Appendix C: Application of the Soil Water Assessment Tool (SWAT) to the Wabash River Watershed, Ohio

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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. 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 homogenous subwatersheds. The model uses a 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 Wabash River watershed in Ohio to support the development of total maximum daily loads (TMDLs) for nutrients and sediments. This appendix provides an overview of the model and a description of the modeling process.

Hydrology

The hydrology component of SWAT is based on the water balance equation. A distributed curve number is generated for the computation of overland flow runoff volume, given by the standard Soil Conservation Service (SCS, now the Natural Resources Conservation Service (NRCS)) runoff equation (USDA, 1986). The curve number method is empirically based and relates runoff potential to land use and soil characteristics. The curve number method combines infiltration losses, depression storage, and interception into a potential maximum storage parameter called S. Runoff depth is given by the following set of empirical relationships:

$$Q = \frac{(P - 0.2S)\text{^}2}{P + 0.8S}$$

where Q is the accumulated runoff depth or rainfall excess (inches), P is the accumulated precipitation (inches), and S is a maximum soil water retention parameter given by

$$S = \frac{1000}{CN} - 10$$

where CN is known as the curve number.

The equation above indicates that precipitation, P, must exceed 0.2S before any runoff is generated. Furthermore, this equation yields a depth of runoff. To calculate runoff volume, the computed depth must be multiplied by area.

The curve number indicates the runoff potential of an area for the combination of land use characteristics and soil type. Higher curve numbers translate into greater 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 4000 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 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 dryer antecedent conditions (Condition I) and for wetter antecedent conditions (Condition III) are found in Table 2.

Table 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. 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 soil 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 1 displays the pathways for water movement within SWAT.

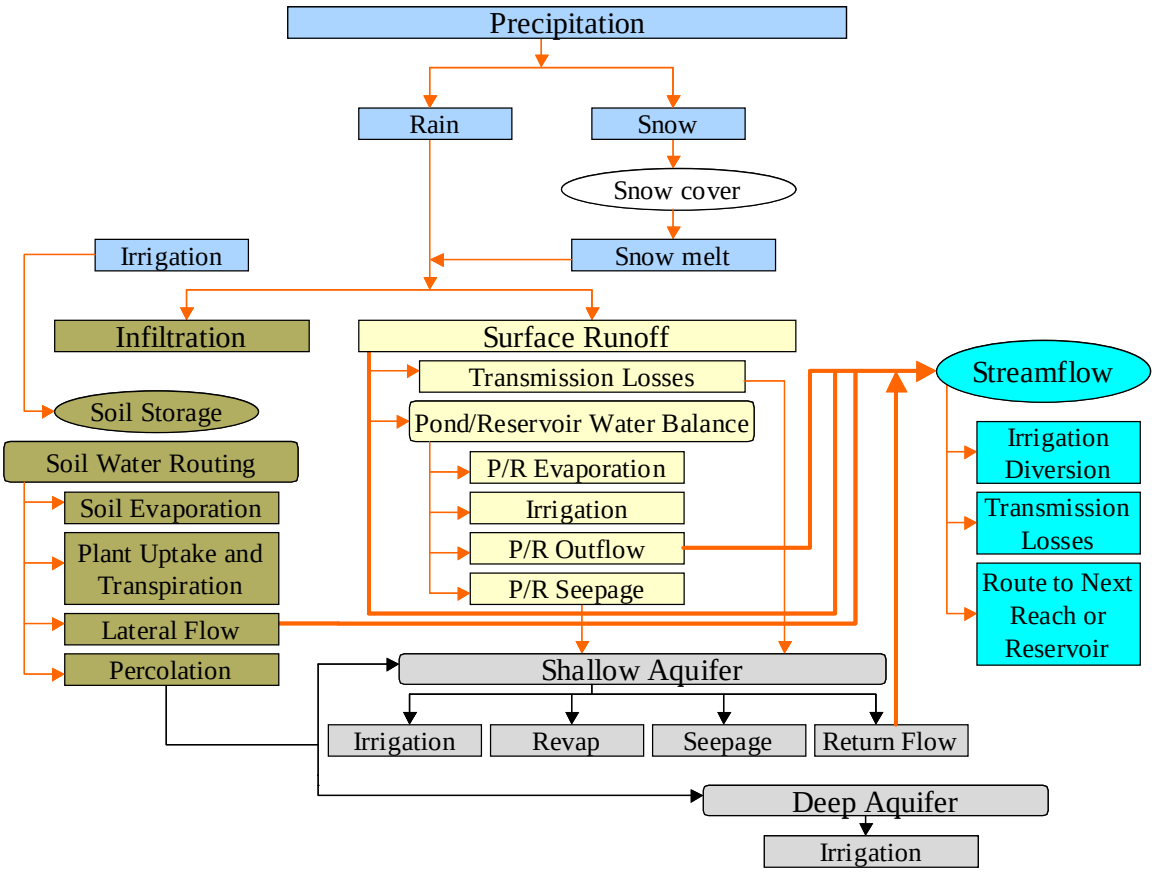

Figure 1. Pathways for water movement within SWAT.

