CHAPTER 4
MODEL METHODOLOGY AND MODIFICATIONS

This chapter describes the methods used to create the input files used in SWAT and details the modifications and corrections made to the SWAT code.

Approach and Model Configuration

Several planing sessions were held with the WDNR, USGS, and the creators of SWAT to outline a modeling approach that addressed specific requirements or limitations of the SWAT model. To accommodate the routing structure of the model, the Rock River Basin was divided into seven areas. Each of these areas was linked together by a series of files that allowed the output from one area to be used as input for the next downstream area. Figure 4.1 shows the seven areas that were modeled and linked together using the save and recall commands in SWAT. These areas do not symbolize anything other than the best method arrived at to model the entire basin given the requirements of SWAT. The seven areas consist of (1) Turtle Creek, (2) Afton and Lower Rock, (3) Yahara River, (4) Bark River, (5) Middle Rock River, (6) Crawfish River, and (7) Upper Rock River.

The delineation of the modeling areas was influenced by 1) the constraints of the model (specifically the number of reservoirs allowed in one model run), 2) the location of USGS gaging stations, and 3) confluence with other major waterways. Within the modeled areas, WDNR watershed boundaries were maintained except for LR02, LR03, LR04, and LR05, which were combined because the Rock River was used as the boundary for the watersheds under their original delineation. SWAT watersheds must discharge surface water to a single point.

A naming convention was created for setting up all modeling files and associated databases. WDNR watershed names were used (i.e. LR01) at the watershed level. All files used at the watershed level would start with the watershed name and use the appropriate extension. Watersheds were subdivided into sub-watersheds and numbered consecutively (i.e. L0101). Input files for sub-watersheds were named according to the sub-watershed and the appropriate file extension. For example, the pond and soil files for watershed LR01, sub-watershed 1 were named L0101.pnd and L0101.sol respectively.

Each sub-watershed was further subdivided into hydrologic response units (HRUs) to capture the variability within the sub-watershed. The HRU numbering format followed that of the sub-watershed, thus watershed LR01, watershed 1, HRU 2 was named L010102. In this manner, files could easily be stored and linked together by name.

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Watershed Delineation and Hydrology/Hydraulics

Watershed delineation was performed using the SWAT *ArcView*™. interface (AVSWAT). The 30-meter DEM for the Rock River Basin was clipped to the boundary of each WDNR watershed and then imported in AVSWAT. This process was repeated for the 1:24,000 hydrography layer displaying streams and rivers. Lake boundaries were eliminated from the coverage. Since lakes and impoundments of any considerable size are depicted on the DEM at a constant elevation, the inlets and outlets were connected through the centroid with a line. This line coverage was amended to the hydrography layer. Once these files were imported into AVSWAT, the stream coverage was burned into the DEM to maintain flow paths.

Next, sinks (internally drained areas) were identified within the DEM and filled. AVSWAT then delineates watershed boundaries based on flow accumulation and a user specified threshold value (minimum size). Generated boundaries were then plotted on USGS digital quad maps (also refereed to as digital rater graphics or DRGs) and checked for accuracy against the USGS contours. This process was repeated for each watershed.

Once the watershed boundaries were delineated, automated routines within AVSWAT were used to generate stream and hydrologic characteristics. AVSWAT generated the average slope and slope length for each sub-watershed from the 30-meter DEM. Flow path and channel characteristics were also calculated. The width of the channel was calculated using the equation:

Channel width = (1.29)*((Area Cumulative/1,000,000)^(0.6))).

The average depth in the channel was calculated using the equation:

Channel depth = (0.13)*((Area Cumulative/1,000,000)^(0.4))).

In both cases, area cumulated is in square meters.

Initially, problems were encountered with the automated routines. The slope calculations produced slopes exceeding those typically encountered in Wisconsin. Review of the code revealed an error in measurement units. Once this problem was corrected, accurate slope and slope length measurements were generated.

The channel width produced by AVSWAT was too large when compared to actual data. Through trial and error, it was found that simply dividing the AVSWAT calculated number by two produced a more accurate result. In general, it seemed that AVSWAT overestimated the width of the channel and underestimated the depth. This problem is being addressed in the next version of SWAT, however, it was found during calibration that channel width had little effect on a watersheds overall water balance.

Climate Inputs:

Daily climate records for the period 1960 through 1999 were analyzed to develop the climate-input files necessary for the SWAT model. Data was collected for monitoring stations within and surrounding the Rock River watershed. The Thiessen polygon method was used to fill in missing precipitation records for individual stations. Missing maximum and minimum temperatures were replaced with average values from nearby stations.

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The climate-input files were developed using an *Excel*™ spreadsheet. All values were converted to metric units and missing records were replaced using the appropriate method. Both the temperature (*.tmp) and precipitation (*.pcp) files were saved using the spaced formatted text option within *Excel*™ to maintain appropriate spacing.

The climate inputs for each sub-watershed were based on the *.pcp and *.tmp files. These files were assigned within *ArcView*™. based on the closest geographical proximity to the subwatershed.

The weather generator input files (*.wgn) contain the statistical data needed to generate representative rainfall intensities and other climate variables from the daily precipitation and max/min temperature data. Creating the *.wgn files requires long term climate data. Four climate stations (Madison, Lake Geneva, Portage and West Bend) had long term data suitable for the *.wgn files. Using *ArcView*™ each station was assigned to a watershed based on the closest geographical proximity.

Originally, an attempt made to provide sub-watershed specific precipitation and temperature estimates from several nearby stations based on a distance-weighted formula. This approach, even though seemingly more accurate, has the effect of reducing a storms' impact (Baumgart, 1998) and thus was discarded for the simpler but more reliable method of assigning a single station to each sub-watershed.

Soils:

Soils data was obtained from the National Resources Conservation Service (NRCS) STATSGO data. The STATSGO data consists of digital maps that display general soil associations along with a linked database on the association's attributes. Within the Rock River basin there are 20 unique soil associations.

