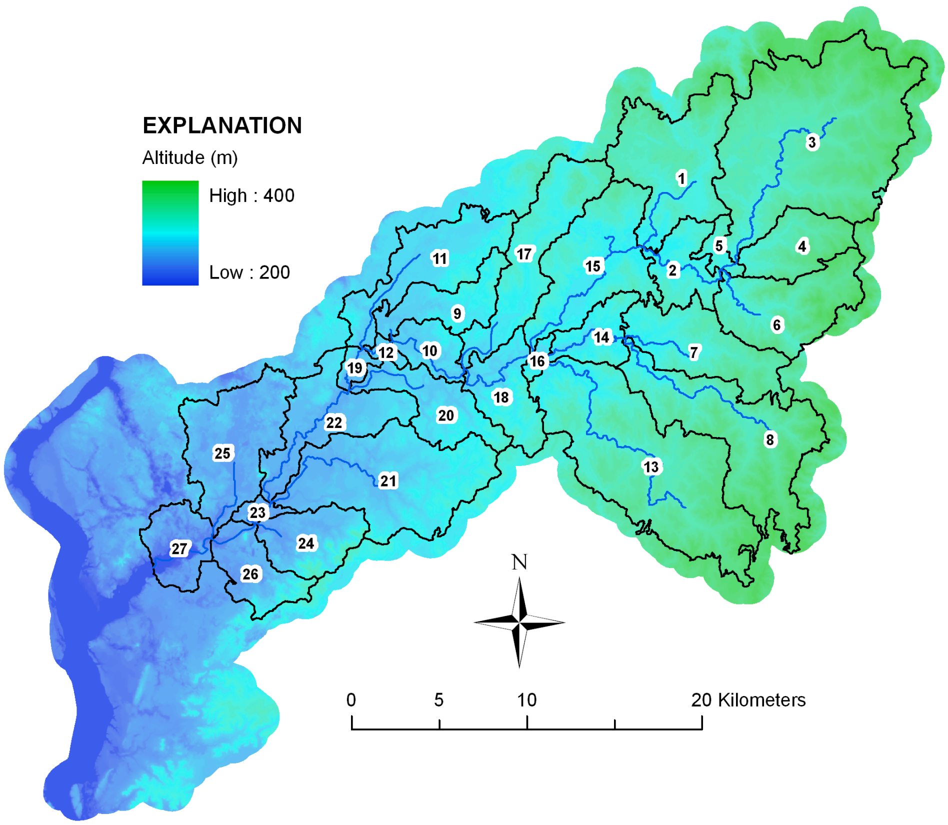
Constructing a SWAT model of the Willow River watershed, western Wisconsin



TAPwaters St. Croix Watershed Research Station Hydrologic Modeling

Science Museum of Minnesota

Constructing a SWAT model of the Willow River watershed, western Wisconsin

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Abstract

The Willow River in western Wisconsin is a valued water resource that is impacted by nonpoint-source pollution. Computer modeling of watershed processes is an important tool to help predict the effectiveness of strategies to mitigate this pollution. The Soil and Water Assessment Tool (SWAT) is a modeling program designed to predict the long-term effect of land management on nonpoint-source pollution in large watersheds. This report describes the data sets and manipulations required to construct a SWAT model of the Willow River watershed. Monitoring data to constrain model parameterization were available for water years 1999 and 2006. The model used spatially referenced data sets of topography, land use, and soils to subdivide the watershed into 27 subbasins with 532 hydrologic response units (HRUs), each representing a unique combination of soil type and land use within a subbasin. Land-use areas were revised to account for changes from the date of the land-use imagery (1992-93) to the dates of available monitoring data. Use of the soil survey geographic (SSURGO) database improved model hydrology relative to use of the less detailed state soil geographic (STATSGO) database. Closed depressions accounted for 29% of the drainage area of the Willow watershed and were modeled with use of the Pond tool in SWAT parameterized to trap all sediment and phosphorus. Cropland coverage (corn, soybeans, and alfalfa) could be reproduced with three representative rotations: corn-grain, corn-silage, and three years of alfalfa (C2A3); corn-grain, corn-silage, soybeans, corn-grain, and three years of alfalfa (C3S1A3); and corn-soybean (C1S1). Each rotation was given appropriate tillage practices and fertilizer applications based on reported rates and numbers of animal units. Soil-test phosphorus level was initialized at 41 ppm according to reported countywide levels. River channel erosion and deposition were disallowed in the basic

model to simplify calibration and interpretation of sediment and phosphorus yields from the uplands. The model was parameterized to produce realistic yields of sediment and phosphorus at both the field scale (gross yields) and the basin scale (net yields). Principal parameters altered in the model to achieve calibration include curve number, snowmelt parameters, days to reach target reservoir volume, support practice factor in the soil loss equation, and phosphorus availability index. The calibrated model fit the 1999 monitoring data with Nash-Sutcliffe coefficient of efficiencies (E_{NS}) of 0.57 for daily mean flow, 0.62 for monthly sediment load, and 0.51 for monthly phosphorus loads. The model was validated against monitoring data from water year 2006, which had an anomalously large storm in October that was not well simulated. Excluding this event, the model fit the 2006 data with an E_{NS} of 0.63 for daily flows, 0.69 for monthly sediment loads, and 0.80 for monthly phosphorus loads. We concluded that the model is not reliable for rainstorm events larger than about 70 mm day^{-1}.

Problems were encountered with use of the SWAT program that had to be corrected or avoided before the Willow watershed model could be calibrated. The three most significant problems are summarized here. First, rotations including alfalfa in the model improperly excluded corn and soybeans and converted to continuous alfalfa, thereby greatly underestimating sediment and phosphorus yields from these landscape units. Revisions to the SWAT model code provided by Paul Baumgart (UW-Green Bay) corrected this problem. Second, infiltration from surface-water bodies did not recharge the shallow aquifer and contribute to baseflow. Consequently when 29% of the watershed was routed to Ponds in SWAT to simulate areas of closed drainage, stream flow decreased by about 29%. To replace this lost flow, artificial point sources were created for each subbasin. Third, SWAT added a chlorophyll load from the uplands to the river channels, which resulted in an extraneous phosphorus load to the channel when stream water-quality routines were activated. To avoid overestimating phosphorus loads, these water-quality routines had to remain de-activated, or the phosphorus content of algae needed to be reduced to a negligible fraction.

Introduction

Problem

The Willow River is a highly valued water resource in western Wisconsin that is tributary to the St. Croix River, a federally designated scenic and recreational riverway (Figure 1). Trout-bearing reaches of the Willow are popular fishing destinations, and Willow River State Park in the lower watershed receives 300,000 visitors each year. Nonetheless, the water quality of the Willow is impacted by nonpoint-source (NP-S) pollution from agriculture in the basin, and the Willow watershed has been identified as one of the major contributors of nutrients to the St. Croix River (Fallon and McNellis 2000, Lenz et al. 2003). In addition, the lower watershed has seen rapid development of residential properties and is likely to see increased development pressure following the construction of a proposed bridge across the St. Croix from Stillwater, MN to Houlton, WI. Lake Mallalieu, the lowermost impoundment on the Willow just prior to its confluence with the St. Croix, is already an impaired water body with noxious algal blooms during the summer. Consequently, the Willow River has been targeted for remediation by the St. Croix Basin Water Resources Planning Team (Basin Team), a collaboration of federal and state agencies with local and private partners.

Computer models of watersheds can integrate watershed processes, including both point and NP-S pollution, and are therefore useful tools to help guide watershed managers in the implementation of remediation practices. Such models can identify which subwatersheds are likely contributing the most NP-S pollution, as well as predict the effectiveness of proposed remediation practices. As a result, the Basin Team requested that a computer model of the Willow River watershed be constructed to assist watershed managers in identifying ways to reduce loads of sediment and nutrients to the Willow, and by extension, to the St. Croix. The Technical Assistance Program for Watersheds (TAPwaters) of the St. Croix Watershed Research Station was given the task of model construction and application.

Purpose and Scope

The purpose of this report is to document the data sets and methods used to construct and calibrate a computer model of the Willow River watershed in western Wisconsin. The calibrated model and required datasets are included on the accompanying CD. This report is written for three different audiences. First, basic background information and terminology is given for a managerial audience with some technical knowledge but without specific experience in modeling. Second, the bulk of the report is aimed at those with enough modeling experience to understand most of the details about how the model was constructed. Third, a subset of those with modeling expertise will have enough experience with the SWAT modeling program (discussed in the next section) so that they will be able to run and manipulate the accompanying model. Unfortunately, the modeling program is not user-friendly enough for practical application without specific training, though the TAPwaters office will assist potential users as needed.

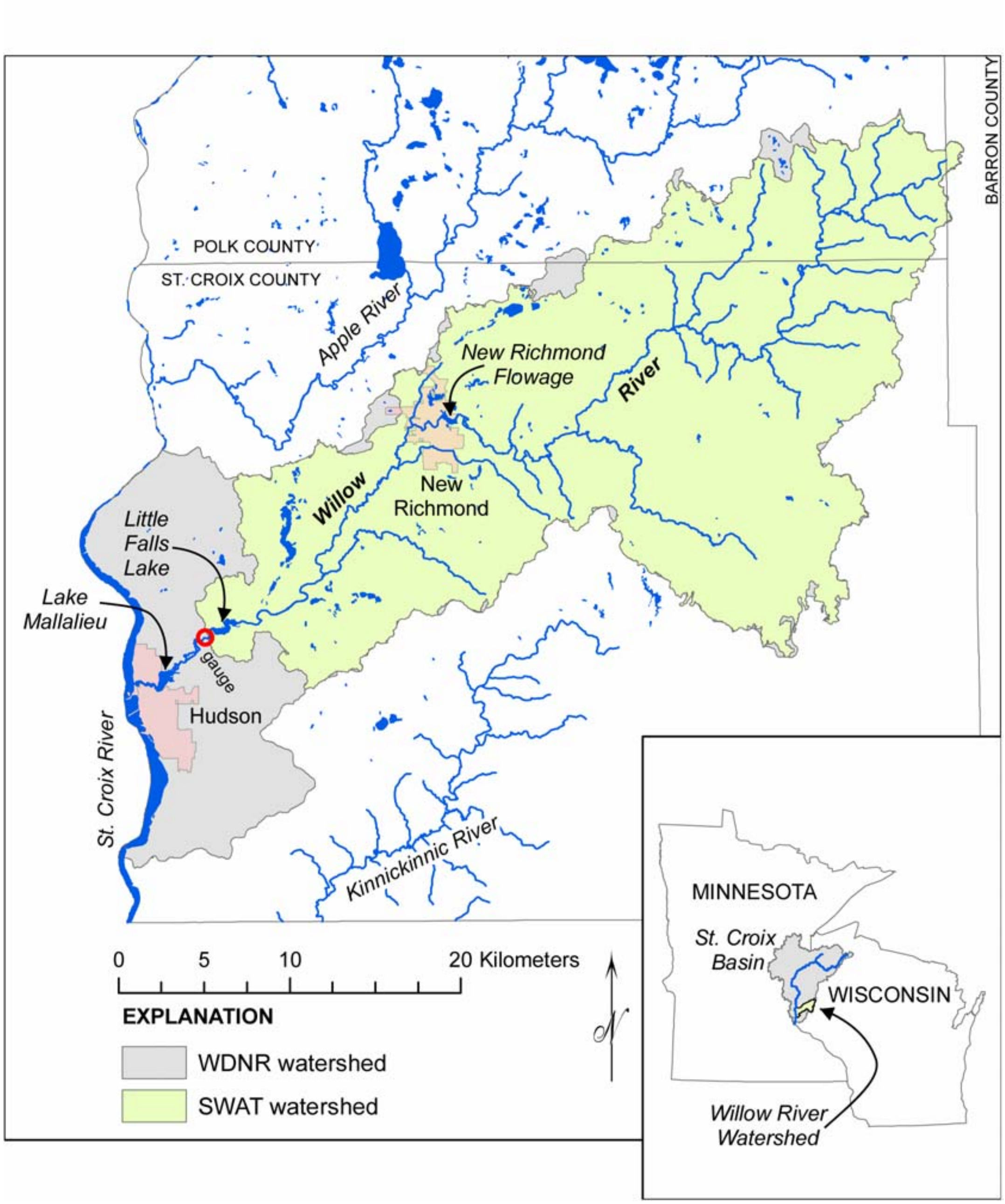


Figure 1. Willow River watershed in the lower St. Croix Basin, western Wisconsin.

Modeling Basics

Model Terminology

A watershed model is a computer program that simulates selected hydrological processes within a study watershed (Figure 2). Watershed here refers to the directly contributing landscape area with continuous downward path to the stream channel, plus smaller areas of closed drainage embedded within or contiguous to the directly contributing area that would contribute runoff should they ever spill. Hydrological processes commonly include components of the hydrological cycle (evapotranspiration, infiltration, overland runoff), processes in channels and reservoirs, and transport of sediment and nutrients. Because these processes operate fundamentally the same in all watersheds, a watershed-modeling program can be written that includes equations describing each of these processes in a generic or default way. A watershed model is initially constructed, then, by providing a watershed-modeling program with geographic data specific to a study watershed, including topography, soils, and land cover.

Input of the geographic data tells the model where landscape features are located, but the model must still be configured by providing information about the specific characteristics of these features. Such information includes reservoir geometries and drainage areas of ponds and wetlands. Additionally, the model must be informed of the land-management practices for each land cover type, in particular what crop rotations, fertilizer applications, and tillage practices should be applied to agricultural land cover. Whether model configuration is considered a separate step or part of initial model construction is arbitrary.

A model is run by providing an input file of (for example) daily precipitation and temperature over a selected period of time. The model then calculates how much water infiltrates, evapotranspires, or runs off to the receiving channel; the sediment and nutrients transported to the channel; and the routing (amount and timing) of water, sediment, and nutrients down the channel network to the watershed outlet. The primary outputs from the model are streamflow and quantities of sediment and nutrients delivered to the watershed outlet (or other selected points within the watershed). To test how well the model simulates reality, model output is compared with actual data collected from the watershed. Essentially always, a newly constructed model must be adjusted to obtain an acceptable fit between the model output and the actual data. This process of adjusting a model is called calibration (or parameterization) and is done by making small changes in the input data or in the coefficients (parameters) within the model equations. The calibrated model is then run over a second time period for which actual monitoring data are available. If the model output acceptably fits this second data set, the model is said to be validated.

In light of the above discussion, "constructing" a model can mean different things. Strictly speaking, model construction could refer only to the initial input of relevant spatial datasets to the modeling program. However, in practice all models require parameter adjustment and comparison to measured data to demonstrate their reliability. In the larger sense, proper model construction includes all steps of data input (initial model construction), configuration, calibration, and validation to the degree possible with the available data.

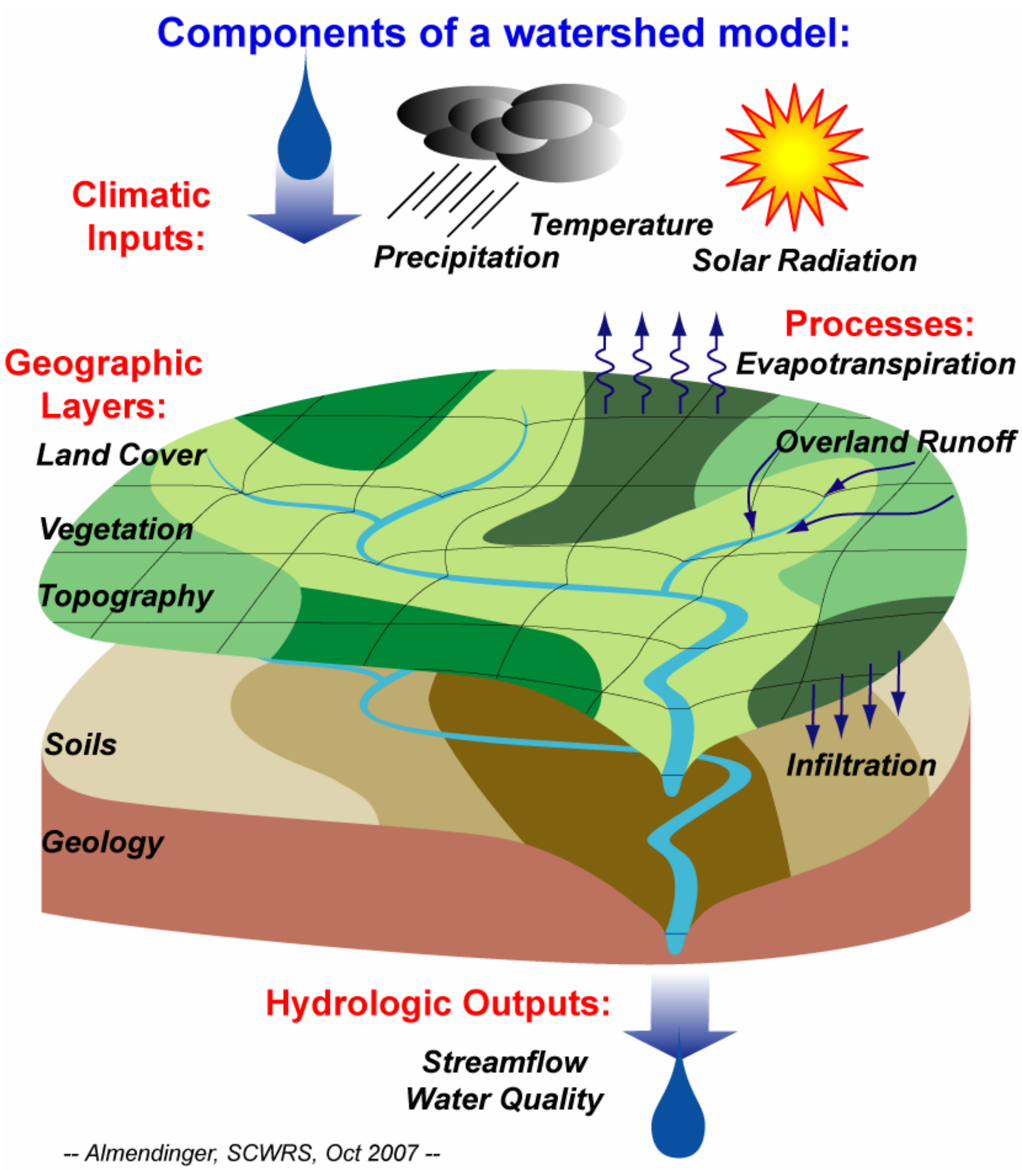


Figure 2. Components of a watershed model

SWAT Modeling Program

The Soil and Water Assessment Tool (SWAT) is a watershed modeling program developed by the Agricultural Research Service (ARS) of the U.S. Department of Agriculture (USDA) (Arnold et al. 1995, Arnold et al. 1998). SWAT's purpose is "to predict the impact of land management practices on water, sediment and agricultural chemical yields in large, complex watersheds with varying soils, land use and management conditions over long periods of time" (Di Luzio et al. 2002). SWAT is a well-supported modeling program with a large user base that has grown over the past ten years. Although SWAT was originally developed for use in rural watersheds, routines to handle urban landscapes have been added and continually improved.

Model construction requires inputs of hydrography, topography, soils, land cover, and agricultural management practices. Data input is facilitated by the program AVSWAT, an interface with ArcView geographic information systems (GIS) software. AVSWAT uses the topographic data to delineate the watershed into subbasins. Within each subbasin, the interface calculates the total area for each unique combination of land cover and soils. Each unique combination is aggregated into a conceptual "hydrologic response unit" (HRU), which is considered to be a contiguous land area with uniform soil, land cover, and slope that drains directly to the subbasin's channel (Figure 3). Hence, the subbasin is the smallest unit with spatial meaning in SWAT; within a subbasin, the spatial relation of different land uses and soils is lost. The HRU concept simplifies the calculations of hydrological processes in the model; however, the loss of spatial information within the subbasin introduces a measure of unrealism and requires caution in interpreting model results.

SWAT runs on a daily time step, requiring input of daily precipitation and (commonly) daily minimum and maximum temperatures. While SWAT has a weather generator that can simulate typical weather conditions based on the nearest long-term National Weather Service stations, most users input actual precipitation and temperature records from the nearest stations to cover the period for which monitoring data exist, thereby allowing model calibration. SWAT allows detailed agricultural management practices to be simulated, tracking planting, tillage, and fertilization operations and calculating resultant plant growth during the year. SWAT partitions daily rainfall into infiltration and runoff based on a modified curve-number method. Evapotranspiration is calculated based on available soil water (which is tracked by SWAT) and climatic conditions. Infiltrated water beyond soil field capacity becomes groundwater recharge, which moves to the stream based on gradient and soil hydraulic conductivity. Overland runoff transports sediment and nutrients to the channel based on soil erodibility, land cover, peak flow velocity, and solubility considerations. The model allows some runoff from each subbasin to be intercepted by ponds or wetlands, where some sediment and nutrient loss can occur, before being delivered to the channel. Water and its load of suspended sediment and nutrients reaching the channel are routed downstream via a variable storage algorithm. The model allows channel sedimentation and erosion, as well as biological transformations of nutrients via algal growth, settling, and decomposition. On-channel reservoirs in the model ameliorate peak flows and allow settling loss of sediment and nutrients.

