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Appendix A – WaterFALL Calibration

Appendix A: WaterFall Calibration

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Abbreviations

Abbreviation	Definition
AWC	Available water capacity
cfs	Cubic feet per second
CN	Curve number
CWWMG	Catawba-Wateree Water Management Group
DA	Drainage area
ET	Evapotranspiration
F	Fahrenheit
ICLUS	Integrated Climate and Land Use Scenarios
in	Inches
in/d	Inches per day
in/yr	Inches per year
kg/ha	Kilograms per hectare
KGE	Kling-Gupta Efficiency
KGElf	Kling-Gupta Efficiency for low flow
lbs/d	Pounds per day
lbs/yr	Pounds per year
lbs/acre/yr	Pounds per acre per year
lbs/ft/yr	Pounds per foot per year
m/d	Meters per day
MAF	Mean annual flow
mg/kg	Milligrams per kilogram
mg/L	Milligrams per liter
MGD	Million gallons per day
mi^2	Square miles
MUSLE	Modified Universal Soil Loss Equation
NHDPlus	National Hydrography Dataset Plus
NLCD	National Land Cover Database
NPDES	National Pollutant Discharge Elimination System
NRMSE	Normalized Root Mean Square Error
NSE	Nash-Sutcliffe Efficiency
PBIAS	Percent Bias
PRISM	Parameter-elevation Regressions on Independent Slopes Model
RTI	RTI International

Abbreviation	Definition
SSURGO	Soil Survey Geographic Database
USLE	Universal Soil Loss Equation
WaterFALL	Watershed Flow and ALLocation model
rNSE	Revised Nash-Sutcliffe Efficiency
TN	Total nitrogen
TP	Total phosphorus
TSS	Total suspended solids
USDA	U.S. Department of Agriculture
USEPA	U.S. Environmental Protection Agency
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
wNSE	Weighted Nash-Sutcliffe Efficiency
WQX	Water Quality Exchange

1 Introduction to WaterFALL Model

The WaterFALL® modeling platform, developed by RTI International (RTI), simulates daily streamflow and selected water quality parameters at high spatial resolution. The model operates at the U.S. Geological Survey (USGS) National Hydrography Dataset Plus Version 2.1 (NHDPlus[1]) catchment scale, representing each catchment as an individual modeling unit connected within a full watershed network (Figure 1-1). This structure supports both localized analysis and watershed-wide summaries of hydrologic and water quality conditions.

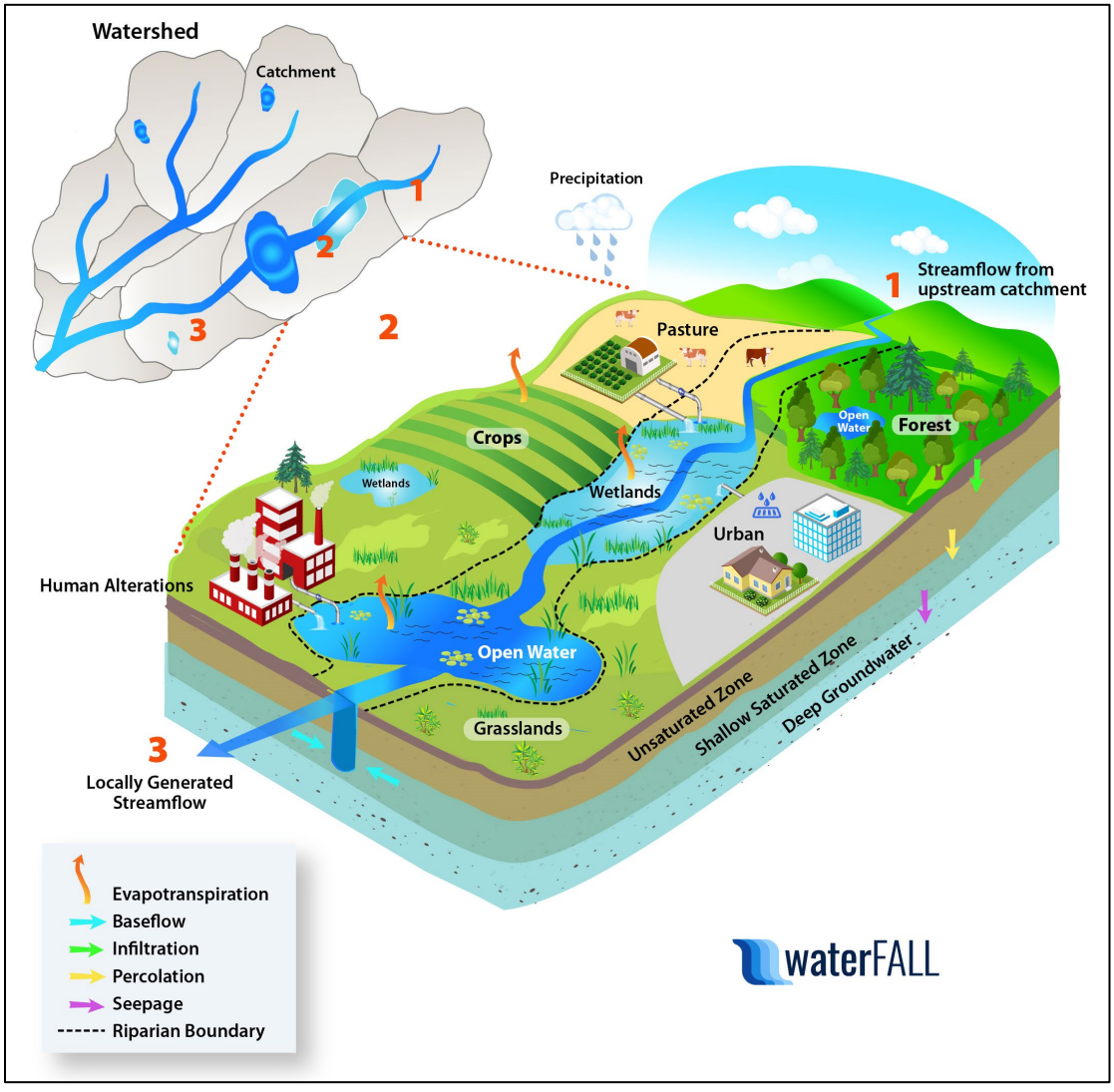


Figure 1-1. WaterFALL Conceptual Diagram.

[1]McKay, L. et al. (2019). NHDPlus Version 2: User Guide, Data Model Version 2.1 (Horizon Systems). Available at https://www.epa.gov/system/files/documents/2023-04/NHDPlusV2_User_Guide.pdf.

1.1 Model Processes

WaterFALL, which stands for Watershed Flow and ALLocation model,simulates two components of surface water flow within a catchment: (1) runoff, storage and overflow runoff within on- and off-stream waterbodies, and simple snowmelt and accumulation modules across the land surface and (2) base flow released from the saturated zone over time through soil moisture and groundwater. Water moves through the compartments represented by the model (i.e., surface, unsaturated zone, shallow saturated zone, and deep groundwater) based on physical parameters and rate constants governed by process-based equations and mass balance principles. Across the surface, WaterFALL separates landscape processes into upland and riparian zones and represents land cover and dominant soil characteristics within each area. The runoff from each land use in the upland (i.e., non-riparian) area is determined first. A portion of runoff is transported to off-stream open water or wetland areas, which can store the water or overflow and contribute to runoff. Runoff from the upland area is then delivered to the riparian areas where the surface runoff can infiltrate or continue running off into the stream channel or onstream waterbodies.

Rainfall that does not run off the land surface infiltrates into the unsaturated soil layer. Infiltrated water resides in the unsaturated soil zone until it percolates downward into the saturated zone. Evapotranspiration (ET), in addition to percolation, depletes water from the unsaturated layer with differentiation in rates between the growing (i.e., leaf out) and dormant seasons. The saturated zone is depleted by local groundwater flow to surface water (i.e., shallow base flow) and by seepage to a regional groundwater system.

In addition to flow, the model simulates the movement of sediment, total nitrogen (TN), and total phosphorus (TP). Loads of these constituents are tracked from their sources, through surface runoff and groundwater pathways, to streams, rivers, and lakes within the model domain. WaterFALL tracks the pathways that each of these chemicals travel through the watershed so that the relative contribution of different pollutant sources can be assessed. WaterFALL can be used to directly assess loadings from individual pervious (rural) land covers with runoff, manure/fertilizer applications, buildup and washoff on impervious (urban) surfaces, onsite wastewater systems (e.g., septic systems), and subsurface load accumulation and transport to the stream with baseflow as well as point sources contributions and streambank erosion within the stream network.

WaterFALL completes this hydrologic cycle simulation for each catchment within the NHDPlus. Local streamflow and constituent loading contributions are routed to estimate downstream cumulative streamflow and loads using a time of travel through each catchment based on its average velocity reported in the NHDPlus dataset.

Within each catchment, the land cover/use, soils, and subsurface are characterized. Coupling the catchment characteristics with daily estimates of temperature, precipitation, water uses (withdrawals or returns with accompanying constituent loadings), and reservoir characteristics within the network provides a stream segment-scale daily rainfall-runoff and base flow simulation of streamflows and water quality for an entire watershed.

1.2 Land Cover/Land Use and Soil Drivers

To represent the hydrologic processes that occur across a land surface, WaterFALL incorporates land cover and land use distributions across the watershed. It utilizes datasets such as the National Land Cover Database (NLCD) to parameterize vegetation, imperviousness, and management-related response differences among catchments. WaterFALL is also parameterized based on the different geophysical areas that exist within a watershed (i.e., riparian and upland areas). Riparian areas are the lands adjacent to the bank of a river or stream while upland areas are those lands in the watershed that are outside the riparian area. Differentiating between these areas is important as the characteristics of the riparian area impact the attenuation of runoff and the transport of water quality constituents.

The model derives soil parameters from sources such as the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service's Soil Survey Geographic Database (SSURGO), which includes attributes related to infiltration capacity, permeability, and water-holding capacity. These properties partition precipitation among surface runoff, soil storage, plant uptake, and groundwater recharge, while also determining the potential for constituent transport during storm events.

1.3 Climate

Daily climate inputs drive model simulations. Required time series include precipitation and temperature, which control the amount of water entering the system and the atmospheric demand for water loss through ET. Due to the distributed nature of the model's catchment framework, gridded climate time series are used rather than observations from a single climate station. Each catchment is assigned the daily time series of precipitation and average temperature for the grid cell which it intersects. If a catchment lies within multiple grid cells, an area-weighted average is applied to produce the daily time series for the catchment from the intersecting grid cells. WaterFALL relies on the 4-kilometer gridded, daily dataset from PRISM[2].

1.4 Anthropogenic Factors

WaterFALL is enhanced with the capability to represent human interactions with the natural hydrologic system such as reservoir releases, water withdrawals, and point source discharges along the stream network. This approach allows simulation of altered streamflow conditions. Using the NHDPlus catchment basis for WaterFALL means that point alterations to the hydrologic network (i.e., withdrawal and discharge pipes) can be indexed directly to the specific segment of stream on which they fall rather than aggregating these uses to larger watersheds or tributaries. WaterFALL allows for either monthly or daily time series of withdrawals and discharges as external inputs to the model, while reservoirs are simulated dynamically within the routing routines of the model.

[2] PRISM Climate Group. (2019, March). PRISM Climate Data. Oregon State University. http://prism.oregonstate.edu

1.5 Model Calibration

Where monitoring data exist, the framework calibrates model parameters against observed streamflow and water quality records. This calibration aligns simulated outputs with measured conditions and improves performance across different hydrologic settings. Gages with observed streamflow across a range of drainage areas and hydrologic conditions are used to ensure the model accurately represents existing conditions and variability. The spatially explicit nature of WaterFALL allows for calibrations to vary by catchment within a single watershed so that the natural and human-caused variations in physical conditions can be accounted for within the model simulations. Further details on the model's calibration parameters and process are included in Section 4.

2 Watershed Model Parameterization

2.1 Land Surface (Land Use/Land Cover)

Land surface characteristics play an important role in the modeling framework because they influence how much precipitation infiltrates the ground surface and how much becomes runoff. To represent both current and future conditions, the model uses a combination of observed land cover data and projected (future) land use information. This approach allows the model to reflect how changes in land development patterns may affect watershed hydrology and water quality over time.

Land cover and land use inputs were developed using two primary datasets: the 2019 NLCD[3] and the Integrated Climate and Land Use Scenarios (ICLUS)[4]. The NLCD provides a detailed, 30-meter resolution map of land cover and describes what is physically present on the land surface, such as forests, wetlands, or developed areas. These data serve as the foundation for assigning hydrologic parameters in the model.

The ICLUS dataset was used to represent human land use patterns and projected future changes. It includes both current conditions and projections through 2070 based on moderate assumptions about population growth and development. These projections help estimate where and how development may occur over time.

Because NLCD and ICLUS describe different aspects of the landscape, they were combined to create a more complete representation of land conditions. NLCD represents physical land cover, while ICLUS represents human land use. This approach maintains the spatial detail of the NLCD while incorporating the forward-looking information provided by ICLUS.

[3] Dewitz, J., and U.S. Geological Survey. (2021). National Land Cover Database (NLCD) 2019 Products (ver. 2.0, June 2021): U.S. Geological Survey data release. Available at https://doi.org/10.5066/P9KZCM54.

[4] U.S. EPA (Environmental Protection Agency). (2016). Updates to the Demographic and Spatial Allocation Models to Produce Integrated Climate and Land Use Scenarios (ICLUS) Version 2. National Center for Environmental Assessment, Washington, DC; EPA/600/R-16/366F. Available at http://www.epa.gov/ncea.

The combined land classifications were simplified into a manageable number of categories referred to as land use IDs. These land use IDs serve as the basis for assigning model parameters and are used consistently across all model scenarios. A complete list of land use IDs used in the model is provided in Table 2-1. Each land use classification was also categorized into a simplified class (i.e., Developed, Exurban; Forests at Risk) and a Vegetation Class (Altered, Vegetated, or Pristine) to facilitate summaries on land use change.

Curve numbers (CNs), which are used to estimate runoff, were assigned primarily based on NLCD land cover in combination with hydrologic soil group (categories A, B, C, or D) from the SSURGO database, with adjustments made where ICLUS provided more detailed information about development type or intensity. Additional parameters assigned to each land use ID include C and P factors used in the Modified Universal Soil Loss Equation (MUSLE) for upland erosion, dissolved and solid nutrient loading rates, nutrient accumulation rates for urban land uses using a buildup and washoff approach, nutrient reduction efficiencies for riparian areas, and nutrient settling rates for wetlands and open water. Like CNs, the C factor is assigned a priori to the model calibration process based on physical information. Both are specified by land use ID in Table 2-1. The P factor was held at 1 for all land cover classifications. The remaining land cover-based parameters are discussed during the calibration process description.

As part of this parameterization, the model distinguishes between upland and riparian land uses. The U.S. Forest Service's (USFS) National Riparian Areas Base Map[5] which identifies 10-meter raster riparian areas for 50-year flood heights, was used to define the riparian area within each catchment. This dataset was modified by RTI to include contiguous open water or wetlands within NLCD 2019 Land Cover that were not already identified as riparian area within the USFS layer. Land within these areas is assigned separate parameter values to reflect differences in hydrology and water quality processes.

Both baseline and future land use conditions use the same set of land use IDs. Baseline conditions were developed by combining NLCD land cover with current ICLUS land use data. Future conditions were created using the projected ICLUS data for 2070 within the same framework, allowing for a consistent comparison between scenarios.

[5] Abood, S. A., Spencer, L., & Wieczorek, M. (2022). U.S. Forest Service National Riparian Areas Base Map for the Conterminous United States in 2019. Fort Collings, CO: Forest Service Research Data Archive.

Table 2-1. Land use types used in WaterFALL model.