An important consideration in modeling the hydrology of the Wabash River watershed is that agricultural land in the basin is heavily tiled, as many of the soils are naturally poorly drained. The presence of tile drains has altered the natural hydrology of the area. 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 ability for pollutants to be naturally filtered through the process of groundwater infiltration.

It is not feasible to simulate individual tile drain systems at the large basin scale with currently available watershed scale models and neither the location nor the total density of tile drainage is known throughout the basin. In most areas, only the ditches are documented in spatial coverages, and the extent of private tile drains is known only for limited areas. Furthermore, the SWAT model has limited routines for the explicit representation of tile.

To address these factors several model parameters were adjusted to simulate the effects of tiling on watershed hydrology. For example, NRCS curve numbers for tiled soils were set lower than for non-tiled soils to simulate the effect of greater infiltration. The storage routing flow coefficient within SWAT was also 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 below).

Upland Erosion

Another important model parameter obtained from the soils database is the Universal Soil Loss Equation (USLE) erodibility factor, k. The erodibility factor is an empirically derived unitless value reflecting a soil's inherent erodibility. The USLE is used in SWAT to estimate initial soil detachment and upland erosion. Sediment yield used for in-stream transport is determined from the Modified Universal Soil Loss Equation (MUSLE) (Arnold, 1992). For sediment routing in SWAT, deposition calculation is based on fall velocities of various sediment sizes. Rates of channel degradation are determined from Bagnold's (1977) stream power equation. Stream power is a useful index for describing the erosive capacity of streams, and has been related to the shape of the longitudinal profile, channel pattern, the development of bed forms, and sediment transport. As stream slopes become steeper and/or velocities increase, stream power increases as does stream erosivity.

Sediment size is estimated from the primary particle size distribution (Foster et al.,1980) for soils that the SWAT model obtains from the State Soil Geographic (STATSGO)(USDA, 1995) database. Stream power is also accounted for in the sediment routing routine, and is used for calculation of re-entrainment of loose and deposited material in the system until all of the material has been removed.

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 Wabash River watershed. The interface requires digital elevation data (DEM), land use/land cover, soils, and meteorological data. Thirty-meter DEM representing 7.5 minute U.S. Geological Survey (USGS) quadrangles were downloaded from GEOCommunity <www.geocomm.com>, the current distribution center for USGS DEM. Watershed and subbasin delineation is based on a DEM of the watershed coupled with a "burn-in" of EPA's National Hydrography Database 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 Wabash River watershed, the USGS 14-digit Hydrologic Unit Code (HUC)

served as the basis for subbasin definition. Additional subbasins were delineated to obtain model output at key locations (e.g., sampling stations). This resulted in a total of 54 subbasins as shown in Figure 2.

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. The land cover for the watershed area was extracted from the Multi-Resolution Land Characterization database for the state of Ohio (MRLC, 1992). This database was derived from satellite imagery taken during the early 1990s and is the most current detailed land use data known to be available for the watershed. Each 100-foot by 100-foot pixel contained within the satellite image is classified according to its reflective characteristics.

The MRLC land cover data must be reclassified to equal land cover and land use classes used by the SWAT2000 model. 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.

The 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 the entire watershed. 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 the land uses is reapportioned so that 100 percent of the land area in the subbasin is included in the simulation.

The ArcView SWAT interface user's manual suggests that a 20 percent land use threshold and a 10 percent soil threshold are adequate for most modeling applications. For the Wabash River watershed, a 10 percent land use threshold and a 10 percent soil threshold were employed. These threshold values resulted in a detailed land use and soil SWAT database, containing many HRUs, which in turn represent a very heterogeneous watershed. Figure 2 shows the SWAT land use distribution in the watershed. Table 3 lists the SCS curve numbers used in the Wabash River watershed. Table 5 summarizes the land use characteristics of the watershed.

Table 3. SCS Curve Numbers (CN-II) for Land Use and Land Cover in the Wabash River Watershed.

SWAT Land Use/Land Cover Classification	SCS Curve Numbers for Land Use and Hydrologic Soil Group			
	A	B	C	D
Water	100	100	100	100
Low Density Urban Residential	46	65	77	82
High Density Urban Residential	63	77	85	88
Urban Commercial	89	92	94	96
Deciduous Forest	45	66	77	83
Pasture	49	69	79	84
Corn/Soybean	67	78	85	89
Grasslands	31	59	72	79
Forested Wetlands	45	66	77	83

Figure 2 and Table 4 show that row crops (corn and soybean) are by far the most dominant land use in the watershed, representing nearly 81 percent of the total land use. It is assumed that corn and soybean crops are rotated on an annual basis. Pasture is the second largest land use, representing 11 percent of the total watershed. Deciduous forest accounts for nearly 6 percent. All other land use classes each represent less than 1 percent of total land use/land cover in the watershed.

Several USLE parameters are used in AVSWAT, including the K-factor, length-slope factor, C-factor, and the P-factor. The K-factor and length-slope factors were derived from the STATSGO soils database and topographic data, respectively, and are automatically determined in AVSWAT. Figure 3 displays the K-factors by subbasin. For the Wabash River watershed, C-factors for corn/soybean and pasture were assumed to be 0.20 and 0.003, respectively and the P-factor was set to 1.0. These values were chosen based on recommendations within the SWAT user's manual.