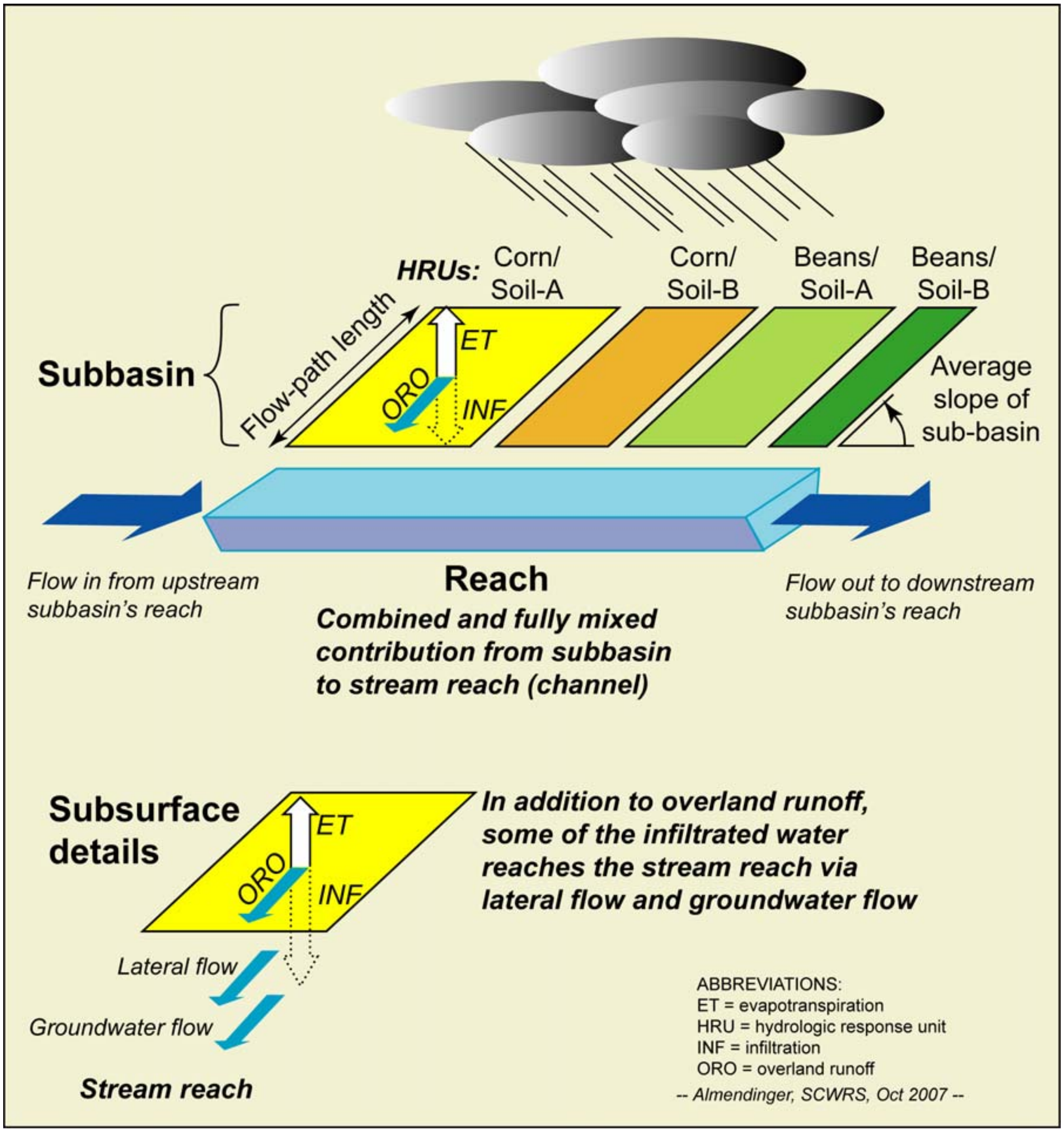


Figure 3. SWAT conceptualization of a subbasin, comprising hydrologic response units (HRUs) contributing to a stream reach.

Study Area

The Willow River, above its confluence with the St. Croix, drains a watershed of about 735 km^2. However, the U.S. Geological Survey (USGS) stream gauge where monitoring data have been collected is located about 6.5 km upstream in Willow River State Park, just downstream of Little Falls Lake (Figure 1). The watershed area draining to this point is about 721 km^2 (Lenz et al. 2003). Because the model must be calibrated to monitoring data, this smaller watershed area provides the base study area for model construction. In practice, the automated watershed delineation routine within the model excluded some small areas (apparently of closed drainage) along the northern edge of this watershed, and the actual area included in the model was 717 km^2. The study area excludes the part of the watershed below the stream gauge, including Lake Mallalieu and inputs from the cities of Hudson and North Hudson, WI.

The resulting modeled watershed includes land area in three counties in western Wisconsin (St. Croix, Polk, and Barron) with the majority of the watershed (72%) in St. Croix County. The primary municipality in the study area is New Richmond (population 6,310 in 2000), which marks the division between the Upper Willow and Lower Willow watersheds as designated by the Wisconsin Department of Natural Resources (WDNR). The channel length of the Willow River is about 90 km, 21 km of which is below New Richmond and 69 km above. Other main branches include South Fork Willow River (26 km), Dry Run (23 km), Hutton Creek (21 km), Tenmile Creek (16 km), Carr Creek (13 km), and Paperjack Creek (11 km) (WDNR 2002).

Above the USGS gauge, there are two man-made reservoirs on the main channel of the Willow. The upper reservoir is the New Richmond Flowage (commonly called the "Widespread"), which has an area of 95.5 ha and mean depth of 1.07m. The control structure impounding the Flowage was originally built to power saw mills in New Richmond. Frequently, this structure proved insufficient to allow the passage of water during large storms and snowmelt resulting in flooding in downtown New Richmond. In 1998, a new control structure was completed that uses computer-controlled gates to hold the Flowage at a constant elevation for recreational purposes. The lower reservoir is Little Falls Lake in Willow River State Park, with an area of 69.6 ha and mean depth of 2.38 m. Little Falls Dam normally spills over its top from the lake surface, although operations may change to allow discharge from the lake bottom to maintain cooler temperatures below the dam to improve trout habitat (Schreiber 1994). The USGS gauge, marking the terminus of our model study area, is about 600 m below the Little Falls Dam.

At the gauge site, Lenz et al. (2003) measured an average annual flow in water year 1999 of 4.7 cms (cubic meters per second), equivalent to 166 cfs (cubic feet per second). At approximately the same location, Schreiber (1994) measured instantaneous flows of 3.6 cms and 5.0 cms in July and August, 1993. For the 10-year period from 1992-2001, during which annual precipitation was typical, our model results gave an average annual flow of 4.78 cms. We defined "typical" annual precipitation as that which was within one root mean squared deviation from the 1949-2005 linear trend in the annual average precipitation of the nearby Baldwin and Amery weather stations. The 1971-2000 normal annual precipitation, averaged from the Baldwin and Amery stations, is 813 mm (32.0 in). However, the 1949-2005 linear trend in annual precipitation indicated 847 mm (33.4 in) for 2000, with an annual increase of 2.4 mm.

Nearly 4 km of the Willow River above Lake Mallalieu is designated an Exceptional Resource Water (ERW) as a Class I (naturally reproducing) cold-water fishery, and much of the rest of the Willow is designated as Class II or III (trout sustained by stocking) cold-water fishery. There are two 303(d)-listed impaired water bodies in the greater Willow watershed. Within the model study area, a river reach near New Richmond (apparently including the New Richmond Flowage) is listed for dissolved oxygen impairment (WDNR 2002). Just below the study area, Lake Mallalieu was listed in 2004 for eutrophication and pH impairments. Indeed, the eutrophication problem in Lake Mallalieu was one of the motivations for investigating remedial actions in the study area. Ironically the ERW reach is located just upstream of the impaired Lake Mallalieu. The high value assigned to this reach for its ability to sustain trout is probably driven by its cold water and coarse substrate suitable for the spawning beds and invertebrate prey required by trout. Apparently, the trout are little affected by the nutrient loads that cause impairment just down stream.

The Willow River watershed differs in topography between the eastern and western halves of the basin. The eastern half of the basin is characterized by greater slopes, greater drainage density, and fewer lakes and enclosed basins. The western half of the basin includes numerous lakes on shallower slopes with lower drainage densities. The study area is underlain by Ordovician sandstone and dolostone of the Prairie du Chien group, itself overlain locally by patches of Ordovician St. Peter sandstone. Most of the study area has 15-60 m (50-200 ft) of overlying glacial drift (Feinstein et al. 2005). However, drift less than 15 m thick is common in the central part of the upper watershed east of New Richmond (Feinstein et al. 2005), and exposed bedrock is common in Willow River State Park. Feinstein et al. (2005) designate this drift as being mostly fine-grained. Soils in the Willow River Basin derived from this glacial parent material are predominately loamy and include moderately poorly-drained to well-drained areas (SCS 1978).

From 1991-93 satellite data, land use in the study area was estimated to be 43% agriculture cropland, 30% grassland, 18% forest, 7% water/wetland, and only 2% urban/developed (Figure 4) (WDNR 1998). Because monitoring data for the Willow were from 1999, considerable effort was expended to determine land-use change from 1992 to 1999 and beyond (Almendinger and Murphy 2005). During this period, approximately 10% of agricultural land was converted to other land uses. Virtually all of this cropland loss was due to loss of hay acreage, as corn acreage remained steady and soybean acreage increased slightly. This change is consistent with a gradual shift from dairy farming to cash cropping of corn and soybeans. From 1980 to 2001, the number of cattle estimated in the watershed dropped from 85,000 to 50,000. During this time, dairy cattle composed 91-92% of the total but have recently dropped to about 88%, the balance being beef cattle. About 80% of the cropland loss from 1992 to 1999 occurred in the lower watershed below New Richmond, and almost two-thirds was due to increased residential development. Other land uses increasing at the expense of cropland included forested, recreational, and urban land. Of the remaining cropland in 1999, hay accounted for 44% of the acreage, corn for 41%, soybeans for 13%, and other crops for 2%. Dairy farming and hay acreage have continued to decline since 1999, and estimated relative cropland acreages for 2004 were 44% for corn, 36% for hay, 18% for soybeans, and 3% for other crops (rounded to the nearest percent). Only about 2-3% of the cropland acreage was irrigated in St. Croix County (NASS 2007), which was too small to be included in the SWAT modeling.

There are four permitted wastewater treatment facilities in the study area that discharge to the Willow and its tributaries (WDNR 2002). Three of these are municipal dischargers: Deer Park and New Richmond in St. Croix County and Clear Lake in Polk County. One is an industrial discharger, Chiquita Processed Foods in St. Croix County. Several other permitted dischargers are in the watershed, but these facilities discharge to groundwater (WDNR 2002), most likely meaning land application of wastes. These loads were not directly included in the model.

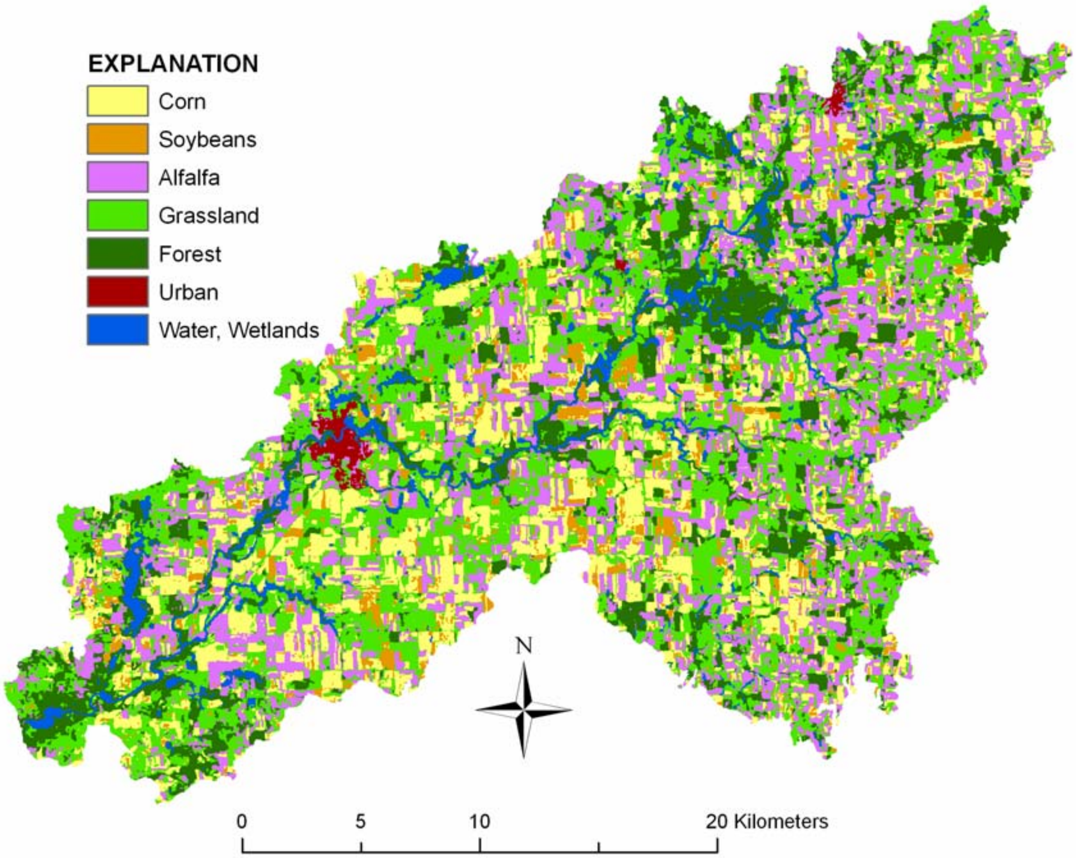


Figure 4. Land cover in the modeled part of the Willow River watershed as determined from satellite imagery, 1991-93.

Initial Model Construction

This section reviews the data sets used to construct the SWAT model of the Willow River watershed, including spatial data and temporal data. The first sub-section lists input data sources, the second sub-section explains the data processing undertaken to get the data into "model-ready" format and initial use of the AVSWAT interface.

Model Input Data

Table 1a lists the spatial datasets required for model construction, which lay the geographic framework for the model. These include hydrography, topography, land cover, and soils. Most of these datasets were downloadable through the web from the listed agencies.

Table 1. Input data sets for the Willow River watershed SWAT model.

Item	Agency	Dataset	Type
(a) SPATIAL DATASETS			
Stream channels	WDNR	Rivers and Streams (24K Hydrography)	Polyline shapefile
Open water	WDNR	Open Water (24K Hydrography)	Polygon shapefile
Watershed base	WDNR	Watersheds digital data (24K Hydrography)	Polygon shapefile
Wetlands	WDNR	Wisconsin Wetland Initiative	Polygon shapefile
Topography	USGS	Digital Elevation Model (DEM), 10-m resolution	Grid
Soils	USDA/NRCS	STATSGO (State Soil Geographic Database) *[not used]*	Polygon shapefile
Soils	USDA/NRCS	SSURGO (Soil Survey Geographic Database)	Polygon shapefile
Land cover	WDNR	WISCLAND (Wisconsin Initiative for Statewide Cooperation on Landscape Analysis)	Grid
(b) TEMPORAL DATASETS			
Precipitation	NCDC	Cooperative Network weather stations	Text, time series
Temperature	NCDC	Cooperative Network weather stations	Text, time series
Solar radiation	MSCWG	Solar radiation data *[not used]*	Text, time series
Point sources	WDNR	Various, compiled by Edlund (2004)	Text, time series

NOTES:
MSCWG, Minnesota State Climatology Working Group; NRCS, Natural Resources Conservation Service; USDA, U.S. Department of Agriculture; USGS, U.S. Geological Survey; WDNR, Wisconsin Department of Natural Resources

The Watersheds dataset provided polygons of the WDRN-delineated boundaries for the Upper and Lower Willow River watersheds, which proved useful for clipping other datasets from statewide coverages to the appropriate area. While the Upper Willow watershed drains entirely to the Willow River, the Lower Willow watershed includes areas of direct drainage to the St. Croix and thus is larger than the strict hydrologic watershed of the Lower Willow alone. The Rivers and Streams dataset lists 10 named creeks in the combined Upper and Lower Willow River watersheds, totaling 230 km in length; unnamed channels totaled 387 km in length. The Open Water dataset included 391 landlocked open water bodies in the modeled watershed area, the smallest being unnamed at 0.0021 ha (0.053 acres) and the largest being Bass Lake at 150 ha (370 acres). The two reservoirs in the watershed were given principal and emergency volumes and areas according to data from the WDNR (lake maps at http://dnr.wi.gov/, accessed 2006).

Topography was determined from standard digital elevation models (DEMs), which were available for the Willow watershed in both 10-m and 30-m resolution from the USGS. Because of its greater resolution, the 10-m dataset was chosen for model construction. Within the model study area, the minimum elevation was 200 m, the maximum was 401 m, and the mean was 330 m (Figure 5).

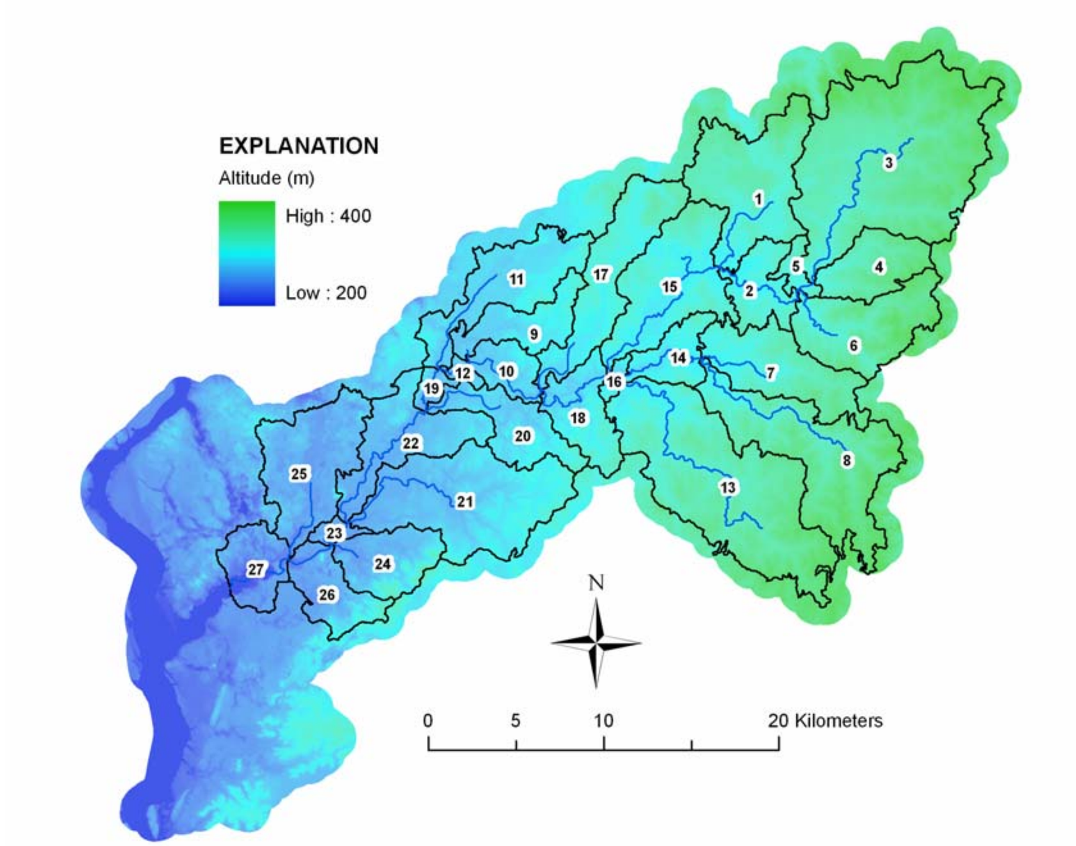


Figure 5. Topography and model subbasin delineation for the Willow River watershed.

The Wisconsin Initiative for Statewide Cooperation on Landscape Analysis (WISCLAND) created a gridded land cover dataset with 30-m resolution for Wisconsin based on LANDSAT Thematic Mapper satellite imagery from 1991 to 1993 (Figure 4) (WDNR 1998). Wetland extents in the WISCLAND dataset compared well with delineated wetlands in the Wisconsin Wetland Initiative spatial dataset. Likewise, the open water land-cover type in the WISCLAND dataset should correspond to the areas in the Open Water dataset. While major lakes coincided in both location and extent, many small water bodies were not represented in WISCLAND.

Two soil spatial datasets were available for the Willow watershed, the State Soil Geographic Database (STATSGO) and the Soil Survey Geographic database (SSURGO). Both datasets were produced by the NRCS (Natural Resources Conservation Service) with STATSGO available as statewide spatial datasets and SSURGO distributed by county (NRCS 2005, 2006). The STATSGO dataset includes soils generalized at 1:250,000 scale and is intended for modeling and decision making over large areas. In contrast, the SSURGO dataset was mapped at scales ranging from 1:12,000 and 1:63,360 and is thus much more detailed and useful over smaller areas, such as townships and individual ownership parcels. For example, in the model study area, the STATSGO dataset listed only six soil associations, whereas the SSURGO soil series dataset contained 181 numbered soils.

The STATSGO dataset could be an adequate input dataset to SWAT if the properties of the soil associations closely reflect the areally weighted average of the SSURGO soils. However, the STATSGO soils were not representative of the SSURGO soils in the Willow River watershed, particularly for hydrologic group. As Table 2 indicates, the STATSGO dataset under-represented the proportion of hydrologic group B soils in the Willow River watershed. In SWAT, the soil hydrologic group is particularly important because it determines the infiltrative capacity of the soil (via a modified curve-number method). Consequently, the SSURGO dataset was chosen as input to the model, though the dataset required significant processing to make the resulting model tractable, as discussed below.

Table 2. Difference in areas of soil hydrologic groups between SSURGO and STATSGO data sets for the Willow River watershed.

Soil Hydrologic Group	Area in SSURGO Dataset		Area in STATSGO Dataset		Difference from SSURGO to STATSGO	
	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)
A	16.4	2.3%	0.3	0.04%	-16.2	-2.3%
B	430.6	60.1%	298.5	41.6%	-132.1	-18.4%
C	240.5	33.6%	418.1	58.3%	177.6	24.8%
D	2.2	0.3%	0	0.0%	-2.2	-0.3%
U	27.2	3.8%	0	0.0%	-27.2	-3.8%
Sum	*716.9*	*100.0%*	*716.9*	*100.0%*	*0.0*	*0.0%*

Table 1b lists the sources of temporal, or time series, datasets required for model construction and operation. Principal among these are the climate data sets that drive the hydrologic cycle in the model. Precipitation and temperature data were purchased on CD from the National Climatic Data Center for three Cooperative Network weather stations near the perimeter of the Willow River watershed at Baldwin and Amery, WI and Stillwater, MN. The Amery and Stillwater stations provided maximum and minimum daily temperatures and daily precipitation; the Baldwin site included only precipitation. Missing data points were replaced with the mean of the observations from the other stations. Other climatic data (solar radiation, wind speed, and humidity) were generated by the model based on the closest National Weather Service long term weather stations, which were St. Croix Falls and Ellsworth, WI, 32 km north and 44 km south of New Richmond, respectively. Measured solar radiation for St. Paul, MN, 50 km southwest of the watershed, was available from the Minnesota Climatology Working Group. However, the measured solar radiation had an insignificant effect on model output, and model-generated values were used instead to simplify model configuration.

As noted above, there are four permitted point sources that discharge into the Willow River and its tributaries (WDNR 2002), data from which were compiled by Edlund (2004) for the period 1994-98. Daily discharge of total phosphorus and flow were available for the New Richmond Wastewater Treatment plant while more irregular data, usually monthly or biweekly grab samples and corresponding discharges were available for the other three plants. Data indicated that during the 1990s annual phosphorus loads were about 3,629 kg yr^{-1} for Clear Lake, 1,531 kg yr^{-1} for New Richmond, 107 kg yr^{-1} for Deer Park, and 16 kg yr^{-1} for Chiquita Processed Foods (Edlund 2004), for a total of about 5,284 kg yr^{-1}. These loads were distributed over the year according to the records to create average monthly flows and discharges of phosphorus. Each year of the model run was presumed to have the same distribution of monthly discharges. By 2005-06, point-source loads of phosphorus were considerably reduced, to about 126 kg yr^{-1} for Clear Lake, 617 kg yr^{-1} for New Richmond, 49 kg yr^{-1} for Deer Park, and 28 kg yr^{-1} for Chiquita Processed Foods, for a total of about 820 kg yr^{-1} (Kathy Bartilson, Wisconsin Department of Natural Resources, written communication, 2007).

