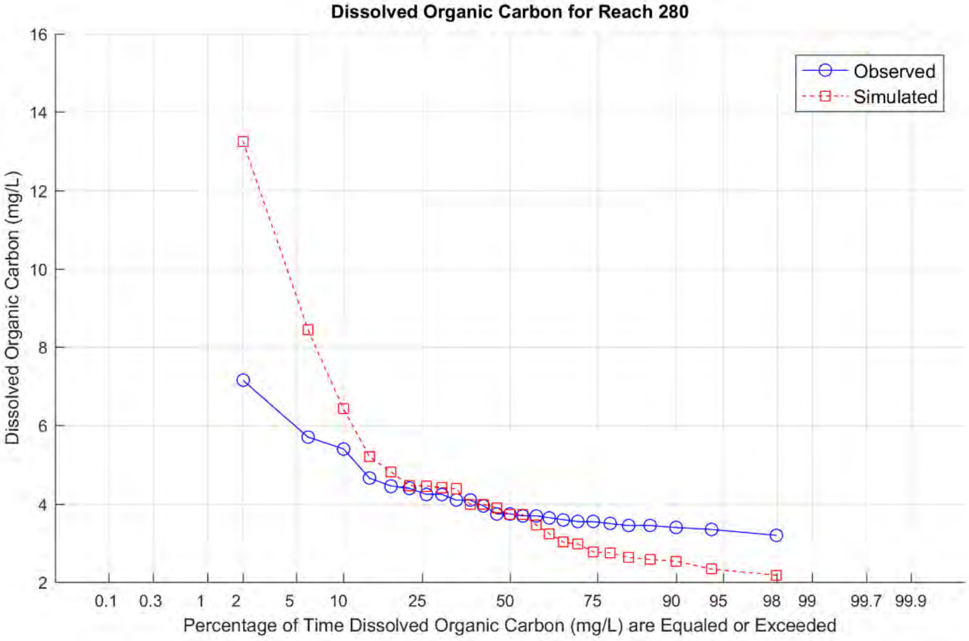

Figure B-13. Dissolved Organic Carbon Concentration Duration Calibration Plot at CC-10.

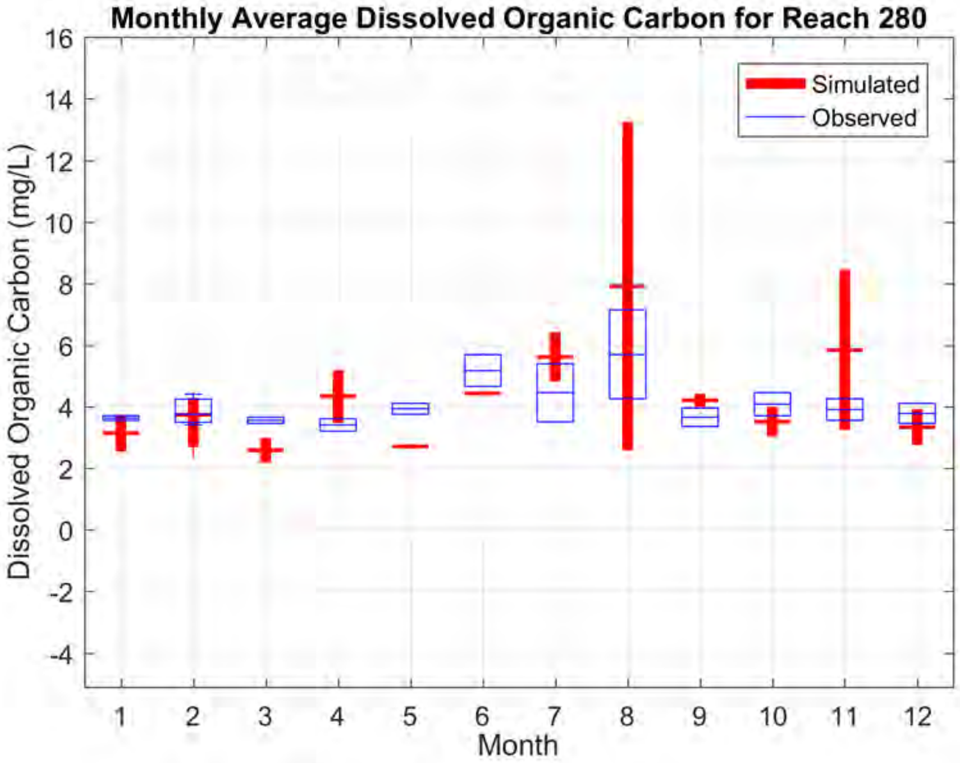

Figure B-14. Dissolved Organic Carbon Monthly Average Calibration Boxplots at CC-10 (Outliers Removed).

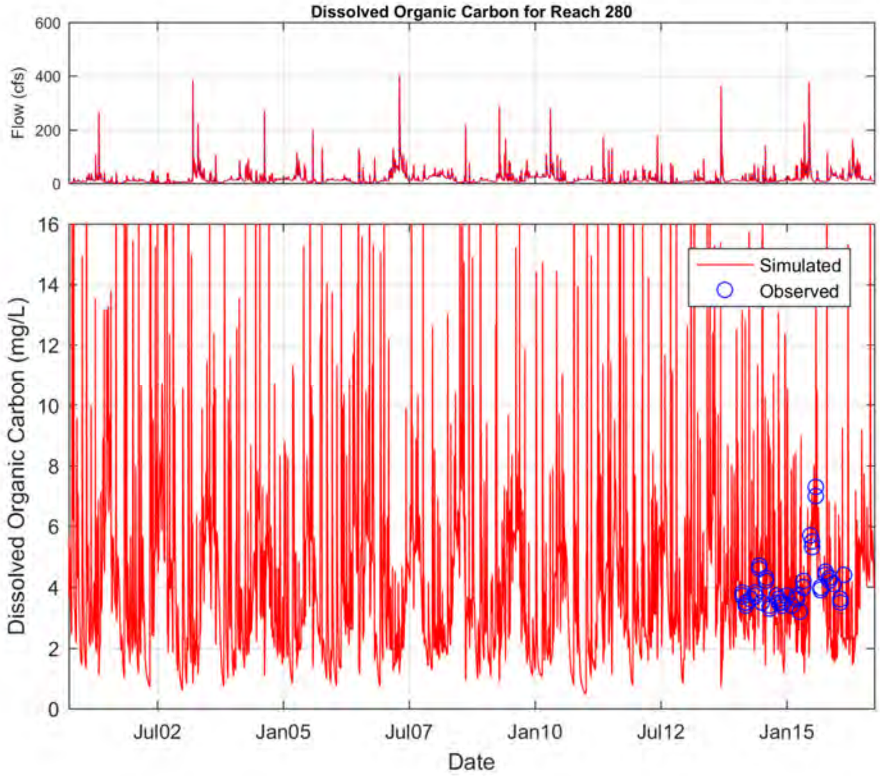

Figure B-15. Dissolved Organic Carbon Time-Series Calibration Plot at CC-10.

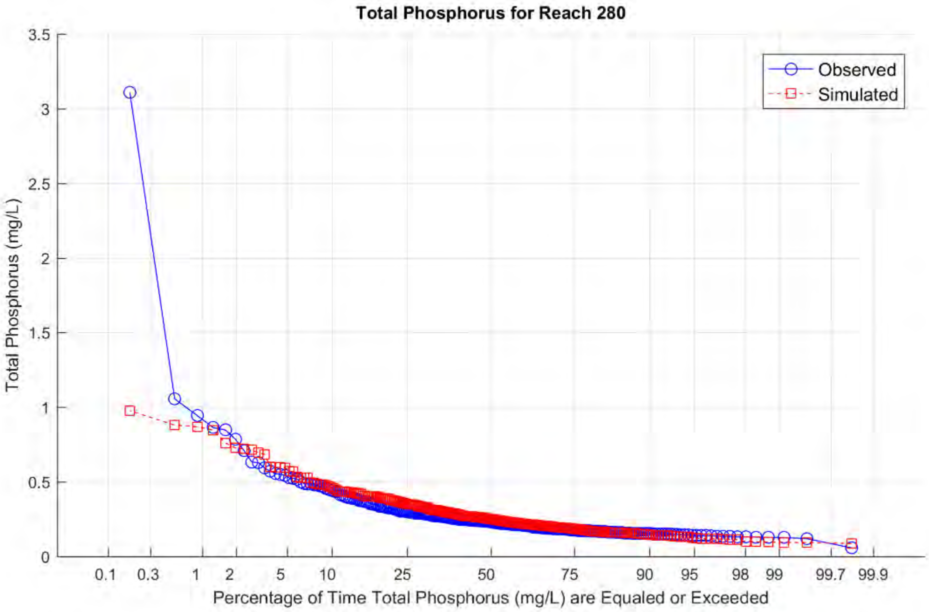

Figure B-16. Total Phosphorus Concentration Duration Calibration Plot at CC-10.

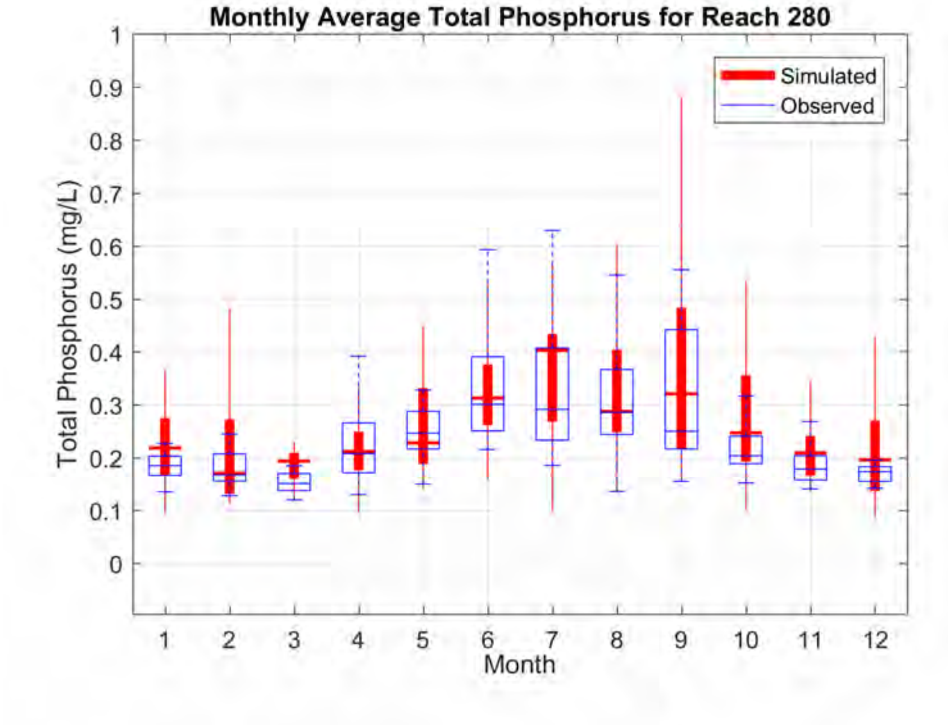

Figure B-17. Total Phosphorus Monthly Average Calibration Boxplots at CC-10 (Outliers Removed).

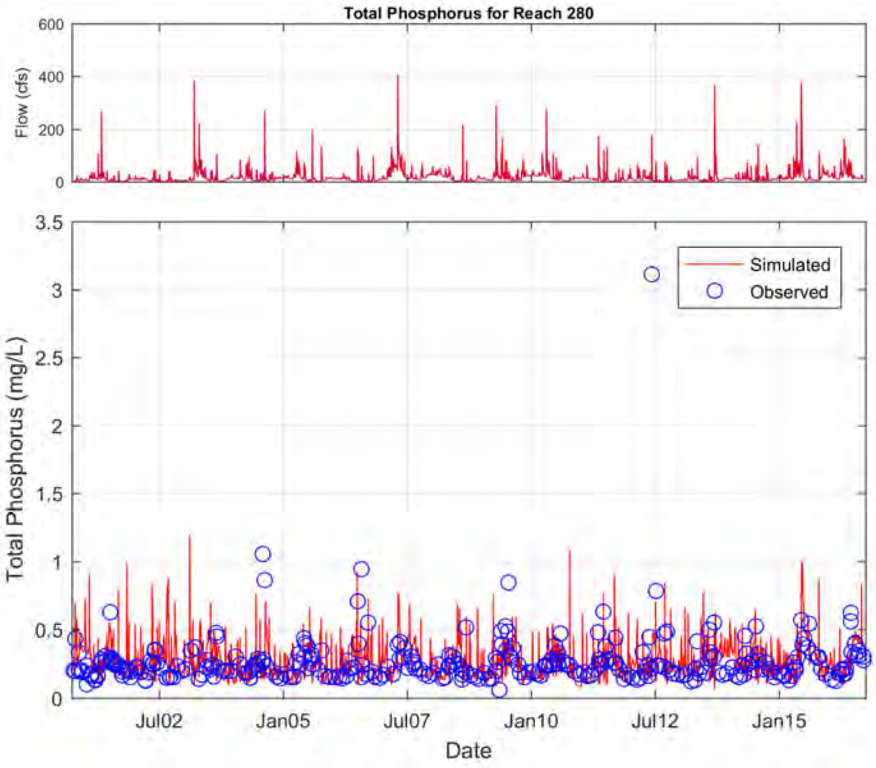

Figure B-18. Total Phosphorus Time-Series Calibration Plot at CC-10.

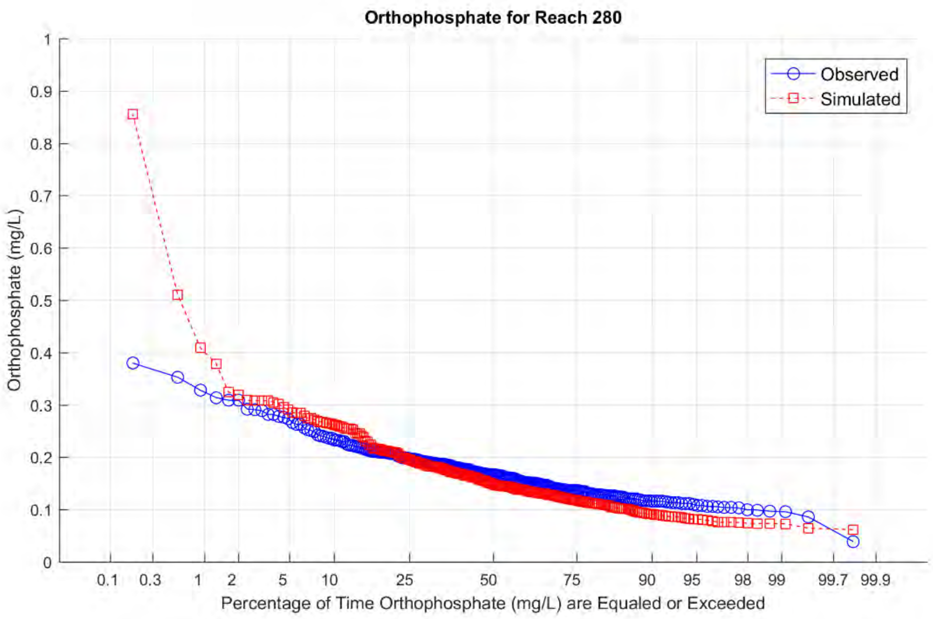

Figure B-19. Total Orthophosphate Concentration Duration Calibration Plot at CC-10.

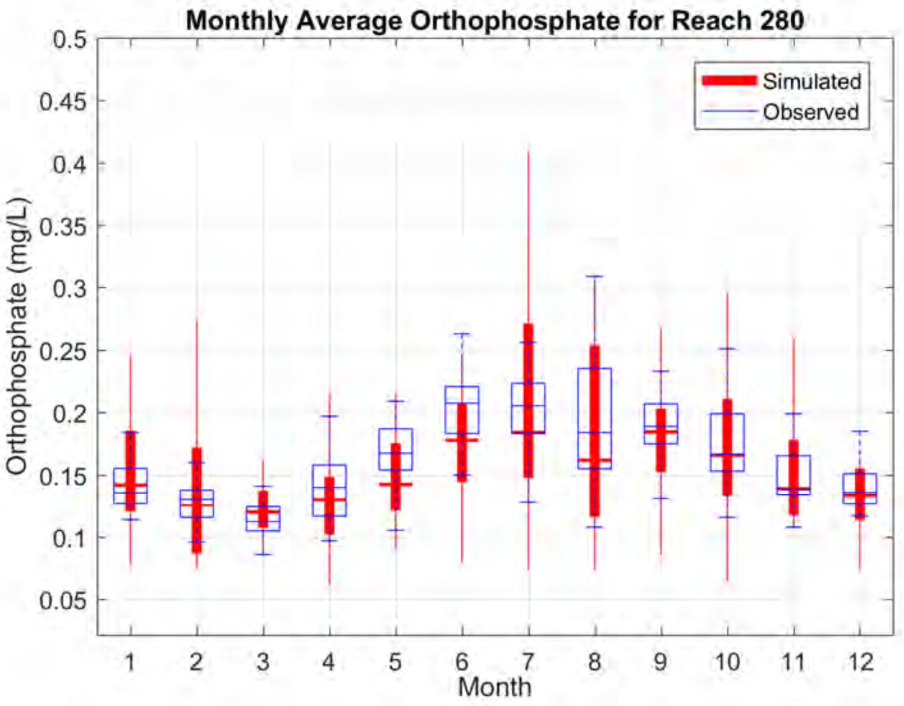

Figure B-20. Total Orthophosphate Monthly Average Calibration Boxplots at CC-10 (Outliers Removed).

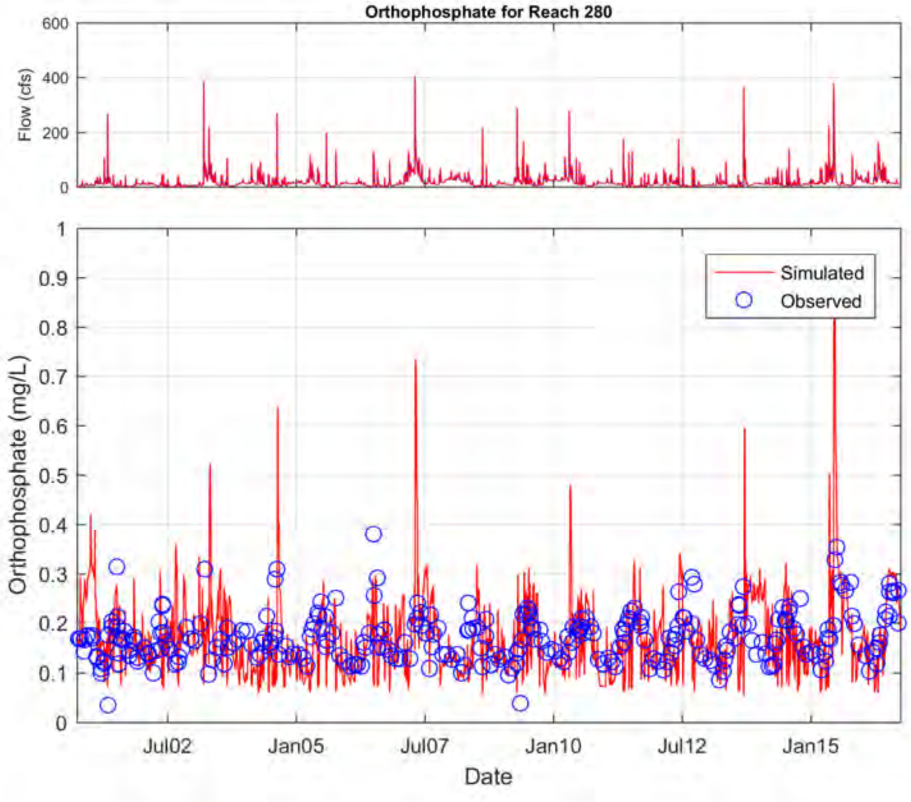

Figure B-21. Total Orthophosphate Time-Series Calibration Plot at CC-10.

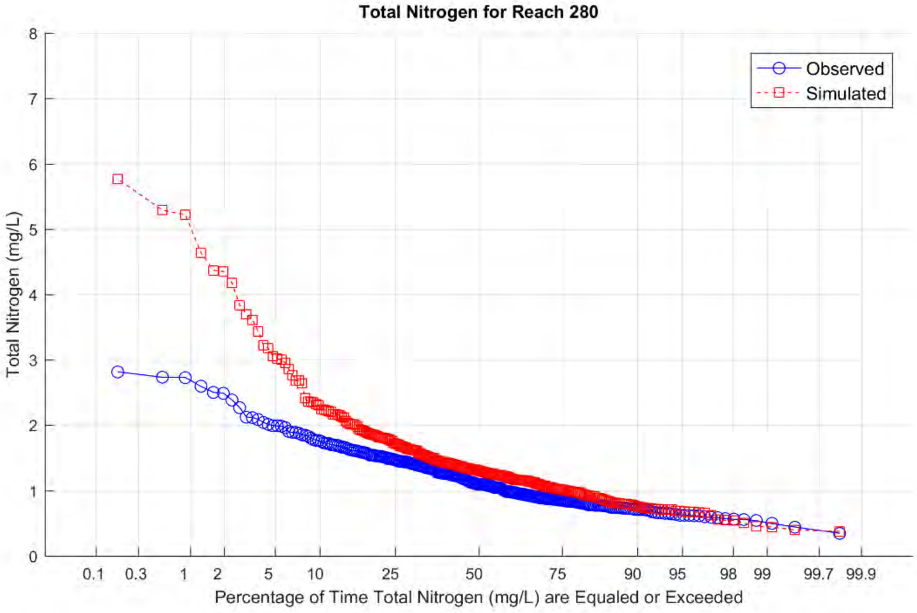

Figure B-22. Total Nitrogen Concentration Duration Calibration Plot at CC-10.

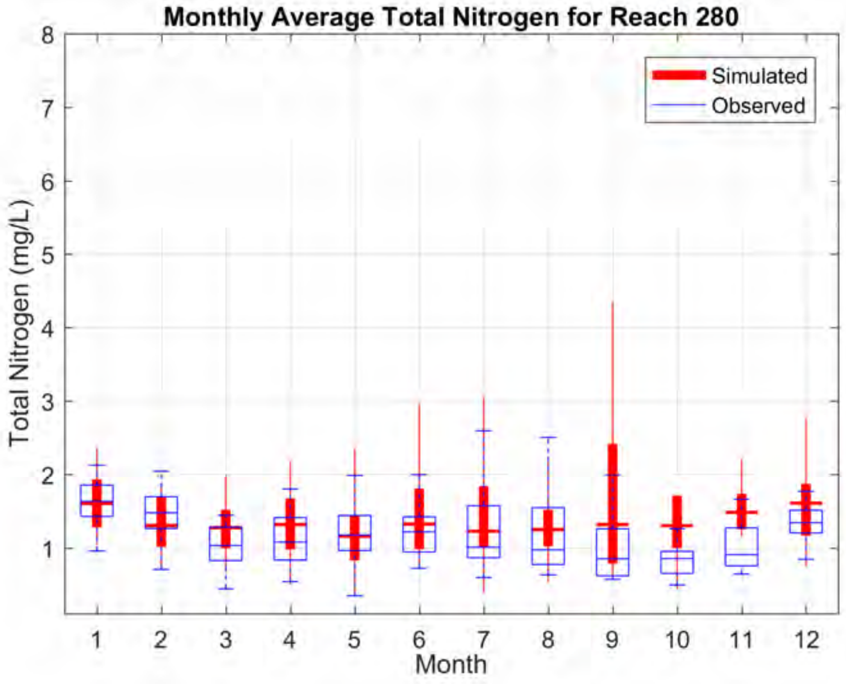

Figure B-23. Total Nitrogen Monthly Average Calibration Boxplots at CC-10 (Outliers Removed).

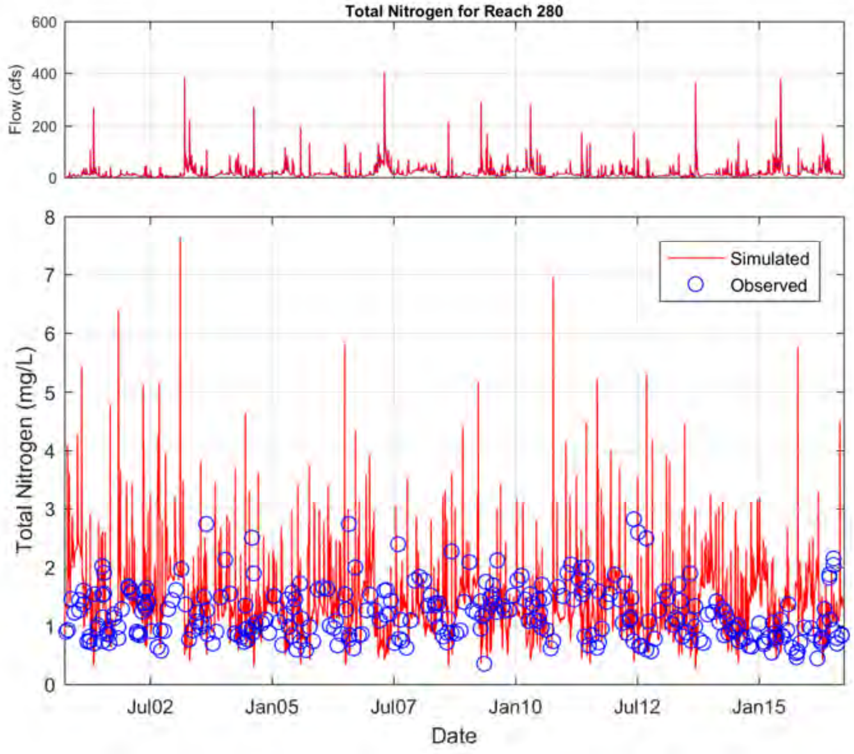

Figure B-24. Total Nitrogen Time-Series Calibration Plot at CC-10.

