Predicting Sediment and Phosphorus Loads in the Rock River Basin Using SWAT


Abstract: The Rock River is considered degraded from excessive amounts of phosphorus. Individual programs are ongoing to reduce phosphorus from point and nonpoint sources. However, a comprehensive phosphorus management approach may prove more cost effective and beneficial. To be successful, such an approach must take into consideration phosphorus from all sources and seek geographically targeted, cost-effective, and holistic solutions. This study utilized the SWAT (Soil and Water Assessment Tool) model to quantify phosphorus sources throughout the basin and quantify impacts from the application of basin-wide BMPs. Results of this study indicate that, under existing land use and management conditions, an average annual phosphorus load of approximately 764,000 kg enters the Rock River and its tributaries. Point sources account for 41% of this value, and nonpoint sources account for 59%. Model results show that, under existing conditions, approximately 160,000 tons of sediment is delivered to the streams and surface water bodies on an average annual basis. Modeling results indicate that implementation of improved tillage practices (predominantly conservation tillage) can reduce sediment yields by almost 20%.

Keyword. SWAT, Water quality, Hydrologic modeling, Sediment, Phosphorus.

Throughout the promulgation of Administrative Code NR 217, wastewater treatment facilities in Wisconsin must achieve an effluent concentration for phosphorus of 1 mg/L. The administrative code allows for alternative limits if it can be demonstrated that achieving the 1 mg/L limit will not “result in an environmentally significant improvement in water quality...” [NR 217.04(2)(b)1]. In response to NR 217, a group of municipal wastewater treatment facilities initiated the formation of the Rock River Partnership (RRP) to assess water quality management issues within the Rock River Basin in an integrated watershed–based approach. Representative members of the RRP include state agencies, municipal wastewater operators, industries, private citizens, and environmental organizations.

The World Resources Institute (WRI) performed an initial study jointly sponsored by the RRP and the Wisconsin Department of Natural Resources (WDNR). The purpose of the study was to seek water quality solutions across all media, and not just pursue additional reductions from point sources. Results indicated that nutrient trading or pollutant trading was a viable option to meet the water quality objectives for the Rock River Basin. Based on results of the WRI study, a second more detailed study was funded jointly by the RRP and WDNR to look at the basin in more detail. A significant portion of the study required a modeling effort to determine the magnitude of various nutrient sources and determine potential reductions through the implementation of global best management practices.

Project Setting

The Rock River Basin (RRB) covers approximately 9,708 square kilometers and lies within the glaciated portion of south central and eastern Wisconsin (fig. 1). The most dominant geologic features are the extensive drumlin fields in Dodge County and portions of Dane, Columbia, and Jefferson counties. The RRB has approximately 6,265 total river kilometers, of which about 3,089 kilometers are classified as perennial. There are approximately 443 lakes and impoundments in the watershed, covering approximately 23,400 hectares. The WDNR divided the basin into two management units, the upper (4,905 square kilometers) and lower (4,805 square kilometers). These basins are further subdivided into 28 watersheds, with 15 in the lower RRB and 13 in the upper RRB. For the purpose of modeling, these watersheds were further divided into 116 sub–watersheds.

The dominant land use in the basin is agriculture, with crops ranging from continuous corn and corn–soybean rotations in the south to a mix of dairy, feeder operations, cash cropping, and muck farming in the north. Table 1 provides a summary of land uses within the basin. Agricultural runoff has often been targeted as a primary source of phosphorus loading to streams, lakes, and impoundments in southern Wisconsin. Phosphorus, an essential element for all plant life, can be the growth–limiting factor for algae and other aquatic vegetation in surface waters. When phosphorus enters surface waters in substantial amounts, it can become a pollutant by contributing to nuisance growth of algae and other aquatic plants and accelerating eutrophication. There is a general conclusion that of all the nutrients necessary for
algal and aquatic plant growth, it is the phosphorus level in water bodies that controls excessive growth (Sharpley et al., 1993). While the direct human health risks of eutrophication are not well documented, the process can cause odor, fish kills, habitat destruction, and a general degradation of the aesthetic and recreational value of the natural environment.

The critical concentration of phosphorus that accelerates growth of algae and other aquatic plants in Midwestern lakes is around 0.01 ppm or above for dissolved phosphorus and 0.02 ppm or above for total phosphorus (Daniel et al., 1998). The required concentration of phosphorus in the soil solution for normal plant growth is usually 0.20 to 0.30 ppm. Thus, frequently the phosphorus concentration in the runoff leaving agricultural fields exceeds the critical value for aquatic plant growth. The concentration and amount of phosphorus in the runoff including sediment depends to a large extent on crop production practices. In southeast Wisconsin, historical cropping factors have caused a surplus of phosphorus in the soil profile. Estimates indicate 50 years or more of excess phosphorus in the soil profile. Since 1970, phosphorus addition, generally in the form of fertilizer and/or livestock manure, has exceeded removal through crop harvesting. However, reductions in fertilizer use and reductions in the number of dairy cattle in Wisconsin have reduced this imbalance (Bundy, 1998).

**Model Goals and Selection**

The focus of the modeling is to construct an intermediate–level, macro–scale model to better quantify phosphorus loads from point and nonpoint sources throughout the basin. The three major goals of the modeling effort are to estimate: (1) average annual phosphorus load from external sources to the Rock River surface water system, (2) the relative contribution of phosphorus loads from nonpoint and point sources, and (3) the changes in annual phosphorus loads resulting from the application of global best management practices (BMPs) and point–source controls (based on NR 217 effluent levels).