The STATSGO soil coverage was clipped with the delineated sub-watersheds using *ArcView*™. For modeling purposes, an area-weighted method was employed to determine soil parameters. Hydric soils were excluded because wetlands were being modeled separately. The averaged values were then assigned to each sub-watershed to generate a unique soil file for each sub-watershed. The top four layers of each dominant soil series within an association were used to find the "average" soil properties. This was conducted using an *Excel*™ spreadsheet macro that was written to average values for each layer and then sum the values based on a weighted average. Averaging of hydrologic soil groups was made possible by assigning values of 1,2,3 and 4 to each soil series with a hydrologic group A, B, C, and D, respectively. In this manner, a soils coverage and input file were created for each sub-watershed.

Internally Drained Areas:

During delineation and calibration of the two pilot areas (Jackson Creek at Petrie Road and Yahara River at Windsor), discrepancies between the drainage area reported by the USGS and the actual contributing area (surface water flow) were noted. Examination of USGS data revealed that in some cases, the size of the noncontributing area is noted, however, this was not always the case. Often, the total water yield reported by the USGS is based on the total drainage area and includes internally drained areas. When modeling, inclusion of the internally drained areas produced excess runoff and exclusion of internally drained areas can reduce groundwater base flow due to reduced infiltration.

Internally drained areas were identified using ARVIEW spatial analyst. During the delineation of sub-watersheds, AVSWAT filled the sinks. During this process, an intermediate coverage was created which

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showed areas that were filled. This grid coverage was converted to a shape file. A digital buffer zone of 1,000 feet was created around the streams in the 1:24,000 hydrography layer. These two layers were then intersected and reversed leaving only those internally drained areas outside of the stream buffer. This shape file was then converted back to grid coverage and the areas and volumes of the sinks were calculated. The contributing drainage areas to the sinks were then determined by overlaying the coverage on the USGS DRG quad maps. The drainage area was delineated by hand and digitized. The resulting areas were summed for each watershed producing a total contributing area and volume needed to fill the sinks contained in each sub-watershed.

Individual sub-watersheds were created for large, segregated internally drained areas such as Goose Lake located near Windsor. The pond/wetland function was used to address smaller discrete internally drained areas. Discrete internally drained areas were merged with the wetland coverage and open water coverage to determine how best to simulate them. If an internally drained area included wetlands, then the wetland routines were used to simulate the hydrologic processes. If the internally drained area included open water, then the pond routine was used to simulate the hydrologic processes. In most cases, large internally drained areas had one or both features. In the case of both features, the wetland routine was employed. If neither feature appeared, the area was rechecked against USGS quads to ensure that the area was indeed internally drained. If it was, the area was lumped in with the wetland function, otherwise the area was added back to the surface flow contributing area of the sub-watershed. In this manner, using actual contributing areas could better approximate surface and subsurface flows.

The WDNR noted that one of the useful results of the Rock River Modeling project was the identification of large internally drained areas such as Goose Lake in the Yahara River and Lake Mendota Watershed. Knowledge of these areas will aid in selecting and targeting potential pollutant trading areas.

Wetlands and Ponds:

During the modeling, limitations were noted in the wetland routine, most notably a lack of accounting for the impact of wetland vegetation on ET and nutrient uptake. This has been modified in the new wetland routine that models wetlands as an HRU and accounts for the effects of wetland vegetation growth on nutrient uptake and ET rates. However, this subroutine was not available for this project so the existing methodology that requires as inputs the area of the wetlands, the volume of water to fill the wetlands (optional), contributing drainage area to wetlands, and infiltration. These inputs are similar to those for the pond function. Sediment and nutrients in the runoff are settled out in much the same manner as ponds.

The actual wetland area was obtained from the WISCLAND coverage by simply summing cells. The infiltration was determined from the hydric soil classification from the STATSGO coverage, and the contributing area to the wetlands was computed in the same manner as that for internally drained areas and checked against the DRGs. The volume to fill the wetlands was used to provide an outlet for water to flow out as surface flow once a certain elevation was reached.

The pond subroutine was utilized to model small lakes and ponds. The input requirements are similar to those of the wetland subroutine. The only noticeable difference will be that the ponds were modeled with a lower infiltration rate than the wetlands.

The pond and wetland files were created using an *Excel*™ macro that was written to automate the file generation. This allowed for adjustment of parameters for calibration. Notably, the infiltration rates needed to be increased for the lakes to account for losses due to evaporation. The infiltration rates had to

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be reduced for wetlands along the main stem of the rivers to allow for sufficient surface runoff. Upland wetlands maintained high infiltration rates consistent with their tendency to be groundwater recharge zones.

Baseflow Separation Model:

An automated baseflow separation model designed by Dr. Arnold (principal developer of SWAT) was run to determine the relative contributions of groundwater (baseflow) and surface water to total stream yield. This base flow separation model is also referred to as a digital filter later in this chapter. The model was run on 23 USGS gaging stations located within the Rock River Basin that had long-term flow records. The results of the analysis were used to assist in calibrating the SWAT model regionally across the Basin.

When calibrating the model for flow, there are three components that must be balanced, (1) surface flow, (2) baseflow or groundwater, and (3) evapotranspiration (ET). SWAT was calibrated to the stream flow from the USGS stations, however calibration can be obtained from manipulating any of the three components. Running the baseflow separation model allows us to determine the baseflow component. The surface runoff component can be calculated from the USGS data (inches of runoff) and average annual ET estimates are available. This data can then be used to ensure that each component reflects actual conditions. A more detailed discussion on calibration is included in Chapter 5.

The baseflow separation model requires drainage basin size (square miles) and daily flow values (cfs) as inputs. This data was obtained from the USGS. The drainage basin area used was the total reported area including internally drained areas. The model separates baseflow from daily stream flows using the digital filter technique (Nathan and McMahon, 1990). A study conducted by Mau and Winter (1997) found that the filter method agreed reasonably well with graphical (manual) partitioning. Arnold et. al. ran the digital filter for six basins located in the Midwest and found R^2 values ranged from 0.62 to 0.98.

Results varied widely across the Rock River Basin. Results for Jackson Creek indicate that approximately 31% of the flow is from baseflow while the Yahara River above Lake Mendota receives in excess of 70% of its flow from baseflow contributions. Pheasant Branch only receives 48% baseflow while the Badfish Creek receives 94% baseflow. The City of Madison supply wells that withdraw considerable amount of water from the aquifer underlying Peasant Branch can explain this large discrepancy (Bradbury et. al., 1996). Water from Madison's water supply system is discharged from the wastewater plant to the Badfish Creek. This constant flow from the plant shows up as baseflow in the digital filter. This is important to note because as impoundments and other hydraulic features dampen hydrographs, the digital filter shows this dampened flow as baseflow. Thus baseflow does not always correlate to groundwater flow.