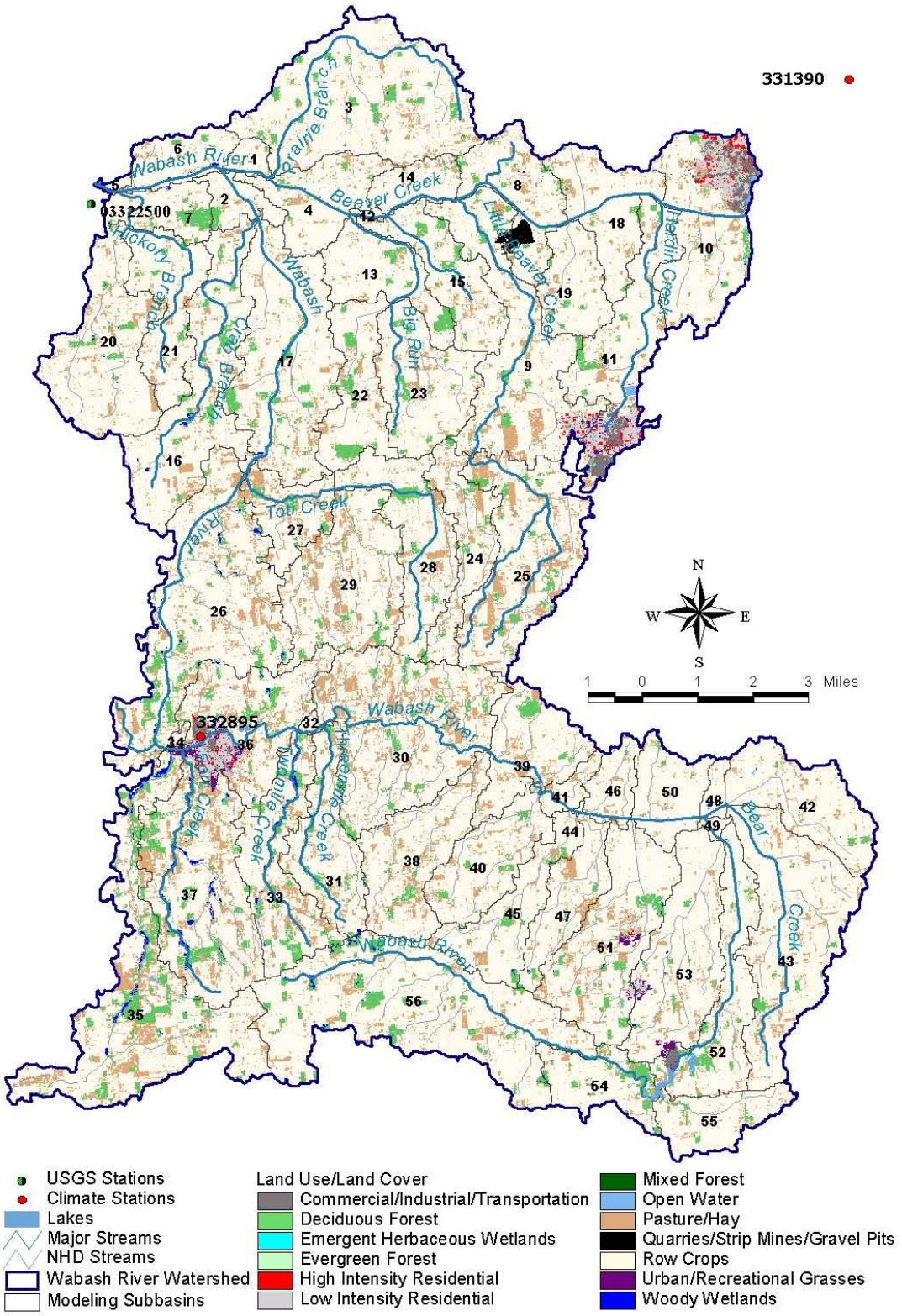

Figure 2. Subbasins and Land Use/Land Cover in the Wabash River Watershed.