Models evaluated included SWAT (Soil and Water Assessment Tool), HSPF, WINHUSTLE, AgNPS, XP–SWMM, and unit area loadings. Evaluation criteria included model data requirements, capability to attain project objectives, and model complexity. The selected model was SWAT 98.1, the most recent version of SWAT (Arnold et al., 1996, 1999). SWAT is the continuation of a long–term effort of nonpoint–source pollution modeling with the USDA Agricultural Research Service. The purpose of the model is to predict the effect of different management techniques on hydrology, sediment, and agricultural chemical yields in large ungaged watersheds. SWAT is a continuous daily time–step model that incorporates the effects of weather, surface runoff, evapotranspiration, crop growth, irrigation, groundwater flow, nutrient and pesticide loading, and water routing on the long–term impacts of varying management procedures.

**Table 1. Summary of land use within the Rock River Basin.**

<table>
<thead>
<tr>
<th>Land Use</th>
<th>Area (km²)</th>
<th>Percent of Basin (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural</td>
<td>6019</td>
<td>62</td>
</tr>
<tr>
<td>Grassland and pasture</td>
<td>1069</td>
<td>11</td>
</tr>
<tr>
<td>Forest</td>
<td>971</td>
<td>10</td>
</tr>
<tr>
<td>Wetlands and open water</td>
<td>872</td>
<td>9</td>
</tr>
<tr>
<td>Urban and other development</td>
<td>777</td>
<td>8</td>
</tr>
</tbody>
</table>
practices. Details concerning how these processes are simulated can be found in the SWAT user’s manual (Arnold et al., 1996, 1999).

Even though SWAT was designed for use in ungaged watersheds, the RRB model was calibrated to available data from approximately 23 USGS gaging sites located throughout the RRB. An average annual phosphorus load could then be calculated for the basin using the calibrated model and compared (validated) to data collected in 1999 from the monitoring sites funded by the RRF. Once existing loads were established, the model was used to evaluate the effects of various management techniques (point and nonpoint sources) on phosphorus loading. It is important to note that even after calibration, the model will predict flows closer to the monitored values in some areas than in others. Variations across the basin, including land use, geology, and soils, will all contribute to determining the hydrologic response. These variations may be subtle or immediately apparent; however, due to the lack of sufficient monitoring and specific input data, not all of these variations can be captured.

The following six scenarios were selected to assess the effect of global best management practices and the implementation of NR 21:

1. Current agricultural practices with current point–source discharges. This includes relative comparison by watershed of point and nonpoint sources.
2. Conventional tillage converted to conservation tillage and existing conservation tillage converted to no–till with current point–source discharge levels.
3. Current tillage practices with nutrient management practices employed and current point–source discharge levels.
4. Conventional tillage converted to conservation tillage and existing conservation tillage converted to no–till and nutrient management practices employed with current point–source discharge levels.
5. Current agricultural practices with point–source discharge phosphorus concentrations reduced to 1 mg/L (the level designated in NR 217).
6. Conventional tillage converted to conservation tillage and existing conservation tillage converted to no–till and nutrient management practices employed with point–source discharge levels at 1 mg/L.

Each of these scenarios was run for a 30–year period to equilibrate parameters. An average annual load was generated from predicted loads for 1989 through 1996. This period was selected because it includes high, low, and normal flow years.

**Pilot–Scale Modeling**

To ensure that modeling results would meet the needs of the study and to test specific routines in SWAT, two pilot areas were selected for testing the model and verifying its capability to accurately predict flow, sediment, and phosphorus loads. The criteria for selecting the areas included size and completeness and availability of USGS gaging and monitoring data. Two locations best met these criteria:

- **Jackson Creek at Petrie Road**: 23.2 square kilometers in size and composed of 4% urban, 76% agriculture (predominately corn–soybean rotations), 8% grassland, 8% forest, and 4% wetlands. This area was modeled as one sub–watershed subdivided into several hydrologic response units (HRUs) representing the smallest unit modeled in the RRB.
- **Yahara River at Windsor**: 190 square kilometers in size and composed of 7% urban, 73% agricultural dominated by dairy rotations (corn–hay), 7% wetlands, 9% grasslands, and 4% other. This area was broken down into five sub–watersheds each further subdivided into HRUs.

Jackson Creek at Petrie road was selected as the first area to be modeled because it encompasses one sub–watershed, the smallest scale at which the RRB was geographically subdivided (note that HRUs are the smallest units but do not have defined geographic boundaries). Jackson Creek has flow data available for 1984 through 1995 and sediment and phosphorus data for 1984 to 1985 and 1994 to 1995. Flow, sediment, and phosphorus data were divided into calibration and validation data sets. Calibration and validation periods were selected based on the distribution of high, normal, and low flow years.

Data collected for Jackson Creek were consistent with the process to be used for the entire basin, so the same level of effort was maintained in both the pilot–scale and full–scale modeling. Information was obtained from public agencies including the U.S. Geologic Survey (USGS); the Wisconsin Department of Natural Resources (WDNR); the USDA; the Wisconsin Department Agriculture, Trade, and Consumer Protection (WDATCP); and county land conservation offices (LCD). USGS historical stream flow records were obtained for 23 locations throughout the RRB. Land use information was determined from the WISCLAND (Wisconsin Initiative for Statewide Cooperation on Landscape Analysis and Data) coverage created through satellite imagery (WDNR, 1998). Individual county land conservation agents verified agricultural land use and general practices. Tillage practices were determined using a transect survey performed by the USDA in 1998. The STATSGO soil data for the state of Wisconsin were used for soil inputs, and the USGS 30–meter digital elevation model (DEM) was used to generate contours, derive average slopes, and delineate watershed boundaries. Climate data for 18 monitoring stations were obtained from the state climatologist’s office. Point–source data were collected from WDNR permit records, with additional data obtained from a survey sent to all municipal and industrial dischargers within the RRB.

For the pilot areas, HRUs were generated based on cropping and tillage practices. Based on information provided by the LCD, it was assumed that the cash crop rotations used conservation tillage (simulated with chisel plow) and that the dairy rotations used conventional tillage (simulated with moldboard plow).