On average, the percent baseflow contributions to surface streams within the Rock River ranged from the upper 60s to the mid 80s. Baseflow contributions did increase from the upper to lower reaches of the basin. To ensure that baseflow contributions would not be overestimated, initial values from upper reaches and of impoundment (typically ranging between 68% to 71%) were used. The results from the digital filter are summarized in Table 4.1. Note that the table includes three passes. The passes are separate calculations that provide a range of values. The first pass is most applicable to areas in the Midwest (Arnold et. al., 1995). Figure 4.2 shows the result from the first pass of the digital filter and illustrates the dampening effect of the hydrograph as one moves down stream through increasing baseflow.

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In addition to baseflow measurement, the digital filter provides estimates on several other SWAT input parameters including the alpha factor which characterizes the groundwater recession curve and the groundwater delay which is the average amount of time it takes water leaving the root zone to reach the shallow aquifer. The alpha factor does not affect the amount of water, just the timing and shape of the hydrograph.

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TABLE 4.1 SUMMARY OF RESULTS FROM AUTOMATED BASEFLOW SEPERATION

USGS ID	Gaging Station Location	Drainage Area (sq. mi.)	Simulation Period Begin	End	Baseflow Contribution Pass 1	Pass 2	Pass 3	Alpha Factor (monthly) Mean	Min	Max
5423000	West Branch Rock River	40.70	1970	1980	68%	51%	42%	0.061	0.009	0.161
5423100	West Branch Rock River @ Cth D	43.90	1970	1980	71%	55%	46%	0.055	0.013	0.139
5423500	South Branch Rock River @ Waupun	63.60	1988	1995	71%	56%	48%	0.054	0.009	0.090
5424082	Rock River @ Hustisford	511.00	1979	1984	71%	54%	41%	0.136	0.001	0.837
5425500	Rock River @ Watertown	969.00	1970	1995	79%	65%	55%	0.052	0.007	0.159
5425912	Beaver Dam River	157.00	1986	1997	75%	60%	49%	0.063	0.009	0.204
5426000	Crawfish River @ Milford	762.00	1970	1995	79%	64%	54%	0.047	0.003	0.099
5426031	Rock River @ Jefferson	1850.00	1979	1991	81%	67%	57%	0.051	0.006	0.171
5426250	Bark River near Rome	122.00	1984	1997	83%	72%	65%	0.029	0.003	0.077
5426900	Whitewater Creek @ Millis Rd	20.60	1979	1980	84%	77%	73%	0.025	0.006	0.044
5427000	Whitewater Creek @ Willis Ray Rd	22.80	1979	1980	82%	75%	70%	0.024	0.006	0.050
5427570	Rock River @ Indianford	2630.00	1976	1995	83%	71%	61%	0.039	0.006	0.209
5427718	Yahara River @ Windsor	73.60	1977	1995	76%	68%	65%	0.029	0.002	0.098
5427900	Sixmile Creek near Waunakee	41.10	1977	1981	70%	57%	50%	0.049	0.006	0.170
5427948	Pheasant Branch @ Middleton	18.30	1975	1995	48%	36%	32%	0.059	0.003	0.240
5430095	Badfish Creek @ Cth A	41.90	1986	1987	94%	91%	88%	0.005	0.005	0.005
5430150	Badfish Creek near Cooksville	82.60	1978	1997	88%	84%	81%	0.022	0.006	0.056
5430175	Yahara River @ St Hwy 59	518.00	1978	1997	84%	75%	69%	0.015	0.003	0.030
5430500	Rock River @ Afton	3340.00	1970	1995	85%	74%	66%	0.030	0.002	0.145
5431014	Jackson Creek @ Petrie Road	8.96	1984	1994	49%	31%	23%	0.116	0.010	0.252
5431016	Jackson Creek @ Mound Road	16.80	1994	1995	54%	39%	32%	0.074	0.022	0.129
5431018	Delavan Lake Trib. @ S Shore Dr.	9.99	1984	1990	64%	46%	37%	0.061	0.020	0.143
5431022	Delavan Lake Outlet @ Borg Rd	42.10	1984	1997	58%	40%	30%	0.122	0.009	0.530
5431486	Turtle Creek @ Carvers Rock Rd	199.00	1970	1995	78%	67%	62%	0.032	0.002	0.116

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Groundwater Interactions:

One of the shortcomings of SWAT is that water percolating to the deep aquifer is lost from the system. This is not necessarily always the case. In many cases, groundwater initially considered lost from a system will re-enter at a different location. This can occur through springs or seepage.

Given the scope of this project, resources do not exist to identify all spring fed water bodies and determine the contribution to flow. In addition, because deep aquifer percolation is lost from the system, it is likely that not enough base flow will be available to adequately represent the Rock River conditions. Communications with Ken Bradbury, (Wisconsin Geological and Natural History Survey) and Ken Potter (UW-Madison Civil Engineering Department) collaborate this. Both stated that the aquifer underlying the Rock River Basin is connected with surface water and that water entering the aquifer will become baseflow at some point. To simulate this, deep percolation will be used to aid in controlling the total water yield at upper reaches. As modeling progresses toward the main stem of the Rock River, the amount of water percolating to the deep aquifer was reduced to increase shallow base flow and offset the return of deep aquifer percolation.

The groundwater inputs within SWAT consist of: 1) initial groundwater height, 2) the alpha factor (estimated from the digital filter), 3) the specific yield, 4) the groundwater delay (estimated by digital filter), 5) the revaporation coefficient, and 6) the deep aquifer percolation coefficient. In most cases, deep percolation was set between 0 and 10% except for Pheasant Branch which was set at 75% to account for the draw down of the Madison supply wells. This water was reinserted into the system through the Madison Metropolitan Sewerage District (MMSD) point source file.