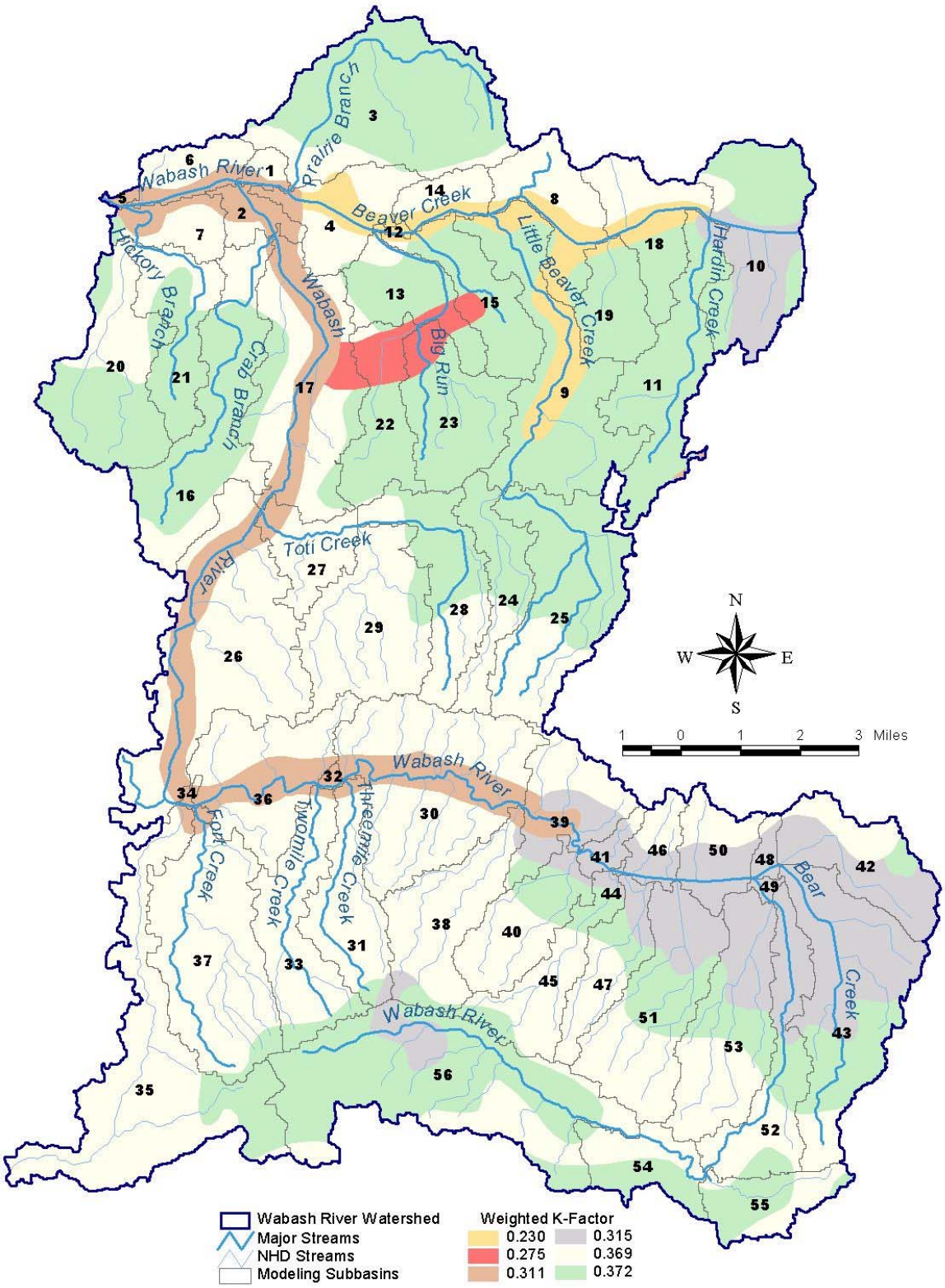

Figure 3. Soil erodibility factors within the Wabash River watershed.

Table 4. Summary of land use characteristics for the Wabash River watershed.

Land Use Land Cover (MRLC)	Area (Acres)	Percent
Row Crops	99,630.0	80.63
Pasture/Hay	13,990.4	11.32
Deciduous Forest	7,091.3	5.74
Low Intensity Residential	1,023.0	0.83
Commercial/Industrial/Transportation	610.7	0.49
Woody Wetlands	399.4	0.32
High Intensity Residential	228.8	0.19
Urban/Recreational Grasses	216.2	0.17
Open Water	173.5	0.14
Quarries/Strip Mines/Gravel Pits	135.2	0.11
Emergent Herbaceous Wetlands	42.3	0.03
Evergreen Forest	16.0	0.01
Mixed Forest	6.4	0.01
Total	**123,563.2**	**100.00**

Meteorological Data

SWAT2000 requires daily precipitation, temperature, relative humidity, solar radiation, and wind speed data. 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. Daily precipitation and temperature data were obtained from the National Climatic Data Center (NCDC) for the Celina 3NE (ID 331390) and Fort Recovery (ID 332895) stations (see Figure 2). Daily data are available for Celina for the period January 1, 1956 to December 31, 2002. Daily data are only available for the Fort Recovery station for the period January 1, 1997 to December 31, 2002. Relative humidity, solar radiation and wind speed were simulated using a climate simulator available in SWAT2000. The climate simulator uses historical data collected from surrounding National Weather Service sites to estimate parameters. It is believed that these stations are quite adequate for estimating relative humidity, solar radiation, and wind speed for the Wabash River watershed.

Reservoir Impact on Hydrology and Water Quality

Two reservoirs in the Wabash River watershed affect downstream streamflows. Streamflow in Beaver Creek is impacted by the volume of water releases from Grand Lake St. Marys. The daily volume of released water was not available for input to the model and was therefore estimated based on existing information. Grand Lake St Mary’s has a surface area of approximately 12,813 acres at normal pool and the principal spillway is 500 foot spillway with a 50 foot notch, 11 inches deep. Discharge from the lake was estimated using available data relating lake elevation and flow.

Information on the conservation district reservoir located in the southern portion of the watershed was provided by the Mercer County Soil and Water Conservation District. The surface area of the reservoir is 152 acres and the reservoir volume is approximately 1,550 acre-feet. The average annual outflow is 5.3 acre-feet per year. It should be noted that the conservation district reservoir provides limited ability to trap sediments, a characteristic often association with other reservoirs. This is due to the extremely fine-grained nature of the soils upstream of the reservoir which have very long settling times.