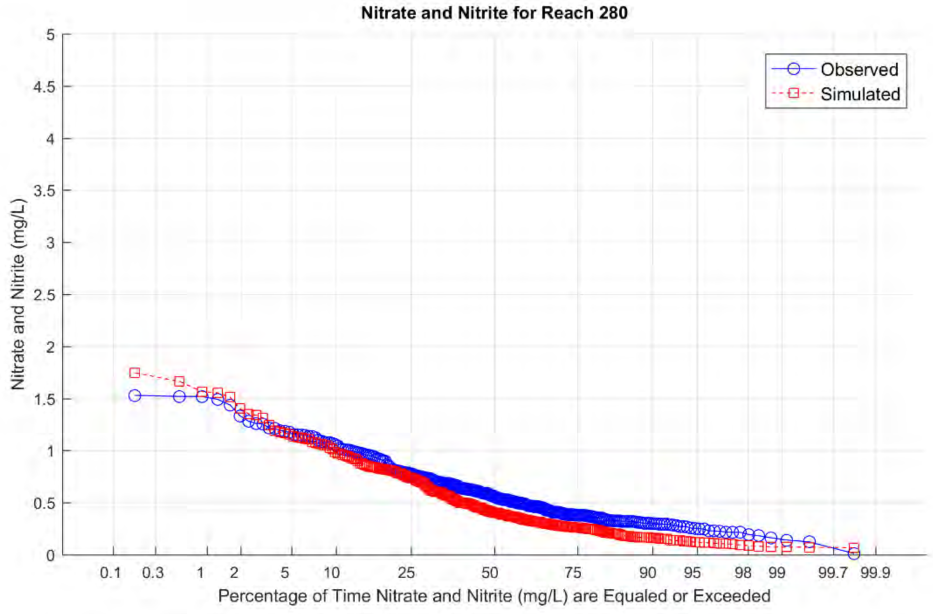

Figure B-25. Nitrate and Nitrite as Nitrogen Concentration Duration Calibration Plot at CC-10.

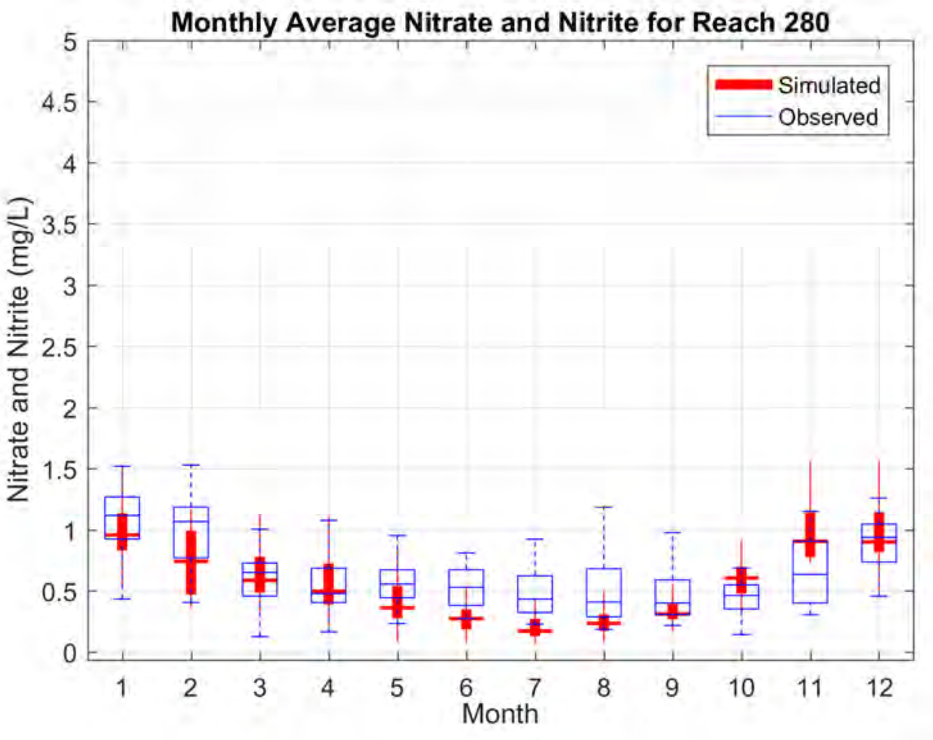

Figure B-26. Nitrate and Nitrite as Nitrogen Monthly Average Calibration Boxplots at CC-10 (Outliers Removed).

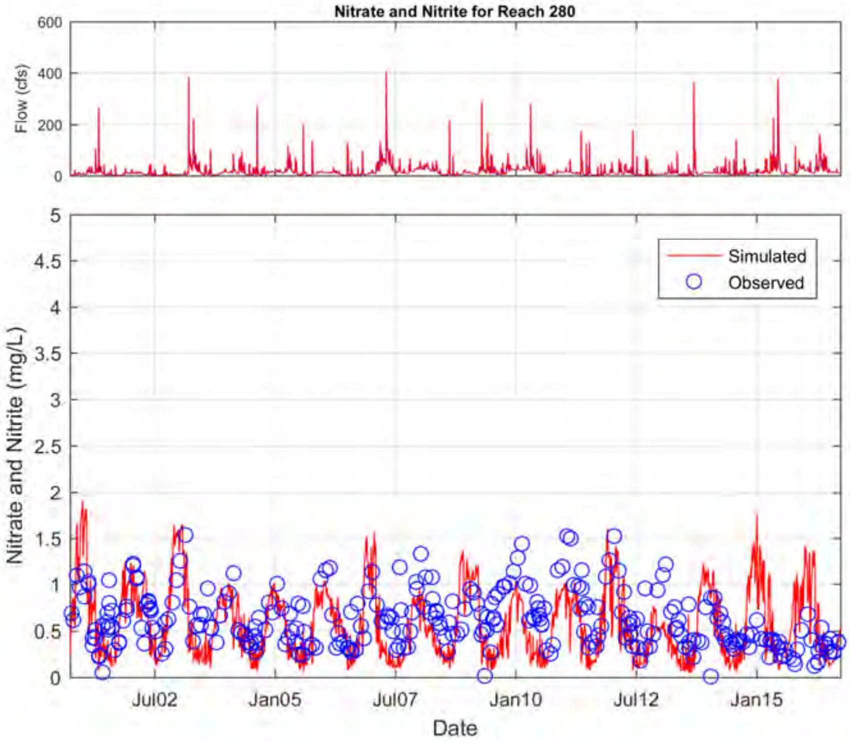

Figure B-27. Nitrate and Nitrite as Nitrogen Time-Series Calibration Plot at CC-10.

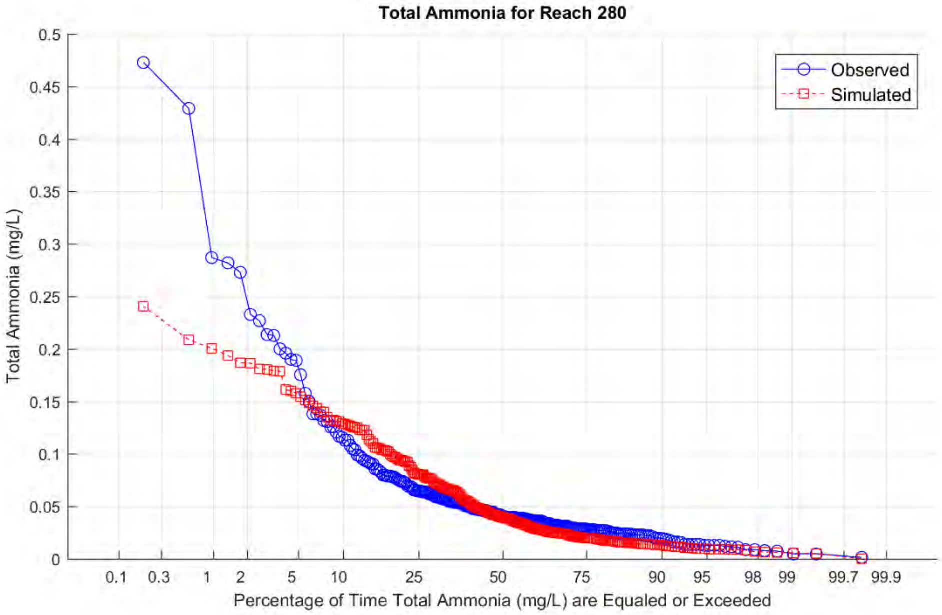

Figure B-28. Ammonia as Nitrogen Concentration Duration Calibration Plot at CC-10.

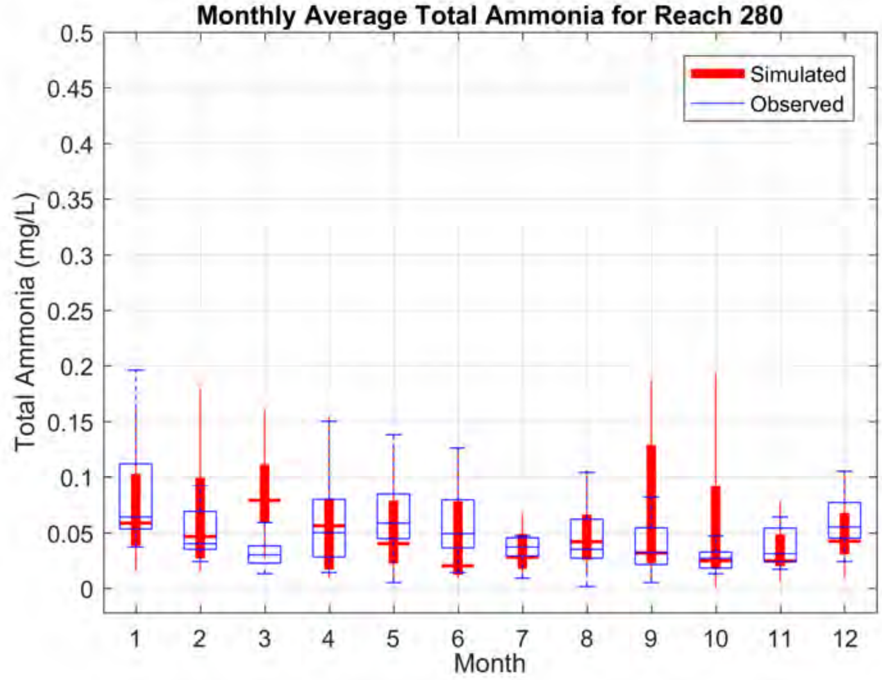

Figure B-29. Ammonia as Nitrogen Monthly Average Calibration Boxplots at CC-10 (Outliers Removed).

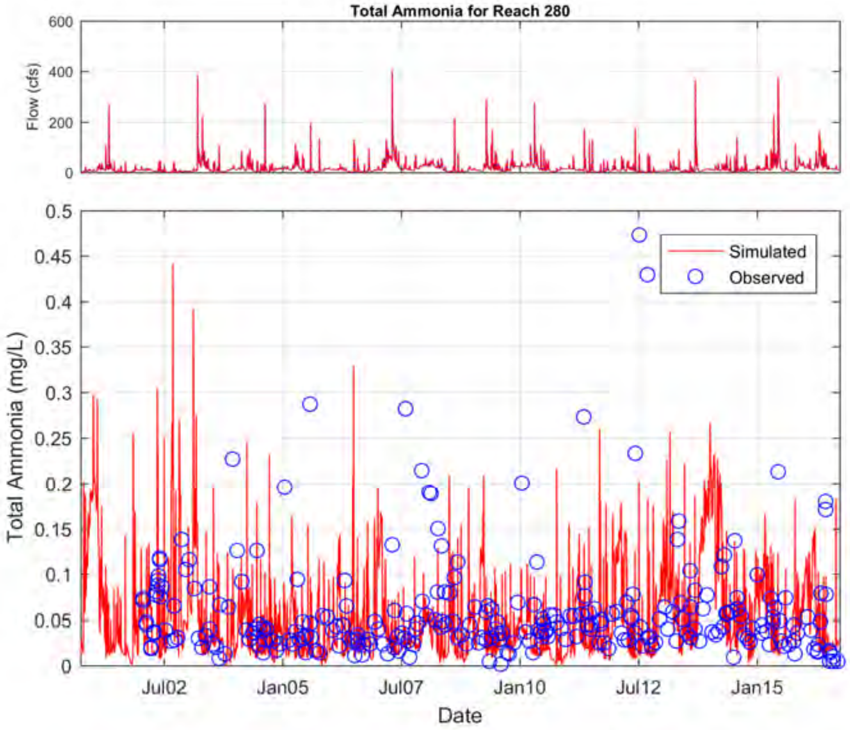

Figure B-30. Ammonia as Nitrogen Time-Series Calibration Plot at CC-10.

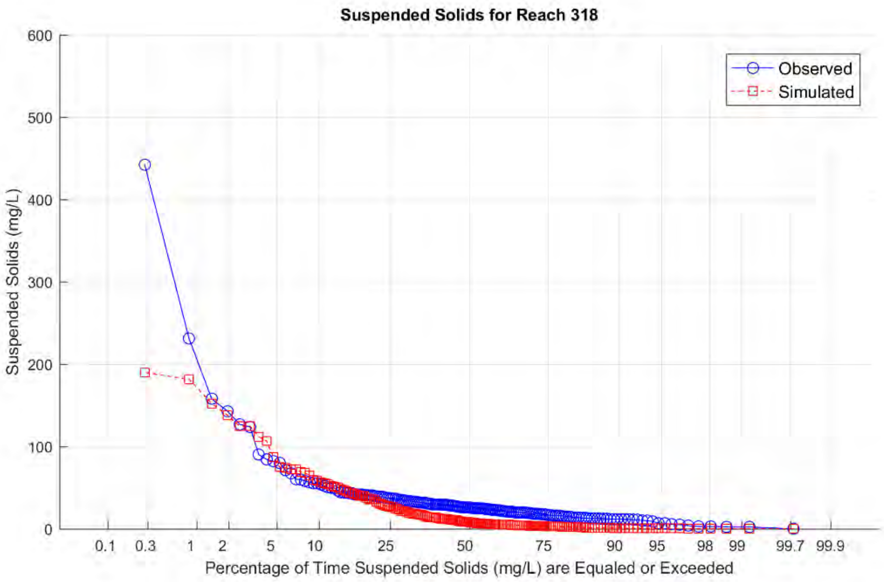

Figure B-31. Sediment Concentration Duration Calibration Plot at CT-2.

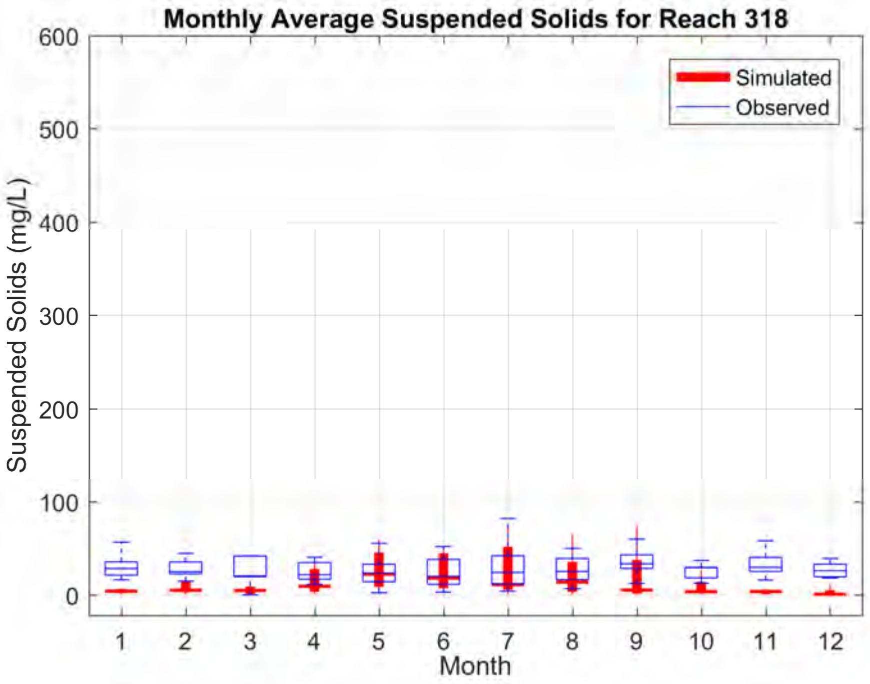

Figure B-32. Sediment Monthly Average Calibration Boxplots at CT-2 (Outliers Removed).

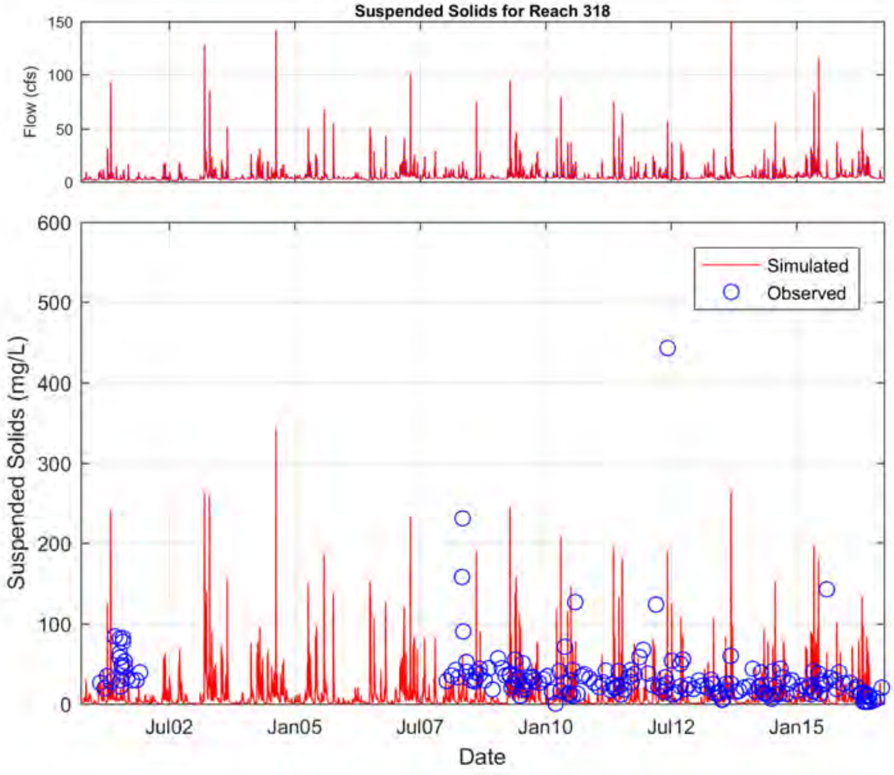

Figure B-33. Sediment Time-Series Calibration Plot at CT-2.

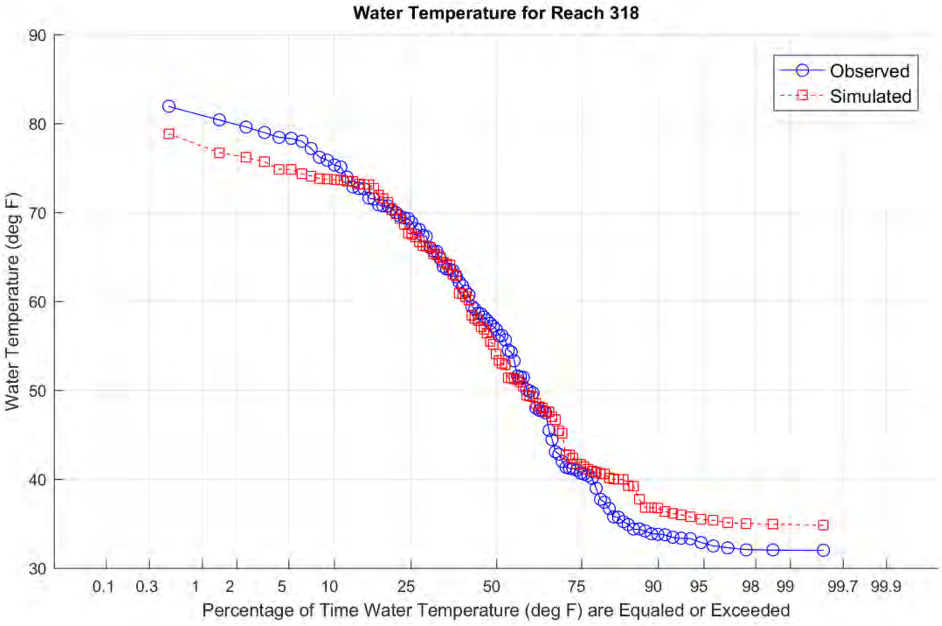

Figure B-34. Temperature Duration Calibration Plot at CT-2.

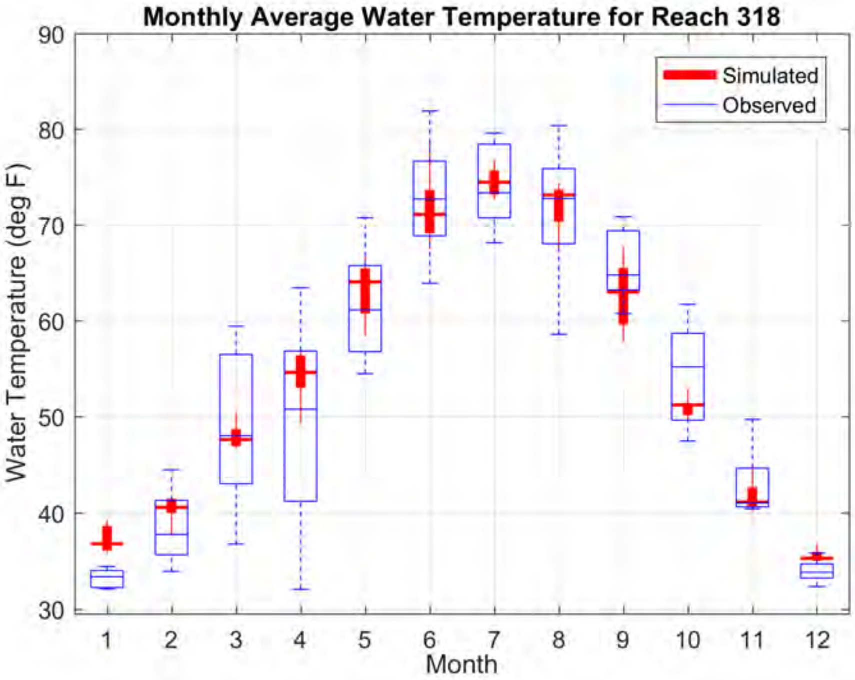

Figure B-35. Temperature Monthly Average Boxplots at CT-2 (Outliers Removed).

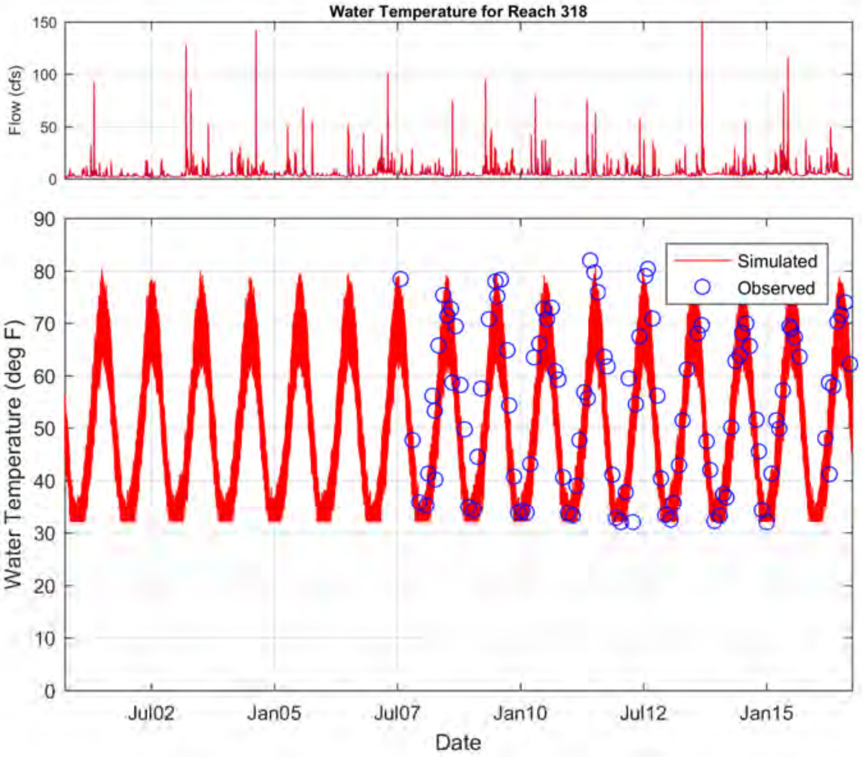

Figure B-36. Temperature Time-Series Calibration Plot at CT-2.

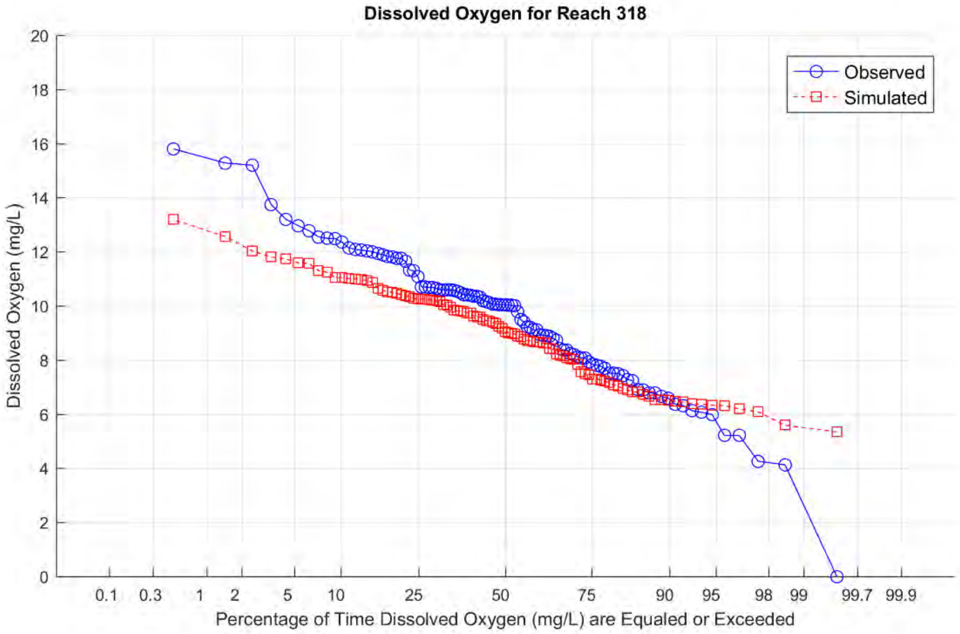

Figure B-37. Dissolved Oxygen Concentration Duration Calibration Plot at CT-2.