The remaining inputs were either determined using the digital filter (base flow separation model), estimated using typical values, or adjusted during calibration. Of these parameters, the revapcoefficient had the largest overall effect on the water balance. The revapcoefficient controls the depth at which water can be extracted by deep-rooted trees and shrubs. Since the Rock River does not contain large amounts of forested land, this value remained fairly low, however, increasing the revapcoefficient cause ET to increase and baseflow to decrease. Thus this value was one parameter adjusted within typical values to help adjust the water yield at gaging stations.

A more detailed linkage exists whereby SWAT can be linked with the groundwater model MODFLOW, however, this was beyond the scope of the modeling effort. Because several of the groundwater inputs were obtained from the digital filter, a unique groundwater file was created for each gaging station and was used to simulate the groundwater interactions of the drainage area above the gaging station

Lakes and Impoundments

The Rock River basin includes many lakes, wetlands, and impoundment areas that affect the flow of water through the watershed. Figure 4.3 shows the location of WDNR identified dams and impoundments within the Rock River Basin. A survey found that of the 218 dams identified in the basin, only 27 (5 in Horicon Marsh) have impoundment areas greater than 300 acres and only 14 dams (1 in Horicon Marsh) have impoundment areas greater than 1000 acres.

Because of the sheer number of dams, only dams that had a significant impact on the flow of water through the watershed were included in the model. Significant reservoirs were selected based on reservoir storage, surface area, and the amount of contributing drainage area. Multiple lakes such as Lake

Monona, Upper Mud Lake, and Lake Waubesa (part of the Madison chain of lakes), which are controlled by a single outlet structure, were modeled as a single reservoir.

Two outflow options within SWAT were used to model impoundments: 1) uncontrolled outlet and 2) target release with specified maximum and minimum release rates. The third option available in SWAT,

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INSERT FIGURE 4.3

DAMS and IMPOUNDMENTS IN ROCK RIVER

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using actual measured outflow, was not used because it would prevent the simulation of alternative BMP practices below impoundments by not allowing alterations of flow with changes in practices.

Average monthly maximum and minimum outflows were calculated for dams that had USGS gages at their outlets for use in the simulated controlled outflow option (option 2). Stage-storage information for reservoirs was obtained from WDNR dam records and the WDNR reports on the Upper Rock River Basin and the Lower Rock River Basin. Minimum and maximum pool elevations were obtained from WDNR dam records and a survey of individual dam operators, generally the municipality that had jurisdiction over the dam. Lakes without control structures were assumed to fluctuate about half a foot with very little change in surface area, resulting in a linear relationship between change in elevation and change in storage.

Hydraulic conductivity of all the lake bottoms was modeled as zero. Information was not available to simulate the groundwater interface with the lakes. In addition, it was assumed that no water was being removed from the reservoirs for consumptive use. Table 4.2 provides a summary of the impoundments that were modeled.

Two approaches were proposed for modeling the water quality impacts of the lakes within the Rock River Basin and their impacts on phosphorus loads/concentrations within the river system.

Method 1 involved modeling the contributing area above the lake or reservoir and routing the water and nutrients down to the lake with SWAT. Once routed to the lake, actual lake monitoring data is used to represent conditions in the lake and provide input for reaches below the lake. The shortcoming of this method is that a break in the model is made at the lakes meaning that the effects of BMPs upstream of the lake can not be propagated downstream of the lake. An advantage is that downstream conditions are based on actual monitored data.

Method 2 involved utilizing the subroutines within SWAT to model the lakes. The SWAT subroutine simulates lakes as well mixed and uniform pollutant distribution under steady state conditions. Specifically, the phosphorus mass balance in SWAT was taken from Thomann and Mueller (1987). For phosphorus, SWAT assumes 1) completely mixed lake, 2) phosphorus is the limiting factor for algae growth, and 3) total phosphorus can be used as a measure of trophic status. Required input parameters include the volume of lake, the total phosphorus concentration in lake, the outflow volume, the overall loss rate of total phosphorus from lake processes (Ks), and total phosphorus inflow. As with the rest of the model, the lakes would be simulated in daily time steps. Ks values were calculated from monitoring data provided by WDNR. When monitoring data was not available, data from a similar lake in size and depth was utilized.

Given the limited availability of monitoring data, method 2 was selected. Data was collected from the WDNR utilizing existing monitoring records for lakes and reservoirs within the Rock River Basin for periods dating from 1960 to the present. Data collected included volume of lake, total phosphorus concentration in lake, and outflow volume. Values for Ks were estimated as outlined in Chapra and Tarapchak (1976).

To use the SWAT lake routines a minimum and maximum in-lake sediment concentration had to be established. Min-max sediment concentrations were determined using two sources: WDNR lake quality data and USGS sediment concentrations reported in: “Measurement and Prediction of Sediment Yields in Wisconsin Streams”(1976). USGS gaging stations located near the outlets of lakes within the Rock River Basin were reviewed to estimate the sediment concentration values during base flows. These were assumed to indicate the upstream lake's sediment concentrations. Each modeled lake or impoundment was assigned a unique min-max sediment concentration based on these data sources.

