Appendix B: SWAT Modeling Report

Table of Contents

List of Tables

List of Figures

1.0 Introduction

The Soil Water Assessment Tool (SWAT) model was developed by the Agricultural Research Service, the main research agency within the U.S. Department of Agriculture (Neitsch et al., 2002). The model predicts the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use, and management conditions over long periods of time. SWAT can analyze large watersheds and river basins (greater than 100 square miles) by subdividing the area into homogeneous subwatersheds. The model uses either an hourly or daily time step, and can perform continuous simulation for a period of one to 100 years. SWAT simulates hydrology, pesticide and nutrient cycling, erosion and sediment transport.

SWAT was applied to the Black River watershed in Ohio (Figure 1-1), to support the development of total maximum daily loads (TMDLs) for nutrients and sediments. An initial model calibration was submitted on May 9, 2006. Subsequent review revealed many areas that could be improved. Tetra Tech undertook a thorough recalibration of the model. This recalibration resulted in greatly improved simulation of hydrology, with all statistical measures of fit meeting recommended criteria. The improved hydrology, together with refinements to the simulation of upland management, also results in an improved simulation of water quality.

SWAT is being used to develop TMDLs for the upstream portions of the watershed and is also being linked to a CE-QUAL-W2 model to further study water quality issues in the most downstream segment of the Black River. This report provides an overview of the SWAT model, a description of the modeling process, and summarizes the hydrologic and water quality calibration results. A section is also included that presents the predicted response to various implementation measures.

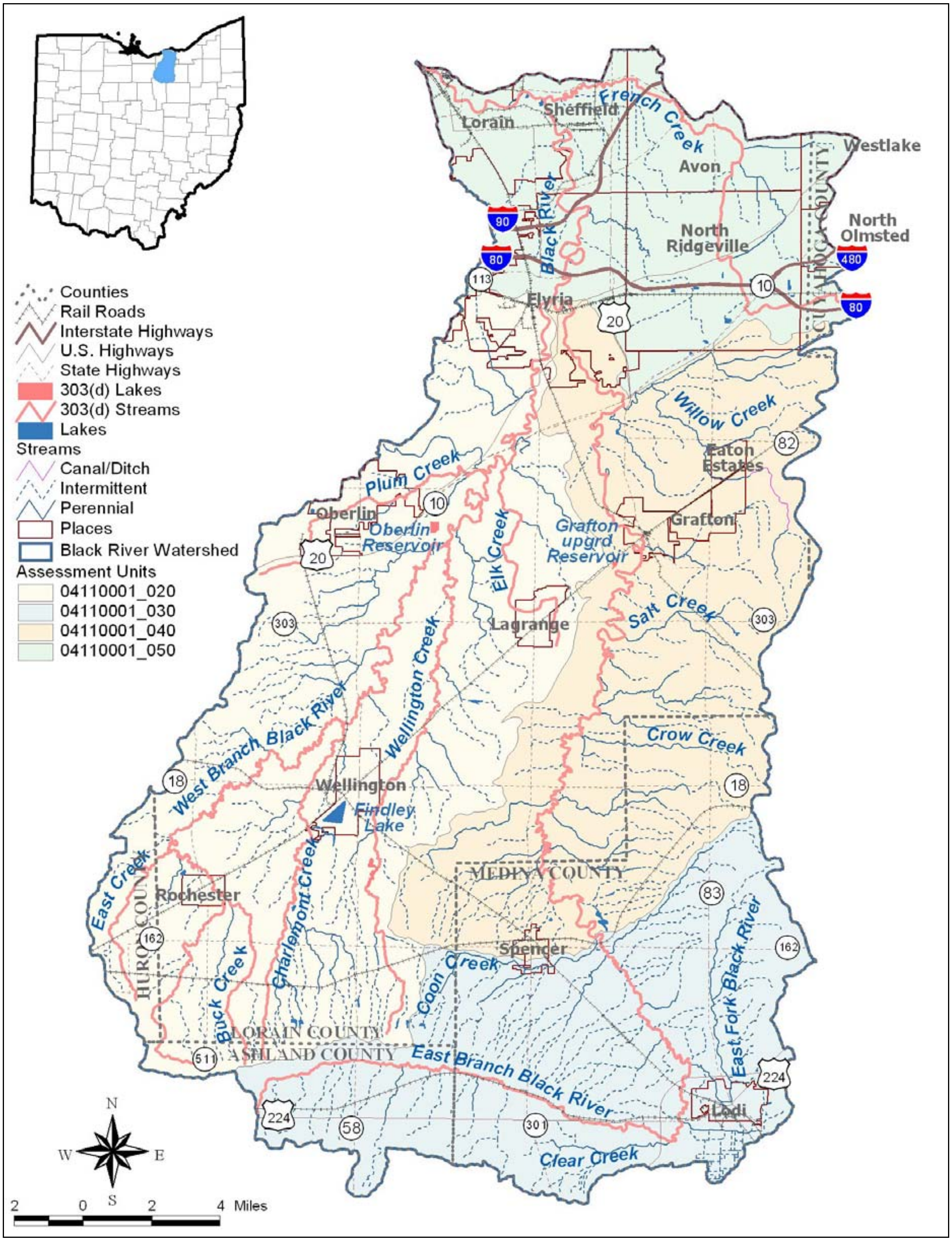

Figure 1-1. Location of the Black River Watershed

2.0 Description of the Model and Model Setup

This section of the report describes the SWAT model and its setup for the Black River watershed.

2.1 Hydrology

The hydrology component of SWAT is based on the water balance equation. The Green & Ampt infiltration method was chosen to simulate surface runoff in the Black River SWAT model. The Green & Ampt infiltration method is physically-based and relates the rate of infiltration to measurable soil properties such as the porosity, hydraulic conductivity, and the moisture content of a particular soil (Green & Ampt, 1911). The equation assumes a homogenous soil profile and uniformly distributed antecedent moisture. As water infiltrates into the soil, the model assumes the soil above the wetting front is completely saturated and there is a sharp break in moisture content at the wetting front.

Using the Green & Ampt equation, Mein and Larson (1973) developed a methodology for determining ponding time with infiltration. The Green & Ampt/Mein-Larson infiltration method is defined as:

$$f_{inf,t} = K_e \cdot \left(1 + \frac{\Psi_{wf} \cdot \Delta\theta_v}{F_{inf,t}} \right)$$

where $f_{inf,t}$ is the infiltration rate at time t (mm/hr), K_e is the effective hydraulic conductivity (mm/hr), Ψ_{wf} is the wetting front matric potential (mm), $\Delta\theta_v$ is the change in volumetric moisture content across the wetting front (mm/mm) and $F_{inf,t}$ is the cumulative infiltration at time t (mm H_20).

The effective hydraulic conductivity parameter, $K_{e,}$ is approximately equivalent to one-half the saturated hydraulic conductivity of the soil, K_{sat}. Nearing et al. (1996) developed an equation to calculate effective hydraulic conductivity as a function of saturated hydraulic conductivity and the curve number. The following equation incorporates land cover impacts into the calculated hydraulic conductivity:

$$K_e = \frac{56.82 \cdot K_{sat}^{0.286}}{1 + 0.051 \cdot \exp(0.062 \cdot CN)} - 2$$

where K_e is the effective hydraulic conductivity (mm/hr), K_{sat} is the saturated hydraulic conductivity (mm/hr), and CN is the curve number. For each time-step, SWAT calculates the amount of water entering the soil. Water that does not infiltrate becomes surface runoff.

Curve numbers are a function of hydrologic soil group, vegetation, land use, cultivation practice, and antecedent moisture conditions. The NRCS has classified more than 4,000 soils into four hydrologic soil groups according to their minimum infiltration rate for bare soil after prolonged wetting. The characteristics associated with each hydrologic soil group are given in Table 2-1. The amount of moisture present in the soil is known to affect the volume and the rate of runoff. Consequently, the NRCS developed three antecedent soil moisture conditions:

- Dryer antecedent conditions (Condition I) reflect soils that are dry, but not to the wilting point.
- Wetter conditions (Condition III) characterize soils that have experienced heavy rainfall, light rainfall and low temperatures within the last five days (saturated soils).
- Condition II is the average condition.

Curve numbers for each of the three conditions are found in Table 2-2.

Table 2-1. Characteristics of Hydrologic Soil Groups

Soil Group	Characteristics	Minimum Infiltration Capacity (in/hr)
A	Sandy, deep, well drained soils; deep loess; aggregated silty soils	0.30-0.45
B	Sandy loams, shallow loess, moderately deep and moderately well drained soils	0.15-0.30
C	Clay loam soils, shallow sandy loams with a low permeability horizon impeding drainage (soils with a high clay content), soils low in organic content	0.05-0.15
D	Heavy clay soils with swelling potential (heavy plastic clays), water-logged soils, certain saline soils, or shallow soils over an impermeable layer	0.00-0.05

Source: NRCS, 1972

Table 2-2. Curve Number Adjustments from Antecedent Moisture Conditions I, II, and III

CN for Antecedent Moisture Condition II	CN for Antecedent Moisture Condition I	CN for Antecedent Moisture Condition III
100	100	100
95	87	99
90	78	98
85	70	97
80	63	94
75	57	91
70	51	87
65	45	83
60	40	79
55	35	75
50	31	70
45	27	65
40	23	60
35	19	55
30	15	50
25	12	45
20	9	39
15	7	33
10	4	26
5	2	17
0	0	0

Source: NRCS, 1972

Curve numbers in SWAT are updated daily as a function of initial soil moisture storage. A soils database is used to obtain information on soil type, texture, depth, and hydrologic classification. In SWAT, soil profiles can be divided into 10 layers. Infiltration, defined in SWAT as precipitation minus runoff, moves into the soil profile where it is routed through the soil layers. A storage routing flow coefficient is used to predict flow through each soil layer, with flow occurring when a layer exceeds field capacity. When water percolates past the bottom layer, it enters the shallow aquifer zone (Arnold et al., 1993). Channel transmission loss and pond/reservoir seepage replenish the shallow aquifer while it interacts directly with the stream. Flow to the deep aquifer system is effectively lost and cannot return to the stream (Arnold et al., 1993). Based on surface runoff calculated using the runoff equation, excess surface runoff not lost to other functions makes its way to the channels where it is routed downstream. Figure 2-1 displays the pathways for water movement within SWAT.

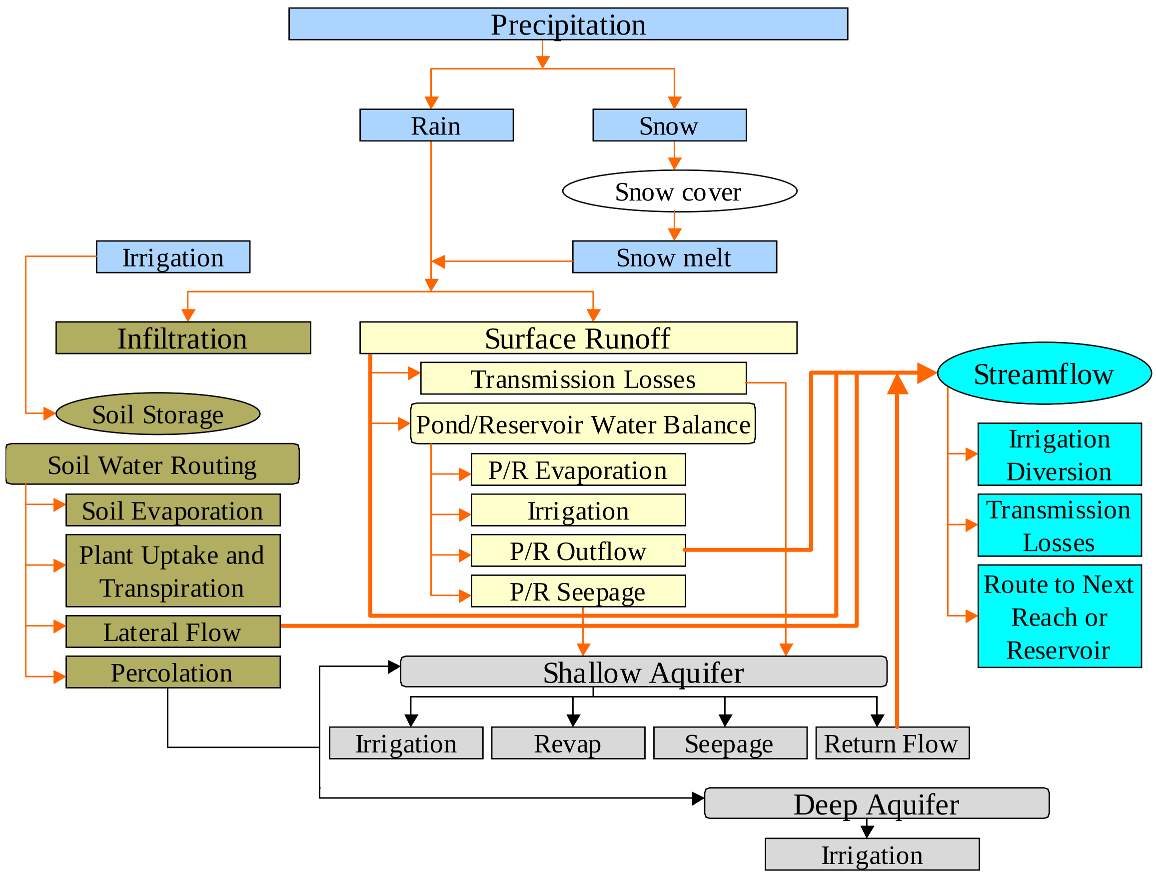

Figure 2-1. Pathways for Water Movement within SWAT

An important consideration in modeling the hydrology of the Black River watershed is that much of the agricultural land in the basin is tiled, since many of the soils are naturally poorly drained. The presence of tile drains has altered the natural hydrology of the area. Excess precipitation is routed to the streams through the tiles, rather than running over the land surface, which results in a shorter time-of-travel and less erosion, but also less ability for pollutants to be naturally filtered through the process of groundwater infiltration.

To address these factors, SWAT's tile drainage option was used for subwatersheds that were estimated to have a significant amount of tile drains as determined from information provided by the Medina County and Lorain County Soil and Water Conservation Districts (Table 2-3 and Table 2-4). In addition, several model parameters were adjusted to simulate the effects of tiling on watershed hydrology. For example, the storage routing flow coefficient within SWAT was adjusted during model calibration to address the effects of tiling. These adjustments, in combination with other calibration activities, resulted in acceptable performance of the model as measured by recommended modeling criteria (see Section 3.0).

Table 2-3. Estimated Extent of Tiling in Lorain County Portion of Black River Watershed

[See Figure 2-2 for location of modeling subwatersheds.]

Modeling Subwatershed Number	Percent Cropland	Percent Tile-Drained
3	60	20
25	75	25
63	70	40
23	60	30
34	60	40
66	65	30
33	65	20
28	55	15-20
29	60	30
27	85	30
65	50	10-15
21	50	15
64	75	45
20	50	70-80
60	60	75
59	75	35
18	75	60
17	50	25
35	30	10
57	70	20
53	50	60
16	55	35-40
54	40	5-10
58	85	25
55	40	20
14	25	10
12	10	0-5
15	50	25-30
57	60	25
56	65	15-20
13	70	25
50	60-65	20-25
38	20	5-10
45	50	20
51	30	10-15
36	15	5
1	50	15
2	60	15-20
61	55	5-10
62	65	10
10	50	25

Table 2-4. Estimated Extent of Tiling in Medina County Portion of Black River Watershed

[See Figure 2-2 for location of modeling subwatersheds.]

Modeling Subwatershed Number	Percent Cropland	Percent Tile-Drained
3	77	39
4	20	8
10	51	26
22	29	15
23	57	17
24	41	21
25	48	24
31	39	20
32	35	11
63	44	22
67	66	20

2.2 Erosion and Sediment Transport

SWAT uses the Modified Universal Soil Loss Equation (MUSLE) to simulate upland erosion. The MUSLE (Williams, 1975, 1995) uses the familiar Universal Soil Loss Equation (USLE) factors for soil erodibility (K), length and slope (LS), cover (C), and management practices (P), but omits the rainfall erosivity factor. USLE provides field-scale estimates of soil loss, while sediment yield at the watershed scale requires application of an empirical sediment delivery ratio. In contrast, MUSLE estimates sediment yield at the subwatershed scale, based on runoff volume, peak runoff rate, USLE factors, and drainage area. This avoids the need for explicit estimation of a delivery ratio or an erosivity factor.

There is a theoretical problem with the SWAT implementation of MUSLE. Specifically, the calculation is made at the land use/soil overlay fragment (HRU) scale, rather than the subwatershed scale. Channel length, which affects time of concentration and in turn peak runoff rate, is apportioned by SWAT to the individual HRUs on an area-weighted basis. In fact, it is the subwatershed time of concentration and peak flow rate that affect sediment retention, and calculation with an artificially shortened channel length tends to lead to an underestimation of time of concentration, an overestimation of peak runoff relative to runoff volume, and a corresponding overestimation of sediment delivery. The error increases as the number of HRUs in a subwatershed increases – causing a noticeable effect of number of HRUs on sediment prediction, as noted in Jha et al. (2004). In addition, the coefficient in the original MUSLE equation was developed on a relatively small number of sites and may well vary (SWAT uses the coefficient originally proposed by Williams in 1975, but a later (Williams, 1995) version uses a lower coefficient). Finally, the approach ignores deposition in smaller channels that are not included in the reach network.

We addressed these problems during calibration by modifying the code to include options to modify the MUSLE coefficient as well as, optionally, to calculate the erosivity-delivery factor $(Q \cdot q_P)^{0.56}$ at the sub-basin scale, followed by adjustment of total load back to the HRU area. The calibrated model reduces the MUSLE coefficient by a factor of 0.275 resulting in a final value of 3.25.

Streambank erosion is also an important source of sediment loading during high flow events. Significant bank erosion has been documented on certain segments of the Black River (USAED Buffalo, 1977). As such, SWAT's streambank erosion module was activated in the model. The two parameters used to simulate streambank erosion were the Channel Erodibility Factor (CH_EROD) and the Channel Cover

Factor (CH_COV). CH_EROD was set by taking the USLE K factor assigned to each subbasin and reducing this value by one order of magnitude, reflecting the general relationship that is observed between soil and channel erodibility (Neitsch et al., 2002). CH_COV was set by using the percent of eroding bank estimated by USAED Buffalo (1977). Bank erosion for the headwater reaches was not estimated by USAED Buffalo (1977); for these subbasins, the CH_COV of the downstream receiving subbasin was applied.

2.3 Description of the ArcView-SWAT Interface

An ArcView interface for SWAT (DiLuzio et al., 2001) was employed to efficiently derive and build the input files for the SWAT modeling of the Black River watershed. The interface requires digital elevation data (DEM), land use/land cover, soils, and meteorological data. Ten-meter DEM data representing 7.5-minute U.S. Geological Survey (USGS) quadrangles were downloaded from the USGS seamless data distribution system < http://seamless.usgs.gov>. Watershed and subbasin delineation is based on a DEM of the watershed coupled with a “burn-in” of EPA’s National Hydrography Dataset spatial database of stream reaches. This approach ensures that the subbasins conform to topography while requiring that catalogued stream segments connect in the proper order and direction.

The interface allows a user to select multiple subbasin outlets, thereby defining multiple subbasins for modeling analysis purposes. The interface then uses the DEM to calculate the upstream area, defined by the total number of up-slope cells, which could contribute flow to each point, thus defining the area of each subbasin. For the Black River watershed, the USGS 14-digit Hydrologic Unit Code (HUC) served as the basis for subbasin definition. Additional subbasins were delineated to obtain model input and output at key locations (e.g., point sources and sampling stations). This resulted in a total of 67 subbasins as shown in Figure 2-2.

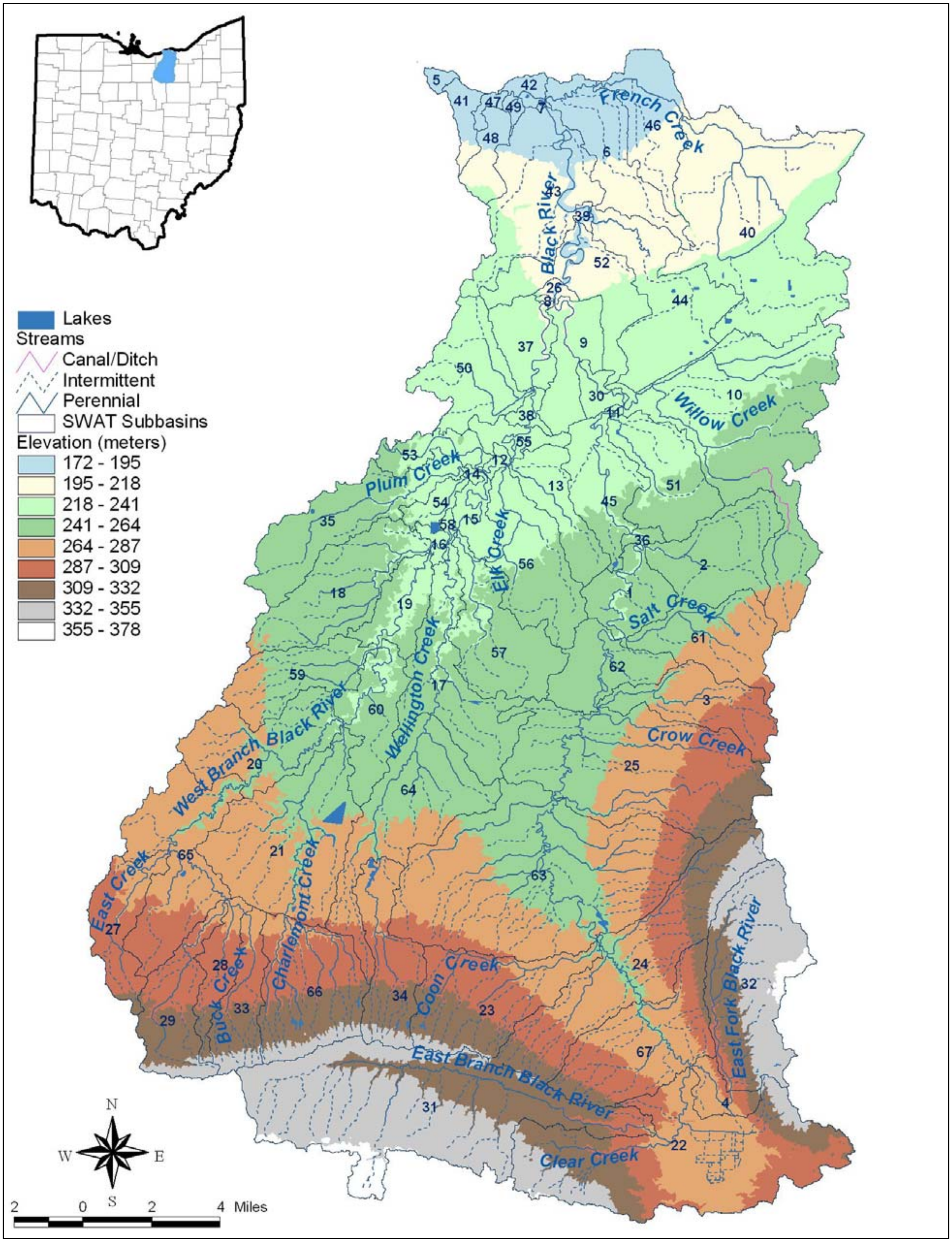

Figure 2-2. Topography and SWAT Delineated Subbasins within the Black River Watershed

After computing watershed topographic parameters for each subbasin, the interface uses land cover and soils data in an overlay process to assign soil parameters and SCS curve numbers. General soils data and map unit delineations for the United States are provided as part of the State Soil Geographic (STATSGO) database (USDA, 1995). The STATSGO data set was created to provide a general understanding of soils data to be used with large-scale analyses. Small, site-specific analyses with the STATSGO data are not appropriate. GIS coverages provide accurate locations for the soil map units at a scale of 1:250,000 (USDA, 1995). A map unit is composed of several soil series having similar properties. Identification fields in the GIS coverages can be linked to a database that provides information on chemical and physical soil characteristics. Table 2-5 lists the map unit names and their extent in the watershed, while the distribution of STATSGO map units in the basin is provided in Figure 2-3.

Table 2-5. STATSGO Map Units and Associated Soil Characteristics in the Black River Watershed

MUID	Map Unit Name	Area (acres)	Area (hectares)	Percent of Watershed	K factor	Hydrologic Soil Group
OH001	Lenawee-Colwood-Lenawee Variant	3,751.7	1,518.3	1.22	0.249	B/D
OH059	Fitchville-Haskins-Sebring	6,155.9	2,491.2	2.00	0.363	C
OH061	Allis-Urban Land-Prout Variant	4,372.2	1,769.4	1.42	0.375	D
OH062	Jimtown-Bogart-Mahoning	36,341.8	14,707.1	11.83	0.334	C
OH063	Bennington-Cardington-Orrville	39,439.6	15,960.7	12.84	0.395	C
OH075	Fitchville-Euclid-Melvin	990.9	401.0	0.32	0.337	C
OH076	Miner-Urban Land-Mahoning	14,612.2	5,913.4	4.76	0.278	D
OH077	Mahoning-Ellsworth-Trumbull	189,486.5	76,682.8	61.68	0.385	D
OH079	Bennington-Condit-Cardington	10,431.0	4,221.3	3.40	0.410	C
OH136	Mitiwanga-Urban Land-Mahoning	1,640.6	663.9	0.53	0.279	C

Two soil attributes important in SWAT modeling applications are hydrologic soil groups and the USLE K factor. The distribution of hydrologic soil groups and the USLE K factor within the Black River watershed are displayed in Figure 2-4 and Figure 2-5, respectively. Figure 2-4 indicates that moderately poorly drained D soils with low infiltration capacities characterize the majority of the watershed, while the headwaters and the area surrounding Elyria are dominated by C soils, characterized by moderately low infiltration capacities.

The USLE K factor represents the inherent erodibility of a given soil, and typically ranges from 0.2 (low erodibility) to 0.67 (highly erosive). Figure 2-5 illustrates that USLE K factors (for surface soil layers) within the Black River watershed range from 0.25 to 0.41, which represent low to moderately erodible soils. The headwaters (southern) portion of the watershed is underlain by moderately erosive soils, while the downstream (northern) portions of the basin are underlain by soils with lower erodibility.