Land Use ID	Riparian ID	Description	Simple Class	Vegetation Class	CN by Soil Hydrologic Group				C Factor
					A	B	C	D	
110	1100	Open water	Water	Pristine	100	100	100	100	0.0111
210	2100	Mixed low-intensity developed and natural areas	Open Space and Altered Crops (No population)	Altered	49	69	79	84	0.0111
211	2110	Developed open space in very low-density areas	Developed, Open Space (Rural)	Altered	39	61	74	80	0.001
215	2150	Developed open space in low-density areas	Developed, Exurban	Altered	61	75	83	91	0.0111
216	2160	Developed open space in higher-density areas	Developed, Exurban	Altered	77	85	90	95	0.0111
220	2200	Mixed grass, shrub, and pasture areas at risk of development	Mixed Use with Developing Population	Altered	52	68.75	79.25	84.25	0.0111
221	2210	Low-intensity development in very low-density areas	Developed, Open Space (Rural)	Altered	46	65	77	82	0.001
222	2220	Low-intensity development on natural pervious land	Developed, Exurban	Altered	51	68	79	84	0.002
223	2230	Low-intensity development on worked pervious land	Developed, Exurban	Altered	57	72	81	86	0.03
224	2240	Low-intensity mixed or altered land	Developed, Exurban	Altered	68	79	86	89	0.03
225	2250	Low-intensity development in low-density areas	Developed, Suburban	Altered	61	75	83	91	0.0111
226	2260	Low-intensity development in higher-density areas	Developed, Medium Urban	Altered	77	85	90	92	0.0111
230	2300	Crops or wetlands under high development pressure	Crops and Wetlands Infringed	Altered	69	80	86.5	89.5	0.0111
231	2310	Medium-intensity development in very low-density areas	Developed, Suburban	Altered	61	75	83	87	0.001
232	2320	Medium-intensity development on natural pervious land	Developed, Suburban	Altered	61	75	83	87	0.002
233	2330	Medium-intensity development on worked pervious land	Developed, Suburban	Altered	61	75	83	87	0.03
234	2340	Medium-intensity mixed or altered land	Developed, Suburban	Altered	61	75	83	87	0.03
235	2350	Medium-intensity development in low-density areas	Developed, Medium Urban	Altered	77	85	90	92	0.0111
236	2360	Medium-intensity development in higher-density areas	Developed, High Urban	Altered	89	92	94	95	0.0111
240	2400	High-intensity developed land		Altered	89	92	94	95	0.0111

Land Use ID	Riparian ID	Description	Simple Class	Vegetation Class	CN by Soil Hydrologic Group				C Factor
					A	B	C	D	
241	2410	High-intensity development in very low-density areas	Developed, High Urban	Altered	77	85	90	92	0.001
242	2420	High-intensity development on natural pervious land	Developed, High Urban	Altered	77	85	90	92	0.002
243	2430	High-intensity development on worked pervious land	Developed, High Urban	Altered	77	85	90	92	0.03
244	2440	High-intensity mixed or altered land	Developed, High Urban	Altered	77	85	90	92	0.03
245	2450	High-intensity development in low-density areas	Developed, High Urban	Altered	91	94	96	97	0.0111
246	2460	High-intensity development in higher-density areas	Developed, High Urban	Altered	98	98	98	98	0.0111
310	3100	Barren land (rock, sand, or clay)	Barren Land	Altered	77	86	91	94	0.15
410	4100	Deciduous forest	Deciduous Forest	Pristine	45	66	77	83	0.004
415	4150	Deciduous forest with low development	Forests at Risk	Vegetated	51	69.5	79.5	84.5	0.004
416	4160	Deciduous forest with higher development	Forests Infringed	Vegetated	57	73	82	86	0.03
420	4200	Evergreen forest	Evergreen Forest	Pristine	30	55	70	77	0.004
425	4250	Evergreen forest with low development	Forests at Risk	Vegetated	43.5	64	76	81.5	0.004
426	4260	Evergreen forest with higher development	Forests Infringed	Vegetated	57	73	82	86	0.03
430	4300	Mixed forest	Mixed Forest	Pristine	36	60	73	79	0.004
435	4350	Mixed forest with low development	Forests at Risk	Vegetated	46.5	66.5	77.5	82.5	0.004
436	4360	Mixed forest with higher development	Forests Infringed	Vegetated	57	73	82	86	0.03
520	5200	Shrub or scrub land	Shrub/Scrub	Vegetated	35	56	70	77	0.04
523	5230	Shrub or scrub on worked pervious land	Shrub/Scrub	Vegetated	35	56	70	77	0.03
710	7100	Grassland or herbaceous land	Grasslands/Herbaceous	Vegetated	50	71	81	89	0.01
713	7130	Grassland on worked pervious land	Grasslands/Herbaceous	Vegetated	68	79	86	89	0.06
714	7140	Grassland with mixed or altered land use	Grasslands/Herbaceous	Vegetated	68	79	86	89	0.01
810	8100	Pasture or hay land	Pasture/Hay	Altered	49	69	79	84	0.07
813	8130	Pasture or hay on worked pervious land	Pasture/Hay	Altered	49	69	79	84	0.08

Land Use ID	Riparian ID	Description	Simple Class	Vegetation Class	CN by Soil Hydrologic Group				C Factor
					A	B	C	D	
815	8150	Pasture or hay with low development	Pasture/Hay	Altered	59	74	82	86	0.03
820	8200	Cultivated crops	Cultivated Crops	Altered	67	78	85	89	0.09
900	9000	Woody wetlands	Wetlands	Pristine	30	58	71	78	0.001
950	9500	Emergent herbaceous wetlands	Wetlands	Pristine	30	58	71	78	0.001

2.2 Reservoirs

Reservoirs are explicitly represented in the WaterFALL modeling framework to account for their influence on streamflow, sediment transport/storage, and nutrient dynamics. Within the model, reservoirs act as storage features that receive inflows from upstream areas and release water downstream based on defined operating rules. This allows the model to capture how reservoirs attenuate streamflows and alter water quality as water moves through the system.

Catchments draining to reservoirs are categorized into three primary types of inflow: mainstem flow, shoreline runoff, and tributary flow. Mainstem flow represents inflow from the primary river channel entering the reservoir. Shoreline runoff represents direct runoff from catchments adjacent to the reservoir. Tributary flow represents inflow from smaller streams that enter the reservoir but are not part of the main channel or immediate shoreline drainage. Figure 2-1 illustrates these inflow types for Lake Wateree, highlighting the spatial distribution of mainstem, shoreline, and tributary catchments. This classification provides a consistent framework for routing water, sediment, and nutrients into each reservoir.

Reservoir behavior is defined using a set of generalized parameters that describe storage capacity, surface area, and flow releases. These parameters control how water is stored and released over time, as well as how the reservoir responds to changing inflow conditions. Site-specific data, such as area and volume relationships, were used to define these parameters where available.

WaterFALL simulates the inflow routing from the watershed to each reservoir. Then monthly reservoir target volumes taken from Duke Energy Lake Levels[6] and storage-elevation curves were used within WaterFALL to determine the water released from each reservoir daily after accounting for any water withdrawals or discharges to the reservoir volume. The reservoir release is considered as the streamflow leaving the catchment designated as the outlet for the reservoir. Watershed streamflow and water quality accumulation continues with the next downstream catchment.

WaterFALL also simulates water quality processes within the reservoirs, including sediment and nutrient retention. Sediment and nutrient dynamics within reservoirs are represented using a simplified settling process. As water enters a reservoir, a portion of the incoming sediment and nutrients is removed from the water column and retained within the reservoir. This process is modeled using a simplified settling rate that reflects the combined behavior of different particle sizes. Reservoirs are represented as well-mixed and the model does not account for reservoir stratification. As a result, reservoirs typically act as sinks for sediment and associated nutrients, reducing the amount transported downstream with the reservoir release.

Together, these components allow the model to represent the role of reservoirs in modifying both the quantity and quality of water moving through the watershed under baseline and future conditions.

[6] Duke Energy Lake Levels Dashboard: https://lakes.hydro-derived.duke-energy.app/

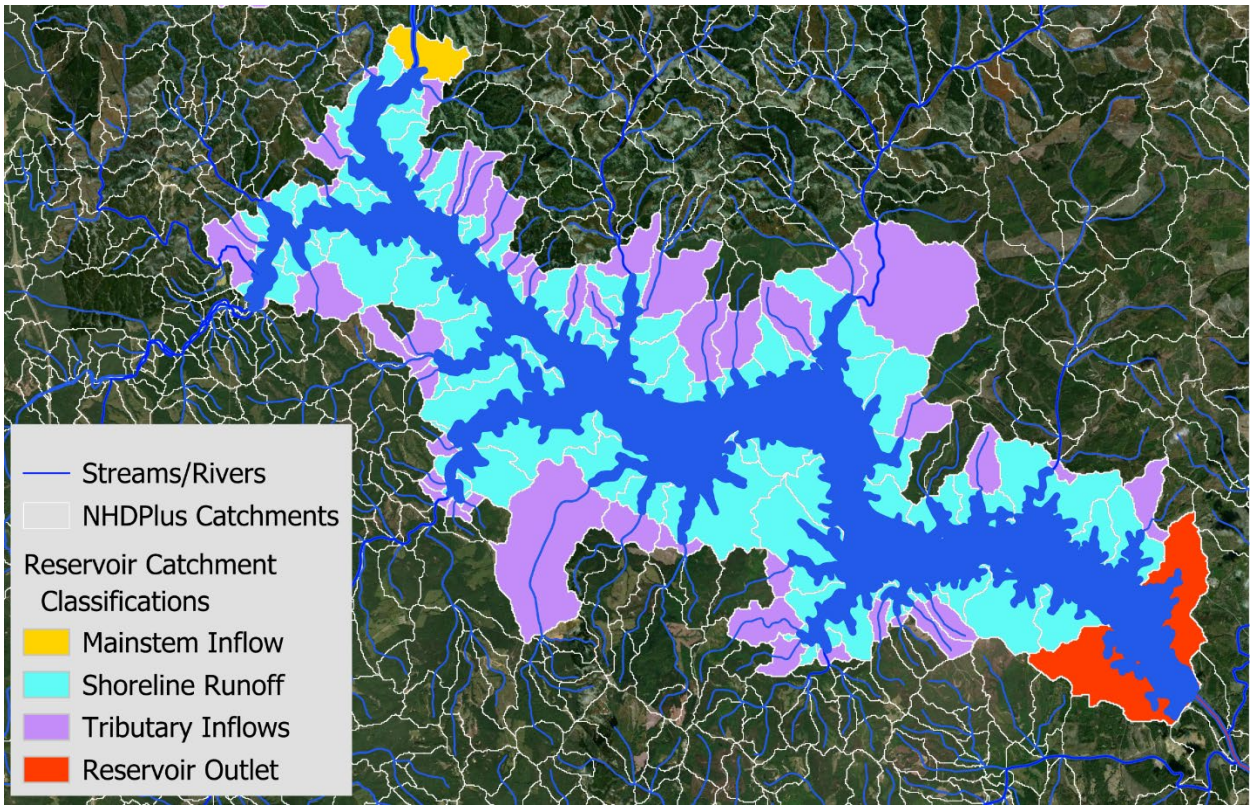


Figure 2-1. Map of Lake Wateree Reservoir showing spatial distribution of reservoir catchment types.

2.3 Flow Alterations (Withdrawals and Discharges)

WaterFALL accounts for changes in streamflow caused by water withdrawals and discharges. Withdrawals represent the removal of water from the stream system, while discharges represent the return of water back to the stream. These flow alterations are incorporated to better represent real-world water use and its influence on hydrology and water quality.

Locations of withdrawals and discharges are spatially linked to model catchments (see Figure 2-2). For each location, a time series of water volume is applied to adjust streamflow within the model. These inputs are typically represented as monthly average values, allowing the model to reflect seasonal variability in water use. Streamflow within each affected reach is increased or decreased accordingly based on the magnitude of the discharge or withdrawal.

For the Integrated Water Resources Plan, withdrawal information was developed by HDR Engineering, Inc. as part of a basin-wide planning effort (Appendix D). These data include major water users such as public water suppliers, industrial facilities, power generation, and agricultural operations. RTI used the available monthly average withdrawal volumes by permit provided by HDR from 2002 through 2020 within the model. Missing months in the time series were filled using average monthly values. The time series were not extended into the past nor into the future for incomplete years at either end of the permit records.

Discharge data were compiled from National Pollutant Discharge Elimination System (NPDES) permits using publicly available monitoring records. Monthly average discharge time series were developed for each permitted outfall based on reported data.

Associated water quality loads for these discharges are discussed in the next section.

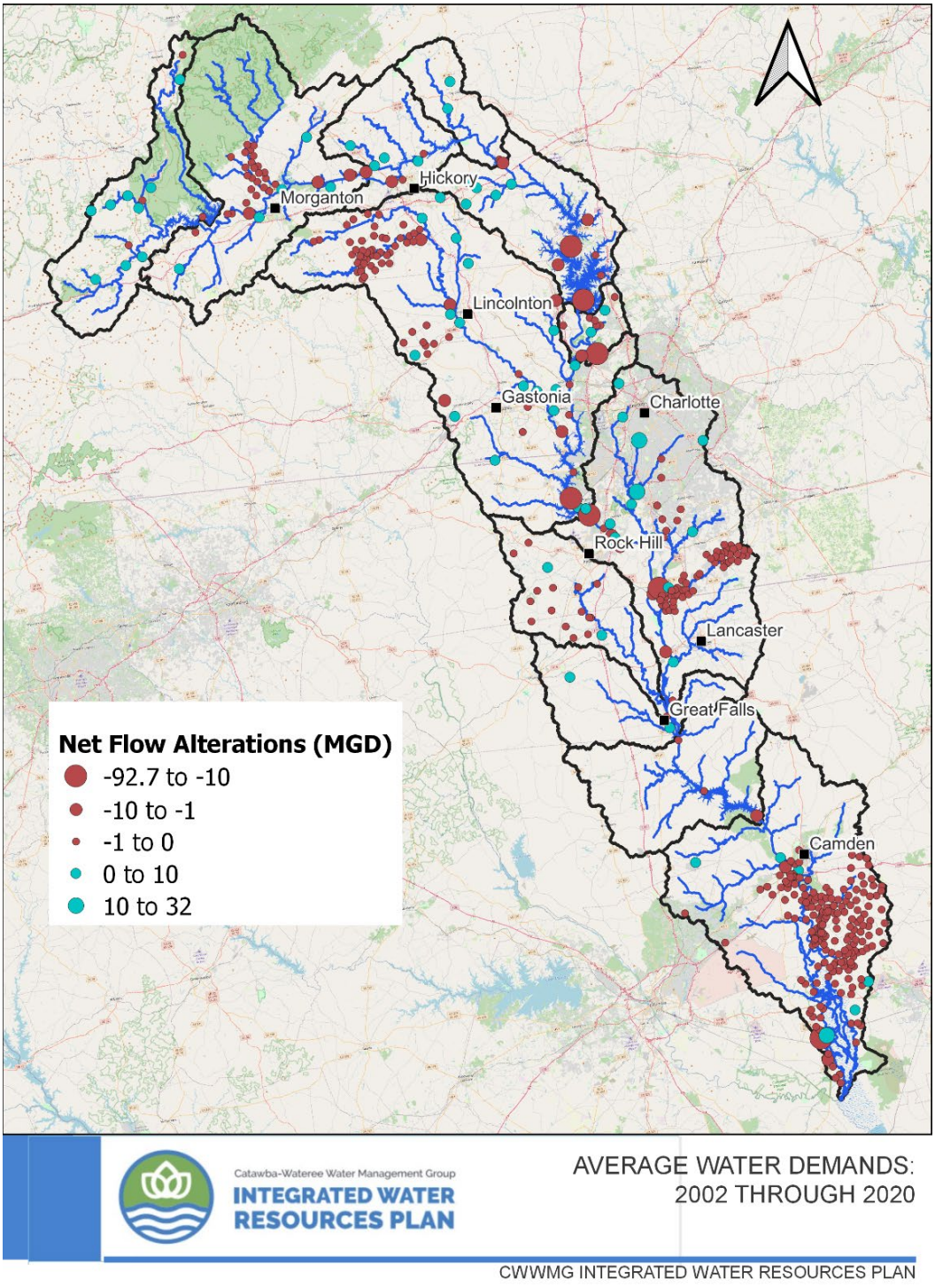


Figure 2-2. Locations of flow alteration due to withdrawals and discharges.

2.4 Water Quality Inputs

2.2.1 Sediment and Nutrient Surficial Loading Generation for Pervious Land Uses

Surface generation of water quality loads is computed on a land use basis within each catchment each day. The sediment load from each land use area is calculated using the MUSLE. To initialize this calculation, soil characteristics derived from SSURGO are mapped to each land use area within each NHDPlus catchment including the K erodibility factor, the slope of each land use area, and the land use slope length. The length-slope factor for each land use is calculated as a function of the slope length, an exponential term, and the angle of the slope (Neitsch et al. 2005)[7]. These factors in addition to the c factor assigned to each land use (and the p factor set to 1 for all land uses) are used in combination with the daily precipitation and runoff from the land use to determine the mass of sediment transported from the land use surface towards the receiving stream/river. Note that the coefficient and exponent for the MUSLE equation are held constant for all models at 11.8 and 0.56, respectively. Similarly, a surface lag coefficient is held constant at 3 for all models. This coefficient is used in conjunction with a time of concentration calculated from the land use area to attenuate the sediment load that actually leaves the land use area given its size. Soil bulk density is 1.186 grams per cubic centimeter was used.

WaterFALL simulates both dissolved and solid nutrient export from catchments to capture the full contribution of TN and TP in surface runoff. Dissolved nutrients are transported with runoff and are calculated by multiplying the dissolved nutrient concentrations by the runoff volume from each land use. Solid-phase nutrients are associated with sediment and are calculated by multiplying the sediment load by the average nutrient content of the soil specified for each land use. These land use specific concentrations (dissolved and solid) are adjusted during calibration.

2.2.2 Sediment and Nutrient Surficial Loading Generation for Urban Land Uses

In urban, impervious-dominated areas, WaterFALL calculates the accumulated sediment and nutrient loads on the land surface as a function of a constant accumulation rate and a depletion rate constant. WaterFALL applies methods from the Storm Water Management Model[8] to determine the buildup rate constant that can be applied in the accumulated loads calculations, which is calculated based on the assumption that buildup reaches 90% of the maximum buildup possible after 18 days. The buildup rate constant equation is built into the accumulated sediment and nutrient load (kg/ha) equations within WaterFALL. Sediment and nutrient accumulation rates are estimated based on the land use and adjusted during calibration.

[7] Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, R. (2005). Soil and Water Assessment Tool (Version 2005, 494 p). Theoretical Documentation, Agricultural Research Service, Grassland, Soil and Water Research Laboratory.

[8] Rossman, L. A., & Huber, W. (2016). Storm water management model reference manual volume III–water quality. US EPA Office of Research and Development, Washington, DC. EPA/600/R-16/093.

2.2.3 Agricultural Manure Application

WaterFALL represents the application of manure to agricultural lands to account for its contribution to nutrient runoff and water quality. Each catchment receives a spatially explicit manure application rate based on gridded datasets of manure nitrogen and phosphorus production and application. Catchment-specific application rates are applied to cropland areas, with manure depth specified in the model setup to accurately represent potential nutrient runoff. An assumed depth of 8 cm is used for all applications.

A manure application period is defined for each growing season. For this modeling effort, the start and end dates were set from March 1 to June 30, reflecting typical manure spreading practices in the region based on guidance from local agricultural extension personnel. Application is assumed to occur only on days with rainfall less than 0.1 cm during this period.

Gridded manure data were derived from a national dataset, *Production and Application of Manure Nitrogen and Phosphorus in the United States since 1860*[9], which provides high-resolution (30 arcsec) annual estimates of nitrogen and phosphorus applied to agricultural lands across the United States. The dataset integrates historical livestock population data, livestock characteristics, crop distribution, crop nutrient demand, land use/land cover, and regional environmental information to produce spatially explicit estimates of manure nutrient application intensity.

This approach allows WaterFALL to simulate both the timing and magnitude of nutrient inputs from manure, supporting accurate representation of agricultural contributions to basin-wide nitrogen and phosphorus loads.

2.2.4 Groundwater Contributions

Groundwater contributions are represented in the model to simulate water quality conditions during low-flow periods, when streamflow is primarily sustained by baseflow. During these conditions, in-stream concentrations of nutrients and sediment are largely influenced by groundwater inputs rather than surface runoff.

Minimum groundwater concentrations of TN, TP, and sediment were estimated using observed in-stream water quality data collected under low-flow conditions. Low-flow periods were identified based on streamflow records, with samples collected during these periods assumed to be representative of groundwater-dominated conditions.