Spatial Data Processing

Whereas the time-series data sets could be created rather simply with spreadsheet calculations as described above, the spatial data required significantly more complicated processing to create “model-ready” datasets. The AVSWAT interface allows direct input of spatial data that are decomposed into ASCII files for use by the SWAT executable. Spatial data were preprocessed with ArcGIS software. All spatial datasets were first converted to Universal Transverse Mercator Projection Zone 15 North, North American Datum 1983 (UTM 15N, NAD83) to assure maximum geographic coherence. The WDNR-delineated watersheds for the Upper and Lower Willow were merged into a single polygon with a 1-km buffer to eliminate edge effects. The resultant polygon was then used to clip the Rivers and Streams, Open Water, DEM, WISCLAND, and soils datasets to smaller, more manageable Willow-specific datasets. The Rivers and Shorelines dataset was modified by removing all lake and river shorelines and segments of streams that did not provide flowpaths to the outlet, thereby producing a simplified stream-channel vector dataset. The elevation values in the DEM were rounded to the nearest meter using Spatial Analyst within ArcGIS. The WISCLAND dataset is divided into several more land-use categories than SWAT processes; the WISCLAND input dataset was reclassified according to SWAT land-use codes as shown in Table 3.

Table 3. Correspondence between WISCLAND classes and SWAT land uses.

				Applied in the Willow Watershed	
WISCLAND Value	WISCLAND Class	Approx SWAT Land Use Code	SWAT Land Use Description	SWAT Land Use Code	SWAT HRU Crop or Land Cover
100	URBAN/DEVELOPED	URMD	Urban, medium density		
101	URBAN/DEVELOPED: high intensity urban	URHD	Urban, high density	URHD	same
104	URBAN/DEVELOPED: low intensity urban	URLD	Urban, low density	URLD	same
105	URBAN/DEVELOPED: golf course	BLUG	Kentucky bluegrass *(Poa pratensis)*	BLUG	same
110	AGRICULTURE: general	CORN	Corn (grain) *(Zea mays)*		
111	AGRICULTURE: herbaceous/field crops	OATS	Oats *(Avena sativa)*		
112	AGRICULTURE: primary row crops	SOYB	Soybeans *(Glycine max)*		
113	AGRICULTURE: corn	CORN	Corn (grain) *(Zea mays)*	CORN	in rotation
118	AGRICULTURE: other row crops	SOYB	Soybeans *(Glycine max)*	SOYB	in rotation
124	AGRICULTURE: forage crops	ALFA	Alfalfa *(Medicago sativa)*	ALFA	in rotation
148	AGRICULTURE: cranberry bog	RICE	Rice *(Oryza sativa)*		
150	GRASSLAND	FESC	Tall fescue *(Festuca arundinacea)*	FESC	BROS (Smooth brome, *Bromus inermis*)
160	FOREST	FRST	Forest -- mixed		
161	FOREST: coniferous	FRSE	Forest -- evergreen		
162	FOREST: jack pine	FRSE	Forest -- evergreen		
163	FOREST: red pine	FRSE	Forest -- evergreen	FRSE	same
166	FOREST: white spruce	FRSE	Forest -- evergreen		
173	FOREST: mixed/other coniferous	FRSE	Forest -- evergreen	FRSE	same
175	FOREST: broad-leaved deciduous	FRSD	Forest -- deciduous		
176	FOREST: aspen	FRSD	Forest -- deciduous	FRSD	same
177	FOREST: oak	FRSD	Forest -- deciduous	FRSD	same
179	FOREST: northern pin oak	FRSD	Forest -- deciduous		
180	FOREST: red oak	FRSD	Forest -- deciduous		
183	FOREST: maple	FRSD	Forest -- deciduous		
185	FOREST: sugar maple	FRSD	Forest -- deciduous		
187	FOREST: mixed/other broad-leaved deciduous	FRSD	Forest -- deciduous	FRSD	same
190	FOREST: mixed deciduous/coniferous	FRST	Forest -- mixed		
200	OPEN WATER	NODA or WATR	No Data, or Water	WATR	same (small area)
210	WETLAND	WETL	Wetlands -- mixed		
211	WETLAND: emergent/wet meadow	WETN	Wetlands -- non-forested	WETL	same
212	WETLAND: floating aquatic herbaceous vegetation	WETN	Wetlands -- non-forested		
217	WETLAND: lowland shrub	WETL	Wetlands -- mixed		
218	WETLAND: lowland shrub: broad-leaved deciduous	FRSD	Forest -- deciduous	FRSD	same
219	WETLAND: lowland shrub: broad-leaved evergreen	FRSE	Forest -- evergreen		
220	WETLAND: lowland shrub: needle-leaved	FRSE	Forest -- evergreen		
222	FORESTED WETLAND	FRST	Forest -- mixed		
223	FORESTED WETLAND: broad-leaved deciduous	FRSD	Forest -- deciduous	FRSD	same
229	FORESTED WETLAND: coniferous	FRSE	Forest -- evergreen	FRSE	same
234	FORESTED WETLAND: mixed deciduous/coniferous	FRST	Forest -- mixed		
240	BARREN	BARR, FESC, or PAST	Barren, Tall fescue, or Pasture	PAST (Pasture)	BROS (Smooth brome, *Bromus inermis*)
250	SHRUBLAND	POPL	Poplar *(Populus sp.)*		
255	CLOUD COVER	FRST or FESC	Forest -- mixed, or Tall fescue		

NOTES:
WISCLAND grid cells were re-classified according to the SWAT land-use codes shown for the Willow watershed. Cropland HRUs (with original CORN, SOYB, or ALFA land uses) were planted in time-lagged rotations to maintain approximate spatial coverage of each crop each year. Brome appears to be more common than fescue in the Willow wateshed, so all HRUs identified as FESC or PAST land uses were planted to BROS (smooth brome). Where the WATR land use coincided with "undefined" or "water" types in the soil data set, land use was left as WATR, even when the POND routine was used to model some open-water bodies. If SWAT adds POND area to the subbasin area where the POND is located, then the total area definde as WATR should be subtracted, to avoid double-counting open-water area. It is unclear how SWAT deals with these areas. In the Willow model, the area of open water was probably too small to make a difference.

The AVSWAT interface was then initiated with these input datasets to delineate subbasins for model operation. The locations of the main watershed outlet, two in-channel reservoirs, and four point sources were input during this initial set up of the model. Then, the interface processed the 10-m DEM by filling sinks and artificially lowering the DEM along the stream-channel vector dataset to force flow through known channel locations. From this processed DEM the interface created its own stream-channel vector dataset and automatically delineated subbasin boundaries. As noted, the resulting total watershed area was 717 km^2, which was smaller than the 721 km^2 delineated by the USGS (Lenz et al. 2003) principally because AVSWAT excluded several areas of closed drainage along the northern edge of the watershed. The exclusion of these areas (less than 0.6% of the total watershed area) was presumed to be inconsequential. The watershed was subdivided into 27 subbasins based on a stream definition threshold area of 1500 hectares as suggested by the interface (Figure 5). Each subbasin was assigned an average calculated slope and slope length, computed from the DEM. The subbasins ranged in size from 1.86 km^2 to 113.4 km^2. The resultant shapefile of subbasin boundaries was then used in processing the soil input dataset outside of the AVSWAT interface.

Input soil tables for SWAT were generated from SSURGO database tables with the SSURGO-SWAT 2.0 extension for ArcView (Peschel et al. 2006). The SSURGO SWAT extension creates a model input file (usersoil.dbf) that includes the required SWAT parameters for each soil in the watershed that has defined properties. However, because of the detailed nature of the SSURGO dataset, soils are delineated for all areas but do not always have defined properties. In the Willow dataset, soils with undefined properties totaled 3.8% of the watershed and were predominately areas covered by open water and wetlands. These undefined soils were assigned the STATSGO soil designation WIW (Wisconsin water). Figure 6 demonstrates the spatial resolution of SSURGO soils as aggregated by hydrologic group, showing the dominance of hydrologic group B and the riverine location of undefined soils.

AVSWAT generates HRUs by intersecting the soils and land use data grids, identifying a separate HRU for each unique combination in each subbasin. Use of the full SSURGO dataset resulted in too many HRUs for the model to run efficiently. Consequently, the SSURGO dataset was simplified by aggregating similar soil types into larger units with averaged properties. In previous studies in Wisconsin (Earth Tech 2000, Baumgart 2005) SSURGO soil properties were areally weighted at the subbasin level to provide one average soil for each subbasin. The disadvantage of any spatial aggregation is the loss of information through separating specific soil properties from their geographic location, which links them to other spatial datasets. Curve number, which depends on soil hydrologic group and land use, is a very sensitive parameter in SWAT. Because of possible relationships between soil hydrologic group and land use, the SSURGO soil dataset was aggregated in such a way to preserve the spatial relationship between the hydrologic group and land use.

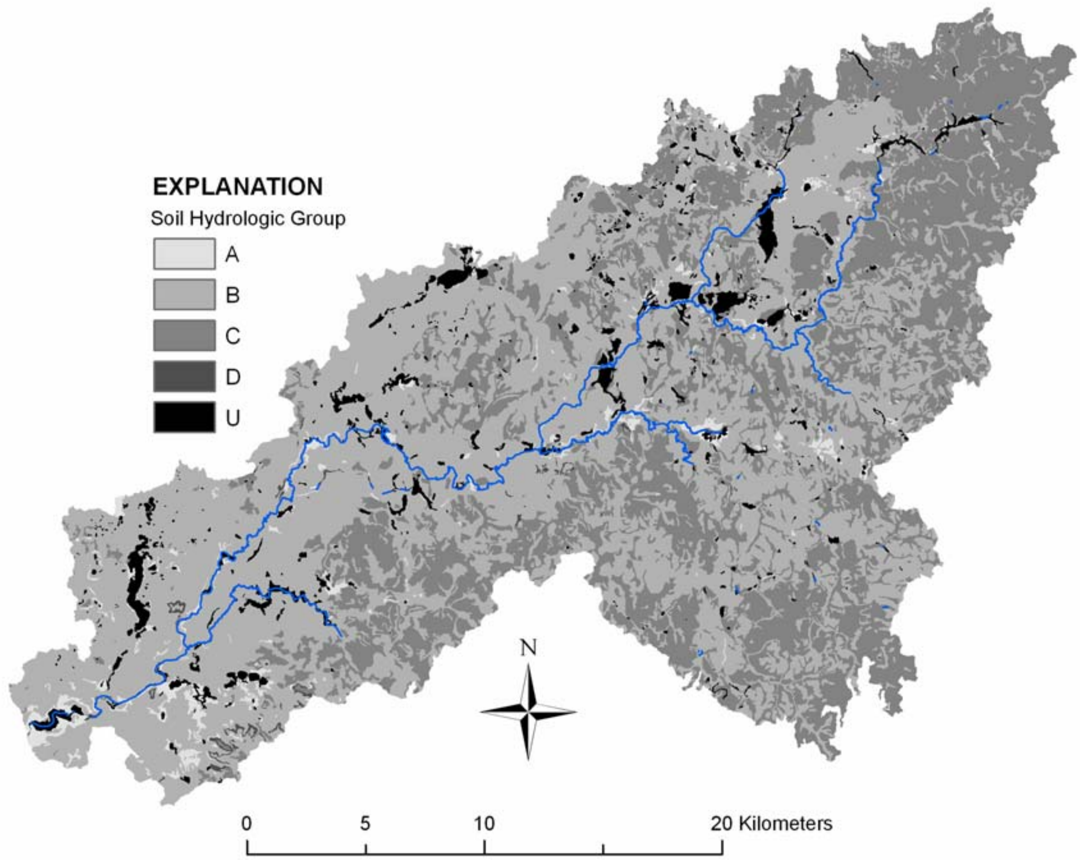


Figure 6. Soils generalized by hydrologic group from SSURGO data set for the Willow River watershed (U = undefined).

Consequently, the subbasin polygon shapefile created by the AVSWAT interface was used to identify the SSURGO soil types and areas within each subbasin. For each subbasin, SSURGO soils of the same hydrologic group and with the same number of soil layers were aggregated. Within these aggregates, all other soil properties were areally averaged. Each subbasin contained approximately six aggregate soils. Subbasins intersected by a county boundary commonly had a few extra units, because soils from each county were aggregated separately. The resulting 162 aggregated soil types were named with a subbasin and sequential number scheme and their averaged properties were entered into a new soil input datafile (usersoil.dbf). These new aggregate names were then substituted for the original SSURGO soil type names in the grid file.

Use of the AVSWAT interface could now continue with the model-ready land-use grid, soil grid, and soil database. The interface intersected the land-use and soil grids within each subbasin, resulting in 532 HRUs. Thresholds for land use and soils were set at 5% and 1%, respectively; i.e., the interface ignored land uses and soils with areas less than the threshold within any one subbasin. HRUs with a WIW soil and a land use other than water were considered ill-defined. Spreadsheet operations were used to give these ill-defined HRUs a negligible area and to distribute their original areas to the other HRUs in the sub-basin with the same land use based on their proportional areas.

Model Configuration

Input of the geographic data informed SWAT of the locations of obvious landscape features. The next step was to configure the model by providing additional features not initially recognized by the AVSWAT interface, fine-tuning the geographic extent of some features, and providing management and other information specific to selected features. In this report, model configuration refers to adjustments to model data sets and parameters to make the model internally consistent and to make model output conform to generally accepted literature values. Model calibration and validation are discussed in a later section and refers to adjusting model parameters so that model output matches measured data specific to the study watershed.

Ponds and Wetlands in SWAT

The automated watershed delineation routine in AVSWAT pre-processes the DEM by filling in sinks to simplify the drainage pattern. Consequently, areas of closed drainage are not recognized and delineated – yet they are real features of the landscape that have large implications for NP-S pollution loads. Closed drainages are common in glacially pocked landscapes and capture all sediment and virtually all phosphorus (except for that small fraction that can be transported by groundwater). In addition, because spatial relations among land covers and drainage patterns are lost within SWAT-delineated subbasins, SWAT cannot automatically recognize the influence of riparian wetlands (or other flow-though wetlands) in reducing sediment and phosphorus loads in flows delivered to them by portions of the subbasins.

SWAT does have some tools, however, to help address these issues. SWAT allows flow from each subbasin to be routed through either a single aggregate “Pond” or “Wetland” feature before reaching the main channel of the subbasin. This allows for sediment and nutrient removal mechanisms to operate, but the user must determine the fractional areas draining to these features and set their hydrologic and water-quality characteristics. The Pond and Wetland tools in SWAT function nearly identically, with the Pond tool having some additional parameters to adjust outflow response. For the Willow model, we chose to use the Pond tool for all closed drainages (whether they led to open-water bodies or wetlands) and the Wetland tool for wetlands that passed flow through to the subbasin channel.

Closed depressions, or sinks, were identified by analyzing the DEM with the Identify Sinks tool in the ArcGIS hydrology toolkit. Isolated wetlands were defined from the WISCLAND dataset as forested and wet meadow wetlands that were not connected to the stream network either by continuous wetland area or a stream. Lakes were identified as landlocked water bodies in the WDNR Open Water dataset. The contributing area for each sink, isolated wetland or landlocked lake was hand-delineated from 1:24,000 (24K) topographic maps, displayed as digital raster graphs (DRGs) within ArcGIS. These areas were summed for each subbasin and divided by the total subbasin area to obtain the fractional area of each subbasin draining to closed depressions. The total area of open water in each subbasin was calculated by aggregating areas of off-stream open-water bodies in the Open Water dataset. Approximately 29% of the Willow watershed drains to closed depressions (Figure 7). These areas were represented in SWAT with the Pond tool.

Likewise, large areas of wetland adjacent to channels were identified in the WISCLAND dataset. For each subbasin, the areas of these wetlands were summed to obtain a single aggregate area. Contributing areas were delineated in ArcGIS by hand from the 24K DRGs, and for each subbasin sum of these areas were divided by the subbasin area to obtain fractional area contributing to wetlands. Approximately 13% of the Willow watershed drains to these large wetlands (Figure 7). These areas were represented in SWAT with the Wetland tool.

Pond principal water volume was calculated assuming an average depth of 1 meter in all open water area. Emergency surface areas were set equal to the principal surface areas, and emergency water volumes were set to 50 times the normal water volume to prevent the ponds from spilling significantly, thereby preserving the essential feature of closed depressions as a trap on the landscape. The pond bottoms were given an arbitrary hydraulic conductivity of 5 mm hr^{-1} to provide seepage to groundwater. Sediment equilibrium concentrations were set to zero and phosphorus settling rates were set very high (100 m yr^{-1}) to force complete capture of these constituents by the ponds. Wetland principal water volume was calculated assuming an average depth of 1/3 meter. Emergency surface areas and volumes were set equal to the principal surface areas and volumes. Wetlands were assigned a hydraulic conductivity of zero to disallow any seepage loss to the shallow aquifer, as near-channel wetlands would be expected to be areas of groundwater discharge, not recharge. Parameters to control trapping of sediment and phosphorus in Wetlands were adjusted during model calibration.

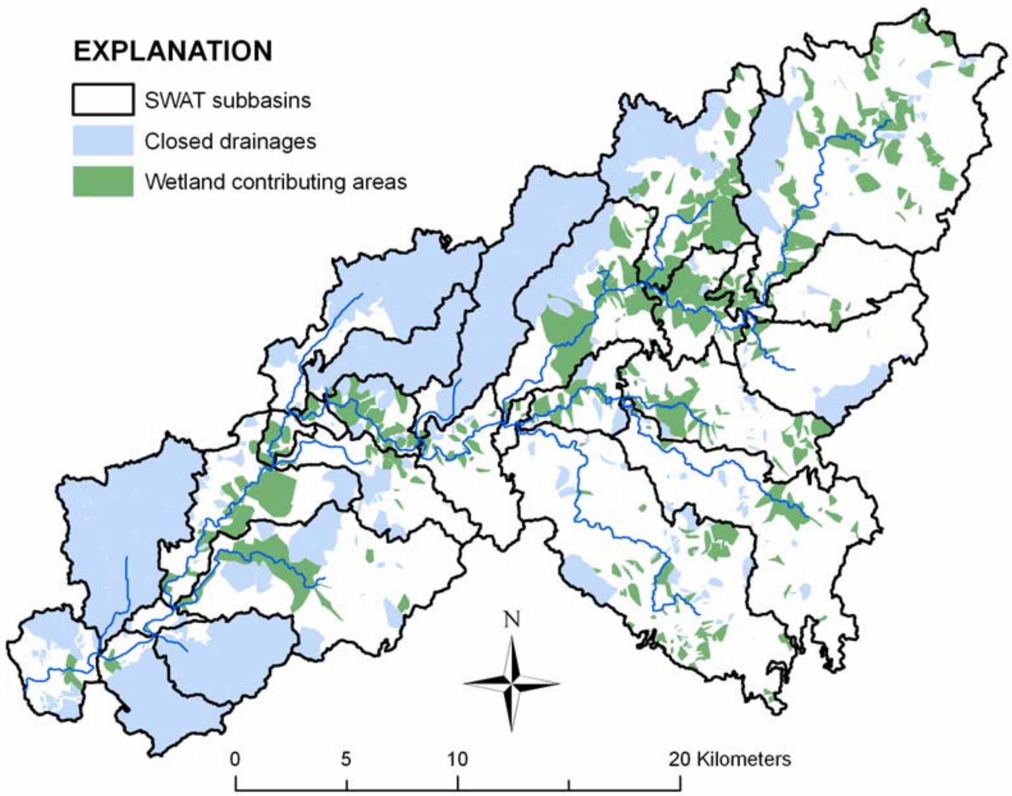


Figure 7. Areas contributing to closed depressions and riparian wetlands in the Willow River watershed.

We note here an apparent significant error in the SWAT2000 executable code (Almendinger and Murphy 2007). Seepage into the shallow aquifer from the conceptually aggregated Pond in each subbasin should be contributing to groundwater recharge, and this water should eventually reach the channel as groundwater discharge. However, seepage from Ponds (and other surface-water bodies in SWAT) is not included as a component of groundwater recharge, and instead gets trapped indefinitely in shallow aquifer storage as a limitless quantity. Consequently, by adding Ponds in the Willow model, flow at the watershed outlet was reduced by about 30%, the same percentage as land draining to Ponds. This lost flow had to be re-introduced in a way that would mimic the groundwater discharge expected to have resulted from infiltrated Pond water. One way was to disallow any seepage by setting the hydraulic conductivity of the Pond bottom to zero, and then force the Ponds to drain very slowly via a conceptual surface outlet by setting their target-days of release (parameter NDTARG) to a large number (300 to 1000 days). This method produced a workable solution to the problem but gave occasional spikes in flow. To smooth further the flow contributions from Ponds, pond outflow was totaled for water year 1999 (our targeted calibration year) and it was found that multiplying groundwater discharge by about 0.4 reproduced the pond outflow volume for the year. This factor was assumed to apply to other years. Monthly groundwater discharges in each subbasin from previous model runs that included pond outflow were then multiplied by this factor to obtain the estimated contribution of Pond infiltration to groundwater discharge in each subbasin over the model-run period (typically 1987-2001). Ponds were then re-parameterized to allow infiltration (hydraulic conductivity set to 5 mm hr^{-1}), thereby trapping pond infiltration; this lost flow was then replaced by adding a point source in each subbasin with the monthly flows determined as discussed above. However, the resulting daily hydrograph was only minimally improved from these manipulations, compared to simply allowing the ponds to drain slowly via a conceptual surface outlet.

Land-Cover Changes

As noted in the Study Area section, the WISCLAND land-cover dataset was based on satellite imagery from 1991-93, but our calibration dataset was from 1999. Because model land cover should correspond to the calibration period, land-cover changes from about 1992 to 1999 were determined by Almendinger and Murphy (2005). Only summary results are presented here. The WISCLAND dataset indicated 35,894 ha of cropland in (about) 1992; by 1999 data from the National Agricultural Statistics Service (NASS 2007) indicated about 32,871 ha of cropland, a loss of 3,023 ha or 8.4%. Table 4 summarizes which land covers replaced this area of lost cropland. About 55% was assigned to rural residential development, 33% to mixed forest, 9% to recreational land, and 2% to growth in New Richmond. 78% of the changes occurred in the lower Willow watershed, below New Richmond.

Rather than create a new gridded land-cover map, land-cover changes were implemented in the ASCII files that were created for each HRU. Transformations between land covers were divided between all of the subbasins by proportional subbasin area within each grouping that contained the land cover that was losing area and the land cover that was gaining area. Within each subbasin, the land-cover changes were partitioned between HRUs proportionally based on the original areas of the HRUs that were losing area in the subbasin. A Java program was written specifically to execute these data manipulations (M. Murphy, Dept. of Geology, Univ. of Minnesota, personal communication, 2005).

Table 4. Conversion of crop areas to other land-use types in the Willow River watershed gauged watershed area, from 1992 to 1999 and from 1999 to 2004.