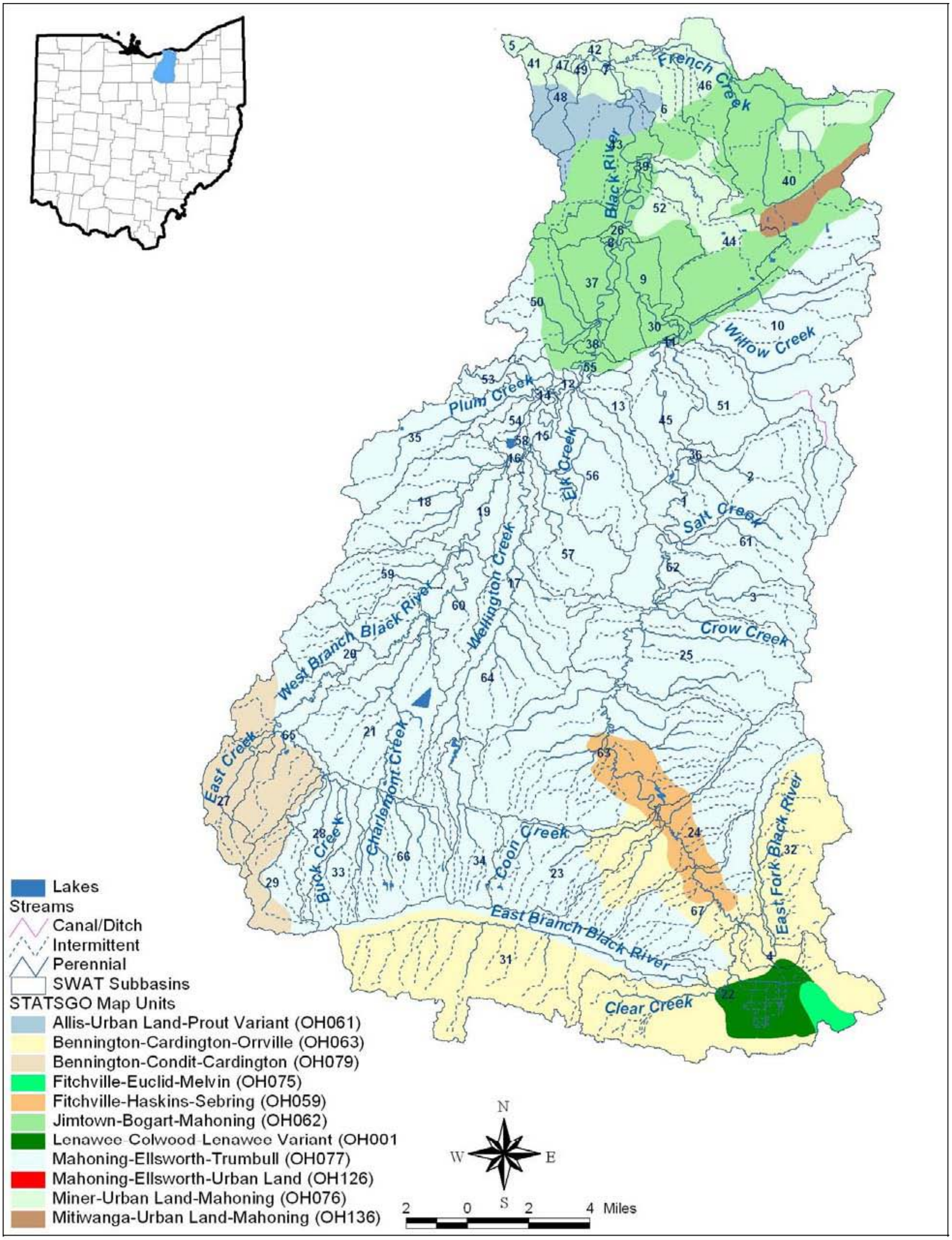

Figure 2-3. STATSGO Map Units within the Black River Watershed

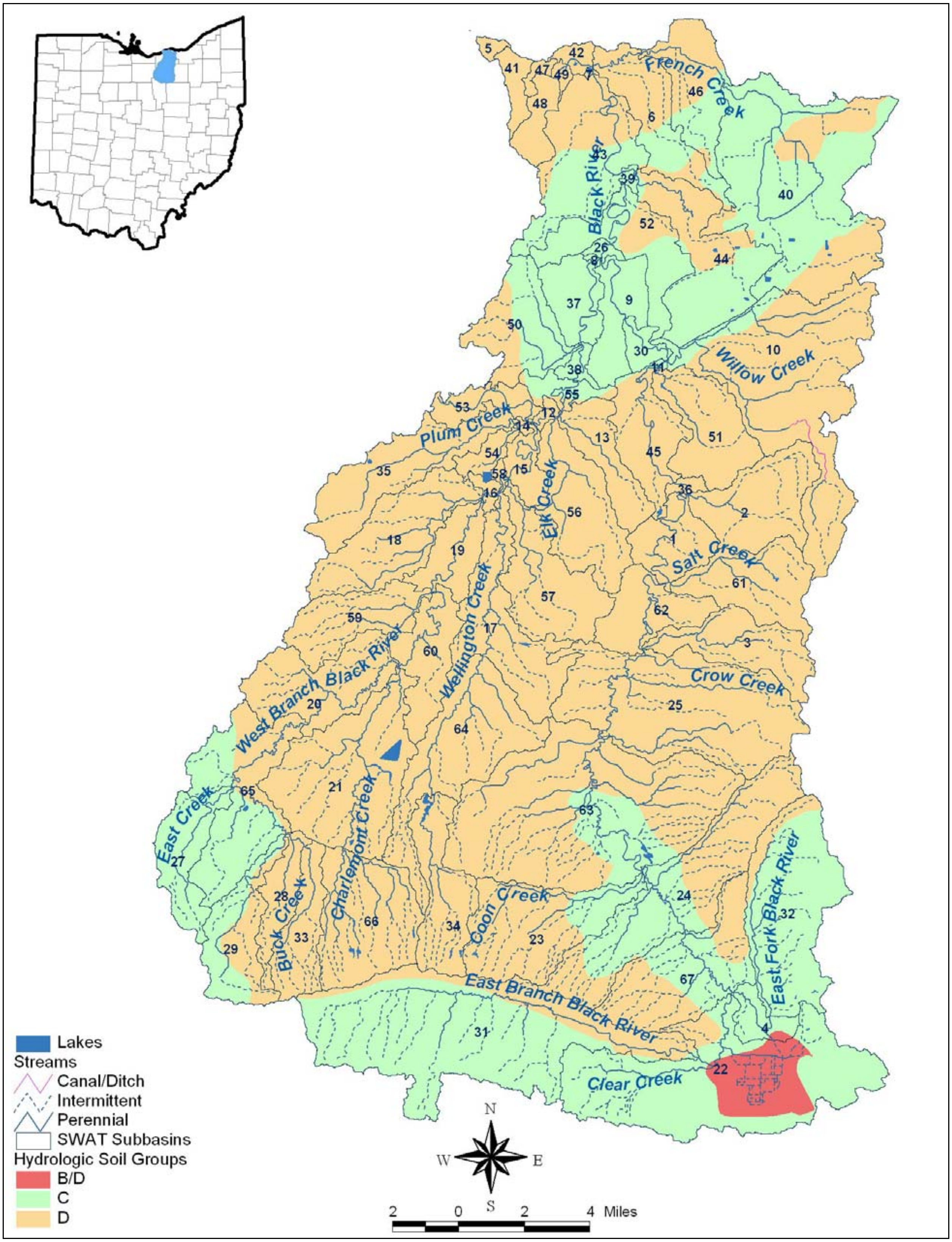

Figure 2-4. Distribution of Hydrologic Soil Groups within the Black River Watershed

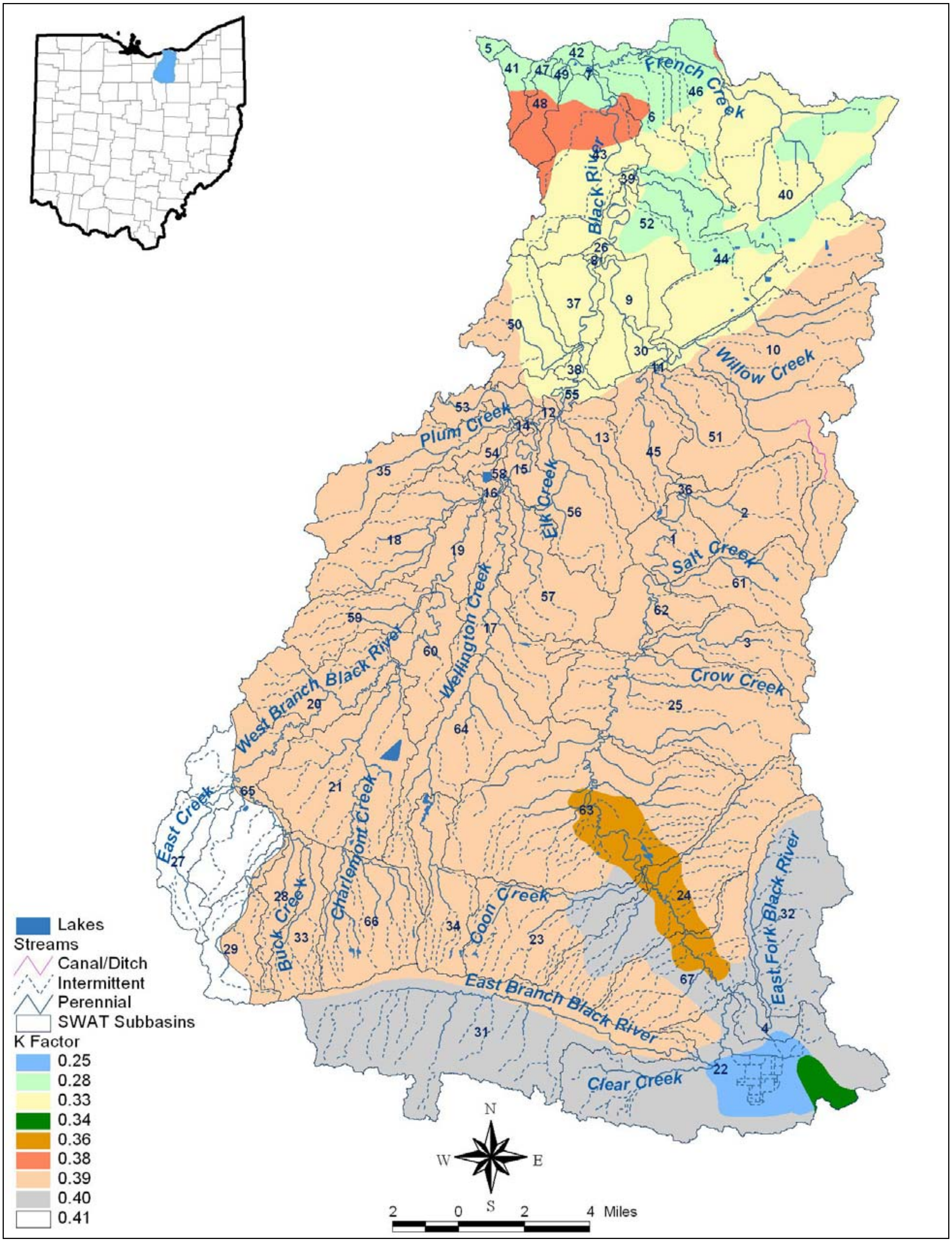

Figure 2-5. Distribution of the USLE K Factor within the Black River Watershed

The land use/land cover for the Black River watershed was extracted from the Ohio Statewide Land Cover Classification. This spatial database was derived from satellite imagery collected from 1999 to 2003 and is the most current detailed land use/land cover data known to be available for the watershed. Each 30-meter (98-foot by 98-foot) pixel contained within the satellite image is classified according to its reflective characteristics. The Ohio land use/land cover data were reclassified to match classes used by the SWAT model. The land use/land cover distribution in the watershed is shown in Figure 2-6. A summary of the land use/land cover characteristics of the watershed is provided in Table 2-6. Table 2-7 lists SWAT land use/land cover classifications and the SCS curve numbers used to represent the Black River watershed.

Figure 2-6 and Table 2-6 show that row crops (corn, soybean, and a smaller proportion of vegetable crops) are by far the most dominant land use/land cover in the watershed, representing nearly 44 percent of the total land use. It is assumed for modeling purposes that corn and soybean crops are rotated on an annual basis. Deciduous forest is the second largest category, representing 25 percent of the total watershed. Additionally, residential, pasture, commercial, and woody wetlands use account for nearly 16 percent, 8 percent, 3 percent, and 3 percent, respectively, of the land cover and land uses in the watershed. All other categories represent less than 1 percent of total land use/land cover in the watershed.

The SWAT user may decide whether or not to use multiple hydrologic response units (HRUs) in the modeling application. An HRU is a combination of land use/land cover and soil characteristics, and represents areas of similar hydrologic response. If multiple HRUs are not employed, the interface will use the dominant land use and soil characteristic for each subwatershed. To model multiple HRUs, the user must determine a threshold level used to eliminate minor land uses in each subbasin. Land uses that cover a percentage of the subbasin area less than the threshold level are eliminated and the area of those land uses is reapportioned so that 100 percent of the land area in the subbasin is included in the model simulation. For the Black River watershed, a two percent land use/land cover threshold and a five percent soil threshold were employed.

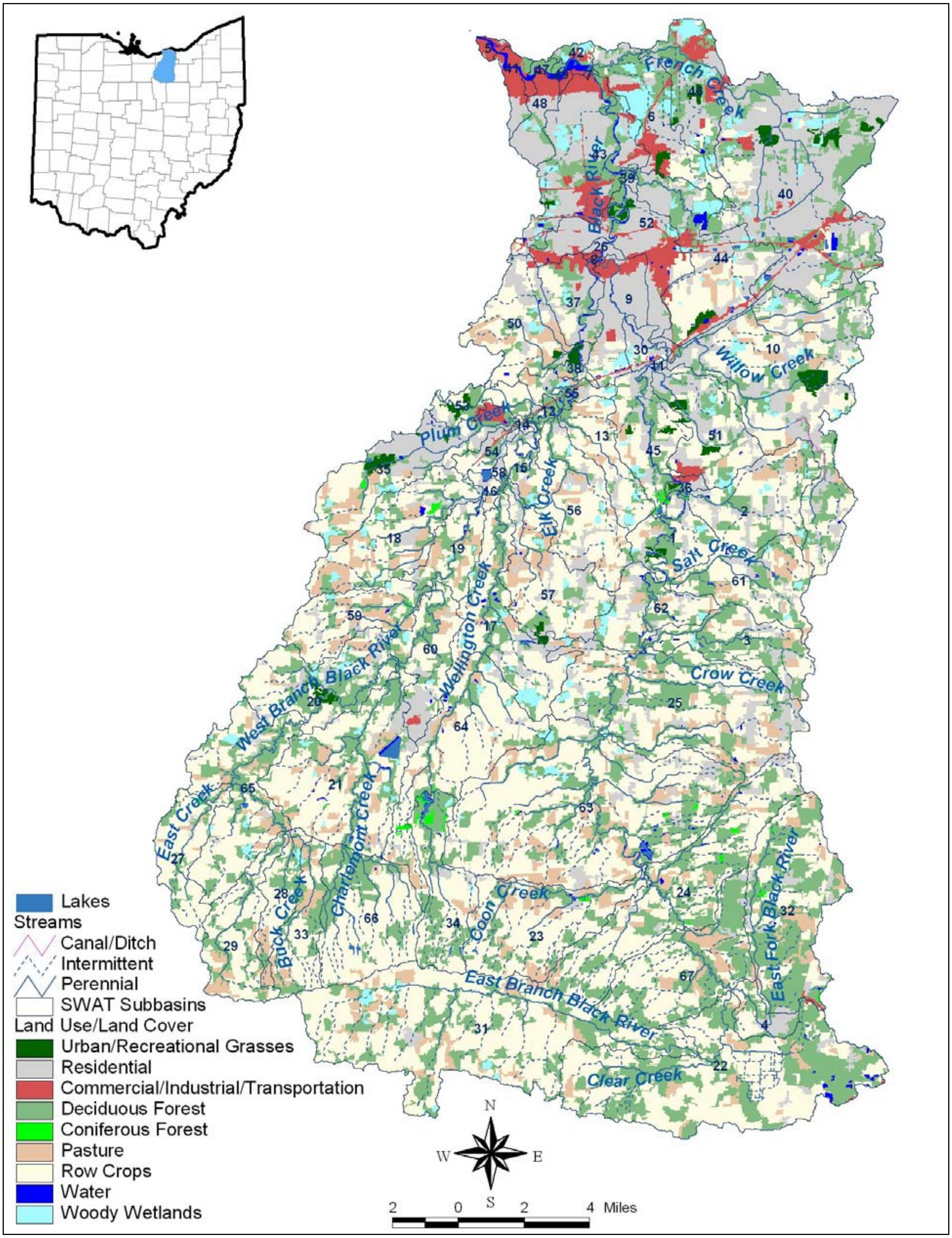

Figure 2-6. Land Use and Land Cover in the Black River Watershed

Table 2-6. Land Use/Land Cover Derived from the Ohio Statewide Land Cover Classification Database for the Black River Watershed

Land Use/Land Cover Description	SWAT Land Use Code	Area (ac)	Area (ha)	Percent of Watershed
Row Crops	AGRR	135,745.9	54,934.5	44.2
Deciduous Forest	FRSD	76,702.3	31,040.4	25.0
Residential	URLD	48,680.0	19,700.1	15.8
Pasture	ALFA	24,850.7	10,056.8	8.1
Commercial/Industrial/Transportation	UCOM	7,883.4	3,190.3	2.6
Woody Wetlands	WETF	7,554.9	3,057.4	2.5
Water	WATR	2,810.8	1,137.5	0.9
Urban/Recreational Grasses	BLUG	2,472.6	1,000.6	0.8
Coniferous Forest	FRSE	535.5	216.7	0.2
	Total	**307,236.4**	**124,334.3**	**100.0**

Table 2-7. SCS Curve Numbers (CN-II) for Land Use and Land Cover in the Black River Watershed

SWAT Land Use Code	SWAT Land Use/Land Cover Description	SCS Curve Numbers for Land Use and Hydrologic Soil Group			
		A	B	C	D
AGRR	Corn	59	70	78	81
AGRR	Soybean	51	67	76	80
FRSD	Deciduous Forest	45	66	77	83
URLD	Low Intensity Urban Residential	46	65	77	82
ALFA	Alfalfa	31	59	72	79
UCOM	Urban Commercial	89	92	94	96
WETF	Forested Wetlands	45	66	77	83
WATR	Water	100	100	100	100
BLUG	Grasslands	31	55	72	79
FRSE	Evergreen Forest	25	55	70	77

2.4 Meteorological Data

SWAT requires daily precipitation, temperature, relative humidity, solar radiation, and wind speed data to drive the simulation. These parameters may be given in a site-specific, user-specified file, estimated using a climate simulator, or a combination of the two. The interface will search and find the station closest to the mean center of each subbasin, and assign that station's meteorological parameters to the subbasin. Since the Green–Ampt infiltration method was applied in the Black River SWAT model, subdaily precipitation data were required. Hourly precipitation and daily temperature data were obtained from the National Climatic Data Center (NCDC) for the Cleveland WSFO Airport (331657), Chippewa Lake (331541), Elyria 3 E (332599), and the Oberlin (336156) climate stations (see Figure 3-1). Hourly precipitation data were not available for the Elyria 3 E climate station. A disaggregation technique was therefore used to create an hourly precipitation record for the Elyria 3 E station using daily precipitation data from Elyria 3 E and hourly data from surrounding stations.

Examination of the raw precipitation data revealed that there were significant periods in which missing data had been entered as zero precipitation. Missing data in the NCDC precipitation files was therefore patched using average relationships to other stations with valid measurements. Missing values in the temperature files were also filled.

Precipitation and temperature typically change with differences in elevation, with precipitation increasing and temperature decreasing. Lapse rates to correct for elevation differences between a subbasin and gauge were implemented in the current version of the model.

Relative humidity, solar radiation and wind speed were simulated using a climate simulator available in SWAT. The climate simulator uses historical data collected from surrounding National Weather Service sites to estimate parameters. It is believed that these stations are adequate for estimating relative humidity, solar radiation, and wind speed for the Black River watershed.

Evapotranspiration, which combines evaporation of water and transpiration of moisture by plants, is the major exit of water from the watershed, and model performance is very sensitive to specification of the potential evapotranspiration (PET). Measured PET values are not available for the watershed. SWAT provides three options for calculating PET values from other meteorological data: the Priestley-Taylor, Penman-Monteith, and Hargreaves methods. As in the previous version of the model, the current version uses the Priestley-Taylor method to estimate PET. However, it was observed that the default implementation of this method yielded much lower PET estimates than the Penman-Monteith and Hargreaves methods.

The Priestley-Taylor method contains an empirical coefficient, α, used to adjust to site-specific conditions. This variable is documented as being a user input in the SWAT user's manual, but the option is not activated in the code. We modified the code to allow user input of α, and found that a much improved fit was obtained by increasing α from the default of 1.28 to 1.62. This also brings the Priestley-Taylor PET estimates in line with those produced by the other PET estimation methods for this basin.

2.5 Point Sources

Sediment, nutrient, and flow contributions from a number of point sources in the Black River watershed were incorporated in the SWAT model. The required SWAT inputs include average monthly flow and average monthly loadings for sediment/total suspended solids, organic nitrogen, organic phosphorus, nitrate, soluble phosphorus, ammonia, and nitrite. Data for all of the significant facilities in the watershed were provided by Ohio EPA from the Surface Water Information System (SWIMS) database. Average monthly loads for SWAT point source inputs were calculated by multiplying the reported monthly concentration, discharge, and a conversion factor. In instances where average concentrations for a certain parameter were not available from SWIMS, the average concentration for that parameter from similar facilities in the watershed was used. Table 2-8 lists the permitted National Pollutant Discharge Elimination System (NPDES) facilities used within the Black River watershed. Some smaller permitted facilities were not included in the model because they were not considered to contribute significant loads.

Point source loadings were reviewed and updated for the revised version of the model. Of particular importance, previously missing monthly data for Elyria were incorporated into the model.

Table 2-8. Permitted NPDES Facilities Located within the Black River Watershed

OEPA Permit	Facility Name	Type	Receiving Waterbody	Design Flow (million gallons per day)
OH0026158	Brentwood Lake	WWTP	Alexandra Creek	0.120
OH0026140	Eaton Estates	WWTP	Willow Creek	0.200
OH0025003	Elyria	WWTP	Black River	13.000
OH00370044	Findlay State Park Campground	WWTP	Wellington Creek	0.025
OH0025372	Grafton	WWTP	East Branch Black River	1.500
OH0046221	LaGrange	WWTP	Kellner Ditch	0.363
OH0020991	Lodi	WWTP	East Branch Black River	0.800
OH0063886	Lorain, Eastside (BR mouth)	WWTP	Black River	15.000
OH0044512	North Ridgeville	WWTP	French Creek	11.250
OH0020427	Oberlin	WWTP	Plum Creek	1.500
OH0022071	Spencer	WWTP	Spencer Creek	0.090
OH0026158	Wellington	WWTP	Charlemont Creek	0.750
OH01290003	Lorain Tubular	Industry	Black River	Outfall 001 - 0.0504 Outfall 006 - 2.58
OH0001562	Republic Eng. Products	Industry	Black River	Outfall 002 - 23.83 Outfall 003 - 53.50 Outfall 004 - 39.73 Outfall 005 - 8.72

2.6 Household Sewage Treatment Systems (HSTS)

Household sewage treatment systems (e.g., septic systems) provide the potential to deliver nutrient loads to surface waters due to system failures caused by improper maintenance, malfunctions, and/or close proximity to a stream. To account for these potential loads, point loads were input to each modeling subwatershed based on the estimated population served by HSTSs and a representative failure rate of 20 percent. The number of systems in the Medina County modeling subwatersheds was estimated based on a database provided by OEPA and the number of systems in the Lorain County modeling subwatersheds was based on an analysis of 2000 Census data. Loadings were based on values used in the Generalized Watershed Loadings Function (GWLF) model (Haith et al., 1992; Mandel, 1993):

- Average number persons served by each system: 2.5
- Percentage failing: 20%
- Per capita daily load in septic tank effluent: 12 g/day nitrogen; 1.5 g/day phosphorus
- Per capita daily plant uptake in drain field (growing season only): 1.6 g/day nitrogen; 0.4 g/day phosphorus
- Load from normally functioning system: 26 g/day nitrogen; 0 g/day phosphorus
- Load from failing system: 30 g/day nitrogen; 0.275 g/day phosphorus

The GWLF approach provides surface and subsurface loadings at the edge of the drain field. Further reductions take place during transport to streams as nutrients are taken up by plants or retained in soils.

Based on past experience with the GWLF model, we assumed that 20 percent of the HSTSs were sufficiently close to perennial streams to provide significant loading. Without this additional discount factor, the model significantly overpredicts baseflow nutrient concentrations in watersheds that have HSTS input but minimal point source input.

2.7 Agricultural Practices and Fertilizer Applications

SWAT uses "Management" (.mgt) files to describe plant growth, tillage, harvest, and fertilization practices. These specifications have an important effect on the simulation of the water balance, erosion, and pollutant load generation. Direct effects on the water balance are primarily through the impacts of the plant growth cycle on evapotranspiration.

Several assumptions had to be made regarding agricultural practices in the watershed to provide appropriate input to the model. These assumptions are summarized below and were based on information obtained during a previous project in the neighboring Huron River watershed and information provided by the Lorain and Medina County Soil and Water Conservation Districts.

- Conservation tillage is widely practiced throughout the watershed for soybeans, but is less prevalent for corn.
- Annual crop rotation occurs between corn and soybeans.
- Alfalfa remains infield for a three year period.
- Fertilizer applications typically occur in the spring and are applied to corn and soybeans. Corn is sidedressed with nitrogen in July.
- Alfalfa fertilizer application occurs in the initial year of planting only.

A majority of the land in the basin is used in row-crop agriculture. The existing model simulates this as a single land cover class (AGRR), subdivided by soil hydrologic group, representing an alternating-year corn-soy rotation. Representation of rotations in a single management file is a standard approach in SWAT; however, if only a single file is used, this has the effect of "synchronizing" the watershed, so that all fields are in corn one year and soybeans the next. This can lead to unexpected and unrepresentative results. Therefore, the AGRR management file for each hydrologic soil group was subdivided into two files, one starting with corn and one starting with soybeans.

The representation of AGRR management was refined with input from the Medina County SWCD. Conservation tillage is practiced on a large portion of the watershed, with no tillage between corn and soybean phases. A typical two year rotation was defined as follows:

20 Apr.	Spring plowing (mixing efficiency 50%)
3 May	Plant corn
3 May	Fertilize (10-28-00)
1 July	Fertilize (anhydrous ammonia)
1 Sept.	Harvest corn
1 Mar.	Plant soybeans (no till)
1 Mar	Fertilize (phosphorus)
3 Oct.	Harvest soybeans
10 Oct.	Conservation tillage (mixing efficiency 25%)

The fertilizer applications were set to provide a total of 150 lb/ac nitrogen and 75 lb/ac P_2O_5 for corn, and 40 lb/ac P_2O_5 for soybeans, as recommended by Medina County SWCD as typical for the region (Table 2-9). Fertilizer application rates for alfalfa (first year only) were based on regional recommendations in Vitosh (2002). It is understood that application rates can vary significantly from field to field and year-to-year and the rates shown in Table 2-9 are therefore meant to represent typical practices solely for the purposes of watershed-scale modeling.

Table 2-9. SWAT Fertilizer Application Rates in kg/ha (lb/ac in parentheses)

Crop	N	P_2O_5
Corn	168 (150)	84 (75)
Soybean	0 (0)	44 (40)
Alfalfa	17 (15)	129 (115)

About 20 percent of the corn is grown for silage rather than seed. We accounted for the lower residue left by silage harvest by modifying the harvest efficiency in the crop database for AGRR.

The seasonal pattern of crop development is determined by the accumulation of heat units relative to the number of heat units required to reach maturity. The previous model application did not specify crop heat units, but rather let the program pick a default value. This results in values that are too small for the crops in the AGRR rotation, resulting in maturity and senescence being simulated too early with consequent effects on evapotranspiration. The Potential Heat Unit Program (http://www.brc.tamus.edu/swat/soft_phu.html) was used to calculate heat units for the area. The period between planting and harvest for corn is about 120 days, but there is likely a dry-down period, so we assumed 110-day corn, yielding a potential heat units value of 1,345. Values of 1,247 and 1,130 were assigned to soybeans and alfalfa, respectively.

3.0 Model Calibration

After initially configuring SWAT, model calibration was performed. Calibration refers to the adjustment or fine-tuning of modeling parameters to reproduce observations. This section of the report presents the process that was used to calibrate the model both for hydrology and water quality. Modeling results are also summarized.