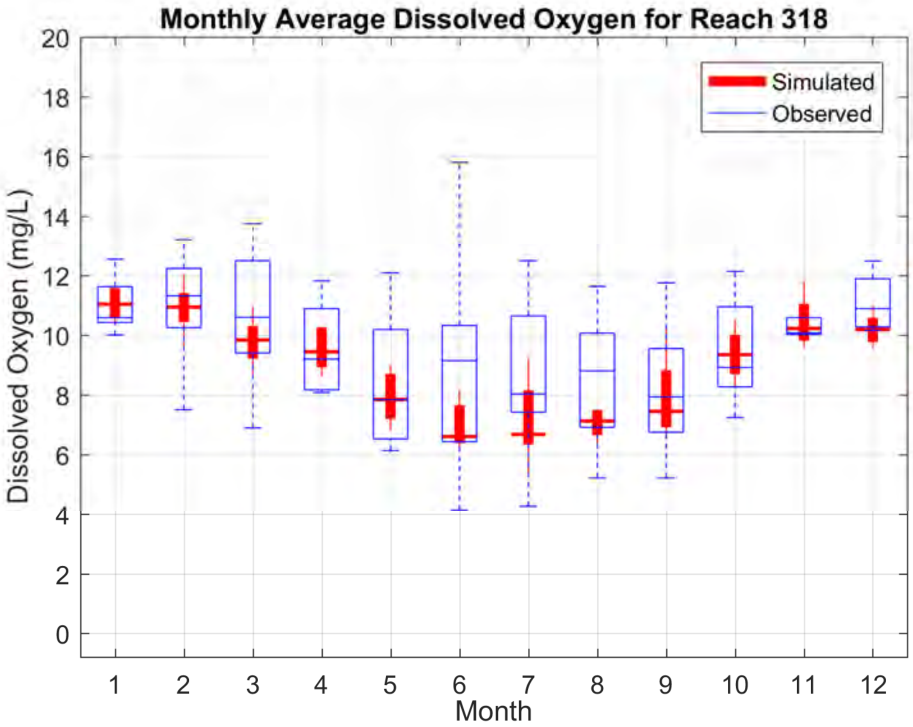

Figure B-38. Dissolved Oxygen Monthly Average Calibration Boxplots at CT-2 (Outliers Removed).

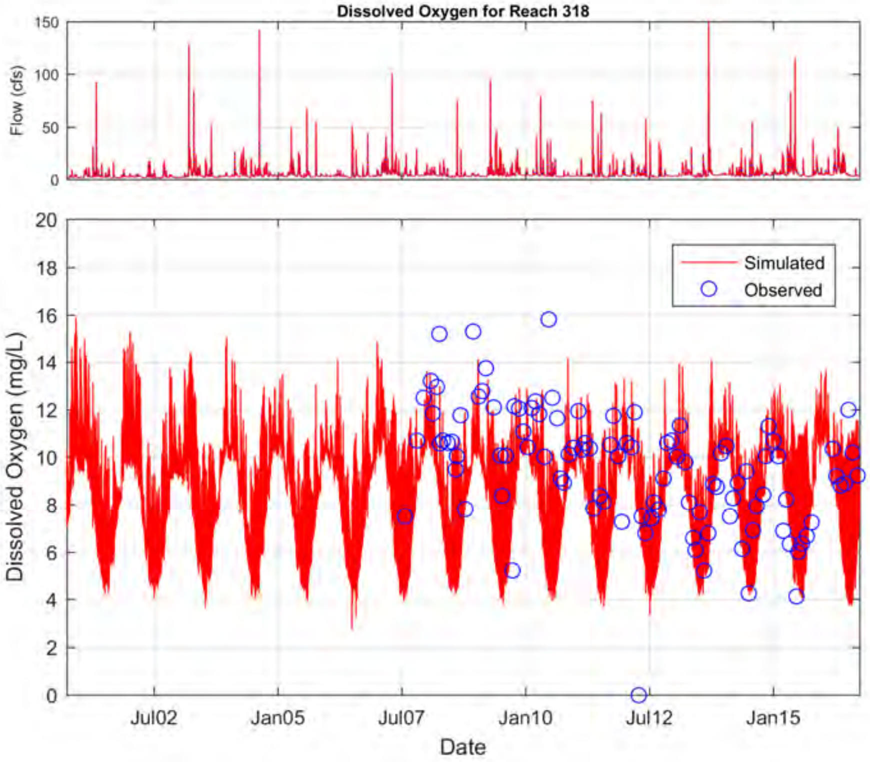

Figure B-39. Dissolved Oxygen Time-Series Calibration Plot at CT-2.

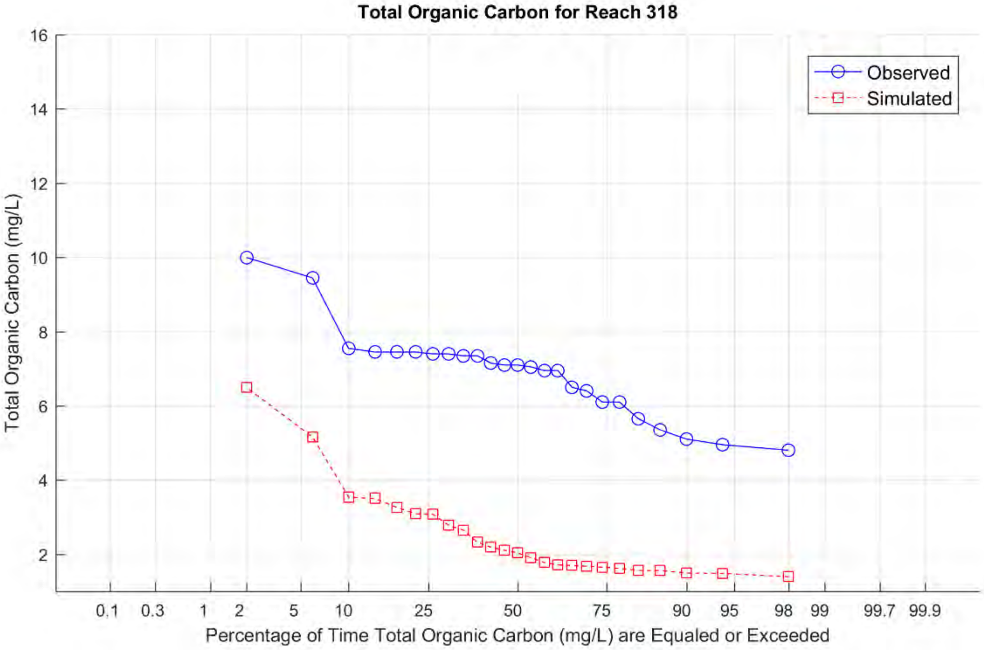

Figure B-40. Total Organic Carbon Concentration Duration Calibration Plot at CT-2.

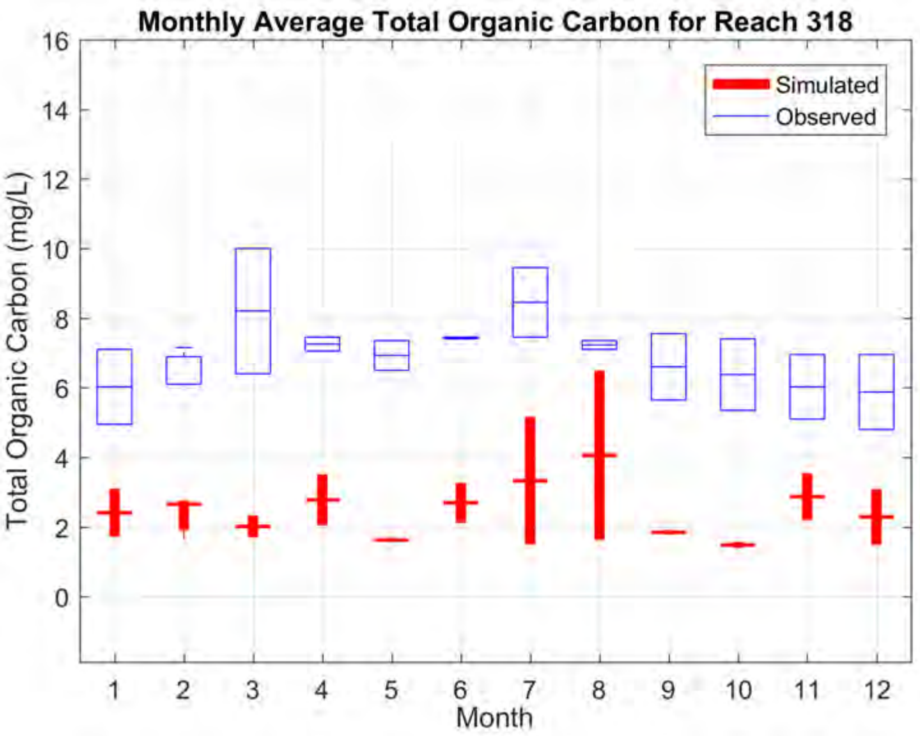

Figure B-41. Total Organic Carbon Monthly Average Calibration Boxplots at CT-2 (Outliers Removed).

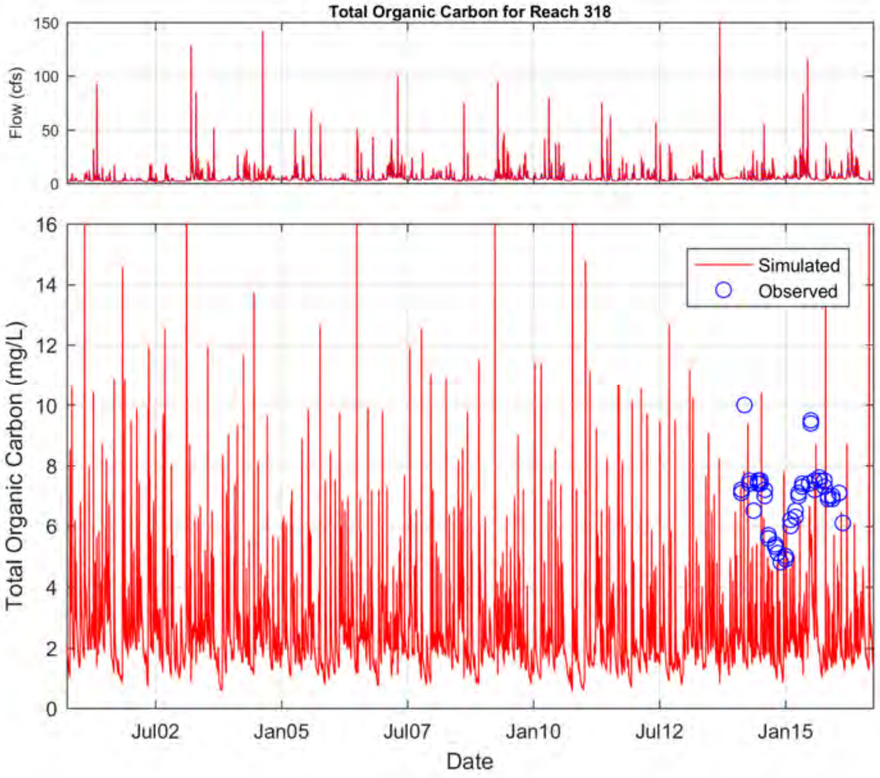

Figure B-42. Total Organic Carbon Time-Series Calibration Plot at CT-2.

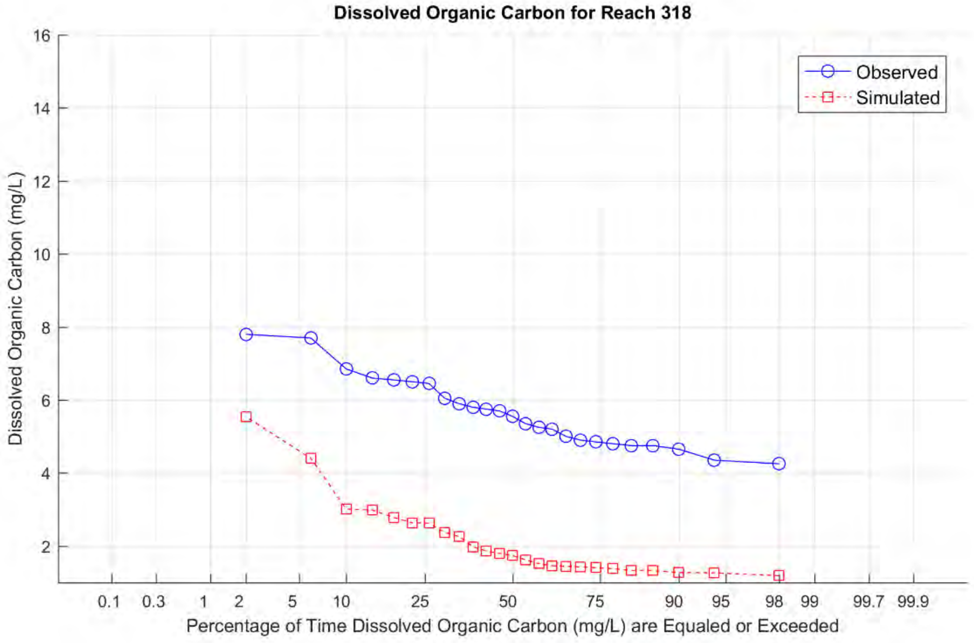

Figure B-43. Dissolved Organic Carbon Concentration Duration Calibration Plot at CT-2.

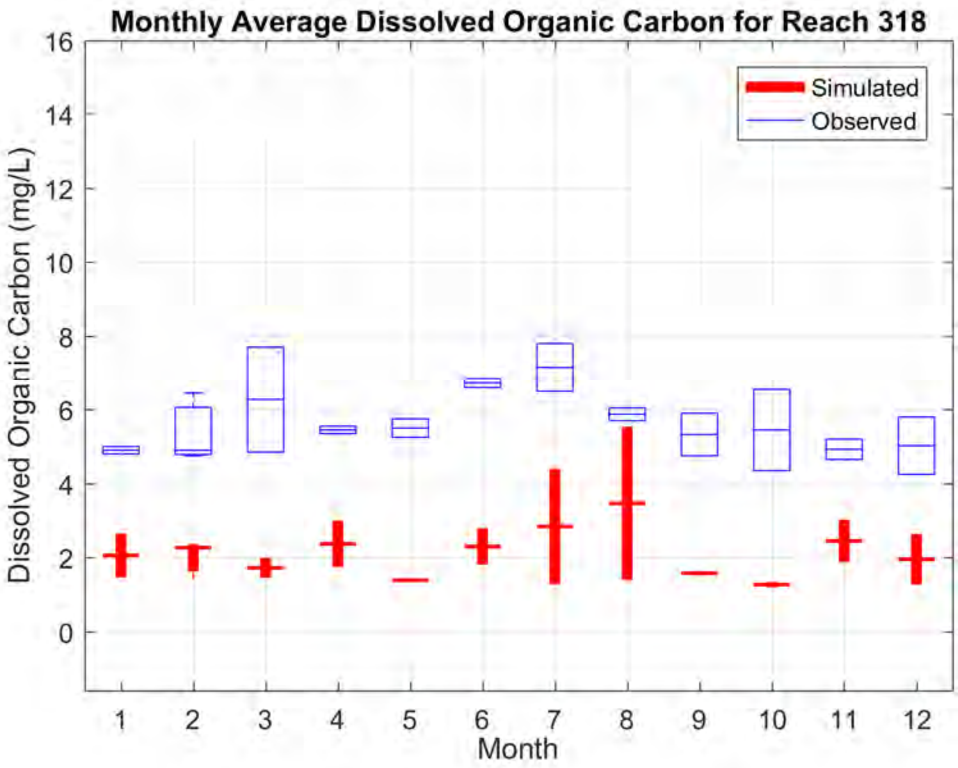

Figure B-44. Dissolved Organic Carbon Monthly Average Calibration Boxplots at CT-2 (Outliers Removed).

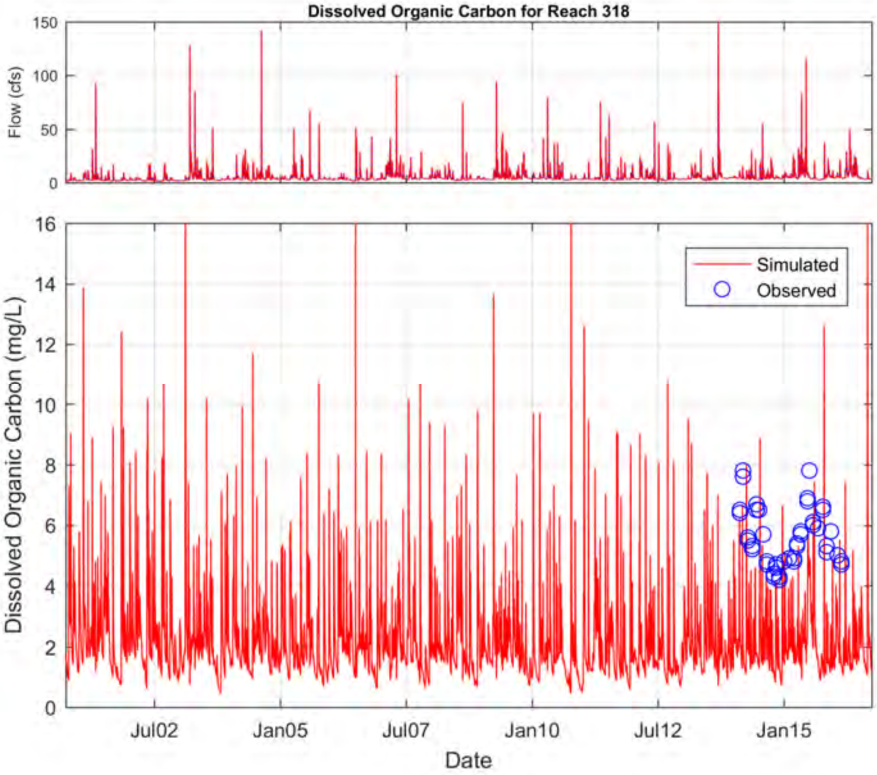

Figure B-45. Dissolved Organic Carbon Time-Series Calibration Plot at CT-2.

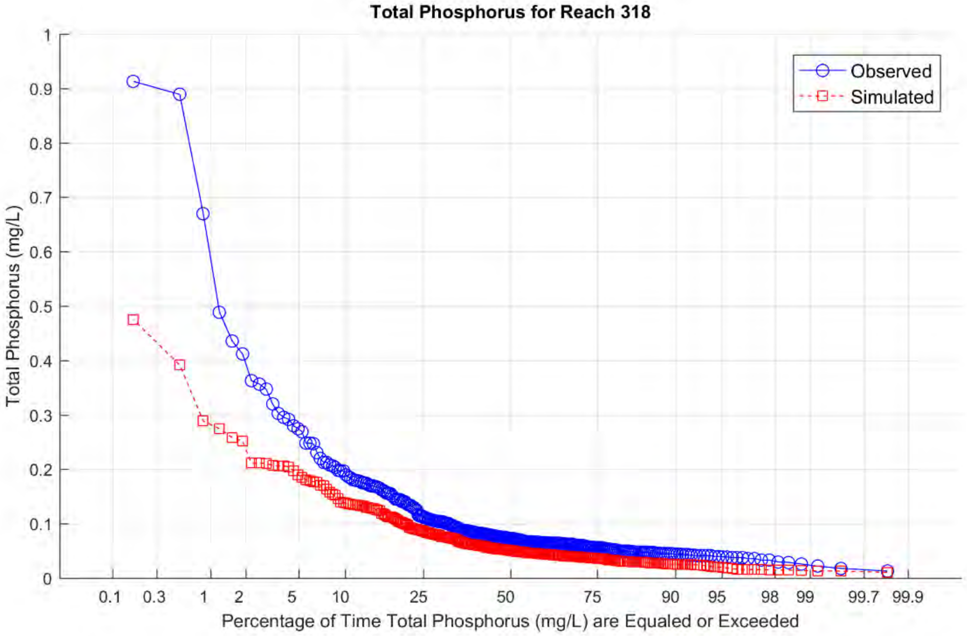

Figure B-46. Total Phosphorus Concentration Duration Calibration Plot at CT-2.

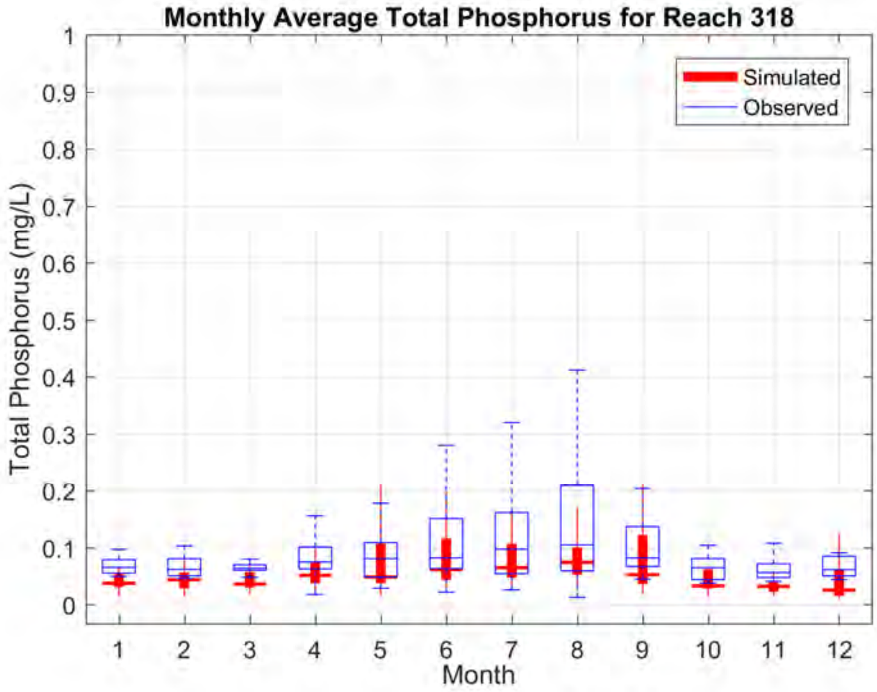

Figure B-47. Total Phosphorus Monthly Average Calibration Boxplots at CT-2 (Outliers Removed).

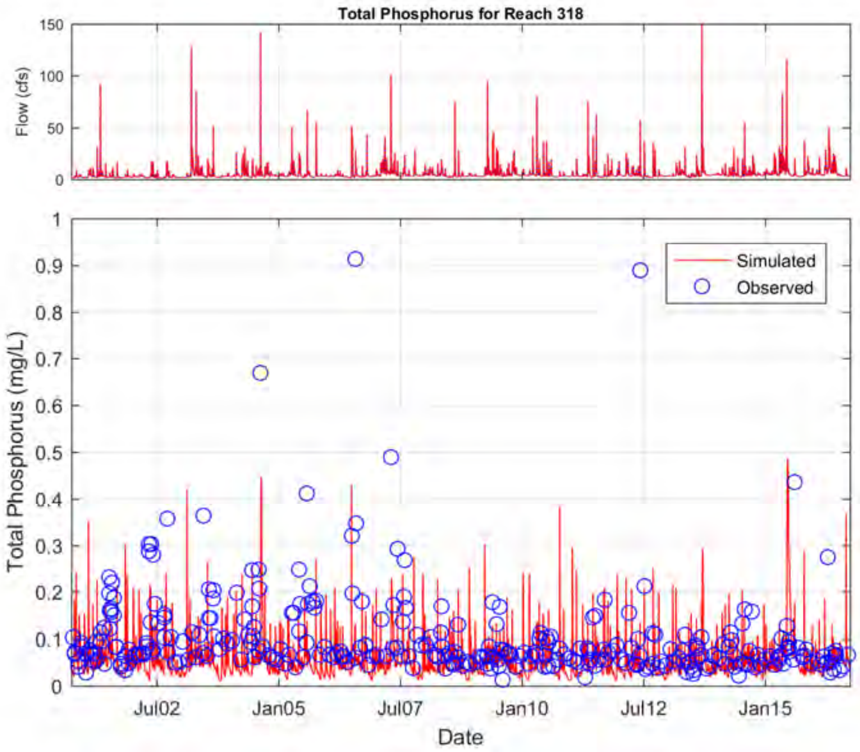

Figure B-48. Total Phosphorus Time-Series Calibration Plot at CT-2.

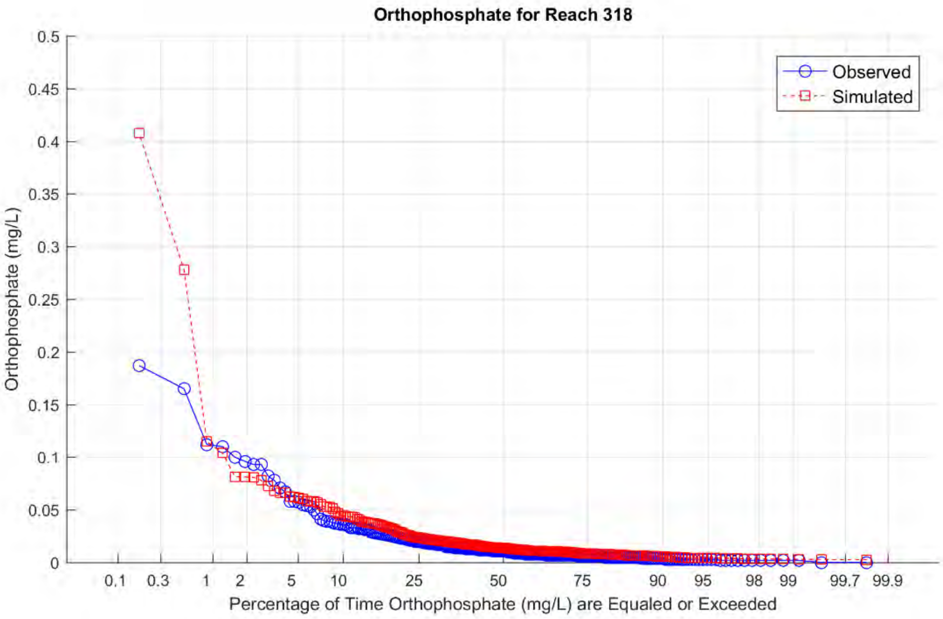

Figure B-49. Total Orthophosphate Concentration Duration Calibration Plot at CT-2.