	1992 to 1999			1999 to 2004		
Cropland converted to:	*(acres)*	*(ha)*	*(%)*	*(acres)*	*(ha)*	*(%)*
Inside New Richmond						
Urban, low intensity	106	43	67%	42	17	67%
Urban, high intensity	53	21	33%	21	9	33%
Subtotal	*158*	*64*	*100%*	*64*	*26*	*100%*
Outside New Richmond						
Upper Willow Watershed						
Residential, low density	411	166	28%	165	67	28%
Forest, mixed	1,051	425	72%	421	171	72%
Recreational	0	0	0%	0	0	0%
Subtotal	*1,462*	*592*	*100%*	*586*	*237*	*100%*
Lower Willow Watershed						
Residential, low density	3,697	1,496	63%	1,482	600	63%
Forest, mixed	1,442	583	25%	578	234	25%
Recreational	710	287	12%	285	115	12%
Subtotal	*5,848*	*2,367*	*100%*	*2,344*	*949*	*100%*
Total crop area lost	7,469	3,023		2,994	1,212	

Notes:

(a) 1992-99 crop area lost was set to 1992 WISCLAND crop area minus 1999 NASS crop area, scaled to gauged watershed area.

(b) 1999-2004 crop area lost was set to 1999 NASS crop area minus crop area from NASS data extrapolated to 2004. This loss (1,212 hectares) was similar to that estimated from St. Croix County Transect data (1,141 hectares).

(c) Of this total crop area lost, 80% was attributed to the lower watershed and 20% to the upper watershed, based on land-use changes in individual townships during 1973-93.

(d) The portion of crop area converted to residential development and urbanization was based on population changes in New Richmond and St. Croix County.

(d1) For New Richmond, the 1992-99 population growth was assumed to be 70% of the 1990-2000 population growth. Each new residence was assumed to contain 2.66 people and occupy 0.33 acre (data from 2000 census). High-intensity urbanization (commercial, industrial, institutional, transportation, and utilities) was assumed to accompany residential development at a 50% rate, i.e., 1 hectare high-intensity per 2 hectares residential.

(d2) For the rest of the watershed, the 1992-99 population growth was assumed to be 70% of the 1990-2000 rural population growth in St. Croix County (towns and villages only; cities excluded), scaled by the gauged watershed area. Each house outside New Richmond was assumed to contain 2.66 people and occupy 1.85 ha (4.57 acres; countywide average for lots developed 2000-04). Of this increase in residential acreage, 90% was attributed to the lower watershed and 10% to the upper watershed, based on relative population growth in the individual townships from 1990-2000.

(d3) The remaining lost crop area was assigned to forest in the upper watershed, and to a 2-to-1 ratio of forest-to-recreational land in the lower watershed, based on 1973-93 land-use data.

(e) The 1999-2004 percentages of area gains for all land uses were assumed to be the same as during 1992-1999.

References:

WDNR 1998; NASS 2005; SCC-LWCD 2004; SCC-Planning Dept. 2000; U.S. Census Bureau on-line data

Agricultural Management Practices

Identification and input of management practices required several involved steps. First, the spatial pattern of cropland identified in the land-cover grids (and adjusted for changes from 1992 to 1999) had to be translated into temporal crop rotations that preserved the spatial pattern from year to year. In addition, selected parameters had to be adjusted within each rotation to account for the different hydrologic characteristics of each crop cover. Second, appropriate tillage practices and inorganic fertilizer application rates had to be determined and scheduled for each rotation. Third, manure quantities and application methods, rates, and locations had to be determined. Irrigation practices could have been considered as well, but only 2-3% of cropland acreage is irrigated in St. Croix County (NASS 2007), which was too small to be included in the SWAT model. Except for the hydrologic parameter adjustment, agricultural management practices were discussed at length in a separate report (Almendinger and Murphy 2005), which consolidated data from a number of sources including an extensive survey of farmers in the watershed (SCC-LWCD 2004). Only essential results from this report are summarized below.

Crop Rotations

Three primary crop rotations (one cash-crop and two dairy) were found adequate to reproduce the spatial distribution of tilled crops on the landscape. The cash-crop rotation was simply alternating years of corn-grain and soybeans (C1S1). The primary dairy rotation was a year of corn-grain, a year of corn-silage, and three years of alfalfa (C2A3). Some dairy farmers have added soybeans into their rotation, so a secondary dairy rotation was constructed as a year of corn-grain, a year of corn-silage, a year of soybeans, another year of corn-grain, and three years of alfalfa (C3S1A3). Because dairy farming is more prevalent in the upper watershed, and cash-cropping in the lower watershed, slight adjustments in the above rotations were originally considered for each half of the watershed (Almendinger and Murphy 2005). However, the spatial pattern of crops in the WISCLAND dataset assured that dairy rotations were concentrated in the upper watershed and cash-cropping rotations in the lower, and the added complexity of slight adjustments in crop rotations did not seem justified.

The public-domain version of SWAT2000 unfortunately does not properly handle crop rotations containing alfalfa. Because of an error in the model code, alfalfa cannot be removed from the landscape once planted in the model. Any rotation containing alfalfa soon becomes continuous alfalfa, with minimal export of sediment and nutrients. Hence this version of the model greatly underestimates loads of sediment and nutrients compared to actual rotations that include corn and soybeans. Test runs indicate that this error caused the model to underpredict sediment yields by 75% and phosphorus yields by 63% for the C2A3 rotation (Almendinger and Murphy 2007). Baumgart (2005) corrected this error and kindly provided an executable copy of his modified version of SWAT, without which our model of the Willow River watershed would have been severely compromised.

No forage grasses were included in the rotations; hence the amount of tilled land may have been slightly underestimated in the model. However, the area of land cover identified as alfalfa in the WISCLAND dataset (WDNR 1998), which was the area of alfalfa included in the rotations, corresponded closely to the total acreage of hay (which includes both alfalfa and harvested forage grasses) identified by the NASS (2007) dataset. Hence inclusion of some of the forage grass acreage in the rotations did not seem to justify the added complexity. Planting and harvest dates were set according to averages determined from the SCC-LWCD (2004) survey data.

Cropping in each rotation should not be synchronous across the basin. For example, in any given year some farmers using the C1S1 rotation plant corn while others plant soybeans; they do not all plant corn one year and soybeans the next in synchrony with their neighbors. Consequently sub-rotations were created that staggered the starting year of the rotation. In sub-rotation C1S1a, corn is planted in the first year of simulation; in sub-rotation C1S2b, soybeans is planted in the first year. Likewise, five sub-rotations were created for the C2A3 rotation (a-e), and seven sub-rotations were created for the C3S1A3 rotation (a-g).

Distributing these sub-rotations among the cropland HRUs was not straightforward. Spreadsheet calculations determined that the relative crop acreages in 1999 (45% alfalfa, 42% corn, and 13% soybeans, excluding other crops) could be achieved if about 60% of the cropland was in the C2A3 rotation, 20% in C1S1, and 20% in C3S1A3. A Java program was written to initially randomly assign cropland HRUs to these rotations based on the original WISCLAND land cover for these HRUs (M. Murphy, Dept. of Geology, Univ. of Minnesota, personal communication, 2005). That is, some of the alfalfa HRUs were assigned to the C2A3 rotation and some to the C3S1A3 rotation; some of the soybean HRUs were assigned to the C1S1 rotation and some to the C3S1A3 rotation; and the corn HRUs were distributed among all three rotations. These random assignments were run repeatedly until a configuration was achieved that produced the correct relative percentage of rotations (60% C2A3, 20% C1S1, and 20% C3S1A3). Next, for the HRUs under a given rotation, spreadsheet calculations were performed to distribute the sub-rotations among these HRUs such that the overall targeted relative percentages of corn, soybeans, and alfalfa were reproduced in any one year. Again, random assignments were run repeatedly until an acceptable configuration was achieved. In the end, some manual assigning of sub-rotations to selected HRUs was necessary to obtain a satisfactory configuration.

Different crops have considerably different rainfall-runoff responses, and so SWAT allows curve numbers to be changed within a rotation. A curve number may be specified for any planting or tillage operation; this parameter is called a CNOP (a curve number for an operation) in SWAT. To keep the model simple, we chose to change CNOPs at the time of planting each year, to correspond to that year's crop. However, SWAT ignored all CNOPs entered at the time of planting corn and for various other operations (viz., for either chisel plowing or disking when that operation was not the first operation of the year). Consequently the CNOP for a designated crop in a rotation was set to the same value for all planting and tillage operations that year, and from these redundant choices SWAT managed to implement the desired curve number for that crop. These curve numbers were further modified based on tillage practice (see next section).

Different crops also have different surface roughness, represented by the parameter Manning's N, which affects overland runoff velocities and hence soil erosion. Manning's N has a lower bound of zero for a completely smooth surface and typical values of 0.06 to 0.5 for vegetated land surfaces. SWAT assigns a single value of Manning's N to each HRU based on the vegetation identified in the input land-use data, in this case the WISCLAND satellite data (after conversion to SWAT-recognized land covers). While this may be adequate for HRUs with unchanging vegetation, it is unsatisfactory for HRUs with crop rotations because the surface roughness of row crops is very different from that for perennials such as alfalfa. Unfortunately, SWAT does not allow Manning's N to change from year to year with different crops or tillage practices. The best compromise we could effect was to assign crop-rotation HRUs an average Manning's N weighted by the years of each crop and tillage practice (see next section) in the rotation. The resulting Manning's N values are given in Table 5a. We note (and perhaps question) the default values given by SWAT. It is not intuitively obvious why the roughness of row crops (0.14) should exceed that of forest (0.1) and alfalfa (0.06).

Table 5. Manning's N (roughness parameter) and biomixing values for different crop rotations and tillage practices.

Corn tillage	Conventional	Mulch	No-Till	Conventional	Conventional	Mulch	No-Till	Mulch	No-Till
Soybean tillage	Conventional	Mulch	No-Till	No-Till	Mulch	Conventional	Conventional	No-Till	Mulch
Abbreviation	CT	MT	NT	CTCNTS	CTCMTS	MTCCTS	NTCCTS	MTCNTS	NTCMTS
Rotation				***(a) MANNING'S N VALUES***					
C1S1	0.12	0.22	0.32	0.22	0.17	0.17	0.22	0.27	0.27
C2A3	0.102	0.122	0.142	0.001	0.001	0.001	0.001	0.001	0.001
C3S1A3	0.107	0.15	0.193	0.136	0.121	0.136	0.136	0.164	0.179
Rotation				***(b) BIOMIXING VALUES***					
C1S1	0.20	0.30	0.40	0.30	0.25	0.25	0.30	0.35	0.35
C2A3	0.20	0.24	0.28	0.20	0.20	0.24	0.28	0.24	0.28
C3S1A3	0.20	0.26	0.31	0.23	0.21	0.24	0.29	0.27	0.30

NOTES:

Conventional tillage defined as leaving 0-15% residue cover; modeled as chisel plowing followed by disking for most crops, and as moldboard plowing followed by disking after year-3 alfalfa prior to planting corn. Mulch tillage defined as leaving 16-50% residue cover; modeled as chisel plowing only. No-till defined as leaving 50-100% residue cover; modeled by omitting all tillage practices. C1S1 rotation alternates corn-grain and soybeans. C2A3 rotation comprises corn-grain, corn-silage, and three years of alfalfa. C3S1A3 rotation comprises corn-grain, corn-silage, soybeans, corn-grain, and three years of alfalfa. Manning's N values taken from Neitsch et al. 2002b for different crops and residue. Biomixing set to 0.2 for conventional tillage (SWAT default) and increased to 0.3 for mulch tillage and 0.4 for no-till. Manning's N and biomixing values above calculated as time-weighted average values based on years of each crop in a given rotation.

Tillage Practices

The most common tillage implements were moldboard plow, chisel plow, disk, and field cultivator (SCC-LWCD 2004). While other secondary and finishing tillage implements were used in the watershed, these four were representative of tillage depth and incorporation as modeled in SWAT. Tillage was scheduled into the model rotations depending on crop type and manure application. The typical sequence was a spring chisel plowing and disking prior to planting for all crops. Cultivation was applied only to corn, about five weeks after planting. Exceptions to the typical sequence included fall chisel plowing to incorporate seasonal manure applications prior to second year corn, and fall moldboard plowing after the final year of alfalfa. In the spring after fall plowing, only disking is done prior to planting the next spring.

Conservation tillage practices, which increase coverage of crop residue, have been increasing in St. Croix County and needed to be configured in the model. Residue coverage is assessed by St. Croix County personnel in the spring of each year along pre-selected transects. Model results of residue biomass were checked on 1 June of selected years to correspond approximately to the timing of the field assessments. As defined here, conventional tillage leaves 0-15% coverage by residue on the surface and is modeled by a primary (chisel or moldboard plow) operation followed by a secondary (disk) tillage operation. Mulch tillage leaves 16-30% coverage by residue and conservation tillage leaves 31-50%; these categories were lumped together (hereafter called simply “mulch” tillage) and modeled by chisel plowing alone, without being followed by disking. No-till leaves 51-100% coverage by residue and was modeled by omitting both primary and secondary tillage operations. Coverage by residue is an effective means of reducing erosion: a 15% coverage reduces erosion by about 30%, and a 50% coverage by about 70% (Figure 8a, modified from McCarthy et al. 1993).

However, SWAT calculates residue in terms of biomass, rather than areal coverage. As residue biomass increases, SWAT decreases the cover and management factor (C_{USLE}) in the Modified Universal Soil Loss Equation (MUSLE), thereby decreasing modeled soil erosion (Figure 8b). In SWAT, C_{USLE} is crop-specific and ranges from a given minimum (C_{MIN}) of 0.2 (for corn and soybeans) to a maximum of 0.8 for all crops; it is unclear why SWAT does not allow C_{USLE} to reach a maximum of one, corresponding to a fallow field with no crop or residue cover. For SWAT to correctly model the effect of crop residue on erosion, the C_{USLE} factors calculated by SWAT based on residue biomass should be similar to C_{USLE} factors based on residue areal coverage. The soil loss ratio given in Figure 8a is similar in concept to C_{USLE}. If we assume that the range of C_{USLE} in SWAT (0.2 to 0.8) corresponds to the range of soil loss ratio in

Figure 8a (0 to 1), then we can approximately relate percent residue coverage to C_{USLE}, as was done by adding the extra y-axis to the right side of Figure 8a. Accordingly, erosion from conventional tillage would be modeled with C_{USLE} values ranging from about 0.63 to 0.8, mulch tillage with C_{USLE} values from about 0.38 to 0.63, and no-till with C_{USLE} values from about 0.25 to 0.38 (see Figure 8a).

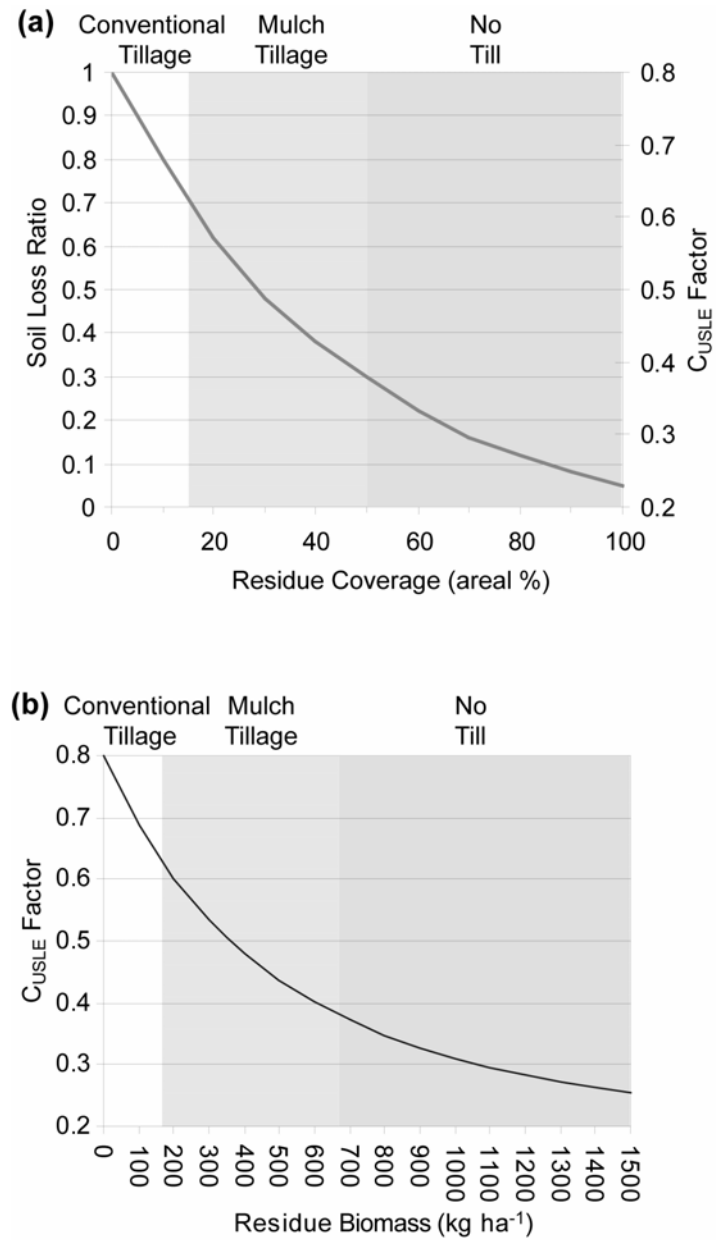


Figure 8. (a) Soil loss ratio as a function of percent residue coverage (modified from McCarthy et al. 1993), and relation to cropping practice factor, C_{USLE}; (b) C_{USLE} as a function of residue biomass, according to algorithm implemented by SWAT.

To make SWAT reproduce these C_{USLE} values for selected tillage practices, residue biomass must be within certain ranges. Figure 8b shows a plot of C_{USLE} as a function of residue biomass according to the algorithm used by SWAT, for C_{MIN} set to 0.2 for corn and soybeans. Given the ranges of C_{USLE} values determined above for each tillage practice, conventional tillage corresponds to a residue biomass of about 0 to 175 kg ha^{-1}; mulch tillage to about 175 to 675 kg ha^{-1}, and no-till to greater than 675 kg ha^{-1}. However, residue amounts in the model were commonly much higher than these amounts under default parameterization. To reduce modeled surface residue biomasses (on 1 June) to the levels necessary to achieve the desired C_{USLE} values, residue decomposition was accelerated for corn and soybeans and mixing efficiency was increased for chisel plow and disk operations. (That is, parameter RSDCO was increased from 0.05 to 0.15 for both corn and soybeans. Parameter EFFMIX was increased from 0.3 to 0.6 for chisel plowing and from 0.85 to 0.9 for disking.) After these changes, selected test HRUs had June 1st average residues of 100 kg ha^{-1} for conventional tillage, 500 kg ha^{-1} for mulch tillage, and 1400 kg ha^{-1} for no-till, well within the residue biomass ranges for these tillage levels shown in Figure 8b.

Tillage practices also affect surface roughness, mixing by soil organisms (biomixing), and infiltration. Surface roughness (Manning's N) is affected by crop type and tillage; the effect of crop type on a weighted-average roughness for a rotation was discussed above. Here we include the effect of increased roughness due to surface residue from conservation tillage practices. Manning's N for corn and soybeans was set at 0.12 for conventional tillage, 0.22 for mulch tillage, and 0.32 for no-till (estimated from tabular data in Neitsch et al. 2002b). Manning's N is an HRU-level parameter and was thus weighted according to the years of each tillage level in a rotation (see Table 5a). Conservation tillage reduces disturbance to soil organisms allowing greater biomixing. Parameter BIOMIX was increased from 0.2 (default) to 0.3 for mulch till crop years and 0.4 for no-till crop years. As with Manning's N, BIOMIX is an HRU-level parameter and thus weighted-average BIOMIX values were assigned to HRUs with crop rotations based on the years of each tillage level in the rotation (Table 5b). Infiltration was increased by decreasing curve numbers (CNOPs) by one point for mulch till years and by two points for no-till years.

In 2005, about 60% of the corn was under conventional tillage, 38% under mulch and conservation tillage, and only 2% under no-till. About 12% of the soybeans were under conventional tillage, 27% under mulch and conservation tillage, and 61% under no-till (S. Olson, SCC-LWCD, personal communication, 2006). For model calibration, these values were adjusted to approximate conditions in 1999. For corn, 80% was presumed to be in conventional tillage and 20% in mulch and conservation tillage. For soybeans, 30% was presumed to be in conventional tillage, 20% in mulch and conservation tillage, and 50% in no-till. All of the areas of no-till and mulch-plus-conservation tillage could be accounted for within the C1S1 HRUs. Spreadsheet operations were used to assign tillage designations to these HRUs for corn and soybeans repeatedly at random until a configuration that reproduced the desired areal percentages was achieved. These HRUs were then modified via the AVSWAT interface to have only chisel-plow tillage (mulch-plus-conservation tillage) or no tillage (no-till) for either corn or soybeans, or both.

From the survey data collected by St. Croix County, 12-15% of the respondents said that they practiced strip cropping, contour strip cropping, or contour tillage (SCC-LWCD 2004). In addition, 66% said they used grass waterways. In theory, SWAT can simulate the effect of these progressive practices by changing (reducing) the support practice factor P_{USLE} in the modified universal soil loss equation (MUSLE). However, in practice the calibration of sediment loads in SWAT can require substantial changes in the soil erosion parameters, and P_{USLE} is a convenient and effective parameter to adjust. In the Willow model, any effect of strip and contour cropping in reducing erosion was subsumed by large reductions in P_{USLE} required to achieve model calibration of sediment loads.

Inorganic Fertilizer Applications

The most common fertilizers and application rates were assessed from the survey of farmland owners in the Willow River watershed (SCC-LWCD 2004) and summarized in Almendinger and Murphy (2005). Of 29 fertilizer formulations identified, three accounted for more than half of the responses (9-23-30, 0-0-60, and 46-0-0). (In fertilizer formulations, the numbers given are the weight percentages of nitrogen as N, of phosphorus as P_2O_5, and of potassium as K_2O, respectively.) Application rates ranged from 56-445 kg/ha (50-400 lbs/acre) and averaged about 225 kg/ha (close to 200 lbs/acre). These application rates were consistent with general target of applying up to 168 kg/ha (150 lb/acre) of nitrogen to corn, either as inorganic fertilizer alone or in combination with manure.

The simplest possible array of fertilizers and application rates that were representative of actual use were planned for input into the SWAT model. Soybeans were given 225 kg/ha (200 lb/acre) of 9-23-30 fertilizer pre-plant. Even though farmers commonly add 0-0-60 fertilizer (potash) to alfalfa, none was added in the model because SWAT neither tracks potassium in the watershed nor has an algorithm to allow alfalfa to respond to potassium amendments. In early model runs for corn in the absence of manure applications, 334 kg/ha (300 lb/acre) of 46-0-0 fertilizer (urea) was surface applied prior to planting, and 225 kg/ha (about 200 lb/acre) of 9-23-30 starter fertilizer was injected with the planting operation. Surface-applied urea was incorporated by disking five days after application. When manure was applied (primarily to second-year corn), these quantities were reduced to about 111 kg/ha (100 lbs/acre) each. However, corn yields were consistently too low in the model compared to data from NASS (2007) because of nitrate losses to leaching. Simulating corn growth and yield was important because of the resulting effects on system hydrology, phosphorus uptake, residue production, and erosion potential. These factors were considered more important than precise controls on nitrogen applications. SWAT has an auto-fertilization routine that minimizes crop stress due to lack of a selected nutrient. Consequently this auto-fertilization routine for nitrogen was substituted for all cases where 46-0-0 fertilizer was applied to corn in earlier model runs.