3.1 Hydrology Calibration

Hydrologic calibration initially focused on the period 1990-1997. Subsequent application to 1998-2004 revealed the need for modifications, due to the fact that 1999-2002 was generally much drier than 1990-1997. Final hydrologic calibration adjustments were performed on the entire 1990-2004 period. As a result, there is not a truly independent model validation period. However, the final model performs equally well on both the 1990-1997 and 1998-2004 periods, as demonstrated below.

Calibration was completed by comparing time-series model results to gaged flow. Output from the watershed model is in the form of daily average flow. Key considerations in the hydrology calibration were the overall water balance, the high-flow to low-flow distribution, storm flows, and seasonal variation. Two criteria for goodness of fit were used for calibration: graphical comparison and the relative error method. Graphical comparisons are extremely useful for judging the results of model calibration; time-variable plots of observed versus modeled flow provide insight into the model's representation of storm hydrographs, baseflow recession, time distributions, and other pertinent factors often overlooked by statistical comparisons. The model's accuracy was primarily assessed through interpretation of the time-variable plots. The relative error method was used to support the goodness of fit evaluation through a quantitative comparison. A small relative error indicates a better goodness of fit for calibration.

Initial parameters were selected based on a previous SWAT application of the neighboring Huron River watershed, a SWAT model of the Buffalo River watershed (Inamdar, 2004), and model default values. Final values were derived during the calibration process and several of the more sensitive parameters are listed in Table 3-1.

Table 3-1. Selected Values of SWAT Parameters used for Black River Model Hydrologic Calibration

Parameter	Description	Min	Max	Selected Value
Basin input file *.bsn				
SFTMP	Snowfall temperature [C]	-5	5	1.0
SMTMP	Snowmelt base temperature [C]	-5	5	0.5
SMFMX	Maximum snow melt rate [mm/C*day]	0.0	10.0	3.7
SMFMN	Minimum snow melt rate [mm/C*day]	0.0	10.0	2.0
TIMP	Snow pack temperature lag factor [-]	0.0	1.0	1.0
SNOCOVMX	Minimum snow water content that corresponds to 100 snow cover [mm]	0.0	500	25.0
SNO50COV	Fraction of snow volume represented by SNOCOVMX that corresponds to 50 snow cover [-]	0.0	1.0	0.5
SURLAG	Surface runoff lag coefficient [days]	1.0	24.0	2.5
ESCO	Soil evaporation compensation factor [-]	0.01	1.00	0.50
EPCO	Plant uptake compensation factor [-]	0.01	1.00	1.0
Groundwater input file *.gw				
GW_DELAY	Groundwater delay time [days]	0	500	15, 80
ALPHA_BF	Baseflow alpha factor [days]	0.0	1.0	0.4
GW_REVAP	Groundwater revap coefficient [-]	0.02	0.20	0.1-0.2
RCHRG_DP	Deep aquifer percolation fraction [-]	0.0	1.0	0.0
AWQMN	Threshold depth of water in shallow aquifer for return flow [mm]	0	-	300.0
HRU input File *.hru				
DDRAIN	Depth to surface drain [mm] for tiled areas	0	2000	990
TDRAIN	Time to drain soil to field capacity [hours]	0	72	48
GDRAIN	Drain tile lag time [hours]	0	100	60
CANMX	Maximum canopy storage [mm]	0	-	2.5

The SWAT model was run to simulate streamflow conditions during the 1988 to 2004 time period. This time period corresponds to the most recent data available at the USGS Black River stream gage at Elyria, Ohio (ID 04200500) (see Figure 3-1 for location). Available daily mean flow data at this station cover the period from October 1, 1944 through September 30, 2004. SWAT was allowed to "spin up" or reach equilibrium[a] during the first two years of the model run; consequently hydrologic calibration was performed for the period 1990 to 2004.

[a] The SWAT model calculates and updates a variety of watershed state variables (e.g., soil moisture) on an hourly or daily basis during each model run. Since these conditions must be specified based on limited data for the first day of the model run and only slowly approach equilibrium with meteorological forcing, the first years of the modeling output are often discarded. This approach is referred to as allowing the model to "spin up" or reach equilibrium.

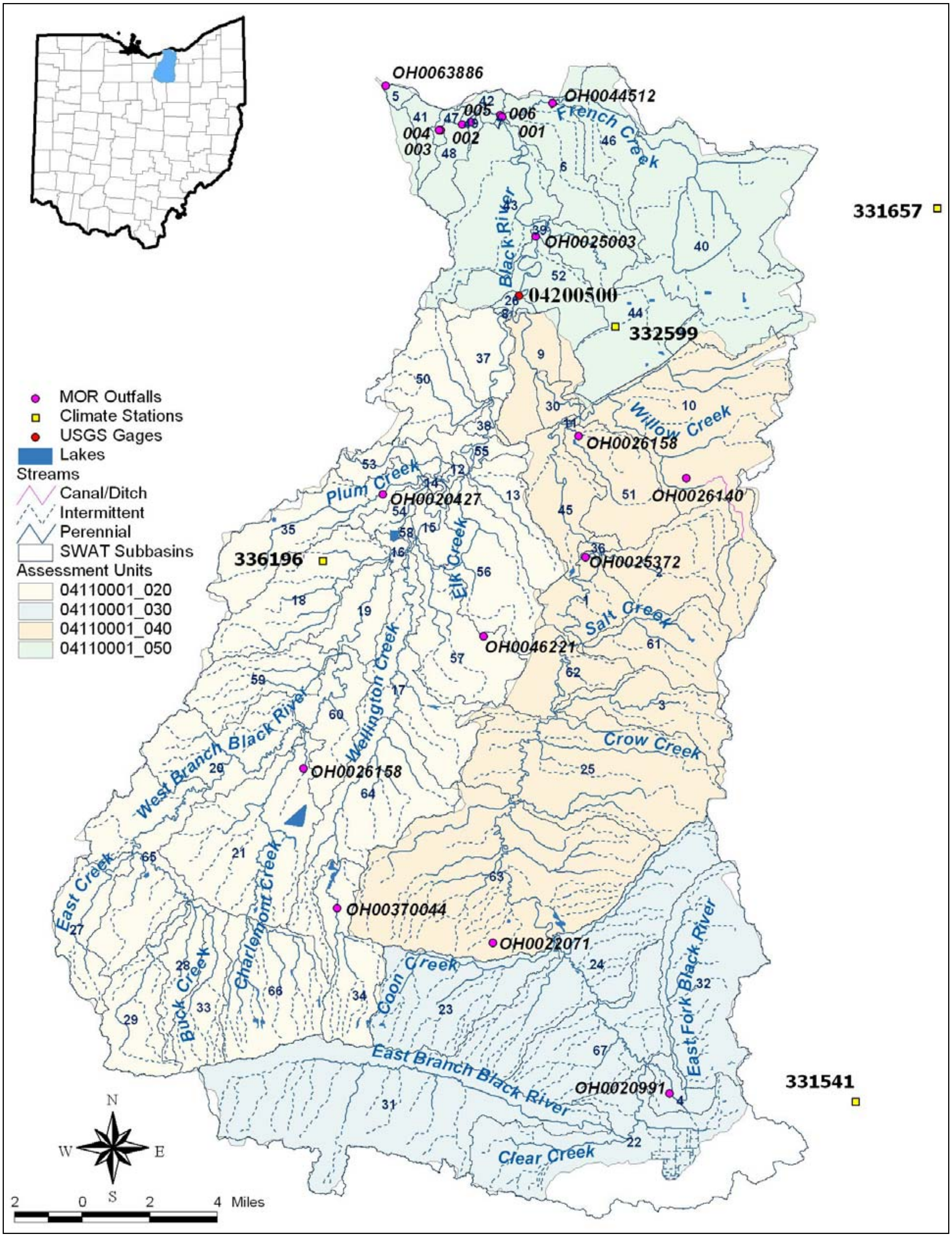

Figure 3-1. Climate Station, Model Calibration Stations, and Major NPDES Facility Locations within the Black River Watershed

Figure 3-2 shows a comparison of the observed versus simulated average annual stream flow for the calibration period, and displays a good level of agreement. A comparison between observed and simulated average monthly streamflow is presented in Figure 3-3. The relationship between observed and simulated flow is also good (slope = 0.97).

Graphical comparisons of observed versus simulated mean monthly streamflow are presented in Figure 3-4, Figure 3-5, and Figure 3-6. These figures show a good level of agreement between observed and simulated mean monthly streamflow. Additionally, an observed versus simulated flow duration analysis is presented in Figure 3-7. With the exception of the very lowest flows, the model adequately describes flow variability within the Black River watershed. Figure 3-8 shows daily observed and simulated flows for a sample time period (January 1996 to December 1996) and indicates that the model underpredicts several large storms but otherwise captures the timing and volume of most storm event and baseflow conditions.

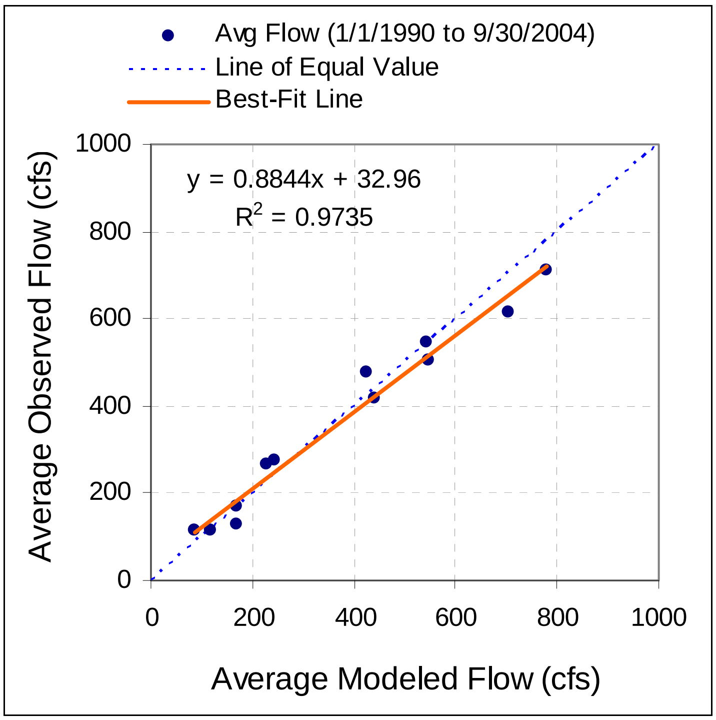

Figure 3-2. Composite (average yearly) Hydrologic Calibration Results, 1990 to 2004

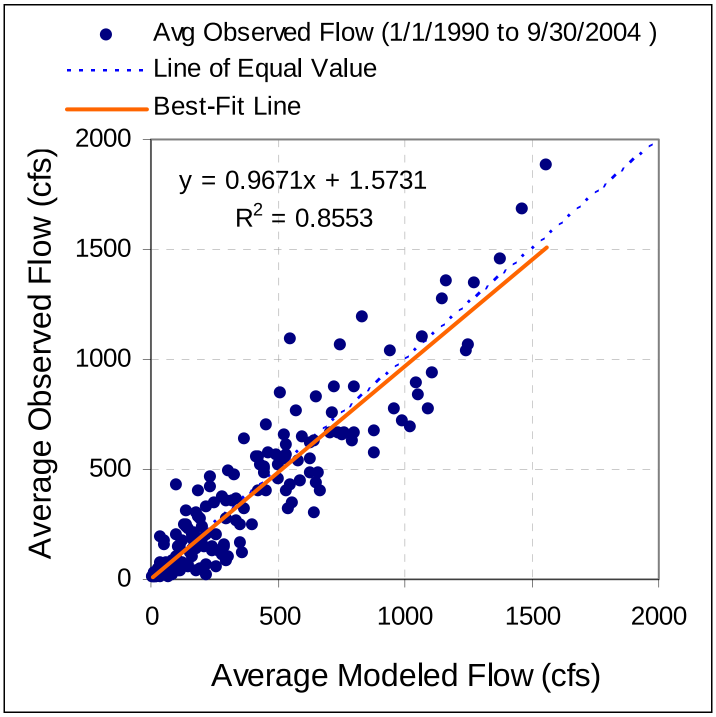

Figure 3-3. Composite (average weekly) Hydrologic Calibration Results, 1990 to 2004

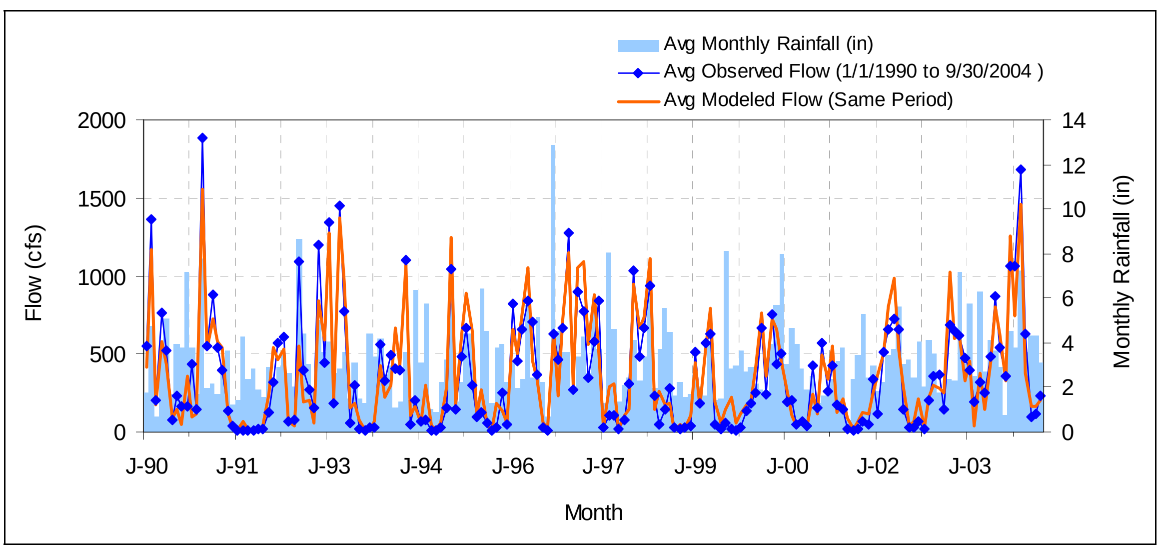

Figure 3-4. Time Series of Monthly Hydrologic Calibration Results, 1990 to 2004

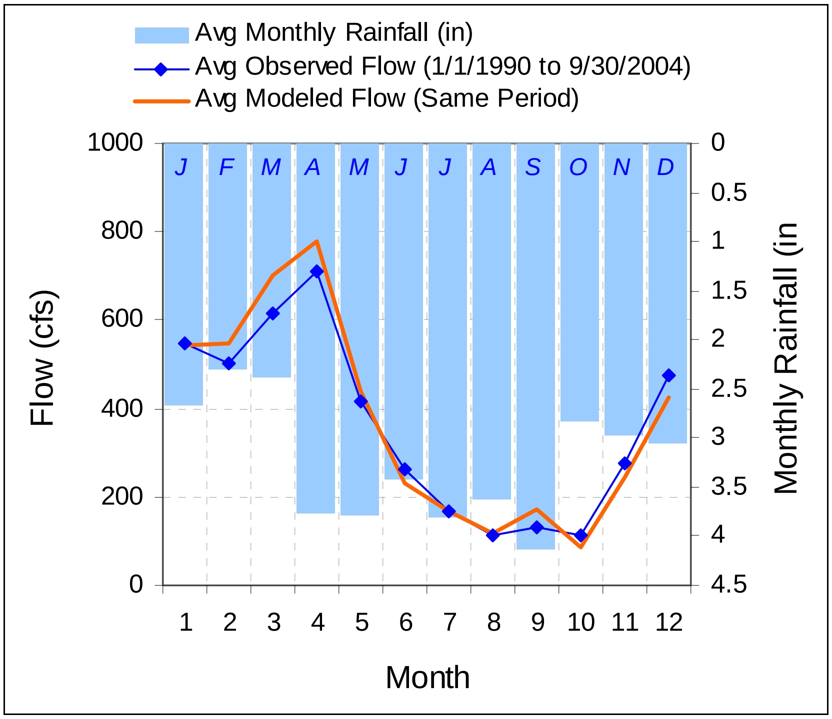

Figure 3-5. Observed versus Simulated Mean Monthly Streamflow, 1990 to 2004

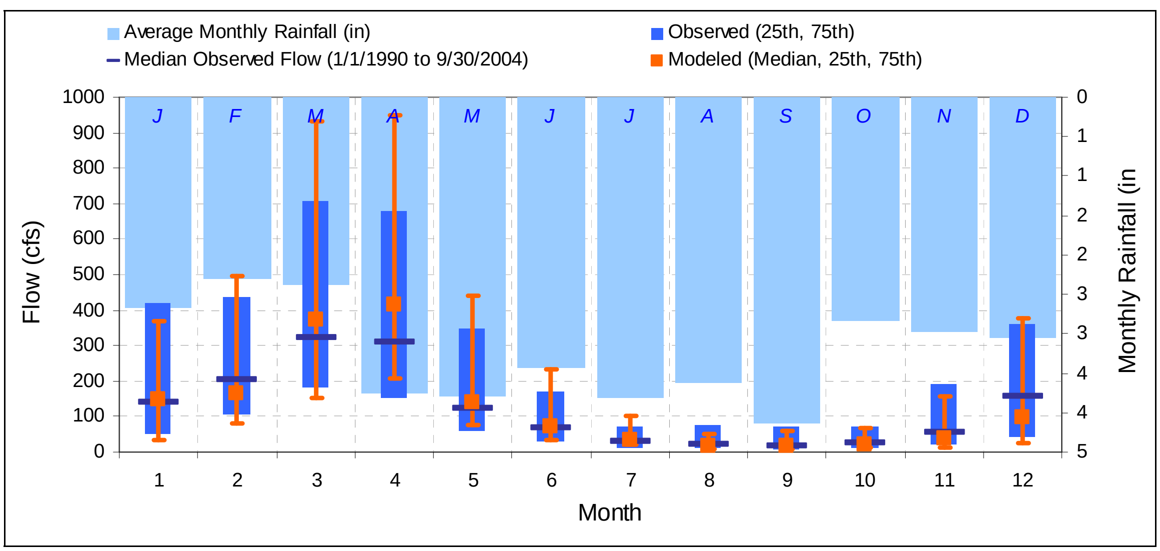

Figure 3-6. Observed versus Simulated 25th Percentile, 75th Percentile, and Median Monthly Streamflow, 1990 to 2004

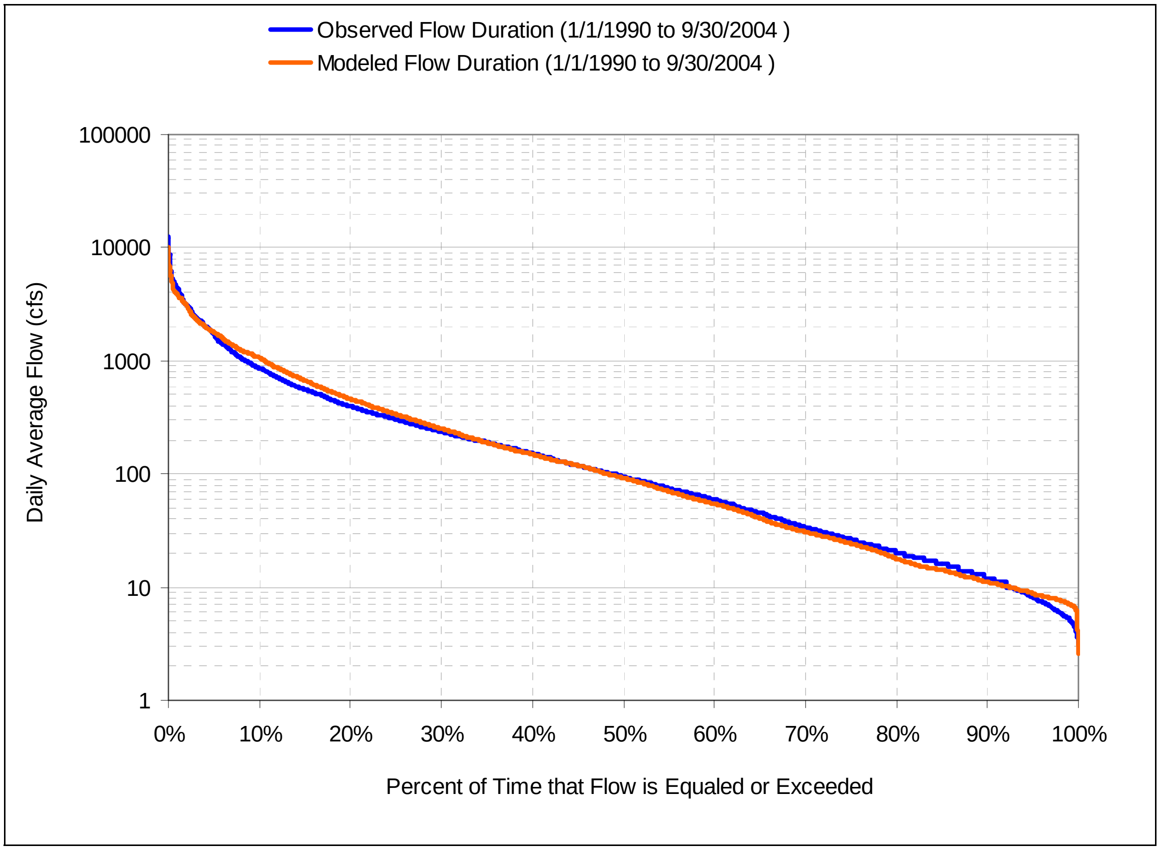

Figure 3-7. Observed versus Simulated Flow Duration, 1990 to 2004

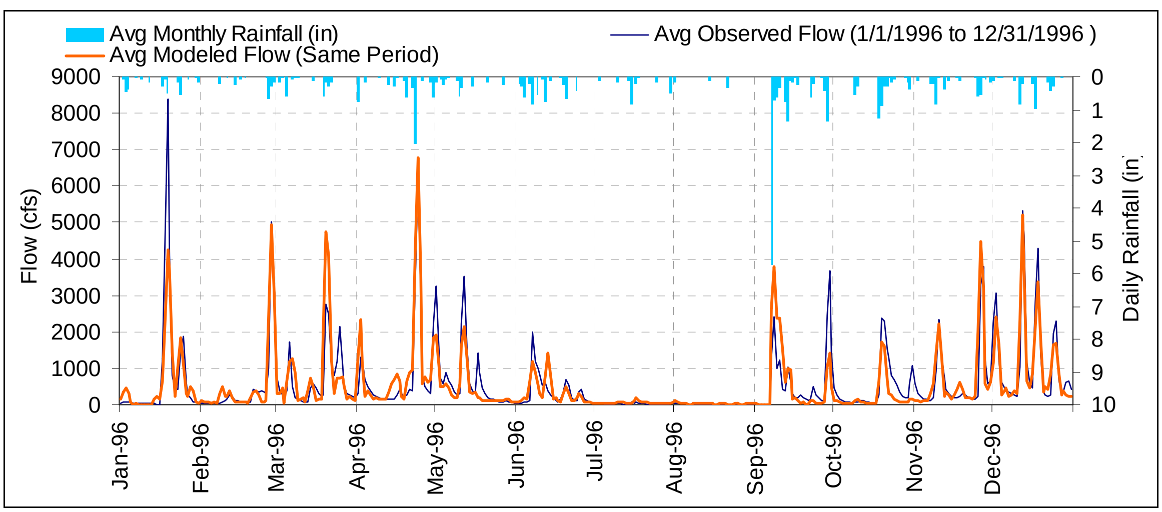

Figure 3-8. Observed versus Simulated Daily Flow for January 1996 to December 1996

Seasonal and annual differences between observed and simulated stream flows for the calibration time period are summarized in Table 3-2. Error statistics are also presented and compared to criteria recommended for the Hydrologic Simulation Program in Fortran (HSPF) model (a more sophisticated watershed model than SWAT). Errors are determined by comparing simulated flow values to observed flow values for various time periods (e.g., for the highest flow periods) using the following equation:

$$\text{Relative Error} = \frac{\text{Simulated Value} - \text{Observed Value}}{\text{Observed Value}} \times 100$$

A goal of the calibration process is to reduce the relative error to less than the recommended criteria for as many flow categories as possible. The table shows that simulated flow for the 12-year period agrees well with observed stream flow data. The simulated total flow volume is within 3 percent of the observed total flow volume and all seasonal volumes are within 20 percent.

Table 3-2. Black River Watershed Calibration Results for the Simulation Period January 1, 1990 to September 30, 2004

[Flow Volumes are normalized, with total observed as 100.]

Total Simulated In-stream Flow:	102.90	Total Observed In-stream Flow:	100.00
Total of Highest 10 Flows:	61.10	Total of Observed Highest 10 Flows:	62.11
Total of Lowest 50 Flows:	4.43	Total of Observed Lowest 50 Flows:	4.78
Simulated Summer Flow Volume:	10.81	Observed Summer Flow Volume:	9.74
Simulated Fall Flow Volume:	16.67	Observed Fall Flow Volume:	19.12
Simulated Winter Flow Volume:	41.65	Observed Winter Flow Volume:	38.65
Simulated Spring Flow Volume:	33.77	Observed Spring Flow Volume:	32.49
Total Simulated Storm Volume:	30.50	Total Observed Storm Volume:	30.34
Simulated Summer Storm Volume:	3.65	Observed Summer Storm Volume:	3.37
Errors (Simulated-Observed)		*Recommended Criteria*[1]	
Error in total volume:	2.90	***±10***	
Error in 50 lowest flows:	-7.26	***±10***	
Error in 10 highest flows:	-1.63	***±15***	
Seasonal volume error - Summer:	11.01	***±30***	
Seasonal volume error - Fall:	-12.84	***±30***	
Seasonal volume error - Winter:	7.76	***±30***	
Seasonal volume error - Spring:	3.96	***±30***	
Error in storm volumes:	0.55	***±20***	
Error in summer storm volumes:	8.21	***±50***	

[1] Recommended criteria are from Lumb et al. (1994) for HSPF Model Applications

Results of the hydrologic calibration for Water Years 1991-1997 and 1998-2004 are shown separately in Table 3-3 and Table 3-4. Because final calibration used the entire data set, the 1998-2004 period cannot properly be considered an independent model validation test. However, the comparison demonstrates the robustness of the hydrological calibration as the model performs equally well on the wetter 1990-1997 period and the drier 1998-2004 period.