Model Calibration and Validation: Hydrology

After initially configuring SWAT, model calibration and validation were performed. Calibration refers to the adjustment or fine-tuning of modeling parameters to reproduce observations. The calibration was performed for different SWAT subbasins at multiple locations throughout the watershed. This approach ensured that landscape heterogeneities were represented. The model validation was performed to test the calibrated parameters at different locations and for different time periods, without further adjustment. Upon completion of the calibration and validation at selected locations, a calibrated dataset containing parameter values for each modeled land use and pollutant was developed.

Calibration and validation were completed by comparing time-series model results to monitoring data. Output from the watershed model are in the form of daily average flow and daily average concentrations for the modeled pollutants for each of the subwatersheds.

Hydrology was the first model component calibrated, and it involved a comparison of observed data from an in-stream USGS flow gauging station to modeled in-stream flow and an adjustment of key hydrologic parameters. Among the modeling parameters that proved to be most sensitive were those governing the partitioning of precipitation between surface and groundwater flows, possibly because of the presence of tiling. The specific parameters were the threshold depth of the shallow aquifer before evaporation can occur and the groundwater revaporation coefficient.

The model was calibrated for the Wabash River watershed to simulate conditions during the period 1977 to 1987. This time period corresponds to the most recent data available at the USGS Wabash River stream gage near New Corydon, Indiana (ID 03322500), which is located near the Ohio/Indiana state line (see Figure 2). Data at this station cover the period April 1, 1951 to September 30, 1988.

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.

An example of the calibration results for a year with average streamflows is given below in Figure 4 for the 1981 water year. Figure 4 shows a comparison of the observed versus the simulated daily stream flow for the entire year. Figure 5 provides a comparison of the observed versus the simulated monthly and weekly stream flows in 1981. Figures 4 and 5 show a good level of agreement between observed and

simulated stream flow, as well as the timing of peak storm flow.

An example of the calibration results for a year with above-average streamflows is given below in Figure 6 for the 1986 water year. Figure 6 shows a comparison of the observed versus the simulated daily stream flow for the entire year. Figure 7 provides a comparison of the observed versus the simulated monthly and weekly stream flows in 1986. Figures 6 and 7 do not show as good a level of agreement between observed and simulated stream flow as Figures 4 and 5, but are still considered acceptable.

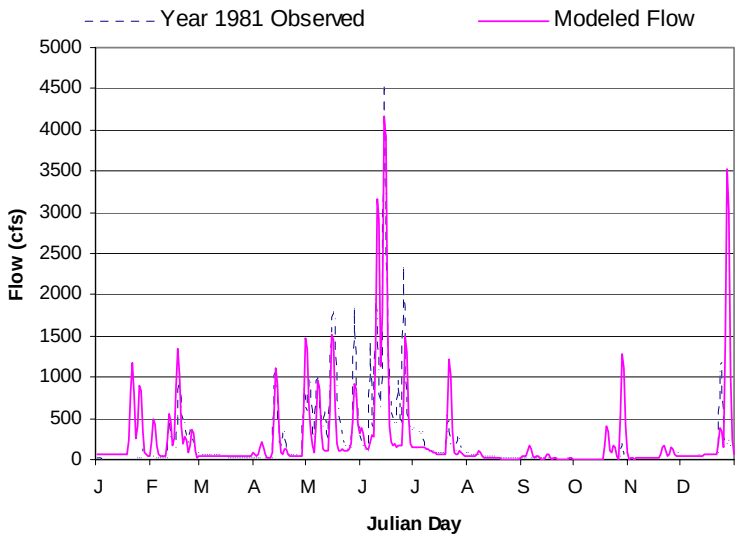

Figure 4. Observed Versus Simulated Daily Stream Flow, 1981.

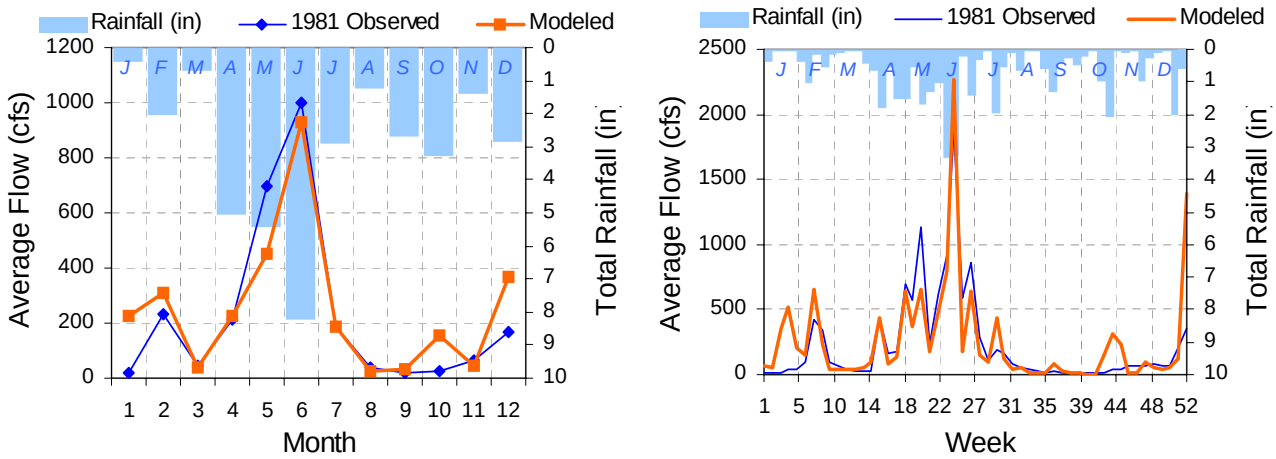

Figure 5. Observed Versus Simulated Monthly and Weekly Stream Flow, 1981.