TABLE 4.2 SUMMARY OF LAKES AND IMPOUNDMENTS SIMULATED BY SWAT

Lake or Impoundment	Watershed	Normal Surface Area	Filled Surface Area (ha)	Max Depth (m)	Mean Depth (m)	Minimum Pool Elevation (m)	Normal Pool Elevation (m)	Highwater Elevation (m)	Normal Storage (m3)	Highwater Storage (m3)
Rock Lake	UR02	555	555	17.1	0.0	252.1	0.0	252.5	3.937E+06	4.164E+06
Lac LaBelle	UR08	471	472	14.0	0.0	25.9	26.1	26.3	1.988E+06	2.203E+06
Lower Mud Lake	LR06	79	79	4.6	1.5	0.0	0.0	0.1	1.500E+05	1.620E+05
Upper Mud Lake	LR08	90	91	2.4	1.2	0.0	257.6	0.1	1.372E+05	1.510E+05
Lower Nemahbin	LR13	110	110	11.0	3.0	0.0	0.0	0.2	4.169E+05	4.419E+05
Wingra	LR08	140	140	6.4	2.4	0.0	0.0	0.2	4.246E+05	4.564E+05
Whitewater	LR14	282	282	11.6	2.4	0.0	0.0	0.2	8.363E+05	9.007E+05
Upper Nemahbin	LR13	115	115	18.6	9.1	0.0	0.0	0.2	1.306E+06	1.332E+06
Fox Lake	UR03	1062	1063	5.8	0.0	27.4	271.9	27.6	2.215E+06	2.518E+06
Sinnissippi	UR08	1155	1158	1.5	0.0	29.8	0.0	30.3	2.000E+06	2.791E+06
Okauchee	UR08	480	481	28.7	3.0	266.0	266.3	266.3	1.692E+06	1.895E+06
Beaver Dam	UR03	2648	2661	2.4	0.0	265.4	0.0	265.5	4.719E+06	5.123E+06
Nagawicka	LR13	371	371	27.4	11.0	0.0	0.0	0.2	5.078E+06	5.163E+06
Delavan	LR01	838.5	838.5	17.1	6.4	28.9	0.0	29.2	1.908E+06	2.226E+06
Koshkonong	LR11	4233	4237	2.1	1.5	236.5	236.5	236.7	8.153E+06	8.958E+06
Kegonsa	LR06	1299	1300	9.4	5.2	256.9	0.0	257.0	8.419E+06	8.567E+06
Waubesa	LR08	842	843	10.4	8.2	257.4	257.6	257.6	5.075E+06	5.203E+06
Monona	LR08	1325	1326	19.5	12.8	0.0	257.6	0.1	2.115E+07	2.135E+07
Mendota	LR09	3983	3985	25.0	12.8	258.8	0.0	258.9	6.359E+07	6.419E+07

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Point Sources

Point source data including flow records and phosphorus concentrations was collected from DNR permits and a questionnaire sent to all permitted dischargers in the Rock River basin. The survey requested treatment plant operators and industrial source managers to provide available information for their facility on both flow and phosphorus concentrations.

Discharge data was gathered for the years 1980, 1985, 1990, and 1993 through 1998 to calculate an average flow for each month. An average value from the endpoints of the data gap was calculated and inserted into missing records. For example, for the years 1981 to 1984 the average value of the flow from January 1980 and January 1985 was interpolated for the month of January 1981 to 1984. The only exception to this method was that 1994 data was averaged with 1990 data to fill data gaps for 1991 and 1992, since 1993 was an unusually wet year. For permitted dischargers with data for 1993 through 1998 only, average monthly discharges were computed. These average monthly values were used for the period back to1960. If data points were missing for the years between 1993 and 1998, an average of the existing monthly values was computed and inserted for missing data.

Monthly phosphorus loads from point source discharges were calculated several ways. Where less than one year of data was available, the average concentration was calculated from the available data and loads were calculated using average monthly discharges. When no phosphorus data was available, the monthly phosphorus loads were calculated based on an assumed average domestic phosphorus concentration of 4.0 mg/l (literature value) and the reported average monthly flows. If a full year of phosphorus concentrations was available, they were used in conjunction with the average monthly flows to calculate an average monthly phosphorus load. If more than one year of data was available, average monthly phosphorus concentrations were calculated to determine the average monthly phosphorus loads.

Point source loads were calculated for existing conditions and for that stipulated under NR 217. Loads under NR 217 conditions were calculated using 1 mg/l except for municipal sources with monthly loads less than 120 pounds per month and industrial sources with loads less than 50 pounds per month. Discharges from point already below 1 mg/l remained the same under existing and NR 217 conditions. Alternative limits above 1 mg/l were not evaluated.

Cooling water discharges were not considered in this study. The assumption is that the water is non-contact (free of additives) and being withdrawn from the system and replaced with minimal losses.

Appendix E provides a summary of the point source input files used.

Land Use, HRUs, and Management Files

Land use information was obtained from the WISCLAND satellite imagery. This information was imported as a grid into *ArcView*™., and clipped by sub-watersheds. Land use information was divided into several types, including open water, forest, urban, wetland, barren, and agricultural. Agricultural lands were further classified as corn, forage, pasture, and other row crops. The other row crops consisted mostly of soybeans with the remainder being commercial vegetable farms.

Within the Rock River Basin, the land use distribution is about 62% agriculture, 11% grassland and pasture, 10% forest, 9% wetland, and 8 % urban and highways. Figure 4.4 shows the land use for the Rock River Basin.

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Each unique land use within the SWAT model was assigned a designation as a Hydrologic Response Unit (HRU). Individual HRUs were determined based on land use, (specifically crop rotation), agricultural management practices, and soil properties. Typical crop rotations were determined based on the most common cropping practices within the Rock River Basin.

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LAND USE MAP

(ARCVIEW FIGURE)

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At any given time, not all farm fields are in the same year of a rotation. To account for this, multiple files where generated for a rotation to simulate part of a field being in one crop and the other in a different crop. The assumption is that in a rotation, a farmer will typically have half his fields in one crop and the other half in a different crop. This may not be always the case however given the scale of the modeling effort this assumption was to define the conditions. For example, in a three year corn-soybean rotation three files were created: “2 year corn – 1 year soybean”, “1 year corn – 1 year soybean – 1 year corn”, and “1 year soybean – 2 year corn”. To control the number of files created, the dairy rotation was modeled as three years corn –three years hay instead of the more typical 4 years of hay.

A system was created to generate the rotations based on the WISCLAND coverage and USDA Agricultural Statistics. The WISCLAND coverage distinguished between corn, forage, pasture, and other row crops. Sub-watersheds were used to divide the land use coverage up and the distribution of land use was examined for incorporation into rotations. All land use classified as forage was put in the dairy rotation with an equal amount of corn. The remaining corn was divided between continuous corn and corn soybean rotations based on the amount of other row crops. This process was “semi-automated” with spreadsheets, however, was not fully automated because examination of each sub-watershed was required because of unique rotations and cropping combinations. The distribution of crops was then summed by county and checked against USDA Agricultural Statistics averaged over the last couple years. Local conservation agents identified areas with unique practices such as sod farms and large vegetable rotations.

The rotations include:

- <u>Corn – Soybean</u>: Two corn –soybean rotations were created: a one-year corn soybean rotation and a 3-year corn soybean rotation. The corn was harvested as corn grain.