Table 3-3. Black River Hydrologic Calibration Results for October 1, 1990 to September 30, 1997

[Flow volumes are normalized, with total observed as 100]

Total Simulated In-stream Flow:	101.88	Total Observed In-stream Flow:	100.00
Total of Highest 10 Flows:	63.21	Total of Observed Highest 10 Flows:	63.72
Total of Lowest 50 Flows:	4.00	Total of Observed Lowest 50 Flows:	4.20
Simulated Summer Flow Volume:	9.95	Observed Summer Flow Volume:	9.59
Simulated Fall Flow Volume:	21.26	Observed Fall Flow Volume:	25.16
Simulated Winter Flow Volume:	41.96	Observed Winter Flow Volume:	39.15
Simulated Spring Flow Volume:	28.72	Observed Spring Flow Volume:	26.11
Total Simulated Storm Volume:	31.23	Total Observed Storm Volume:	31.48
Simulated Summer Storm Volume:	3.37	Observed Summer Storm Volume:	2.98
Errors (Simulated-Observed)		*Recommended Criteria*[1]	
Error in total volume:	1.88	***±10***	
Error in 50 lowest flows:	-4.95	***±10***	
Error in 10 highest flows:	-0.80	***±15***	
Seasonal volume error - Summer:	3.80	***±30***	
Seasonal volume error - Fall:	-15.51	***±30***	
Seasonal volume error - Winter:	7.17	***±30***	
Seasonal volume error - Spring:	9.99	***±30***	
Error in storm volumes:	-0.81	***±20***	
Error in summer storm volumes:	13.01	***±50***	

[1] Recommended criteria are from Lumb et al. (1994) for HSPF Model Applications

Table 3-4. Black River Hydrologic Calibration Results for October 1, 1997 to September 30, 2004

[Flow volumes are normalized, with total observed as 100]

Total Simulated In-stream Flow:	106.92	Total Observed In-stream Flow:	100.00
Total of Highest 10 Flows:	60.86	Total of Observed Highest 10 Flows:	61.62
Total of Lowest 50 Flows:	4.81	Total of Observed Lowest 50 Flows:	5.18
Simulated Summer Flow Volume:	11.37	Observed Summer Flow Volume:	9.24
Simulated Fall Flow Volume:	13.64	Observed Fall Flow Volume:	14.73
Simulated Winter Flow Volume:	41.19	Observed Winter Flow Volume:	36.27
Simulated Spring Flow Volume:	40.63	Observed Spring Flow Volume:	39.76
Total Simulated Storm Volume:	30.12	Total Observed Storm Volume:	29.18
Simulated Summer Storm Volume:	3.84	Observed Summer Storm Volume:	3.66
Errors (Simulated-Observed)		*Recommended Criteria*[1]	
Error in total volume:	6.82	***±10***	
Error in 50 lowest flows:	-7.07	***±10***	
Error in 10 highest flows:	-1.25	***±15***	
Seasonal volume error - Summer:	23.05	***±30***	
Seasonal volume error - Fall:	-7.45	***±30***	
Seasonal volume error - Winter:	13.57	***±30***	
Seasonal volume error - Spring:	2.18	***±30***	
Error in storm volumes:	3.22	***±20***	
Error in summer storm volumes:	4.76	***±50***	

[1] Recommended criteria are from Lumb et al. (1994) for HSPF Model Applications

In general, the hydrologic calibration appears adequate in that it reflects the total water yield, seasonal variability, and magnitude of individual storm events in the basin. All recommended criteria are met.

3.2 Water Quality

After hydrology was sufficiently calibrated, water quality calibration was performed for suspended solids, nitrogen species, and total phosphorus. (Dissolved oxygen is not calibrated because SWAT does not provide for the input of BOD from point sources; however adjustments were made to keep DO in a reasonable range because of its impact on nutrient cycling.) Modeled versus observed in-stream concentrations were directly compared during model calibration. The water quality calibration consisted of running the watershed model, comparing water quality time series output to available water quality observation data, and adjusting pollutant loading and in-stream water quality parameters within a reasonable range. The objective was to best simulate the observed data for individual samples, as well as to obtain modeling output with disturbances (i.e., mean, median, minimum and maximum) similar to the observed data.

3.2.1 Model Enhancements

Instream water quality in SWAT is simulated at a daily time step, using kinetic routines based on the QUAL2E stream model. The use of a daily time step limits the accuracy that can be achieved with the model. In addition, there are important processes, such as the growth of benthic algae and macrophytes, that are not addressed in the model.

Benthic organisms (including algae, fungi, and bacteria) along with rooted macrophytes can play an important role in stream nutrient cycling. The general impact of these processes is to retain and convert inorganic nutrients to organic forms. To provide an approximate representation of this process, we modified the SWAT code (watqual.f) to allow for conversion of nitrate to organic N, with the rate constant represented through the unused variable RK6 in the swq input files.

Most water quality monitoring stations in the Black River basin are downstream of WWTP discharges. Effluent total phosphorus is monitored for these facilities. However, during low flow conditions, the model consistently over-predicted observed instream concentrations below the point source discharges. Therefore, a provision was also included in the model to provide rapid loss of phosphorus downstream of WWTPs. These losses are likely primarily associated with settling of a particle-bound fraction, of which sorption to iron hydroxides formed when the treatment train moved from anaerobic to aerobic conditions may be particularly important. Other losses may occur due to uptake by benthic organisms and rooted macrophytes. Because SWAT assumes that inorganic phosphorus is equivalent to soluble phosphorus and that no settling losses of inorganic phosphorus occur, the discrepancy between total phosphorus measured and effluent and total phosphorus observed instream was represented by applying a reduction factor of 25 percent to the monitored effluent load. This is implemented in the model via the unused RBO_A1 variable in the bsn file. The reduction is only applied to WWTP phosphorus loads.

Modifications were also made to the simulation of sediment, as described above in Section 2.2.

3.2.2 Calibration Approach

Water quality calibration involved the examination of observed and predicted data at seven calibration sites, as shown in Figure 3-9. These seven sites correspond to the following Ohio EPA water quality monitoring stations:

- Station 501510 is on the main stem of the Black River and drains most of the watershed.
- Station 501520 is further upstream on the mainstem.
- Station B01S13 drains most of the West Branch Black River.
- Station B01S11 drains most of the East Branch Black River.
- Station B01P02 drains the Plum Creek watershed.
- Station B01W10 drains the East Fork Black River.
- Station B01S36 drains the East Branch Black River headwaters.

Water quality samples have been collected approximately monthly at Station 501510 for the period January 1990 to October 2004 and at Station 501520 for January 1990 to July 1994 and June to September 1997. Water quality samples at the other stations are limited to the periods January 1992 to November 1993, July 1997 to October 1997, and July 2001 to December 2001. As with the hydrology calibration, the final water quality calibration used the entire span of data, so there is not an independent validation period. However, the model appears to perform well across all available monitoring years.

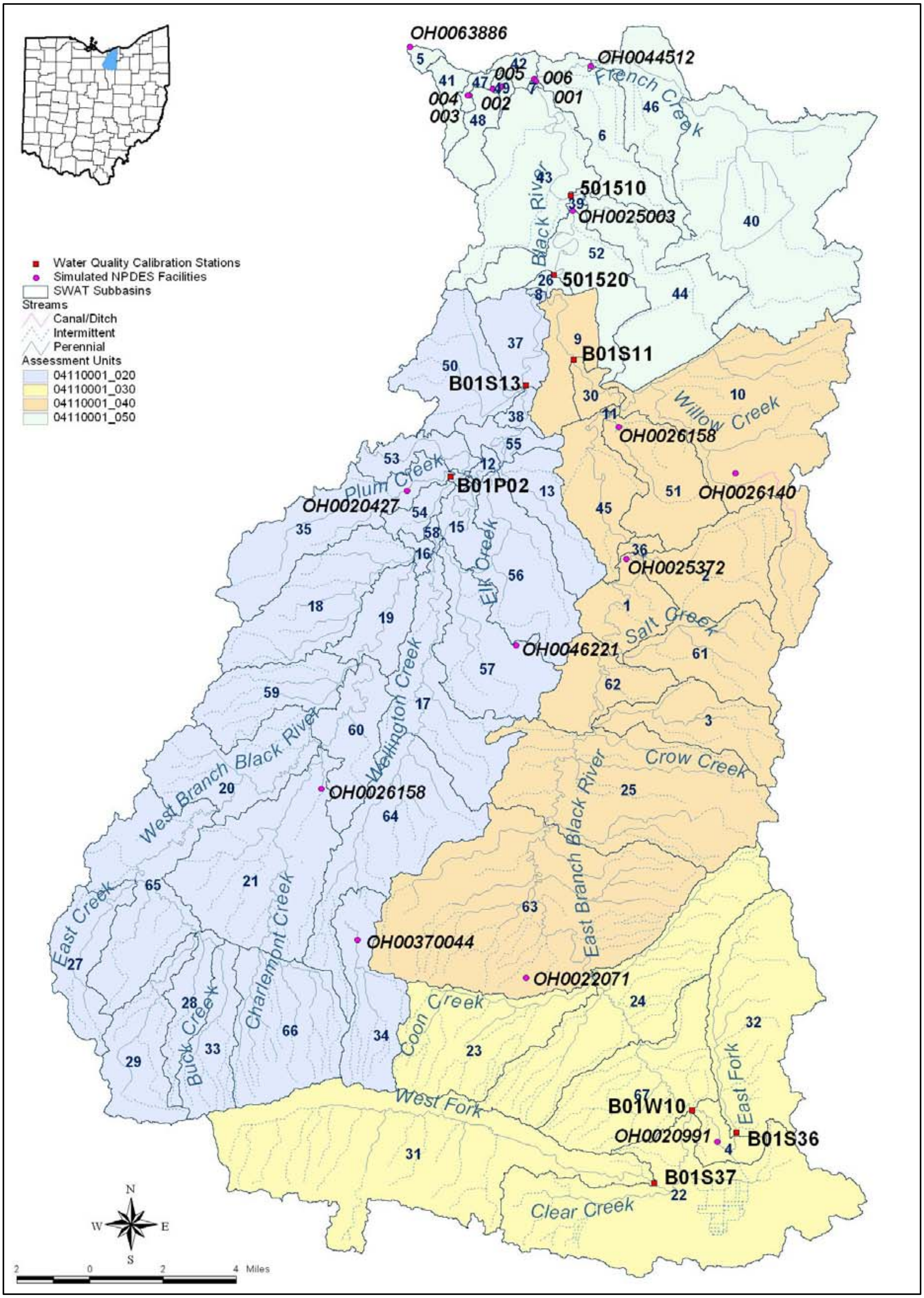

Figure 3-9. Black River Swat Subbasins, Water Quality Stations, and Permitted Discharge (MOR) Outfalls

The general water quality calibration approach includes graphical comparison of time-series plots, concentration-duration plots and statistical comparison. Because of the simplified implementation of instream kinetics in SWAT, coupled with uncertainty in the specification of boundary conditions (particularly point source loads), it cannot be expected that all observations will be reproduced in the model; however, the general trend should be replicated.

Instream suspended solids result from the interaction of upland loading and scour/deposition processes in the stream channels. We assumed that the basic USLE factors and management practices are fixed and known. Suspended solids were then calibrated using the MUSLE alpha factor for upland loads (see Section 2.2) and the factors controlling sediment re-entrainment rates (PRF, SPCON, SPEXP).

For nutrients, the primary calibration adjustments were the groundwater discharge concentrations, the nutrient percolation factors, settling rates for the organic fraction, and kinetic coefficients for transformation between different nutrient forms. Key parameter values are summarized in Table 3-5. Most other parameters are set at SWAT default values.

Most parameters are set at single values throughout the watershed. One exception is the groundwater nitrate concentration (GWNO3). Based on monitoring data at BO1S36, baseflow nitrogen concentrations are lower in the Lodi area. This part of the watershed has soils that differ from the remainder of the basin, with poorly drained B/D soils present and extensive use of tile drainage. The resulting higher water table in this area is suspected to promote denitrification, resulting in lower nitrogen concentration in groundwater discharged to streams. An improved fit to observations was obtained by setting GWNO3 to 1 mg/L in the subbasins of this portion of the watershed (subbasins 4, 22, 24, 31, 32, 63, and 67).

Table 3-5. Key Water Quality Parameters

Parameter	SWAT file	Recommended Range	Calibrated Value
ALPHA - MUSLE alpha coefficient	.bsn (Tt version only)	NA	3.25
PRF – Peak rate adjustment factor for main channel	.bsn	NA	0.3
SPCON – Linear parameter for sediment reentrainment	.bsn	0.0001 – 0.01	0.0001
SPEXP – Exponential parameter for sediment reentrainment	.bsn	1.0 – 1.5	3.0
NPERCO – Nitrogen percolation coefficient	.bsn	0.0 – 1.0	0.4
PPERCO – Phosphorus percolation coefficient	.bsn	10.0 – 17.5	17.5
RBO_A1 – Phosphorus reduction factor for WWTP loads	.bsn (Tt version only)	NA	0.25
RS4 – Coefficient for organic N settling (day^{-1})	.swq	0.001 – 0.10	0.10
RS5 – Coefficient for organic P settling (day^{-1})	.swq	0.001 – 0.10	0.10
RK6 – Coefficient for conversion of NO_3 to organic N (day^{-1})	.swq (Tt version only)	NA	0.08
BC3 – Rate constant for hydrolysis of organic N to NH_3	.bsn	0.2 – 0.4	0.05
BC4 – Rate constant for mineralization of organic P	.bsn	0.01 – 0.70	0.005
GWNO3 – Concentration of nitrate in groundwater discharge (mg/L)	.gw	NA	2.0 1.0 (Lodi area)
GWSOLP – concentration of soluble phosphorus in groundwater discharge (mg/L)	.gw	NA	0.05

Obtaining a reasonable calibration required several parameters to be set outside the recommended ranges in Neitsch et al. (2001). The best fit for instream sediment was obtained with a high value for SPEXP combined with a low value for SPCON. This combination likely compensates for incomplete knowledge regarding channel dimensions and the resulting relationship of shear stress to flow. For the nutrients, the settling coefficients for the organic fractions were set at the high end of the recommended range, while the hydrolysis/mineralization rates were set below the recommended range. These parameters work together to promote removal of nutrients from the system. (Low hydrolysis/mineralization rates keep a larger fraction in the organic pool, which is the only fraction subject to loss in SWAT.) In fact, much of the apparent loss of nutrients in the system is likely due to uptake by benthic organisms and macrophytes. SWAT does not simulate these components, so the values assigned to RS4, RS5, BC3 and BC4 must compensate for this phenomenon.

3.2.3 Calibration Results

SWAT water quality modeling results are presented graphically for the seven calibration sites in Figure 3-10 to Figure 3-45. The graphs compare observed versus simulated daily total suspended solids (TSS), nitrite+nitrate (NO_2+NO_3), total nitrogen, and total phosphorus (TP) concentrations.

Two types of graphs are presented. First are traditional time series graphs, in which obervations and model predictions are presented against time. These graphs allow visual assessment of the model's ability to reproduce observed trends – although it should be noted that the model predicts daily averages, whereas the observations are point-in-time grabs. Because the observations are not daily averages, they are likely to exhibit greater variability than model predictions.

The second type of graph plots simulated and observed concentration versus flow. This type of comparison is important to ensure that the model is reproducing observed behavior over different portions of the flow regime. They also serve to filter out some of the discrepancies that may occur because of uncertainty in individual flow event predictions. For many of the stations, the highest concentrations occur at low flows, indicating a situation in which observed concentration is dominated by point source discharges.

Table 3-6 provides a statistical comparison of paired observed and simulated values at the five stations with the greatest amount of data.

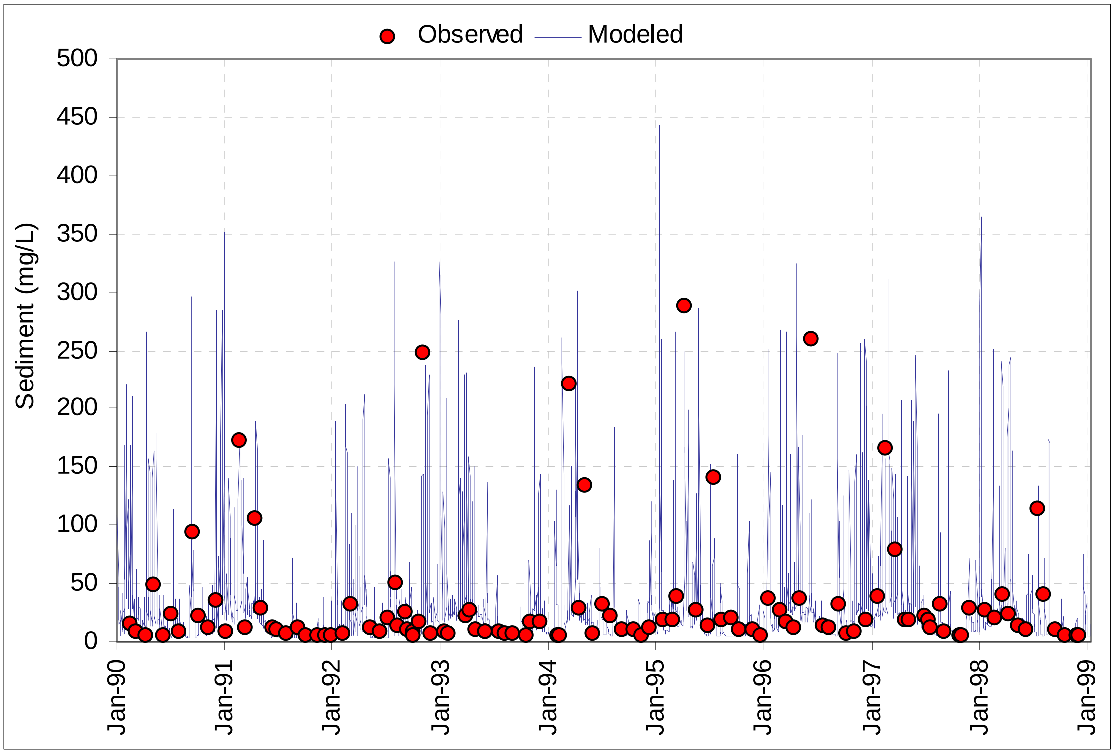

Figure 3-10. Observed versus Simulated Total Suspended Solids at Station 501510 [Note that many observed TSS values are at the detection limit of 5 mg/l.]

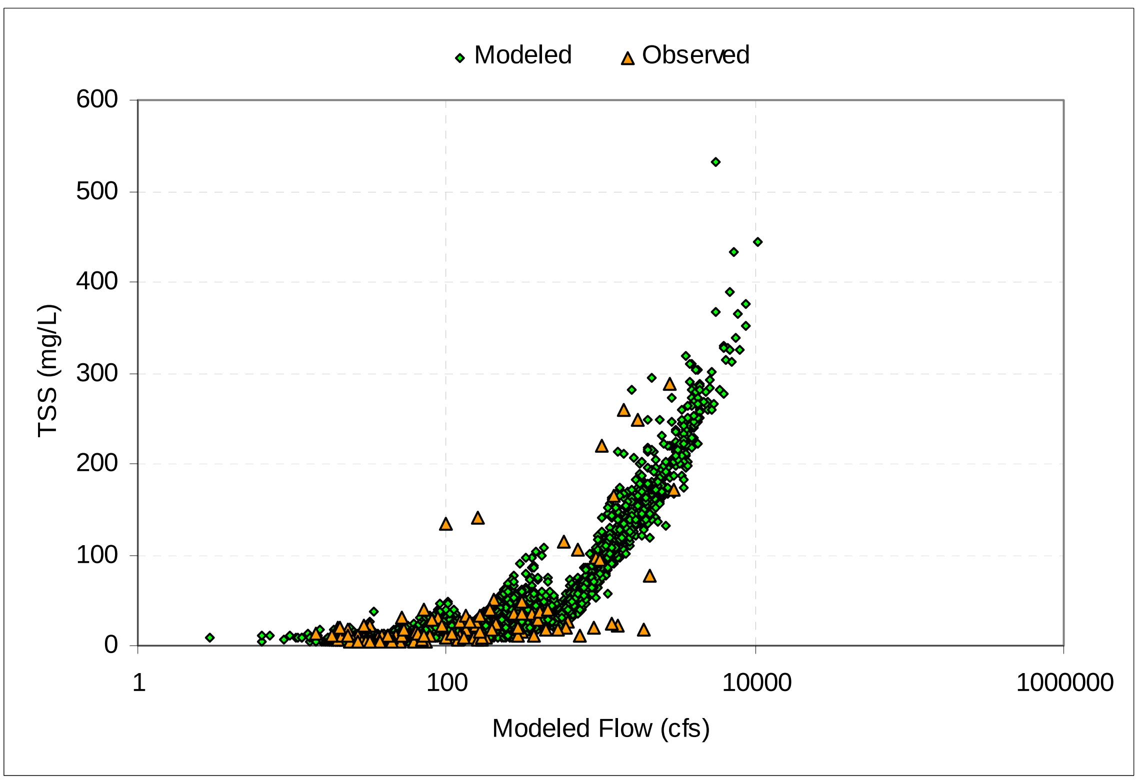

Figure 3-11. Observed and Simulated Total Suspended Solids versus Simulated Flow at Station 501510

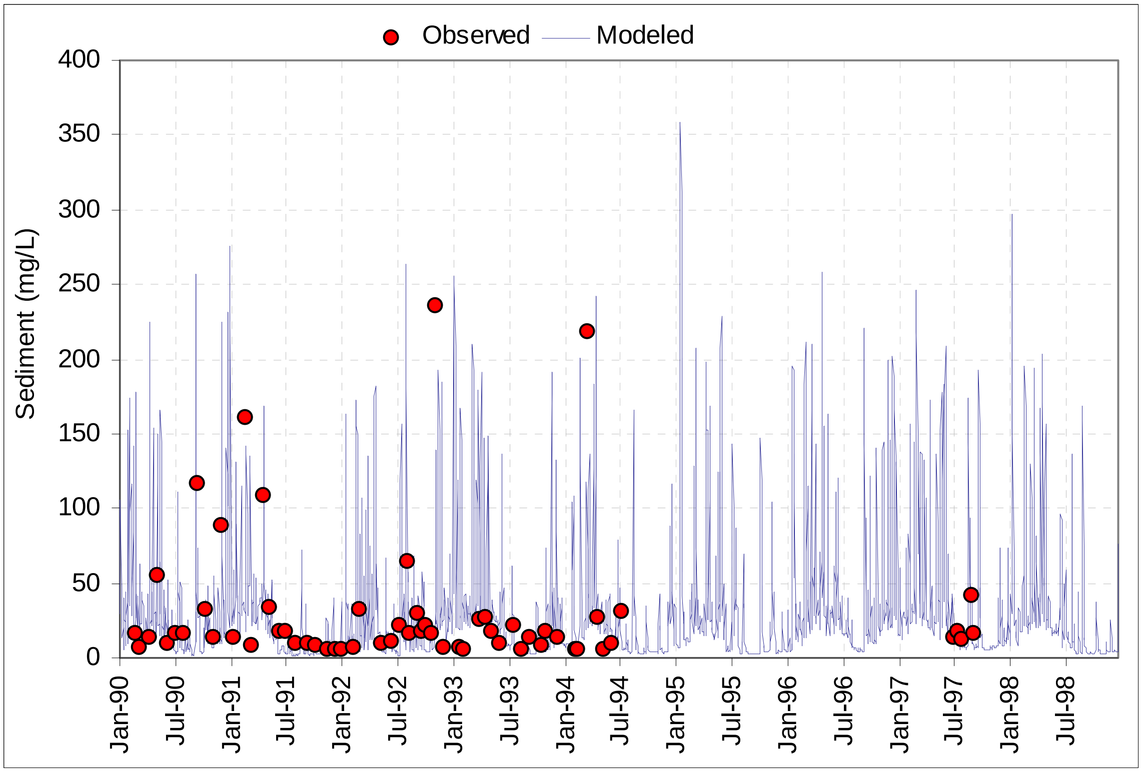

Figure 3-12. Observed versus Simulated Total Suspended Solids at Station 501520

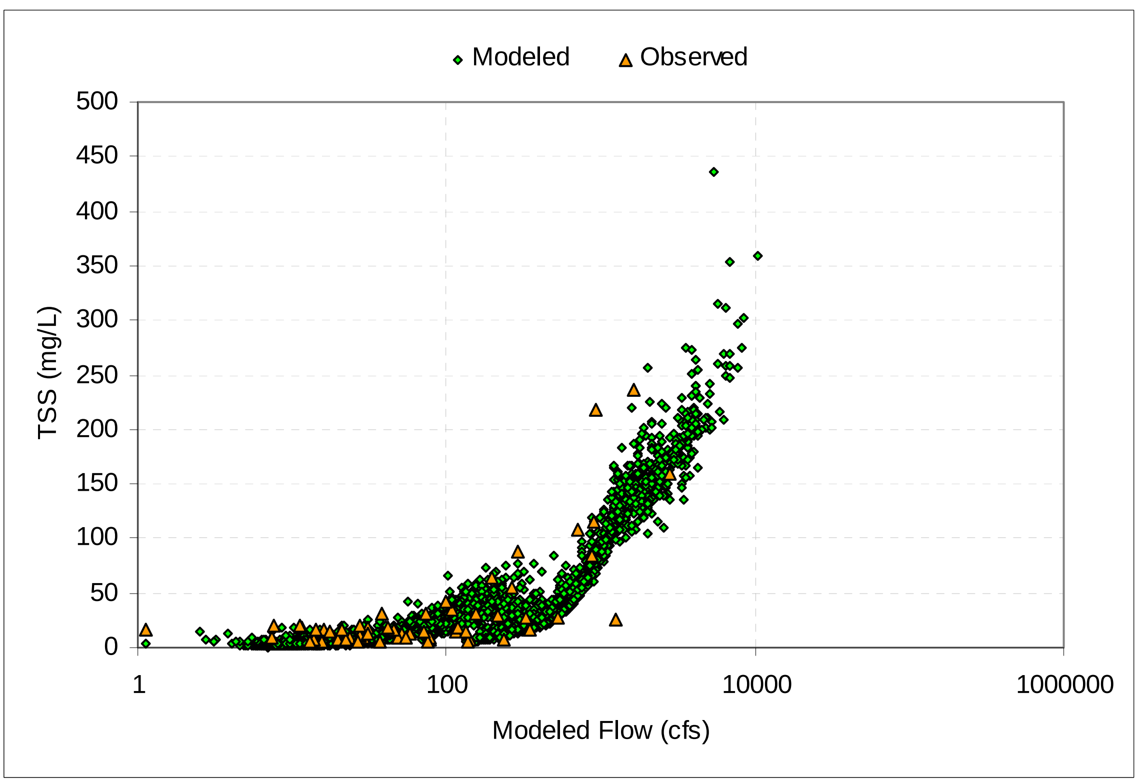

Figure 3-13. Observed and Simulated Total Suspended Solids versus Simulated Flow at Station 501520