The beta test version of the SWAT ArcView (AVSWAT) interface was used to automate the delineation of sub–watersheds. The AVSWAT delineation was checked against a manual delineation using USGS quads and a second delineation that was provided by the USGS. All three compared well with only slight variances. The AVSWAT interface was not used to generate the HRUs because it could not accurately account for crop rotations in its assessment because the WISCLAND land coverage does not include the temporal changes associated with rotations.
CALIBRATION AND SENSITIVITY ANALYSIS

Initial sensitivity analysis was performed on the evapotranspiration (ET) routines. The three ET options within SWAT (Priestly–Taylor, Penman–Monteith, and Hargreaves) each produced different results for the same given input. Hargreaves was selected because of its reliance on only temperature instead of wind speed and humidity, and it provided results that most closely matched the monitored data. Within the ET routine, the variables ESCO (controls soil evaporation), EPCO (controls plant uptake of moisture to account for root density), and ETCO (controls extent from which water can be drawn from the soil based on wilting point) were evaluated (Arnold et al., 1996). Groundwater influences in Jackson Creek were determined to be minimal, so not a great deal of effort was spent on evaluating groundwater parameters. Most of the effort was spent on the ET variables and generating accurate and realistic land use management files. Adjustments of all model parameters were made based on supporting data, such as known groundwater elevations and crop yields, and adjustments of parameters were maintained within the limits given in the SWAT user’s manual (Arnold et al., 1996, 1999).

Two methods for evaluation of model predictions were used during the calibration and validation periods: (1) linear regression ($R^2$), and (2) the Nash–Sutcliffe coefficient of efficiency (COE) (Nash and Sutcliffe, 1970). Regression line slopes and $R^2$ values near unity indicate a close relationship between predicted and measured yields. Predicted and measured yields were compared on an average annual basis. The validation data for Jackson Creek are listed in table 2.

An examination of the calibration and validation data indicated that in springs with high precipitation or relatively cool temperatures resulting in poor growing seasons, SWAT was less accurate (i.e., 1993). The yield for other years tended to be overestimated by the model in order to obtain the best fit to the average annual flow. Removal of 1993 (the highest runoff year) from the validation data set improves the COE to a value of 0.53. The calibrated model constructed for Jackson Creek was applied on the Yahara River with little or no adjustment of parameters except for slope factors, land use and associated management files, and soils. The initial results for the application of the Jackson Creek model to the Yahara River at Windsor watershed were poor, with greater than 100% error. The failure of the Jackson Creek model parameters to successfully predict flows for the Yahara River illustrates that all of the parameters are not uniformly applicable across the basin. A calibrated model does not necessarily mean it is correct; failure of the Jackson Creek calibrated parameters to work in the Yahara River at Windsor watershed may indicate “errors” in the calibration of the Jackson Creek model.

Examination of the two models started by taking a closer look at the parameters and physical characteristics of the Yahara River at Windsor watershed. As with Jackson Creek, the Yahara River at Windsor watershed was delineated using the AVSWAT interface. During delineation of the Yahara River at Windsor watershed, discrepancies between the drainage areas reported by the USGS and the actual area contributing to surface water flow were noted. Total water yield reported by the USGS is based on the total drainage area and often includes internally drained areas. In the model, inclusion of internally drained areas produced excess runoff and reduced groundwater baseflow. Examination of the Yahara River at Windsor watershed revealed the presence of several large internally drained areas. These areas were not present in Jackson Creek and thus were not an issue.

To identify internally drained areas, a temporary coverage created by the AVSWAT interface was used. Contributing areas were manually verified using USGS quad maps. SWAT’s pond/wetland function was utilized to account for runoff and pollutant contributions from these discrete internally drained areas. During calibration of the Yahara River at Windsor watershed, sensitivity analysis was performed on the groundwater files. All parameters were evaluated with particular attention to the “critical” parameters: alpha baseflow factor, groundwater delay, and groundwater revaporation. Details on these variables can be found in the SWAT user’s manual (Arnold et al., 1996, 1999).

In the Yahara River at Windsor watershed, adjustment of the groundwater files and identification of the internally drained areas allowed for a decrease in surface flow and an increase in baseflow, resulting in a better match to gaging data. Additional adjustment of the ET equations and adjustment of soil infiltration parameters were also required to increase infiltration potential. Once soil, groundwater, and ET equations were adjusted for the Yahara River at Windsor watershed, an acceptable fit to gaging data was obtained (table 3). After the successful calibration of the Yahara River at Windsor watershed model, the model was re–applied to Jackson Creek. Slight modifications to the groundwater file for Jackson Creek were made based on the results from a baseflow separation analysis (Arnold et al., 1995). The new model generated similar results to those of the original Jackson Creek model.

FULL–SCALE MODELING

During the modeling efforts, WDNR watershed boundaries were maintained whenever possible. Each watershed
was subdivided into sub–watersheds, which were further subdivided into hydrologic response units (HRUs) to capture the variability within the sub–watershed. Watershed delineation was performed using the SWAT ARCVIEW interface (AVSWAT) and a 30–meter digital elevation model (DEM) for the RRB clipped to the boundary of each WDNR watershed. Once boundaries were delineated, automated routines within AVSWAT were used to generate stream and hydrologic characteristics for each sub–watershed. 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.

**CLIMATE INPUTS**

Daily climate records for the period 1960 through 1999 were collected to develop the climate input files. Data were collected for monitoring stations within and surrounding the RRB. The Thiessen polygon method was used to fill missing precipitation records for individual stations. Missing maximum and minimum temperatures were replaced with average values from nearby stations. Stations were assigned to each sub–watershed by proximity measured from the centroid of the sub–watershed.

**SOILS**

Soils data were obtained from the National Resources Conservation Service (NRCS) STATSGO database. An area–weighted method was employed to determine soil parameters for each sub–watershed. Hydric soils were excluded because wetlands were simulated separately. The top four layers of each dominant soil series within an association were used to find the “average” soil properties that were assigned to 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), the influence of internally drained areas became apparent. Inclusion of the internally drained areas produced excess runoff, and exclusion of internally drained areas reduced groundwater baseflow due to reduced infiltration. Internally drained areas were identified using ArcView Spatial Analyst. The resulting coverage was 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 routine was used to simulate the baseflow contributions from the wetland. If it was mostly of open water, then the pond routine was used. If neither feature appeared, the area was rechecked against USGS quads to ensure that the area was indeed internally drained. If it was, then 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.