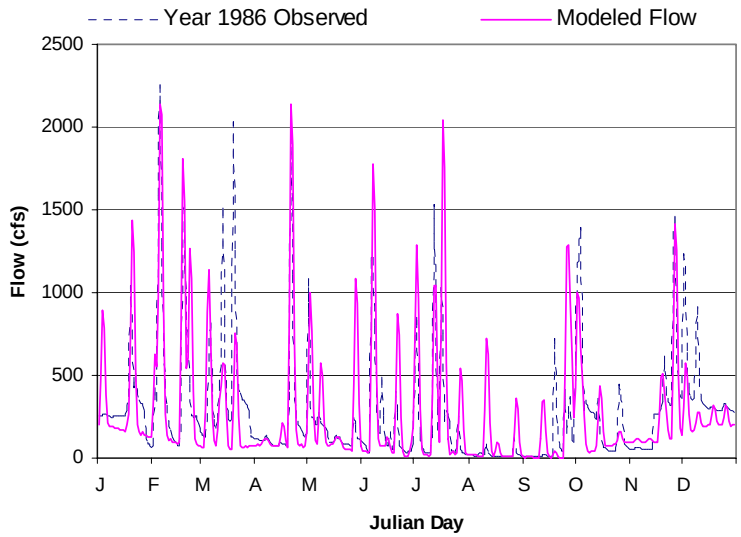

Figure 6. Observed Versus Simulated Daily Stream Flow, 1986.

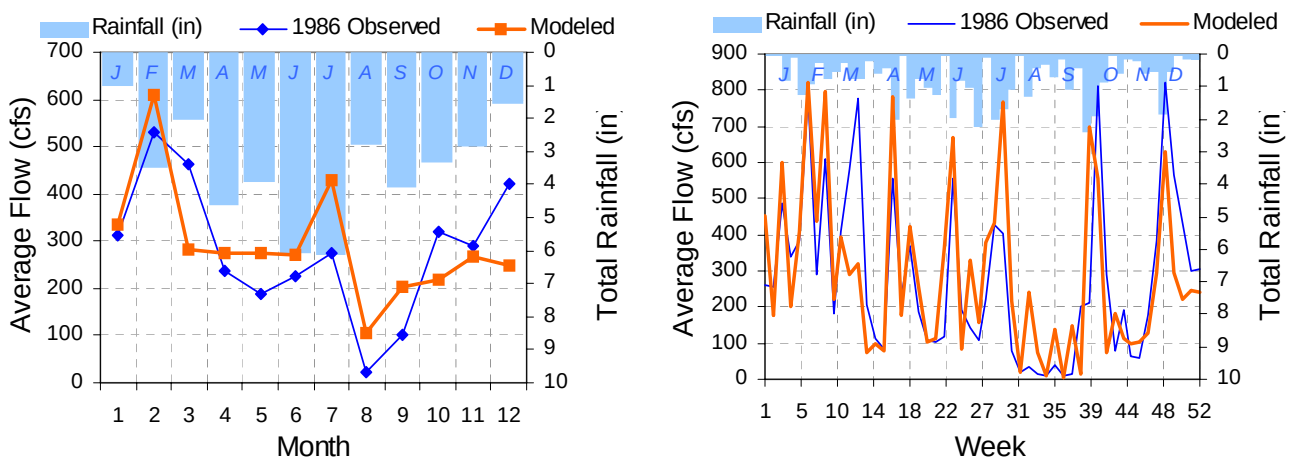

Figure 7. Observed Versus Simulated Monthly and Weekly Stream Flow, 1986.

The ten year flow comparison is summarized in Figure 8 and Table 5. Figure 8 shows that the level of agreement between monthly observed versus monthly simulated stream flow is good ($R^2 = 0.76$).

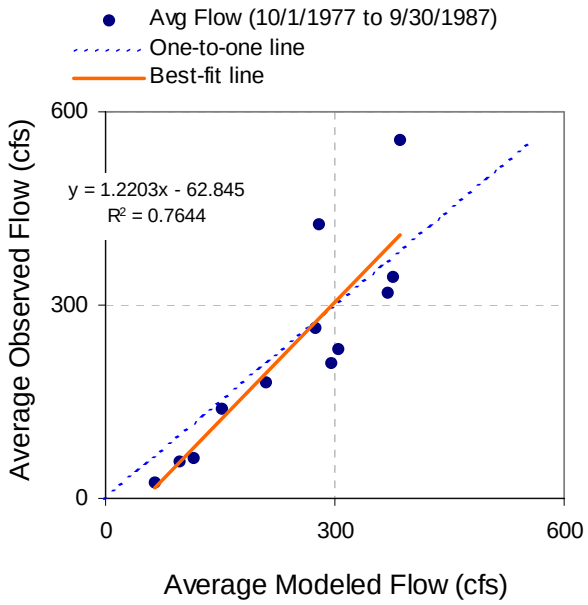

Figure 8. Statistical Comparison of Observed Versus Simulated Annual Stream Flow, 1977 to 1987.