- <u>Continuous Corn</u>: A continuous corn rotation was created and used mostly in Rock and Walworth counties. The corn was harvested as grain.

- <u>Dairy Rotation</u>: A six-year dairy rotation corn – hay was created. Manure was applied to the corn and on the last cutting of hay. The corn was harvested as silage.

- <u>Vegetable rotations</u>: Vegetable rotations were created for sweet peas and sweet corn. These rotations were most prevalent in Dodge County.

Dane County LCD, Jefferson County LCD, Dodge County LCD, and UW-Madison Extension reviewed these rotations.

It was important to distinguish between corn grain and corn silage because harvesting corn as silage leaves considerably less residue on the field than corn grain. The amount of residue in turn affects the potential for erosion. USDA Agricultural Statistics were consulted to help determine the ratio of grain to silage, however, these numbers are not always accurate because of how farmers report harvests (Baumgart, 1998). UW-Extension suggested close to equal amounts of corn grain and silage with the silage being dominant in a dairy rotation.

Statewide average planting dates were available from the USDA. Because, average dates were available by crop, but not location, adjustment of the dates was required. On average, the southern portion of the state plants crops ahead of the northern part of the state thus 3 to 5 days was subtracted from the average statewide planting date. Dates were then reviewed by UW-Extension and further adjusted as needed.

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Crop rotations were further subdivided by typical tillage practices obtained from a recently completed USDA Tansect Survey. The results of the survey were applied to the SWAT analysis because the survey data provided a high degree of consistency throughout the basin. The transect survey divided tillage practices by percent residue on the field which was then correlated to tillage implements. Table 4.3 summarizes the break out and assumed tillage practices. Transect survey data is summarized in Appendix A. SWAT models different tillage practices by adjusting the depth of tillage and the mixing efficiency.

TABLE 4.3
SUMMARY OF CROPLAND TILLAGE PRACTICES USED IN THE SWAT INPUT FILES

Transect Survey Residue	Assumed Tillage Practice	SWAT Mixing Efficiency
Conventional: < 15% Cover	Moldboard Plow	98 %
Other: 15-30% Cover	2 passes w/ Chisel Plow	75%
Mulch: > 30% Cover	1 pass w/ Chisel Plow	37%
No – Till	No –Till	NA

The survey summarized the percent and actual acreage of tillage practice for each crop by WDNR watershed. For generation of management files in SWAT, the hierarchy of tillage practices was that conventional tillage (moldboard plow) was first applied to the dairy and forage rotations because these operations typically use conventional tillage to kill off the alfalfa crop. The remaining tillage practices were then divided up among the cash grain rotations. It should also be noted that SWAT does not have an input for percent residue, rather the tillage practice is modeled as percent incorporation. The actual percent residue varies over time because SWAT models the breakdown of residue into organic matter or humus.

Typically tillage occurs either in the fall or the spring and is dependent on the crop being planted, the type of soil, and soil moisture. Historically, there is a tendency to till in the fall to ensure that a wet spring will not disrupt planting operations. The timing of tillage practices varies greatly from operation to operation. This is important because the timing of tillage effects the residue decomposition. Fall tillage leaves less residue than tillage operations preformed in the spring just before planting. To generate input files a hierarchy was established based on typical practices. All moldboard plowing was performed in the fall. The reasoning being that the soil needs to be drier for moldboard than chisel and often, spring conditions are too wet for moldboard plowing. Tillage on hydrologic soil class D was also assumed to be fall tilled because of the tendency to remain wet in the spring. Conservation tillage was performed in the spring

In addition to tillage and crop rotations, nutrient management practices vary greatly across the basin. Again, a standard approach was created based on average and typical application methods and practices. UW-Extension was consulted on nutrient management practices. Two scenarios were devised, (1) to model current practices and (2) to model nutrient application rates recommended by UW-Extension. Commercial fertilizer was applied based on the information provided by UW-Extension. This information was obtained from surveys of agricultural operations performed by UW-Extension. The data is summarized in Table 4.4.

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TABLE 4.4
TYPICAL NUTRIENT APPLICATION RATES
COMMERCIAL FERTILIZERS

Nutrient	**Average Recommendation**	**Average Applied**	**High Range Applied**
Nitrogen	160 lbs/A	188 lbs/A	484 lbs/A
Phosphorus	40 lbs/A	91 lbs/A	383 lbs/A
Potassium	25 lbs/A	207 lbs/A	940 lbs/A

Actual nutrient application rates vary greatly and recommended application rates should be based on results of soil analysis for each field and crop requirements, however, because this data was not available for each field, average values were entered into SWAT.

Additional data on the timing and method of nutrient applications was obtained from UW-Extension. In all rotations, commercial fertilizers were spring applied during planting. Manure application occurred several times during the year including in the fall after harvest and in the spring before planting. Manure application rates were determined based on an examination of the number of animal units within a county. This data was available from the USDA Agricultural Statistics and was summarized by county. On average, a typical dairy cow produces 120 pounds of manure per day or 21.9 tons per year on a wet weight basis (ASAE STANDARDS, 1998). Manure loading rates were generated based on typical generation rates and the number of animal units. Because most of the manure is generated by diary operations, manure was applied only to the dairy crop rotation. Application rates varied based on the amount of manure generated and the acreage of land dairy rotation.

A summary of the HRUs and sub-watersheds is provided in Appendix F.

Animal Lot Runoff

Due to the lack of data across the basin, phosphorus runoff from individual barnyards was not modeled. Originally, it was planned that barnyards would be simulated with the computer model BARNY under several conditions and average sediment and phosphorus loads would be generated and inserted as a point source for barnyards. However, based on the lack of data on barnyards this approach became cost prohibitive. Barnyards were simply absorbed by the general agricultural nonpoint loading generated by SWAT. Given the wide range of runoff potentials from barnyards, it was agreed by the involved parties that this was the best approach.

Urban Areas:

Urbanization and the associated changes in land use have been significant within portions of the basin. During the simulation period, significant expansion of urban areas occurred, however, constructing a model framework for simulating the changes in the spatial distribution throughout the simulation period is not feasible for purposes of this project. The extent of urbanization was left constant to that level displayed on the WISCLAND coverage.