**WETLANDS AND PONDS**

Wetland area was obtained from the WISCLAND coverage. 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 for internally drained areas. The pond subroutine was utilized to model small lakes and ponds.

**BASEFLOW SEPARATION MODEL**

An automated baseflow separation model (Arnold et al., 1995) was used to determine the relative contributions of groundwater (baseflow) and surface water to total stream flow. The model was run on 23 USGS gaging stations located within the RRB with results used to assist in calibrating the SWAT model regionally across the basin. 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. (1995) ran the digital filter for six basins located in the Midwest and found $R^2$ values ranged from 0.62 to 0.98.

Baseflow contributions vary widely across the RRB. Results for Jackson Creek indicate that approximately 31% of the flow is from baseflow, while the Yahara River above Lake Mendota receives almost 70% of its flow from baseflow contributions. Pheasant Branch receives only 48% baseflow, while Badfish Creek receives over 90% baseflow. The city of Madison’s supply wells, which withdraw water from the aquifer underlying Pheasant Branch, and Madison’s wastewater treatment plant, which discharges to Badfish Creek, are the causes of these variations. The constant discharge 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. On average, the percent baseflow contributions to surface streams within the

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**Table 3. Calibration results for Yahara and Mendota watershed, Windsor gaging site.**

<table>
<thead>
<tr>
<th>Year</th>
<th>SWAT</th>
<th>USGS</th>
<th>Rel. Error (%)</th>
<th>SWAT</th>
<th>USGS</th>
<th>Rel. Error (%)</th>
<th>SWAT</th>
<th>USGS</th>
<th>Rel. Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1989</td>
<td>60</td>
<td>75</td>
<td>–19</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>1990</td>
<td>95</td>
<td>62</td>
<td>53</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>1991</td>
<td>90</td>
<td>76</td>
<td>18</td>
<td>3,248</td>
<td>514</td>
<td>532</td>
<td>7,869</td>
<td>2,867</td>
<td>64</td>
</tr>
<tr>
<td>1992</td>
<td>169</td>
<td>177</td>
<td>–5</td>
<td>1,117</td>
<td>1,108</td>
<td>1</td>
<td>7,219</td>
<td>3,352</td>
<td>54</td>
</tr>
<tr>
<td>1994</td>
<td>80</td>
<td>102</td>
<td>–22</td>
<td>2,443</td>
<td>2,186</td>
<td>12</td>
<td>9,341</td>
<td>9,654</td>
<td>–3</td>
</tr>
<tr>
<td>1995</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1,028</td>
<td>1,029</td>
<td>0</td>
<td>6,386</td>
<td>3,009</td>
<td>55</td>
</tr>
<tr>
<td>Average</td>
<td>102</td>
<td>106</td>
<td>–4</td>
<td>3,031</td>
<td>2,516</td>
<td>20</td>
<td>8,883</td>
<td>7,285</td>
<td>22</td>
</tr>
</tbody>
</table>

[a] $R^2 = 0.74$ and COE = 0.61.
[b] $R^2 = 0.82$ and COE = 0.75.
[c] $R^2 = 0.95$ and COE = 0.07.
Rock River Basin ranged from around 65% to 85%. Baseflow contributions increased from the upper to the lower reaches of the basin. To ensure that baseflow contributions would not be overestimated, initial values from the upper reaches and of impoundment (typically ranging between 68% to 71%) were used.

**Groundwater**

In addition to baseflow prediction, the digital filter (Arnold et al., 1995) provided estimates of several other SWAT input parameters contained in the groundwater files. A unique groundwater file was created for each gaging station and used to simulate the groundwater interactions of the drainage area above the gaging station. The remaining inputs were either determined through the baseflow separation model or estimated using typical values.

**Lakes and Impoundments**

The RRB includes many lakes, wetlands, and impoundments that affect the flow of water through the watershed. A survey found that, of the 218 dams identified in the basin, only 27 have impoundment areas greater than 300 acres, and only 14 dams 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. Selection for inclusion was 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. Average monthly maximum and minimum outflows were calculated for dams that had USGS gages at their outlets. Stage-storage information for reservoirs was obtained from WDNR dam records and reports. Minimum and maximum pool elevations were obtained from WDNR dam records and a survey of individual dam operators. Lakes without control structures were assumed to fluctuate about half a foot with 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.

To simulate aquatic interactions, SWAT simulates lakes as well mixed with a uniform distribution under steady-state conditions. Specifically, the phosphorus mass balance in SWAT was taken from Thomann and Mueller (1987). For phosphorus, SWAT assumes (1) a 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 the lake, the total phosphorus concentration in the lake, outflow volume, overall loss rate of total phosphorus from lake processes (Ks), and total phosphorus inflow. Data were collected from the WDNR, using existing monitoring records for lakes and reservoirs within the RRB for periods dating from 1960 to the 1999. Data collected included volume of lakes, total phosphorus concentration in lakes, and outflow volume. Values for Ks were estimated as outlined in Chapra and Tarapchak (1976).

To simulate sediment transport, the initial min–max sediment concentrations were determined from two sources: WDNR lake quality data and USGS sediment concentrations reported in “Measurement and Prediction of Sediment Yields in Wisconsin Streams” (Hindall, 1976). USGS gaging stations located near the outlets of lakes within the RRB were reviewed to estimate the sediment concentration values during baseflows. 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.