Available water quality observations were screened to include only samples collected during low-flow conditions. These data were then used to develop representative minimum baseflow concentrations for TN, TP, and sediment within the saturated zone. If, after infiltration and percolation, constituent concentrations within saturated zone are less than the minimum baseflow concentrations, the baseflow is set to the minimum concentration. These values represent typical baseflow conditions and provide a consistent estimate of groundwater inputs to

[9] Bian, Z., Tian, H., Yang, Q., Xu, R., Pan, S., and Zhang, B. (2020). Gridded datasets of animal manure nitrogen and phosphorus production and application in the continental U.S. from 1860 to 2017 [dataset]. PANGAEA, https://doi.org/10.1594/PANGAEA.919937

the stream network. These initial baseflow minimum concentrations were adjusted during model calibration to improve agreement with observed in-stream water quality.

2.2.5 Streambank Erosion

Streambank erosion potential was evaluated for each catchment using a screening-level, scoring-based approach and applied within the WaterFALL modeling framework to estimate sediment and nutrient contributions from channel processes. Because field observations of erosion are not available across the entire basin, this method provides a consistent and data-driven way to identify stream segments that are more vulnerable to erosion and sediment mobilization.

Within WaterFALL, streambank erosion is represented as a function of both hydrologic conditions and channel stability. Each catchment is assigned a streambank erosion vulnerability classification, which is translated into either high or low erosion potential. This classification determines the rate at which sediment, represented as total suspended sediment (TSS), TN, and TP are generated from streambank erosion.

Erosion processes are triggered based on streamflow conditions within each catchment. When streamflow exceeds a threshold defined by the 75th percentile of streamflow for that specific catchment, streambank erosion is activated. At that point, erosion is simulated along a specified portion of the stream length, with the rate of erosion determined by whether the catchment is classified as having high or low erosion potential. Higher erosion rates are applied to unstable streambanks, while lower rates are applied to more stable stream reaches. For the whole basin, a standard assumption is that 70% of each reach experiences erosion.

The erosion potential classification is based on a combination of channel characteristics, land use, soils, and riparian condition. Multiple datasets were used to represent factors known to influence erosion risk, including channel slope and shape, the extent of urban and agricultural land use in the watershed, soil erodibility, and vegetation condition along the stream corridor. The specific characteristics and thresholds used to define high erosion risk are summarized in Table 2-2.

Table 2-2. Criteria used to evaluate and score catchment streambank erosion potential.

Catchment Characteristic	Description	Criteria for High Erosion Potential
Channel Slope	The channel slope within the catchment, based on NHDPlus.	Slope > 10%
Percent of Impervious Land in Catchment	Percent of impervious surface in the catchment, based on baseline land use layer.	Impervious Cover > 30%
Soil Erodibility in Riparian Area	USLE K[1] factor for the riparian area, based on SSURGO database.	K > 0.29
Headwater Catchment	If the catchment is a headwater or downstream catchment, based on NHDPlus.	Downstream Catchment
Percent of Urban Land in Riparian Area	The percent of developed land in the riparian area, based on baseline land use layer.	Urban Land > 5%
Percent of Agriculture Land in Catchment	Percent of agricultural area in the catchment, based on baseline land use layer.	Agricultural Land > 5%

Catchment Characteristic	Description	Criteria for High Erosion Potential
Vegetation Condition of the Riparian Area	The area weighted vegetation condition index for the riparian area in each catchment, based on USDA National Agricultural Statistics Service's Vegetation Condition Explorer (VegScape).	Mean Vegetation Condition Index < -5
Channel Sinuosity	The sinuosity (a measure of the degree of meandering) of the channel within the catchment, based on NHDPlus.	Sinuosity < 1.15

[1] Universal Soil Loss Equation K factor = Soil Erodibility Factor

For each catchment, these characteristics were evaluated against predefined thresholds to indicate higher or lower erosion risk. Catchments received a cumulative score based on the number of factors indicating elevated risk of erosion, with additional emphasis placed on urban land use in riparian areas due to its strong influence on streambank stability. The resulting scores were used to classify catchments into either high or low streambank erosion potential.

The final classification was incorporated into the model as a simplified representation of streambank erosion processes, allowing WaterFALL to simulate sediment and nutrient loading from streambanks under both existing and future conditions. The resulting classification of erosion potential across the basin for current is shown in Figure 2-3. Across the basin 1,200 out of the 7,310 catchments classified (approximately 16%) were determined to likely exhibit high rates of erosion.

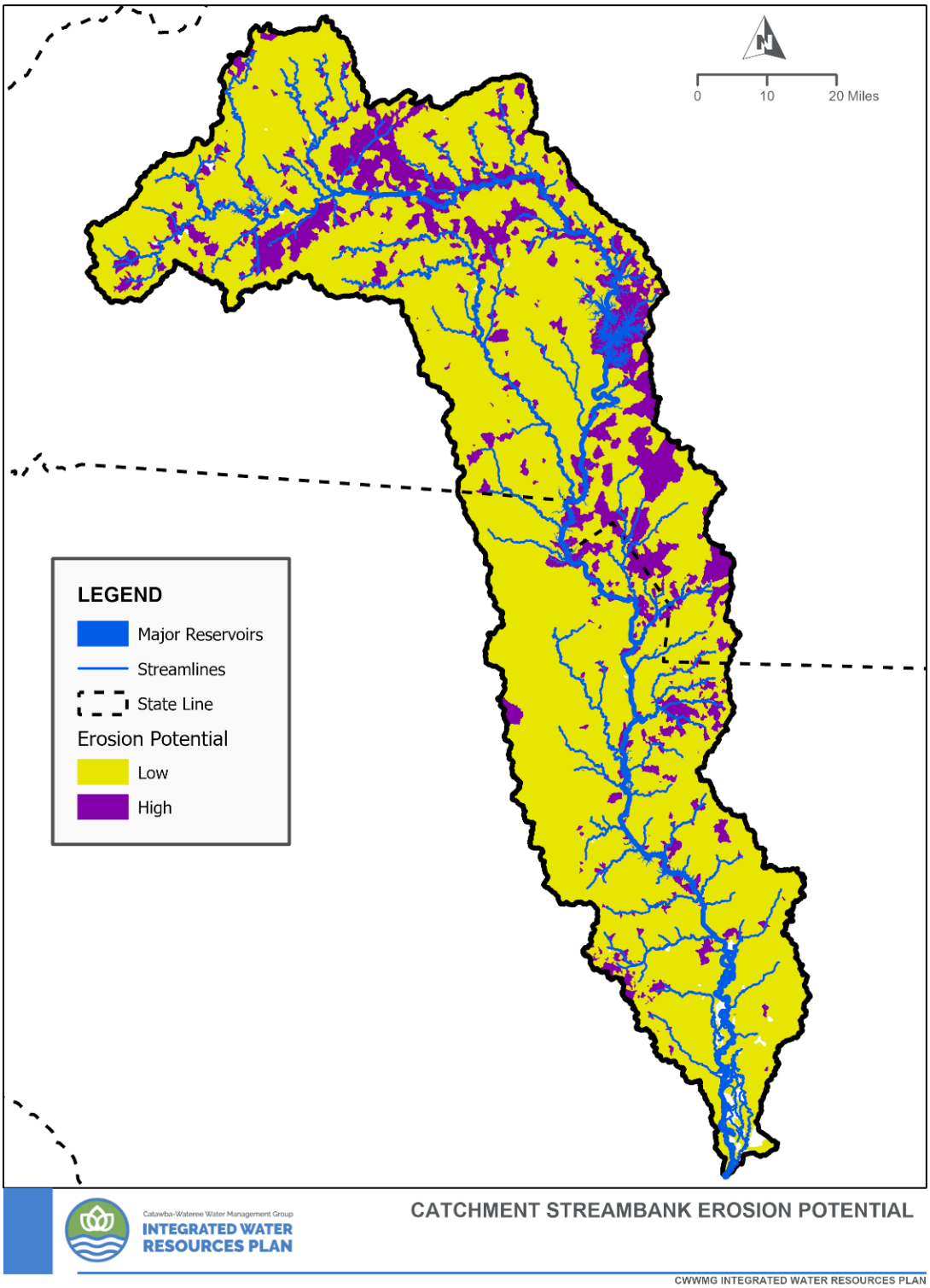


Figure 2-3. Classification of catchments by streambank erosion potential (high and low) across the Catawba-Wateree Basin.

2.2.6 Point Sources

Point sources are explicitly represented in the model to capture contributions of water, nutrients, and sediment from permitted discharges. Each point source is linked to a model catchment based on its location, allowing inflows to be routed appropriately through the stream network. Figure 2-4 illustrates the spatial distribution of permitted discharges across the basin.

The model incorporates both the volume of discharge and associated constituent concentrations to represent the influence of point sources on streamflow and water quality. Discharge and water quality data were compiled from NPDES permit records and processed to develop a monthly time series of flow and constituent loads, including TSS, TN, and TP. Observations were screened for missing or outlier values and corrected using standardized rules, such as filling gaps with monthly or overall averages and adjusting anomalous or inconsistent values. Discharges reported at multiple outfalls within a facility were combined to produce a single representative time series per permit.

In the model, point source discharges are applied directly to receiving catchment as monthly average flows and loads. Constituent loads from each point source are calculated by multiplying the reported concentration by the discharge volume. This approach allows the model to represent both the hydrologic and water quality effects of point source inputs throughout the basin.

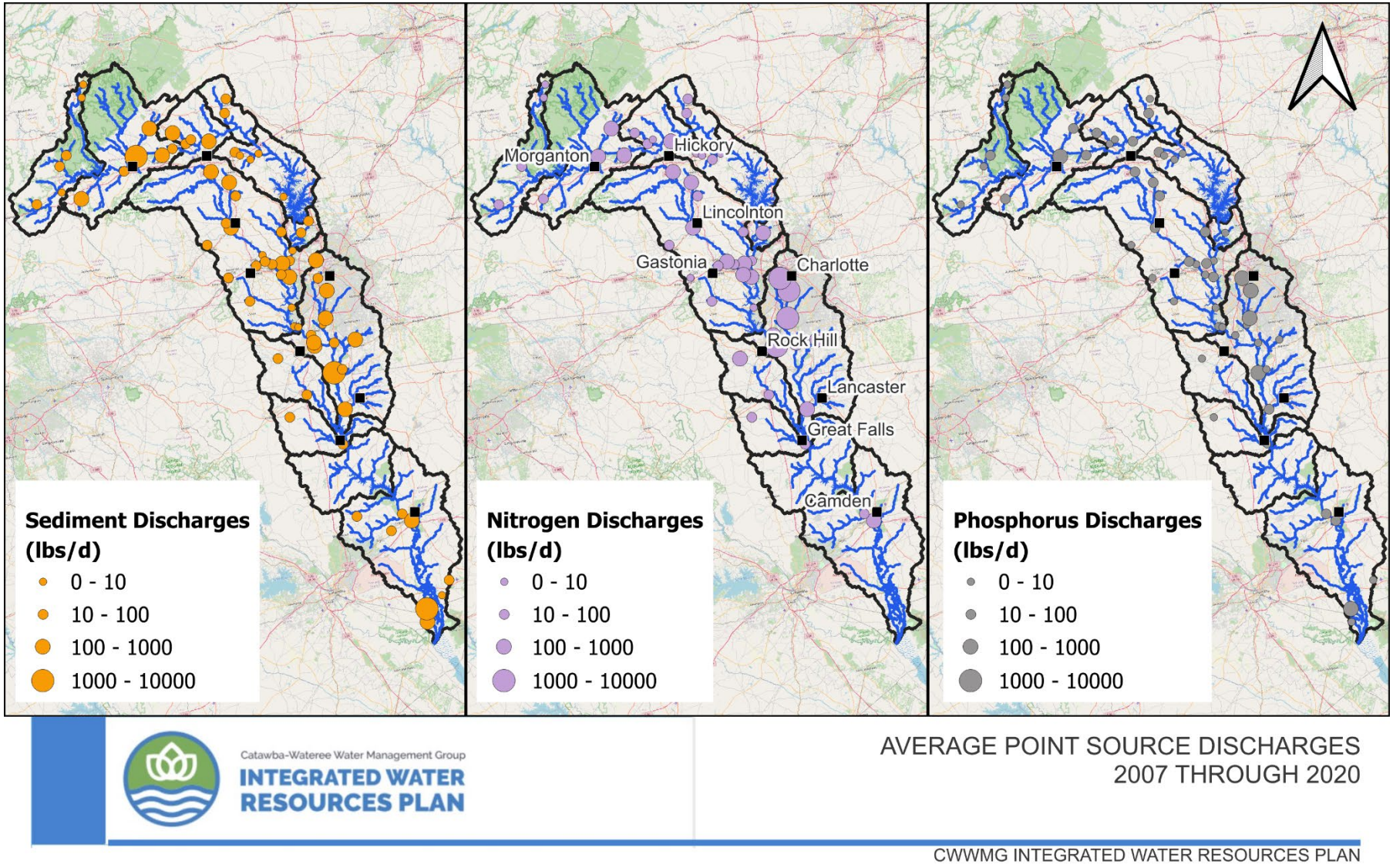


Figure 2-4. Point sources within the Catawba-Wateree Basin.

2.2.7 Septic Systems

The representation of septic systems in the model accounts for their contribution to nitrogen loading in surface waters. Septic system locations within the basin were estimated by combining gridded population data with sewer service boundaries. Population estimates were derived from the LandScan USA 2021 dataset[10], while sewer coverage was obtained from North Carolina Department of Environmental Quality[11], Catawba-Wateree Water Management Group members, and local sewer system operators. The number of septic systems in each catchment was estimated for areas outside the sewered extent by dividing the population by median household size. A basin-wide map of estimated septic systems is provided in Figure 2-5.

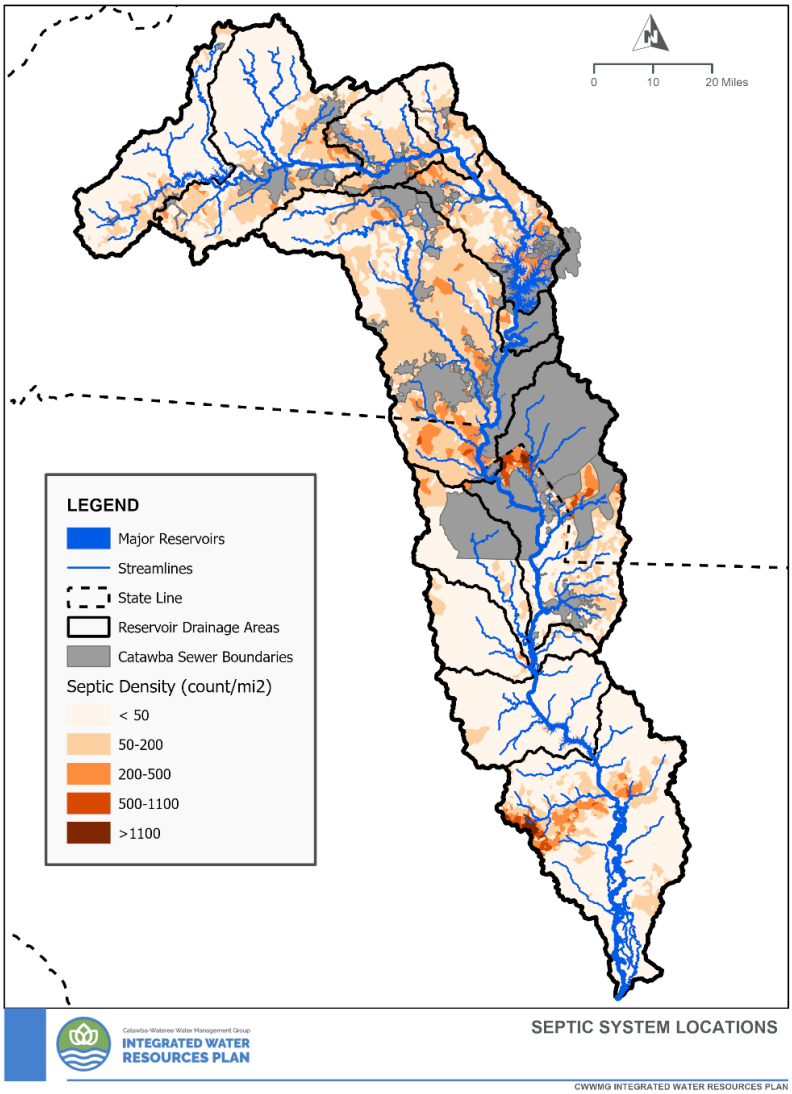


Figure 2-5. Location of septic systems within the Basin.

[10] Oak Ridge National Laboratory. (2022). LandScan. Available at https://landscan.ornl.gov/.
[11] NC OneMap. https://www.nconemap.gov/datasets/nconemap::public-municipal-stormwater-systems/about

Nutrient loading from septic systems is calculated using per capita nitrogen concentrations from conventional subsurface discharge systems, accounting for both functioning and failing systems (Table 2-3). Daily nitrogen loads per household are determined by multiplying the effluent concentration by per capita water use and household size. A failure rate of 7% of systems is applied to represent malfunctioning septic systems, consistent with previous regional modeling efforts. Overall, each septic system is assumed to serve 2.5 people with functional systems contributing 4.9 g/person/day and failing systems contributing 8.9 g/person/day. The contributions from septic systems are also assumed to be attenuated by plant uptake and subsurface processes at a rate of 2.5 g/day.

This approach allows the model to represent the contribution of onsite wastewater treatment systems to basin-wide nitrogen loads and incorporate both functioning and failing systems in the overall water quality simulation.

Table 2-3. Onsite wastewater loading rates determined for Falls Lake Watershed[12]

Category	TN (mg/L)	TN (g/person/day)[1]	TP (mg/L)	TP (g/person/day)[1]
Privy/wastewater with no treatment	57.5	12.02	9.8	2.05
Conventional, functioning, subsurface discharge (accounting for attenuation in the soil treatment unit)	23.6	4.93	0.29	0.06
Conventional, malfunctioning, subsurface discharge	42.6	8.90	6.86	1.43
Advanced treatment, functioning, subsurface discharge	16.2	3.39	0.29	0.06
Advanced treatment, malfunctioning, subsurface discharge	42.6	8.90	6.86	1.43
Single pass, sand filter discharging to land surface	32.8	6.86	4.31	0.90
Single pass, sand filter discharging to stream	32.8	6.86	4.31	0.90
Recirculating sand filter discharging to stream	29.3	6.12	4.31	0.90

[1]g/person/day = grams per person per day

[12] O'Driscoll, M., Humphrey Jr., C., Iverson, G., and Hoben, J. (2020). Estimating the Influence of Onsite Wastewater Treatment Systems on Nutrient Loading to Falls Lake Watershed, North Carolina. NC Policy Collaboratory. Available at https://nutrients.web.unc.edu/wp-content/uploads/sites/19393/2020/10/Falls-Lake-2019-2020-Annual-Report_ODriscoll_.pdf.