Manure Management

Livestock numbers in the watershed were assessed to determine the amount of manure to apply to agricultural areas. Countywide data for dairy cattle, beef cattle, and hogs in 1999 were available from NASS (2007) and scaled to the modeled watershed area. Numbers of sheep, chickens, and horses were estimated from the SCC-LWCD (2004) survey data; though these estimates are not likely very accurate, they are probably small enough to justify omitting these manure types from the model. Numbers of turkeys were not pursued in detail because the total amount of turkey manure applied in St. Croix County was directly available (K. Hafstad, Jenny-O Turkey Store, personal communication, 2005). Livestock numbers of each species were translated into quantities of manure per year based on typical animal weights and empirical conversion factors per 1000-lb body weight. Resulting tonnage of manure, based on numbers of animals and estimated weights, was converted to metric tons of manure dry weight per year (metric T/yr) for input into SWAT.

Cattle were clearly the largest source of manure by weight to the watershed in 1999, with dairy cattle (and calves) producing over 290,000 shT/yr (short tons raw manure per year; nearly 37,000 metric T dry weight; 82% of the total) and beef cattle producing 50,000 shT/yr (nearly 7,000 metric T dry weight; 14% of the total). Hog (about 2%) and turkey (about 1%) manure tonnage was deemed small enough to be omitted from the baseline calibration model (Table 6). To simplify model input, a mixture of dairy and beef manure was typically applied within the same rotations, rather doubling the number of rotations to accommodate dairy and beef manure separately; exceptions are noted below. While dairy and beef farms may commonly be separate operations, we felt that for water-quality purposes the most important factor was applying the proper total amount of manure at realistic rates on the landscape, and that the simplification afforded by mixing the two types of manure was justified.

Table 6. Typical manure characteristics and calculated quantities in the Willow River gauged watershed area, 1999.

Livestock Type	(a) Manure characteristics: Raw Manure (lbs/day/1000-lb animal unit)	Total Solids (Dry Wt) (lbs/day/1000-lb animal unit)	Nitrogen (lbs/day/1000-lb animal unit)	Phosphorus (lbs/day/1000-lb animal unit)	(b) Manure in the gauged Willow watershed: Numbers of Animals	Animal Est'd Wt (lbs)	Raw Manure (short T/yr)	Total Solids (Dry Wt) (metric T/yr)	Percent of Total (%, raw manure)
Dairy cattle, adult	86	12	0.45	0.094	9,733	1,350	206,232	26,161	58.37%
Dairy calf	86	12	0.45	0.094	7,757	700	85,222	10,810	24.12%
Beef cattle, adult	58	8.5	0.34	0.092	2,572	1,200	32,663	4,352	9.24%
Beef calf	58	8.5	0.34	0.092	2,049	800	17,354	2,312	4.91%
Hogs	84	11	0.52	0.18	2,543	175	6,821	812	1.93%
Sheep	40	11	0.42	0.087	58	100	42	11	0.01%
Chickens (layers)	64	16	0.84	0.3	994	4	46	11	0.01%
Turkeys	47	12	0.62	0.23	n/a	n/a	3,526	818	1.00%
Horses	51	15	0.3	0.071	191	800	1,426	381	0.40%
Totals							353,333	45,667	100%

Abbreviations:
Dry Wt, dry weight; Est'd Wt, estimated weight; lbs, pounds; short T, short ton = 2000 lb; metric T, metric ton = 1000 kilograms; n/a, not applicable
Notes:
Manure charactistics obtained from American Society of Agricultural Engineers (1998), as cited by Neitsch et al. (2002).
Numbers of cattle and hogs for St. Croix County obtained from the National Agricultural Statistics Service web data, scaled from countywide totals down to the gauged watershed area. Beef cattle and total number of calves interpolated between 1997 and 2002 data. Calves apportioned according to the proportions of adult cattle.
Numbers of sheep, chickens, and horses estimated from 2004 survey of farmers in the watershed (SCC-LWCD 2004). We suspect that sheep and chickens were underestimated, but still unlikely to be a major contributor of manure relative to other sources. Turkey numbers in St. Croix County were not relevant, as turkey manure from other counties is trucked to St. Croix County; tons spread in 1999 were scaled down to the gauged watershed area from a countywide total (K. Hafstad, Jenny-O Turkey Store, personal communication, 2005).

In the model, manure was applied to grasslands by grazing animals, or to cropland by either daily-haul applications or seasonal (spring and fall) applications. Calculations based on the SCC-LWCD (2004) survey indicated that about 9% of the dairy manure and 46% of the beef manure was spread via grazing on grasslands, and that the grazed grassland acreage (about 44 km^2) amounted to 14% of total cropland acreage (Almendinger and Murphy 2005). Grassland HRUs were randomly selected via spreadsheet operations until a configuration that totaled 44 km^2 was achieved, and grazing was applied to these HRUs. Grazing was allowed for 165 days per year, beginning on 20 May. Based on the total tonnage of manure to be spread by grazing each year, an application rate over this area was calculated on a kg ha^{-1} d^{-1} basis for both dairy and beef cattle for input into SWAT. Manure quantities were back-converted to animal units to allow an estimate of biomass eaten by grazing cattle. Useful conversion factors resulting from these calculations were that grazing dairy cattle eat 2.08 kg of biomass for every kg of manure deposited, and that grazing beef cattle eat 2.94 kg biomass for every kg of manure deposited. Biomass trampled by grazing animals was set at 20% of that eaten.

About 21% of the dairy manure and 23% of the beef manure was estimated to be applied to cropland by the daily haul method (Almendinger and Murphy 2005). Because dairy cattle greatly outnumber beef cattle, dairy manure composed about 90% of the total daily-hauled amount. To simplify model inputs, the tonnage of dairy manure was increased by about 10% and the beef manure ignored. The acreage of farms that daily-hauled manure amounted to about 28% of the total cropland in the watershed (SCC-LWCD 2004). However, farmers tend to haul manure only to the most convenient one-third of their available fields (Jackson-Smith et al. 2005) so the acreage of cropland receiving daily haul applications of manure was reduced to 10% of the total, or about 3,100 ha. The C2A3 rotation was selected to receive this manure, and out of all the HRUs with the C2A3 rotation, an array was selected at random via spreadsheet operations until the desired area (3,100 ha) was achieved. Dairy manure was then applied to this array of HRUs on the 15th of every month (260 kg ha^{-1}), except from May through October in the years when corn was planted. Specifying daily application of manure in the model was not tractable, and monthly applications seemed to be an appropriate simplification. Others have simulated daily manure hauls by grazing virtual cattle that did not eat or trample biomass. However, SWAT disallows grazing when field biomass falls to low levels, which was common during the winter months. Hence in our model virtual cattle failed to apply the required amount of manure, whereas monthly applications were exactly reliable.

The remaining amount of manure (70% of the dairy manure and 31% of the beef manure) was applied seasonally (fall and spring) prior to planting second-year corn in the C2A3 and

C3S1A3 rotations. When distributed over the acreage of all second-year corn in these rotations, the application rate was about 22 shT acre^{-1} yr^{-1} (short tons per acre per year, fresh weight, dairy plus beef). This seemed to be a reasonable amount, recognizing that some farmers may apply far more while others may apply none. Hence all of these HRUs received seasonal manure at this rate, rather than selecting HRUs at random to achieve an area that would receive some other pre-selected application rate. Fall applications were incorporated by chisel plowing; spring applications were incorporated by disking. Manure application rates in selected rotations are summarized in Table 7.

Synthesis into SWAT Management Rotations

The above information on crop rotations, tillage practices, fertilizer applications, and manure management was combined into SWAT-specific agricultural management rotations, with each event scheduled throughout the year (Appendix A, Tables A1 to A5). Assignment of these rotations and other management considerations to specific HRUs is documented in Appendix B. Out of 532 total HRUs, 225 were cropland (corn, soybeans, or alfalfa) and received one of these rotations (Table B1). Out of 118 grassland HRUs, 17 received manure by grazing (Table B2). Out of the 225 cropland HRUs, 17 received manure by daily haul operations, simulated as monthly applications (Table B3).

Table 7. Manure application rates for different crop rotations in the SWAT model of the Willow River watershed, 1999.

Rotation	Area Relative to Total Cropland Area (%)	Typical Units in USA: Dairy (sh T/acre/yr, wet wt)	Typical Units in USA: Beef (sh T/acre/yr, wet wt)	Typical Units in USA: Total (sh T/acre/yr, wet wt)	Units for SWAT Input: Dairy (see column to right for units)	Units for SWAT Input: Beef (see column to right for units)	Units (dry mass basis)	Rules
Pasture	14%	2.31	2.02	4.33	4.39	4.04	kg/ha/day	Grazing 20 May to 1 Nov (165 days) each year
C2-A3, daily haul	10%	8.57	0.96	9.53	260	0	kg/ha/mon	Applied on15th of each month all year for hay fields, Nov-Apr for corn fields
C2-A3, seasonal	50%	20.06	1.99	22.06	6296	656	kg/ha/year	Half in fall, half in spring before yr-2 corn
C3-S1-A3, seasonal	20%	20.06	1.99	22.06	6296	656	kg/ha/year	Half in fall, half in spring before yr-2 corn
C1-S1, no manure	20%	n/a	n/a	n/a	n/a	n/a		

Abbreviations:
lbs, pounds; sh T, short ton = 2000 lbs; yr, year; wt, weight; kg, kilograms; ha, hectare; n/a, not applicable

Notes:

• Pasture area is in addition to cropland area, calculated at 14% of cropland area. Biomass (forage, dry weight basis; parameter BMEAT) eaten by dairy cows calculated at 2.08 kg forage grazed per kg of manure produced, and by beef cattle at 2.94 kg forage grazed per kg of manure produced. Biomass trampled (parameter BMTRMP) was set at 20% of that eaten.

• C, corn; S, soybeans; A, alfalfa; number following letter designates number of years of that crop in the rotation.

For C-A and C-S-A rotations: yr-1 corn is grain; yr-2 corn is silage; yr-3 corn (if any) is grain following soybeans. For C-S rotations: all corn is grain. Cropland comprises the C-A, C-S-A, and C-S rotations and totals 100%.

Miscellaneous Configurations

A number of additional details needed configuration before model calibration could begin in earnest.

Slope and Slope Length

AVSWAT calculates the average slope and slope length for each subbasin and assigns these variables to every HRU in that subbasin. However, different land covers can be associated with different slopes. For example, agricultural land may occupy flatter land than forests. To account for these differences, ArcGIS was used to derive an average slope from the DEM for each land-cover type in each subbasin. This slope was then assigned to all HRUs with that land-cover type in each subbasin. (Recall that HRUs are combinations of land cover and soil type, so HRUs with the same land cover differ only in respect to soil type.) Slope length was then calculated by the following equation (Baumgart 2005) from these newly calculated slopes.

$$\text{slope length (m)} = 91.4 / (\%\ \text{slope} + 1)^{0.4}$$

Resulting slope lengths ranged from about 30 to 60 m, consistent with literature values, whereas slope lengths calculated by AVSWAT were closer to 100 m.

Time of Concentration

By default, SWAT calculates runoff time of concentration for each HRU based on the fractional area and channel length attributable to that HRU. However, as Baumgart (2005) points out, HRUs have no physical basis as a contiguous landscape unit; they are instead conceptual aggregations of commonly non-contiguous patches scattered within each subbasin. Time of concentration calculations are applicable to physically coherent landscape units, and subbasins are the smallest such landscape unit within a SWAT model. Consequently, Baumgart (2005) modified the SWAT code to calculate subbasin-wide times of concentration based on subbasin area, dimensions, and channel length. This time of concentration is then applied to each HRU within that subbasin, rather than each HRU having its own time of concentration. Because subbasin dimensions are nearly always larger than HRU dimensions (unless there is only one HRU per subbasin), times of concentration based on subbasin dimensions are longer than those based on HRU dimensions. Consequently, sediment yields tend to be reduced in models using Baumgart’s modified code – which we are using for the Willow – compared to models using the standard SWAT2000 code. (We note, however, that adjustments to the surface runoff lag coefficient, SURLAG, may narrow this difference.)

Channel Parameters

AVSWAT has algorithms to assign default parameter values for channel roughness (Manning's N), bed hydraulic conductivity, net channel erosion, and cross-sectional dimensions. The default Manning's N assigned by AVSWAT to channels was 0.014, which applies to uniform straight ditches and was thus not appropriate for the Willow River. This value was changed to 0.05 for both tributary and main channels, which applies to winding channels with some weeds and brush (Neitsch et al. 2002b). In SWAT, streambed hydraulic conductivity is used to control seepage out of the stream, typically more important in arid climates. (In contrast, the model ignores bed hydraulic conductivity when calculating groundwater discharge into the stream.) Because losing reaches (channels with out-seepage) are much less common than gaining reaches in perennial streams in the Midwest, streambed hydraulic conductivities were set to zero to disallow seepage losses. In addition, this configuration avoided the problem of SWAT trapping the infiltrated water in shallow aquifer storage and removing it from the watershed water balance, a consequence of the same model code error noted above for Ponds and Wetlands.

Net erosion or deposition in channels in SWAT is highly sensitive to a few parameters, and no field data existed to constrain these parameters. To simplify interpretation of initial calibration runs, channels were made into passive conduits that disallowed both erosion and deposition. Erosion was disallowed by setting the channel erodibility factor to zero. (Channel cover factor, the proportion of channel uncovered by vegetation and thus exposed to erosion, was set to one, so that erosion was controlled by the erodibility factor alone.) Deposition was disallowed by setting the sediment re-entraining factor (SPCON) to 0.01 (rather than the default value of 0.001), which maintained nearly all sediment delivered to the channel in suspension.

During model construction for the Willow, AVSWAT calculated default cross-sectional channel dimensions (width and depth of the main channel and floodplain) that were about five times too wide compared to field data. However, attempts to change channel dimensions to more realistic (smaller) values made the model even more sensitive to the erosion and deposition parameters, apparently because of increased water velocities resulting from smaller cross-sectional areas. These model results were not easily interpretable, and consequently the default channel dimensions as calculated by AVSWAT were retained. We note that the problems in SWAT with channel erosion, deposition, and cross-sectional dimension deserve greater investigation, as understanding these processes is critically important in interpreting sediment loads from the Midwestern landscape.

Extraneous Phosphorus Loads

Early model runs revealed that the channels ("reaches" in SWAT) were carrying more phosphorus than was delivered to them by overland runoff, lateral flow, and groundwater flow from the subbasins. The extraneous source of phosphorus was traced to an algorithm in SWAT that calculates a chlorophyll load from the subbasins to the channel. Once this chlorophyll is in the channel, the stream water-quality module in SWAT (QUAL2E) presumes that the chlorophyll is in the form of algae, and that these algae contain phosphorus. QUAL2E then decomposes the algae, thus releasing an extra phosphorus load that is unrelated to the phosphorus budget in the watershed. In the Willow watershed, this extraneous phosphorus increased the whole-basin load by 19% and more than doubled the phosphorus load from some individual subbasins (Almendinger and Murphy 2007). To avoid overestimating the phosphorus load from the landscape, either QUAL2E must be inactivated, or the phosphorus content of algae must be reduced to a negligible value (e.g., reduce parameter AI2, the fraction of algal biomass that is phosphorus, from the default value of 0.015 down to 0.001). For initial runs of the Willow model, we chose to inactivate QUAL2E to keep the model as simple as possible.

Soil and Groundwater Phosphorus Content

Model results were sensitive to the initial labile phosphorus content assigned to the soil. The inventory of phosphorus in the soil tends to be large relative to the transfer of phosphorus among pools, and so even after 20 or 30 years of model runs, the output was still influenced by the initial setting. St. Croix County has an average soil-test phosphorus concentration of 41 ppm for 1995-99 (University of Wisconsin Soil and Plant Analysis Lab 2007). Hence the initial labile (solution) phosphorus concentration in soil layer 1 (SOL_LABP1 in file chm.dbf) was set to 41 ppm (mg kg^{-1}) for all cropland HRUs. In addition, rural residential HRUs were given the same level of soil phosphorus, because such lands were likely farmland prior to development. All other lands were given the default value of 5 ppm by SWAT.

However, phosphorus yields from the landscape depend on the total phosphorus concentration in the soil, not just the labile phosphorus content. Eutrophication of receiving waters depends total phosphorus loads because much of the total phosphorus can eventually be made available for algal uptake, even though the labile phosphorus loads may cause a more rapid initial response. Hence the total phosphorus content of the soil is an important quantity for the model to estimate. While the total phosphorus content of bulk soils can be highly variable, Panuska (2006) commonly found values of about 400 to 600 ppm for the agricultural soils he studied. Jarrell and Bundy (2002) related total phosphorus to Bray-1 soil-test phosphorus levels according to the following equation:

particle total P concentration (ppm) = 3*BrayP1 + 350

where units are given in ppm (mg P per kg soil). This equation was developed for Dane County, WI, and must be considered only approximate when applied to other locations. For soils in the Willow watershed with test-phosphorus levels of 41 ppm, this equation gives a total phosphorus level of 473 ppm. (Note that the phosphorus concentration on particles ultimately delivered to aquatic ecosystems depends further on an enrichment ratio due to preferential transport of finer grained particles. Enrichment ratios are discussed below under the Phosphorus Yield Constraints section.)

SWAT could reproduce these values quite well. In addition to the phosphorus content of the above-ground living and residue organic matter, SWAT monitors five other pools of phosphorus: labile solution phosphorus, active and stable inorganic phosphorus, and active and stable organic (humic) phosphorus. From the initial labile phosphorus concentration in soil layer 1, SWAT calculates the phosphorus in the active and stable inorganic phosphorus pools based on a parameter called the phosphorus availability index (PSP). The organic phosphorus is initialized based on soil organic carbon content, assuming a C:N ratio of 14:1 and an N:P ratio of 8:1 for soil humic matter. Given a labile phosphorus content of 41 ppm, soil carbon contents from the SSURGO data files, and a PSP value of 0.45 (changed slightly from the default of 0.40), the SWAT model of the Willow watershed gave total phosphorus concentrations in the range of 400 to 500 ppm. We note that SWAT considers the phosphorus availability index (PSP) to be a basin-wide parameter; one might think it should be a soil-specific parameter.

SWAT has the capability of delivering phosphorus to the channels from groundwater. While groundwater tends to have low phosphorus concentrations relative to surface-water sources, it can be an important contributor to stream-water phosphorus during periods of baseflow. Nolan and Stoner (2000) give median values of 0.01 to 0.02 mg L^{-1} for dissolved phosphorus in groundwater underlying agricultural and urban land uses. In SWAT, the groundwater soluble phosphorus concentration may be set for each HRU though it remains constant for the entire model run. We initialized values at 0.01 mg L^{-1} for all HRUs, with the intention of adjusting this value during calibration to achieve measured baseflow phosphorus loads. Note that in SWAT the groundwater load of phosphorus is independent of the phosphorus budget of the soil column; the loss of phosphorus from soil to groundwater is considered negligible compared to other soil inputs and outputs.

Rural Residential and Recreational Land

The density of rural-residential land in the Willow watershed is about one house per five acres (Almendinger and Murphy 2005), too low to be considered "urban" land according to land-use categories in SWAT. The WISCLAND dataset classified such areas as grassland, yet the hydrologic characteristics of developed grassland (lawn) are considerably different from those of undeveloped grassland (e.g., brome). Construction activities compact the soil and the added impervious surfaces (roofs and driveways) further impede infiltration. To approximate these conditions, each rural household was first assumed to have about 1 ha (about 2.5 acres) of land impacted by the construction. From the estimated number of rural households in 2000 (about 4900), a total area of impacted grassland was calculated (about 49 km^2). Recreational lands were included in this "impacted grassland" category (about 9 km^2). Of the grassland HRUs in the model (excluding those with grazing), an array of 19 was chosen at random with spreadsheet operations until the desired area (58 km^2) was achieved (Table B4). For these selected HRUs, the curve number was increased to a value corresponding to a soil type that was one category less well drained than indicated in the SSURGO data set. For example, an impacted grassland on a hydrologic group B soil would be given a curve number corresponding to a group C soil.

Model Calibration and Validation

Goodness of Fit Measure

Model calibration (or parameterization) means to adjust model parameters so that model output matches measured data from the watershed as closely as possible. Model validation means to compare output from a calibrated model to a second, independent set of measurements from the watershed as a test of model reliability, without any further parameter adjustment. Variables used for the comparison commonly include flow (daily or monthly), constituent loads (typically monthly), and sometimes constituent concentrations.

Both calibration and validation require a goodness of fit measure to quantify how well the model matches the target data. A common measure is the Nash-Sutcliffe Coefficient of Efficiency (E_{NS}) (Nash and Sutcliffe 1970):

$$E_{NS} = 1 - [\Sigma(O_i - P_i)^2 / \Sigma(O_i - O_{mean})^2]$$

where O_i is the i^{th} observed value, P_i is the i^{th} predicted (modeled) value, and O_{mean} is the mean of the observed values. Values of E_{NS} range from negative infinity to +1, where +1 indicates a perfect model fit, 0 indicates the model predicts values no better than does the mean (O_{mean}), and a negative value indicates a poor model fit. For this study, we consider 0.5 an adequate model representation of the data. E_{NS} is known to be greatly influenced by larger deviations (Legates and McCabe 1999, Krause et al. 2005). Thus, in comparing modeled flows for example, E_{NS} is a better measure simulating peak flows rather than baseflows. Modifications to E_{NS} have been suggested that reduce this sensitivity; however, the use of the standard E_{NS} formulation is retained here for comparability with other values in the literature.

Calibration Targets and Constraints

Calibration targets are the datasets of measured variables that the model is parameterized to simulate as closely as possible. Typically these variables are measured flows and constituent loads at the watershed mouth or other selected locations along the channel network. However, other lines of evidence from the watershed can help constrain the model as well.

Stream Monitoring Data

The flows and constituent loads of the major tributaries to the St. Croix were measured for water year (WY) 1999 by the USGS (Lenz et al. 2003). The Willow was included among these tributaries and data from this project form the most critical calibration targets for the SWAT model of the Willow. Streamflow was recorded at 15-minute intervals from 1 October 1998 through 26 September 1999, with flows estimated for the remaining four days of September to complete the water year. The hydrograph has a large and consistent baseflow as would be expected for a Midwestern trout stream dependent upon groundwater discharge to maintain equable water temperatures. Water-quality samples were collected monthly and for selected runoff events (snowmelt, spring storm, and two summer storms) (Lenz et al. 2003).

The Willow was again monitored for flow and water quality for a period including WY2006, specifically from 23 June 2005 through 26 October 2006, with the same methods as before. This hydrograph has a more pronounced snowmelt peak and a peak for a large storm event on 4-5 October 2005.