**Point Sources**

Point–source loads were calculated for existing conditions and under NR 217 requirements. Point–source data including flow records and phosphorus concentrations were collected from WDNR permits and a survey sent to all permitted dischargers in the RRB. The survey requested treatment plant operators and industrial source managers to provide flow data and phosphorus concentrations for their facility. Flow data were gathered for the years 1980, 1985, 1990, and 1993 through 1998 to calculate an average flow for each month. Monthly phosphorus loads from point–source discharges were calculated using one of three methods. 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 were available, the monthly phosphorus loads were calculated based on an assumed average domestic phosphorus concentration of 4.0 mg/L and reported average monthly flows. If a full year of phosphorus concentrations was available, then they were used in conjunction with the average monthly flows to calculate an average monthly phosphorus load.

**Land Use**

Land use information was obtained from the WISCLAND satellite imagery. The WISCLAND classification scale used for this study consisted of 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. Each unique land use within a sub–watershed 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 dominant cropping practices within the RRB. To account for yearly field rotations, multiple files were generated for a rotation to simulate the different crops. A simplifying assumption was that during a rotation, a farmer typically plants 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 required to define land use conditions.

A statistical system was created to generate the rotations based on the WISCLAND coverage and USDA agricultural statistics. The WISCLAND coverage distinguishes between corn, forage, pasture, and other row crops. Sub–watersheds were used to divide the land use coverage. The resulting 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 rotation based on the amount of other row crops. This process was “semi–automated” with spreadsheets but was not fully automated because examination of each sub–watershed was required due to unique rotations and cropping combinations. The distribution of crops was summed by county and checked against USDA agricultural statistics averaged over the last two years. Local conservation agents identified areas with unique practices, such as sod farms and large vegetable rotations.

The dominant rotations used in the model include:

- **Corn–soybean**: Two corn–soybean rotations were created: a one–year rotation and a three–year rotation. The corn was harvested as corn grain.

- **Continuous corn**: A continuous corn rotation was created and used mostly in Rock and Walworth counties. The corn was harvested as grain.

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

- **Vegetable rotations**: Vegetable rotations were created for sweet peas and sweet corn. These rotations were most prevalent in Dodge County.

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 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 by location, adjustment of the dates was required. On average, the southern portion of the state plants crops before the northern part of the state, so three to five days was subtracted from the average statewide planting date.

Crop rotations were further subdivided by typical tillage practices obtained from a statewide USDA–funded transect survey. Survey results were used because the survey data provided a high degree of consistency throughout the basin. The transect survey divided tillage practices by percent residue left on the field, which was correlated to tillage implements. Table 4 summarizes the tillage practices. SWAT simulates different tillage practices by adjusting the depth of tillage and the mixing efficiency. The transect survey summarized the percent and actual acreage of tillage practice for each crop by WDNR watershed. For generation of management files in SWAT, a hierarchy of tillage practices was applied. 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 among the cash grain rotations. It should be noted that SWAT does not have input for percent residue; instead, the tillage practice is modeled as percent incorporation. Actual percent residue varies over time because SWAT models the breakdown of residue into organic matter or humus.

The timing of tillage affects the residue decomposition. Fall tillage leaves less residue over the winter and early spring than tillage operations performed in the spring just before planting. Typically, tillage occurs either in the fall or the spring and is dependent on the crop being planted, the type of soil, and the soil moisture. Historically, there is a tendency to till in the fall to ensure that a wet spring will not disrupt planting operations. Again, because of the scope of this project, a hierarchy was established based on typical practices. All moldboard plowing was performed in the fall because soil needs to be drier for moldboard use. Tillage on hydrologic soil class D was also assumed to occur in the fall because of its tendency to remain wet in the spring. Conservation tillage was performed in the spring.

In addition to tillage and crop rotations, nutrient management also had to be included. Again, a standard approach was created based on average and typical application practices. UW–Extension was consulted on nutrient management practices. Commercial fertilizer was applied based on the information provided by UW–Extension. This information was obtained from surveys conducted by UW–Extension and is summarized in table 5. Additional data on the timing and method of nutrient applications was obtained from UW–Extension and county LCD staff. In all rotations, commercial fertilizers were applied during spring planting. Manure applications were performed several times during the year. Manure application rates were determined based on an examination of the number of animal units within a county. These data were available from the USDA agricultural statistics and summarized by county. On average, a typical dairy cow produces 54.4 kg of manure per day, or 20 metric 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 dairy operations, manure was applied only to the dairy rotation. Application rates varied based on the amount of manure generated and the acreage of land in dairy rotation.

### Table 4. Summary of cropland tillage practices used in the SWAT input files.

<table>
<thead>
<tr>
<th>Transect Survey Residue</th>
<th>Assumed Tillage Practice</th>
<th>SWAT Mixing Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional (&lt;15% cover)</td>
<td>Moldboard plow</td>
<td>98</td>
</tr>
<tr>
<td>Other (15% to 30% cover)</td>
<td>2 passes with chisel plow</td>
<td>75</td>
</tr>
<tr>
<td>Mulch (&gt;30% cover)</td>
<td>1 pass with chisel plow</td>
<td>37</td>
</tr>
<tr>
<td>No–till</td>
<td>No–till</td>
<td>NA</td>
</tr>
</tbody>
</table>

### Table 5. Typical nutrient application rates of commercial fertilizers.

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Average Recommendation (kg/ha)</th>
<th>Average Applied (kg/ha)</th>
<th>High Range Applied (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>179</td>
<td>211</td>
<td>543</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>45</td>
<td>102</td>
<td>430</td>
</tr>
<tr>
<td>Potassium</td>
<td>28</td>
<td>232</td>
<td>1056</td>
</tr>
</tbody>
</table>

### 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 98.1 code. This version of the model already had several modifications resulting from the work performed on the Fox River Basin in Wisconsin (Baumgart, 1998). These modifications include changes to the evapotranspiration routine, the sediment equations, the snowmelt routine, the snow cover and TSS reduction equation, the groundwater module, the erosion control P factor, the transmission losses, and modifications to the input/output format (Baumgart, 1998). During the course of this project, several additional modifications were made to the code. The major modifications are listed below. Note that SWAT 2000 incorporates these changes as well as some additional modifications.