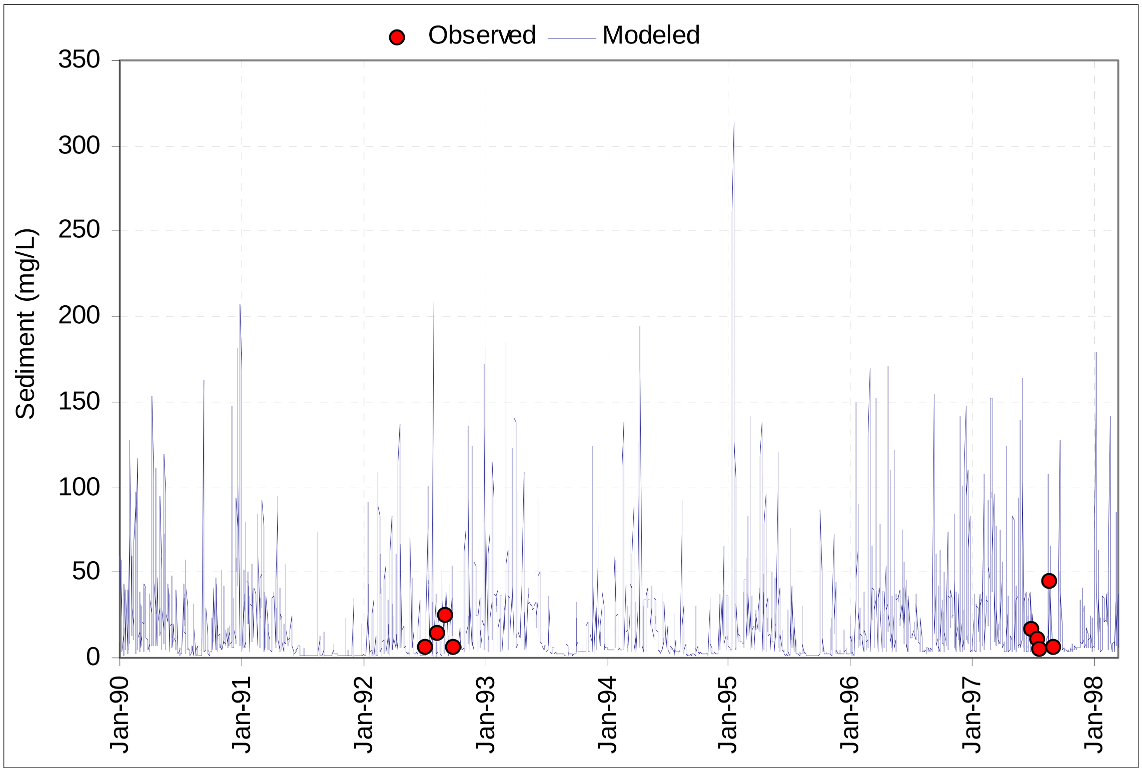

Figure 3-14. Observed versus Simulated Total Suspended Solids at Station B01S11

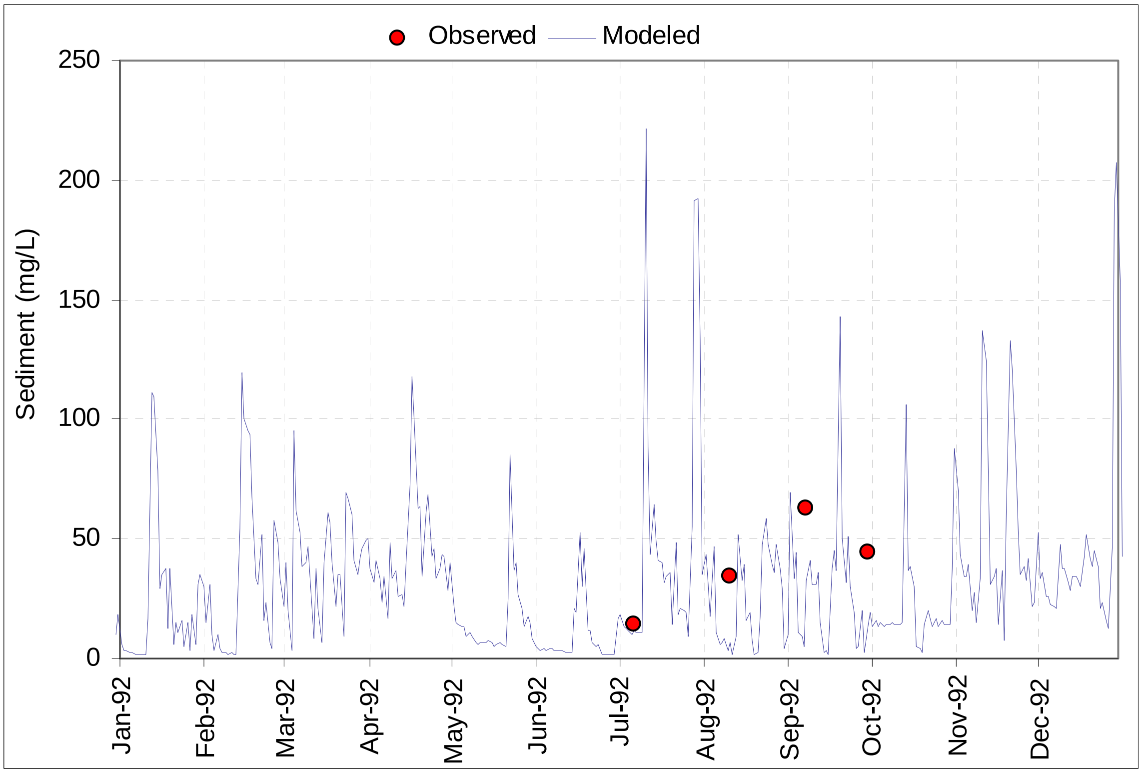

Figure 3-15. Observed versus Simulated Total Suspended Solids at Station B01S13

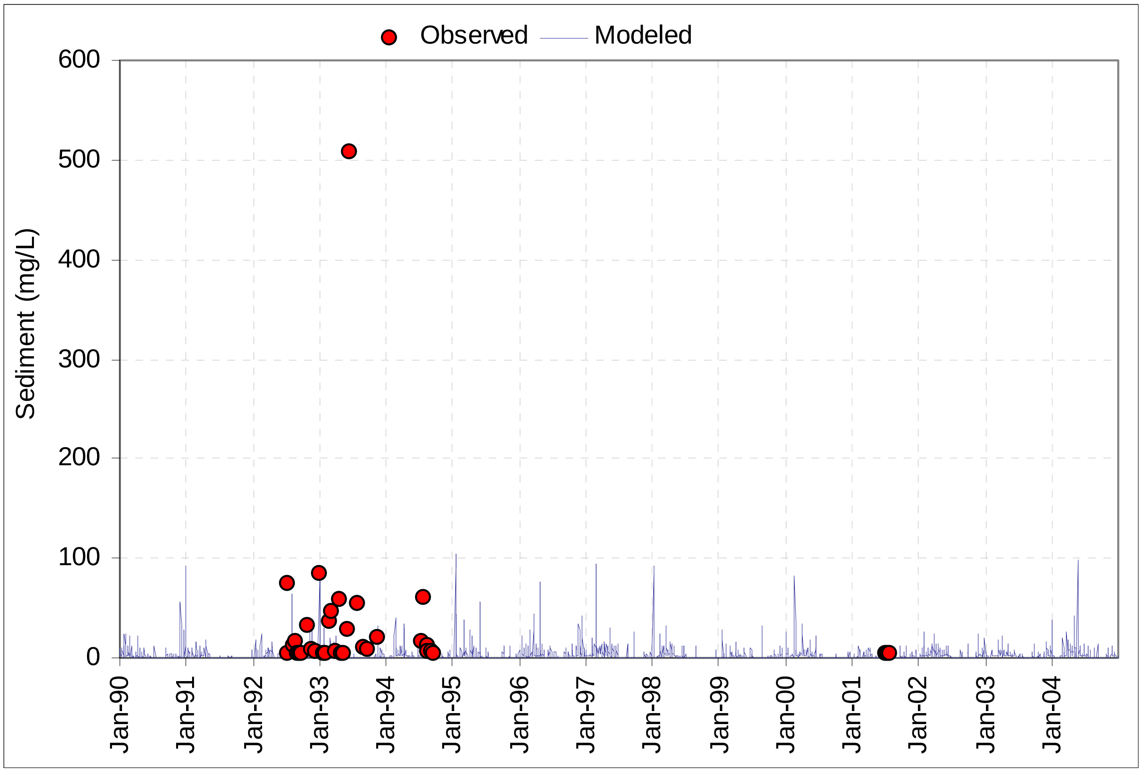

Figure 3-16. Observed versus Simulated Total Suspended Solids at Station B01PO2

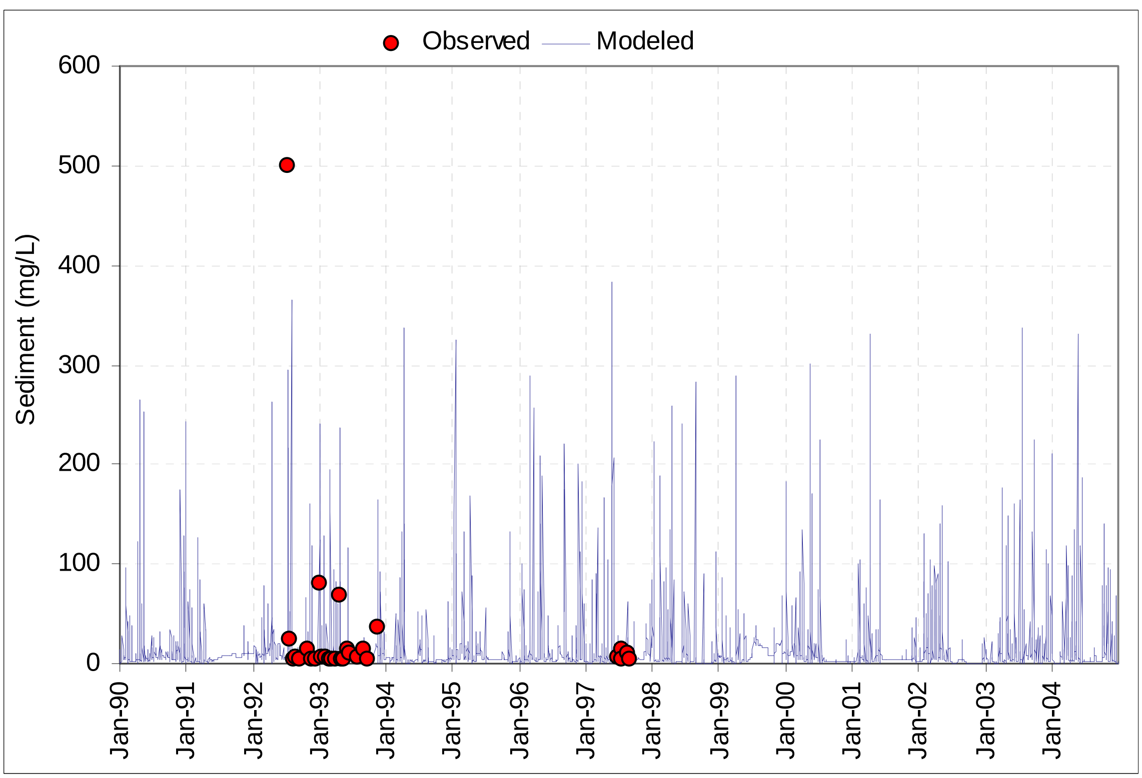

Figure 3-17. Observed versus Simulated Total Suspended Solids at Station B01W10

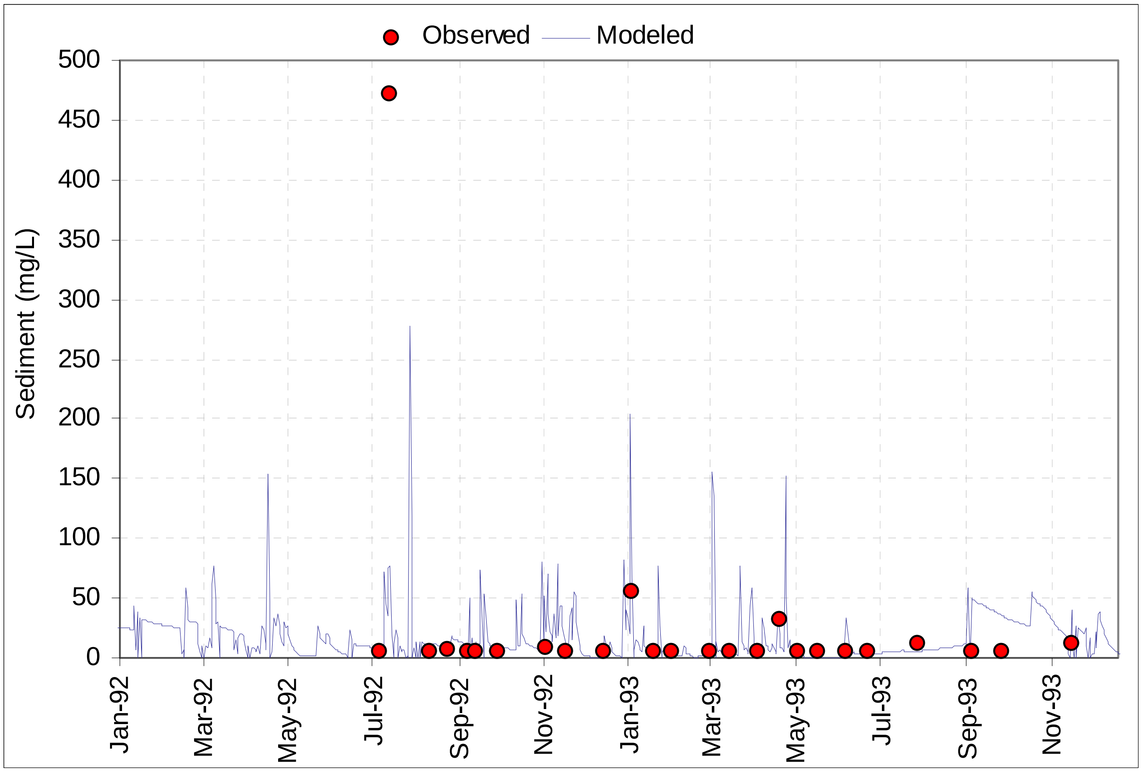

Figure 3-18. Observed versus Simulated Total Suspended Solids at Station B01S36

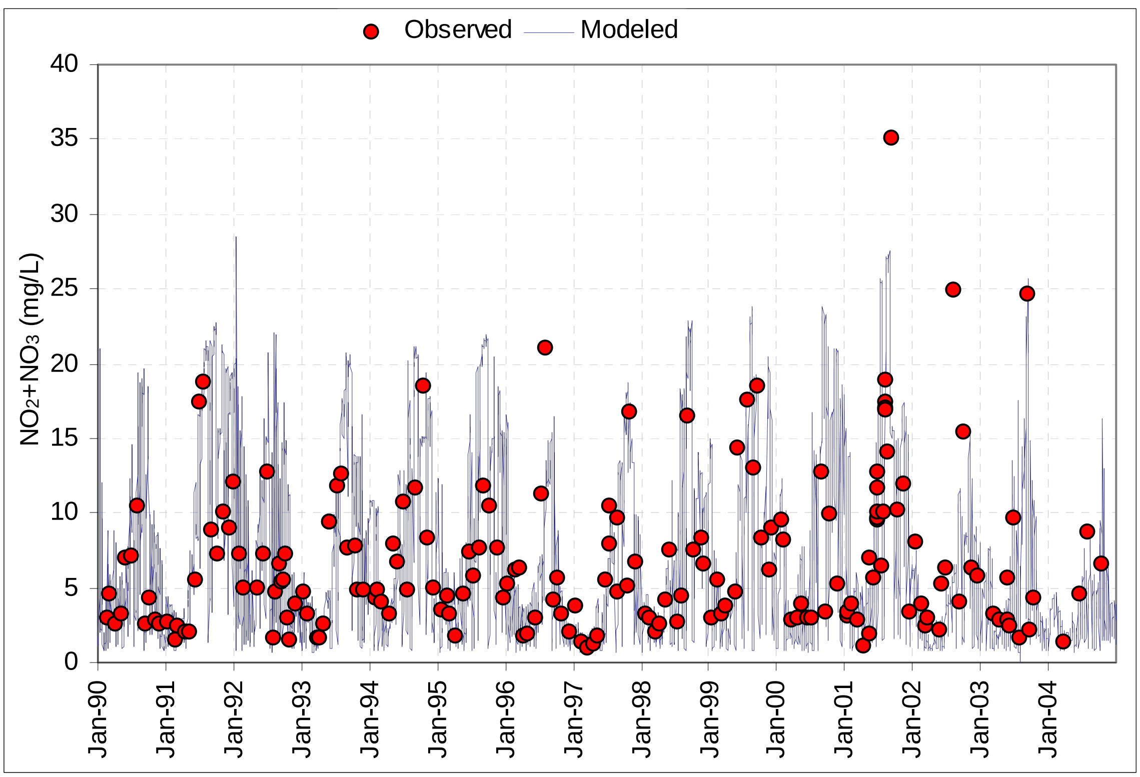

Figure 3-19. Observed versus Simulated Nitrite + Nitrate at Station 501510

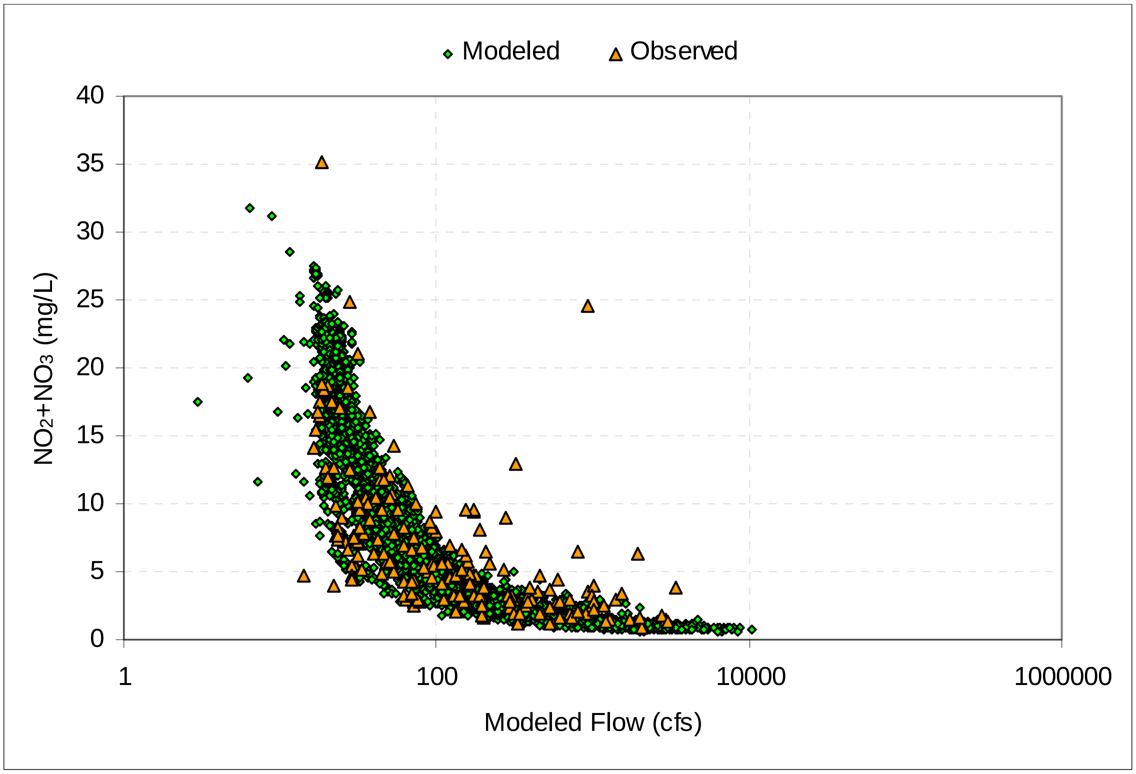

Figure 3-20. Observed and Simulated Nitrite + Nitrate versus Simulated Flow at Station 501510

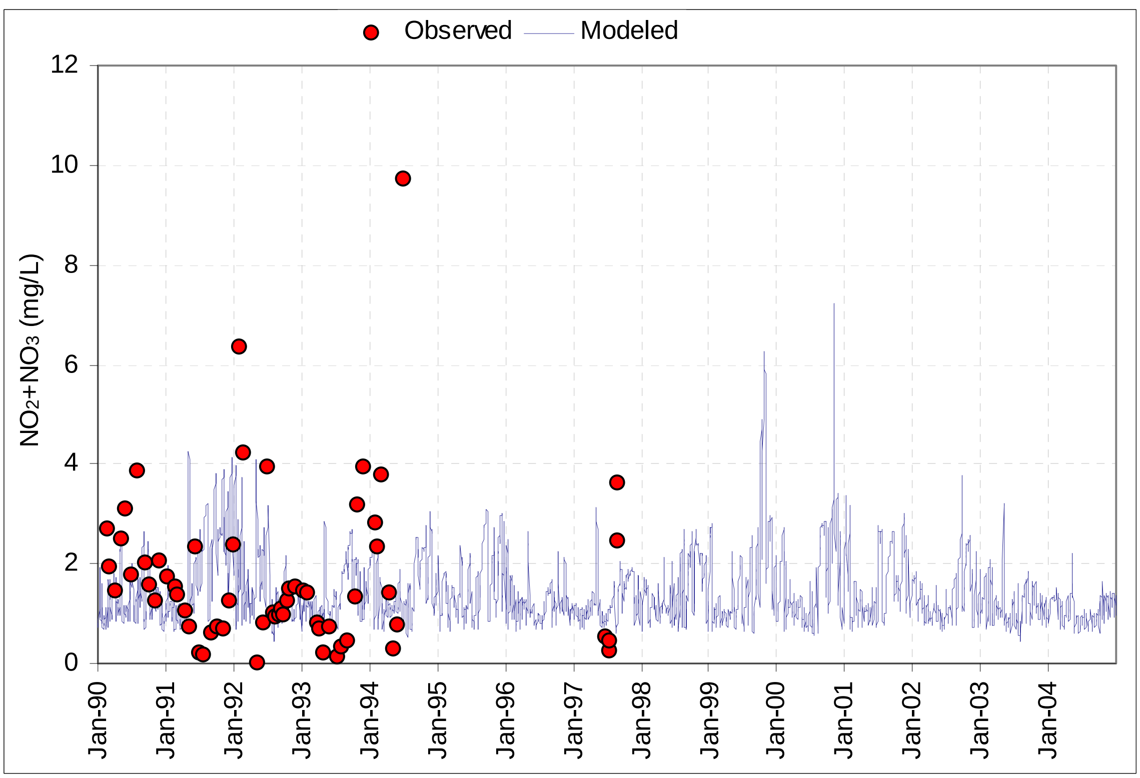

Figure 3-21. Observed versus Simulated Nitrite + Nitrate at Station 501520

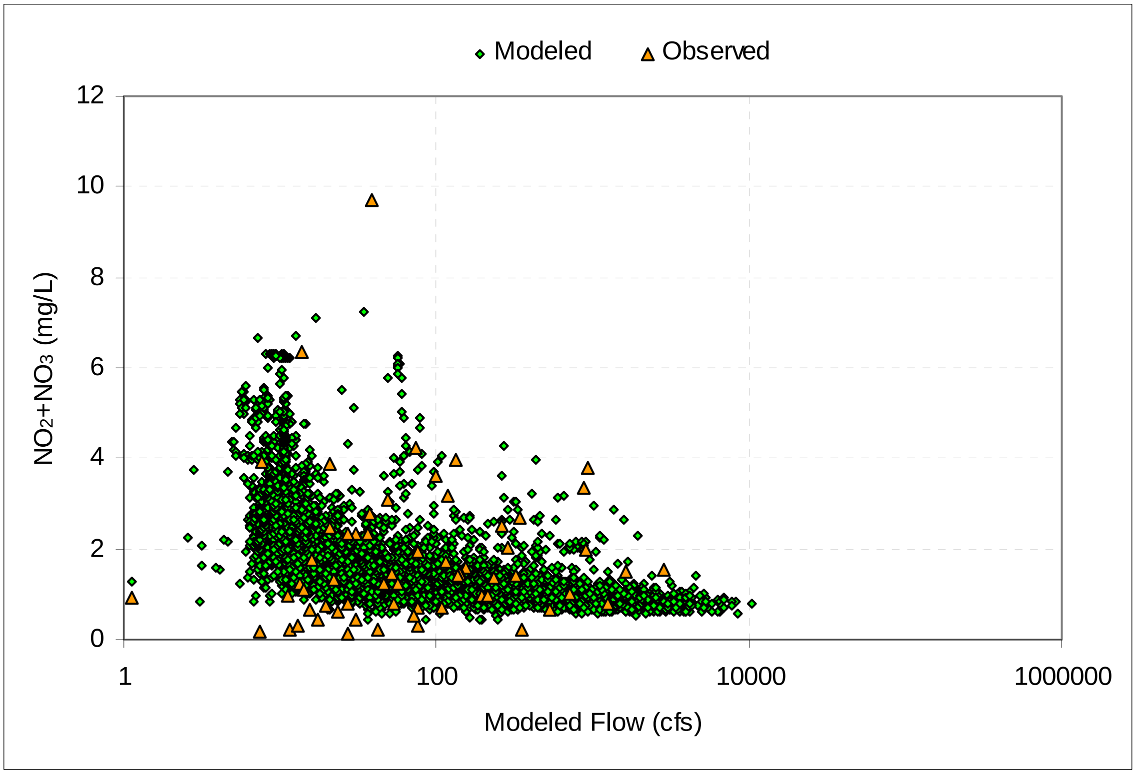

Figure 3-22. Observed and Simulated Nitrite + Nitrate versus Simulated Flow at Station 501520