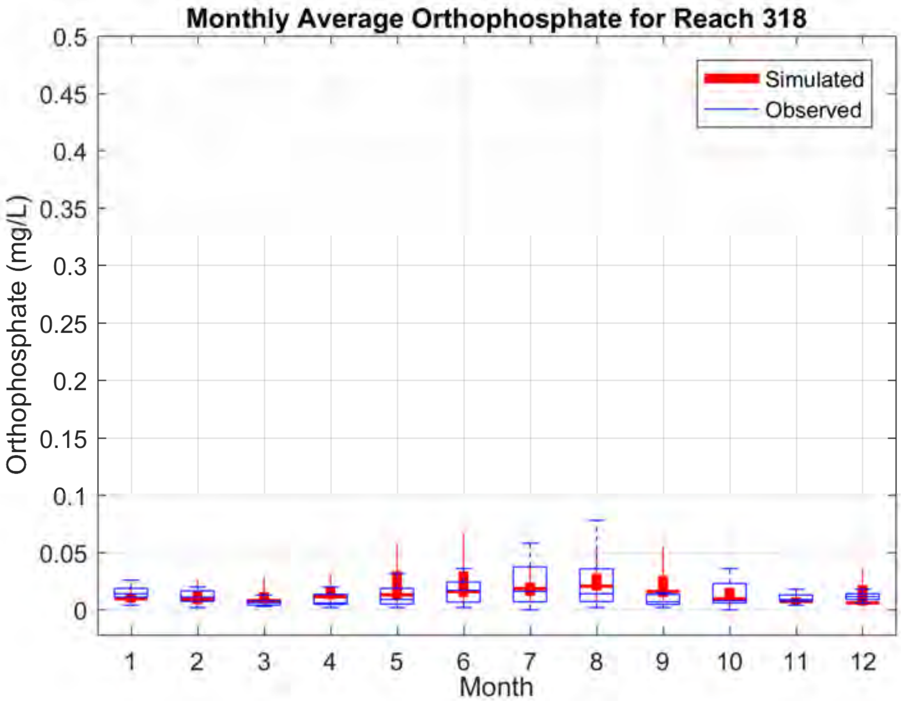

Figure B-50. Total Orthophosphate Monthly Average Calibration Boxplots at CT-2 (Outliers Removed).

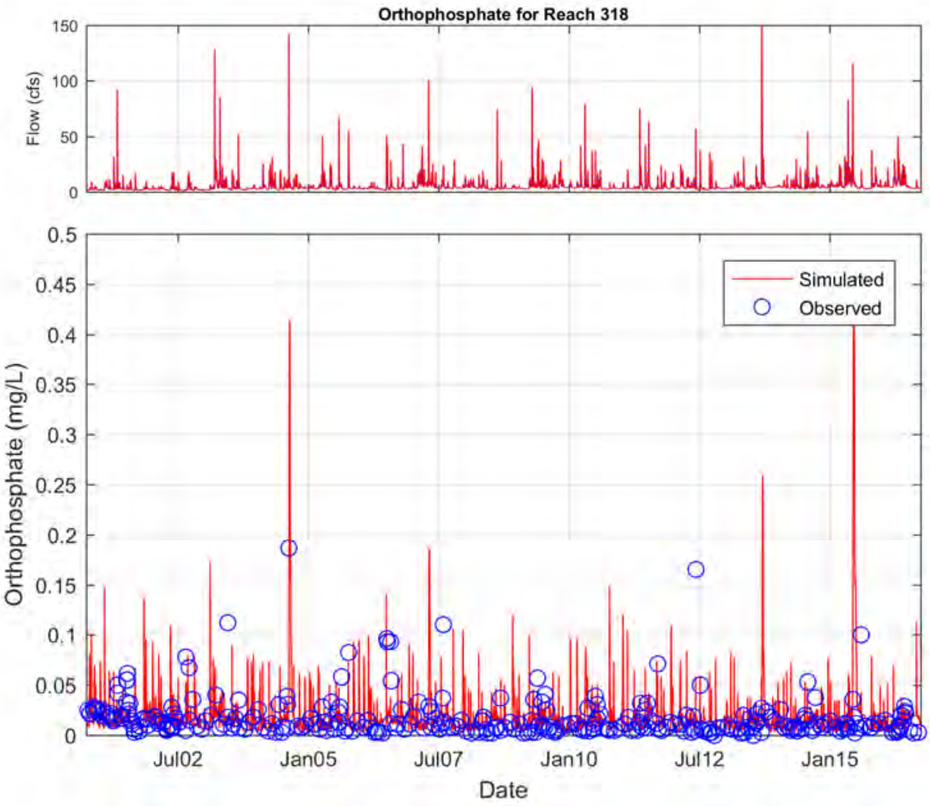

Figure B-51. Total Orthophosphate Time-Series Calibration Plot at CT-2.

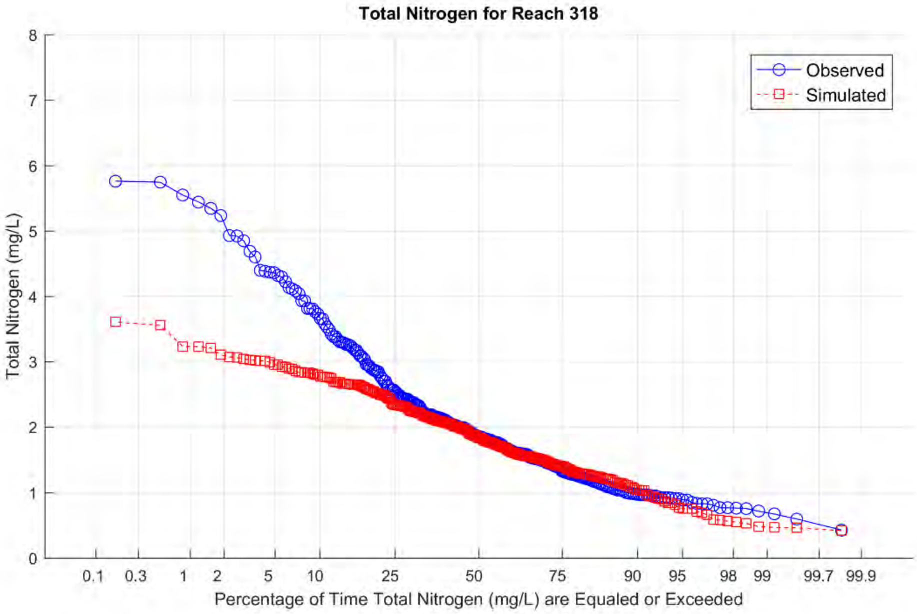

Figure B-52. Total Nitrogen Concentration Duration Calibration Plot at CT-2.

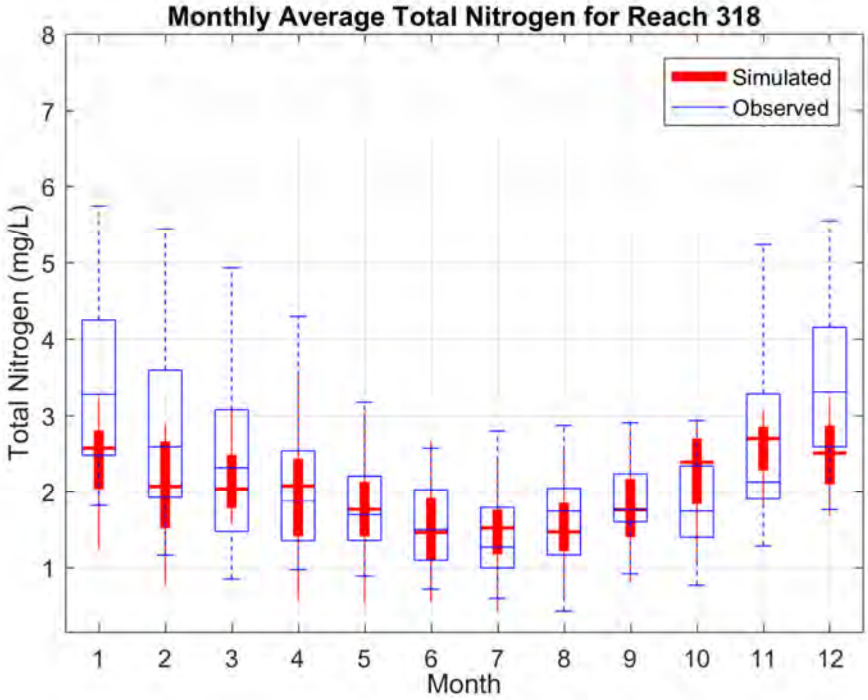

Figure B-53. Total Nitrogen Monthly Average Calibration Boxplots at CT-2 (Outliers Removed).

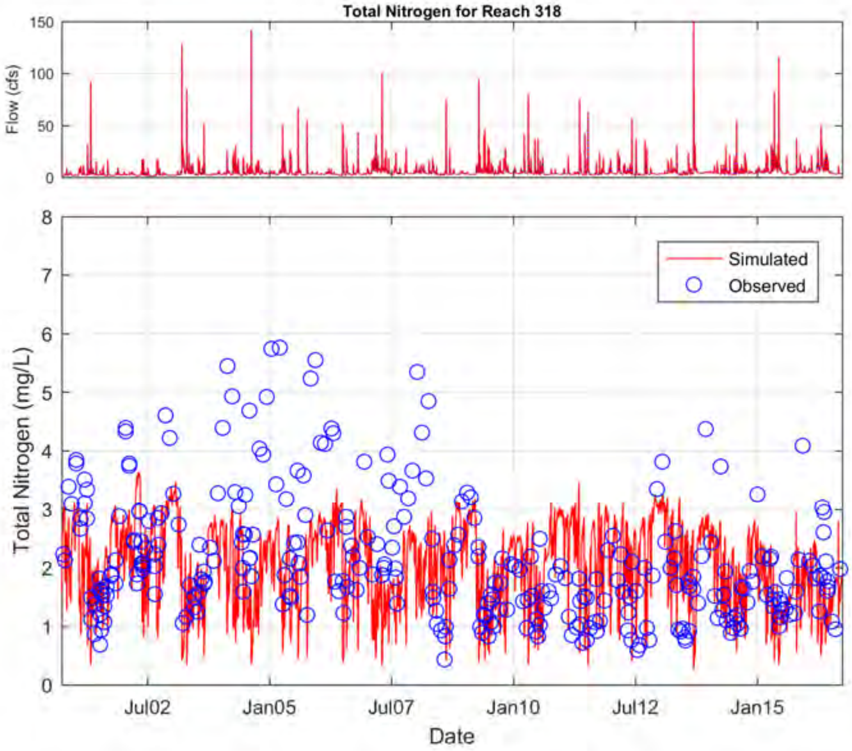

Figure B-54. Total Nitrogen Time-Series Calibration Plot at CT-2.

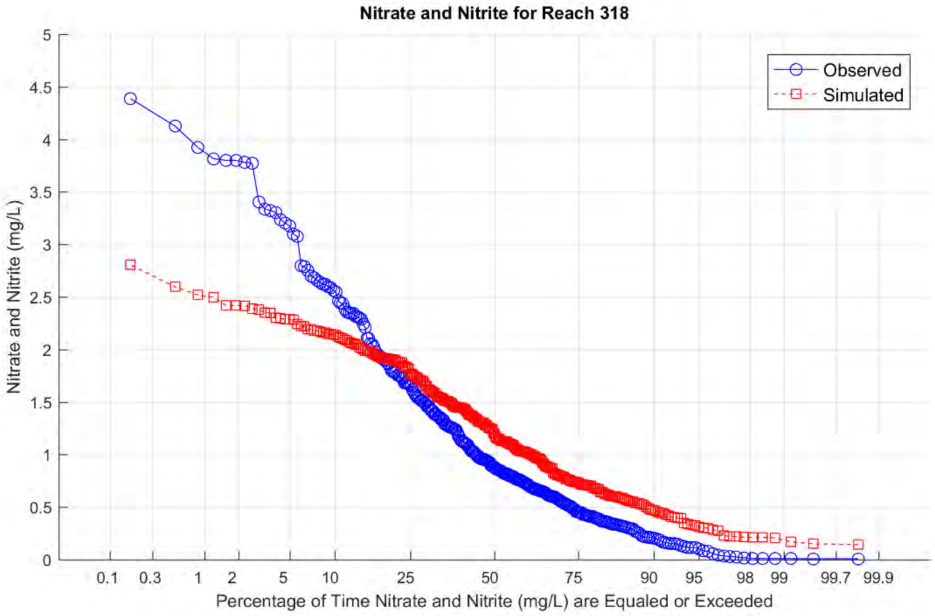

Figure B-55. Nitrate and Nitrite as Nitrogen Concentration Duration Calibration Plot at CT-2.

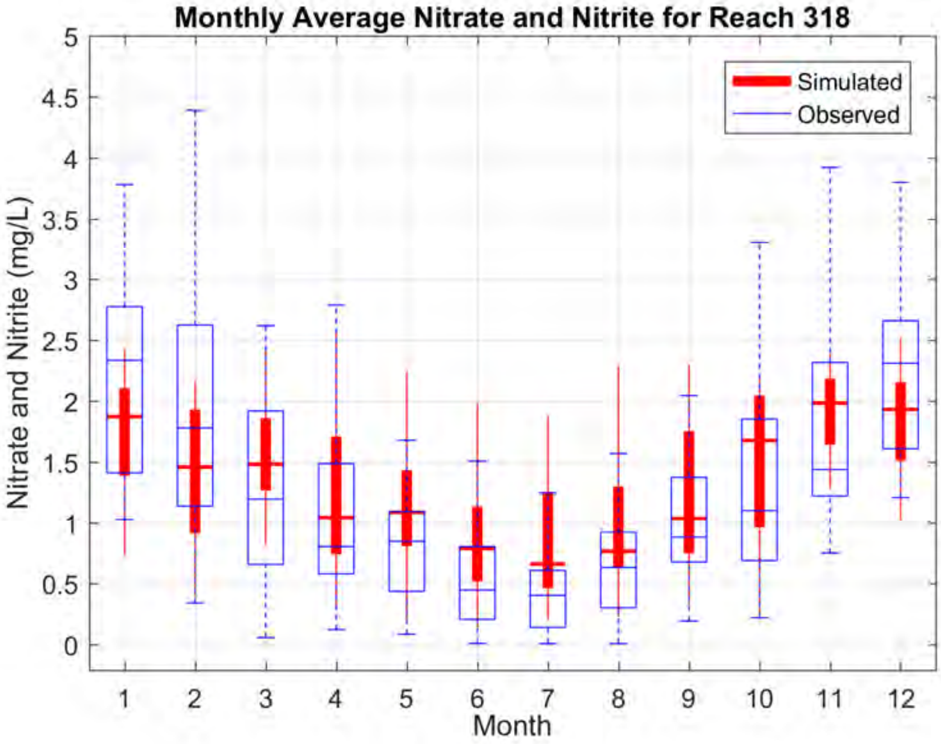

Figure B-56. Nitrate and Nitrite as Nitrogen Monthly Average Calibration Boxplots at CT-2 (Outliers Removed).

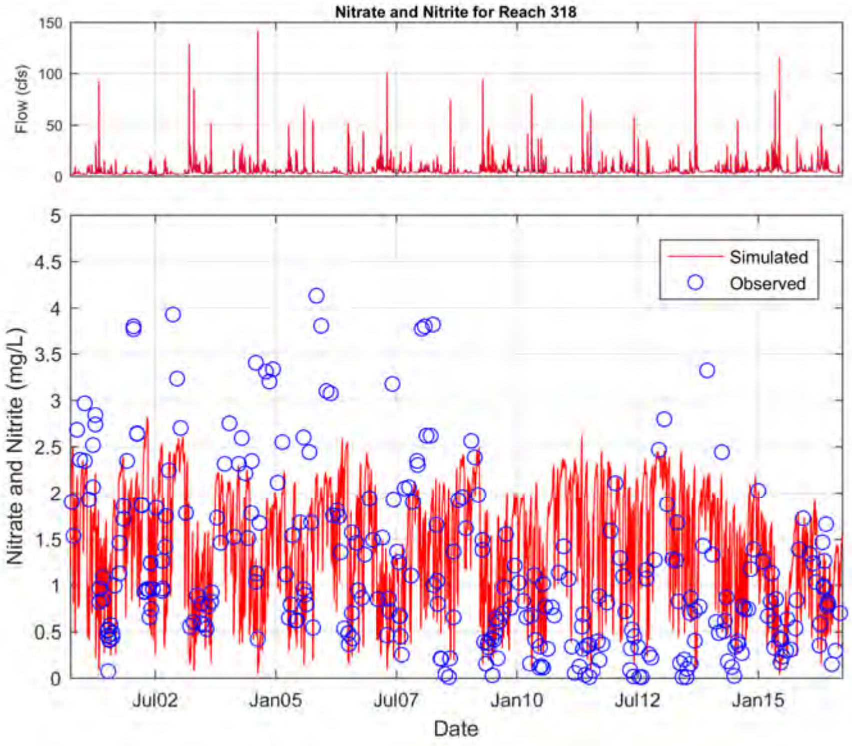

Figure B-57. Nitrate and Nitrite as Nitrogen Time-Series Calibration Plot at CT-2.

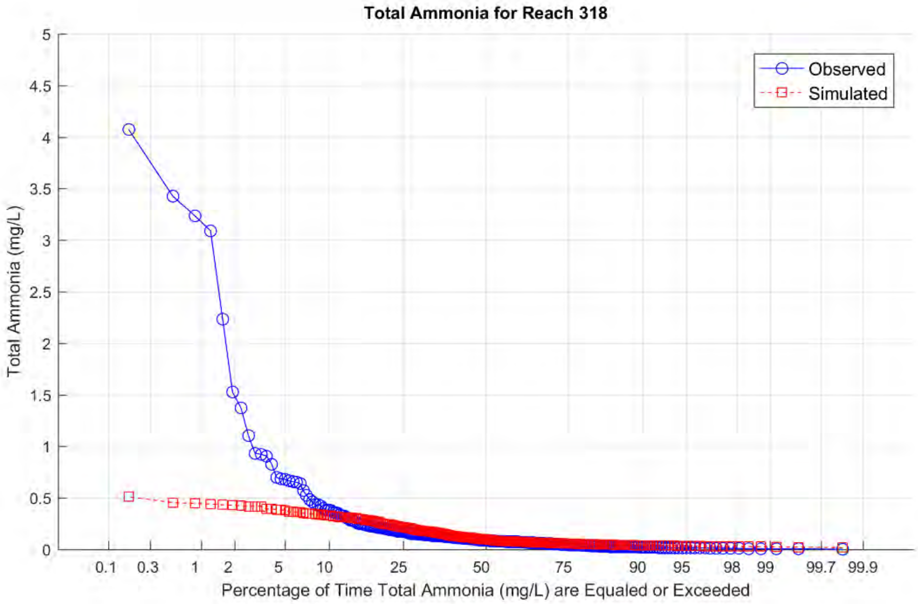

Figure B-58. Ammonia as Nitrogen Concentration Duration Calibration Plot at CT-2.

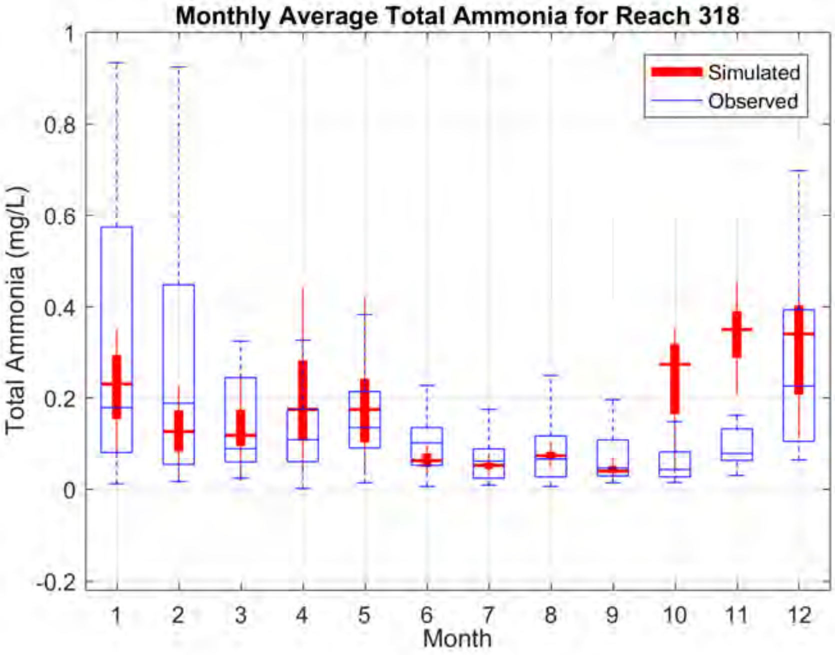

Figure B-59. Ammonia as Nitrogen Monthly Average Calibration Boxplots at CT-2 (Outliers Removed).

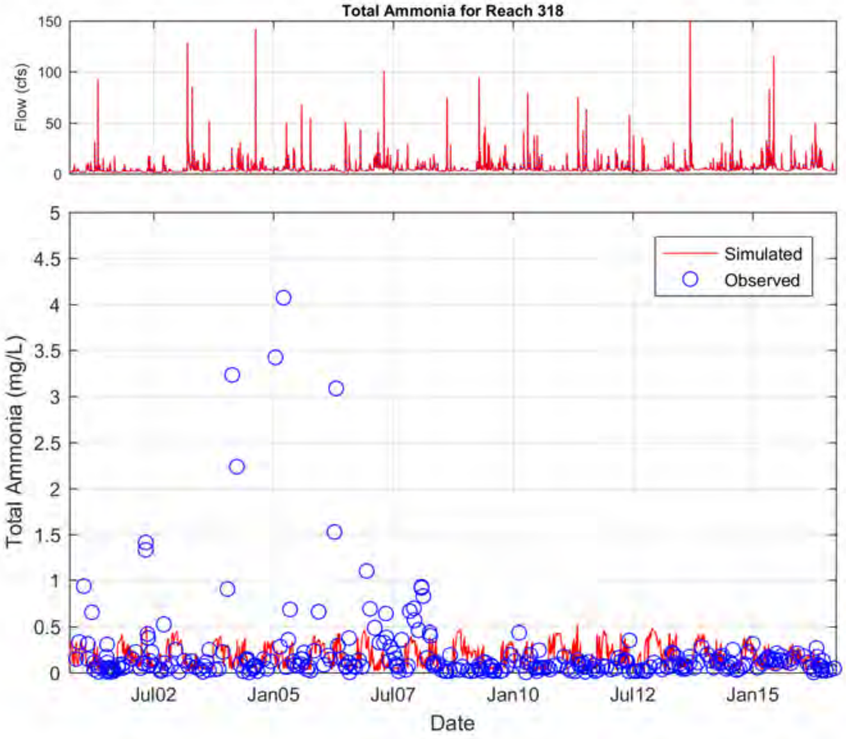

Figure B-60. Ammonia as Nitrogen Time-Series Calibration Plot at CT-2.

APPENDIX C

WATER QUALITY CALIBRATION RESULTS FOR CHERRY CREEK NEAR FRANKTOWN (CASTLEWOOD STATION IN MODEL REACH 80) AND CHERRY CREEK NEAR PARKER (CC-4 IN MODEL REACH 210)

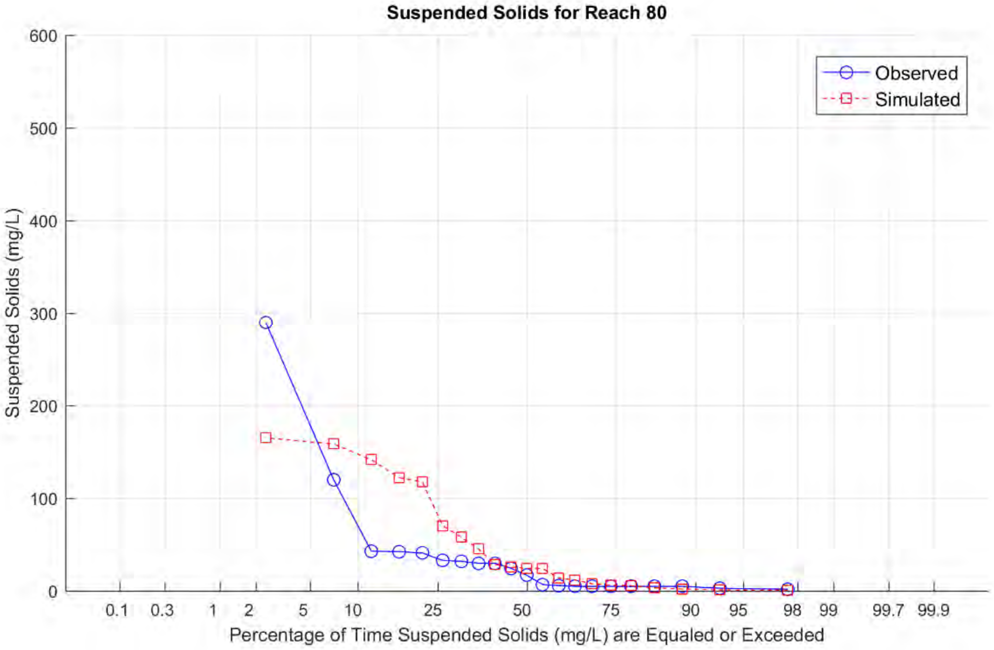

Figure C-1. Sediment Concentration Duration Calibration Plot at Reach 80.

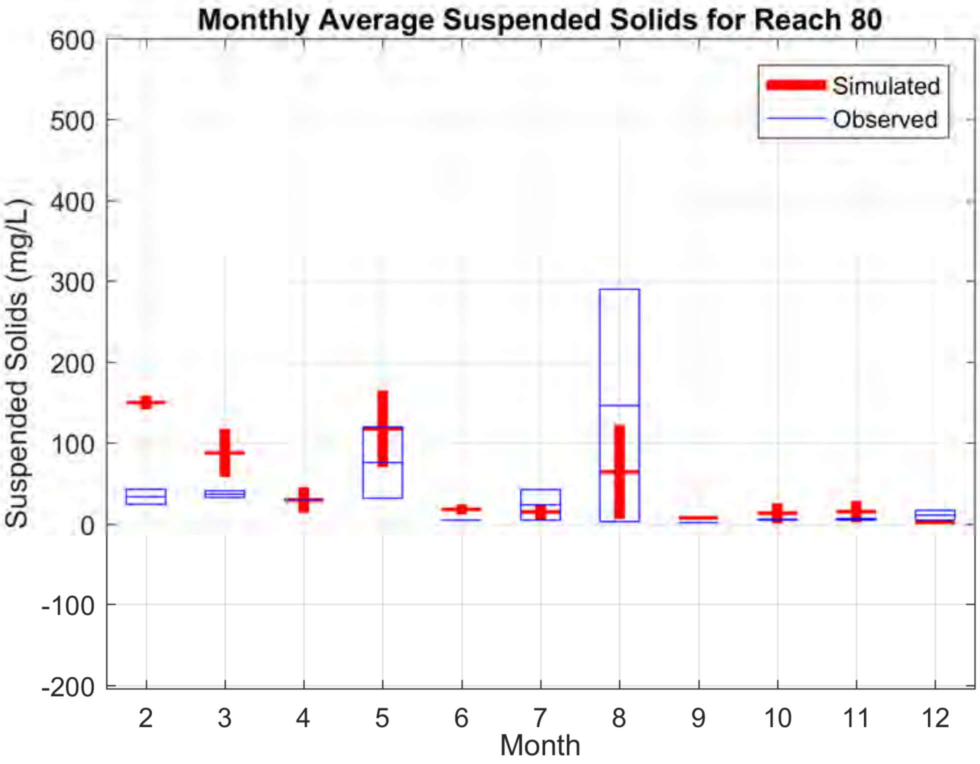

Figure C-2. Sediment Monthly Average Calibration Boxplots at Reach 80.