**WATER BALANCE**
During modeling of the pilot areas, it was noted that SWAT 98.1 underpredicted 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. High ET rates predicted by the model versus the actual rates that had been depressed due to poor crop growth explained the discrepancy. SWAT predicted high crop yields because of the excess available moisture, but in reality the excessively high moisture hindered crop growth. SWAT has crop growth responses for nutrient stress and water stress due to lack of water but not due to excessive amounts of water. To alleviate this, code was added to limit plant uptake of water when total soil water approaches field capacity, and to limit percolation when the entire soil profile approaches field capacity.

**RESERVOIR ROUTINE**
It was assumed that phosphorus attached to sediment would settle out at the same rate as sediment, and that 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.

**MODEL CALIBRATION AND VALIDATION**
Once SWAT was calibrated and validated for the pilot areas, a similar process was employed to model the remainder of the basin. To accommodate the routing structure of SWAT, the RRB was divided into seven separate models. These runs were linked together by a series of files that allowed the output from one area to be used as input for the next downstream model. The selection of the seven 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.

SWAT was first calibrated to flows, then to sediment, and finally to phosphorus. The two pilot areas were used as the primary calibration sites. The remaining gaging stations had primarily long-term flow data with nine stations having one year of continuous sediment and phosphorus data. The first calibration step was to match the hydrology. This was accomplished by balancing surface water, groundwater, and ET to match corresponding measured values. Adjustment of surface water and groundwater was made by adjustment of the groundwater parameters, the runoff curve numbers, soil hydraulic conductivity and bulk density, and the crop growth routine. Adjustment of ET was made based on adjusting the ET parameters and the crop growth routine. The portioning between groundwater and surface flow was estimated using the base-flow separation model. ET rates were verified by data collected from the UW--Extension Agricultural Research Station at Arlington.

Calibration and validation was performed against data obtained from the USGS gaging stations. Several discrepancies in data obtained from USGS gaging stations were noticed. Particular periods of concern are during the spring when ice jams may cause gages to record artificially high flow measurements. The USGS attempts to flag these data, but there were several occurrences when ice jams may have been missed. If high flows in early spring could not be correlated with a precipitation event, then it was assumed that an ice jam condition existed, and the reported flows were adjusted based on flows before and after the ice jam.

The spatial and temporal variations in rainfall were addressed during calibration and validation. Often during modeling a precipitation event occurred at one station, but changes in monitored flow were not observed in an adjacent watershed. Due to the insufficient number of stations, climate data had to be assigned to adjacent watersheds. This is important to remember when viewing output hydrographs. At times, the monitoring data showed a large runoff event while the model had not predicted one, or vice versa. When precipitation was added to the graph, it was clear that in some cases the climate data did not record a precipitation event, and thus a runoff event was not simulated; however, the monitoring data showed a large runoff event. This indicated either an error in the gaging records or a spatial or temporal variation in rainfall; thus, no attempt was made to calibrate to these periods.

The management files and associated files were not adjusted during calibration because sufficient data were not generally available to support such adjustment. Calibration at gaging stations for flow was limited to adjustment of the reservoir files, the baseflow and groundwater files, and regional soil infiltration parameters. Suspended solid loads were adjusted primarily by modification of model parameters that accounted for the channel characteristics including channel cover and channel erosion parameters. These parameters were adjusted so that baseflow sediment loads corresponded to monitored numbers. Additional data were obtained from a USGS publication (Hindall, 1976). In addition, the version of SWAT used in this study had global adjustment of the Modified Universal Soil Loss Equation (MUSLE) for routing of sediment. These variables in the MUSLE equation were adjusted based on the characteristics of the watershed. Phosphorus numbers were not adjusted at this scale because the phosphorus parameters had been calibrated during the pilot--scale modeling and sufficient data did not exist to justify modification of the parameters.

The RRB had 23 USGS gaging station available for flow calibration. To determine the accuracy of the SWAT runs based on measured values from the gaging stations, the Nash–Sutcliffe coefficient of efficiency and R² were utilized. The tests compare simulated and monitored annual, monthly, and daily values for flows. Values greater than 0.6 from either test applied to the annual flow values were considered a reasonable fit. The R² values tend to be higher than the
Nash–Sutcliffe values. This is because an outlying value on a single event will significantly lower the Nash–Sutcliffe coefficient while only slightly affecting the R² value. The gages used for calibration and validation of flow are shown in figure 2.

Calibration and validation proceeded from upstream to downstream. Once calibration was completed at a station, alterations were not made to the input files associated with that station to obtain a better fit at a downstream station. In addition, model parameters were not adjusted for downstream watersheds to offset overpredictions or underpredictions in flows. For example, if upstream stations were underpredicting flows by 20%, then we would not expect the next downstream station to be within 5% of measured flows. If this occurred, then runoff was likely being overestimated in the downstream area. Of course, reservoirs, confluence with other rivers, and changes in groundwater contributions could offset this.

**AFTON MODEL.**

The gage at Afton (USGS Gage No. 5430500) is the last gage before entering Illinois and includes most of the RRB in Wisconsin. This station was used primarily for validation because, at this point in the system, parameters cannot be adjusted to make the model predictions match without altering results at upstream gages. Table 6 provides a summary of the validation data.