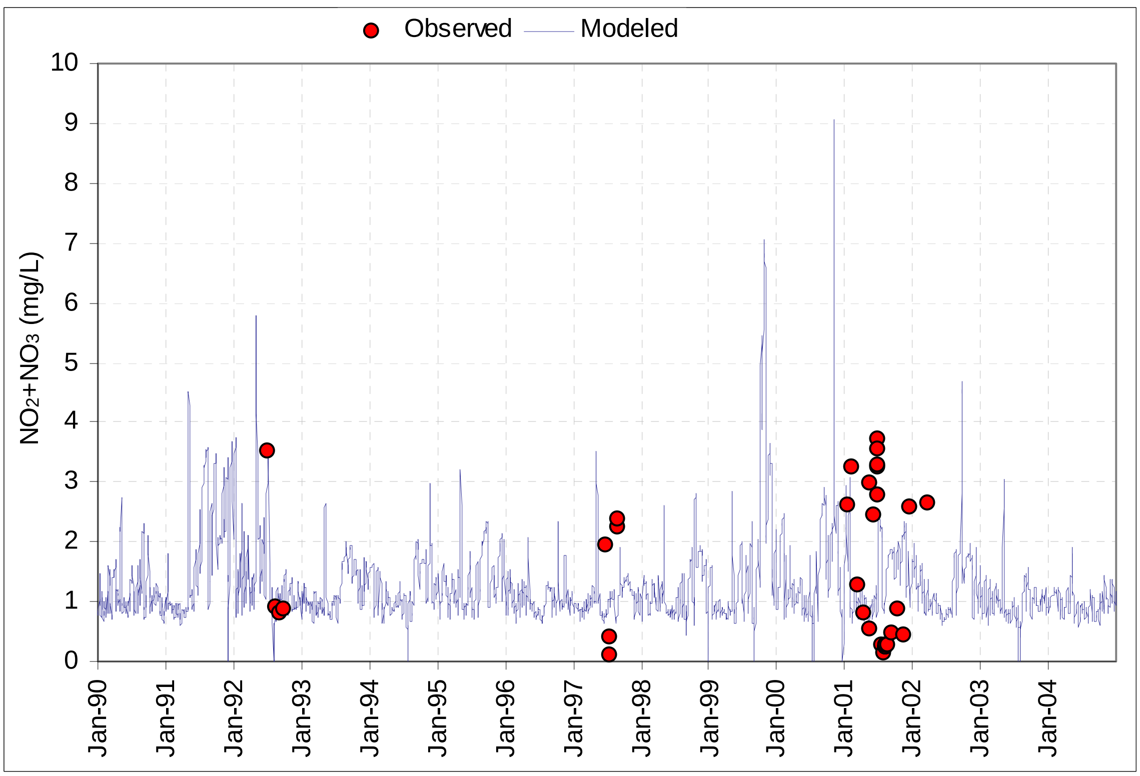

Figure 3-23. Observed versus Simulated Nitrite + Nitrate at Station B01S11

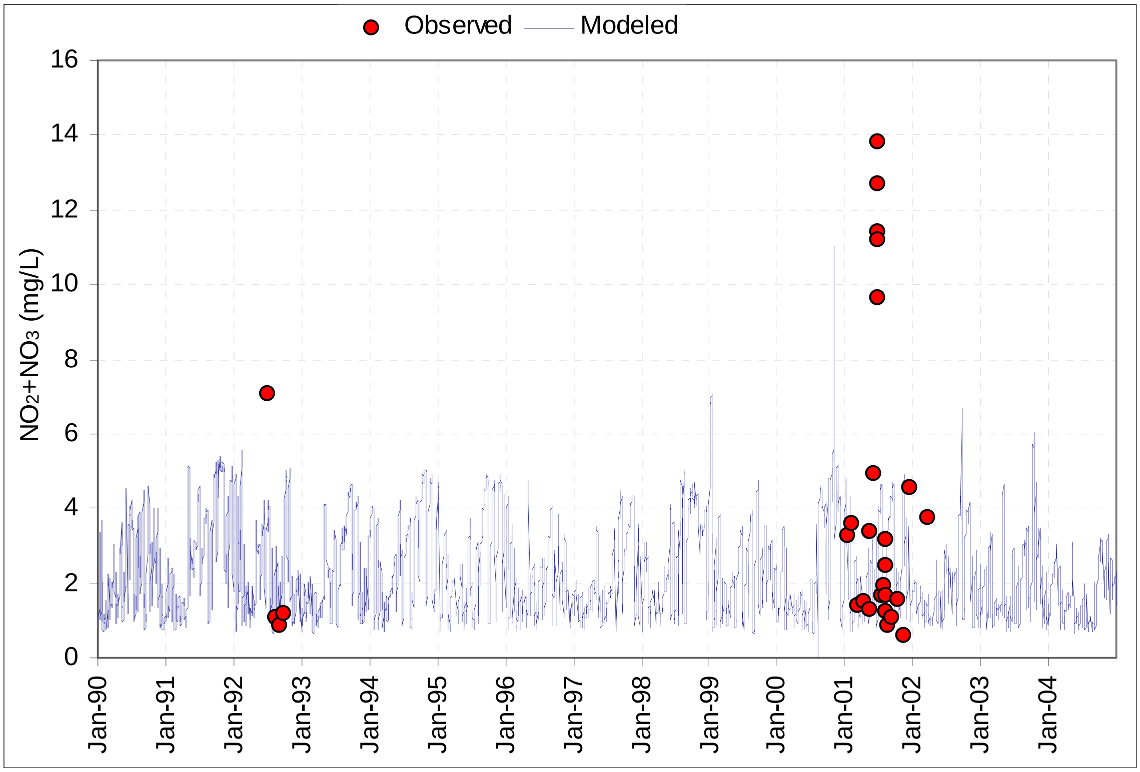

Figure 3-24. Observed versus Simulated Nitrite + Nitrate at Station B01S13

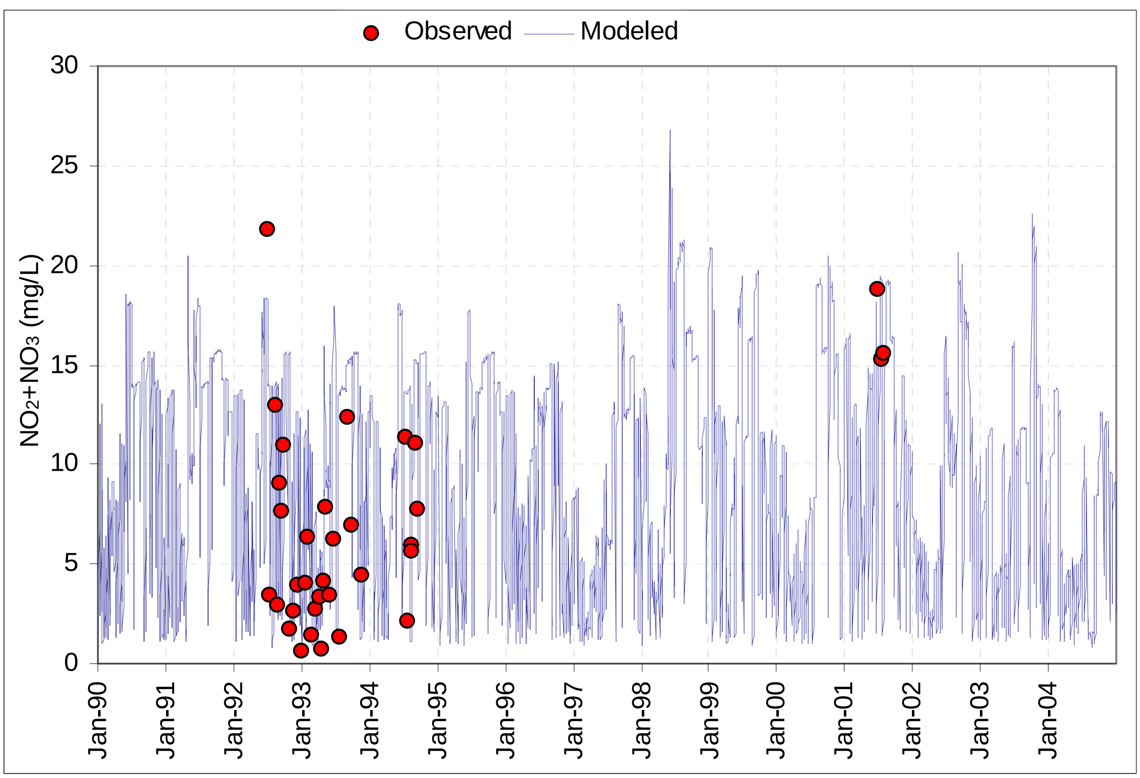

Figure 3-25. Observed versus Simulated Nitrite + Nitrate at Station B01PO2

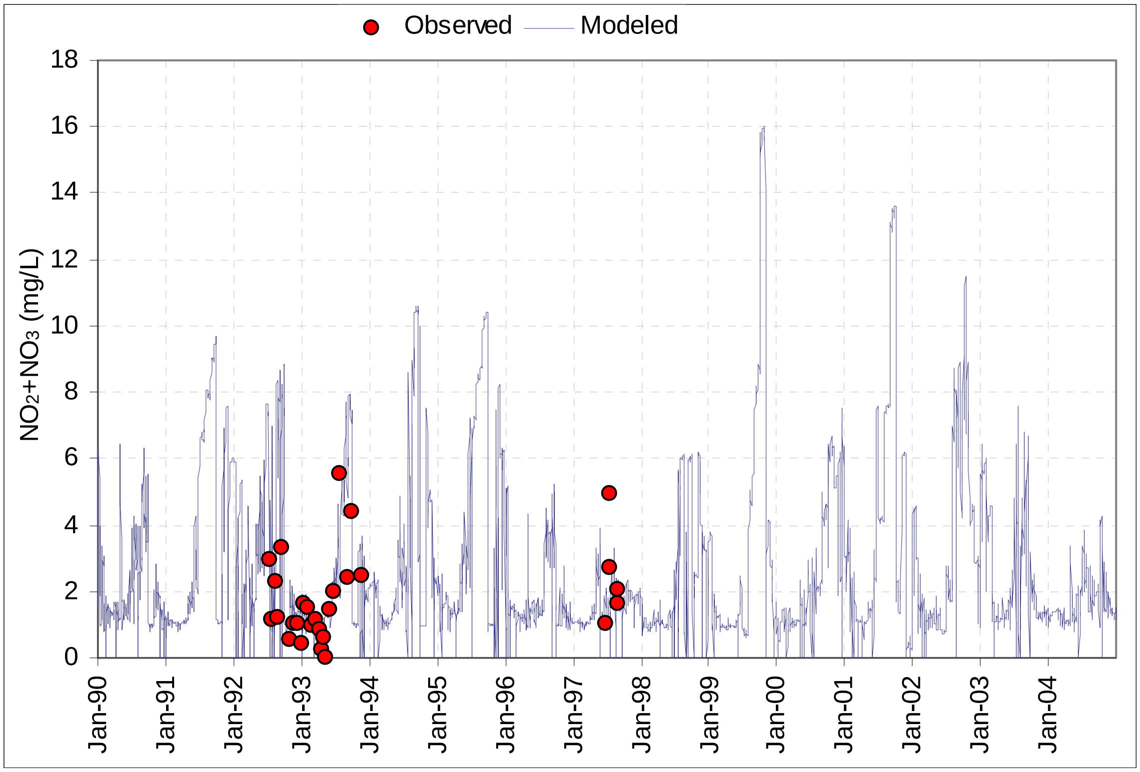

Figure 3-26. Observed versus Simulated Nitrite + Nitrate at Station B01W10

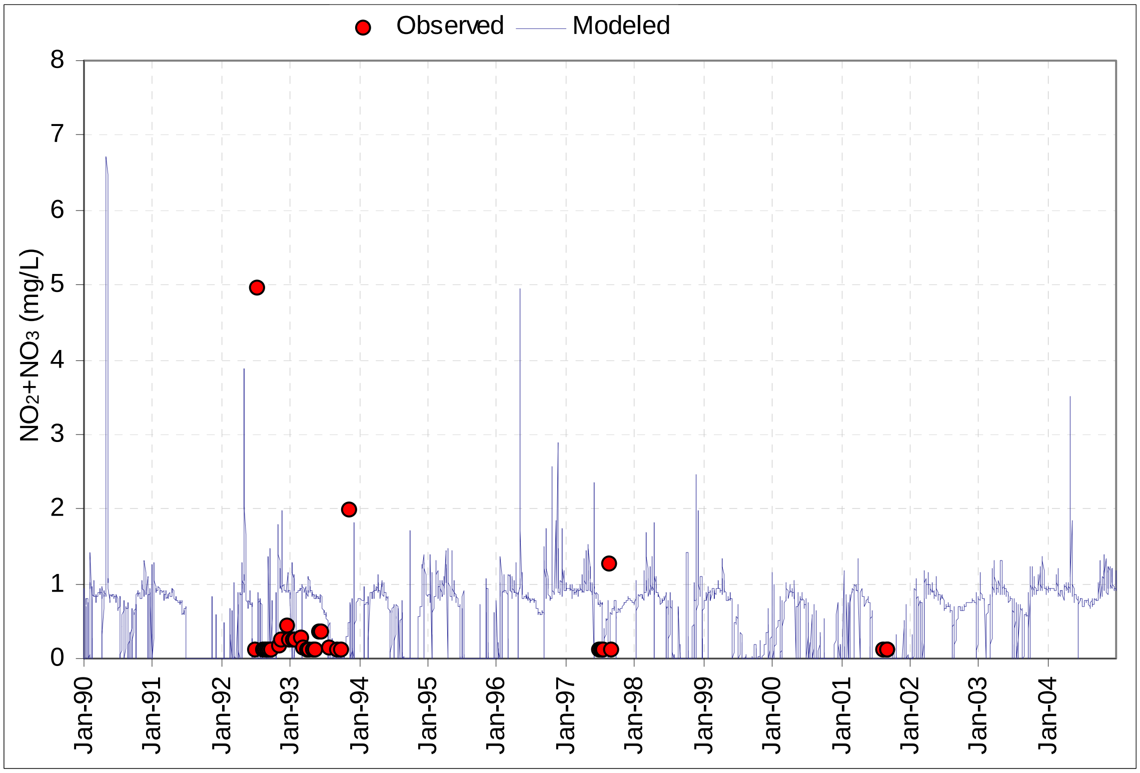

Figure 3-27. Observed versus Simulated Nitrite + Nitrate at Station B01S36

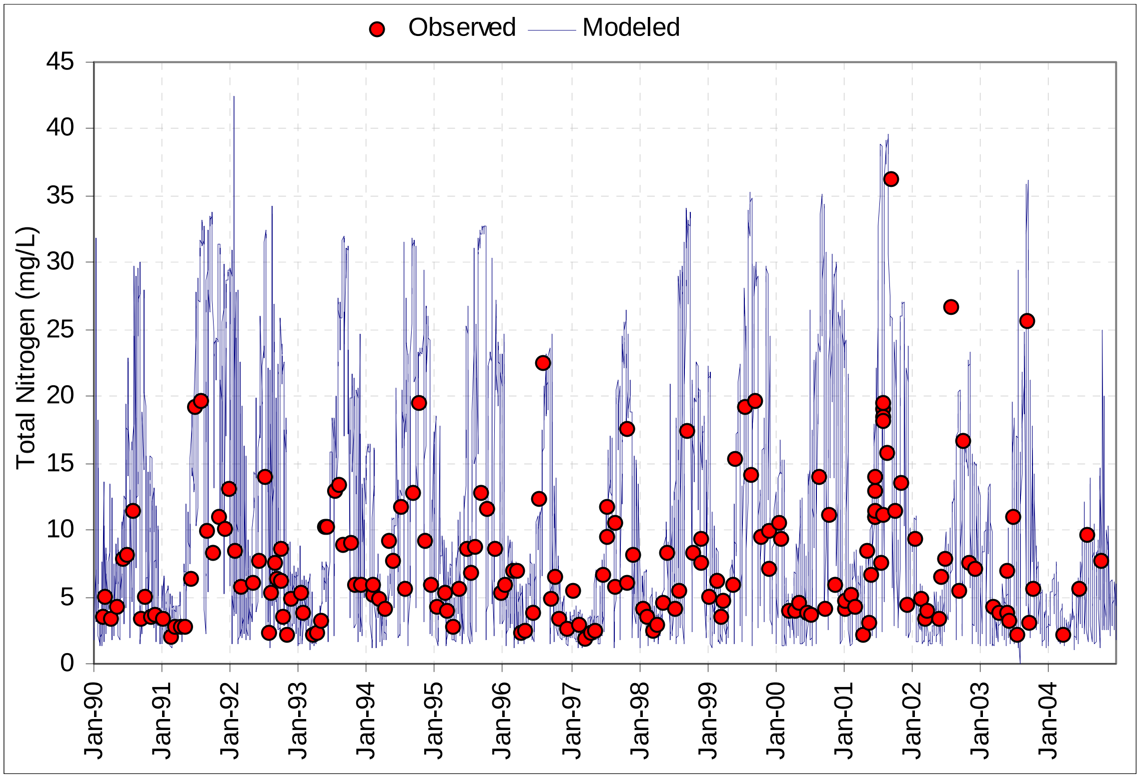

Figure 3-28. Observed versus Simulated Total Nitrogen at Station 501510

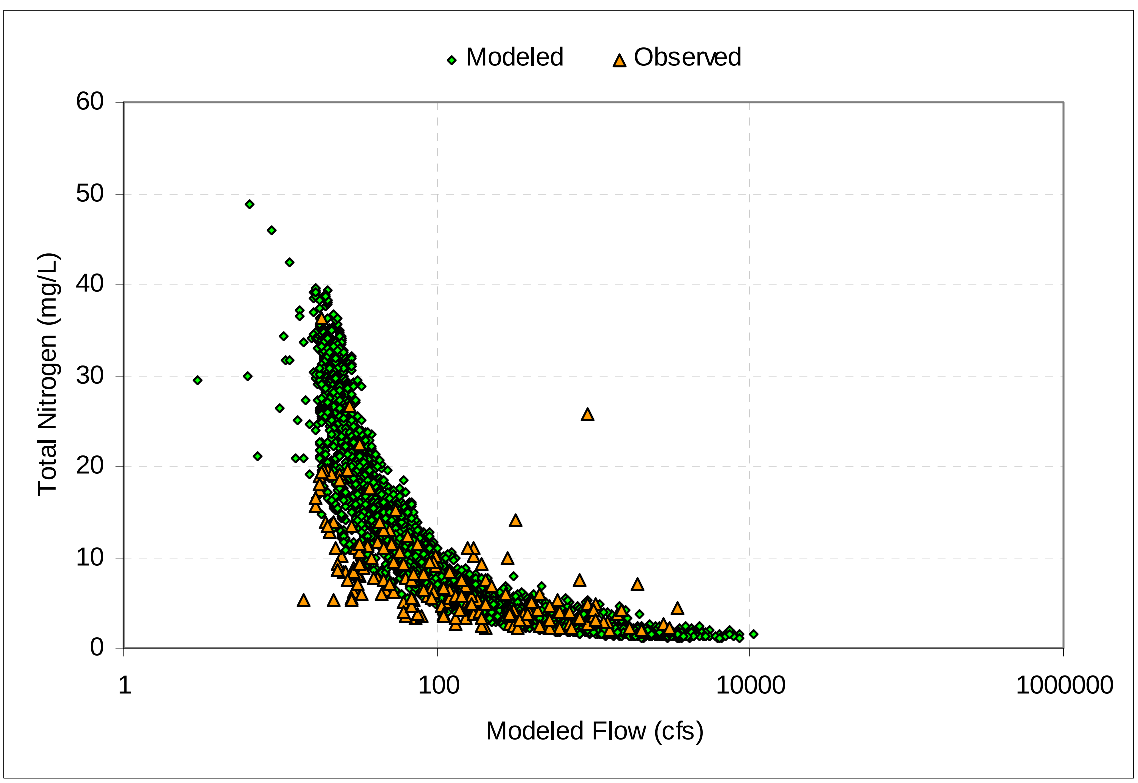

Figure 3-29. Observed and Simulated Total Nitrogen versus Simulated Flow at Station 501510

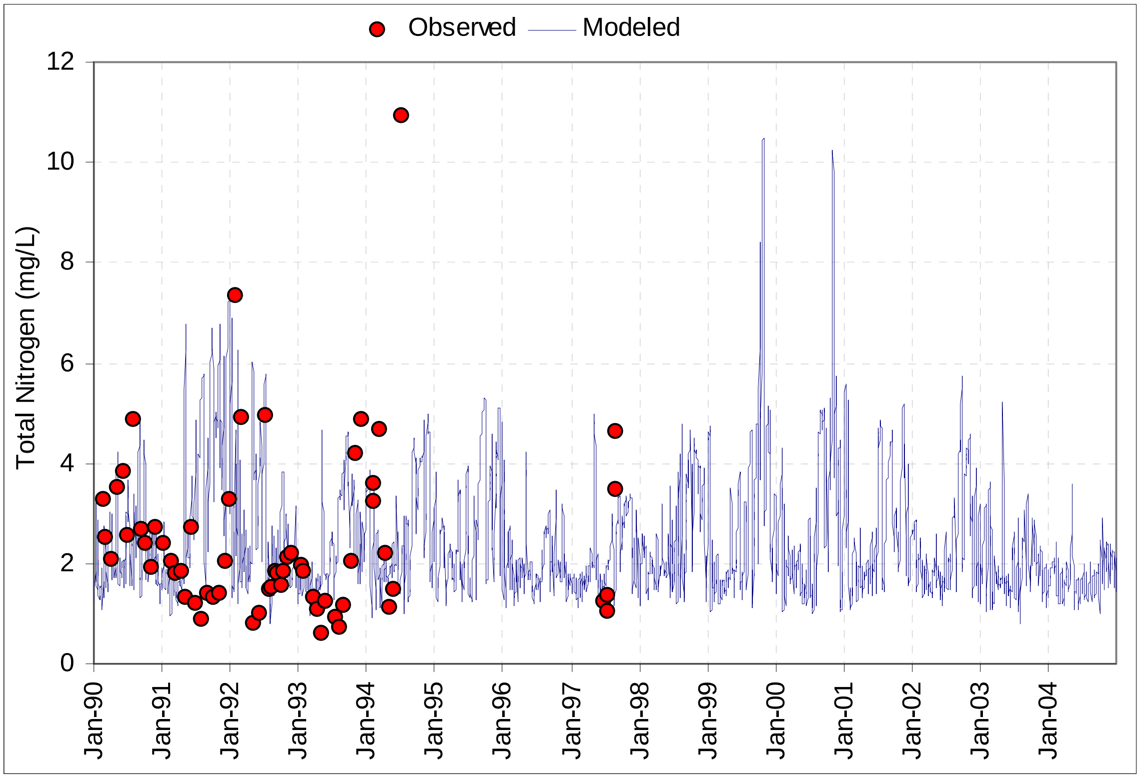

Figure 3-30. Observed versus Simulated Total Nitrogen at Station 501520

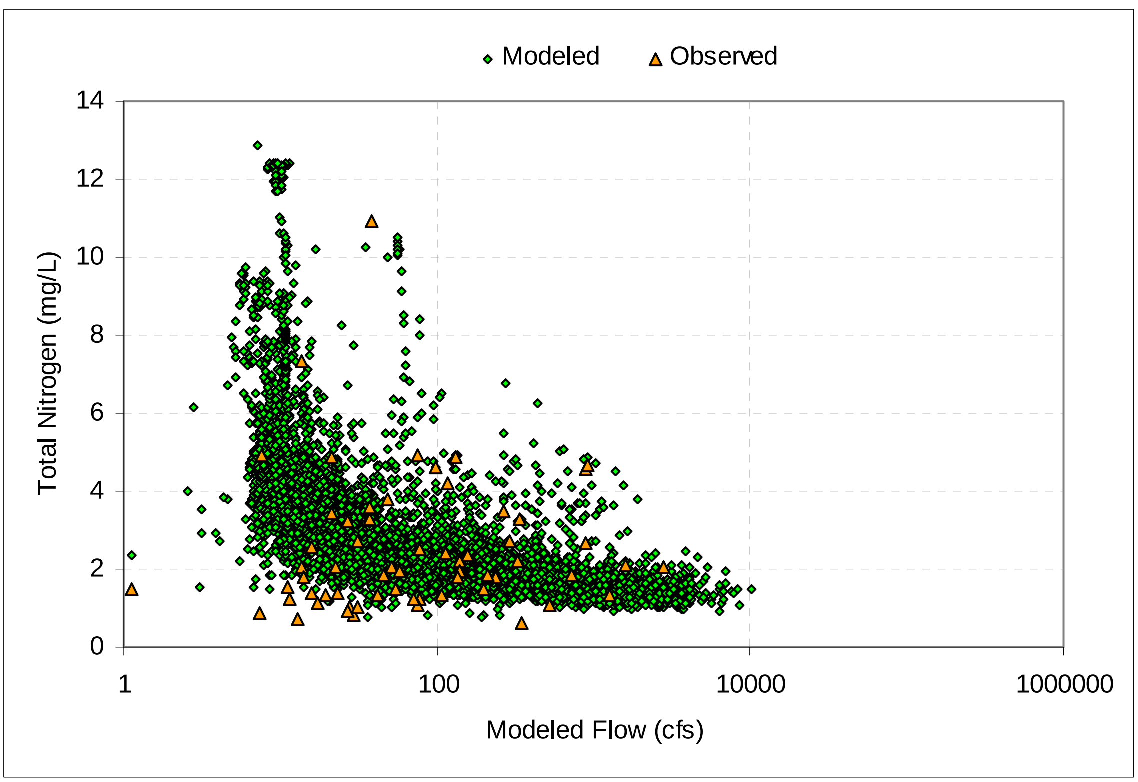

Figure 3-31. Observed and Simulated Total Nitrogen versus Simulated Flow at Station 501520