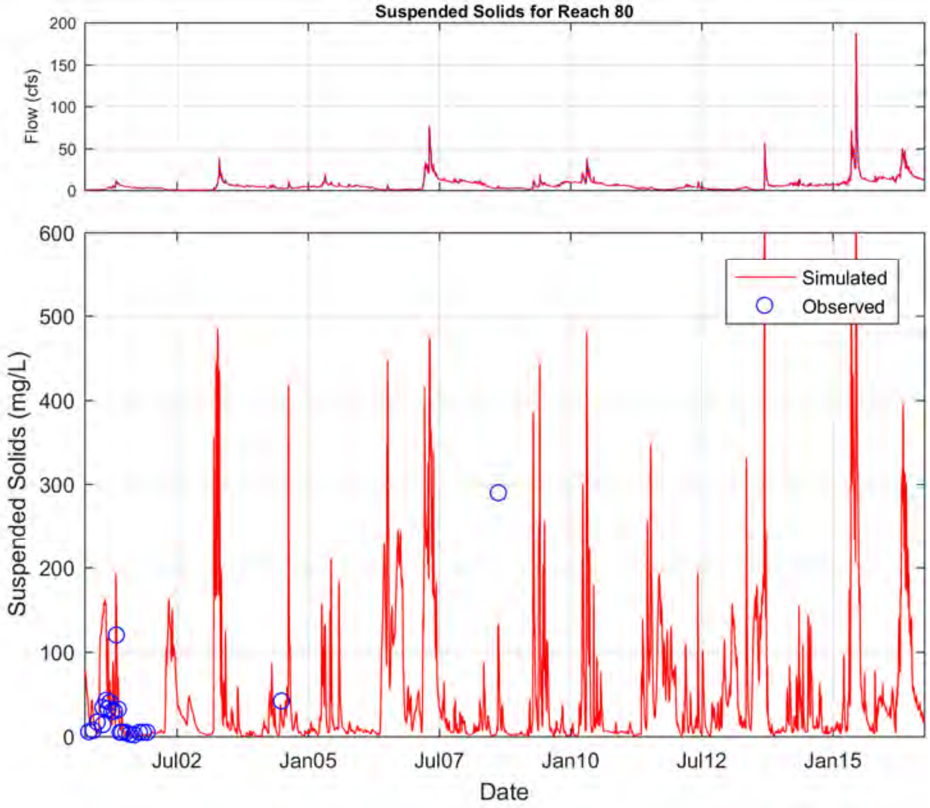

Figure C-3. Sediment Time-Series Calibration Plot at Reach 80.

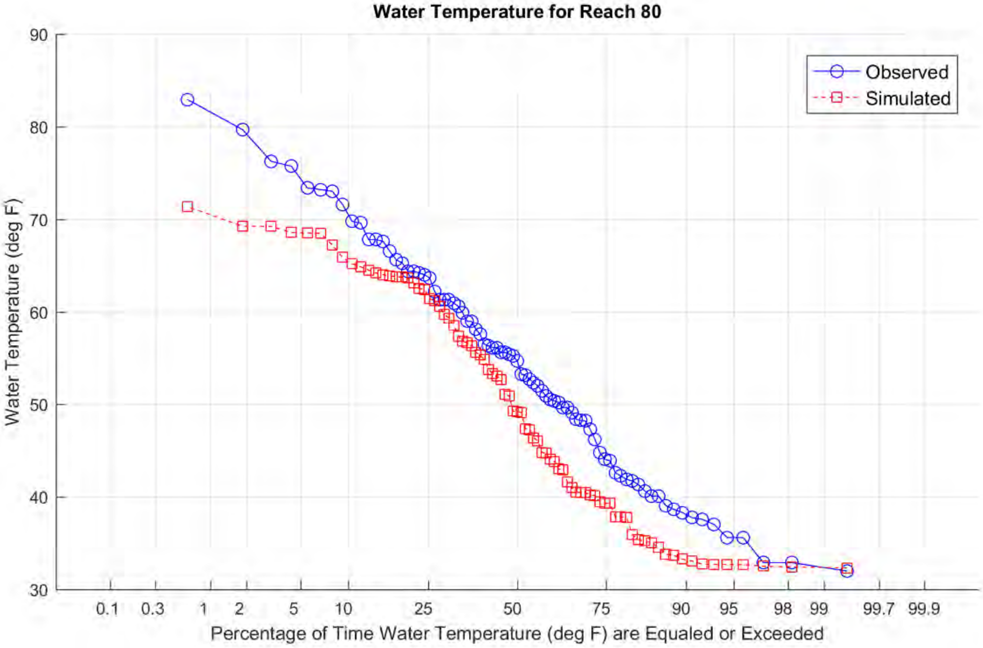

Figure C-4. Temperature Duration Calibration Plot at Reach 80.

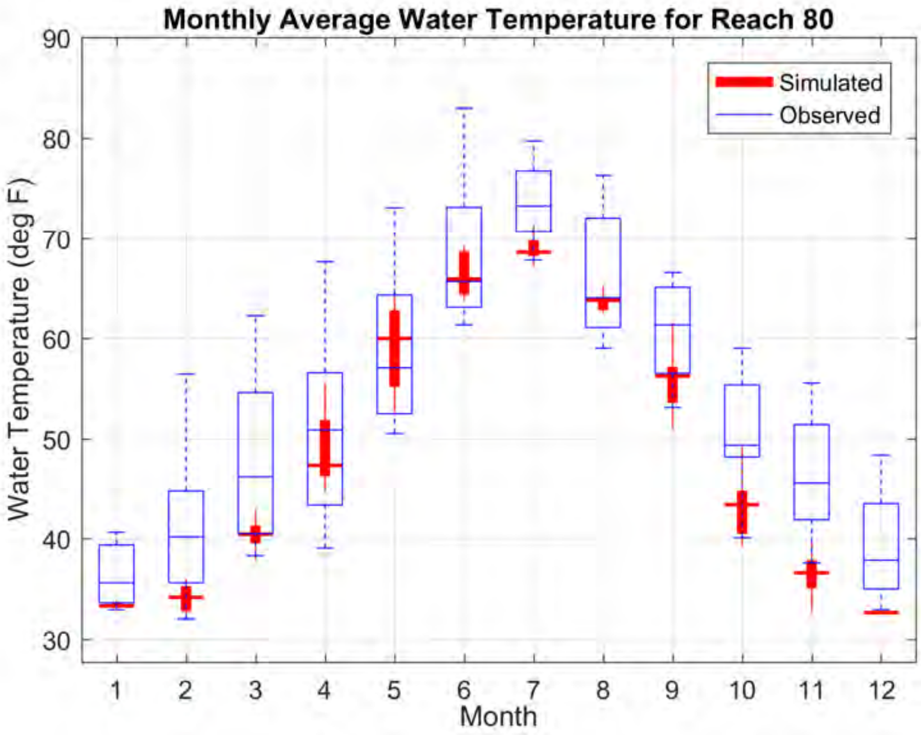

Figure C-5. Temperature Monthly Average Boxplots at Reach 80.

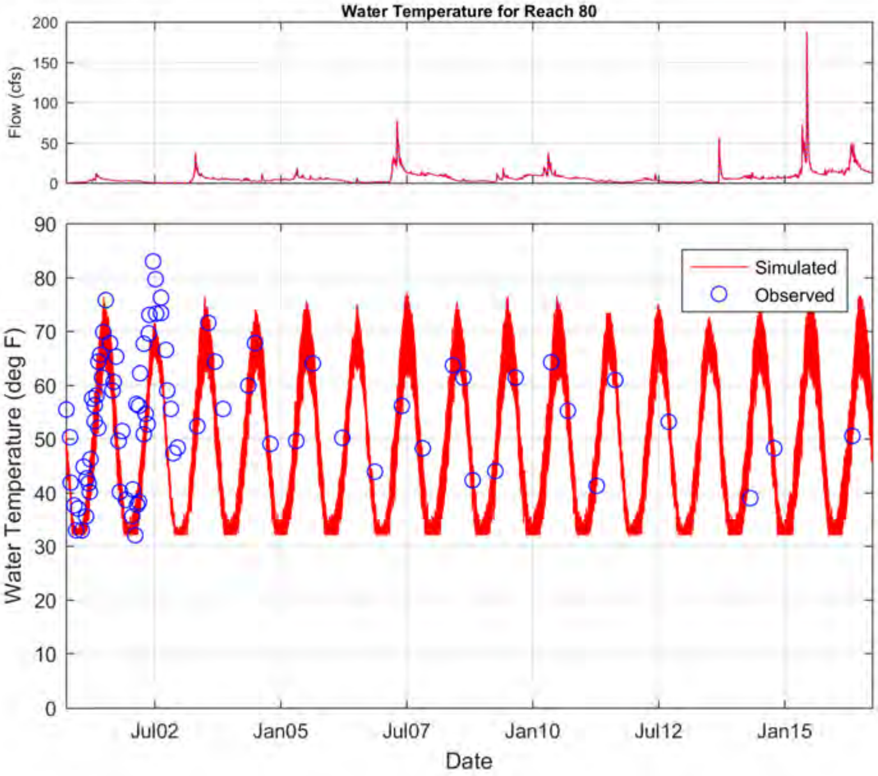

Figure C-6. Temperature Time-Series Calibration Plot at Reach 80.

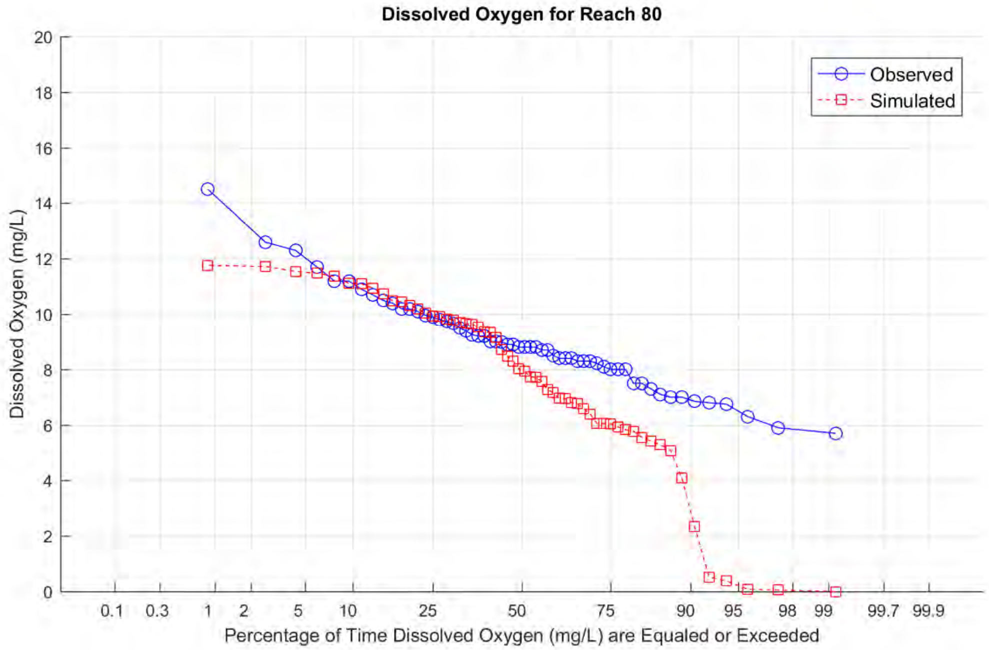

Figure C-7. Dissolved Oxygen Concentration Duration Calibration Plot at Reach 80.

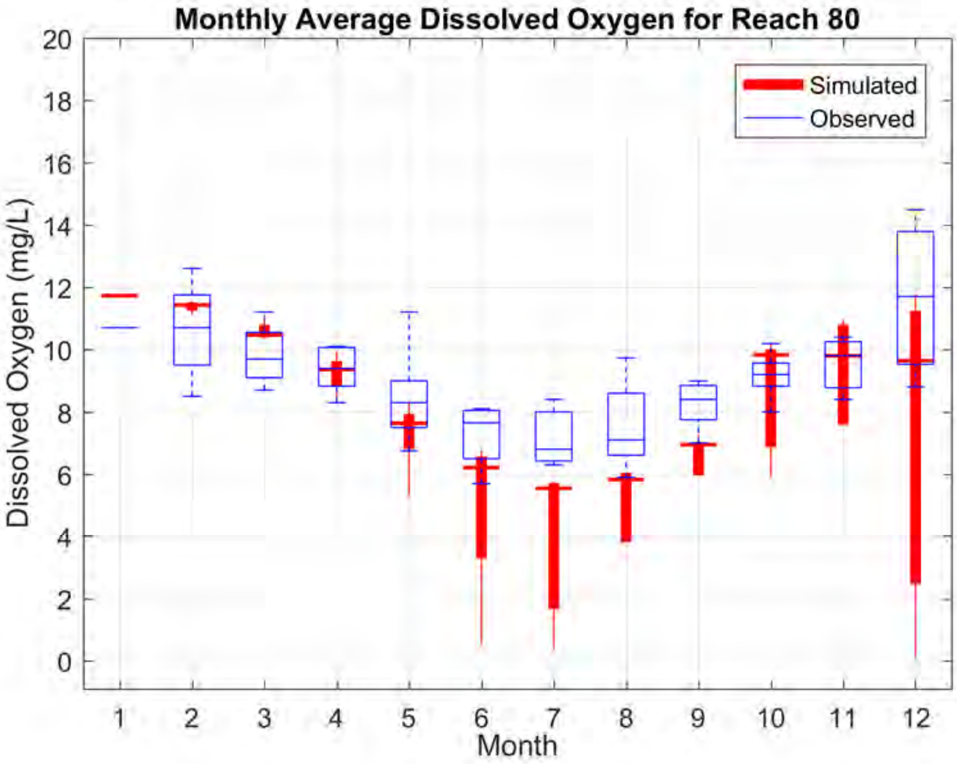

Figure C-8. Dissolved Oxygen Monthly Average Calibration Boxplots at Reach 80.

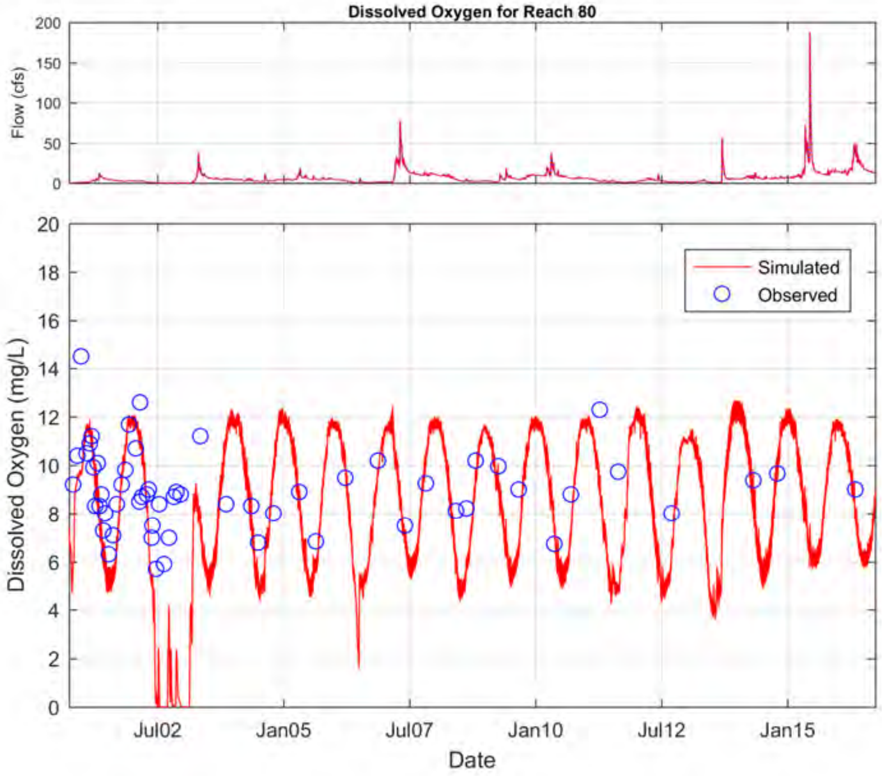

Figure C-9. Dissolved Oxygen Time-Series Calibration Plot at Reach 80.

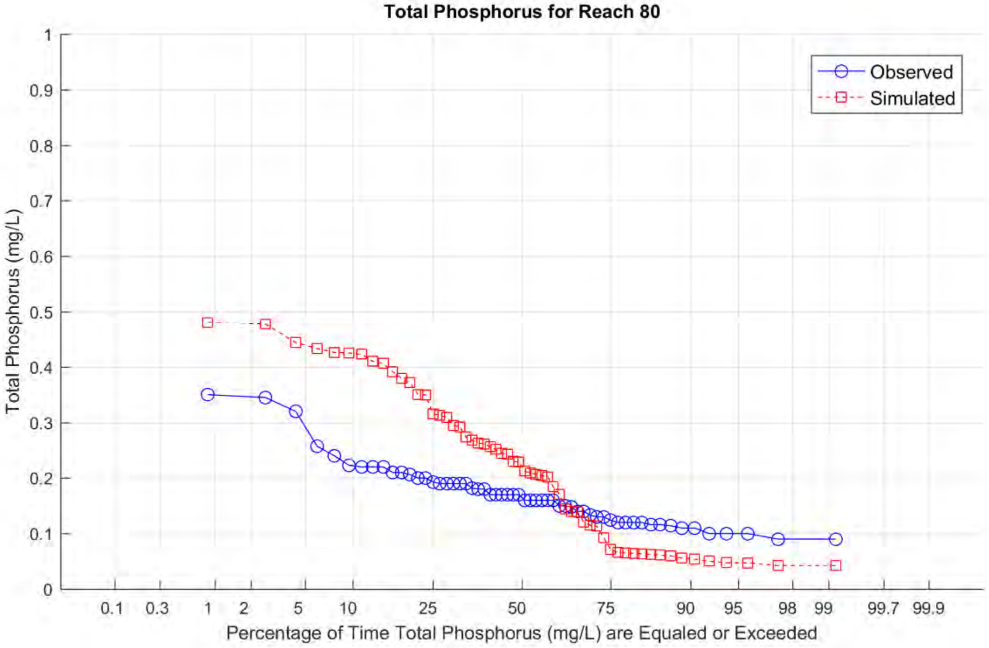

Figure C-10. Total Phosphorus Concentration Duration Calibration Plot at Reach 80.

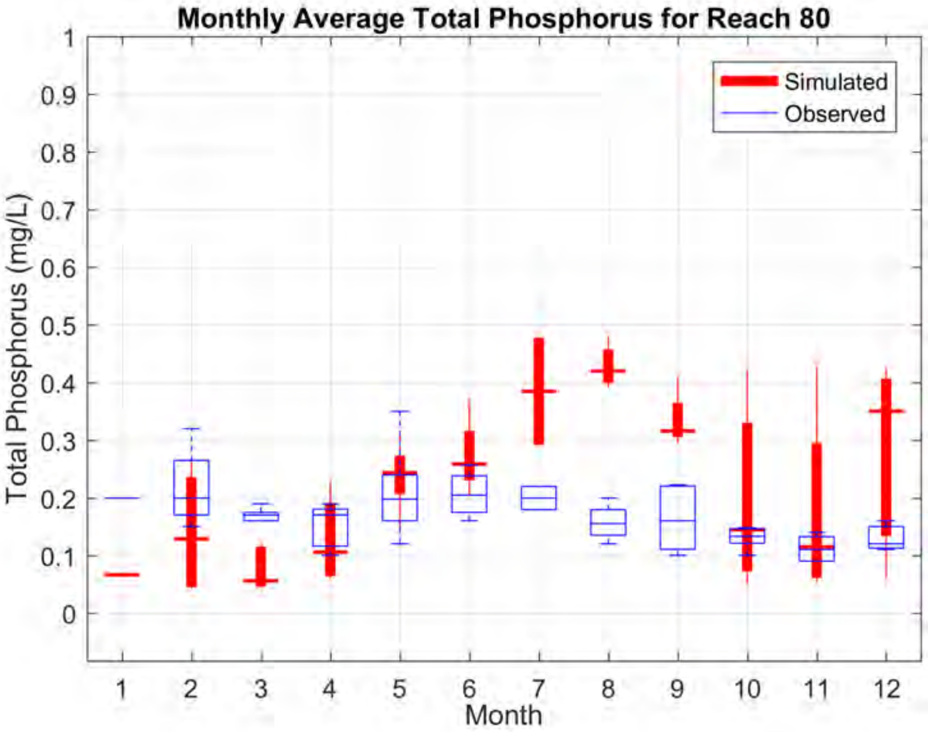

Figure C-11. Total Phosphorus Monthly Average Calibration Boxplots at Reach 80.

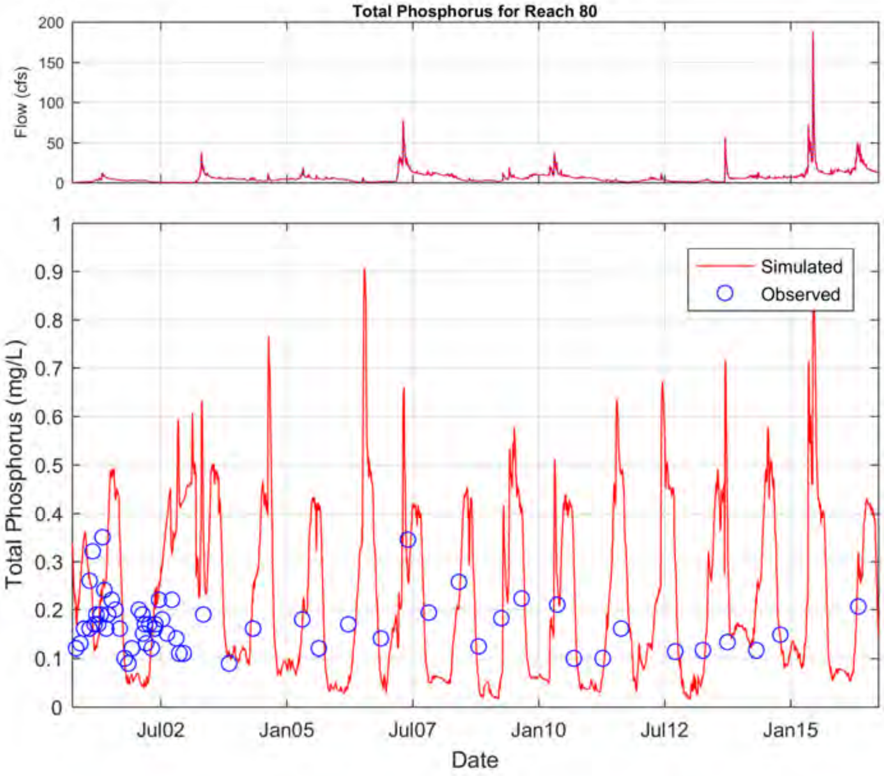

Figure C-12. Total Phosphorus Time-Series Calibration Plot at Reach 80.

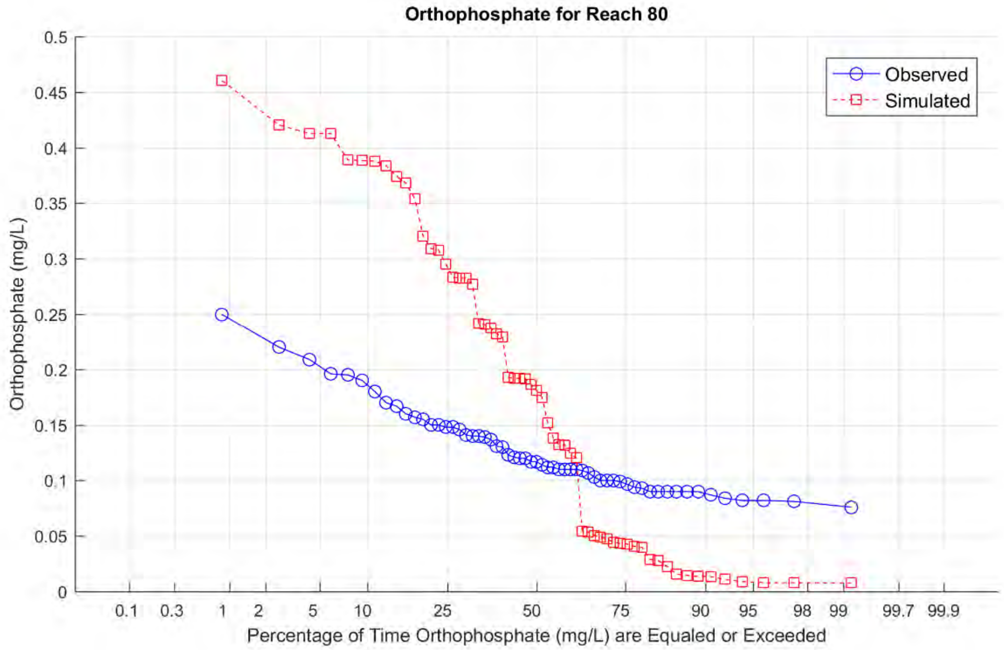

Figure C-13. Total Orthophosphate Concentration Duration Calibration Plot at Reach 80.