**BARK RIVER MODEL.**

The Bark River model simulates the Bark River watershed before its confluence with the Rock River. Data were collected from two gaging stations located in the Bark River

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**Table 6. Calibration results of annual flows at twelve USGS gaging stations in the Rock River Basin.**

<table>
<thead>
<tr>
<th>River</th>
<th>USGS Gage Number</th>
<th>Years</th>
<th>Average Annual Measured/Predicted Flow (mm)</th>
<th>Average % Difference in Annual Flows</th>
<th>R²</th>
<th>COE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock River at Afton</td>
<td>5430500</td>
<td>1989–1996</td>
<td>225/226</td>
<td>16</td>
<td>0.78</td>
<td>0.76</td>
</tr>
<tr>
<td>Bark River near Rome</td>
<td>5426250</td>
<td>1989–1996</td>
<td>237/235</td>
<td>18</td>
<td>0.68</td>
<td>0.68</td>
</tr>
<tr>
<td>Beaver Dam</td>
<td>5425912</td>
<td>1989–1996</td>
<td>376/236</td>
<td>75</td>
<td>0.73</td>
<td>0.44</td>
</tr>
<tr>
<td>Crawfish River at Milford</td>
<td>5426000</td>
<td>1989–1996</td>
<td>231/235</td>
<td>32</td>
<td>0.65</td>
<td>0.37</td>
</tr>
<tr>
<td>South Branch of the Rock River at Waupun</td>
<td>5423500</td>
<td>1989–1996</td>
<td>112/219</td>
<td>47</td>
<td>0.70</td>
<td>0.32</td>
</tr>
<tr>
<td>Rock River at Watertown</td>
<td>5425500</td>
<td>1989–1996</td>
<td>198/225</td>
<td>18</td>
<td>0.77</td>
<td>0.42</td>
</tr>
<tr>
<td>Rock River at Jefferson</td>
<td>5426031</td>
<td>1989–1993</td>
<td>237/217</td>
<td>20</td>
<td>0.98</td>
<td>0.57</td>
</tr>
<tr>
<td>Lake Delavan Outlet</td>
<td>5431022</td>
<td>1989–1996</td>
<td>190/160</td>
<td>46</td>
<td>0.46</td>
<td>0.18</td>
</tr>
<tr>
<td>Turtle Creek at Carvers Rock Road</td>
<td>5431486</td>
<td>1989–1996</td>
<td>216/208</td>
<td>17</td>
<td>0.72</td>
<td>0.55</td>
</tr>
<tr>
<td>Pheasant Branch at Middleton</td>
<td>5427948</td>
<td>1989–1996</td>
<td>101/95</td>
<td>38</td>
<td>0.69</td>
<td>0.67</td>
</tr>
<tr>
<td>Yahara River at STH 59</td>
<td>5430175</td>
<td>1994–1997</td>
<td>263/273</td>
<td>18</td>
<td>0.31</td>
<td>0.84</td>
</tr>
<tr>
<td>Yahara River at STH 59</td>
<td>5430175</td>
<td>1980–1984</td>
<td>266/239</td>
<td>12</td>
<td>0.28</td>
<td>0.20</td>
</tr>
</tbody>
</table>
watershed. However, after review of the data, only one station had records adequate for calibration and validation. Validation results are summarized in table 7.

CRAWFISH RIVER MODEL
Station 5425912 is located at the outlet of Beaver Dam Lake. Station 5426000 is located on the Crawfish River near Milford and captures almost the entire Crawfish River watershed. The management of Beaver Dam Lake upstream of the Beaver Dam River influences flow predictions.

UPPER ROCK RIVER MODEL
The Upper Rock River has three USGS stations with long–term flow records; results are summarized below. The poor correlation of the predicted values to monitored flows at this station were traced back to three causes: (1) poor climate and rainfall data, (2) soil associations in different locations in the basin may have different physical characteristics (i.e., infiltration), and (3) the presence of large wetland complexes (Horicon Marsh) in the Upper Rock River. This seemed to be a problem with the entire Upper Rock River, but it was not observed as profoundly in the Crawfish River. Downstream of Lake Sinissippi and Horicon Marsh, results at gaging station 542550 were not as influenced by Horicon Marsh. However, errors between predicted and measured values mirrored those from upstream, just slightly dampened. The effect of the lake and marsh were not as influenced by Horicon Marsh. However, errors between predicted and measured data for the USGS 1999 and 2000 years. At the completion of modeling, only 1999 data were available. The locations of these stations are shown in figure 3.

MIDDLE ROCK RIVER MODEL
The Middle Rock River model was created to allow the joining of the Crawfish and Upper Rock River models and provided an ending point that matched the WDNR delineation for the upper RRB. The Middle Rock River model had one USGS gaging station. Results for this station, which is located at Jefferson, are summarized in table 6.

TURTLE CREEK MODEL
Turtle Creek does not enter the Rock River until after it crosses the Wisconsin–Illinois border. The Turtle Creek model has several gaging stations. However, most are associated with studies of Lake Delavan. In addition to the pilot area, two additional gaging stations were selected. One is located near the outlet of Lake Delavan, and the other is located at Carvers Rock. Results at the outlet for Lake Delavan are misleading. The lake was drained in 1990 and 1991 for restoration work, and a dam controls the lake level. Even though the average annual value is fairly close, examination of daily flows reveals that the model was unable to accurately predict the flows, as is expected given the management of the lake. These fluctuations evened out as the simulation moved downstream and the influence of the lake tapered off.

YAHARA RIVER MODEL
The Yahara River model includes the Madison chain of lakes and the Badfish Creek watersheds and extends to the Yahara River confluence with the Rock River. Several gaging stations with water quality and flow data are located in the model area in addition to the pilot area. Calibration and validation results are summarized in table 6. The results for this model reflect the significant contributions from point sources in this portion of the RRB and the management of the Yahara chain of lakes (Mendota, Monona, etc.) through a series of large dams.

PHOSPHORUS AND SEDIMENT VALIDATION
In general, the calibration results compared favorably to monitored data, and the validation data suggested that SWAT was accurately predicting average annual flows. Unlike flow, only a few gaging stations had water quality data. Thus, sediment and phosphorus loads were validated using the eight stations sponsored by the RRB (the ninth station is located in Illinois after the confluence with the Pecatonica, limiting its use as a validation site). These stations collected sediment and phosphorus data for the USGS 1999 and 2000 water years. At the completion of modeling, only 1999 data were available. The locations of these stations are shown in figure 3.