Seasonal and annual differences between observed versus simulated stream flow are summarized in Table 5. The table shows that simulated flow for the ten-year period agrees well with observed stream flow data. The greatest errors occur in simulated summer storm volumes, yet these errors are within recommended calibration parameters (Lumb et al., 1994). In general, the hydrologic calibration appears adequate in that it reflects the total water yield, annual variability, and magnitude of individual storm events in the basin. All recommended criteria are met.

Table 6. Wabash River Watershed Calibration Results for the Simulation Period October 1, 1977 to September 30, 1987. Units shown are inches.

Total Simulated In-stream Flow:	**102.17**	Total Observed In-stream Flow:	**98.26**
Total of highest 10% flows:	**57.54**	Total of Observed highest 10% flows:	**55.73**
Total of lowest 50% flows:	**6.46**	Total of Observed Lowest 50% flows:	**6.05**
Simulated Summer Flow Volume:	**11.08**	Observed Summer Flow Volume:	**7.82**
Simulated Fall Flow Volume:	**24.54**	Observed Fall Flow Volume:	**19.88**
Simulated Winter Flow Volume:	**36.52**	Observed Winter Flow Volume:	**38.50**
Simulated Spring Flow Volume:	**30.03**	Observed Spring Flow Volume:	**32.06**
Total Simulated Storm Volume:	**102.04**	Total Observed Storm Volume:	**95.66**
Simulated Summer Storm Volume:	**11.05**	Observed Summer Storm Volume:	**7.17**
Errors (Simulated-Observed)		*Recommended Criteria*[1]	
Error in total volume:	**3.83**	10	
Error in 50% lowest flows:	**6.24**	10	
Error in 10% highest flows:	**3.13**	15	
Seasonal volume error - Summer:	**29.39**	30	
Seasonal volume error - Fall:	**18.99**	30	
Seasonal volume error - Winter:	**-5.42**	30	
Seasonal volume error - Spring:	**-6.76**	30	
Error in storm volumes:	**6.25**	20	
Error in summer storm volumes:	**35.08**	50	

[1] Recommended criteria are form Lumb et al., 1994

Model Calibration and Validation: Water Quality

After hydrology was sufficiently calibrated, water quality calibration was performed. Modeled versus observed in-stream concentrations were directly compared during model calibration. The water quality calibration consisted of executing 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, as well as to obtain modeling output within the range of all observations (i.e., the observed minimum and maximum water quality concentrations should be within the range of the simulated minimum and maximums).

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 personal observations made during a site visit, discussions with the Wabash River watershed coordinator, and SWAT default values.

- Minimal conservation tillage is practiced in the watershed due to the large amounts of manure application.
- Manure application typically occurs in the spring (April), fall (October), and winter (January) but can occur at other times of the year due inadequate storage facilities.
- Phosphorus can build up on the land surface because plant uptake is not always able to utilize all of the applied phosphorus.

Adjusted water quality parameters within the model included USLE P and C factors, instream decay rates, and denitrificaiton coefficients. Water quality calibration adequacy was primarily assessed through review of time-series plots. Looking at a time series plot of modeled versus observed data provides more insight into the nature of the system and is more useful in water quality calibration than a statistical comparison. Flow (or rainfall) and water quality can be compared simultaneously, and thus can provide insight into conditions during the monitoring period (dry period versus storm event). The response of the model to storm events can be studied and compared to observations (data permitting). Ensuring that the storm events are represented within the range of the data over time is the most practical and meaningful means of assessing the quality of a calibration. Furthermore, due to the relative lack of water quality monitoring data, it was not possible to make statistical comparisons of the predicted and observed data.

Figures 9, 10, and 11 present the results of the model calibration for TP, NN, and TSS. They indicate that the model is a reasonable description of the significant water quality processes in the watershed and is suitable for use in TMDL development.