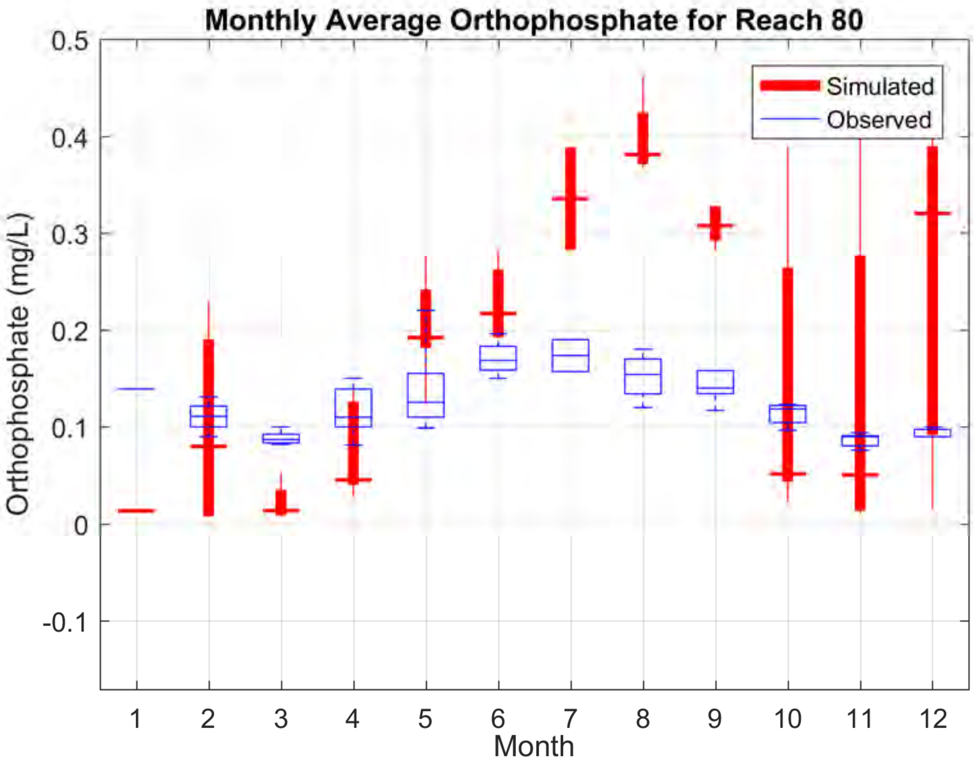

Figure C-14. Total Orthophosphate Monthly Average Calibration Boxplots at Reach 80.

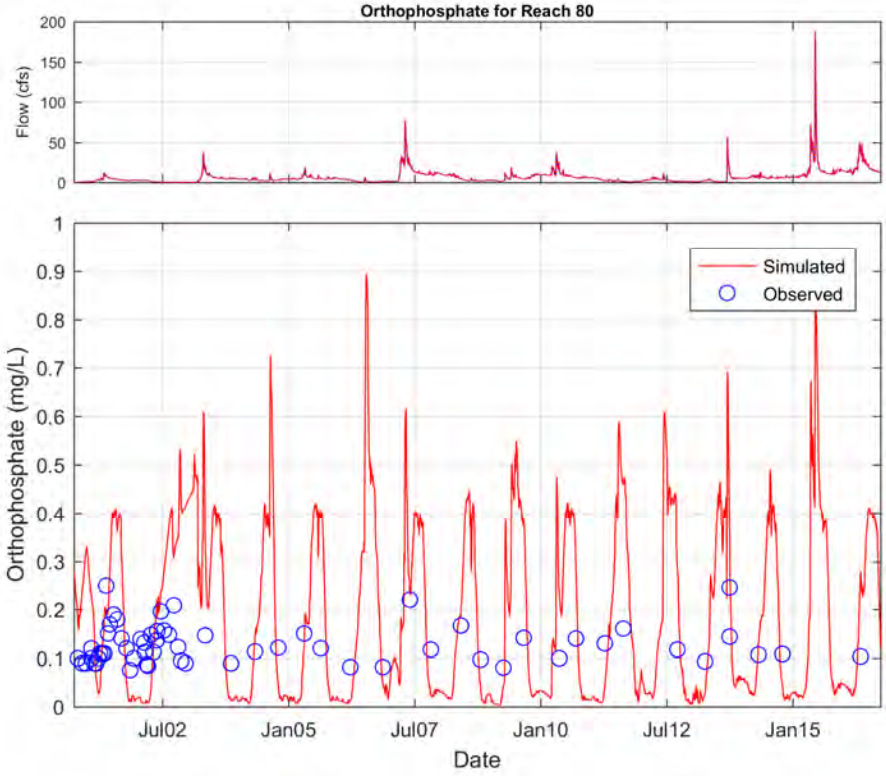

Figure C-15. Total Orthophosphate Time-Series Calibration Plot at Reach 80.

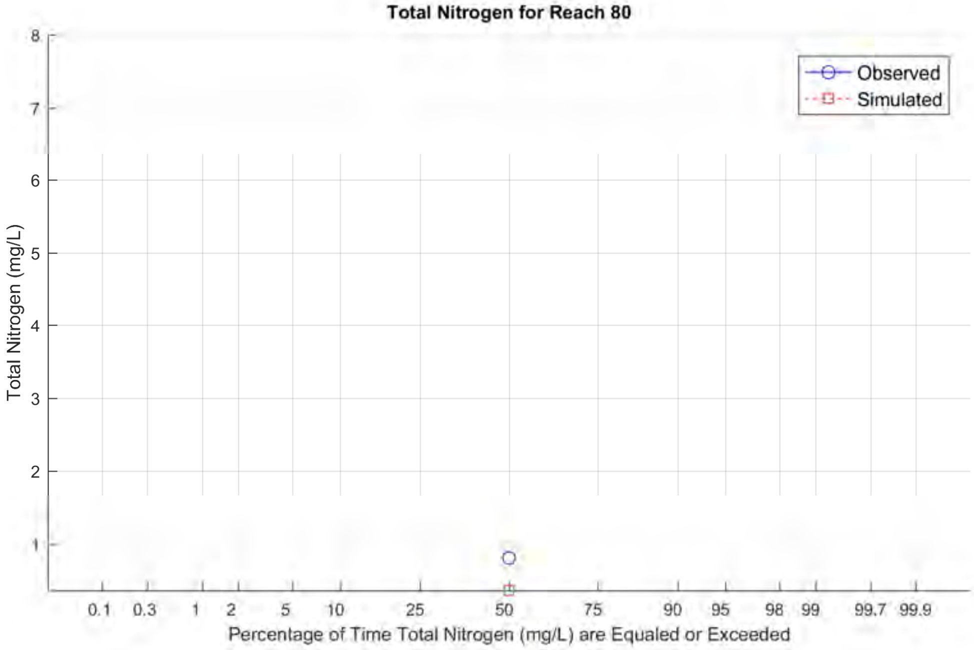

Figure C-16. Total Nitrogen Concentration Duration Calibration Plot at Reach 80.

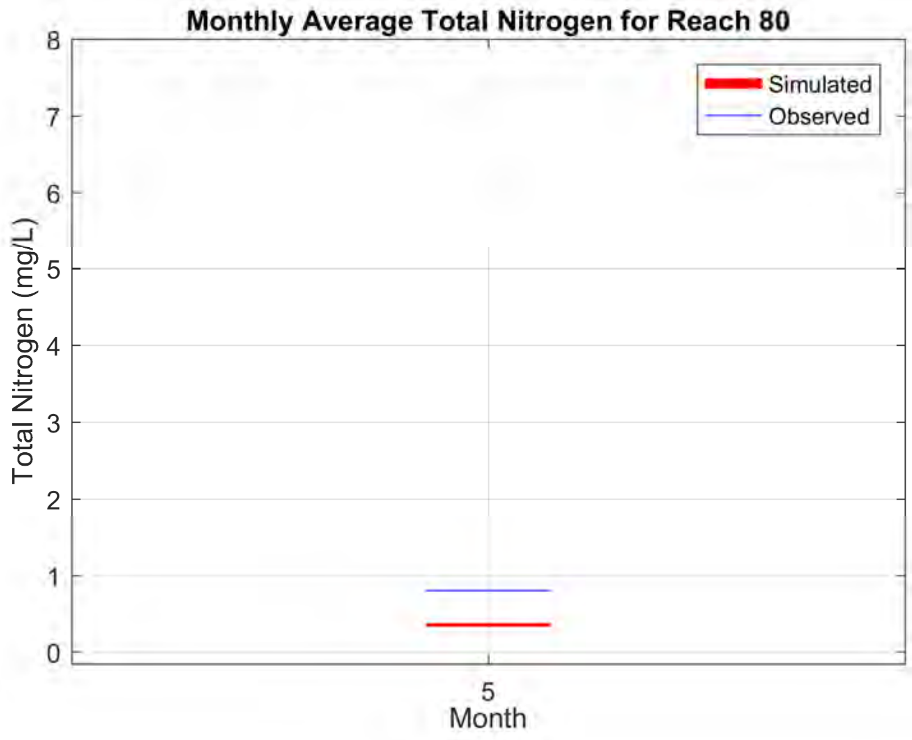

Figure C-17. Total Nitrogen Monthly Average Calibration Boxplots at Reach 80.

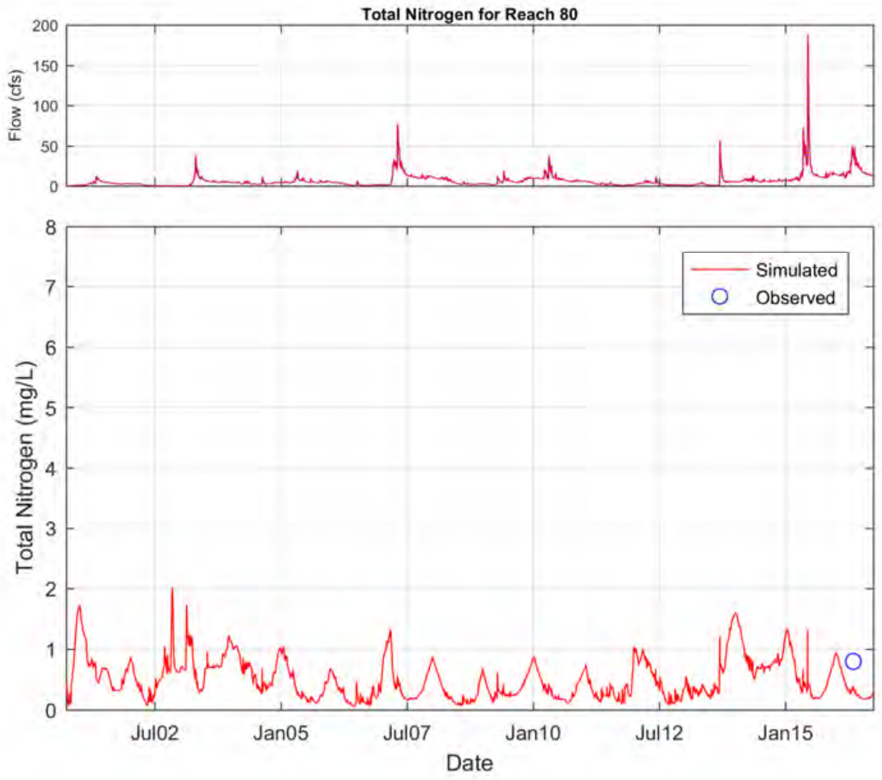

Figure C-18. Total Nitrogen Time-Series Calibration Plot at Reach 80.

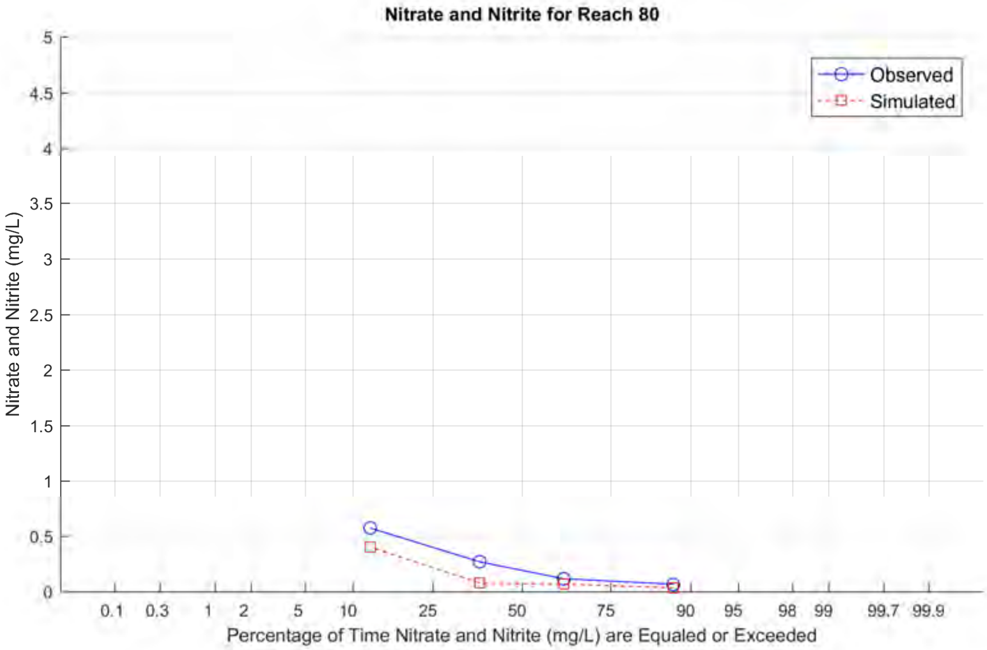

Figure C-19. Nitrate and Nitrite as Nitrogen Concentration Duration Calibration Plot at Reach 80.

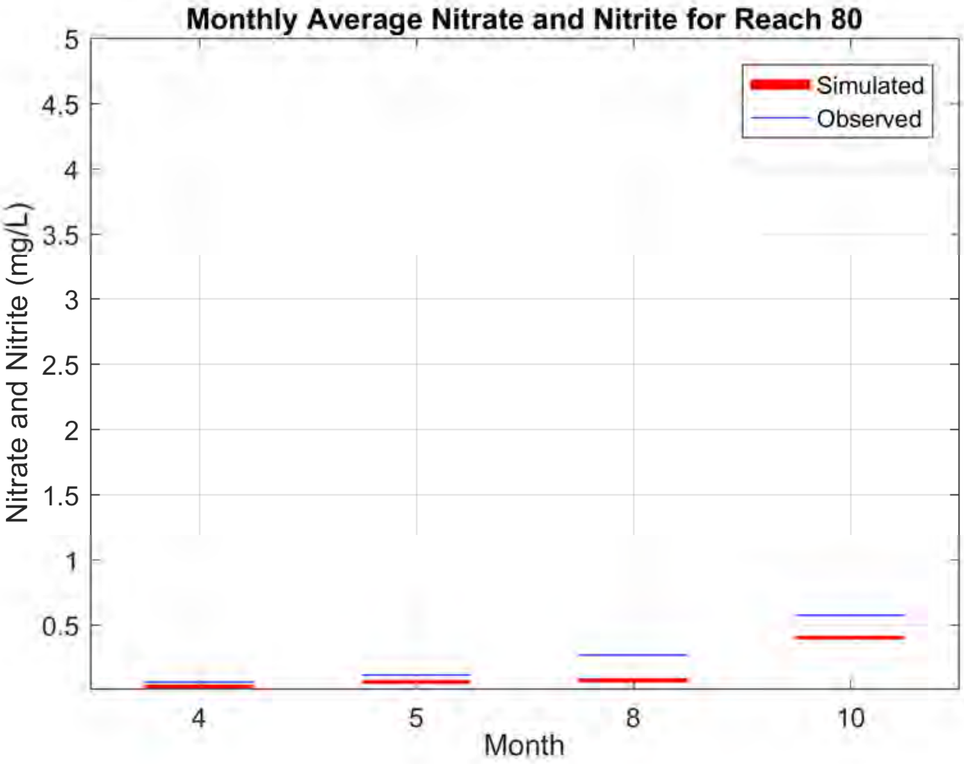

Figure C-20. Nitrate and Nitrite as Nitrogen Monthly Average Calibration Boxplots at Reach 80.

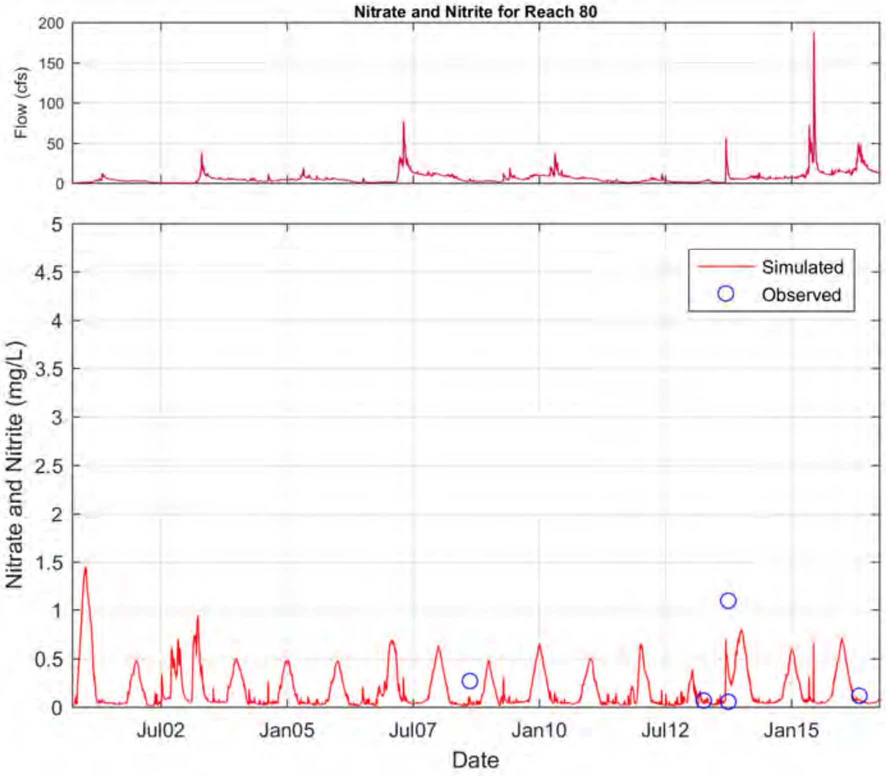

Figure C-21. Nitrate and Nitrite as Nitrogen Time-Series Calibration Plot at Reach 80.

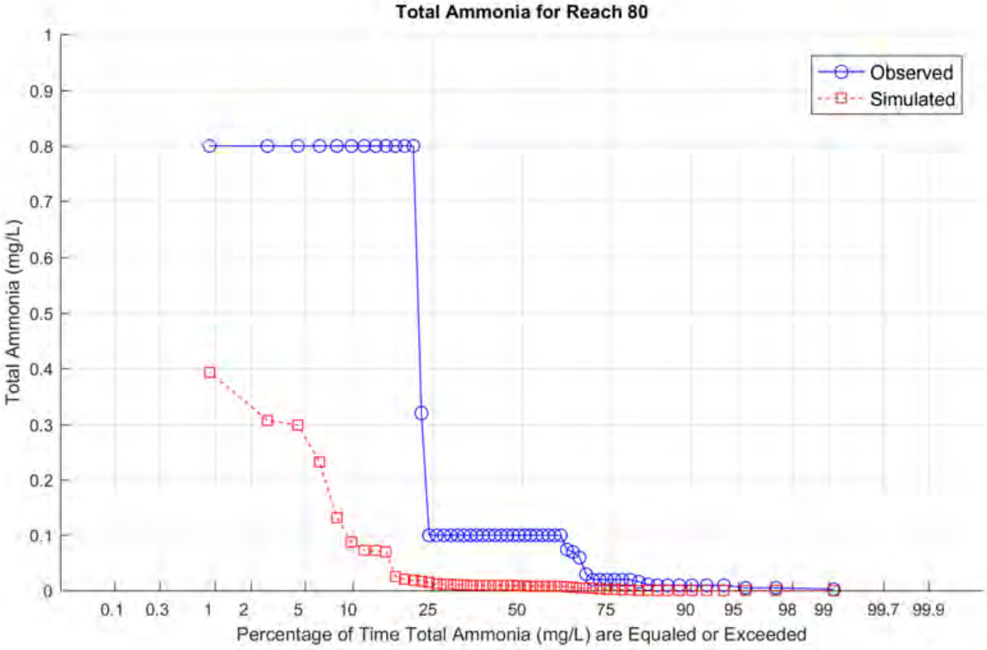

Figure C-22. Ammonia as Nitrogen Concentration Duration Calibration Plot at Reach 80.

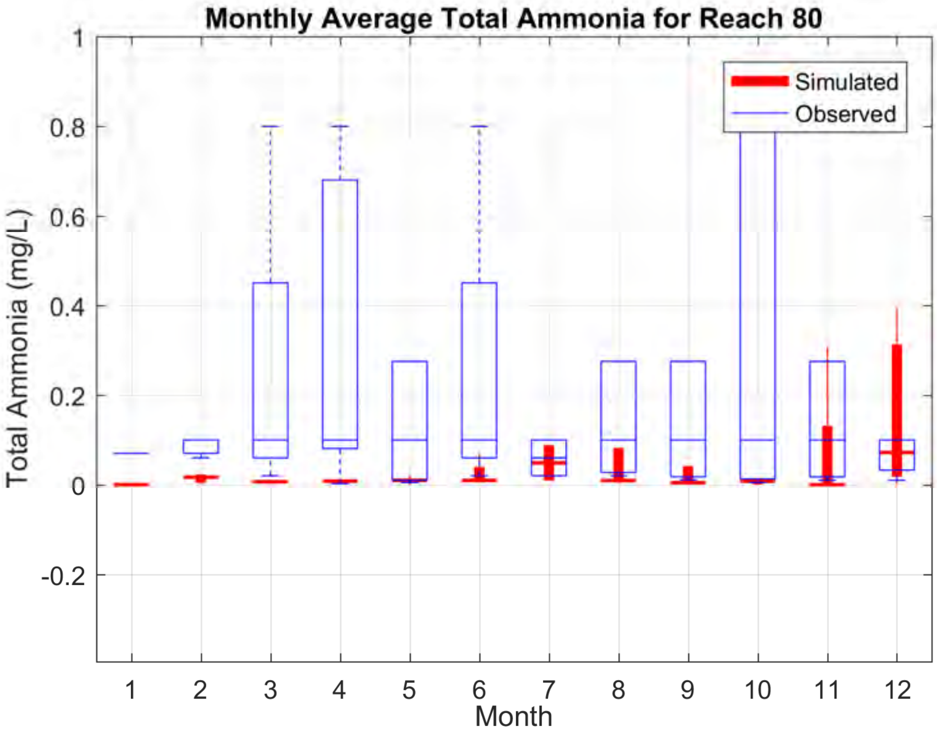

Figure C-23. Ammonia as Nitrogen Monthly Average Calibration Boxplots at Reach 80.

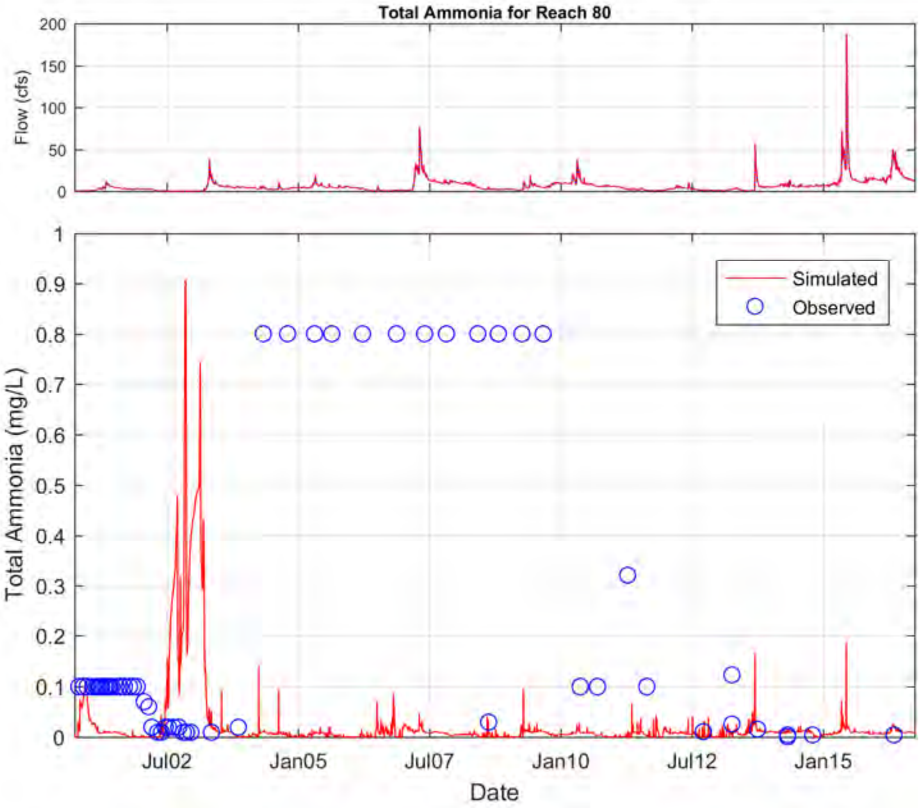

Figure C-24. Ammonia as Nitrogen Time-Series Calibration Plot at Reach 80.

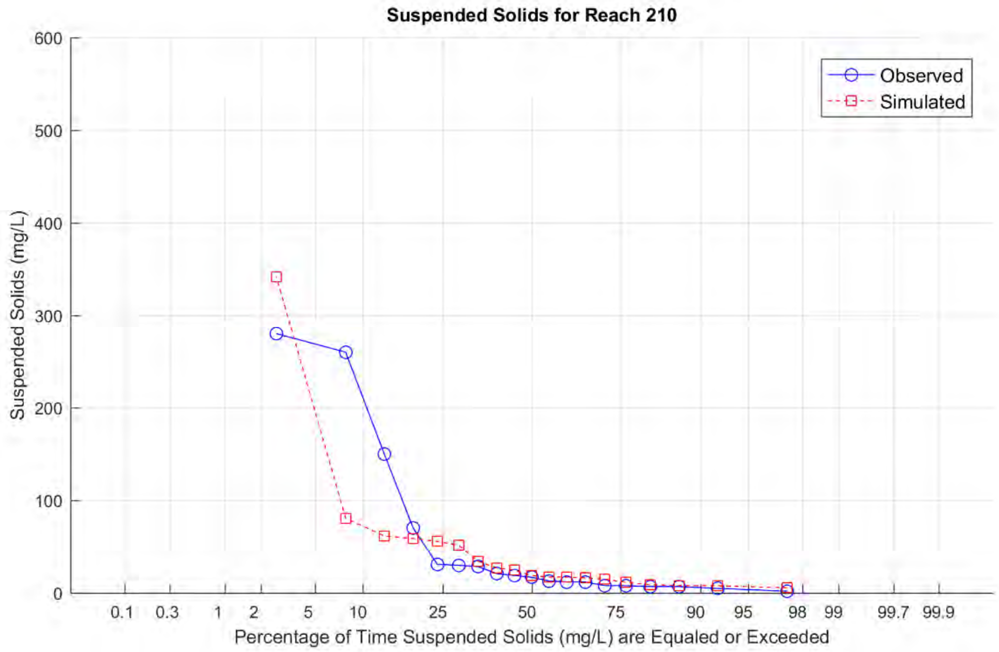

Figure C-25. Sediment Concentration Duration Calibration Plot at Reach 210.