3 WaterFALL Outputs (Metrics)

3.1 Hydrologic Metrics

Many metrics can be used to distill time series of streamflow to individual summary values as summarized in Table 3-1. Hydrologic metrics used to describe the flow regime for individual catchments, tributaries, and reservoir inflows modeled for the current (i.e., baseline) conditions and the projected future scenarios that examine the impacts of future land use and climate change on the Catawba-Wateree Basin are summarized in the Integrated Water Resources Plan (Table 4-1 of Section 4: Surface Water Quantity and Availability).

Table 3-1. Hydrology metrics calculated from WaterFALL simulations

Metric	Name	Units	Difference Calculation	Description
Hydrology Metrics				
avgAnnMax	Average annual maximum daily streamflow	cfs	Percent	Average annual maximum daily streamflow.
avgTotalAnn	Mean annual total flow	cfs	Percent	Average total annual streamflow. Sum the daily flows for each year. Take the mean of those annual totals.
dl20	Low flow duration	days	Diff	Low flow duration. Compute the 25th percentile value for the entire flow record. Compute the average duration of flow events with flows below a threshold equal to the 25th percentile value for the median annual flows. DL20 is the average duration of the events.
dh15	High flow pulse duration	days/yr	Diff	High flow pulse duration. Compute the average duration of flow events with flows above a threshold equal to the 75th percentile value for each year in the flow record. DH15 is the mean of the yearly average durations.
dh16	Variability in high flow pulse duration	%	Percent	Variability in high flow pulse duration. Compute the standard deviation for the yearly average high pulse durations. DH16 is 100 times the standard deviation divided by the mean of the yearly average high pulse durations.
dh20	High flow duration	days	Diff	High flow duration. Compute the 75th percentile value for the entire flow record. Compute the average duration of flow events with flows above a threshold equal to the 75th percentile value for the median annual flows. DH20 is the average duration of the events.
fh1	High flow puse count	number/yr	Diff	High flow pulse count. Compute the average number of flow events with flows above a threshold equal to the 75th percentile value for the entire flow record. FH1 is the average number of events.
fh3	High flood pulse days	days/yr	Diff	High flood pulse count. Compute the average number of days per year that the flow is above a threshold equal to three times the median flow for the entire record. FH3 is the mean of the annual number of days for all years.
l_max	Maximum average daily local flow	in/d	Diff	Maximum of annual maximum daily local flow.
l_mean	Average daily local flow	in/d	Diff	Long-term average daily locally generated flow (runoff + baseflow) within the catchment. Compute the mean of all daily values across the assessment period.
locMAmax	Mean annual maximum local daily flow	cfs	Percent	Mean annual maximum daily local flow. Find the maximum daily local flow for each year. Average across years.
locMAtot	Mean annual total local flow	cfs	Percent	Mean annual total locally generated flow. Compute the total locally generated flow for each year in the assessment period. Take the mean of the annual values.
ma1	Mean daily flow	cfs	Percent	Mean of the daily flow values for the entire flow record (MA1).
ma2	Median daily flow	cfs	Percent	Mean of the daily mean flow values for the entire flow record.

Metric	Name	Units	Difference Calculation	Description
ma3	Mean of the coefficient of variation	%	Percent	Mean of the coefficients of variation (standard deviation/mean) for each year. Compute the coefficient of variation for each year of daily flows. Compute the mean of the annual coefficients of variation.
ma42	Variability in annual flows	unitless	Percent	Variability across annual flows. MA42 is the maximum annual flow minus the minimum annual flow divided by the median annual flow.
mav1	Mean daily flow in January	cfs	Percent	Mean daily flow in January.
mav10	Mean daily flow in October	cfs	Percent	Mean daily flow in October.
mav11	Mean daily flow in November	cfs	Percent	Mean daily flow in November.
mav12	Mean daily flow in December	cfs	Percent	Mean daily flow in December.
mav2	Mean daily flow in February	cfs	Percent	Mean daily flow in February.
mav3	Mean daily flow in March	cfs	Percent	Mean daily flow in March.
mav4	Mean daily flow in April	cfs	Percent	Mean daily flow in April.
mav5	Mean daily flow in May	cfs	Percent	Mean daily flow in May.
mav6	Mean daily flow in June	cfs	Percent	Mean daily flow in June.
mav7	Mean daily flow in July	cfs	Percent	Mean daily flow in July.
mav8	Mean daily flow in August	cfs	Percent	Mean daily flow in August.
mav9	Mean daily flow September	cfs	Percent	Mean daily flow September.
meanYearlyFlow	Mean of mean annual daily flow	cfs	Percent	Mean of the yearly mean daily flow.
medAnnMin	Median of mean annual daily minimum flow	cfs	Percent	Median of the yearly mean daily flow.
medYearlyFlow	Median of mean daily flow	cfs	Percent	Mean of the yearly minimum daily flow.
mh1	Mean max January flow	cfs	Percent	Mean maximum flows for each month across all years. Compute the maximums for each month over the entire flow record. MH10 is the mean of the maximums of all January flow values over the entire record.
mh10	Mean max October flow	cfs	Percent	Mean maximum flows for each month across all years. Compute the maximums for each month over the entire flow record. MH10 is the mean of the maximums of all October flow values over the entire record.
mh11	Mean max November flow	cfs	Percent	Mean maximum flows for each month across all years. Compute the maximums for each month over the entire flow record. MH8 is the mean of the maximums of all November flow values over the entire record.
mh12	Mean max December flow	cfs	Percent	Mean maximum flows for each month across all years. Compute the maximums for each month over the entire flow record. MH10 is the mean of the maximums of all December flow values over the entire record.

Metric	Name	Units	Difference Calculation	Description
mh2	Mean max February flow	cfs	Percent	Mean maximum flows for each month across all years. Compute the maximums for each month over the entire flow record. MH10 is the mean of the maximums of all February flow values over the entire record.
mh3	Mean max March flow	cfs	Percent	Mean maximum flows for each month across all years. Compute the maximums for each month over the entire flow record. MH10 is the mean of the maximums of all March flow values over the entire record.
mh4	Mean max April flow	cfs	Percent	Mean maximum flows for each month across all years. Compute the maximums for each month over the entire flow record. MH10 is the mean of the maximums of all April flow values over the entire record.
mh5	Mean max May flow	cfs	Percent	Mean maximum flows for each month across all years. Compute the maximums for each month over the entire flow record. MH10 is the mean of the maximums of all May flow values over the entire record.
mh6	Mean max June flow	cfs	Percent	Mean maximum flows for each month across all years. Compute the maximums for each month over the entire flow record. MH10 is the mean of the maximums of all June flow values over the entire record.
mh7	Mean max July flow	cfs	Percent	Mean maximum flows for each month across all years. Compute the maximums for each month over the entire flow record. MH10 is the mean of the maximums of all July flow values over the entire record.
mh8	Mean max August flow	cfs	Percent	Mean maximum flows for each month across all years. Compute the maximums for each month over the entire flow record. MH10 is the mean of the maximums of all August flow values over the entire record.
mh9	Mean max September flow	cfs	Percent	Mean maximum flows for each month across all years. Compute the maximums for each month over the entire flow record. MH10 is the mean of the maximums of all September flow values over the entire record.
ml1	Mean min January flow	cfs	Percent	Mean minimum flows for each month across all years. Compute the minimums for each month over the entire flow record. ml1 is the mean of the minimums of all January flow values over the entire record.
ml10	Mean min October flow	cfs	Percent	Mean minimum flows for each month across all years. Compute the minimums for each month over the entire flow record. ml10 is the mean of the minimums of all October flow values over the entire record.
ml11	Mean min November flow	cfs	Percent	Mean minimum flows for each month across all years. Compute the minimums for each month over the entire flow record. ml11 is the mean of the minimums of all November flow values over the entire record.
ml12	Mean min December flow	cfs	Percent	Mean minimum flows for each month across all years. Compute the minimums for each month over the entire flow record. ml12 is the mean of the minimums of all December flow values over the entire record.
ml17	Baseflow ratio	unitless	RPD	Baseflow ratio. Compute the mean annual flows. Compute the minimum of a 7-day moving average flow for each year and divide them by the mean annual flow for that year. Baseflow ratio (ML17) is the mean of those ratios.
ml2	Mean min February flow	cfs	Percent	Mean minimum flows for each month across all years. Compute the minimums for each month over the entire flow record. ml2 is the mean of the minimums of all February flow values over the entire record.

Metric	Name	Units	Difference Calculation	Description
ml3	Mean min March flow	cfs	Percent	Mean minimum flows for each month across all years. Compute the minimums for each month over the entire flow record. ml3 is the mean of the minimums of all March flow values over the entire record.
ml4	Mean min April flow	cfs	Percent	Mean minimum flows for each month across all years. Compute the minimums for each month over the entire flow record. ml4 is the mean of the minimums of all April flow values over the entire record.
ml5	Mean min May flow	cfs	Percent	Mean minimum flows for each month across all years. Compute the minimums for each month over the entire flow record. ml5 is the mean of the minimums of all May flow values over the entire record.
ml6	Mean min June flow	cfs	Percent	Mean minimum flows for each month across all years. Compute the minimums for each month over the entire flow record. ml6 is the mean of the minimums of all June flow values over the entire record.
ml7	Mean min July flow	cfs	Percent	Mean minimum flows for each month across all years. Compute the minimums for each month over the entire flow record. ml7 is the mean of the minimums of all July flow values over the entire record.
ml8	Mean min August flow	cfs	Percent	Mean minimum flows for each month across all years. Compute the minimums for each month over the entire flow record. ml8 is the mean of the minimums of all August flow values over the entire record.
ml9	Mean min September flow	cfs	Percent	Mean minimum flows for each month across all years. Compute the minimums for each month over the entire flow record. ml9 is the mean of the minimums of all September flow values over the entire record.
p25	25th percentile of daily flow	cfs	Percent	25th percentile of daily flow.
p75	75th percentile of daily flow	cfs	Percent	75th percentile of daily flow.
r_max	Maximum daily runoff	in/d	Diff	Maximum of the daily runoff.
r_mean	Average daily runoff	in/d	Diff	Long-term average daily runoff. Compute the mean of all daily values across the assessment period.
rbi	Richards-Baker Flashiness Index	unitless	Percent	Richards-Baker Flashiness Index
rechrgMAtot	Mean annual total catchment GW recharge	in	Percent	Mean annual total groundwater aquifer recharge from the catchment.
runMAmax	Mean annual maximum daily runoff	in/d	Diff	Mean annual maximum daily runoff. Find the maximum daily runoff each year. Average across years.
runMAtot	Mean annual total catchment runoff	in/yr	Diff	Mean annual total runoff. Compute the total runoff for each year in the assessment period. Take the mean of the annual values.
runoff90	Runoff: Long-term peak daily depth	in/d	Diff	90th percentile of daily runoff.
n_peak	Number of peak flow days	days	Diff	Number of days with flow greater than the historic 90th daily percentile across the analysis period.
n_high	Number of high flow days	days	Diff	Number of days with flow greater than the historic 75th daily percentile across the analysis period.

Metric	Name	Units	Difference Calculation	Description
Climate Metrics				
avgTemp1	Average temperature in January.	F	Diff	Average temperature in January.
avgTemp10	Average temperature in October.	F	Diff	Average temperature in October.
avgTemp11	Average temperature in November.	F	Diff	Average temperature in November.
avgTemp12	Average temperature in December.	F	Diff	Average temperature in December.
avgTemp2	Average temperature in February.	F	Diff	Average temperature in February.
avgTemp3	Average temperature in March.	F	Diff	Average temperature in March.
avgTemp4	Average temperature in April.	F	Diff	Average temperature in April.
avgTemp5	Average temperature in May.	F	Diff	Average temperature in May.
avgTemp6	Average temperature in June.	F	Diff	Average temperature in June.
avgTemp7	Average temperature in July.	F	Diff	Average temperature in July.
avgTemp8	Average temperature in August.	F	Diff	Average temperature in August.
avgTemp9	Average temperature in September.	F	Diff	Average temperature in September.
et10	10th percentile of daily ET	in	Diff	10th percentile of daily ET depth.
et90	90th percentile of daily ET	in	Diff	90th percentile of daily ET depth.
etMAtot	Mean annual total ET	in	Diff	Mean annual total ET. Compute the total ET for each year. Average across years.
precip_n	Number of days with precipitation	number	Diff	Number of days with precipitation during the 20-year period of record
precipMAtot	Mean annual total precipitation	in	Diff	Mean annual total precipitation. Compute the total precipitation for each year. Average across years.
tempMAavg	Mean annual average daily temperature	F	Diff	Mean annual average daily temperature. Find the average daily temperature for each year. Average across years.

Notes:
cfs = cubic feet per second; in = inches; F=Fahrenheit
[1] The metric is based on a threshold set by assessing the flow data in the period considered current conditions. The current condition threshold for each catchment is then used when calculating this metric value for any future scenarios so that a change from existing conditions can be determined.

3.2 Water Quality Metrics

The water quality evaluations conducted using WaterFALL provide information on existing water quality and sources of pollution within each subbasin. This information can help communities plan for the future by quantifying the effects of management decisions on water quality. As described above, WaterFALL simulates TN, TP, and TSS. Loads of these constituents are tracked from their sources, through surface runoff and groundwater pathways, to streams, rivers, and lakes within the model domain. WaterFALL tracks the pathways that each of these chemicals travel through the watershed so that the relative contribution of different pollutant sources can be assessed. WaterFALL can be used to directly assess loadings from individual pervious (rural) land covers with runoff, manure/fertilizer applications, buildup and washoff on impervious (urban) surfaces, onsite wastewater systems (e.g., septic systems), and subsurface load accumulation and transport to the stream with baseflow as well as point sources contributions and streambank erosion within the stream network. Modeled estimates of pollutant loads can be compared against water quality observations collected throughout the watershed. Parameterization of each of these model capabilities is described in the following sections.

Total loads, calculated for each catchment within the greater watershed can be used to identify regions of the watershed that are responsible for the greatest contribution to the total watershed nutrient and sediment load. Calculation of these metrics across different time intervals can be used to evaluate how different hydrologic conditions may influence the magnitude and distribution of water quality constituent loads.

Table 3-2 provides information on the water quality metrics available to analyze temporal and spatial patterns. The water quality metrics used to describe the range in loadings and concentrations for individual catchments, tributaries, and reservoir inflows modeled for the current (i.e., baseline) conditions and the projected future scenarios that examine the impacts of future land use and climate change on the Catawba-Wateree Basin are summarized in the Integrated Water Resources Plan (Table 5-2 of Section 5: Water Quality Evaluations).

Table 3-2. Water quality metrics to characterize water quality constituent loads from WaterFALL simulations

Metric	Name	Units	Difference Calculation	Description
bankNitrMAtot	Nitrogen load from streambank erosion	lbs/yr	Percent	Nitrogen load from streambank erosion.
bankPhosMAtot	Phosphorus load from streambank erosion	lbs/yr	Percent	Phosphorus load from streambank erosion.
bankSedMAtot	Sediment load from streambank erosion	lbs/yr	Percent	Sediment load from streambank erosion.
cuNitrAmax	Maximum annual total cumulative nitrogen load	lbs/yr	Percent	Maximum annual total cumulative nitrogen load.
cuNitrHighMAtot	Nitrogen: Mean annual total stream load during high flows	lbs/yr	Percent	Mean annual total nitrogen load during high flows where high flows are those greater than the historic 75th daily percentile.
cuNitrMAtot	Nitrogen: Mean annual total stream load	lbs/yr	Percent	Mean annual total locally generated nitrogen load. Compute the total locally generated nitrogen load for each year in the assessment period. Take the mean of the annual values.
cuNitrPeakMAtot	Nitrogen: Mean annual total stream load during peak flows	lbs/yr	Percent	Mean annual total nitrogen load during peak flows where peak flows are those greater than the historic 90th daily percentile.
cuPhosAmax	Maximum annual total cumulative phosphorus load	lbs/yr	Percent	Maximum annual total cumulative phosphorus load.
cuPhosHighMAtot	Phosphorus: Mean annual total stream load during high flows	lbs/yr	Percent	Mean annual total phosphorus load during high flows where high flows are those greater than the historic 75th daily percentile.
cuPhosMAtot	Phosphorus: Mean annual total stream load	lbs/yr	Percent	Mean annual total locally generated phosphorus load. Compute the total locally generated phosphorus load for each year in the assessment period. Take the mean of the annual values.
cuPhosPeakMAtot	Phosphorus: Mean annual total stream load during peak flows	lbs/yr	Percent	Mean annual total phosphorus load during peak flows where peak flows are those greater than the historic 90th daily percentile.
cuSedAmax	Maximum annual total cumulative sediment load	lbs/yr	Percent	Maximum annual total cumulative sediment load.
cuSedHighMAtot	Sediment: Mean annual total stream load during high flows	lbs/yr	Percent	Mean annual total sediment load during high flows where high flows are those greater than the historic 75th daily percentile.
cuSedMAtot	Sediment: Mean annual total stream load	lbs/yr	Percent	Mean annual total cumulative sediment load. Compute the total routed sediment load at the outlet of the catchment for each year in the assessment period. Take the mean of the annual values.