Within SWAT, two methods were available for modeling pollutant loads from established urban areas. Method 1 uses the USGS regression equations as described by Driver and Tasker (1988). Method 2 uses a pollutant build-up and wash off routine. Both methods were run and results were compared to the loadings generated by the Source Loading and Management Model (SLAMM). After examining the two methods, it was found that the build-up wash off method best simulated the SLAMM results from the urban areas.

The WISCLAND land use divided urban areas into two classifications: (1) high intensity and (2) low intensity. SWAT management files were created for each of the classifications. The high intensity was generated to reflect commercial and industrial land areas and the low intensity areas were created to reflect residential areas. Model inputs include curb density, maximum amount of sediment allowed to build-up, the period for build-up, average pollutant concentrations, and population density. These parameters were set to the default values and then adjusted to match typical Wisconsin values. Average pollutant concentrations were obtained from USGS and WDNR publications cited above.

Several shortcomings were noted in the SWAT urban routines most notably, the lack of flexibility in modeling different land uses. As a result, a new urban routine was developed in cooperation with the WDNR and Texas A&M. This routine has much more detailed urban routines however it was not completed in time for incorporation into this project.

While examining urban areas, concerns regarding construction site runoff were raised by USGS and WDNR. Historic monitoring has shown significant sediment and phosphorus loads stemming from construction sites. In response, it was proposed to model the construction sites as an HRU with the management options set to a fallow field. The land area devoted to construction sites was to be based on published growth rates and land area under development. Average annual values (for acres under construction and sediment rates from construction sites) were to be utilized in the simulation, however, insufficient information was available to generate such estimates. Table 4.5 shows the relative population growth by watershed within the Rock River. It was believed that this data could be used as a surrogate indicator of which watersheds are experiencing increased erosion rates due to construction, however, Earth Tech was unable to establish a relationship between population growth and acreage of construction. As a result, the sediment and phosphorus loads due to construction sites were not broken out separately in the model results.

TABLE 4.5 ESTIMATED POPULATION GROWTH BY WATERSHED

Watershed	Growth Estimate (Number of People)	Percent
LR01	2674	3.9%
LR02	4853	7.0%
LR03	4375	6.3%
LR04	532	0.8%
LR05	0	0.0%
LR06	3236	4.7%
LR07	2217	3.2%
LR08	12257	17.7%

Watershed	**Growth Estimate (Number of People)**	**Percent**
LR09	11096	16.0%
LR10	12535	18.1%
LR11	1135	1.6%
LR12	3257	4.7%
LR13	3011	4.3%
LR14	664	1.0%
LR15	212	0.3%
UR01	827	1.2%
UR02	127	0.2%
UR03	460	0.7%
UR04	0	0.0%
UR05	512	0.7%
UR06	227	0.3%
UR07	686	1.0%
UR08	806	1.2%
UR09	433	0.6%
UR10		0.0%
UR11	2517	3.6%
UR12	211	0.3%
UR13	459	0.7%

Note: Percent growth based on growth experienced by entire Rock River Basin.

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Model Modifications

Numerous modifications were made to the SWAT code to create the version of the model that was used for this project. The initial version of the model used for this study was a modified version of the SWAT 98 code that was provided by Paul Baumgart. This version of the model already had several modifications resulting from the work performed on the Fox River Basin. These modifications included changes to the:

- evapotranspiration routine,
- sediment equations,
- snow melt routine,
- snow cover – TSS reduction equation,
- snowfall threshold temperature,
- groundwater module,
- erosion control P factor,
- transmission losses, and
- modifications to the input/output format (Baumgart, 1998).

During the course of this project, several additional modifications were required or made of the code. The major modifications are listed below. A number of these changes were incorporated into SWAT 2000 which was available in BETA version just as this project was being completed.

<u>Slope and channel width</u>: Originally, it was planned that the AVSWAT interface would not be used on this project, however, a BETA version was available when modeling work commenced. The AVSWAT interface was used to delineate watersheds and obtain several input factors (slope, slope length, area, etc.) because it provided a consistent, uniform, and repeatable method for determining the inputs. It was during this process that it was discovered that the interface was not correctly determining subwatershed slope and channel characteristics. Examination of the code revealed an error in the code for determining slope. A similar error was found in ESRI's spatial analyst. The problem stemmed from the units used in the DEM. The distance units were in meters and the elevation units were in feet, which caused the incorrect slope to be calculated. Alteration of the conversion units in the AVSWAT routine corrected this problem.

Channel width and depth are determined using equations relating accumulated flow to the channel characteristics. While the average channel depth seemed accurate, the channel widths were far too wide. On average, the channel widths seemed double actual widths. As such, dividing the AVSWAT calculated width by two provided a quick fix. It was not clear if the overestimation of channel width was an artifact of incorrect slope determinations or some other problem. Texas A&M has reviewed these routines and has modified them in SWAT 2000.

<u>Water Balance</u>: During modeling of the pilot areas it was noted that SWAT 98 under predicted surface runoff during extremely wet years. For example, Jackson Creek had a monitored runoff of 17.82 inches in 1993 while the model predicted only 9.21 inches. When looking at the results, the extremely high ET rates predicted by the model verses the actual rates which were somewhat depressed could explain this discrepancy in the water balance. The depression in actual ET was a function of poor crop performance, while the model predicted high crop yields because of the available moisture. In reality, the excessively high moisture hindered crop growth. SWAT 98 allows for nutrient stress and water stress on plant growth. However, SWAT allows water stress on plants only due to *lack* of water not an excessive amount of water. Attempts were made to minimize the effect of high ET rates by decreasing the evaporation

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coefficients. This increased the surface water yield for 1993, however, it caused an over prediction of runoff for the remaining years. To alleviate this, code was added to the SWU (plant soil water uptake) parameter to limit plant uptake of water when total soil water approaches field capacity and new code was added to the PERC parameter to limit percolation when the entire soil profile approaches field capacity. These modifications will also be included with SWAT 2000.

Point Source Data and file import: Originally, SWAT 98 allowed for input of measured data as either daily or average annual values. Not enough data was available for the daily input and the average annual did not capture the variability given the variety of point sources, which included canneries. To capture the variability without creating large input files it was decided a monthly input format would be appropriate. SWAT 98 was modified to accept monthly inputs. This modification is being carried on in SWAT 2000.