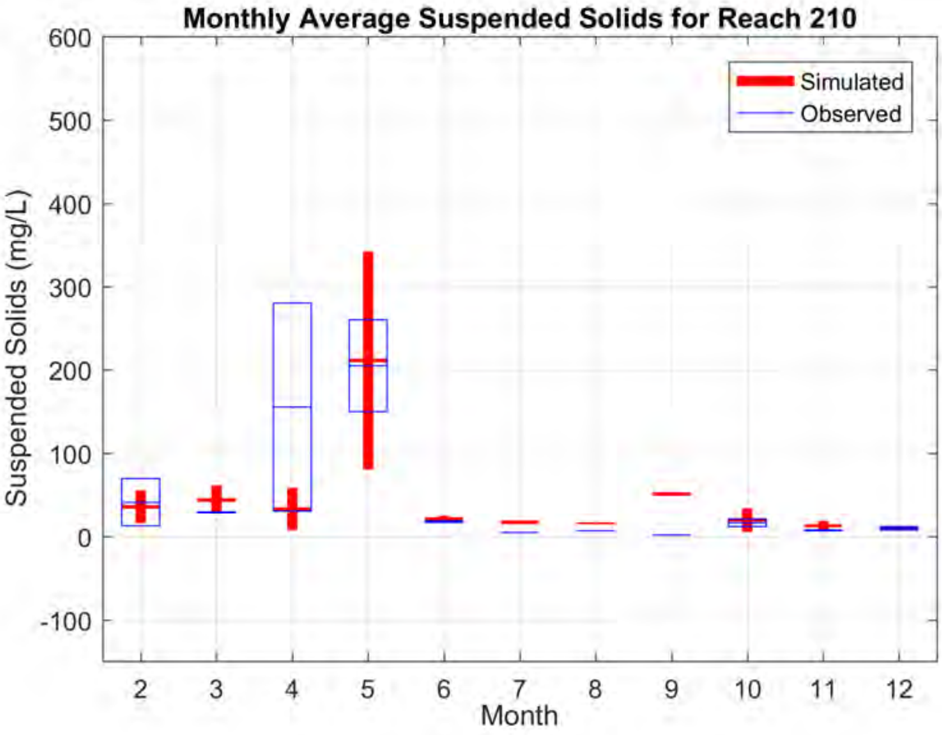

Figure C-26. Sediment Monthly Average Calibration Boxplots at Reach 210.

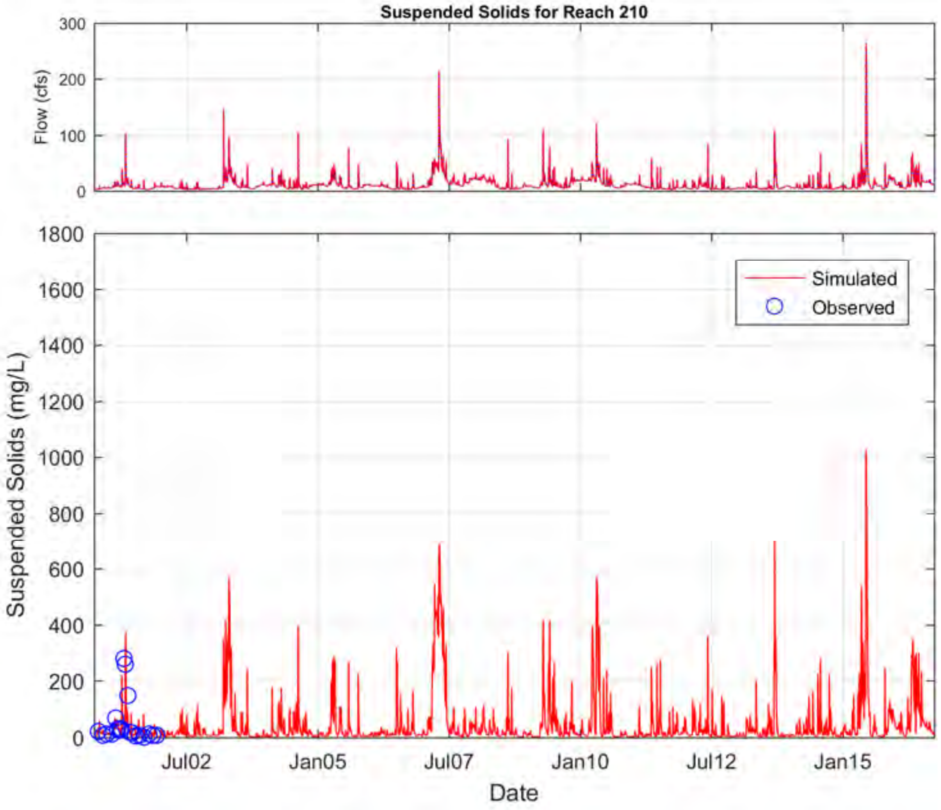

Figure C-27. Sediment Time-Series Calibration Plot at Reach 210.

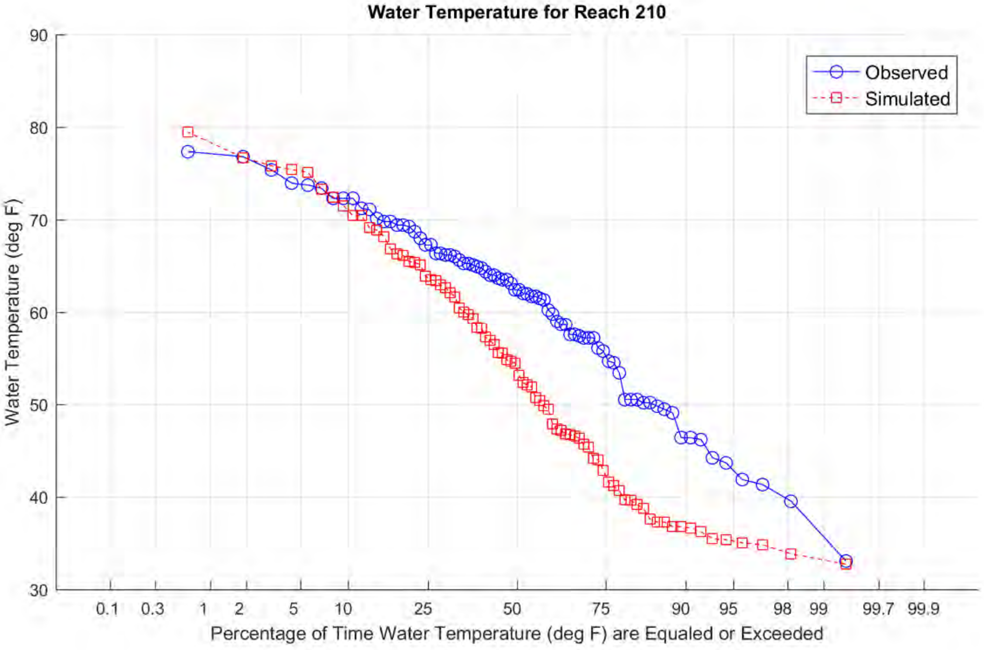

Figure C-28. Temperature Duration Calibration Plot at Reach 210.

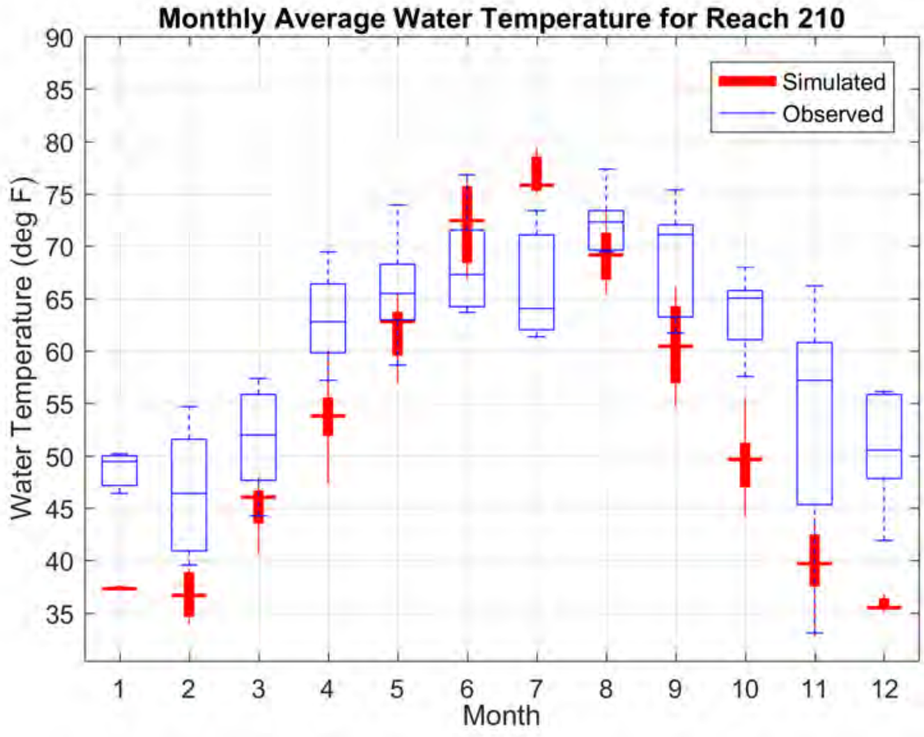

Figure C-29. Temperature Monthly Average Boxplots at Reach 210.

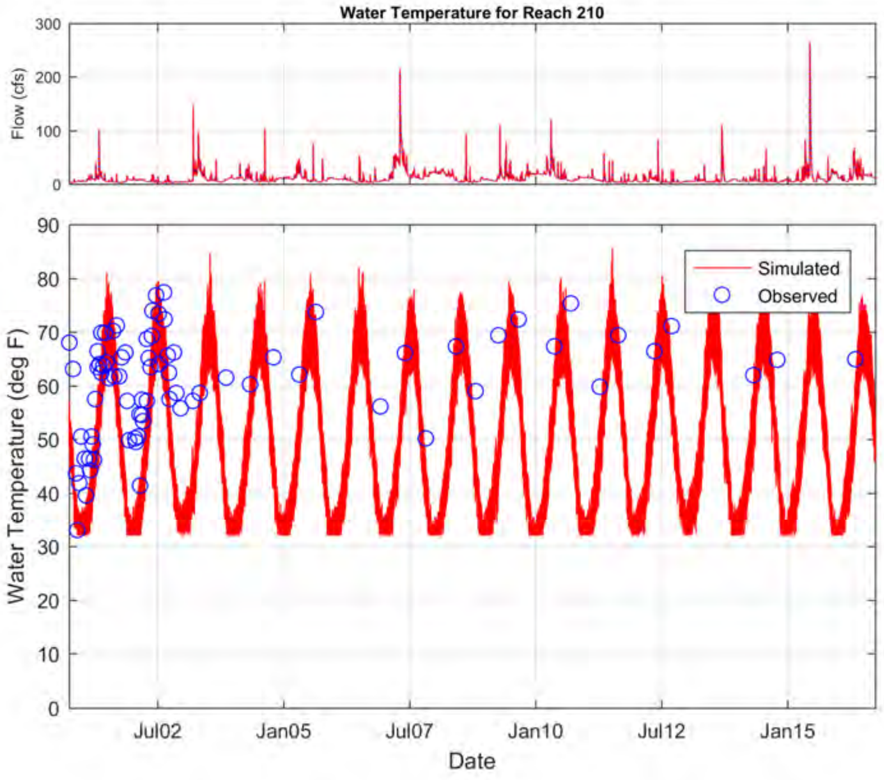

Figure C-30. Temperature Time-Series Calibration Plot at Reach 210.

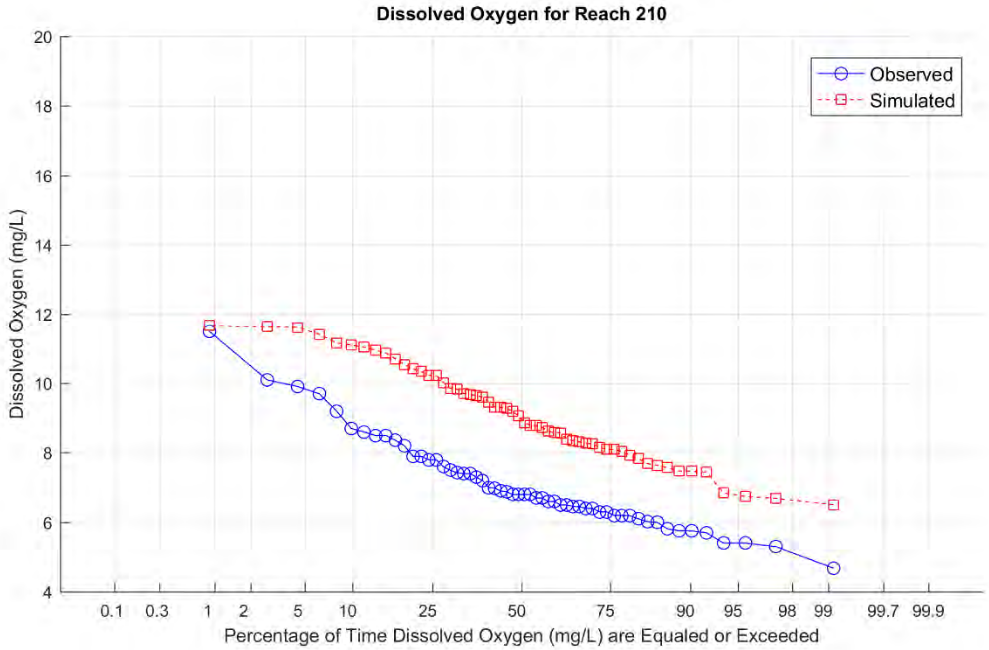

Figure C-31. Dissolved Oxygen Concentration Duration Calibration Plot at Reach 210.

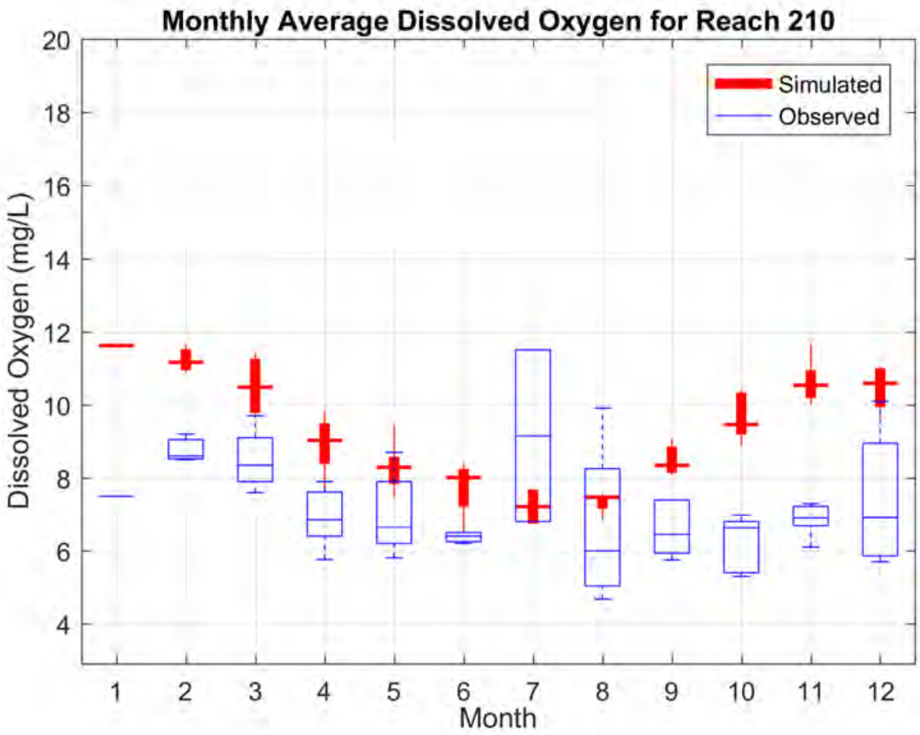

Figure C-32. Dissolved Oxygen Monthly Average Calibration Boxplots at Reach 210.

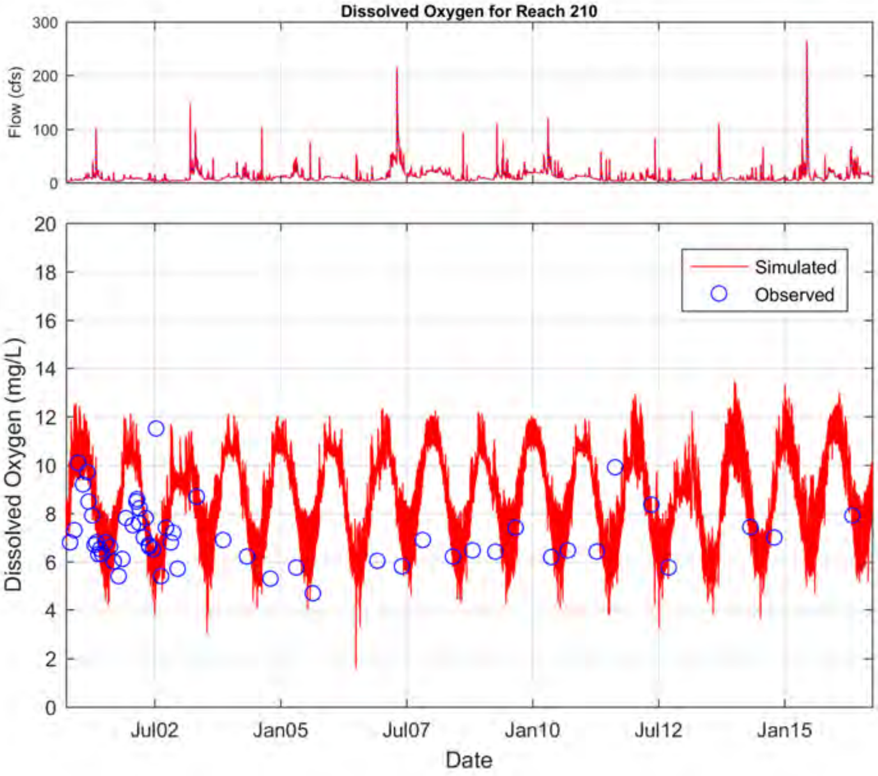

Figure C-33. Dissolved Oxygen Time-Series Calibration Plot at Reach 210.

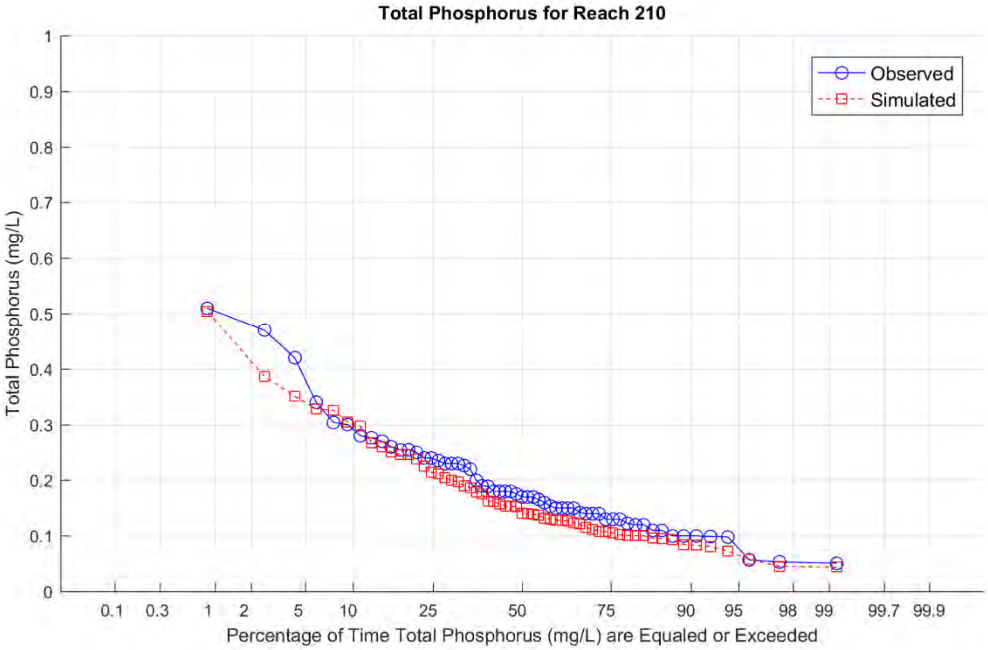

Figure C-34. Total Phosphorus Concentration Duration Calibration Plot at Reach 210.

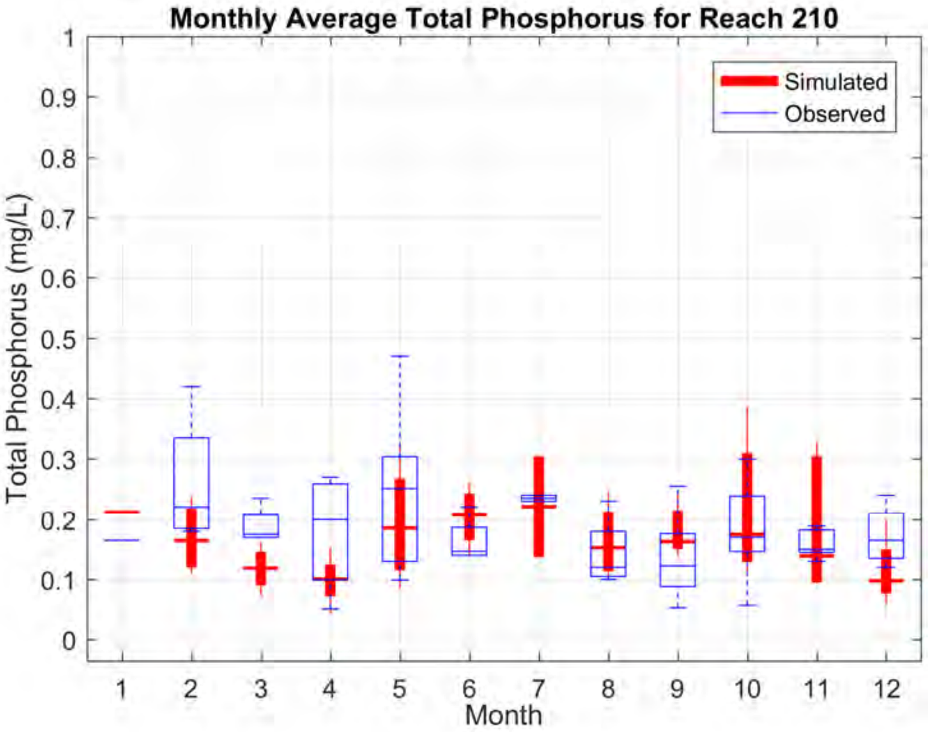

Figure C-35. Total Phosphorus Monthly Average Calibration Boxplots at Reach 210.

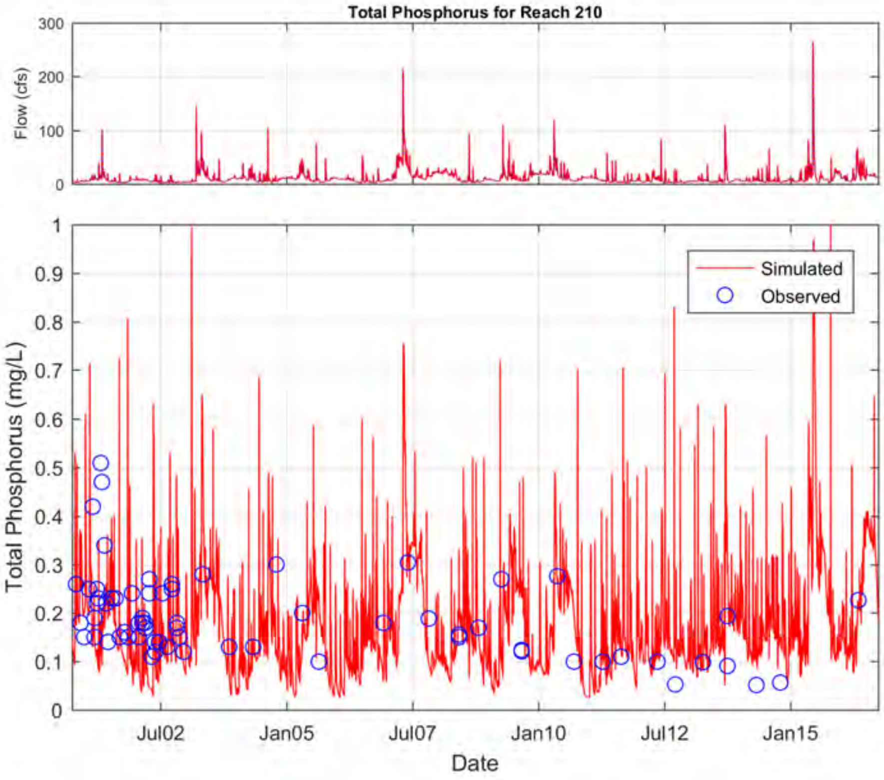

Figure C-36. Total Phosphorus Time-Series Calibration Plot at Reach 210.