Metric	Name	Units	Difference Calculation	Description
cuSedPeakMAtot	Sediment: Mean annual total stream load during peak flows	lbs/yr	Percent	Mean annual total sediment load during peak flows where peak flows are those greater than the historic 90th daily percentile.
gwNitrMAtot	Mean annual baseflow nitrogen load	lbs/yr	Percent	Mean annual total nitrogen load delivered to the stream reach through baseflow
gwPhosMAtot	Mean annual baseflow phosphorus load	lbs/yr	Percent	Mean annual total phosphorus load delivered to the stream reach through baseflow
gwSedMAtot	Mean annual baseflow sediment load	lbs/yr	Percent	Mean annual total sediment load delivered to the stream reach through baseflow
Nitr_D90	Nitrogen: 90th percentile of daily cumulative load	lbs/d	Percent	90th percentile of daily cumulative nitrogen load.
Nitr_Dmax	Maximum daily cumulative nitrogen load	lbs/d	Percent	Maximum daily cumulative nitrogen load
Nitr_Dmean	Average daily cumulative nitrogen load	lbs/d	Percent	Average daily cumulative nitrogen load.
Nitr_Dmedian	Median daily cumulative nitrogen load	lbs/d	Percent	Median daily cumulative nitrogen load.
NitrNrmBankMAtot	Nitrogen: Streambank erosion load per length	lbs/ft/yr	Percent	Mass of nitrogen added to the streamflow load per unit length of the stream channel on average across a year
NitrNrmGwMAtot	Nitrogen: Baseflow load per area	lbs/acre/yr	Percent	Mass of nitrogen within baseflow per unit area of the catchment on average across a year
NitrNrmSurfMAtot	Nitrogen: Surface load per area	lbs/acre/yr	Percent	Mass of nitrogen generated on the surface per unit area of the catchment on average across a year
Phos_D90	Phosphorus: 90th percentile of daily cumulative load	lbs/d	Percent	90th percentile of daily cumulative phosphorus load.
Phos_Dmax	Maximum daily cumulative phosphorus load	lbs/d	Percent	Maximum daily cumulative phosphorus load
Phos_Dmean	Average daily cumulative phosphorus load	lbs/d	Percent	Average daily cumulative phosphorus load.
Phos_Dmedian	Median daily cumulative phosphorus load	lbs/d	Percent	Median daily cumulative phosphorus load.
PhosNrmBankMAtot	Phosphorus: Streambank erosion load per length	lbs/ft/yr	Percent	Mass of phosphorus added to the streamflow load per unit length of the stream channel on average across a year
PhosNrmGwMAtot	Phosphorus: Baseflow load per area	lbs/acre/yr	Percent	Mass of phosphorus within baseflow per unit area of the catchment on average across a year
PhosNrmSurfMAtot	Phosphorus: Surface load per area	lbs/acre/yr	Percent	Mass of phosphorus generated on the surface per unit area of the catchment on average across a year

Metric	Name	Units	Difference Calculation	Description
Sed_D90	Sediment: 90th percentile of daily cumulative load	lbs/d	Percent	90th percentile of daily cumulative sediment load.
Sed_Dmax	Maximum daily cumulative sediment load	lbs/d	Percent	Maximum daily cumulative sediment load
sed_Dmean	Average daily cumulative sediment load	lbs/d	Percent	Average daily cumulative sediment load.
sed_Dmedian	Median daily cumulative sediment load	lbs/d	Percent	Median daily cumulative sediment load.
SedNrmBankMAtot	Sediment: Streambank erosion load per length	lbs/ft/yr	Percent	Mass of sediment added to the streamflow load per unit length of the stream channel on average across a year
SedNrmGwMAtot	Sediment: Baseflow load per area	lbs/acre/yr	Percent	Mass of sediment within baseflow per unit area of the catchment on average across a year
SedNrmSurfMAtot	Sediment: Surface load per area	lbs/acre/yr	Percent	Mass of sediment generated on the surface per unit area of the catchment on average across a year
surfNitrMAtot	Nitrogen load from the land surface	lbs/yr	Percent	Nitrogen load generated with runoff from the land surface in the catchment
surfPhosMAtot	Phosphorus load from the land surface	lbs/yr	Percent	Phosphorus load generated with runoff from the land surface in the catchment
surfSedMAtot	Sediment load from the land surface	lbs/yr	Percent	Sediment load generated with runoff from the land surface in the catchment

lbs/d **=** Pounds per day**;** lbs/yr= Pounds per year; lbs/acre/yr= Pounds per acre per year; lbs/ft/yr= Pounds per foot per year

4 Watershed Model Calibration

4.1 WaterFALL Calibration Process

4.1.1 Hydrology Process

The hydrologic calibration of the baseline model focused on optimizing a set of statistical measures that quantify the difference between daily simulated and observed streamflows for the most recent 10-year period available for each USGS streamflow gage. The location of USGS streamflow stations used for hydrology calibration is provided on Figure 4-1. These gages were selected as having long-term, mostly complete observation records.

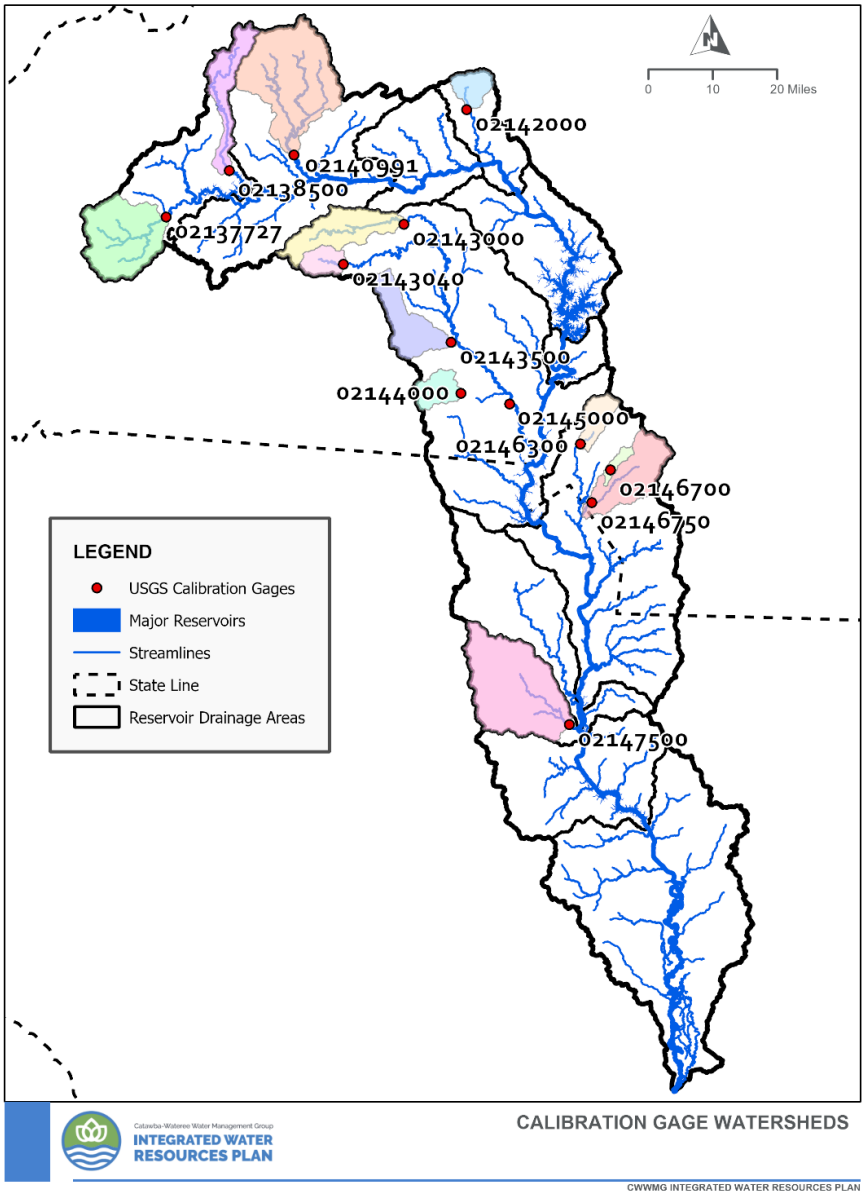


Figure 4-1. USGS streamflow stations used for hydrology calibration.

The evaluation of model performance during the calibration process focuses on the statistical measures Nash-Sutcliffe Efficiency[13] (NSE; daily and monthly values), Kling-Gupta Efficiency[14] (KGE), and percent bias (PBIAS). For NSE and KGE, variations that characterize the daily low flows (rNSE, KGElf) and high flows (wNSE) are also used to assess performance for the tails of the streamflow distributions. Additional measures considered included bias in the interquartile values and normalized root mean square error (NRMSE) at daily and monthly time steps.

NSE compares residual variance to measured variance, meaning it is an indicator of how well the spread of the simulated data matches the observed data. Because it is weighed by volume, it is particularly sensitive to large streamflow values. It is a common metric that has been used in many studies and can be used to evaluate model performance especially in high-flow conditions. The rNSE is a revised form of the NSE in which flows are normalized by magnitude, thus removing the bias towards high-flow values. However, the rNSE value does not provide a suitable measure when observations show days with no streamflow. The KGE, another goodness-of-fit measure, provides an alternative to the NSE. It scores models using a combination of the Pearson correlation coefficient, variability in simulation errors, and bias.

In addition to statistical measures, calibration performance was evaluated using graphical tools, including flow-duration curves and hydrographs at daily and monthly time steps. These methods allowed comparison of the distribution of streamflow, plus analysis on model performance for individual events. Combining statistical and graphical measures helps overcome biases associated with individual evaluation techniques. For example, statistical measures can be quite sensitive to small errors in timing, particularly when being evaluated at a daily timestep.

The seepage parameter, which is the percent of the saturated subsurface lost each day to the deep groundwater, is directly calibrated. In the model structure, the direct parameter value instead of the scalar multipliers used for available water capacity of the unsaturated zone and recession coefficients is denoted as a negative value.

4.1.2 Hydrologic Calibration Parameters

4.1.2.1 CURVE NUMBER

The curve number is the most important calibration parameter in the rainfall-runoff functions of WaterFALL, serving as a measure of imperviousness. It controls the allocation of water between surface runoff and infiltration from precipitation. The value is assigned according to land use and soil type, with harder, more impervious surfaces on compact soils having the highest curve number values. Less impervious surfaces with less consolidated, more porous soils have lower curve number values. As the curve numbers are set by land use prior to any model runs, the calibration of curve numbers can be done globally by applying a multiplicative factor to all curve number values (i.e., 1.1 to increase all values by 10%) or specifically by manually updating curve numbers within the database for certain catchments and/or land uses. Because the initial

[13] Nash, J. E., & Sutcliffe, J. V. (1970). *River flow forecasting through conceptual models. Part I—A discussion of principles*. Journal of Hydrology, 10(3), 282–290.
[14] Gupta, H. V., Kling, H., Yilmaz, K. K., & Martinez, G. F. (2009). *Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling*. Journal of Hydrology, 377(1–2), 80–91.

curve numbers were set based on the previously calibrated Soil-Water Balance model, adjustments were limited to the curve numbers and, when necessary, the global adjustment was applied rather than fine-tuning individual areas or land cover/soil hydrologic group combinations.

4.1.2.2 AVAILABLE WATER CAPACITY

The available water capacity, parameterized directly from the geographically indexed SSURGO soils data, can be adjusted through a multiplicative factor, if necessary.

4.1.2.3 BASEFLOW

The baseflow rate is controlled by setting recession coefficient values for the summer and winter periods, where a transition value is calculated for the months starting and ending the winter season. Initial estimates for the annual recession coefficient value were populated based on previous national modeling. Those values were adjusted again through a multiplicative factor and by changing the start and end month for winter and separate summer and winter multiplicative factors, if deemed necessary. Then the recession delay factor was adjusted to account for slowing of base flow on days with no percolation, further tailoring the slope of the recession period and the hydrograph in the days between runoff generating events.

4.1.2.4 GROWING / DORMANT SEASONS

Similarly, scaling multipliers are calibrated for the erosivity coefficients for the growing and dormant seasons for each catchment, which are set based on default values for each land use type, which are area-weighted to derive an overall catchment value. The start and end of the growing season are set based on date of the last freeze in the spring and the first freeze in the fall but can be adjusted during the calibration process. The additional loss of water through ET processes in the open water and wetlands storage is adjusted with the Water Evapotranspiration Factor, which adjusts the potential ET calculated based on the day's temperature. The movement of water from the open water and wetland storage into the unsaturated zone as infiltration (as a percentage of daily volume) is controlled by the Infiltration Rate (Water).

4.1.2.5 SEEPAGE RATE

Finally, the seepage rate (i.e., the rate at which shallow groundwater infiltrates down to the deeper aquifer) is directly calibrated, meaning that the linear rate at which the saturated storage loses water to the deeper aquifer is manually adjusted. The model can be highly sensitive to these rates so they are often the last parameters to be calibrated to fine-tune model performance and adjust the low-flow simulation performance.

4.1.3 Water Quality Process

To calibrate the simulated water quality loadings against observed concentrations, water quality data were downloaded from USEPA's Water Quality Exchange (WQX) network. The water quality sample locations were indexed to the NHDPlus catchments, and the data were summarized, screened, and refined to yield the set of nutrient and sediment calibration sites. The locations where sufficient water quality data were obtained to perform a calibration are presented in Figure 4-2. The map delineates the contributing area for each water quality calibration location and provides the corresponding USGS streamflow gage number. Observed streamflow data were used with observed concentrations to calculate estimated observed daily

load values, which were then used for calibration of the water quality parameters in WaterFALL. WaterFALL simulated loads were also translated into concentrations using the simulated streamflow so that both loads and concentrations could be examined during calibration. Note that observations for USGS Gage 02144000 were not co-located in the same catchment exact catchment as the streamflow gage. Calibration for loads at this gage is therefore less certain due to the mismatch in observed streamflow and concentration measurements.

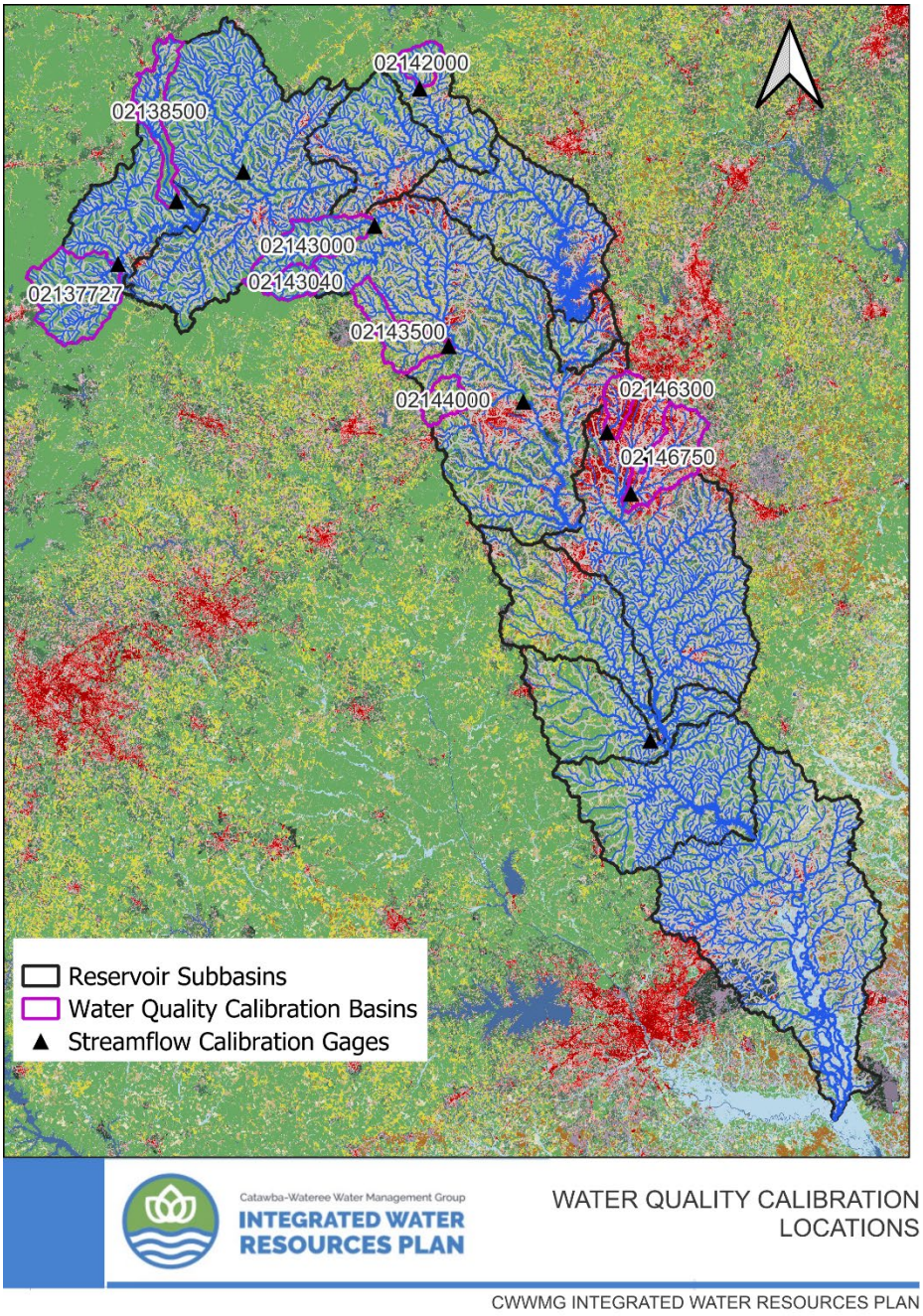


Figure 4-2. Water quality calibration locations.

It is important to note that WaterFALL simulates daily average loads, while the observations measure instantaneous concentrations (unless collected under specific continuous sampling protocols, which did not appear to be a focus in the available observed data). There is often an inherent error in calibrating to grab sample observations, particularly from storm events (grab samples represent conditions for an instant in time, while model results represent a daily average load/concentration). For this reason, the calibration focus is less on reducing error for single observations and more on representing the observed trend in the data, focusing on loads within low-, median-, and high-flow conditions and on representing the overall range, median, and interquartile values of expected concentrations.

The water quality calibration process focuses on 1) loading rates by land use type, 2) streambank erosion rates, and 3) baseflow concentrations. Each of these water quality parameter groups are discussed in further in the following section. The number/size of septic systems is a known quantity and is not adjusted as part of the calibration process. The assessment of water quality simulation performance was based on load estimation and concentration trends in terms of magnitude and range, which are visualized through a series of graphics.

4.1.4 Water Quality Calibration Parameters

4.1.4.1 LAND USE BASED WATER QUALITY RATES

Land use is a primary driver of watershed condition and plays a critical role in shaping both water quantity and water quality outcomes. Different land cover types influence runoff generation, infiltration, and pollutant loading through variations in imperviousness, vegetation cover, soil disturbance, and land management practices. For example, developed areas typically contribute higher runoff volumes and pollutant loads due to increased impervious surface area, while forested and natural lands tend to promote infiltration and reduce sediment and nutrient transport. As a result, accurately representing land use is essential for evaluating watershed processes and identifying potential sources of water quality impairment.