From these monitoring datasets, daily mean flows and monthly loads of suspended sediment and total phosphorus were extracted (B. Lenz, D. Robertson, H. Garn, and D. Hanson, USGS, WI and MN Districts, electronic communications, 2005-07). Constituent loads were calculated with the algorithms used by the LOADEST program of the USGS (Runkel et al. 2004). The suspended sediment load included both organic, volatile sediment (presumably algae from the reservoirs) and inorganic non-volatile sediment, whereas SWAT sediment output is largely the inorganic component. Hence the monitored sediment data needed to be corrected for the organic sediment component. Based on a single low-flow sample collected below Little Falls Lake in 2006 in which 39% of the total suspended load was organic (volatile), we assumed that 39% of the average total sediment load for the three months with lowest flow was organic, which amounted to about 18 t month^{-1}. We then assumed that this was the average monthly load of organic solids to the total suspended sediment load, and that sediment in excess of this amount was inorganic. Subtracting this organic amount from each monthly total load resulted in an estimated inorganic suspended sediment load to be targeted during calibration of the SWAT model. We recognize the large potential errors in these calculations, but believe that to ignore the algal component of the monitored suspended sediment load would have been the greater error.

The WY1999 data were used for model calibration, and the WY2006 data were used for model validation. A single year of data is sub-optimal for model calibration; five or ten years of data would be much preferable. Consequently, other lines of evidence to constrain the model were of critical importance.

Crop Yield Data

Annual yields of corn grain, corn silage, soybeans, and alfalfa were obtained for the period 1992 through 2006 for St. Croix County, WI (NASS 2007) and presumed to be representative of those in the Willow watershed. Yields given in bushels per acre were corrected for standard moisture content and converted to dry weight kg ha^{-1} for comparison with output from SWAT. These calculations assumed 56 lbs bushel^{-1} at 15.5% moisture for corn grain, 65% whole-plant moisture for corn silage, and 60 lbs bushel^{-1} at 13% moisture for soybeans. Alfalfa was reported directly as dry mass.

Sediment Yield Constraints

The movement of soil particles from uplands, across the land surface, through riparian floodplain zones, down the channel network, and through impoundments is complex. Yields can be highly variable over space and time, and model output is likewise sensitive and variable; hence it is critical to check that the model is giving reasonable results at selected points in the watershed. Unfortunately, datasets to constrain sediment yields along the path from field to watershed outlet are scarce. We considered three questions to check the reasonableness of model output along the erosional pathway. First, is the gross erosion from selected land uses reasonable? Second, as a basin-wide average yield, how much sediment is delivered from the uplands to the channel system, where the sediment will either get trapped in the reservoirs or passed to the watershed outlet? Third, does the output load of suspended material match that measured by the USGS for WY1999 (Lenz et al. 2003)?

In this report, gross erosion refers to delivery of particles to the edge of field or end of slope length, whichever is shorter. Values of gross erosion for selected crops with various soils, slopes, cropping patterns, and rainfall intensities have been well studied by the NRCS and form basis for calculating soil erosion with the Universal Soil Loss Equation (USLE) and its variants, notably the Modified USLE (MUSLE) and Revised USLE (RUSLE2). The estimated gross erosion rates for Wisconsin agricultural lands in 1997 (the closest available year to 1999) were 831 t km^{-2} yr^{-1} for cultivated cropland, 741 t km^{-2} yr^{-1} for all cropland, and 135 t km^{-2} yr^{-1} for pasture and CRP lands (USDA 2000). (These values correspond to 3.7, 3.3, and 0.6 short tons $acre^{-1}$ yr^{-1}, respectively.) From transect surveys in the Willow watershed from 2000-05, county personnel estimated sediment yields at about 845 t km^{-2} yr^{-1}, similar to the USDA value for cultivated cropland (S. Olson, St. Croix County Land and Water Conservation Department, personal communication, 2006). Based on the USDA gross erosion estimates, if 40% of the Willow watershed is cropland and 60% non-cropland (similar to pasture), then an area-weighted basin-wide sediment yield would be about 377 t km^{-2} yr^{-1}.

Our version of SWAT did not give exactly comparable estimates of USLE-calculated gross erosion rates; instead, it used the MUSLE, which generally estimates lower sediment yields than the USLE (Neitch et al. 2002). Hence these USDA values were considered upper bounds for sediment yields generated by SWAT for selected croplands. In addition, SWAT output was checked to make sure MUSLE-generate sediment yields from selected land covers were ordered correctly, i.e., that sediment yields were largest for soybeans and progressively smaller for corn, alfalfa, and brome. Based on USDA (2000) estimates of gross erosion in Wisconsin for 1992 and 1997, erosion from tilled crops should exceed that of non-tilled crops (i.e., alfalfa) by a factor of 3 to 4, and erosion from non-tilled crops should exceed that of pasture or CRP (e.g., brome) by a factor of 1.5 to 2.

The two reservoirs on the Willow River (the New Richmond Flowage and Little Falls Lake) complicated interpretation of the sediment loading data. Yet even approximate estimates of the sediment they have trapped added information that helped constrain the model. The sum of the amount of suspended sediment leaving the watershed at its outlet (which can be measured) plus the amount of sediment trapped by the reservoirs (which can be estimated) gives the amount of suspended sediment delivered to the reservoirs, which is a useful quantity for model calibration. Direct measurement of trapped sediment by collecting an array sediment cores from each reservoir was beyond the scope of this project. As an alternative we estimated the reservoir trapping efficiencies by the methods of Brune and Churchill, as described in USACE (1995). For reservoirs the size and shape of those in the Willow watershed, the two methods gave widely varying estimates ranging from about 50% to 85%; we chose to apply an efficiency of 75% to each reservoir. Knowledge of trapping efficiency allows the sediment load leaving a reservoir to be translated into the load entering the reservoir, and knowledge of catchment area can translate this input load into a sediment yield from the landscape (assuming negligible channel sedimentation or scour, which is questionable). Calculations for a single reservoir are trivial; for two reservoirs in series as in the Willow watershed, the calculations were only slightly more complicated and required the assumption that yield was the same in the upper and lower watersheds. The consequence of two (or more) reservoirs in series is that the combined trapping efficiency exceeds that of individual reservoirs because the lower reservoir traps some of the sediment that escaped the upper reservoir. For the Willow, the combined trapping efficiency amounted to 88%, and the basin-wide sediment yield was calculated to be about 23 t km^{-2} yr^{-1}.

The reasonableness of this calculation can be checked in several ways. First, is it reasonable that only 23 t km^{-2} yr^{-1} of sediment be delivered to the channel system and reservoirs, when gross sediment yields were estimated to be more than ten times greater, at about 377 t km^{-2} yr^{-1} as a basin-wide average (see above)? Clearly most of the sediment moved as gross erosion never makes it to the watershed outlet and is retained, however temporarily, in intermediate traps such as swales, vegetated buffers, ponds, wetlands, fence rows, and so forth. The larger the watershed, the more of these intermediate traps are available. Consequently, the ratio of delivered sediment yield to gross sediment yield – known as the sediment delivery ratio, SDR – is proportional to basin area. The following relationship is given in Shen and Julien (1993), who cite Boyce (1975):

$$SDR = 0.41\ A^{-0.3}$$

where A is basin area in km^2. For the Willow River basin with an area of 717 km^2, this equation would predict an SDR of 0.057; i.e., about 5.7% of gross erosion actually makes it to watershed outlet. This is surprisingly close to an SDR of 0.061 (or 6.1%) for Willow estimated by taking the ratio of 23 t km^{-2} yr^{-1} to 377 t km^{-2} yr^{-1}, thereby indicating that 23 t km^{-2} yr^{-1} is a reasonable measure of net sediment yield, as a basin-wide average.

The second check on this estimate of net sediment yield is whether it results in realistic sediment accumulation rates in the reservoirs. This calculation requires estimates of the age of the reservoir (set to 80 years), the area of deposition (set to the reservoir surface area), and the bulk density of reservoir sediment (set to 0.5 g ml^{-1}, or 0.5 t m^{-3}). Under these assumptions, the sediment thickness in the New Richmond Flowage would be 1.9 m and the thickness in Little Falls Lake would be 1.8 m. We believe that these thicknesses are reasonable. Because of its downstream position and larger area, Lake Mallalieu should have thinner sediment than Little Falls Lake, and reconnaissance coring in Mallalieu demonstrated sediment thicknesses of only about 1 m.

Finally, literature values of sediment yield can provide some context for our calculated 23 t km^{-2} yr^{-1} value, though these values require careful interpretation. Lenz et al. (2003) give much smaller values for 13 St. Croix tributaries for water year 1999, ranging from about 1.3 to 3.8 t km^{-2} yr^{-1}. However, most of these tributaries (including the Willow) have reservoirs that greatly reduce sediment loads, and hence watershed-wide sediment yields calculated from these loads are not representative of the loading from the landscape to the channel system. Corsi et al. (1997) give a median value of 38.9 t km^{-2} yr^{-1} for rural areas in Wisconsin, on the same order as our calculated value for the Willow, although the range of variability in their data is large (0.8 to 555 t km^{-2} yr^{-1}; n = 36). For comparison, Robertson et al. (2006) determined a median sediment yield of 4.7 t km^{-2} yr^{-1} from 84 relatively undisturbed reference sites in the upper Midwest. This value should approach the natural background sediment yield, and is about 20% of our calculated sediment yield for the Willow.

To summarize, we believe 23 t km^{-2} yr^{-1} was a reasonable net basin-wide sediment yield to use as a target for model calibration, based on considerations of estimated gross erosion rates, sediment delivery ratio, and reservoir trapping efficiency. However, depending on channel processes, there still remains a large uncertainty about the source of this sediment. Does all the 23 t km^{-2} of sediment originate from field erosion that is just passed downstream once it enters the channel system? Or do fields supply less sediment, with the remainder being derived from bank erosion? Or do fields supply even more sediment, with the excess load being trapped in the floodplain and channel system? We have no data to distinguish among these three example configurations, or among any of the other possible combinations of field and bank erosion. Emerging data from radioisotopic fingerprinting of suspended sediment indicates that bank erosion can be a significant contributor to the suspended sediment load (Shawn Schottler, St. Croix Watershed Research Station, personal communication, 2007). The model could be calibrated to any of these configurations, demonstrating that model calibration is not unique. These possible configurations are portrayed in Figure 9.

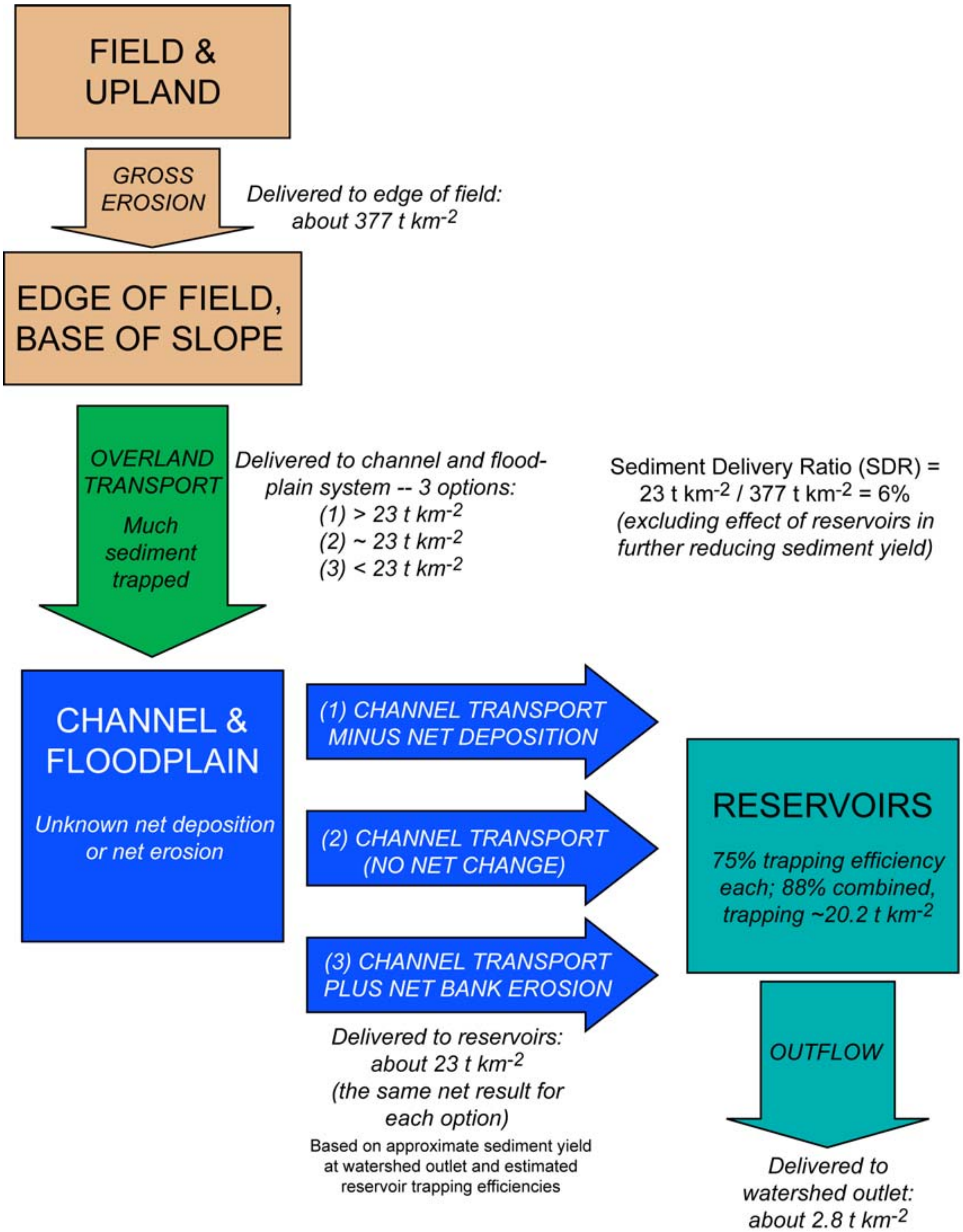


Figure 9. Considerations in attempting to constrain sediment yields at different scales in the watershed, showing the large difference between gross erosion at the field scale and measured sediment yields at the watershed scale, thereby demonstrating large uncertainties in where sediment is trapped.

Phosphorus Yield Constraints

As with sediment, few data sets exist to constrain phosphorus yields, beyond the one-year data set collected by the USGS for water year 1999. That year, the measured annual load was about 10,300 kg; subtracting the point-source load of 5,300 kg leaves a nonpoint-source load of 5,000 kg corresponding to a basin-wide (717 km^{-2}) yield of about 7.0 kg km^{-2} yr^{-1}. For comparison, phosphorus yields from other tributaries measured by Lenz et al. (2003) in 1999 ranged from 6 to 33 kg km^{-2} yr^{-1}. Kroening and Andrews (1997) give a phosphorus yield of 10 kg km^{-2} yr^{-1} for the entire St. Croix basin. However, these values are heavily influenced by phosphorus settling losses in reservoirs, and possibly by losses (or gains) from the floodplain and channel system. To better constrain the model, we wanted realistic estimates of the delivery of phosphorus from the upland subbasins to the stream channel system, prior to settling losses that may occur in the floodplain or reservoirs. For reference, Smith et al. (2003) give a natural background phosphorus yield of about 6-8 kg km^{-2} yr^{-1} for the upper Midwest region including western Wisconsin. We expected modern phosphorus yields (as delivered from the uplands) in agricultural watersheds to be many multiples of this baseline value.

Literature values of phosphorus yield gave only very general guidance to constrain model output. Harmel et al. (2006) compiled field-scale data from about 40 studies across the USA and found a median phosphorus yields of 105 kg km^{-2} yr^{-1} for conventional tilled plots, and 129 kg km^{-2} yr^{-1} for corn, though variability among studies appeared to be large. From a plot shown in CALS (2005), about half of 18 test fields in Wisconsin had phosphorus yields exceeding 100 or 200 kg km^{-2}. Data from a no-till Discovery Farm in Wisconsin with corn-soybean rotation had a three-year average phosphorus yield of 191 kg km^{-2} yr^{-1}(Dennis Frame, University of Wisconsin-Extension Discovery Farms Program, written communication, 2007). We concluded from these studies that gross phosphorus yields from tilled crops in the Willow watershed should at least exceed 100 kg km^{-2} yr^{-1} and probably exceed 200 kg km^{-2} yr^{-1} unless under no-till management.

Watershed-scale phosphorus yields should be less than field-scale yields because of topographic traps for sediment and nutrients. Corsi et al. (1997) gave a median phosphorus yield of 114 kg km^{-2} yr^{-1} from rural Wisconsin watersheds (n = 24); however, this yield is probably greater than should be expected for the Willow, because watersheds in their data set commonly had more agricultural land and steeper slopes than did the Willow. An equation that explicitly accounts for agricultural land coverage has been developed for western Wisconsin (W. James, U.S. Army Corps of Engineers, written communication, 2007; based on a data set expanded from James 2004):

$$\text{P yield (kg km}^{-2}\text{ yr}^{-1}) = 14.7 * e^{0.0178x}$$

where x = % cropland area in watershed. In 1999 the Willow watershed had about 40% cropland coverage; according to the above equation, the estimated phosphorus yield would be about 30 kg km^{-2} yr^{-1}.

Another way to constrain phosphorus loads is to link them to the sediment load constraints determined from reservoir sedimentation and sediment delivery ratio considerations discussed above. This way our estimated sediment and phosphorus yields can be made to be consistent with each other. These calculations require estimating the concentration of phosphorus on particles delivered to the channel, and estimating the partitioning of transported phosphorus between dissolved and particulate phases. As discussed above in the model configuration section, total phosphorus concentrations of soils in fields were expected to be in the range of about 500 ppm. However, by the time eroded soil reaches the stream channel, its phosphorus content tends to be enriched because coarse particles with little phosphorus have been trapped along the way. Enrichment ratios can range from about 1.1 to over 4 (Jarrell and Bundy 2002); if a ratio of 2 is arbitrarily selected, then a soil with 500 ppm total phosphorus would have about 1000 ppm, or 1 mg g^{-1}, by the time it reached the channel. This value is similar to that found by Wierl et al. (1998) in eastern Wisconsin. Triplett et al. (2003) found an average of 1.4 mg g^{-1} total phosphorus on lake sediment particles accumulating in Lake St. Croix, the receiving water for the Willow River (and the entire St. Croix Basin). Lake sediment might be enriched in phosphorus relative to eroded soil because of the addition of algal remains. In truth, phosphorus concentration on particles is grain-size dependent and highly variable. Yet the above data indicate that phosphorus concentration of about 1 mg g^{-1} is a justifiable approximation for our purposes. Hence, given this phosphorus concentration (the same as 1 kg t^{-1}), and the sediment yield of 23 t km^{-2} yr^{-1} estimated above, we estimated the delivery of particulate phosphorus from the uplands to the channel systems at about 23 kg km^{-2} yr^{-1}.

The total phosphorus yield would include a dissolved component, in addition to this particulate component. In water year 1999, Lenz et al. (2003) measured the dissolved phosphorus load as being 40% of the total phosphorus load. If this proportionality holds during transport, then the total phosphorus yield from the uplands to the channel would be about 38 kg km^{-2} yr^{-1}; given the potential errors involved, rounding the value to 40 kg km^{-2} yr^{-1} seemed justified. Excluding additions or subtractions by channel processes, this 40 kg km^{-2} yr^{-1} delivered from the uplands to the channel should equal the sum of the amount trapped by the reservoirs and the amount exiting the watershed outlet. Given the reservoir sediment trapping efficiency assumed above, and the particulate phosphorus concentration of 1 mg g^{-1} as explained above, the reservoirs would trap about 15,000 kg yr^{-1}, or about 20 kg km^{-2} yr^{-1} when expressed as a basin-wide yield.

For the total yield to equal 40 kg km^{-2} yr^{-1}, the amount exiting the watershed would also have to total about 15,000 kg yr^{-1}. This appeared to be a reasonable amount considering the conclusion of Lenz et al. (2003) that typical loads for southern St. Croix tributaries would be greater than what they measured in water year 1999 (10,300 kg for the Willow) because of atypical storm patterns that year.

To summarize, based on considerations of sediment yields, phosphorus concentrations on particles, dissolved phosphorus fractions, trapping of phosphorus in reservoir sediments, and approximated total basin exports, we chose a value of 40 kg km^{-2} yr^{-1} as the targeted basin-wide nonpoint-source phosphorus yield for the delivery of phosphorus from the uplands to the channel system. However, much like sediment transport, intermediate traps affecting phosphorus transport make this calibration target ambiguous. Should all 40 kg km^{-2} come from the uplands and be transported downstream to the reservoirs and watershed outlet, without any contribution from the channel? Or should only part come from the uplands, and the rest come from the channel? Alternatively, should more than 40 kg km^{-2} come from the uplands, with the excess being trapped in the floodplain and channel system? The model could be calibrated to any of these combinations, again demonstrating the non-unique nature of model calibration.

Calibration Procedure and Results

Model calibration is hardly a linear process. The procedure given below summarizes much trial and error, and many of the results of these efforts were discussed above in the Model Configuration section. The general procedure is to (a) adjust the physical hydrology, (b) check crop yields, (c) adjust sediment yields, and finally (d) adjust nutrient yields. The rationale for this sequence is that each item in this list significantly affects other items farther down the list, with less interaction going the other direction. However, during the calibration process feedbacks among hydrology, plant growth, erosion, and nutrient budgets may result in the need to re-adjust previously calibrated components.

The use of automated calibration (parameter estimation) routines, in particular PEST (Doherty 2004), can be a valuable tool to help find possible parameter values at various stages during model calibration. However, the large number of parameters in SWAT and the non-unique nature of a SWAT calibration imply that there are many possible parameter combinations that could result in similarly “calibrated” versions of a model. Consequently, first the modeler should manually adjust the major parameters of SWAT to get the model functioning realistically and close to the targeted calibration data set. Once the model is close to the desired configuration, then automated parameter estimation can be used to obtain an optimized parameter set.

Hydrology I

Initial adjustment of hydrologic parameters was necessary to approximately fit annual runoff volume, baseflow, and flood peak amplitude and duration. Choice of evapotranspiration method greatly affected water balance. We chose the Penman-Monteith method because it resulted in approximately correct annual runoff volumes, whereas both the Hargreaves and Priestley-Taylor methods resulted in too much runoff. Baseflow was much too low and variable among months under default parameterization; increasing the groundwater delay parameter from the default of 30 days to 400 days greatly improved the fit. Flood peaks were too high and narrow initially, with reservoir outflow set to the average annual release rate option. Instead, the target release option gave much better results, with the number of days needed by the reservoir to reach its target storage volume (NDTARG) set to two or three days.