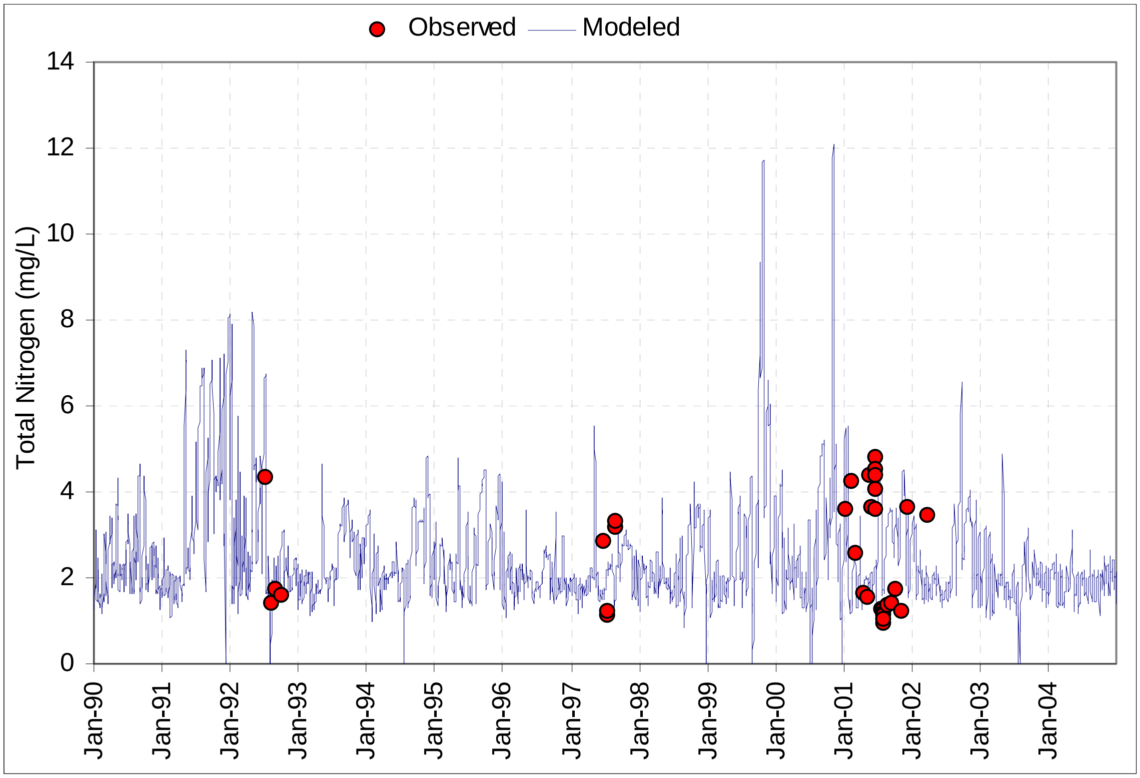

Figure 3-32. Observed versus Simulated Total Nitrogen at Station B01S11

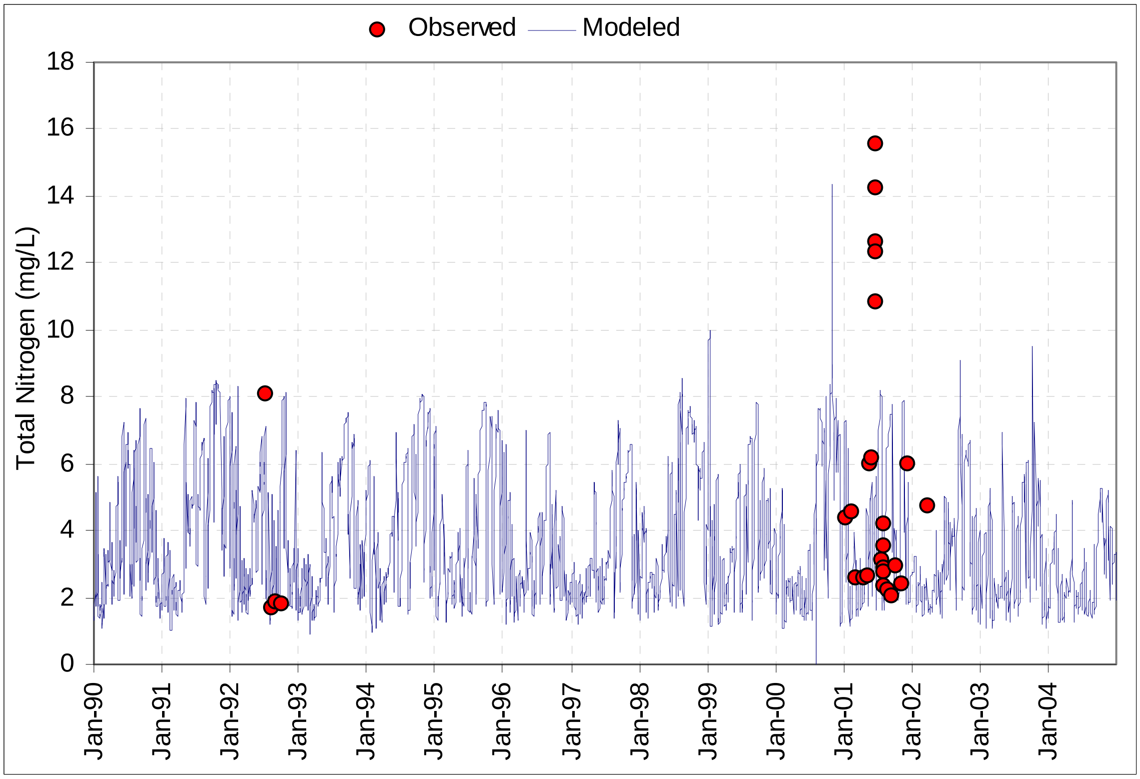

Figure 3-33. Observed versus Simulated Total Nitrogen at Station B01S13

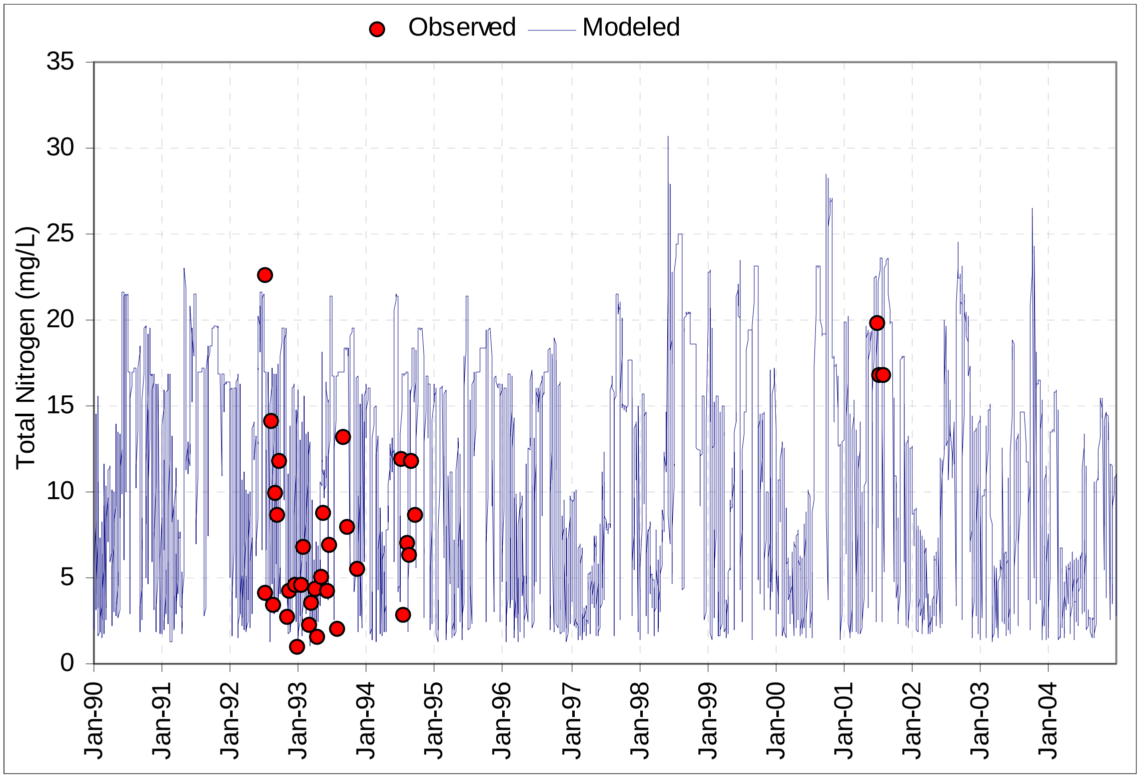

Figure 3-34. Observed versus Simulated Total Nitrogen at Station B01PO2

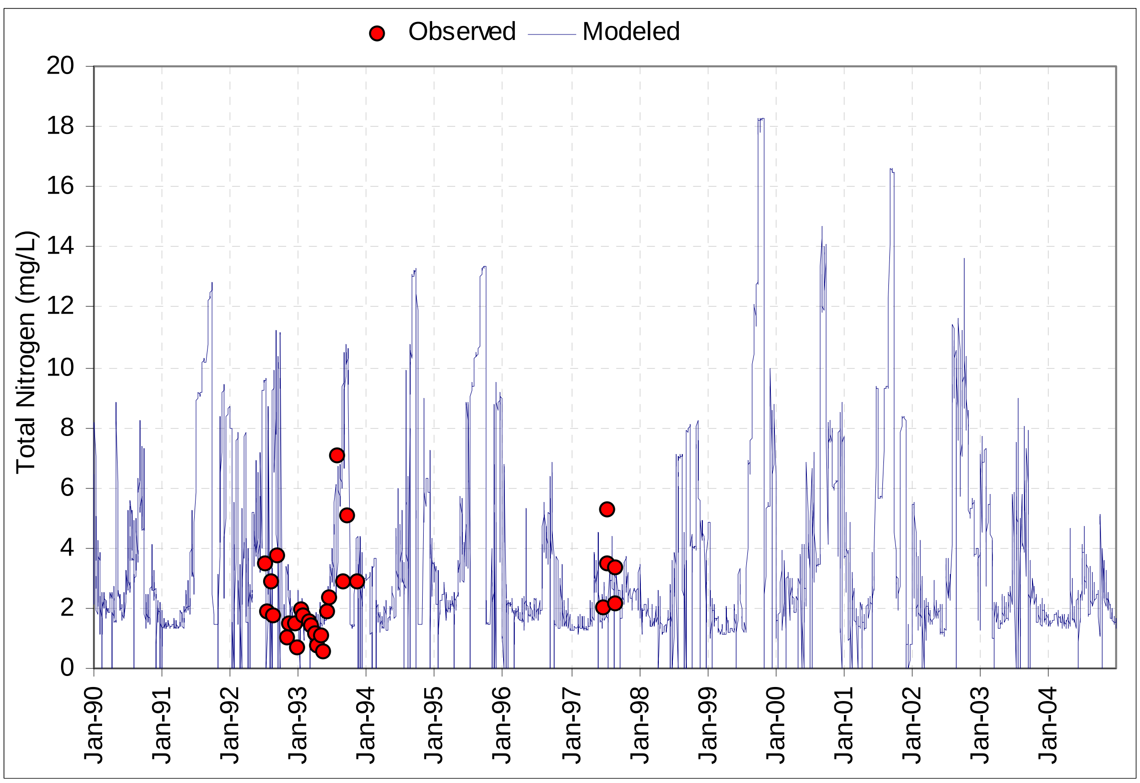

Figure 3-35. Observed versus Simulated Total Nitrogen at Station B01W10

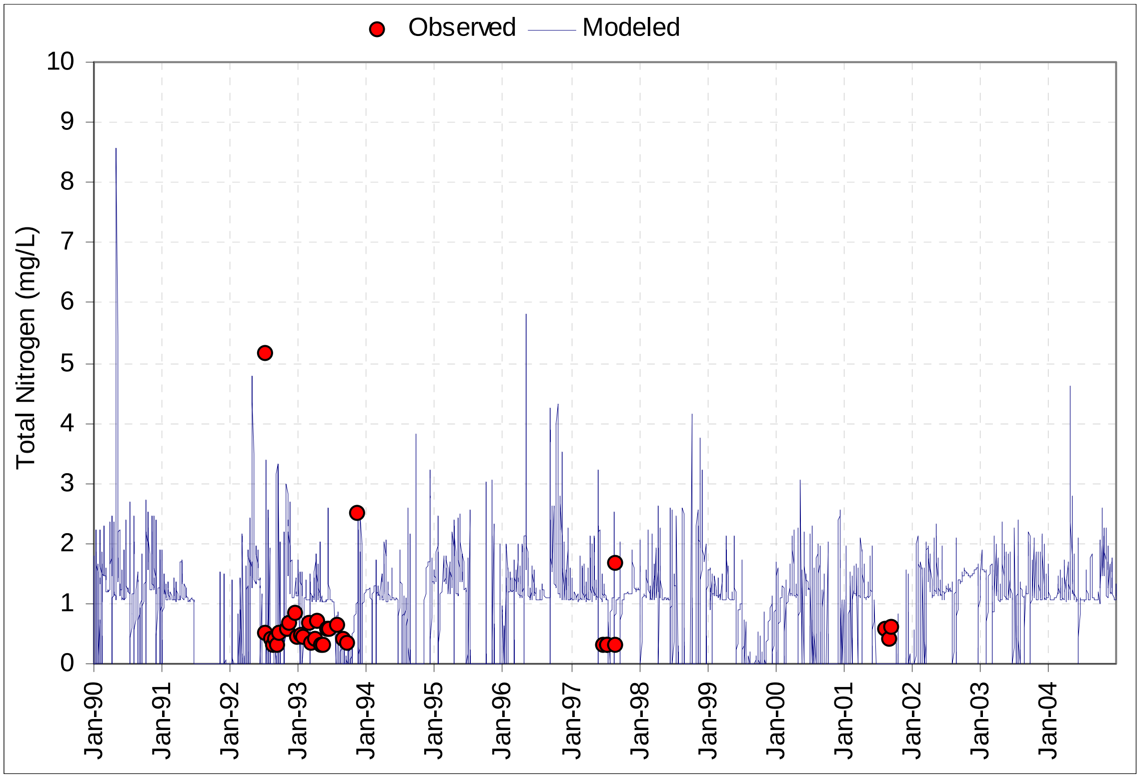

Figure 3-36. Observed versus Simulated Total Nitrogen at Station B01S36

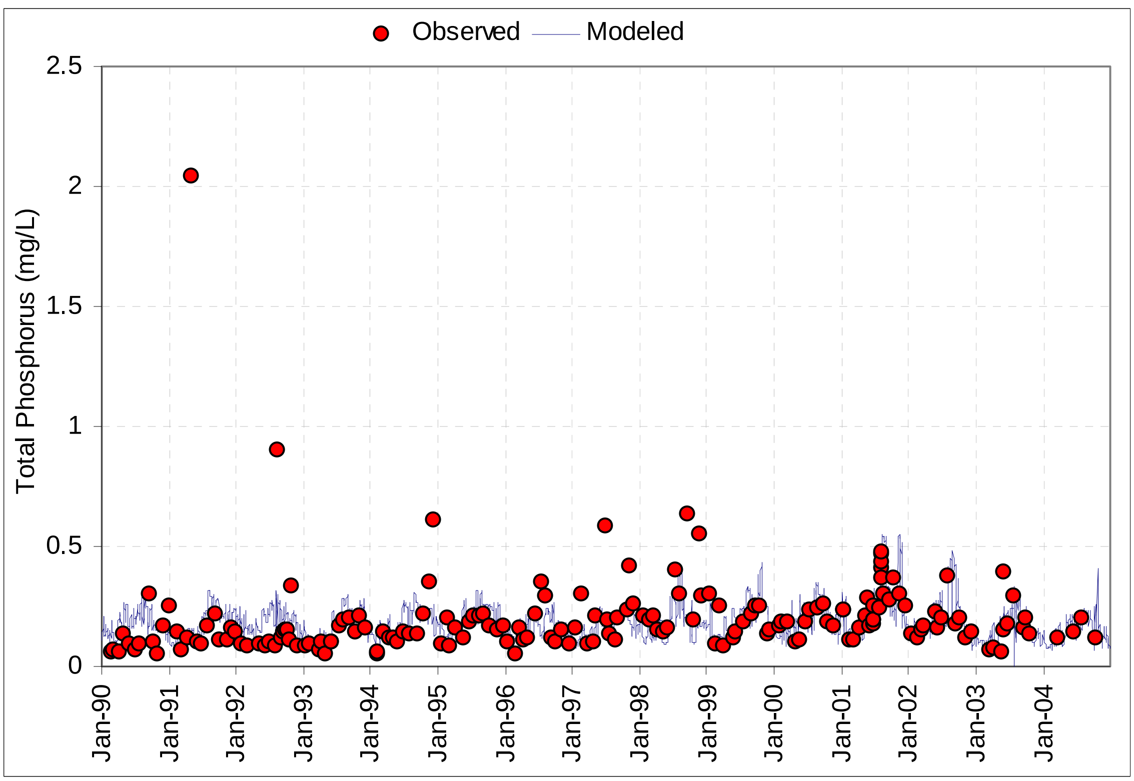

Figure 3-37. Observed versus Simulated Total Phosphorus at Station 501510

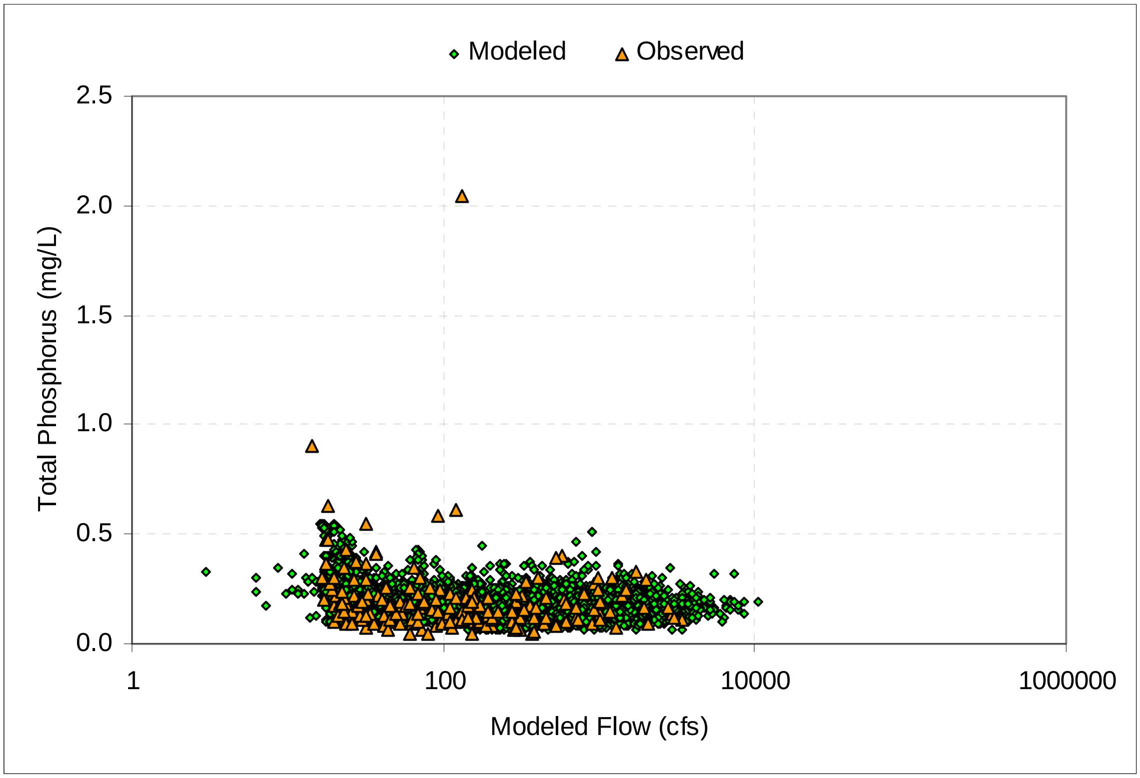

Figure 3-38. Observed and Simulated Total Phosphorus versus Simulated Flow at Station 501510

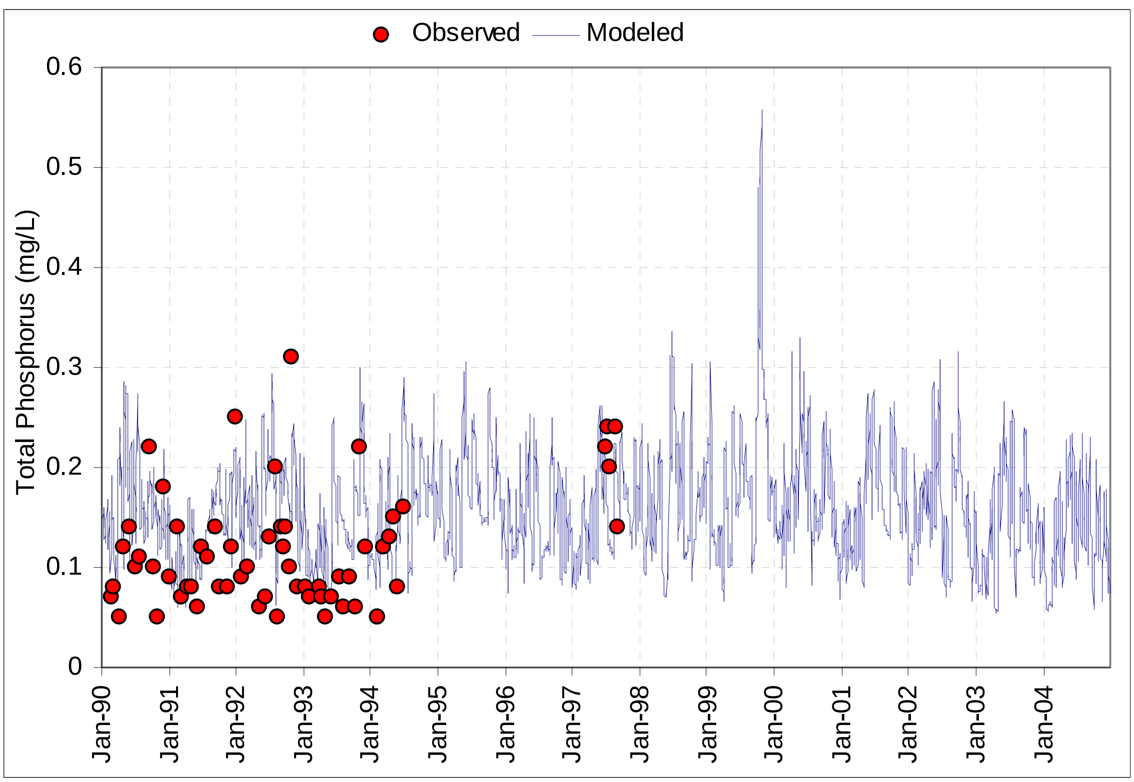

Figure 3-39. Observed versus Simulated Total Phosphorus at Station 501520

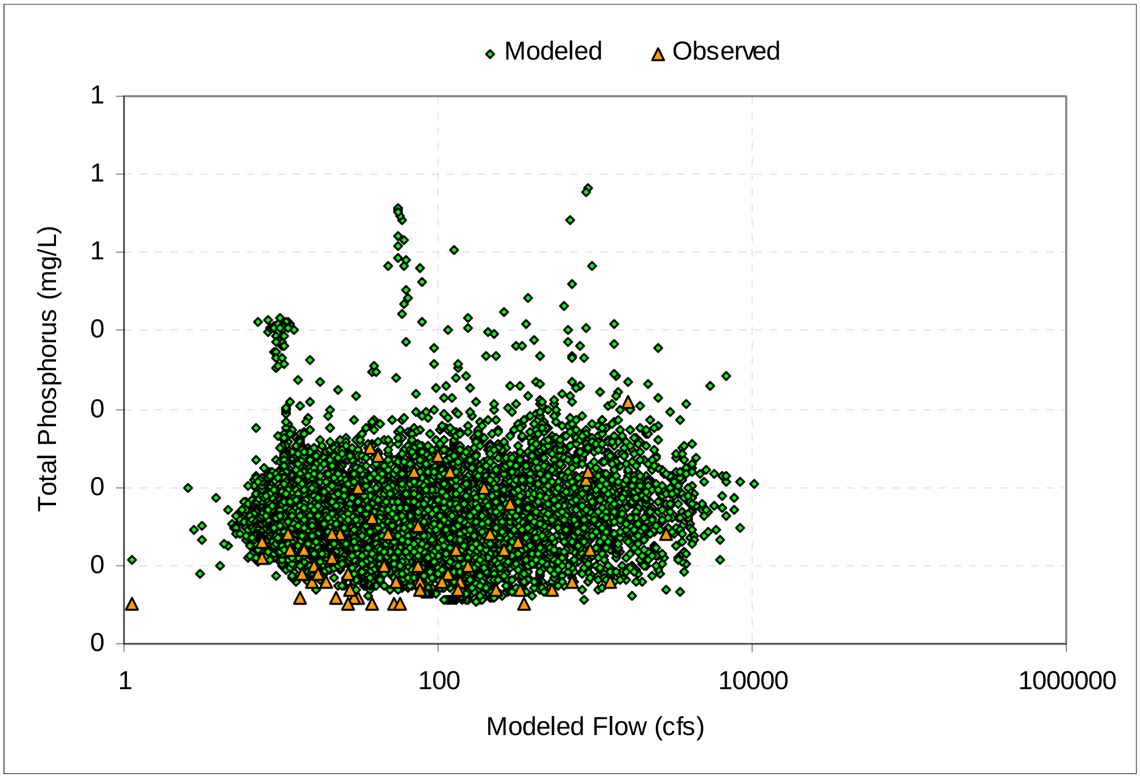

Figure 3-40. Observed and Simulated Total Phosphorus versus Simulated Flow at Station 501520