Within WaterFALL, land use is incorporated as a key spatial input that governs both hydrologic response and associated water quality processes. Table 4-1 below presents the land use–specific concentrations, accumulation rates, and process parameters applied within the model for each land use classification. These parameters include dissolved and particulate nutrient concentrations, sediment loads, and rates controlling pollutant buildup, removal, and settling. Together, they provide the basis for simulating how different land use types contribute to runoff, sediment transport, and nutrient dynamics across the watershed, supporting integrated assessments of water quantity and quality.

As shown in the table, parameterization varies by land use type to reflect differences in dominant hydrologic and water quality processes across the watershed. Urban and developed land uses are assigned accumulation (build-up) rates for sediment and nutrients, consistent with the model’s use of a build-up and wash-off approach to simulate pollutant generation from impervious surfaces. In contrast, natural and rural land uses generally rely on event-based loading defined through concentration parameters rather than accumulation processes. Settling rates are primarily applied to open water and wetland classes, where lower flow velocities and longer residence times promote sedimentation and associated nutrient removal. Additionally,

removal efficiencies are only assigned to select riparian land uses, representing the filtering and attenuation functions provided by vegetated buffers along stream corridors. These patterns ensure that the model reflects the underlying physical and biogeochemical behavior of each land use category while maintaining a consistent and streamlined parameterization framework across the study area.

Table 4-1. Calibrated water quality concentrations and rates by land use classification

Land Use ID	Description	Type	Dissolved Solids (mg/L)	Dissolved TN (mg/L)	Solid -Phase TN (mg/kg)	Dissolved TP (mg/L)	Solid -Phase TP (mg/kg)	TSS Accumulation (kg/ha)	TN Accumulation (kg/ha)	TP Accumulation (kg/ha)	Sediment Removal Efficiency (%)	Nitrogen Removal Efficiency (%)	Phosphorus Removal Efficiency (%)	Sediment Settling Rate (m/d)	Nitrogen Setting Rate (m/d)	Phosphorus Settling Rate (m/d)
110	Open water	Water	0	0	0	0	0	0	0	0	0	0	0	0.04	0.027	0.05
210	Mixed low-intensity developed and natural areas	Rural	7	0.175	2200	0.02	402	0	0	0	0	0	0	0	0	0
211	Developed open space in very low-density areas	Rural	4	0.015	2000	0.0015	402	0	0	0	0	0	0	0	0	0
215	Developed open space in low-density areas	Rural	6	0.15	2200	0.01	482.4	0	0	0	0	0	0	0	0	0
216	Developed open space in higher-density areas	Rural	5.6	0.021	2000	0.0021	562.8	0	0	0	0	0	0	0	0	0
220	Mixed grass, shrub, and pasture areas at risk of development	Rural	8	0.28	2200	0.03	397	0	0	0	0	0	0	0	0	0
221	Low-intensity development in very low-density areas	Rural	6	0.08	2000	0.008	397	0	0	0	0	0	0	0	0	0
222	Low-intensity development on natural pervious land	Rural	6	0.08	2000	0.008	397	0	0	0	0	0	0	0	0	0
223	Low-intensity development on worked pervious land	Rural	7.2	0.096	2000	0.0096	476.4	0	0	0	0	0	0	0	0	0
224	Low-intensity mixed or altered land	Rural	8.4	0.112	2000	0.0112	555.8	0	0	0	0	0	0	0	0	0

Land Use ID	Description	Type	Dissolved Solids (mg/L)	Dissolved TN (mg/L)	Solid -Phase TN (mg/kg)	Dissolved TP (mg/L)	Solid -Phase TP (mg/kg)	TSS Accumulation (kg/ha)	TN Accumulation (kg/ha)	TP Accumulation (kg/ha)	Sediment Removal Efficiency (%)	Nitrogen Removal Efficiency (%)	Phosphorus Removal Efficiency (%)	Sediment Settling Rate (m/d)	Nitrogen Setting Rate (m/d)	Phosphorus Settling Rate (m/d)
225	Low-intensity development in low-density areas	Urban	6	0.04	0	0.004	0	0.5	0.007	0.0012	0	0	0	0	0	0
226	Low-intensity development in higher-density areas	Urban	6	0.05	0	0.005	0	0.85	0.012	0.0021	0	0	0	0	0	0
230	Crops or wetlands under high development pressure	Rural	6	0.1	2000	0.01	395	0	0	0	0	0	0	0	0	0
231	Medium-intensity development in very low-density areas	Urban	6	0.05	0	0.005	0	0.7225	0.01	0.0021	0	0	0	0	0	0
232	Medium-intensity development on natural pervious land	Urban	6	0.05	0	0.005	0	0.7225	0.01	0.0021	0	0	0	0	0	0
233	Medium-intensity development on worked pervious land	Urban	7.2	0.06	0	0.006	0	0.867	0.012	0.00252	0	0	0	0	0	0
234	Medium-intensity mixed or altered land	Urban	8.4	0.07	0	0.007	0	1.0115	0.014	0.00294	0	0	0	0	0	0
235	Medium-intensity development in low-density areas	Urban	4.8	0.04	0	0.004	0	0.578	0.01	0.00168	0	0	0	0	0	0
236	Medium-intensity development in higher-density areas	Urban	7.2	0.06	0	0.006	0	0.867	0.018	0.00252	0	0	0	0	0	0
240	High-intensity developed land	Urban	6	0.055	0	0.0055	0	1.02	0.025	0.0028	0	0	0	0	0	0

Land Use ID	Description	Type	Dissolved Solids (mg/L)	Dissolved TN (mg/L)	Solid -Phase TN (mg/kg)	Dissolved TP (mg/L)	Solid -Phase TP (mg/kg)	TSS Accumulation (kg/ha)	TN Accumulation (kg/ha)	TP Accumulation (kg/ha)	Sediment Removal Efficiency (%)	Nitrogen Removal Efficiency (%)	Phosphorus Removal Efficiency (%)	Sediment Settling Rate (m/d)	Nitrogen Setting Rate (m/d)	Phosphorus Settling Rate (m/d)
241	High-intensity development in very low-density areas	Urban	4.8	0.044	0	0.0044	0	0.816	0.02	0.00224	0	0	0	0	0	0
242	High-intensity development on natural pervious land	Urban	4.8	0.044	0	0.0044	0	0.816	0.02	0.00224	0	0	0	0	0	0
243	High-intensity development on worked pervious land	Urban	6	0.055	0	0.0055	0	1.02	0.025	0.0028	0	0	0	0	0	0
244	High-intensity mixed or altered land	Urban	6	0.055	0	0.0055	0	1.02	0.025	0.0028	0	0	0	0	0	0
245	High-intensity development in low-density areas	Urban	4.8	0.044	0	0.0044	0	0.816	0.02	0.00224	0	0	0	0	0	0
246	High-intensity development in higher-density areas	Urban	6	0.055	0	0.0055	0	1.02	0.025	0.0028	0	0	0	0	0	0
310	Barren land (rock, sand, or clay)	Rural	5	0.06	2000	0.006	393	0	0	0	0	0	0	0	0	0
410	Deciduous forest	Rural	3	0.08	1800	0.004	162.4	0	0	0	0	0	0	0	0	0
415	Deciduous forest with low development	Rural	4	0.12	2000	0.006	194.88	0	0	0	0	0	0	0	0	0
416	Deciduous forest with higher development	Rural	5	0.15	2200	0.008	227.36	0	0	0	0	0	0	0	0	0
420	Evergreen forest	Rural	3	0.08	1800	0.004	162.4	0	0	0	0	0	0	0	0	0
425	Evergreen forest with low development	Rural	4	0.12	2000	0.006	194.88	0	0	0	0	0	0	0	0	0

Land Use ID	Description	Type	Dissolved Solids (mg/L)	Dissolved TN (mg/L)	Solid -Phase TN (mg/kg)	Dissolved TP (mg/L)	Solid -Phase TP (mg/kg)	TSS Accumulation (kg/ha)	TN Accumulation (kg/ha)	TP Accumulation (kg/ha)	Sediment Removal Efficiency (%)	Nitrogen Removal Efficiency (%)	Phosphorus Removal Efficiency (%)	Sediment Settling Rate (m/d)	Nitrogen Setting Rate (m/d)	Phosphorus Settling Rate (m/d)
426	Evergreen forest with higher development	Rural	5	0.15	2200	0.008	227.36	0	0	0	0	0	0	0	0	0
430	Mixed forest	Rural	3	0.08	1800	0.004	162.4	0	0	0	0	0	0	0	0	0
435	Mixed forest with low development	Rural	4	0.12	2000	0.006	194.88	0	0	0	0	0	0	0	0	0
436	Mixed forest with higher development	Rural	5	0.15	2200	0.008	227.36	0	0	0	0	0	0	0	0	0
520	Shrub or scrub land	Rural	3	0.114	2200	0.0114	406	0	0	0	0	0	0	0	0	0
523	Shrub or scrub on worked pervious land	Rural	3	0.114	2200	0.0114	406	0	0	0	0	0	0	0	0	0
710	Grassland or herbaceous land	Rural	3	1.38	2200	0.069	397	0	0	0	0	0	0	0	0	0
713	Grassland on worked pervious land	Rural	3	1.38	2200	0.069	397	0	0	0	0	0	0	0	0	0
714	Grassland with mixed or altered land use	Rural	3.6	1.656	2640	0.0828	476.4	0	0	0	0	0	0	0	0	0
810	Pasture or hay land	Pasture	4	2	3000	0.07	400	0	0	0	0	0	0	0	0	0
813	Pasture or hay on worked pervious land	Rural	4	2	3000	0.07	400	0	0	0	0	0	0	0	0	0
815	Pasture or hay with low development	Rural	4.8	2.4	3600	0.09	450	0	0	0	0	0	0	0	0	0
820	Cultivated crops	Agriculture	15	2.31	4500	0.1155	400	0	0	0	0	0	0	0	0	0
900	Woody wetlands	Water	0	0	0	0	0	0	0	0	0	0	0	0.022	0.011	0.05
950	Emergent herbaceous wetlands	Water	0	0	0	0	0	0	0	0	0	0	0	0.022	0.011	0.05
1100	Riparian open water	Water	0	0	0	0	0	0	0	0	0	0	0	0.04	0.027	0.05

Land Use ID	Description	Type	Dissolved Solids (mg/L)	Dissolved TN (mg/L)	Solid -Phase TN (mg/kg)	Dissolved TP (mg/L)	Solid -Phase TP (mg/kg)	TSS Accumulation (kg/ha)	TN Accumulation (kg/ha)	TP Accumulation (kg/ha)	Sediment Removal Efficiency (%)	Nitrogen Removal Efficiency (%)	Phosphorus Removal Efficiency (%)	Sediment Settling Rate (m/d)	Nitrogen Setting Rate (m/d)	Phosphorus Settling Rate (m/d)
2100	Riparian mixed low-intensity developed and natural areas	Rural	7	0.175	2200	0.02	402	0	0	0	0.14	0.14	0.14	0	0	0
2110	Riparian developed open space in very low-density areas	Rural	4	0.015	2000	0.0015	402	0	0	0	0.12	0.12	0.12	0	0	0
2150	Riparian developed open space in low-density areas	Rural	6	0.15	2200	0.01	482.4	0	0	0	0.1	0.1	0.1	0	0	0
2160	Riparian developed open space in higher-density areas	Rural	5.6	0.021	2000	0.0021	562.8	0	0	0	0.1	0.1	0.1	0	0	0
2200	Riparian mixed grass, shrub, and pasture areas at risk of development	Rural	8	0.28	2200	0.03	397	0	0	0	0	0	0	0	0	0
2210	Riparian low-intensity development in very low-density areas	Rural	6	0.08	2000	0.008	397	0	0	0	0	0	0	0	0	0
2220	Riparian low-intensity development on natural pervious land	Rural	6	0.08	2000	0.008	397	0	0	0	0	0	0	0	0	0
2230	Riparian low-intensity development on worked pervious land	Rural	7.2	0.096	2000	0.0096	476.4	0	0	0	0	0	0	0	0	0
2240	Riparian low-intensity mixed or altered land	Rural	8.4	0.112	2000	0.0112	555.8	0	0	0	0	0	0	0	0	0

Land Use ID	Description	Type	Dissolved Solids (mg/L)	Dissolved TN (mg/L)	Solid -Phase TN (mg/kg)	Dissolved TP (mg/L)	Solid -Phase TP (mg/kg)	TSS Accumulation (kg/ha)	TN Accumulation (kg/ha)	TP Accumulation (kg/ha)	Sediment Removal Efficiency (%)	Nitrogen Removal Efficiency (%)	Phosphorus Removal Efficiency (%)	Sediment Settling Rate (m/d)	Nitrogen Setting Rate (m/d)	Phosphorus Settling Rate (m/d)
2250	Riparian low-intensity development in low-density areas	Urban	6	0.04	0	0.004	0	0.5	0.007	0.0012	0	0	0	0	0	0
2260	Riparian low-intensity development in higher-density areas	Urban	6	0.05	0	0.005	0	0.85	0.012	0.0021	0	0	0	0	0	0
2300	Riparian crops or wetlands under high development pressure	Rural	6	0.1	2000	0.01	395		0		0	0	0	0	0	0
2310	Riparian medium-intensity development in very low-density areas	Urban	6	0.05	0	0.005	0	0.7225	0.01	0.0021	0	0	0	0	0	0
2320	Riparian medium-intensity development on natural pervious land	Urban	6	0.05	0	0.005	0	0.7225	0.01	0.0021	0	0	0	0	0	0
2330	Riparian medium-intensity development on worked pervious land	Urban	7.2	0.06	0	0.006	0	0.867	0.012	0.00252	0	0	0	0	0	0
2340	Riparian medium-intensity mixed or altered land	Urban	8.4	0.07	0	0.007	0	1.0115	0.014	0.00294	0	0	0	0	0	0
2350	Riparian medium-intensity development in low-density areas	Urban	4.8	0.04	0	0.004	0	0.578	0.01	0.00168	0	0	0	0	0	0

Land Use ID	Description	Type	Dissolved Solids (mg/L)	Dissolved TN (mg/L)	Solid -Phase TN (mg/kg)	Dissolved TP (mg/L)	Solid -Phase TP (mg/kg)	TSS Accumulation (kg/ha)	TN Accumulation (kg/ha)	TP Accumulation (kg/ha)	Sediment Removal Efficiency (%)	Nitrogen Removal Efficiency (%)	Phosphorus Removal Efficiency (%)	Sediment Settling Rate (m/d)	Nitrogen Setting Rate (m/d)	Phosphorus Settling Rate (m/d)
2360	Riparian medium-intensity development in higher-density areas	Urban	7.2	0.06	0	0.006	0	0.867	0.018	0.00252	0	0	0	0	0	0
2400	Riparian high-intensity developed land	Urban	6	0.055	0	0.0055	0	1.02	0.025	0.0028	0	0	0	0	0	0
2410	Riparian high-intensity development in very low-density areas	Urban	4.8	0.044	0	0.0044	0	0.816	0.02	0.00224	0	0	0	0	0	0
2420	Riparian high-intensity development on natural pervious land	Urban	4.8	0.044	0	0.0044	0	0.816	0.02	0.00224	0	0	0	0	0	0
2430	Riparian high-intensity development on worked pervious land	Urban	6	0.055	0	0.0055	0	1.02	0.025	0.0028	0	0	0	0	0	0
2440	Riparian high-intensity mixed or altered land	Urban	6	0.055	0	0.0055	0	1.02	0.025	0.0028	0	0	0	0	0	0
2450	Riparian high-intensity development in low-density areas	Urban	4.8	0.044	0	0.0044	0	0.816	0.02	0.00224	0	0	0	0	0	0
2460	Riparian high-intensity development in higher-density areas	Urban	6	0.055	0	0.0055	0	1.02	0.025	0.0028	0	0	0	0	0	0

Land Use ID	Description	Type	Dissolved Solids (mg/L)	Dissolved TN (mg/L)	Solid -Phase TN (mg/kg)	Dissolved TP (mg/L)	Solid -Phase TP (mg/kg)	TSS Accumulation (kg/ha)	TN Accumulation (kg/ha)	TP Accumulation (kg/ha)	Sediment Removal Efficiency (%)	Nitrogen Removal Efficiency (%)	Phosphorus Removal Efficiency (%)	Sediment Settling Rate (m/d)	Nitrogen Setting Rate (m/d)	Phosphorus Settling Rate (m/d)
3100	Riparian barren land (rock, sand, or clay)	Rural	5	0.06	2000	0.006	393	0	0	0	0	0	0	0	0	0
4100	Riparian deciduous forest	Rural	3	0.08	1800	0.004	162.4	0	0	0	0.49	0.49	0.49	0	0	0
4150	Riparian deciduous forest with low development	Rural	4	0.12	2000	0.006	194.88	0	0	0	0.42	0.42	0.42	0	0	0
4160	Riparian deciduous forest with higher development	Rural	5	0.15	2200	0.008	227.36	0	0	0	0.35	0.35	0.35	0	0	0
4200	Riparian evergreen forest	Rural	3	0.08	1800	0.004	162.4	0	0	0	0.49	0.49	0.49	0	0	0
4250	Riparian evergreen forest with low development	Rural	4	0.12	2000	0.006	194.88	0	0	0	0.42	0.42	0.42	0	0	0
4260	Riparian evergreen forest with higher development	Rural	5	0.15	2200	0.008	227.36	0	0	0	0.35	0.35	0.35	0	0	0
4300	Riparian mixed forest	Rural	3	0.08	1800	0.004	162.4	0	0	0	0.49	0.49	0.49	0	0	0
4350	Riparian mixed forest with low development	Rural	4	0.12	2000	0.006	194.88	0	0	0	0.42	0.42	0.42	0	0	0
4360	Riparian mixed forest with higher development	Rural	5	0.15	2200	0.008	227.36	0	0	0	0.35	0.35	0.35	0	0	0
5200	Riparian shrub or scrub land	Rural	3	0.114	2200	0.0114	406	0	0	0	0.2	0.2	0.2	0	0	0
5230	Riparian shrub or scrub on worked pervious land	Rural	3	0.114	2200	0.0114	406	0	0	0	0.2	0.2	0.2	0	0	0
7100	Riparian grassland or herbaceous land	Rural	3	1.38	2200	0.069	397	0	0	0	0.3	0.3	0.3	0	0	0

Land Use ID	Description	Type	Dissolved Solids (mg/L)	Dissolved TN (mg/L)	Solid -Phase TN (mg/kg)	Dissolved TP (mg/L)	Solid -Phase TP (mg/kg)	TSS Accumulation (kg/ha)	TN Accumulation (kg/ha)	TP Accumulation (kg/ha)	Sediment Removal Efficiency (%)	Nitrogen Removal Efficiency (%)	Phosphorus Removal Efficiency (%)	Sediment Settling Rate (m/d)	Nitrogen Setting Rate (m/d)	Phosphorus Settling Rate (m/d)
7130	Riparian grassland on worked pervious land	Rural	3	1.38	2200	0.069	397	0	0	0	0.25	0.25	0.25	0	0	0
7140	Riparian grassland with mixed or altered land use	Rural	3.6	1.656	2640	0.0828	476.4	0	0	0	0.25	0.25	0.25	0	0	0
8100	Riparian pasture or hay land	Pasture	4	2	3000	0.07	400	0	0	0	0.12	0.12	0.12	0	0	0
8130	Riparian pasture or hay on worked pervious land	Rural	4	2	3000	0.07	400	0	0	0	0.1	0.1	0.1	0	0	0
8150	Riparian pasture or hay with low development	Rural	4.8	2.4	3600	0.09	450	0	0	0	0.1	0.1	0.1	0	0	0
8200	Riparian cultivated crops	Agriculture	15	2.31	4500	0.1155	400	0	0	0	0	0	0	0	0	0
9000	Riparian woody wetlands	Water	0	0	0	0	0	0	0	0	0	0	0	0.022	0.011	0.05
9500	Riparian emergent herbaceous wetlands	Water	0	0	0	0	0	0	0	0	0	0	0	0.022	0.011	0.05

Note: mg/L = milligrams per liter; mg/kg = milligrams per kilogram; kg/ha = kilograms per hectare; and m/d = meters per day.