Crop Yields

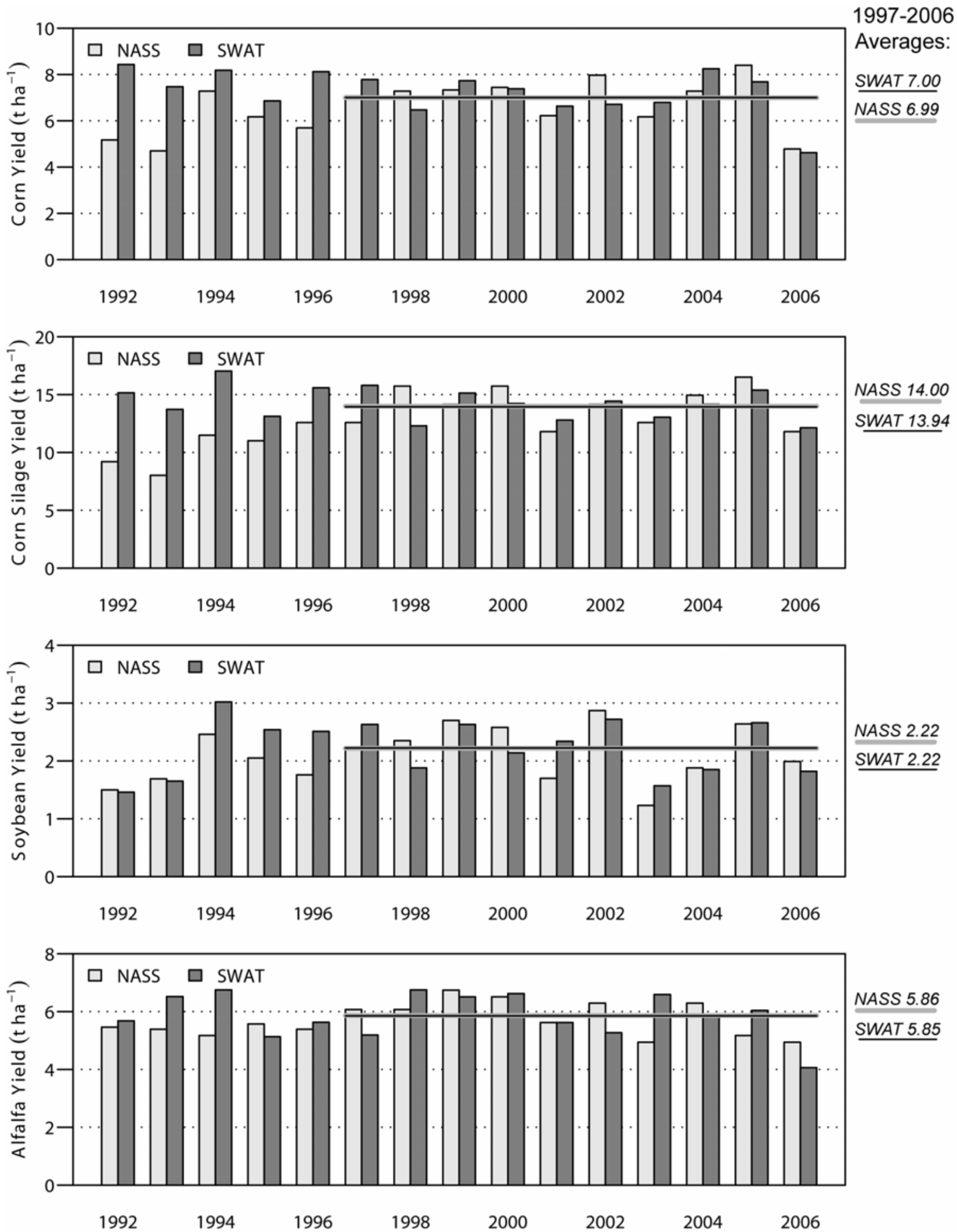
Because of the large area of crops, the vastly different surface characteristics of fields during the growing season, and the large uptake of nutrients by crops, proper simulation of crop growth is essential to realistically estimate nonpoint-source loadings of sediment and nutrients. Once the watershed water budget was adjusted so that water availability to crops was approximately correct, then other factors affecting crop growth could be adjusted. In particular, we examined corn and soybean yields because of their known critical influence on nonpoint-source loads and because of robust data availability from NASS (2007). Modeled soybean yields seemed to track recorded annual yields reasonably well, indicating that moisture balance and any consequent moisture stress to plants was operating appropriately in the model. However, corn yields were significantly underestimated under default parameterization due to nitrogen stress. Baumgart (2005) also found similar stresses due to excessive denitrification of applied fertilizers, which he noted should be about 15% of applied nitrogen. Using Baumgart's modified SWAT engine, we could reduce denitrification to 11% and thereby greatly improve corn yields. However, corn yields were still too small, partially because of remaining nitrogen stress resulting from large losses of nitrogen to leaching to the shallow aquifer. We did not find an appropriate parameterization in the model to limit the loss of nitrate by leaching. Instead, the simplest solution was to allow SWAT to autofertilize for nitrogen, which reduced nitrogen stress and allowed corn yields to approximate recorded values.

After both moisture and nutrient stresses were considered, the parameter BIO_E (biomass-energy ratio, or radiation use efficiency) for each crop was adjusted slightly to make average modeled crop yields match reported yields. Over the 15 years of data shown in Figure 10 from 1992 to 2006, NASS-reported corn yields trended upward slightly, whereas modeled corn yields during the same period did not show an obvious trend. Perhaps the upward trend in reported yields was due to improved genetics that effectively increased corn BIO_E over time. However, SWAT assumes a constant BIO_E during the period of simulation. To make the model better represent current conditions, the BIO_E values were adjusted for the more recent 10-year period, rather than the full 15-year period. BIO_E was reduced slightly for alfalfa and soybeans, and increased for corn grain and corn silage. During this period from 1997 to 2006, the resulting 10-year average annual yields for all crops in the model matched within 1% of those for reported yields (Figure 10).

Hydrology II

Once crop growth and its effect on soil-moisture balance were reasonably simulated, the model could be parameterized to better fit the details of the target hydrograph of daily mean flows from WY1999. The model had trouble fitting the snowmelt peaks in March and April, predicting an earlier and larger snowmelt peak under default parameterization. Each of four snowmelt parameters (SMTMP, SMFMX, SMFMN, and TIMP) was systematically adjusted to five values around the default to seek the optimal combination of these parameters. Especially, reducing the minimum snowmelt melt factor (SMFMN) from 4.5 to 1.5 mm water per deg-day and the snowmelt temperature lag factor (TIMP) from 1 to 0.4 slowed the melt and reduced peak flows in the model.

As used in SWAT, curve number is effectively an empirical infiltration parameter. Much controversy surrounds curve numbers (Ponce et al. 1996, Garen and Moore 2005), which were derived to empirically describe basin-wide rainfall-runoff responses (Mockus 1949, as cited and developed in NRCS 2004). As such, they would seem applicable to the subbasin or larger scale within SWAT. However, SWAT applies curve numbers to individual HRUs, which mimic large test plots of uniform vegetation, soils, and slopes draining directly to a receiving channel. And, the curve numbers applied to these HRUs were derived from field-scale test plots, essentially experimental HRUs. Hence, we feel that curve numbers in SWAT are field-scale parameters, and as such cannot be expected without modification to directly account for subbasin-scale factors that might alter infiltration, such as ponding in swales and transport of runoff from one landscape unit to another. It should come as no surprise that curve numbers need to be adjusted to account



NOTES: NASS, National Agricultural Statistics Service; t, metric tons; ha, hectares. All data given here as dry mass. In converting NASS data to dry mass, corn yield assumes 56 pounds per bushel at 15.5% standard moisture content; corn silage yield assumes 65% whole-plant moisture content; soybean yield assumes 60 pounds per bushel at 13% standard moisture content; alfalfa yield was reported directly as dry mass.

Figure 10. Reported versus modeled crop yields for the Willow River watershed, 1992-2006.

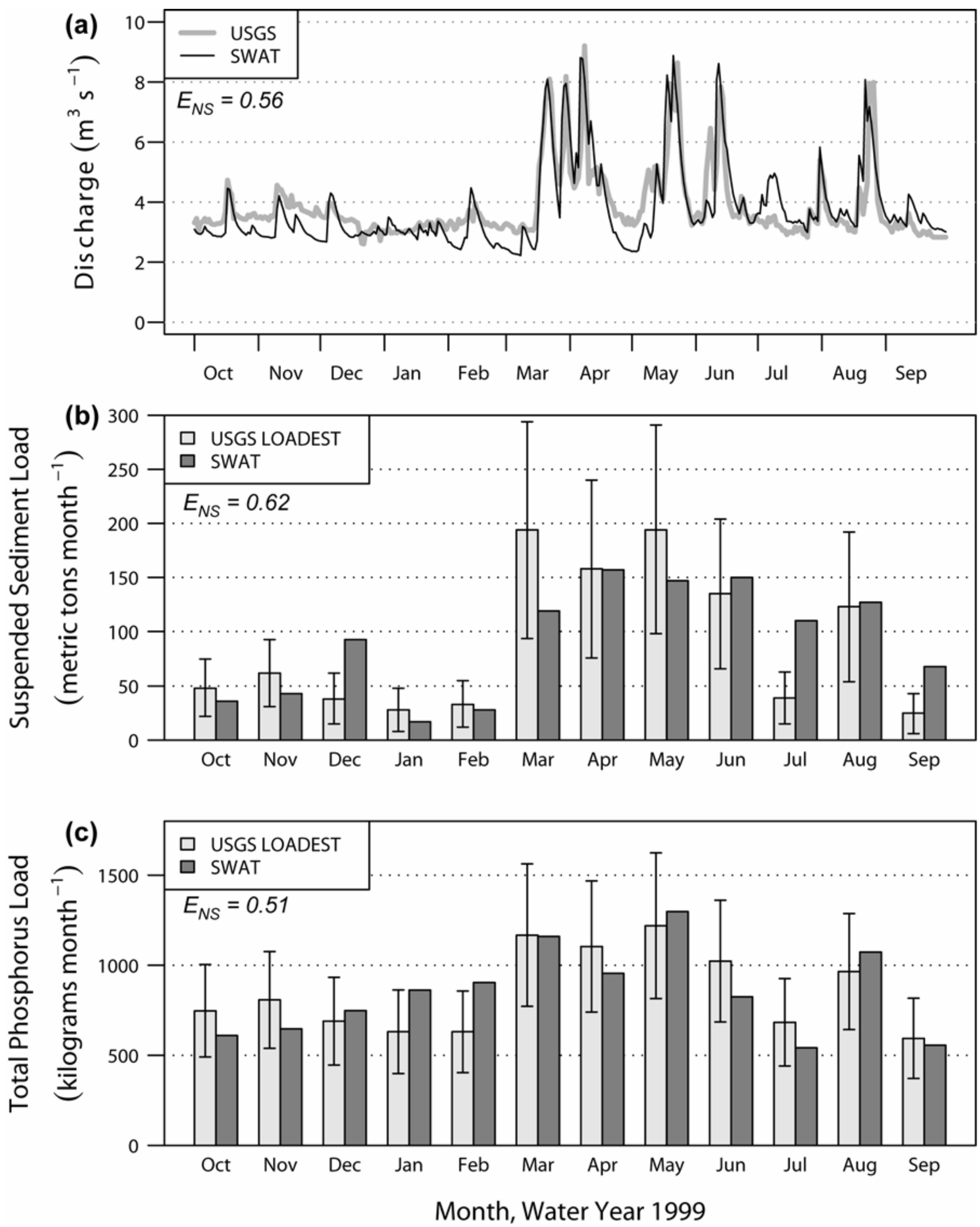


Figure 11. Calibration plots for the Willow River SWAT model compared to monitoring data collected by the U.S. Geological Survey and calculated with the LOADEST program for water year 1999: (a) daily discharge, (b) monthly suspended sediment load, and (c) monthly total phosphorus load.

for these factors. In the Willow model, curve numbers were reduced by 10% from their default values (both CN2 in mgt1.dbf and CNOP in mgt2.dbf) to increase infiltration, thereby increasing baseflow and decreasing flood peaks.

Final adjustments added minor improvement to the fit of the model output to the target hydrograph. Reductions of hydraulic conductivity (SOL_K1, SOL_K2, and SOL_K3) in the upper soil layers slowed lateral flow of water from uplands to the channel, slightly reducing flood peaks. Total water yield was reduced by lowering the soil evaporation compensation factor (ESCO) from 0.95 to 0.91. The resulting model hydrograph of daily flows for WY1999 fit the target hydrograph with a E_{NS} of 0.56 (Figure 11a). For monthly average flows (not shown), the E_{NS} increased to 0.69.

Sediment

Sediment calibration required sequential model runs to test for gross field erosion rates, net basin-wide sediment yields, reservoir sedimentation, and monthly loads of suspended sediment for WY1999. Selected components in the model had to be either activated or removed so that model output reflected the quantity being tested. To test for gross field erosion from selected crops or HRUs, the Pond and Wetland components had to be deactivated (by setting contributing areas to zero), else the sediment they trapped would reduce yields given in the SWAT output files (either the basins.sbs or basins.bsb files). Tillage was set to conventional for that period (chisel plowing followed by disking prior to each planting, plus moldboard rather than chisel plowing following alfalfa), and all MUSLE factors were kept at default values to maximize model estimates of gross erosion, as an upper bound for comparison to USLE rates.

The relative rates of erosion among crops can be adjusted in SWAT via the C_{min} parameter for each crop, which is the minimum value of the cover and management factor (C_{USLE}) used in the MUSLE. SWAT updates C_{USLE} each day for each HRU, reducing C_{USLE} to account for the erosion protection afforded by crop growth and residue accumulation – but C_{USLE} is not allowed to drop below C_{min}. In test model runs with HRUs planted in continuous corn, soybeans, alfalfa, or brome, sediment yields were in the expected order: soybeans > corn-silage > corn-grain > > alfalfa > brome. In model runs with representative crop rotations, corn-silage had slightly lower sediment yields than corn-grain, because residue from corn-grain reduced erosion in the following year's crop and corn-silage always followed corn-grain in our rotations. To make the ratios of sediment yields from tilled, non-tilled, and pasture land covers similar to those found by the USDA (2000), C_{min} values for alfalfa and brome were increased from 0.003 to 0.05 and 0.04, respectively, while C_{min} values for corn-grain, corn-silage, and soybeans were kept at their default value of 0.2. These change resulted in model-estimated gross sediment yields of about 210 t km^{-2} yr^{-1} for tilled crops, about 70 t km^{-2} yr^{-1} for alfalfa, and about 40 t km^{-2} yr^{-1} for brome. For comparison, these MUSLE-estimated gross erosion rates are several times less than the USLE-estimated rates for Wisconsin in 1997, which were 831 t km^{-2} yr^{-1} for cultivated crops, 269 t km^{-2} yr^{-1} for non-cultivated crops, and 135 t km^{-2} yr^{-1} for pasture (USDA 2000). (We presume that "cultivated" corresponds to tilled, "non-cultivated" to alfalfa, and "pasture" to brome in our SWAT model.) In the model, the resulting basin-wide area-weighted average gross sediment yield was about 80 t km^{-2} yr^{-1}.

Once relative rates of erosion among crops and pasture were configured, the model was adjusted to reduce the 80 t km^{-2} yr^{-1} gross sediment yield to the targeted net basin-wide sediment yield of 23 t km^{-2} yr^{-1}. The first step was to re-activate Ponds and Wetlands, which captured about 42% of the runoff and decreased sediment yield to about 49 t km^{-2} yr^{-1}. To reduce sediment yield further, the principal available parameters were topographic factors such as slope and slope length, soil composition factors such as erodibility, and MUSLE factors. Because topographic and soil factors were based on field-supported data, we chose to modify a MUSLE factor, namely the support practice factor, P_{USLE}. This factor was designed to account for the reduction in erosion afforded by applying tillage practices along contours, rather than up-and-down the test-plot slope. However, while some of these practices are used in the Willow watershed, we used the P_{USLE} parameter simply as a way to scale down the basin-wide sediment yield to our target value. Reducing P_{USLE} from 1.0 to 0.47 allowed the modeled to match the targeted net sediment yield of 23 t km^{-2} yr^{-1}.

Finally, the reservoirs were parameterized so that they would trap a reasonable amount of sediment and pass the remainder to the watershed outlet to match the monitored data set from WY1999. SWAT determines reservoir sedimentation based on an equilibrium sediment concentration parameter (NSED): when the suspended sediment concentration in the reservoir exceeds this amount, the excess is deposited in the reservoir. By trial and error, NSED was set for both the New Richmond Flowage (70 mg L^{-1}) and for Little Falls Lake (16 mg L^{-1}) such that both reservoirs had similar trapping efficiencies (about 77%) and the total sediment yield passed to the watershed outlet in WY1999 matched the total indicated from the monitoring data, which amounted to about 1,080 t yr^{-1} of inorganic suspended sediment. The resulting modeled monthly pattern of sediment load fit the monitoring data for WY1999 with an E_{NS} of 0.62. For most months the SWAT sediment loads fell within the error bars given for the USGS-estimated sediment loads (Figure 11b).

The model calibrated to sediment yields as described above was called a "passive channel" version because the channel passively transported all sediment delivered from the uplands to the reservoirs and watershed outlet. Channel processes such as scour and deposition that would alter the sediment load were disallowed in the model. Clearly, scour and deposition occur in all rivers, but if they are in approximate equilibrium, then a passive channel model is a reasonable configuration. It is entirely possible, however, that for many systems there are net differences between scour and deposition. The well established observation that sediment delivery ratio decreases with basin area (Shen and Julien 1993, who cite Boyce 1975) could indicate that storage of sediment in floodplain and channel systems exceeds channel erosion. Alternatively, mounting evidence from agricultural regions where sediment sources have been radioisotopically fingerprinted indicate that bank erosion can add a significant suspended sediment load (Shawn Schottler, St. Croix Watershed Research Station, personal communication, 2007).

Phosphorus

Once the sediment load was calibrated, the targeted basin-wide net phosphorus yield of 40 kg km^{-2} yr^{-1} was achieved without further parameterization. As noted in the model configuration section, the phosphorus availability index PSP needed to be increased slightly to 0.45 from its default value of 0.40. We remind the reader that these model results were obtained with the stream water-quality routines in SWAT de-activated; had these routines been activated, the phosphorus yields would have been overestimated by about 20% for the whole basin, and over 100% for some subbasins.

Dissolved phosphorus composed 39% of the modeled annual load, essentially identical to the dissolved fraction as measured by Lenz et al. (2003) for WY1999. For the technical reader with SWAT modeling background, phosphorus speciation in output files is somewhat obscure. The upland routines transport phosphorus as soluble (SOLP) and particulate forms; the particulate forms are further divided into organic (ORGP) and sediment (SEDP, presumably inorganic) forms; and these organic and sediment particles are further divided into active and inactive forms. The basins.bsb and basins.sbs output files give values for SOLP, ORGP, and SEDP, but not the active and inactive fractions of ORGP and SEDP. Upon entering the channel (reaches), phosphorus is re-partitioned into two categories, essentially dissolved and particulate (though for unclear reasons, SWAT calls these categories "mineral" and "organic", respectively, as listed in the basins.rch output files). The dissolved component consists of the sum of the SOLP, the active part of the SEDP (apparently because it desorbs easily), and any groundwater P entering the channel. The particulate component consists of everything else, namely, ORGP plus the inactive part of SEDP (Paul Baumgart, University of Wisconsin-Green Bay, written communication, 2006).

To check the reasonableness of gross phosphorus yields, Ponds and Wetlands were de-activated in the model, and MUSLE factors were re-set to default values. Under these conditions, the model calculated an area-weighted phosphorus yield of about 223 kg km^{-2} for tilled crops, which was in line with our expectations of more than 200 kg km^{-2} yr^{-1}, though this value was based on admittedly sparse literature values (see Phosphorus Yield Constraints section above). To summarize to this point, gross phosphorus yields from cropland were consistent with literature values; these gross yields were reduced to appropriate net yields by entrapment in closed depressions (Ponds) and other intermediate traps; and phosphorus speciation into dissolved and particulate components was consistent with available data.

The last step was to match monthly phosphorus loads as measured during WY1999. Groundwater contributions of dissolved phosphorus (GWSOLP in file gw.dbf) were useful in fitting phosphorus loads during low-flow months; we kept the concentration at 0.01 mg L^{-1} as during the configuration trial runs. Matching monthly loads and the annual total for WY1999 in particular required parameterizing the reservoirs to trap the required amount of phosphorus. This was done by setting the phosphorus settling rate during the high runoff months (March through June) to the relatively high value of 77 m yr^{-1} for Reservoir 1 (New Richmond Flowage) and 138 m yr^{-1} for Reservoir 2 (Little Falls Lake); settling rate was set to zero for July through February. The resulting phosphorus trapping efficiencies were about 27% for the New Richmond Flowage and about 17% for Little Falls Lake. The modeled monthly loads fit the monitoring data for WY1999 with an E_{NS} of 0.51 and were usually within the error bars for the USGS-estimated loads (Figure 11c).

Final Parameter Set

The final parameter set of the calibrated Willow River watershed model is given in Table 8. With a few exceptions, only those parameters with values changed from default during the configuration or calibration processes are included.

Table 8. Parameter set used for the Willow River watershed SWAT model.

(alphabetical by file name; dbf files in tablesin folder; dat files in AvSwatDB folder)

File & Parameter	Description	units	Default	Calibrated	Rationale
file bsn.dbf					
SFTMP	Snowfall temperature	deg C	1	1	
SMTMP	Snowmelt base temperature	deg C	0.5	1	Snowmelt too early with default
SMFMX	Snowmelt melt factor, max	mmH2O/deg-day	4.5	5.5	
SMFMN	Snowmelt melt factor, min	mmH2O/deg-day	4.5	1.5	Lower values slow melt
TIMP	Snowpack temperature lag factor	unitless	1	0.4	Snowmelt too fast (early) with default
SURLAG	Surface runoff lag coefficient	unitless	4		
SPCON	Linear parameter, channel sediment transport	unitless	0.001	high 0.01, low 0.0015	Higher value essentially stops deposition of sediment in channel for "passive channel" model version. Lower value used to trap sediment in "active channel" model version.
SPEXP	Exponent parameter, channel sediment transport	unitless	1.5	1.5	Left at default; used SPCON to stop deposition
PARM3	Option to choose subbasin-based time-of-concentration calculations (1), rather than default HRU-based calculations (0)	unitless	0	1	Option created by Paul Baumgart, UW-Green Bay
PARM4	CDN, denitrification parameter	unitless	-1.4	-0.3	Parameter unavailable for modification in original SWAT2000; made available by Paul Baumgart, UW-Green Bay
PARM5	SNDCO, soil water denitrification point parameter	unitless	0.95	0.99	Parameter unavailable for modification in original SWAT2000; made available by Paul Baumgart, UW-Green Bay
PSP	Phosphorus availability index	unitless	0.4	0.45	Set to achieve realistic total phosphorus concentrations in top layer of agricultural soils, after setting SOL_LABP1 to soil-test phosphorus levels
RSDCO	Residue decomposition coefficient	unitless	0.05	variable	RSDCO ineffective here; change in crop.dat file
file chm.dbf					
SOL_LABP1	Soil labile P content, layer 1	ppm	5	41	Assumed to be soil-test P values, set to 41 for cropland and rural residential HRUs. Entries of zero in the table actually default to 5 ppm.