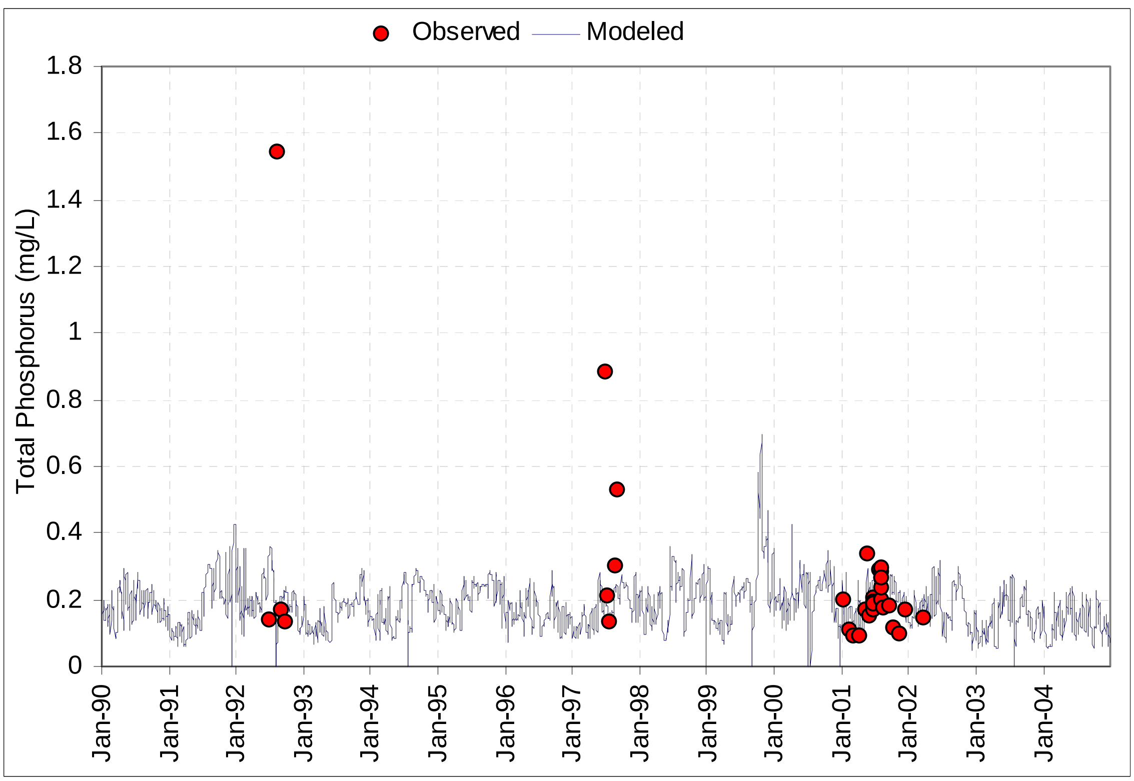

Figure 3-41. Observed versus Simulated Total Phosphorus at Station B01S11

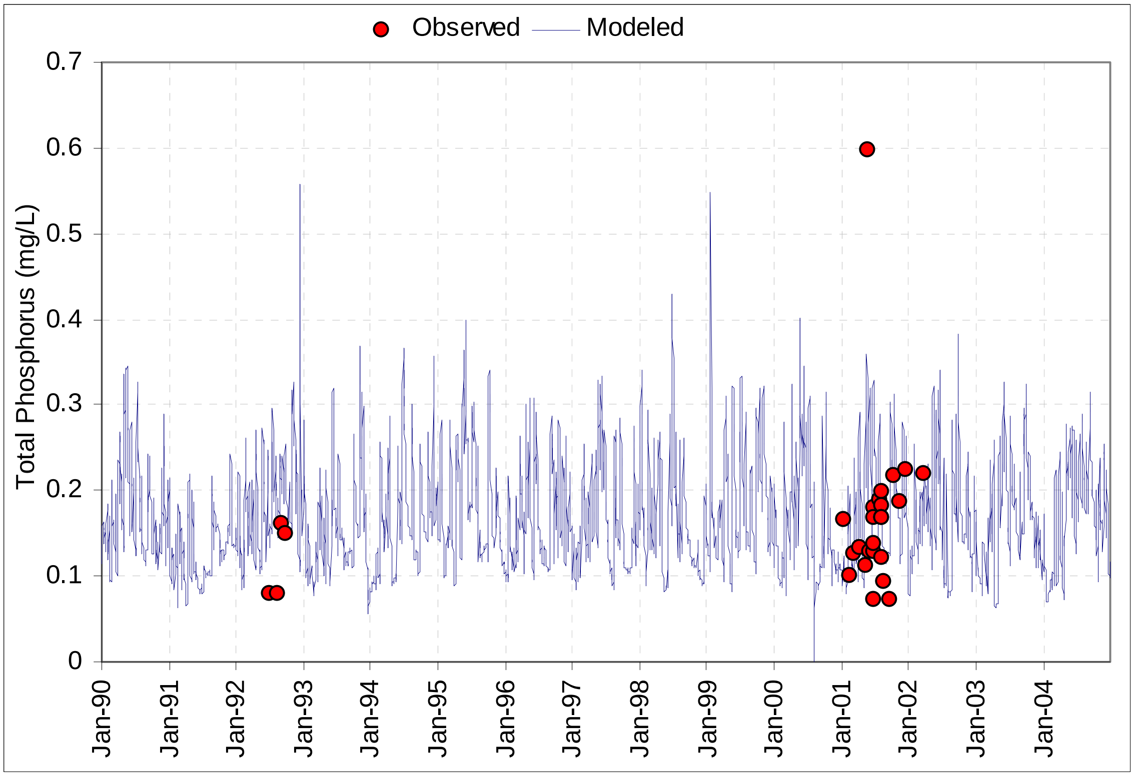

Figure 3-42. Observed versus Simulated Total Phosphorus at Station B01S13

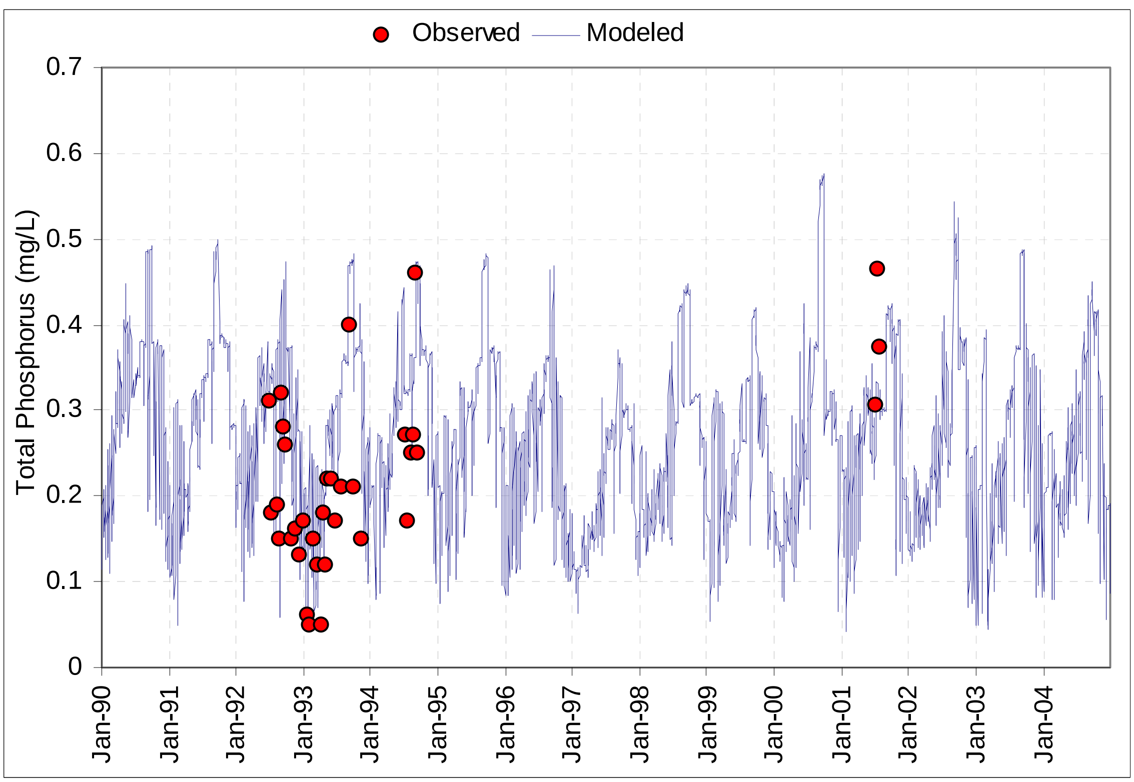

Figure 3-43. Observed versus Simulated Total Phosphorus at Station B01PO2

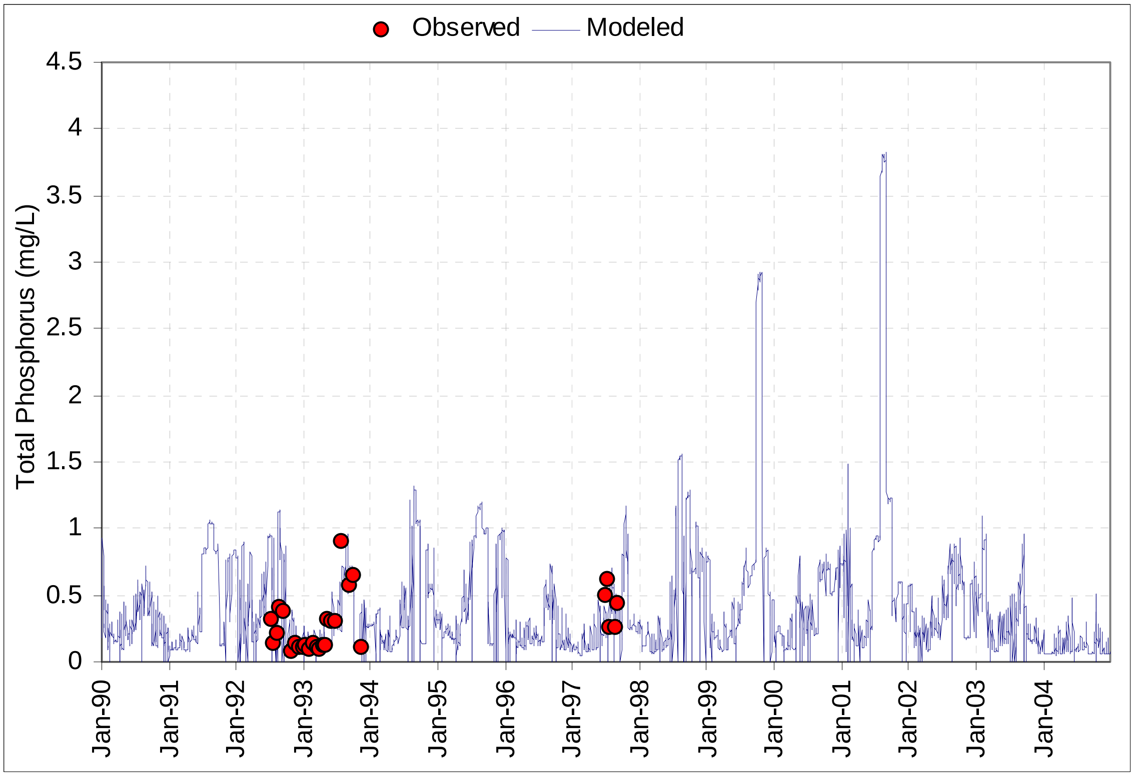

Figure 3-44. Observed versus Simulated Total Phosphorus at Station B01W10

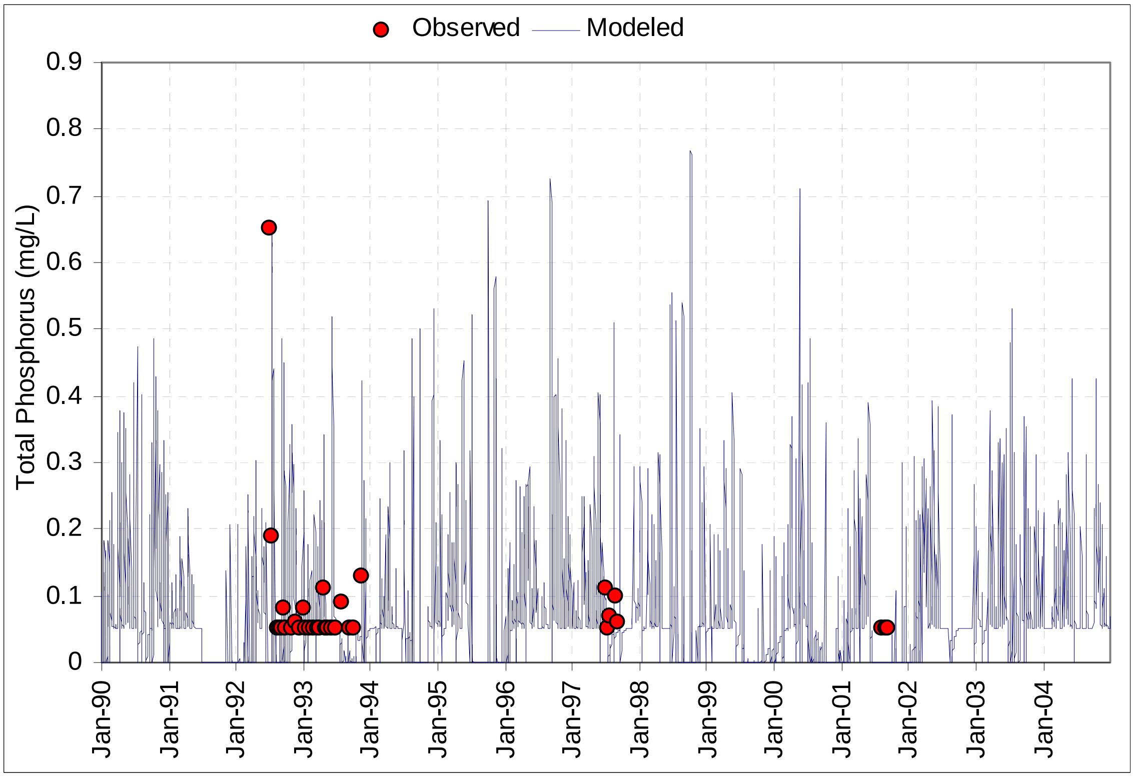

Figure 3-45. Observed versus Simulated Total Phosphorus at Station B01S36

Table 3-6. Statistical Comparison of Paired Observed and Simulated Water Quality Data

	TSS (mg/L)	NH4 (mg/L)	TKN (mg/L)	NO_2+NO_3 (mg/L)	Total N (mg/L)	Total P (mg/L)
Station 501520 Observed						
Minimum	5	0.1	0.2	0.1	0.6	0.05
Median	16	0.1	0.7	1.4	2.0	0.10
Average	31	0.1	0.7	1.8	2.5	0.12
Maximum	236	0.4	1.2	9.7	10.9	0.31
Station 501520 Simulated (Subbasin 26)						
Minimum	2	0.0	0.4	0.4	0.8	0.07
Median	14	0.1	1.0	1.2	2.2	0.14
Average	25	0.1	1.1	1.5	2.6	0.15
Maximum	136	0.3	2.6	4.1	6.5	0.27
Station 501510 Observed						
Minimum	5	0.1	0.1	1.0	1.8	0.05
Median	14	0.1	0.9	5.2	6.1	0.16
Average	33	0.1	0.9	6.8	7.8	0.20
Maximum	288	1.5	2.0	35.1	36.2	2.04
Station 501510 Simulated (Subbasin 39)						
Minimum	3	0.0	0.4	0.7	1.2	0.07
Median	18	0.2	2.8	4.8	7.7	0.18
Average	32	0.3	4.1	7.2	11.3	0.20
Maximum	242	0.9	12.0	27.3	39.3	0.54
Station B01S11 Observed						
Minimum	5	0.1	0.5	0.1	0.9	0.09
Median	10	0.1	0.9	0.9	1.7	0.18
Average	15	0.1	0.9	1.6	2.5	0.26
Maximum	45	0.3	1.4	3.7	4.8	1.54
Station B01S11 Simulated (Subbasin 30)						
Minimum	1	0.1	0.5	0.8	1.3	0.09
Median	6	0.1	0.9	1.0	1.8	0.22
Average	13	0.1	1.1	1.2	2.2	0.22
Maximum	79	0.4	3.3	3.4	6.7	0.36

	TSS (mg/L)	NH4 (mg/L)	TKN (mg/L)	NO_2+NO_3 (mg/L)	Total N (mg/L)	Total P (mg/L)
Station B01S36 Observed						
Minimum	5	0.1	0.2	0.1	0.3	0.05
Median	5	0.1	0.3	0.1	0.4	0.05
Average	24	0.1	0.3	0.4	0.7	0.08
Maximum	472	0.1	0.6	4.9	5.1	0.65
Station B01S36 Simulated (Subbasin 32)						
Minimum	0	0.0	0.0	0.0	0.0	0.00
Median	10	0.0	0.3	0.7	1.1	0.05
Average	15	0.0	0.4	0.6	1.0	0.10
Maximum	77	0.0	2.3	1.3	3.2	0.59
Station B01P02 Observed						
Minimum	5	0.1	0.4	0.6	1.0	0.05
Median	8	0.1	0.8	5.8	6.5	0.20
Average	35	0.1	0.8	6.9	7.8	0.22
Maximum	508	1.0	1.6	21.8	22.6	0.46
Station B01P02 Simulated (Subbasin 35)						
Minimum	0	0.0	0.2	1.1	1.6	0.07
Median	1	0.4	2.3	10.5	12.7	0.29
Average	3	0.5	2.2	9.4	11.6	0.30
Maximum	43	1.2	4.4	19.2	23.6	0.47

A visual inspection of the calibration graphs together with the statistics indicates that the model provides a reasonable description of the significant water quality processes occurring throughout the watershed. Results at Station 501510 are particularly significant because this station has the most observed data and represents the largest drainage area. Observed pollutant concentrations at this station are within the range of simulated concentrations and most seasonal trends are reproduced. Further, the model performs equally well during the early, wetter period (1990-1997) and the later, drier period (1998-2004). Both baseflow and high flow conditions appear to be reasonably simulated by the model.

There are some discrepancies evident in the simulation for Station 501510. In particular, several high total phosphorus concentrations (> 0.5 mg/L) and nitrite+nitrate concentrations (> 20 mg/L) are not reproduced by the model. Examination of the data shows that all of these high-concentration anomalies are associated with very low to moderately low flow conditions. This station is immediately downstream of the major point source discharge at Elyria, which is specified by monthly average concentrations. Occasional high concentrations instream during low flow conditions thus likely represent variability in the Elyria discharge.

Station 501520 is also on the mainstem, but is upstream of Elyria, although affected by several smaller point source discharges further up in the watershed. Anomalously high phosphorus concentrations are not seen at this station; indeed, the model appears to over-predict total phosphorus by a small amount.

For all stations affected by point source discharges, simulation of total nitrogen is more problematic than other nutrients. This occurs because discharge monitoring does not report organic nitrogen, which is a major component of total nitrogen. Instead, the organic nitrogen discharge is represented by a constant concentration assumption.

Some discrepancies between model and observations are evident at Station B01P02 on Plum Creek. Here the model appears to underestimate sediment while overestimating nutrient concentrations. The nutrient anomalies may reflect in part poor characterization of the Oberlin discharge, while the differences in sediment predictions may be due to the specification of stream channel dimensions, resulting in an overprediction of deposition and underprediction of scour.

Despite these small discrepancies, model performance in general is good across the whole suite of monitored sites. In sum, the model calibration and validation appear acceptable for use in nutrient and suspended sediment TMDLs.

4.0 Scenario Screening

The Black River TMDLs for streams upstream of the lacustuary area will be based on meeting monthly average concentration targets for stream TSS, NO_3, and TP. In addition, the loading of nutrients to the Black River lacustuary is of interest to address DO problems in those reaches.

The calibrated SWAT model has been applied to test seven types of potential management options. Each management option was considered alone in one of the seven scenarios. Results are presented for subbasins 8 and 9 (the downstream portions of the East and West Branch of the Black River, just above their confluence and the domain of the CE-QUAL-W2 model of the lacustuary), and for subbasin 24 (upstream on the East Branch, near Lodi). Results are compared to one another and to the calibrated model run ("Baseline") in terms of total annual load and the frequency in which preliminary Ohio EPA monthly average concentration criteria are predicted to be exceeded.

A final management approach for the Black River will likely combine several of the more promising individual management options. The scenario runs provide information on the potential benefits associated with the individual management options.

4.1 Single-focus Management Scenarios

In addition to the Baseline, the following seven single-focus scenarios were evaluated:

Scenario 1 – Agricultural Tillage

The dominant corn-soybean crop rotation in use in the Black River watershed already includes a conservation tillage approach, with no tillage between the corn and soy phases. This scenario investigated going to a very low tillage approach on the corn-soy rotation, with only one conservation tillage pass prior to the corn phase, to maximize surface residue and reduce erosion. The scenario is based on recommended approaches for no-till systems in Rehm et al. (2002) and FAPRI (2006). Fertilizer applications are assumed unchanged, but all fertilizer application is assumed to occur via subsurface banding at seed depth (e.g., with a Coulter and knife assembly). Runoff Curve Numbers for the fallow period were reduced consistent with NRCS guidance.

Scenario 2 – Increased Riparian Buffers

Properly designed riparian buffers provide an effective strategy for removing pollutants in surface runoff from agricultural land. This scenario simulates use of 15' filter strips, as recommended by USDA for 1-10 percent slopes, adjacent to all crop land (both corn-soy and alfalfa).

Scenario 3 – Manage Tile Drainage for Denitrification

The Black River watershed contains significant amounts of tile drainage. Controlled tile drainage, in which the water level is raised in the outlet and in the soil profile, is an effective means to control nitrogen loading by providing an increased anaerobic zone for denitrification (Skaggs et al., 1994; Sands, 2001). In this scenario, control of depth to water table to encourage anaerobic denitrification is achieved by reducing the depth to drain (DDRAIN, in .hru file) to 300 mm.

Scenario 4 – Eliminate Failing Septic Tanks

The Black River SWAT model includes loads from both properly functioning and failing septic tanks, input as point sources. This scenario simulated elimination of failing septic tanks by re-estimating loading with failure rate changed to zero.

Scenario 5 – Reduce Streambank Erosion

Many segments of the Black River watershed are subject to channel erosion. This scenario evaluated the benefits of reducing channel erosion by improving channel cover. In the model, the CH_COV parameter representing relative sensitivity to channel erosion was set by using the percent of eroding bank estimated by USAED Buffalo (1977). For this scenario, CH_COV (in the .rte files) was reduced to 0.01 in all basins.

Scenario 6 – Better Fertilizer Management

This scenario involves reducing the P content of agricultural fertilizer by 20 percent from existing levels, for both the corn-soy and alfalfa crop rotations.

Scenario 7 – Point Source Controls

A significant amount of the nutrient load in the Black River derives from wastewater treatment plant discharges – although the largest are in the lacustuary area. This scenario evaluated a TP limit of 0.5 mg/L and TN of 10 mg/L for the wastewater treatment plants. The scenario was developed as a limit, rather than fixed allocation, over the 1988-2004 simulation period. Specifically, if the reported discharge concentration was greater than the scenario limit concentration during a given month, it was reduced to the limit concentration. If the reported discharge concentration was less than the scenario limit concentration during a given month it was left at the lower reported value.

4.2 Single-focus Scenario Results

Average annual loading for the 16 year simulation period is summarized in Table 4-1. In general, riparian buffer strips are predicted to provide the greatest reduction in loading of all pollutants. Reductions associated with tillage changes are relatively small, primarily because the existing tillage practices already maintain high residue levels. Reducing channel erosion has a large impact on solids loads, but this does not result in any predicted change in NO_3 or TP loads because SWAT does not directly simulate the nutrient content of eroded channel sediment. Various options such as tile drainage changes, septic system management, fertilizer management, and point source limits affect nutrient loads, but not sediment. Scenarios 3 (tile drain management) and 4 (elimination of failing septic systems) are predicted to have little impact on the overall pollutant loading.

Table 4-1. Average Annual Loads for Single-focus Scenarios

Scenario	TSS (tons/yr)	NO_3 (kg/yr)	TP (kg/yr)
Subbasin 8			
B	12,726	148,131	27,411
1	12,347	144,182	24,130
2	10,874	97,036	13,020
3	12,765	147,184	26,654
4	12,726	148,101	27,366
5	8,576	148,131*	27,411*
6	12,732	148,222	24,278
7	12,726	137,631	26,985
Subbasin 9			
B	14,385	167,075	31,984
1	14,141	164,371	28,852
2	12,914	112,661	16,200
3	14,532	166,471	30,885
4	14,385	167,043	31,949
5	8,845	167,075*	31,984*
6	14,388	167,247	28,465
7	14,385	155,756	30,614
Subbasin 24			
B	6,200	72,990	18,568
1	6,017	73,413	18,095
2	3,794	52,511	9,243
3	6,035	73,769	18,122
4	6,200	72,986	18,549
5	6,034	72,990*	18,568*
6	6,202	73,030	16,972
7	6,200	70,630	17,804

*SWAT does not simulate the effects of reduced channel erosion on nutrient loads. Therefore, the nutrient loads from Scenario 5 may be lower than estimated by the model.

Table 4-2 summarizes the monthly concentration results. It will be noted here that Scenario 7 (WWTP nutrient limits) has a much greater effect on nutrient concentrations than on nutrient loads. This occurs because point sources form a significant amount of the total load present under low flow conditions.

Finally, Table 4-3 summarizes the average number of months per year with average concentrations exceeding the preliminary Ohio EPA criteria.

Table 4-2. Average of Monthly Concentration (1989-2004) for Single-focus Scenarios

Scenario	TSS (mg/L)	NO_3 (mg/L)	TP (mg/L)
Subbasin 8			
B	25.46	1.996	0.157
1	25.60	1.959	0.138
2	23.72	1.743	0.090
3	25.62	1.970	0.152
4	25.46	1.994	0.155
5	16.31	1.996	0.157
6	25.48	1.996	0.140
7	25.46	1.391	0.148
Subbasin 9			
B	22.53	1.211	0.175
1	22.44	1.221	0.157
2	21.19	0.970	0.110
3	22.41	1.213	0.169
4	22.53	1.210	0.174
5	14.80	1.211	0.175
6	22.54	1.211	0.158
7	22.53	0.891	0.137
Subbasin 24			
B	16.62	1.127	0.177
1	16.07	1.108	0.164
2	11.91	0.961	0.118
3	15.83	1.161	0.171
4	16.62	1.126	0.176
5	16.08	1.127	0.177
6	16.63	1.127	0.166
7	16.62	1.000	0.139

Table 4-3. Average Number of Months per Year Greater than OEPA Target Concentrations for Single-focus Scenarios

Scenario	Months/Year > 41 mg/L TSS	Months/Year > 1.5 mg/L NO_3	Months/Year > 0.17 mg/L TP
Subbasin 8			
B	2	8	4
1	2	8	2
2	2	7	<1
3	2	8	4
4	2	8	4
5	<1	8	4
6	2	8	2
7	2	4	3
Subbasin 9			
B	1	2	7
1	1	2	4
2	1	1	1
3	1	2	6
4	1	2	6
5	<1	2	7
6	1	2	4
7	1	1	3
Scenario	**Months/Year > 29 mg/L TSS**	**Months/Year > 1.0 mg/L NO_3**	**Months/Year > 0.1 mg/L TP**
Subbasin 24			
B	2	5	10
1	2	5	10
2	<1	3	6
3	2	6	10
4	2	5	10
5	2	5	10
6	2	5	10
7	2	4	9

4.3 Allocation Scenarios

None of the single-focus scenarios achieve full compliance with OEPA target concentrations. (Full compliance is defined as achieving a value less than 1 for the average number of months per year greater than the Ohio EPA target.) Thus, a combination of several of the more promising management options needs to be pursued to achieve management options.

An initial draft allocation scenario (Combo1) was constructed by combining the management options tested in Scenario 2 (Increased Riparian Buffers), Scenario 4 (Eliminate Failing Septic Tanks), and Scenario 7 (Point Source Controls). This combination resulted in a marked improvement in water quality predictions, but does not achieve full compliance (less than one month per year) for any of the three constituents at all locations (see Table 4-6).

A second allocation scenario (Combo2) was then created by expanding Combo1. In addition to the three components of Combo1, the management option from Scenario 5 (Reduce Streambank Erosion) was included to meet TSS targets. To further control total phosphorus and nitrate at the subbasin 24 compliance point, the riparian buffer width for agriculture was increased from 15 to 20 feet in the upstream subbasins (4, 22, 24, 31, 32, 63, and 67). Finally, nitrate concentrations were further reduced by changing the point source limit from 10 mg/L to 9 mg/L.

Annual average loads and concentrations for the allocation runs are provided in Table 4-4 and Table 4-5. Table 4-6 displays the number of months per year exceeding Ohio EPA targets, and shows that the Combo2 scenario achieves water quality standards at the compliance points. The loads associated with Combo2 in Table 4-4 then provide the average annual loads consistent with attaining standards. To complete the TMDL, these results must be interpreted into total maximum *daily* load limits, consistent with recent court rulings.

Table 4-4. Average Annual Loads for Allocation Scenarios

Scenario	TSS (tons/yr)	NO_3 (kg/yr)	TP (kg/yr)
Subbasin 8			
Combo1	11,250	85,080	12,477
Combo2	6,632	83,987	12,477
Subbasin 9			
Combo1	13,257	101,517	14,845
Combo2	6,976	98,374	14,101
Subbasin 24			
Combo1	13,257	49,333	8,367
Combo2	6,976	47,166	7,549

Table 4-5. Average of Monthly Concentration (1989-2004) for Allocation Scenarios

Scenario	TSS (mg/L)	NO_3 (mg/L)	TP (mg/L)
Subbasin 8			
Combo1	24.38	0.922	0.065
Combo2	13.85	0.878	0.065
Subbasin 9			
Combo1	20.45	0.670	0.070
Combo2	11.70	0.637	0.067
Subbasin 24			
Combo1	11.86	0.746	0.070
Combo2	10.53	0.712	0.066

Table 4-6. Average Number of Months per Year Greater than OEPA Target Concentrations for Allocation Scenarios

Scenario	Months/Year > 41 mg/L TSS	Months/Year > 1.5 mg/L NO_3	Months/Year > 0.17 mg/L TP
Subbasin 8			
Combo1	2	1	<1
Combo2	<1	<1	<1
Subbasin 9			
Combo1	1	<1	<1
Combo2	<1	<1	<1
Subbasin 24			
Combo1	<1	1	1
Combo2	<1	<1	<1

5.0 Literature Cited

Arnold, J.G., P.M. Allen, and G.T. Bernhardt. 1993. A comprehensive surface-groundwater flow model. *Journal of Hydrology*, 142: 47-69.

Census. 2000. United States Census 2000. U.S. Census Bureau. Washington, D.C.

DiLuzio, M., R. Srinivasan, and J. Arnold. 2001. ArcView Interface for SWAT2000: User's Guide. Blackland Research Center, Texas Agricultural Experiment Station, Temple, Texas.

FAPRI. 2006. Miami Creek Watershed, Computer Based Evaluation of the AgNPS-SALT Project. FAPRI-UMC Report #18-06. Food and Agricultural Policy Research Institute, University of Missouri, Columbia, MO.

Green, W.H. and G.A. Ampt. 1911. Studies on soil physics, 1: the flow of air and water through soils. *Journal of Agricultural Sciences*, 4:11-24.

Haith, D. A., R. Mandel, and R. S. Wu. 1992. Generalized Watershed Loading Functions Version 2.0 User's Manual, Cornell University, Ithaca, New York.

Inamdar, S. 2004. Sediment Modeling for the Buffalo River Watershed. Great Lakes Center, Buffalo State College, Buffalo, New York.

Jha, M., P.W. Gassman, S. Secchi, R. Gu and J. Arnold. 2004. Effect of watershed subdivision on SWAT flow, sediment, and nutrient predictions. *Journal of the American Water Resources Association*, 40: 811-825.

Lumb, A.M., R.B. McCammon, and J.L. Kittle, Jr. 1994. Users Manual for an Expert System (HSPEXP) for Calibration of the Hydrological Simulation Program–Fortran. Water-Resources Investigations Report 94-4168, U.S. Geologic Survey, Reston, Virginia.

Mandel, R. 1993. The Impact of Septic Systems on Surface Water Quality. M.S. diss., Cornell University, Ithaca, New York.

Mein, R.G. and C.L. Larson. 1973. Modeling infiltration during a steady rain. *Water Resources Research*, 9:384-394.

Nearing, M.A., B.Y. Lui, L.M. Risse, and X. Zhang. 1996. Curve Number and Green-Ampt effective hydraulic conductivities. *Water Resources Bulletin* 32:125-136.

Neitsch, S.L., J.G. Arnold, J.R. Kiniry, J.R. Williams, and K.W. King. 2002. Soil and Water Assessment Tool, Theoretical Documentation, Version 2000. Grassland, Soil and Water Research Laboratory, Agricultural Research Service, Temple, Texas.

NRCS. 1972. Hydrology Guide for Use in Watershed Planning. National Engineering Handbook, Section 4: Hydrology, Supplement A. U.S. Department of Agriculture, Natural Resources Conservation Service. Washington, D.C.

Ohio Environmental Protection Agency (OEPA). 1999. Association Between Nutrients, Habitat, and the Aquatic Biota in Ohio Rivers and Streams. OEPA Technical Bulletin MAS/1999-1-1. Columbus, Ohio.

Rehm, G., G. Randall, and S. Evans. 2002. Fertilizer Management for Corn Planted in Ridge-Till or No-Till Systems. FO-06704-GO. University of Minnesota Extension, St. Paul, MN.

Sands, G. 2001. Feasibility of Controlled Drainage for Mitigating Nutrient Loss from Tile Drainage Systems in South Central Minnesota. Water Resources Center, University of Minnesota Extension, St. Paul, MN. http://wrc.umn.edu/research/competitivegrants/2001sands.html.

Skaggs, R.W., M.A. Breve, and J.W. Gilliam. 1994. Hydrologic and water quality impacts of agricultural drainage. *Critical Reviews in Environmental Science and Technology*, 24:1-32.

USAED Buffalo. 1977. Assessment of Streambank Erosion for Major Streams of the Buffalo District. U.S. Army Engineer District, Buffalo, Buffalo, New York.

USDA. 1995. State Soil Geographic (STATSGO) Data Base Data Use Information. Miscellaneous Publication Number 1492. U.S. Department of Agriculture, Natural Resources Conservation Service, Fort Worth, Texas.

Vitosh, M.L., J.W. Johnson, D.B. Mengel, 2002. Tri-State Fertilizer Recommendations for Corn, Soybeans, Wheat, and Alfalfa. Purdue University Cooperative Extension Service. West Lafayette, Indiana.

Williams, J.R. 1975. Sediment-yield prediction with universal equation using runoff energy factor. pp. 244-252 *in* Present and Prospective Technology for Predicting Sediment Yield and Sources: Proceedings of the Sediment-Yield Workshop, USDA Sedimentation Lab, Oxford, MS, November 28-30, 1972. ARS-S-40.

Williams, J.R. 1995. Chapter 25, The EPIC Model. pp. 909-1000 *in* Computer Models of Watershed Hydrology. Water Resources Publications, Highlands Ranch, Colorado.