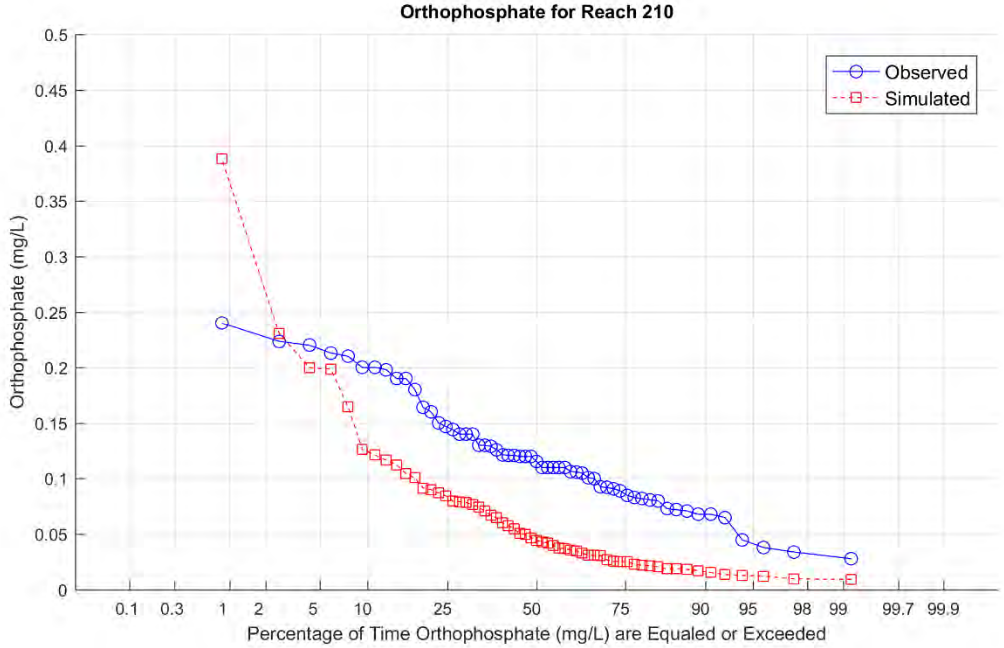

Figure C-37. Total Orthophosphate Concentration Duration Calibration Plot at Reach 210.

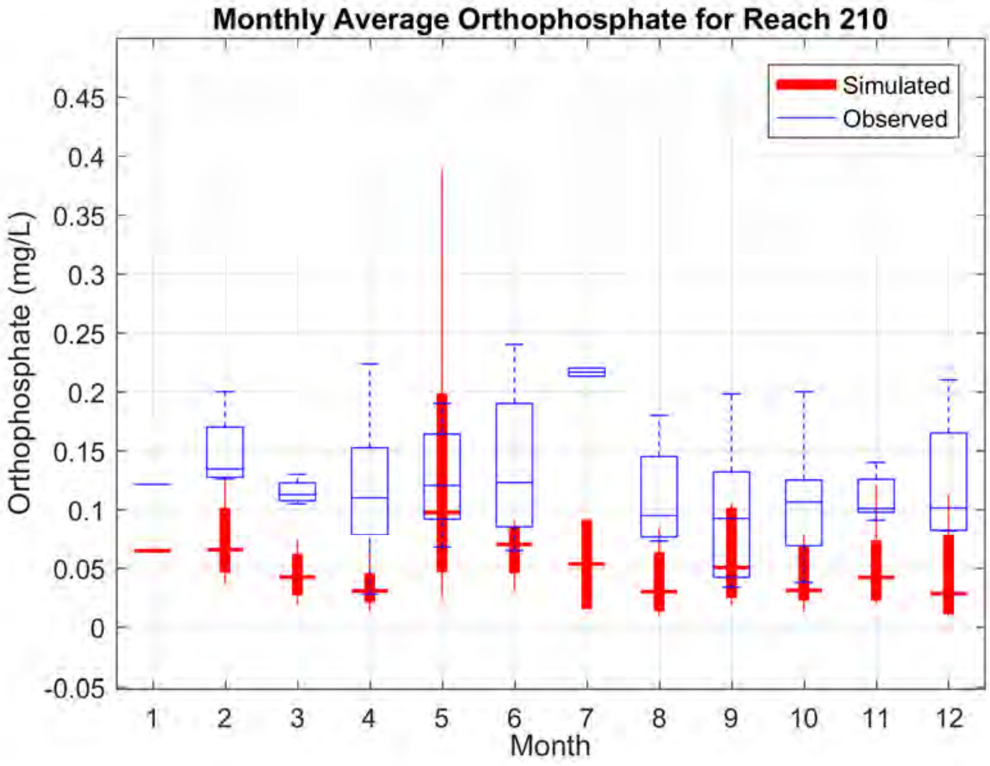

Figure C-38. Total Orthophosphate Monthly Average Calibration Boxplots at Reach 210.

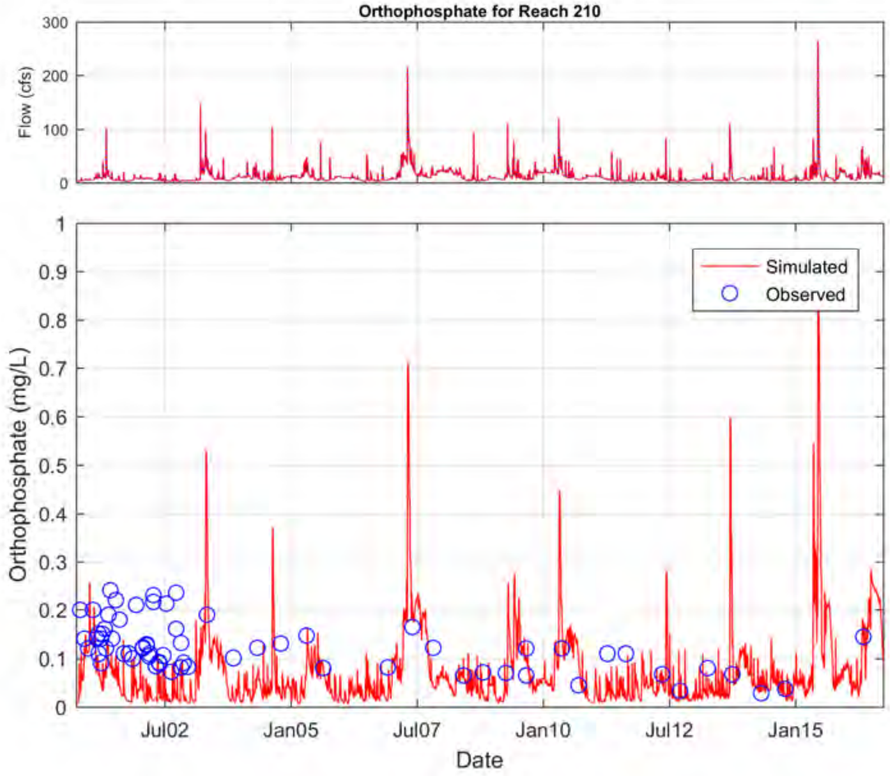

Figure C-39. Total Orthophosphate Time-Series Calibration Plot at Reach 210.

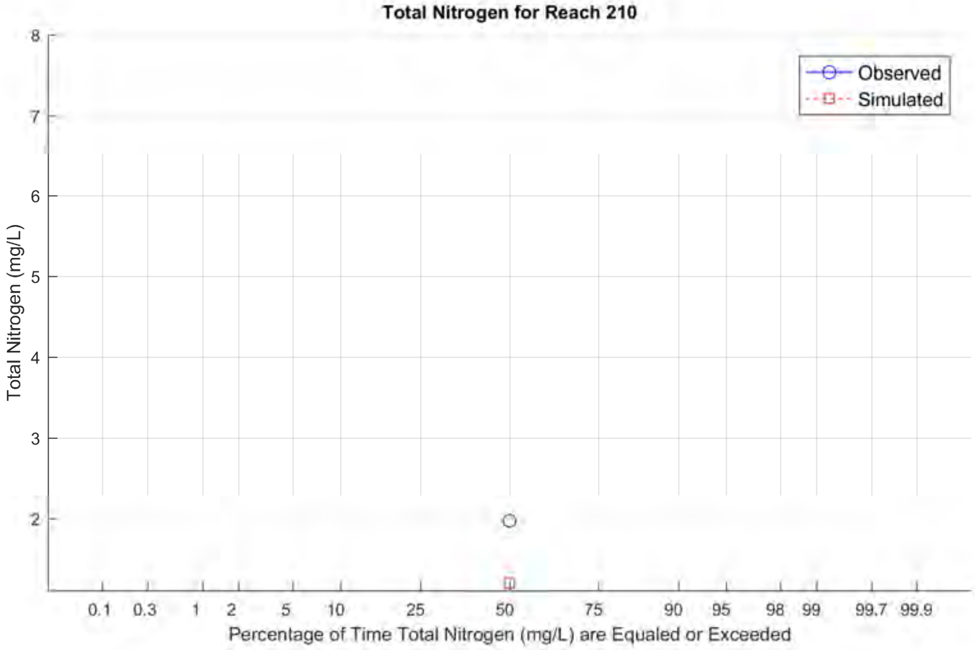

Figure C-40. Total Nitrogen Concentration Duration Calibration Plot at Reach 210.

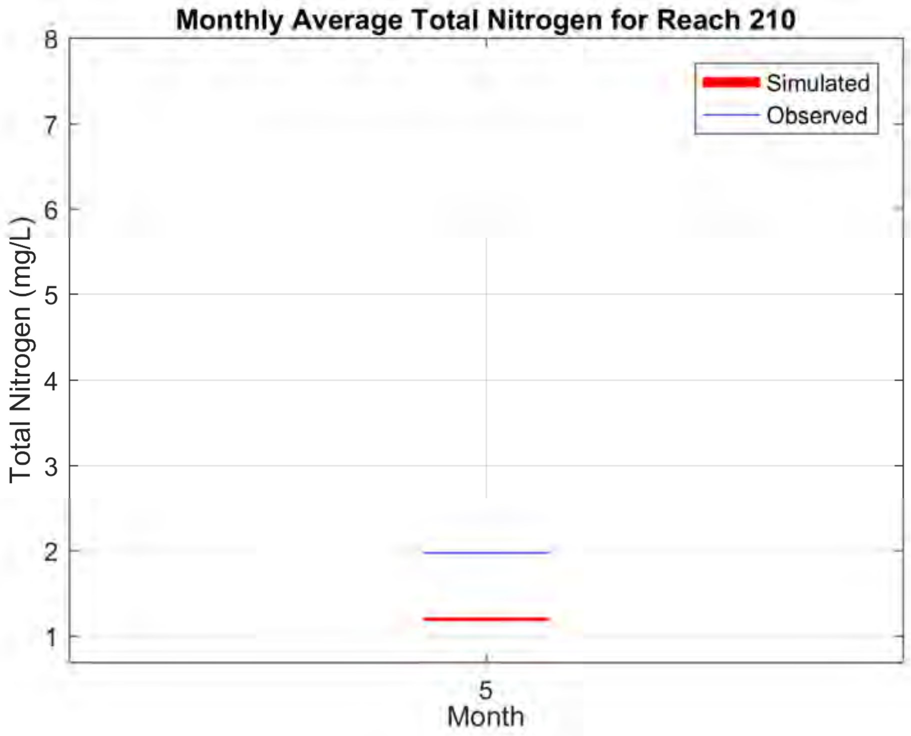

Figure C-41. Total Nitrogen Monthly Average Calibration Boxplots at Reach 210.

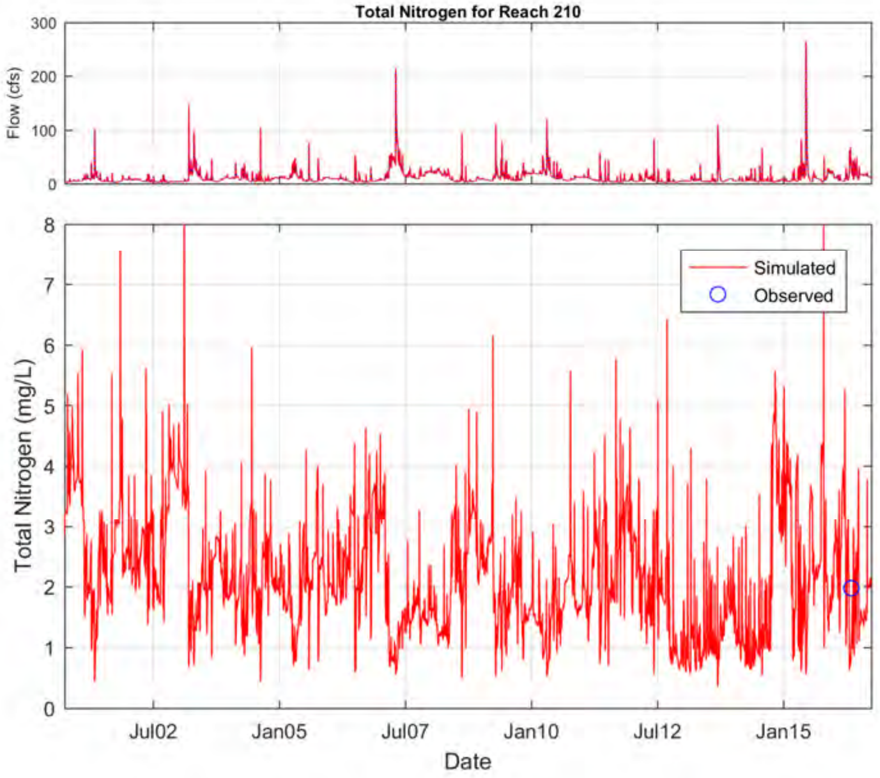

Figure C-42. Total Nitrogen Time-Series Calibration Plot at Reach 210.

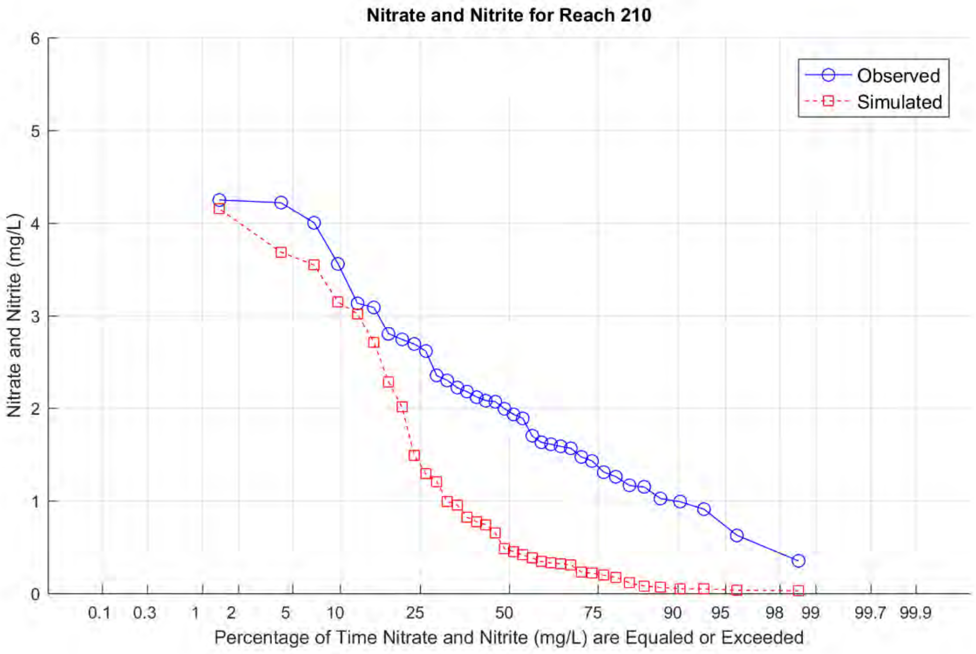

Figure C-43. Nitrate and Nitrite as Nitrogen Concentration Duration Calibration Plot at Reach 210.

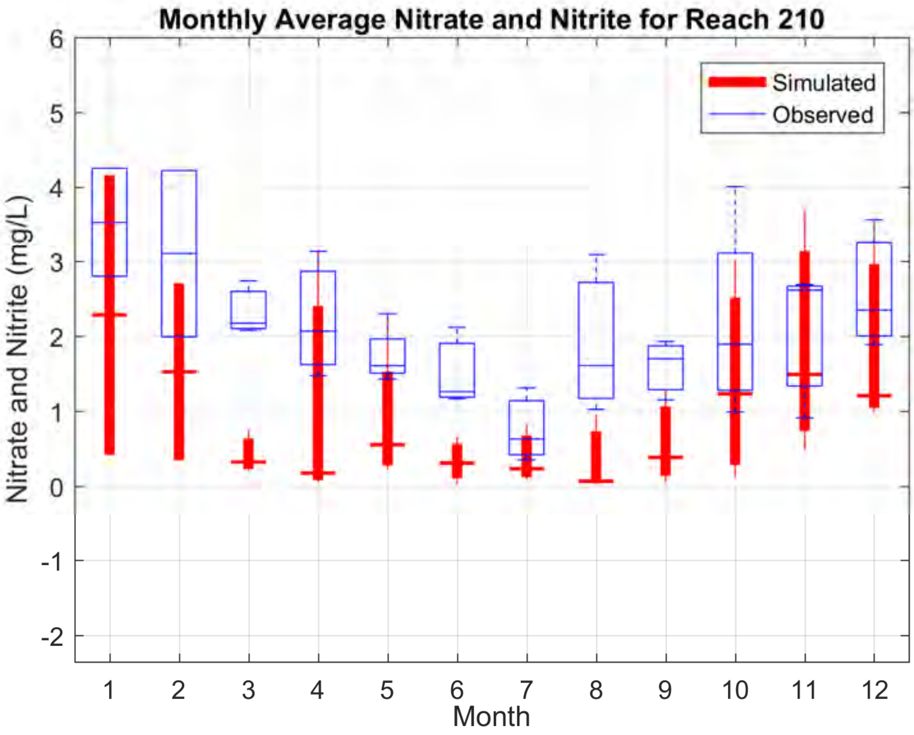

Figure C-44. Nitrate and Nitrite as Nitrogen Monthly Average Calibration Boxplots at Reach 210.

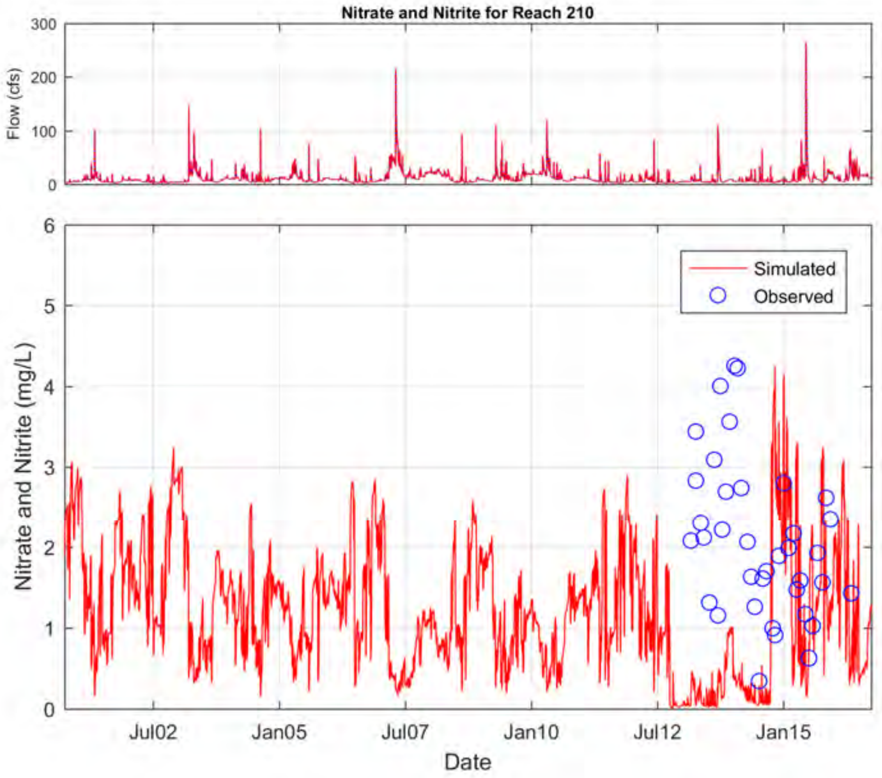

Figure C-45. Nitrate and Nitrite as Nitrogen Time-Series Calibration Plot at Reach 210.

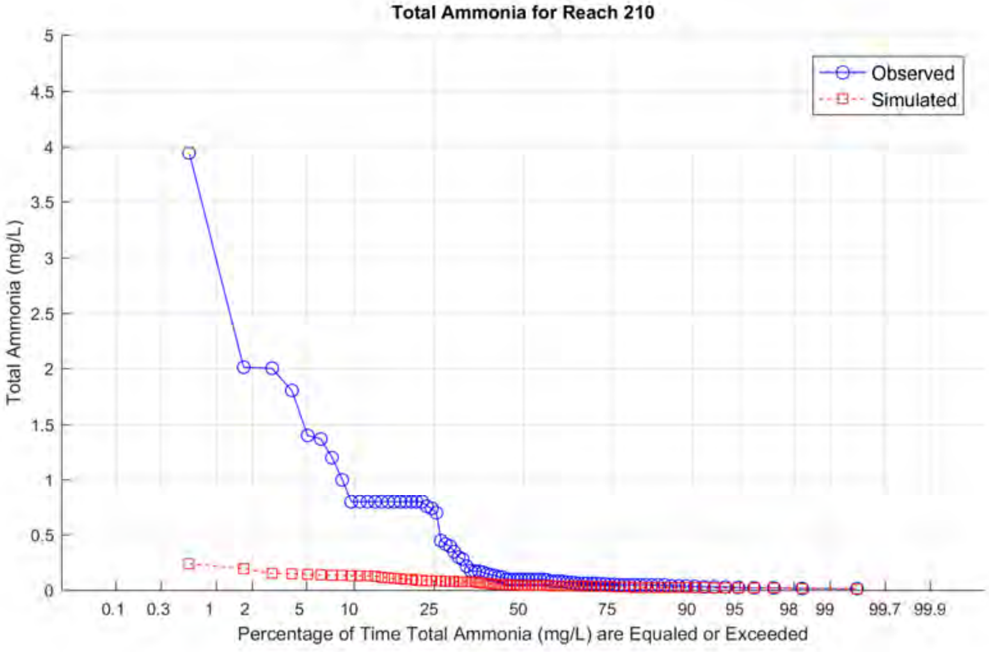

Figure C-46. Ammonia as Nitrogen Concentration Duration Calibration Plot at Reach 210.

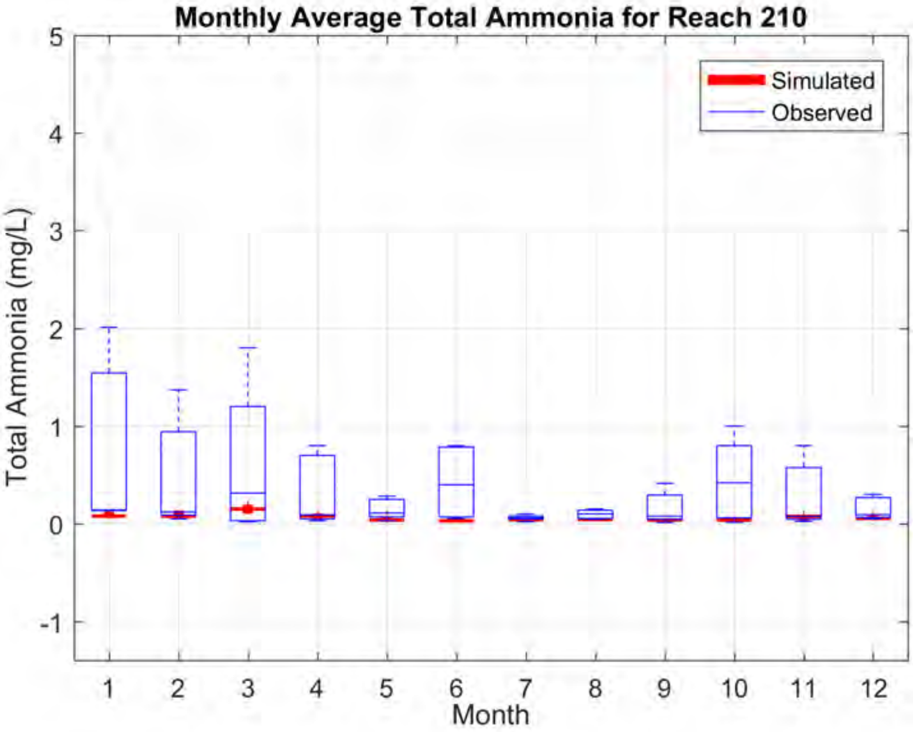

Figure C-47. Ammonia as Nitrogen Monthly Average Calibration Boxplots at Reach 210.

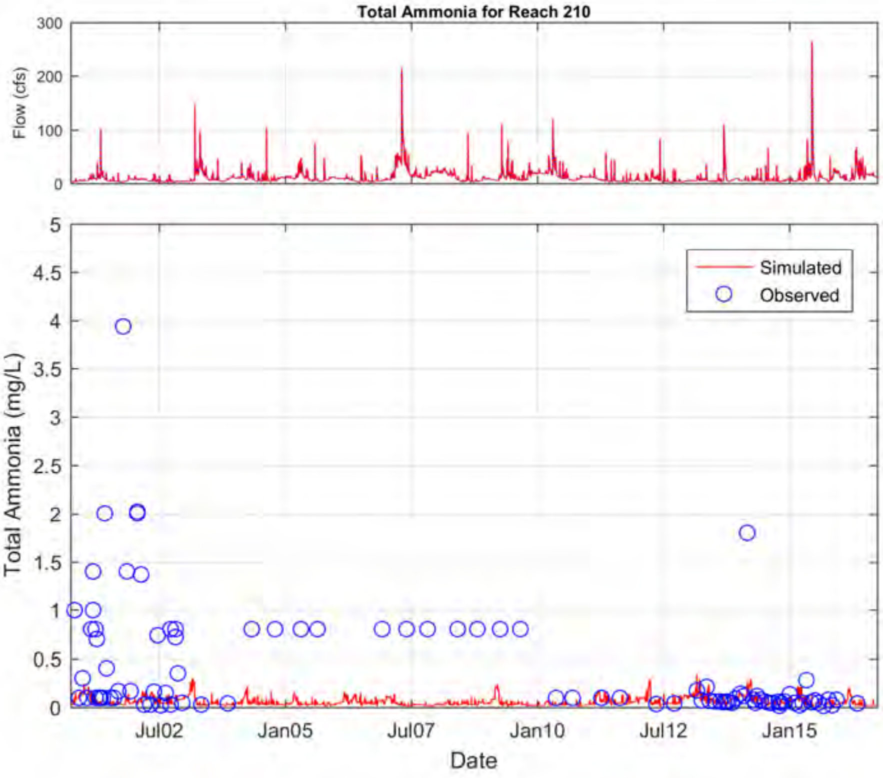

Figure C-48. Ammonia as Nitrogen Time-Series Calibration Plot at Reach 210.