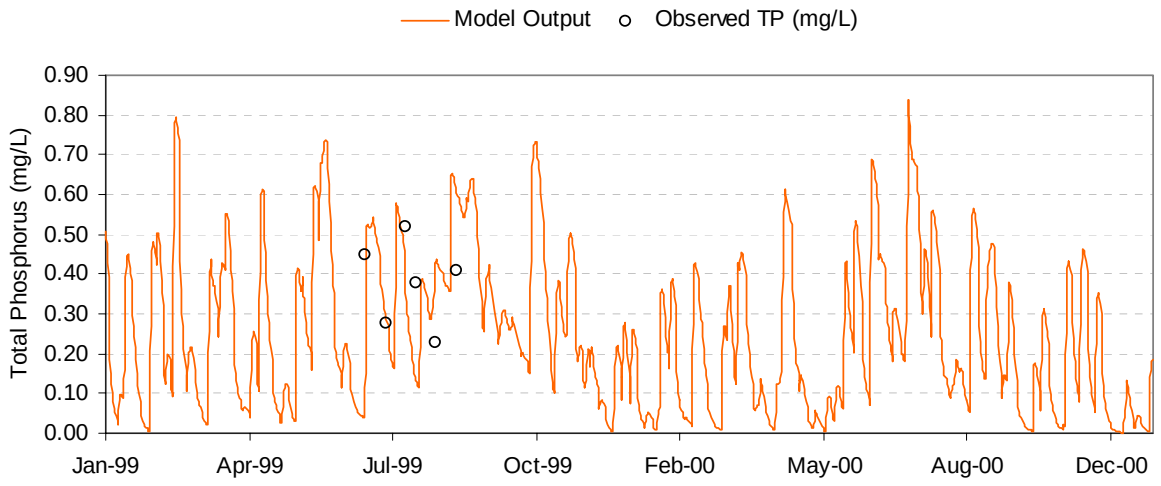

Figure 9. Comparison of predicted and observed total phosphorus data for the Wabash River at State Line Road.

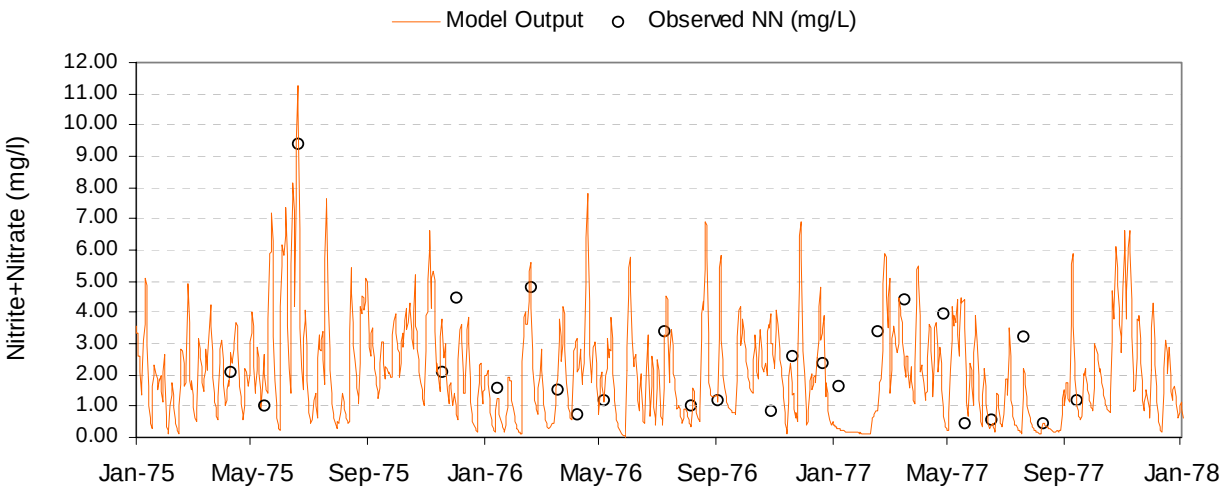

Figure 10. Comparison of predicted and observed nitrite+nitrate data for the Wabash River at State Line Road.

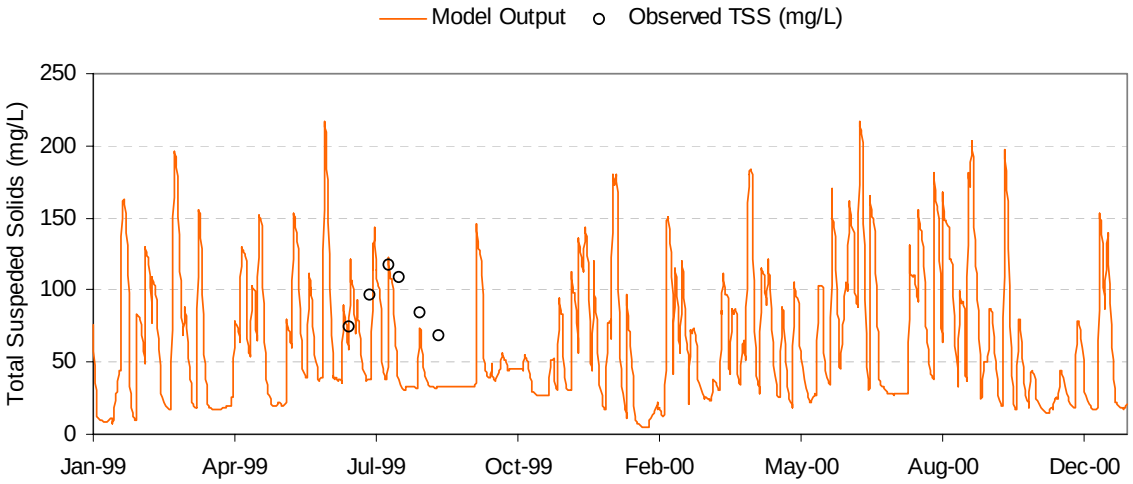

Figure 11. Comparison of predicted and observed total suspended solids data for the Wabash River at State Line Road.

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