In addition to adding the monthly input option, it was noted that the daily format did not produce consistent results. The daily format was being used to save the results from an upstream model run and insert it at the head of the next reach. This approach was required due to the size of the Basin and no problems were expected, however, during review of results it appeared that the files were not always being correctly read in. Examination of the code revealed several errors that required correction. These corrections will also be in SWAT 2000.

Array Initialization: During review of calibration data it was noted that simulations did not consistently produce identical results. The initial reason was an error in the file format, however, it was later found that several of the arrays in the model were not reinitialized at the start of a model run. Thus, a model run started with the final values from the previous run in the arrays. This error was corrected and will be carried through on the SWAT 2000 code.

Cropland Residue Mixing Efficiency: In the code provided by Paul Baumgart, the mixing efficiency for a moldboard plow was increased from 1.0 to 1.07 to ensure that no residue was left. If this was not done, changes to other tillage practices did not show the reductions in sediment commonly documented by field scale studies. During this study it was found that this modification had an additional unintended affect. When the mixing efficiency was set to a value greater than 1.00, negative organic phosphorus runoff values from the 1st rainfall event following moldboard plow tillage were reported. This error was corrected and modifications to the tillage routine have been made in SWAT 2000 to better account for the effect of residue level left after tillage.

Biological Mixing: In SWAT 98, the biological mixing factor which accounts for the mixing mainly due to earthworms was in the basin file (*.bsn) meaning that an entire basin had to be given the same value. This is not a significant issue under conventional tillage, however no-till results in large increases in earthworm activity. The increased earthworm activity in turn causes considerable mixing and development of cracks for infiltration. One study noted a doubling of earthworm activity under no-till systems (Kladivko, 1995). Under the current SWAT code structure, this mixing could not be accounted for. As a result, initially no-till management scenarios did not produce the reductions in flow and sediment commonly documented by field scale studies. To produce similar results as the field studies, the CN had to be artificially lowered to cause reduction in runoff. Code for SWAT 2000 has been modified so that biological mixing can be adjusted in the management file at the HRU level.

Reservoir Routine: Initially, there was a clarification required on the flow units for the reservoir outflow. The manual indicated cubic meters per second instead of the cubic meters per day required in the code. During calibration, it was noted that phosphorus loads remained unaffected after passing through a reservoir. Sediment was settled out, however, the routines for phosphorus did not appear to be working correctly. SWAT 2000 has a completely revamped reservoir routine utilizing discrete particle settling for sediment, first order kinetics for nutrients, and chemical kinetics for pesticides. Since these routines were not available during this project, the existing reservoir routine was modified to simulate phosphorus fate and transport. It was assumed that organic phosphorus (phosphorus attached to sediment) would settle out at the same rate that sediment does in the model and soluble phosphorus passes through without changing. Given 1) the dynamics in a reservoir and their tendency to act as sinks and sources and 2) that the goal of this project was to determine mass loading and not route phosphorus this appeared the best approach.

<u>Pond Routine:</u> As with other routines, the pond routine within SWAT 2000 has been completely revamped, however, this version was not available during this study. With the exception of some changes in units, the pond routine in SWAT 98 is the same as that in SWAT 97. During calibration, it was noted that the ponds did not affect the organic phosphorus (sediment phosphorus) load when the contributing area was set to 1.0 (representing 100% of the watershed contributing flow to the pond). When the contributing area was set below 1.0, organic phosphorus was settled out. To avoid this problem, the contributing area was never set higher than 0.98. Logically, the organic phosphorus load should be affected when the entire subwatershed flows through the pond, particularly given that sediment yields are still affected.

<u>Urban Routine</u>: When modeling started, SWAT 98 had a simplified urban routine. During the project modifications were made which allowed for the use of either the USGS regression equations or build-up wash off method. The build-up wash off method was selected for this project and several adjustments were made to the parameters based on results from SLAMM modeling runs for the Midwest. These modifications are continued in SWAT 2000, which includes additional urban land use classifications and modified routines.

<u>Phosphorus Routine</u>: Most of the modifications to SWAT 98 dealt with the hydrology however once results were generated, several anomalies were noted in the phosphorus loads. A problem was identified in the code because the results for the phosphorus loads under various BMP scenarios were not consistent with those found in literature reviews of field scale tests. A step by step review of the model code revealed an error in the phosphorus routine dating back to its predecessor EPIC.

SWAT had split phosphorus into two “pools”: soluble and organic. The organic pool accounted for organic phosphorus from manure applications or other natural sources. The soluble pool accounted for the labile (soluble) phosphorus and the phosphorus attached to sediment. This produced results under existing conditions that were dominated by the soluble pool that supposedly included sediment phosphorus. This result was consistent with the observed partitioning of phosphorus. However, once BMPs were applied, it was found that phosphorus loads increased. This is not consistent with literature values and led to a re-examination of the model code.

Examination of the model code revealed that the model was tracking four pools of phosphorus but only reporting two. The other two pools were the active and reactive pools tied to the sediment. It was also found that the model treated the soluble pool as 100% soluble with no phosphorus interactions with sediment. Thus the largest pool of phosphorus (phosphorus attached to sediment) was not being reported. Even though the model was a not reporting the complete phosphorus load, the total phosphorus loads for existing conditions mimicked those of gaging stations because phosphorus was being over applied in the model. This over application was the result of an error in the input format. The model requested inorganic phosphorus applications in the form of pounds of phosphorous but treated it as phosphate. In

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addition, manure applications were made on a wet weight basis but calculated nutrient loads from manure were performed on a dry weight basis causing excess phosphorus to be applied (dry weight for manure is 0.14 times wet weight).

Corrections were made to the code so that all four pools of phosphorus were reported and that the correct amounts and proportions of phosphorus were being applied. The organic pool remained the same, the soluble pool was adjusted to report just the labile phosphorus, and the reactive and active pools were combined and used to report the sediment load. When the new routines were used, reductions in phosphorus akin to those found in field scale tests were observed. Phosphorus loads were reduced as sediment delivery was reduced. These modifications are being incorporated into SWAT 2000 and nutrient loads generated by SWAT prior to this modification should be closely examined.

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