Results indicate that SWAT is predicting a higher sediment settlement rate in the lakes than is actually occurring and is not allowing for enough biological uptake of phosphorus. These problems are associated with the routing routines and do not affect the loading predictions for each sub–watershed, which are summarized before routing. For example, station 5424082 is located at the outlet of Lake Sinissippi on the Rock River at Hustisford. Given the influence of the Horicon Marsh and the influence of the dam on the gaging site, SWAT had a difficult time simulating the flows out of the lake. For Turtle Creek, validation results for flow and sediment are excellent. However, the predicted phosphorus load is considerably higher than the monitored load. Several explanations for these results were evaluated, but a definite cause could not be determined. Possible explanations include (1) the influence of Lake Delavan, (2) a difference from the normal Rock River fate and transport phenomena that occurs in Turtle Creek because of stream characteristics, or (3) the generalization of fertilizer applications does not accurately reflect actual practices in Turtle Creek.
MANAGEMENT SCENARIO SIMULATION

Under existing land use and management conditions, the model predicted a total basin average annual phosphorus load of approximately 764,000 kg. Point sources accounted for 41% of this value, and nonpoint sources accounted for 59%. These numbers are reported as total phosphorus and do not distinguish between the different forms (ortho, soluble, particulate, etc.) of phosphorus. It is important to note that the BMP practices that were analyzed were limited to two options: modifications in tillage practices, and adoption of recommended nutrient application rates. No other BMP practices (i.e., urban controls, riparian buffer strips, etc.) were simulated. Thus, loadings depicted by SWAT under these management scenarios do not necessarily represent the lowest attainable loads.

The implementation of alternative tillage practices was limited to conventional tillage being changed to conservation tillage and existing conservation tillage being phased into no–till. In the opinion of UW–Extension staff and county LCD staff, changing from conventional tillage to no–till systems was not likely to occur. Implementation of improved nutrient management was limited to fertilizer applications. Since no infrastructure currently exists for “manure trading,” manure application rates remained unchanged. Fertilizer application rates were reduced from the existing average application rates to the recommended application rates. Actual application rates should be based on individual soil test values. Since these data are too specific for the scope of the project, application rates were set at UW–Extension “generic” recommended rates. Table 8 summarizes the management scenarios described above.

Figure 4 shows simulated point and nonpoint loads under each management scenarios. The scenarios shown corre-

Table 8. Management scenarios analyzed by SWAT.

<table>
<thead>
<tr>
<th>Management Scenario</th>
<th>Tillage Practices</th>
<th>Nutrient Management</th>
<th>Effluent Concentrations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Current</td>
<td>Current</td>
<td>Current</td>
</tr>
<tr>
<td>2</td>
<td>Improved</td>
<td>Current</td>
<td>Current</td>
</tr>
<tr>
<td>3</td>
<td>Current</td>
<td>Improved</td>
<td>Current</td>
</tr>
<tr>
<td>4</td>
<td>Improved</td>
<td>Improved</td>
<td>Current</td>
</tr>
<tr>
<td>5</td>
<td>Current</td>
<td>Current</td>
<td>NR 217 levels</td>
</tr>
<tr>
<td>6</td>
<td>Improved</td>
<td>Improved</td>
<td>NR 217 levels</td>
</tr>
</tbody>
</table>

spond to those described above. Evaluation of various BMP scenarios shows that with implementation of NR 217 (applicable point–source effluent at 1 mg/L of phosphorus) and changes in tillage practices and nutrient application practices, the total phosphorus can be reduced across the basin by approximately 40% (scenarios 1 to 6). This reduction representation is a hypothetical “best case” condition. An estimated 25% reduction in phosphorus loads can be obtained by just implementing NR 217 (scenarios 1 to 5), and a 14% reduction can be obtained by implementing improved tillage and nutrient management practices (scenarios 1 to 4). Figure 5 provides a summary of phosphorus loads by WDNR watershed for existing conditions.

In addition to phosphorus loads, information was generated on sediment loads stemming from nonpoint sources. Modeling results indicate that, under existing conditions, approximately 160,000 tons of sediment is delivered to the bodies of water within the RRB on an average annual basis. Through the implementation of improved tillage practices (predominantly conservation tillage), SWAT predicted that sediment delivery could be reduced by almost 20%, and
through a combination of nutrient management, improved tillage practices, and point–source control, phosphorus loads can be reduced by almost 40% (fig. 4).

**DISCUSSION AND CONCLUSIONS**

Because of the diversity in the agricultural landscape, there is a wide range in the potential for losses of phosphorus from the land. Contributing to this diversity are: characteristics of the soils, topography, crop and plant vegetation, crop production cultural practices, phosphorus levels in the soil, and method of phosphorus application (from fertilizers). Most watersheds include sites that differ in one or more characteristics. If phosphorus loss from a watershed is a concern, then it is beneficial to further identify the site(s) within that watershed that have the greatest potential for phosphorus loss. Modeling results from SWAT viewed by both watershed and sub–watershed help identify areas of high phosphorus and sediment loading, but identification of individual sources requires a more detailed screening. This conclusion is supported by several studies showing that up to 90% of annual phosphorous loss comes from less than 10% of the land (Heathwaite et al., 1998). Knowing where these critical fields are located is an important part of implementing practical and effective BMP measures.

Results suggest that a combination of point and nonpoint controls will be required to attain phosphorus reductions. Past and current research shows that fields with excessively high soil phosphorus levels (levels well beyond the point at which crop production responds to additional phosphorus) can contribute significant phosphorus loads to surface waters through runoff and sediment loss. However, not all fields contribute to this potential problem. It is important that guidelines, BMPs, and restrictions on phosphorus discharges have a scientific basis. Additional research needs to address these issues and include additional in–stream modeling, continued monitoring, and research into effective BMPs for phosphorus control.

**REFERENCES**


WDNR. 1998. WISCLAND Land Cover (WLCGW930). Madison, Wisc.: Wisconsin Department of Natural Resources.