4.1.4.2 STREAMBANK EROSION RATES

The WaterFALL streambank erosion algorithms estimate the quantity of TSS exported from catchments resulting from streambank erosion processes. These values parameterize rates of sediment and nutrient loading due to lateral erosion of the banks (i.e., the lateral width and height per length unit along the stream channel). The length of channel experiencing erosion to which these rates are applied is assumed to be 70% of the catchment's stream length. Erosion is only simulated during periods of high flow (defined as the highest 25% of the streamflow regime) and erosion is scaled up by the ratio of the streamflow to the streamflow erosion threshold raised to the power of the erosion exponent, which was held constant at 0.9 for all subbasins. This scaling factor provides for an exponential load generation with streambank loads increasing swiftly as the streamflow increases above the threshold and then tapering off as the channel becomes inundated at higher streamflows.

Erosion rates were developed for each category of erosion potential (i.e., high and low). First, literature values for streambank erosion rates were estimated by comparing similar studies in the Southeast. Then the literature-based values were adjusted during calibration, where the strategy was to address instream loads during high flow periods (Table 4-2).

Table 4-2. Calibrated streambank erosion rates (lbs/day/m^2 lateral erosion)

Applicable Subbasins	Parameter	Sediment	Nitrogen	Phosphorus
South Fork and Fishing Creek	Low Loading Rate	0.000008	0.00000021	0.00000003
	High Loading Rate	0.00008	0.0000021	0.0000003
James and Lookout Shoals	Low Loading Rate	0.000004	0.00000015	0.00000002
	High Loading Rate	0.00004	0.0000015	0.0000002
All Other Subbasins	Low Loading Rate	0.000004	0.00000021	0.00000003
	High Loading Rate	0.00008	0.0000021	0.0000003

4.1.4.3 BASEFLOW CONCENTRATIONS

Minimum baseflow concentrations determined from observation data were 0.15 mg/L, 0.012 mg/L, and 1.5 mg/L for TN, TP, and TSS, respectively. Nitrogen baseflow minimum concentrations were changed during calibration for Long Creek (0.12 mg/L) and for gages within the Lake James, Lookout Shoals, South Fork (other than Long Creek), and Fishing Creek subbasins (0.225 mg/L).

4.2 WaterFALL Calibration Results

4.2.1 Hydrology

Hydrologic models are calibrated to observed streamflow data to ensure that simulated runoff, baseflow, evapotranspiration, and groundwater recharge processes reasonably represent watershed behavior across a range of hydrologic conditions. Calibration typically involves adjusting model parameters within physically defensible ranges to improve agreement between simulated and observed streamflow, with particular attention to matching flow magnitude, timing, and distributional characteristics.

For this study, WaterFALL was calibrated using observed data from the USGS gages identified in Table 4-3. Calibration was performed by systematically adjusting the parameters listed in the

same table, beginning with available water capacity and continuing through recession delay. Parameter adjustments were guided by achieving the best possible agreement between simulated and observed flow duration curves, while also optimizing model performance statistics summarized in Table 4-4. This process ensured that both the overall flow distribution and key performance metrics were represented as accurately as practicable across the calibration gages.

Table 4-3 presents the final calibration parameters for the 12 calibration gages. Important findings from the calibration results include the following:

- Adjustments to available water capacity (AWC) were required across the basin to better represent soil storage and subsurface retention processes. In general, reductions from initial soil-based estimates were necessary, reflecting the influence of surface water storage (e.g., wetlands and open water) and subsurface drainage pathways on effective storage.
- Seasonal variability in recession behavior was observed, with distinct winter and summer recession coefficients required to adequately represent baseflow conditions. Higher recession coefficients during winter reflect reduced ET and vegetation uptake, while lower summer values capture increased evapotranspiration demand and slower recession contributions.
- CN multipliers were increased in many subbasins to better reproduce peak runoff responses and high-flow conditions. These adjustments improved representation of storm-driven runoff while maintaining reasonable agreement with overall water balance components.
- ET parameters required localized refinement to capture both growing and dormant season dynamics. Adjustments were generally modest for the growing season but more pronounced for dormant season conditions, consistent with reduced vegetation activity. Additional adjustments to open water and wetland evapotranspiration factors were necessary to better represent surface water evaporation.
- Seepage rates varied spatially across the basin, reflecting differences in subsurface conditions and connectivity to deeper groundwater systems. Variability in seepage between headwater and downstream areas suggests localized differences in infiltration and groundwater exchange processes.

The range of quantitative metrics provides several ways to examine model performance (Table 4-4). The NSE and KGE measures compare the day-to-day or month-to-month streamflow values against the corresponding days or months in the observed streamflow record. The rNSE and KGElf values are presented for daily flows as they remove some of the bias single high-flow events can have on the standard NSE and KGE measures. The wNSE is presented for daily flows as it focuses on the high flow values. Using the NSE, KGE, and PBIAS measures together

ensure all aspects of the simulated streamflow regime are considered when examining performance[15].

The model performed very well (NSE greater than 0.75) for monthly flows for almost all gages, except for the highly urbanized McMullen (02146700) and Irwin (02146300) Creeks, the smaller mixed-use headwaters of Lower Little River (02142000), and Rocky Creek (02147500), which has poor gage records for low flows. The daily simulations showed several high performing gages using the NSE (greater than 0.5) and very good performance using the KGE (greater than 0.75), such as in the Catawba River at Pleasant Gardens (02137727), Johns River (02140991), and Jacob Fork (02143040). Both high and low flows were satisfactorily simulated according to the performance measures across the region, with no generalized concerns for either hydrograph tail, although Irwin showed poor performance for high flow and low flow according to the wNSE and KGElf, respectively. However, the rNSE was high (0.79) for this gage, pointing again to the necessity of using multiple statistical measures to examine performance.

All but two gages—the two most downstream gages in McMullen Creek (02146700) and Rocky Creek—had PBIAS within ±9%, with the average within ±5%, indicating very good model performance. McMullen Creek had a PBIAS of 16% and Rocky Creek had a PBAIS of -12%, which are still considered good performance in terms of volume error. All models were successful with the representation of the lowest flows as indicated by comparing the observed USGS flows and simulated WaterFALL flows at the 25th percentile/first quartile.

The qualitative evaluations conducted during calibration and subsequent validation are completed using the daily time series, monthly time series, monthly mean and medians, and the flow duration curve. These charts are compiled into a single graphic for each calibration and validation model runs. Examples are provided for the Catawba River at Pleasant Gardens calibration (Figure 4-3) and validation (Figure 4-4) results. Calibration graphics for all gages can be made available upon request.

[15] Knoben, W. J., Freer, J. E., & Woods, R. A. (2019). Technical note: Inherent benchmark or not? Comparing Nash-Sutcliffe and Kling-Gupta efficiency scores. *Hydrology and Earth System Sciences, 23*, 4323–4331.

Table 4-3. Hydrologic calibration parameters by gage

Region	Subbasin	Gage ID	Water Quality Calibration	AWC	Seepage	Winter R	Summer R	CNMulti	WinStart	WinEnd	Start Grow Season	End Grow Season	Grow Season Cover Factor	Dorm Season Cover Factor	Water ET Factor	Infiltration Rate (Water)	mavel	Recession Delay
Northern	James	02137727	Y	0.4	-0.004	0.12	0.12	1.06	12	5	4	11	0.98	0.84	0.91	0.037	0.85	0.52
	James	02138500	Y	0.8	-0.008	0.3	0.2	1.09	1	4	4	11	0.98	0.84	0.91	0.037	1	0.52
	Rhodhiss	02140991	N	0.31	-0.008	0.25	0.23	1.09	12	5	4	11	0.93	0.74	0.92	0.032	1.076	0.3
	Lookout Shoals	02142000	Y	0.31	-0.01	0.12	0.23	1.05	1	5	4	11	0.93	0.74	0.92	0.032	0.86	0.4
South Fork	South Fork	02143000	Y	0.26	-0.005	0.165	0.119	1.02	1	4	4	11	0.85	0.94	0.89	0.036	0.96	0.31
	South Fork	02143040	Y	0.37	-0.005	0.17	0.076	1.03	12	5	4	11	0.86	0.82	0.92	0.04	0.87	0.4
	South Fork	02143500	Y	0.16	-0.02	0.32	0.165	1	12	5	4	11	0.9	0.93	0.86	0.045	0.95	0.4
	South Fork	02144000	Y	0.16	-0.022	0.32	0.165	1	12	5	4	11	0.9	0.93	0.86	0.045	0.9	0.4
Southern	Fishing Creek	02146300	Y	0.8	-0.008	0.12	0.12	1.037	12	5	4	11	0.88	0.87	0.84	0.02	1	0.5
	Fishing Creek	02146700	N	0.16	-0.034	0.1	0.05	1.05	12	4	4	11	0.93	0.89	0.93	0.012	0.86	0.5
	Fishing Creek	02146750	Y	0.23	-0.033	0.165	0.094	1.05	12	5	4	11	0.92	0.7	0.93	0.017	1.05	0.42
	Great Falls/ Cedar Creek	02147500	N	0.75	-0.03	0.16	0.1	1.08	12	5	4	11	0.93	0.76	0.92	0.04	0.99	0.33

AWC = Available Water Capacity. Seepage = Seepage Rate. Winter R = Winter Recession Coefficient. Summer R = Summer Recession Coefficient. CNMulti = Curve Number Multiplier. WinStart = Winter Start Date. WinEnd = Winter End Date. StartGrow Season = Growing Season Start Date. EndGrow Season = Growing Season End Date. GrowSeason Cover Factor = Growing Season Cover Factor. DormSeason Cover Factor = Dormant Season Cover Factor. Water ET Factor = Water Evapotranspiration Factor. Infiltration Rate (Water) = Water Infiltration Rate. mavel = Mean Annual Velocity. Recession Delay = Recession Delay.

Table 4-4. Hydrology calibration performance statistics by gage.

Region	Subbasin	Gage ID	DA (mi^2)	NSE-daily	NSE-monthly	rNSE (daily)	KGE (daily)	wNSE (daily)	KGElf (daily)	NRMSE-daily	NRMSE-monthly	PBIAS	MAF Bias	IQR Bias	1st Q USGS	1st Q WF
Northern	James	02137727	126	0.63	0.9	0.88	0.82	0.74	0.75	60.7	32.1	3.5	2.62	7.03	100	110
	James	02138500	66.7	0.51	0.81	0.92	0.55	0.46	0.65	70.2	43.1	-6.6	-6.32	2.76	60	65
	Rhodhiss	02140991	202	0.51	0.82	0.82	0.75	0.65	0.77	69.8	41.7	4.9	4.35	-0.88	160	170
	Lookout Shoals	02142000	28.2	0.14	0.67	0.75	0.59	0.4	0.47	92.8	56.9	9.3	8.46	-7.56	12	14
South Fork	South Fork	02143000	83.2	0.55	0.85	0.81	0.72	0.63	0.74	66.7	38.3	2.6	1.94	-4.66	45	49
	South Fork	02143040	25.7	0.55	0.76	0.85	0.76	0.66	0.71	67.3	49.2	-5.2	-7.38	-3.84	13	13
	South Fork	02143500	69.2	0.57	0.83	0.85	0.66	0.66	0.64	65.6	41.5	-1.7	-2.79	24.81	18	17
	South Fork	02144000	31.8	0.2	0.8	0.28	0.62	0.32	0.65	89.6	44.4	2.7	0.8	11.95	4.1	4.2
Southern	Fishing Creek	02146300	30.7	-0.09	0.7	0.79	0.51	0.08	0.33	104.4	54.9	6.6	6.25	-35.49	12	16
	Fishing Creek	02146700	92.4	0.59	0.75	0.65	0.76	0.73	0.69	64.2	49.9	8.1	9.54	30.2	11	14
	Fishing Creek	02146750	7	-0.26	0.56	-	0.44	0.55	0.41	112.2	65.9	16	11.44	-8.08	0.71	0.85
	Great Falls/ Cedar Creek	02147500	514.2	0.48	0.7	-	0.69	0.72	0.58	71.9	54.7	-11.7	-11.86	4.24	8.2	8.1

DA = drainage area. NRMSE = Normalized root mean square error. PBIS=percent bias. IQR = Interquartile range

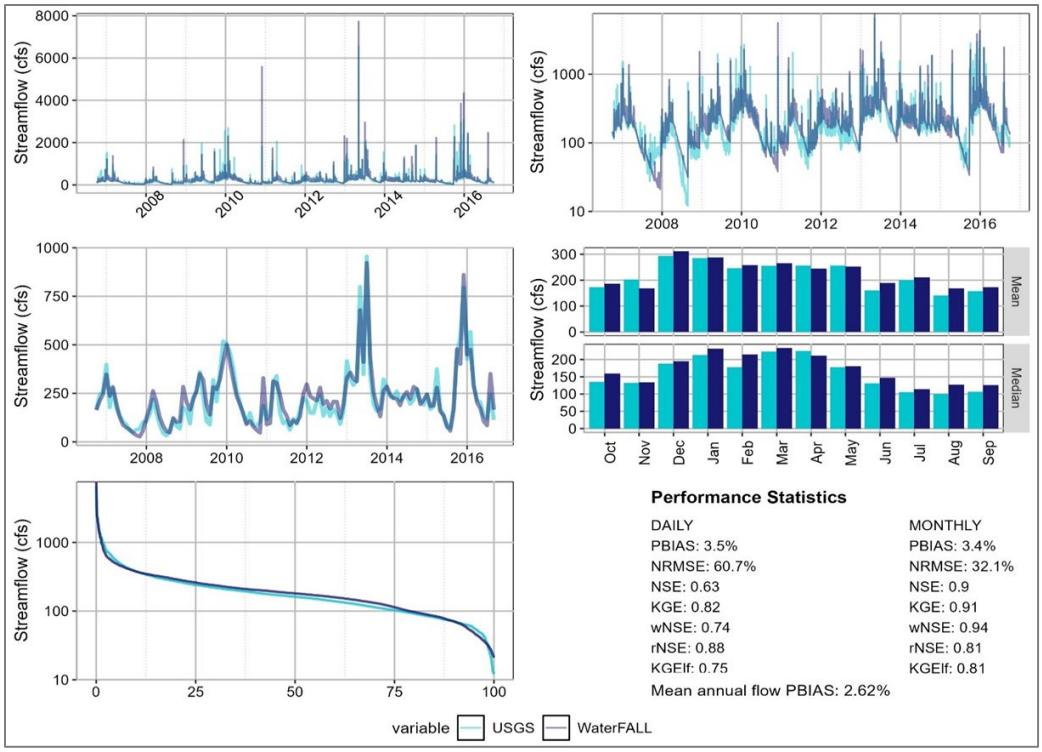


Figure 4-3. Calibration compilation for Catawba River at Pleasant Gardens (USGS Gage 02137727)

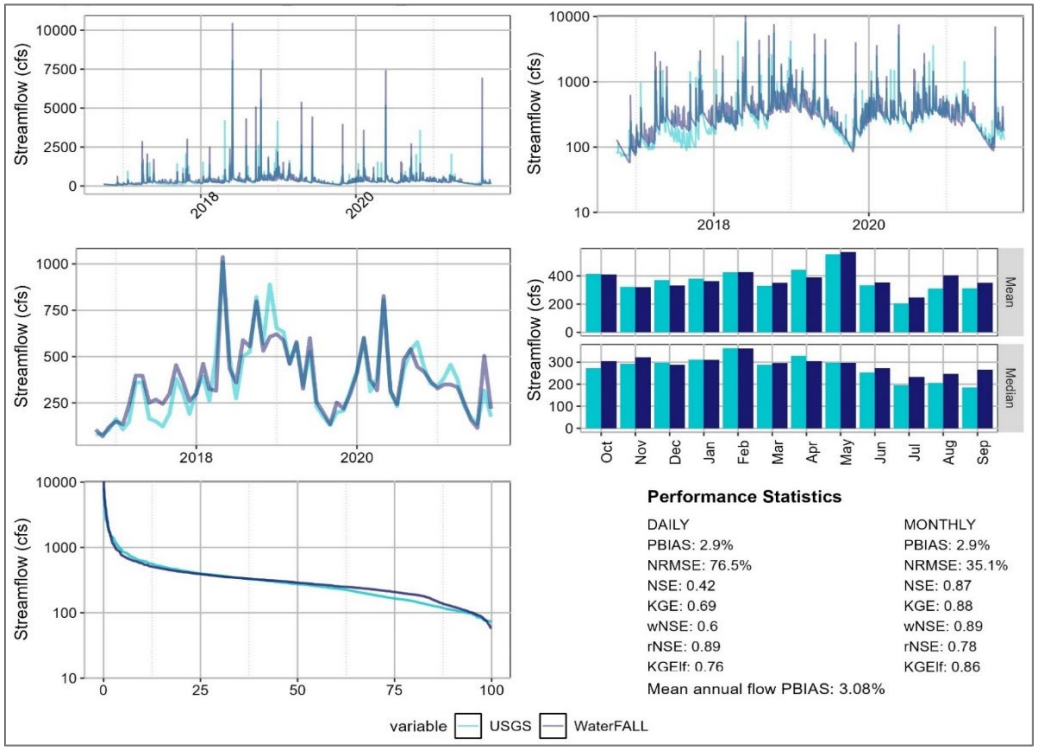


Figure 4-4. Validation compilation for Catawba River at Pleasant Gardens (USGS Gage 02137727)

4.2.2 Water Quality

The calibration results for each water quality parameter (TSS, TN, TP) are displayed in two sets of figures. The first set of figures for each water quality parameter represents the box and whisker plots for the simulation and observations. The “box” represents the interquartile range (data falling between the 25th and 75th percentile of the ranked dataset). The line through the center of the box represents the median of the dataset. Whiskers represent the range between the boundary of the interquartile range and values 1.5 times greater/less than that value. Points represent outliers. Boxplots are useful for making comparisons of the measured and modeled dataset distributions. When evaluating model performance by boxplot comparison, it is important to remember that the number of points used to construct the boxplot of the simulation is often far greater than the number of points used to construct the boxplot of the observations/measurements.

Figure 4-5 displays boxplots for daily loads across all water quality calibration gages by parameter, while Figure 4-6 provides the same display but for concentrations. The y-axis in each figure is displayed in log-scale to clearly identify the range in values across the basin. In general, for both loads and concentrations, the median and interquartile ranges for each parameter match within the same order of magnitude. The largest differences are in the sediment simulations where there are a greater number of extreme, high values and a tighter interquartile range. As sediment loading is driven significantly by large events, which are not typically sampled, and therefore included in the observed data, this result occurrence is not unexpected.

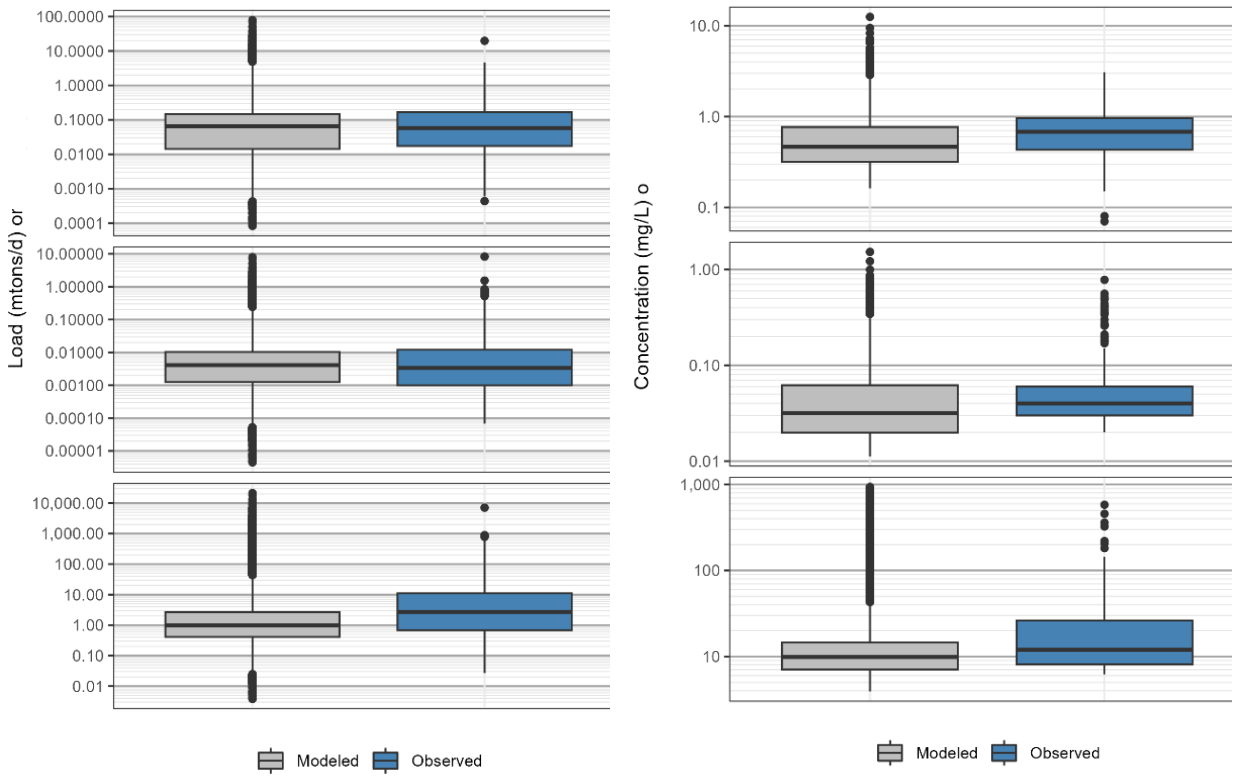


Figure 4-5. Boxplots of modeled and observed loads (left) and concentrations (right) across calibration locations.

The second set of figures provides context around the range in observations available for calibration. The load versus flow relationships for all calibration sites are shown in Figure 4-6 for TN, Figure 4-7 for TP, and Figure 4-8 TSS. In each of these sets of figures, the simulated values are open grey squares and the observations are closed blude circles. These plots allow for the examination of relative flow and load differences among the locations as well as the overall representation observations across the flow regime. For most sites, the observations occur at mid-flow ranges with only scant representation of high flow events. This water quality collection behavior limits the ability for calibrating the model on an event basis. Rather, as is demonstrated by the points in these figures, the focus is on representing the lower bounds, peak values, and spread within median flows.

Log scales are again used so that the full flow and water quality regime can be considered even though the higher flows and corresponding loads are less frequent. TSS has the fewest observations to calibrate to across all gages but also the largest spread in loads occurring within each flow magnitude. TN, which has the least influence from sediment, shows the least spread in both observations and simulated loads for each flow magnitude. Despite the data limitations, the model appears to represent the general behavior of the water quality loadings across the flow regime once the water quality parameters by land use and, importantly, streambank erosion were calibrated.

The box and whisker plots for individual gage locations for the TSS, TN, and TP results can be made available upon request.

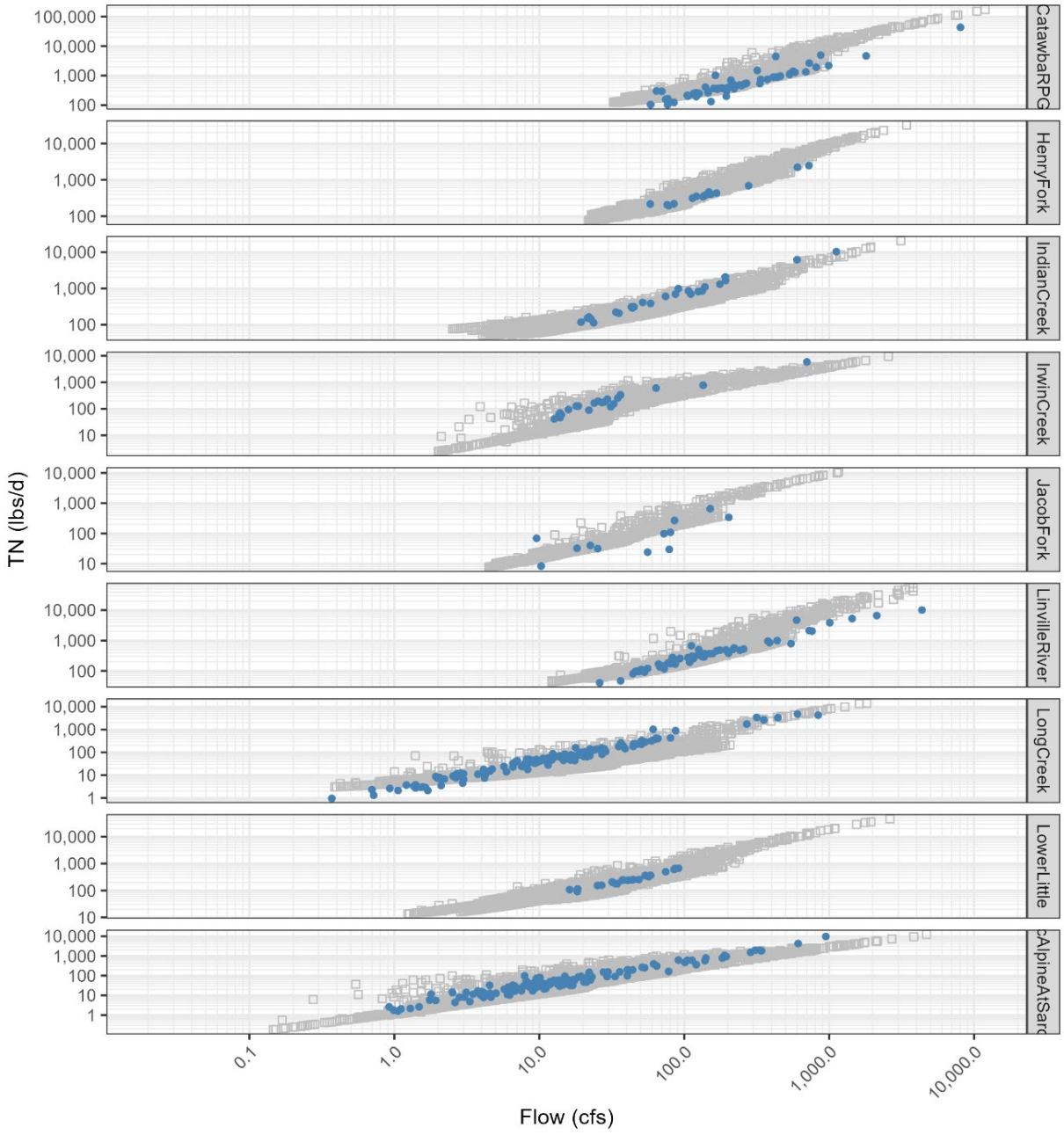


Figure 4-6. Streamflow vs. observed (blue points) and modeled (grey squares) TN loads across water quality calibration gages.

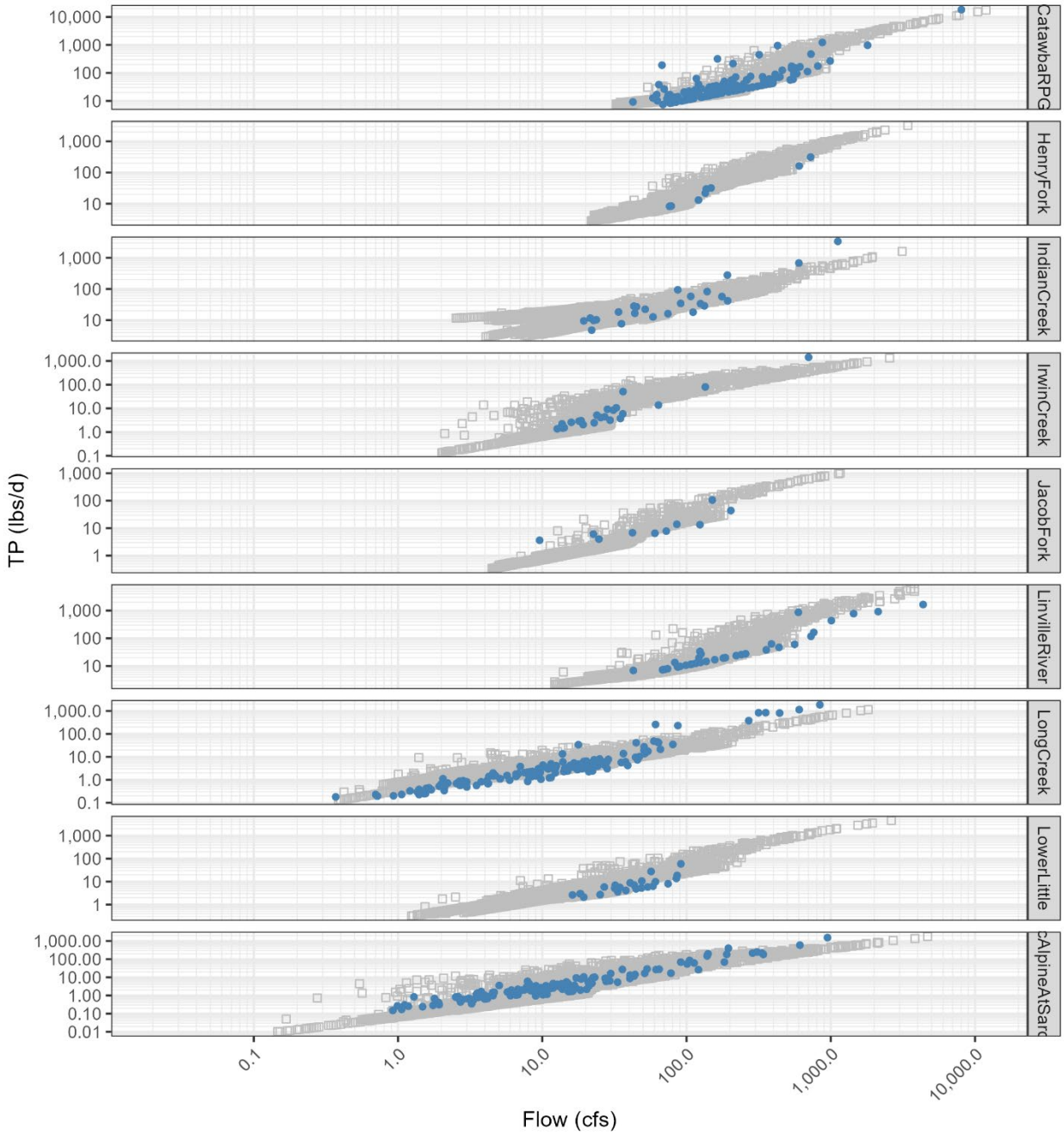


Figure 4-7. Streamflow vs. observed (blue points) and modeled (grey squares) TP loads across water quality calibration gages.

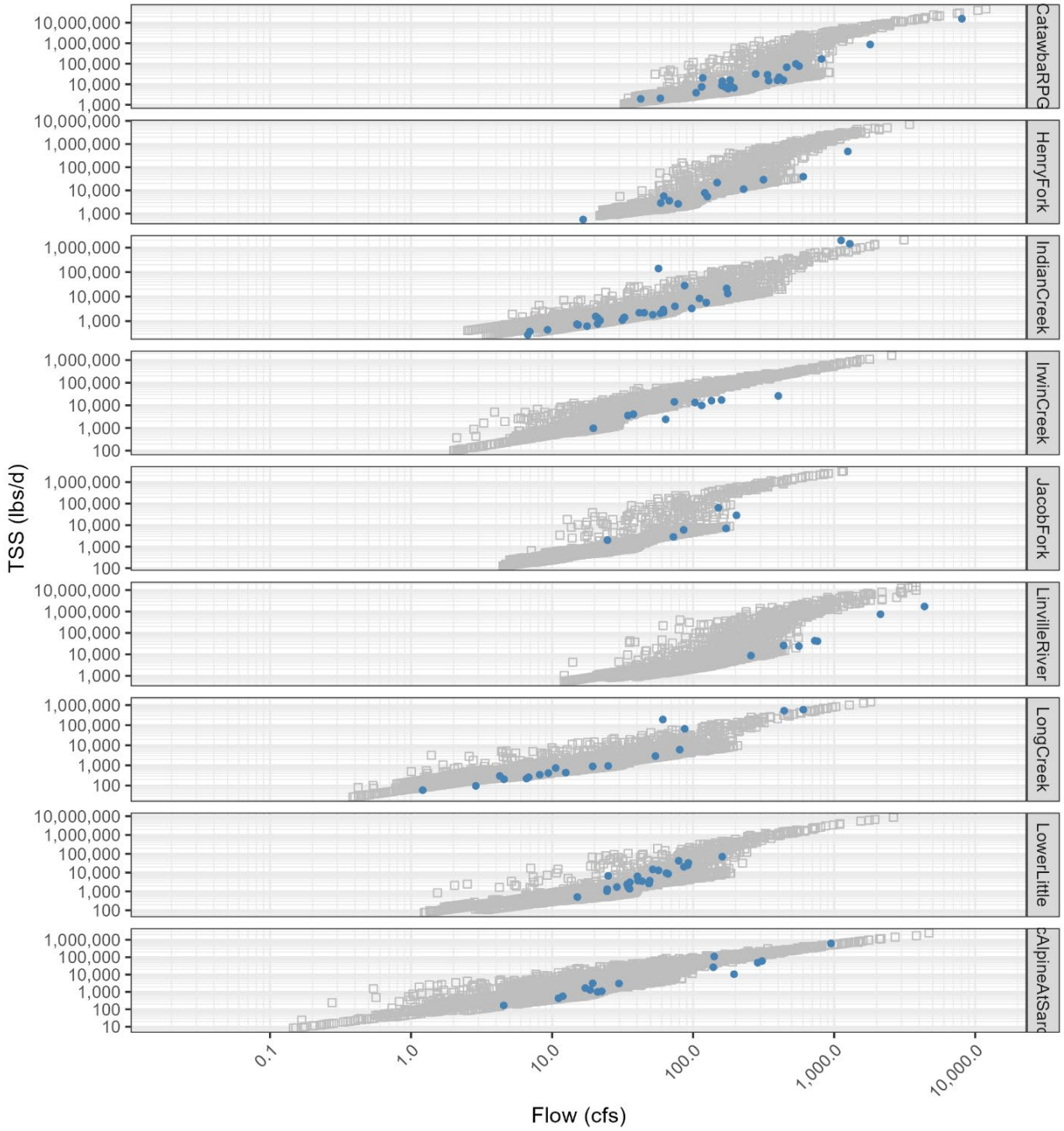


Figure 4-8. Streamflow vs. observed (blue points) and modeled (grey squares) TSS loads across water quality calibration gages.