Table 8. (continued) Parameter set used for the Willow River watershed SWAT model.
(alphabetical by file name; dbf files in tablesin folder; dat files in AvSwatDB folder)

File & Parameter	Description	units	Default	Calibrated	Rationale
file crop.dat					
USLE_C for BROS	Minimum C_{USLE} for smooth brome	unitless	0.003	0.04	To make erosion rates from brome about half that from alfalfa
USLE_C for ALFA	Minimum C_{USLE} for alfalfa	unitless	0.01	0.05	To make erosion rates from alfalfa about 1/3 to 1/4 that from cultivated crops
USLE_C for CORN, CSIL, and SOYB	Minimum C_{USLE} for corn-grain, corn-silage, and soybeans	unitless	0.2	0.2	Kept at default; relative erosion rates for these crops were in order as expected: SOYB>CSIL>CORN
RSDCO for CORN	Plant residue decomposition coefficient for corn-grain	unitless	0.05	0.15	Increased decomposition allowed residue (a) to approach zero at the time of planting the following year under conventional tillage, so it would not build up to unrealistic levels, and (b) to approach appropriate levels for reduced tillage practices, to result in targeted C_{USLE} factors
RSDCO for CSIL	Plant residue decomposition coefficient for corn-silage	unitless	0.05	0.15	ditto
RSDCO for SOYB	Plant residue decomposition coefficient for soybeans	unitless	0.05	0.15	ditto
CPYLD for CORN	Normal fraction of phosphorus in yield for corn-grain	unitless	0.0016	0.003	Literature indicated value different from default
CPYLD for CSIL	Normal fraction of phosphorus in yield for corn-silage	unitless	0.0016	0.0023	Literature indicated value different from default
CPYLD for SOYB	Normal fraction of phosphorus in yield for soybeans	unitless	0.0091	0.0091	Kept at default
BIO_E for CORN	Radiation use efficiency, or biomass-energy ratio	$(kg/ha)/(MJ/m^2)$	39	42	Used to adjust crop yields, beyond effects of water and nutrient stresses
BIO_E for CSIL	Radiation use efficiency, or biomass-energy ratio	$(kg/ha)/(MJ/m^2)$	39	42	Used to adjust crop yields, beyond effects of water and nutrient stresses
BIO_E for SOYB	Radiation use efficiency, or biomass-energy ratio	$(kg/ha)/(MJ/m^2)$	25	22	Used to adjust crop yields, beyond effects of water and nutrient stresses
BIO_E for ALFA	Radiation use efficiency, or biomass-energy ratio	$(kg/ha)/(MJ/m^2)$	20	13	Used to adjust crop yields, beyond effects of water and nutrient stresses
file gw.dbf					
GW_DELAY	Groundwater delay time	days	~30	400	Large values smooth contribution by groundwater to baseflow
ALPHA_BF	Baseflow recession constant	1/days	~0.1	0.1	Commonly from just above 0 to 1; smaller units have slower (less steep) baseflow recession
GWSOLP	Phosphorus concentration in groundwater	mg/L	0	0.01	Value of 0.01 mg/L found in some studies (Nolan and Stoner)
file hru.dbf					
SLSUBBSN	Slope length	m	by subbasin	by forumula	Formula used to calculate slopelength as a function of slope; generally close to 50 m
SLOPE	Slope	m/m (unitless)	by subbasin	by hru	GIS used to calculate slope for each HRU, rather than subbasin
OV_N	Overland runoff Manning's N	unitless	0.014	by hru	Default too low, generally. Values assigned here according to crop and tillage level (weighted-average for years in rotation); see Table 5a.
SLSOIL	Slope length for lateral flow in soil	m	by subbasin	by forumula	Same as for SLSUBBSN
ESCO	Soil evaporation compensation factor	unitless	0.95	0.91	Smaller values reduce overall water yield from basin

Table 8. (continued) Parameter set used for the Willow River watershed SWAT model.
(alphabetical by file name; dbf files in tablesin folder; dat files in AvSwatDB folder)

File & Parameter	Description	units	Default	Calibrated	Rationale
file mgt1.dbf					
BIOMIX	Biological mixing efficiency	unitless	0.2	0.2 generally; 0.3 for mulch till; 0.4 for no-till	Increased for reduced tillage scenarios
CN2	Curve number, initial, soil moisture condition 2	unitless	by land cover	90% of initial value	Decreasing CN increases infiltration and baseflow, reduces hydrograph spikes
USLE_P	USLE support practice factor, nominally	unitless	1	0.45	Used as a primary calibration scaling parameter to reduce sediment delivery from subbasins; applied indiscriminately to all HRUs
file mgt2.dbf					
CNOP	Curve number for scheduled ag operation	unitless	CN2 above	90% of initial value; further reduced 1 point for mulch till and 2 points for no-till	CNOP set in rotations each year based on crop, soil hydrologic group, and tillage level; repeatedly set with each operation of each year to ensure implementation by SWAT
file pnd.dbf					
PND_FR	Pond drainage fractional area in subbasin	unitless	0	subbasin-specific	Fractional area of closed drainages in subbasin
PND_PSA	Pond principal surface area	ha	0	subbasin-specific	Aggregate area of open water in closed drainages
PND_PVOL	Pond principal volume	ha-m	0	100x PND_PSA	Large volume so Ponds had enough storage to rarely, if ever spill -- since Ponds represent closed depressions in the model
PND_EVOL	Pond emergency volume	ha-m	0	>100x PND_PSA	ditto
NDTARG	Number of days to reach target storage	days	15	1000	Increased values smooth the release of water, to mimic groundwater discharge
PND_NSED	Equilibrium sediment concentration	mg/L	1	0	Zero ensures that all sediment gets trapped in Ponds (closed depressions)
PND_K	Pond hydraulic conductivity	mm/hr	~0.5	10	High infiltration rate to minimize any chance of surficial outflow from closed depressions, which Ponds represent in the Willow model
PND_PSET1	Phosphorus settling rate, settling season 1, ponds	m/yr	1	100	High rate ensures all phosphorus gets trapped in Ponds (closed depressions)
WET_FR	Wetland drainage fractional area in subbasin	unitless	0	subbasin-specific	Fractional area of subbasin land draining through large wetlands en route to channel
WET_NSA	Wetland normal surface area	ha	0	subbasin-specific	Aggregate area of wetlands in subbasin receiving drainage. Max area set to same.
WET_NVOL	Wetland normal volume	ha-m	0	WET_NSA/3	Assumes wetlands have about 1/3 m (1 ft) of effective water depth. Max volume set to same value.
WET_NSED	Equilibrium sediment concentration	mg/L	1	0	Let wetlands capture all sediment (probably pass some, but no data to parameterize)
WET_K	Wetland hydraulic conductivity	mm/hr	~0.5	0	Zero precludes loss of pond water by seepage -- which would get lost in this version of SWAT
PSETLW1	Phosphorus settling rate, settling season 1, wetlands	m/yr	15	0	Let wetlands pass all phosphorus (probably capture some -- but no data to parameterize)

Table 8. (continued) Parameter set used for the Willow River watershed SWAT model.
(alphabetical by file name; dbf files in tablesin folder; dat files in AvSwatDB folder)

File & Parameter	Description	units	Default	Calibrated	Rationale
file res.dbf	*(parameters are changed in reservoir dialogue box or lwq text files -- not directly in this dbf file)*				
RES_NSED	Equilibrium sediment concentration	mg/L	1	70 for RES1 16 for RES2	Increased to pass more sediment through the reservoirs. Different NSEDs for the two reservoirs to make each one capture the same percentage of sediment (about 75%).
RES_K	Reservoir hydraulic conductivity	mm/hr	~0.5	0	Zero precludes water loss by outseepage
IRESCO	Outflow simulation code	unitless	0-3	2	Outflow simulated by target days to reach principal volume
NDTARGR	Number of days to reach target storage volume	days	user input	2 to 3	3 days seemed about right for both reservoirs; 2 days made the hydrograph spikier; no separate flood vs non-flood period (IFLOD1R = IFLOD2R)
PSETLR1	Phosphorus settling rate, season 1	m/yr	~15	77 for RES1 138 for RES2	Mar-Jun (IRES1=3, IRES2=6) -- high effective settling of phosphorus.
PSETLR2	Phosphorus settling rate, season 2	m/yr	~15	0	Jul-Feb -- no effective settling of phosphorus
file rte.dbf					
CH_N2	Main channel Manning's N	unitless	0.014	0.05	Set to correspond to natural stream, with some stones and brush (SWAT User's Manual)
CH_K2	Channel hydraulic conductivity	mm/hr	~0.5	0	Zero precludes water loss by outseepage
CH_EROD	Channel erodibility factor	cm/hr/Pa	0-1	0	Zero precludes any channel erosion
CH_COV	Channel cover factor	unitless	0-1	1	Set to one to allow erosion, to simplify interpretation should erodibility be changed in the model
file sol.dbf					
SOL_K1, 2, and 3	Hydraulic conductivity of soil layers 1, 2, and 3	mm/hr	soil database	no change	K values could be reduced to slow lateral flow in soil, somewhat reducing hydrograph peaks; after experimental model runs we decided to leave these values alone.
file sub.dbf					
CH_K1	Tributary channel hydraulic conductivity	mm/hr	~0.5	0.5	Maybe should have set to zero (as for ponds, wetlands, and the main channel), to avoid all water loss from seepage; relatively minor amount here
CH_N1	Tributary channel Manning's N	unitless	0.014	0.05	Set to correspond to natural stream, with some stones and brush (SWAT User's Manual)

Table 8. (continued) Parameter set used for the Willow River watershed SWAT model.
(alphabetical by file name; dbf files in tablesin folder; dat files in AvSwatDB folder)

File & Parameter	Description	units	Default	Calibrated	Rationale
file swq.dbf					
RS5	Organic phosphorus settling rate	1/day	0.05	not used, or set to 0.14	This parameter is not used in the "passive channel" model version. In the "active channel" version, RS5 is used to trap excess phosphorus in the floodplain and channel system.
file till.dat					
EFTMIX for 6 FLDCULT	Mixing efficiency of field cultivator	unitless	0.3	0.3	Kept at default
EFTMIX for 47 MLDBOARD	Mixing efficiency of moldboard plow	unitless	0.95	0.95	Kept at default
EFTMIX for 48 CHISPLOW	Mixing efficiency of chisel plow	unitless	0.3	0.6	Increased to reduce surface residue to selected levels under different tillage levels
EFTMIX for 50 DISKPLOW	Mixing efficiency of disk plow	unitless	0.85	0.9	Increased to reduce surface residue to selected levels under different tillage levels
file wwq.dbf					
AI2	Fraction of algal biomass that is phosphorus	mg P / mg algae	0.015	not used, or set to 0.001	This parameter is not relevant to the "passive channel" model version. However, when stream-water quality processes are activated for the "active channel" version, AI2 must be set low to avoid spurious phosphorus input.

Validation

The model was validated against flow and water-quality data collected for the Willow River during WY2006. To do this, the land use and point-source inputs had to be adjusted from 1999 to 2006 conditions. The cropland conversion to other land uses during that time period was taken from Table 4, assuming that conditions in 2006 were similar to 2004. Cropland HRUs were reduced and impacted grassland areas expanded in selected subbasins to account for this conversion, and an additional 6 grassland HRUs were changed from conventional to impacted (with curve numbers increasing to the next soil hydrologic group) (Table B4, bottom). Change within agricultural land from dairy to cash-crop (C1S1) rotations was estimated with data from NASS (2007). This change was largely a matter of soybean acreage replacing alfalfa acreage. Increased percentages of mulch till and no-till operations were set according to annual data collected by county personnel along transects (S Olson, St. Croix County Land and Water Conservation Department, written communication, 2007). Point-source time series for monthly flows and phosphorus loads were updated to include 2005-06 data. For this time series, data from Edlund (2004) were used through 1999; data from the WDNR (Kathy Bartilson, WDNR, written communication, 2007) were used for 2005-06 and assumed to continue through 2010. Average values between 1999 and 2005-06 were used for the intervening years 2000-04.

Modeled daily flows fit the WY2006 hydrograph with an E_{NS} of 0.51 (Figure 12a). However, this time period included an exceptional rainstorm on 4-5 October 2005, where the Stillwater station recorded 128 mm (5.0 in, in one day), the Amery station recorded 112 mm (4.4 in, over two days), and the Baldwin station recorded 68 mm (2.7 in, over two days). The model significantly overestimated peak flow during this event. Given the variability in the rainfall amounts, and that in the model the Stillwater station controls rainfall input to the six lower subbasins, rainfall inputs to the model may have been overestimated. If rainfall at Stillwater was reduced to that measured at Amery, then modeled and measured peak flows were quite close. If the month of October is excluded, then the model fit improves to an E_{NS} of 0.63. SWAT also somewhat missed the magnitude of the snowmelt peak in late March and the spring rain peak in early April 2006. Spring runoff events (from either snowmelt or rains) are difficult to model consistently year after year.

The overestimated flows during the October runoff event resulted in greatly overestimated sediment and phosphorus loads during that month which influenced the statistical fit of the model during the validation period. During WY2006 the model fit monthly sediment loads with an E_{NS} of only 0.20; the fit for phosphorus was much worse, with an E_{NS} of -3.5. The poor fit was due almost entirely to the overestimated October loads. If October was excluded from the statistical calculation, then the model fit sediment loads with an E_{NS} of 0.69 for sediment and 0.80 for phosphorus (Figures 12b and c). Apparently the model worked well for common flows and runoff events resulting from rainfalls of about 70 mm day^{-1} or less (about what Amery recorded on 5 October), but is unreliable for more extreme events.

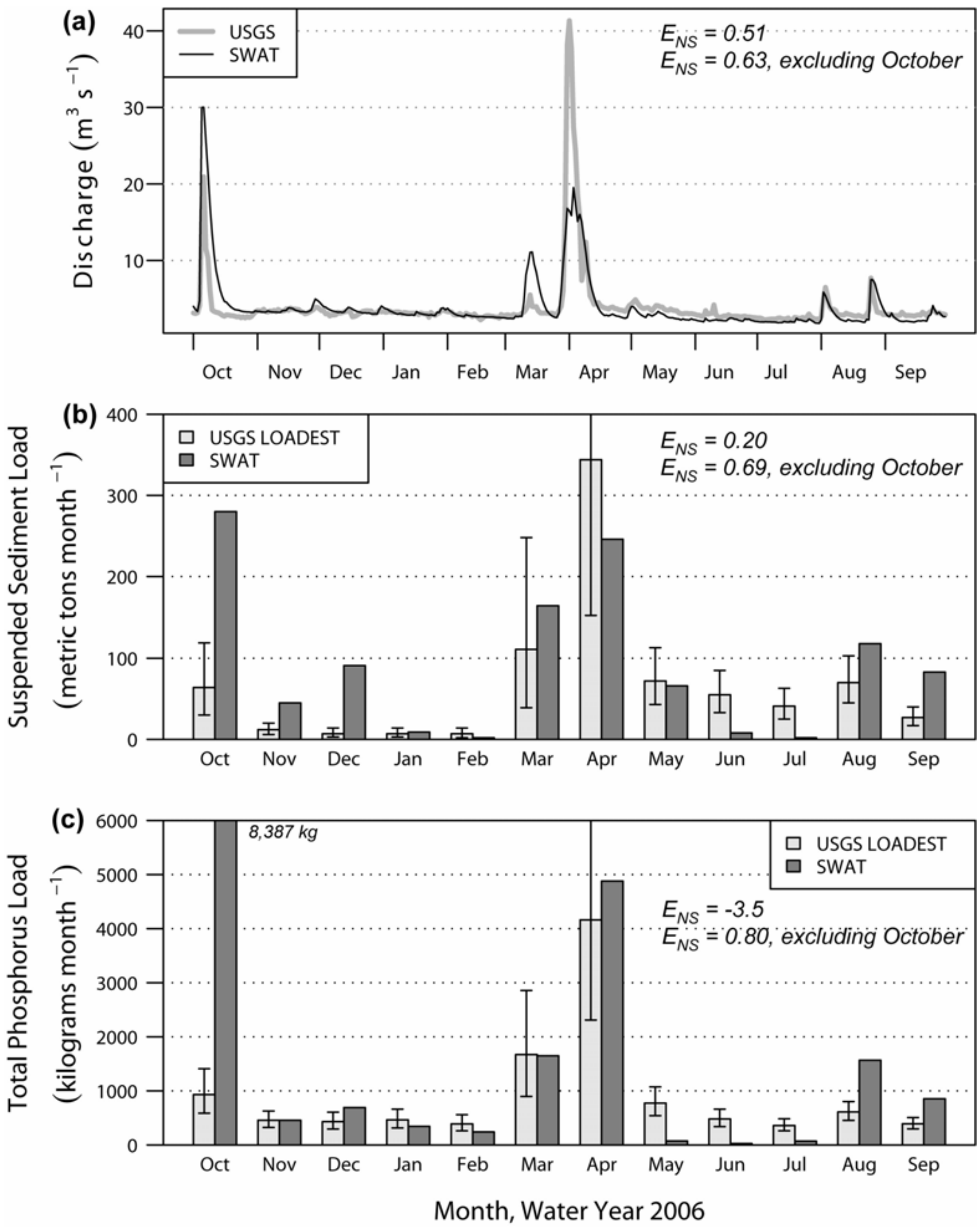


Figure 12. Validation plots for the Willow River SWAT model compared to monitoring data collected by the U.S. Geological Survey and calculated with the LOADEST program for water year 2006: (a) daily discharge, (b) monthly suspended sediment load, and (c) monthly total phosphorus load.

Summary and Conclusions

The Willow River in western Wisconsin is a valued water resource that is impacted by nonpoint-source pollution. Computer modeling of watershed processes is an important tool to help predict the effectiveness of strategies to mitigate this pollution. The Soil and Water Assessment Tool (SWAT) is a modeling program designed to predict the long-term effect of land management on nonpoint-source pollution in large watersheds. AVSWAT is the ArcView geographic information system (GIS) interface with the model to facilitate data input and output. This report describes the data sets and manipulations required to construct a SWAT model of the Willow River watershed. Initial model construction involved processing primarily spatial data sets of topography (digital elevation models), hydrography, land cover, and soils. The soils data (SSURGO) in particular required significant simplification by combining soils of the same hydrologic group into fewer aggregate categories that retained their spatial resolution and essential hydrologic characteristics. AVSWAT delineated the watershed into 27 subbasins and intersected the land cover and soils data into 532 hydrologic response units (HRUs).

The model was configured by adding features not initially recognized by the AVSWAT interface, fine-tuning the geographic extent of some features, and providing management and other information specific to selected features. Closed depressions play an important role in trapping nonpoint-source pollution in the glaciated Upper Midwest, and they were hand-delineated to determine their contributing areas in each subbasin. These areas were modeled in SWAT with the Pond tool, which trapped all sediment and phosphorus from runoff. Contributing areas to large riparian wetlands were modeled in SWAT with the Wetland tool, which trapped sediment but allowed some phosphorus to pass. Land cover in the model was updated to 1999 conditions to correspond to years with monitoring data for model calibration. Representative agricultural management practices were input to all cropland identified in the land-cover data set. Two dairy rotations were constructed: corn-grain, corn-silage, and three years of alfalfa (C2A3); and corn-grain, corn-silage, soybeans, corn-grain, and three years of alfalfa (C3S1A3). A simple corn-soybean (C1S1) cash-crop rotation was also constructed. These three rotations were sufficient to reproduce the relative acreages of corn, soybeans, and alfalfa each year. Each rotation was given appropriate tillage practices and fertilizer applications. Autofertilization with nitrogen by the model was used to produce corn yields at reported levels. Manure quantities were determined from reported numbers of animal units (principally cows). In the model, about 10% of this manure was spread by grazing on selected grassland HRUs, about 20% was spread monthly on selected C2A3 HRUs (to approximate daily-haul applications), and about 70% was stored and later applied seasonally (fall or spring) to fields prior to planting second-year corn in both selected C2A3 and C3S1A3 rotations.

Many other components of the model required configuration. Slope was determined for each HRU, rather than accepting the subbasin-wide average determined by the AVSWAT interface. Slope length was determined from these slopes, giving more realistic values that were about half of what the interface had estimated. The time of concentration of runoff in each subbasin was calculated based on subbasin dimensions, rather than on aggregate HRU dimensions. The channel reaches were configured to disallow any scour or sedimentation, to simplify interpretation of model output. Stream water-quality routines were deactivated to obviate extraneous phosphorus inputs from the subbasins, delivered as algal chlorophyll. Labile phosphorus in the upper soil layer was initialized to reported levels of soil-test phosphorus. Infiltration on residential and recreational land was reduced to reflect potential impacts from construction and unconnected impervious surfaces.

The model was calibrated to monitoring data collected during water year (WY) 1999. Daily flows during WY1999 were fit with an E_{NS} of 0.57, monthly sediment loads with an E_{NS} of 0.62, and monthly phosphorus loads with an E_{NS} of 0.51. In addition to direct comparison of model output against these monitoring data, sediment and phosphorus loads were constrained by estimated gross (field or HRU-scale) yields, net basin-wide yields, and deposition in reservoirs. After converting land use and management to 2006 conditions, the model was then validated against monitoring data from WY2006, for which modeled daily flows were fit with an E_{NS} of 0.51. The validation period included a very large rainstorm on 4-5 October 2005 which was not well simulated; in particular, the model overestimated both sediment and phosphorus loads. If the month of October 2005 was excluded, then the fits for both monthly sediment loads (E_{NS} = 0.69) and monthly phosphorus loads (E_{NS} = 0.80) were good, and the fit for daily flows improved to an E_{NS} of 0.63. We concluded that the model is valid for runoff events resulting from daily rainfall amounts of about 70 mm or less, and that the model overestimates sediment and especially phosphorus loads for larger rainfalls.

A number of problems in SWAT had to be either fixed or avoided in order to achieve an acceptably calibrated model. Some of these problems appeared to be errors in the model code; others were based on questionable algorithms included in the model. Alfalfa could not be removed from a rotation once planted in the original model; code changes by Baumgart (2005) were required to correct this problem. Without this change, sediment yield from corn-alfalfa (C2A3) HRUs would have been underestimated by 75%, and phosphorus yield underestimated by 63%. A second major problem was that infiltrated water from surface-water bodies such as ponds, wetlands, and tributary channels did not enter the groundwater flow system but was instead trapped in the shallow aquifer. This apparent error in model code was a large problem for the Willow River model because the Pond tool was used to simulate closed depressions, which captured about 30% of the precipitation excess, resulting in a 30% loss in stream flow. This flow was replaced by creating artificial point sources in each subbasin. A third significant problem derived from an algorithm that SWAT uses to estimate a chlorophyll load from subbasin uplands to the receiving channel. When stream water-quality routines are activated, this chlorophyll load is considered to represent algae with an associated phosphorus content. Subsequent release of this phosphorus adds an extraneous load to the channel above and beyond that delivered via runoff and groundwater. In the Willow watershed, these spurious loads increased the whole-basin phosphorus yield by about 20%, and increased phosphorus yields in some subbasins by over 100%. The problem was avoided by keeping the stream water-quality routines de-activated, at least for our "passive channel" model version. These problems appear to be unrecognized in most of the published literature. We conclude that it is possible that many previous SWAT models of watersheds in the Midwest have produced systematically biased results, depending on model configuration.

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Appendices

Appendix A – Crop Rotations

Table A 1. Pasture rotation.

Year	Date	Operation	Item	Rate	Units	Notes
Year 1	20-May	Graze start	Dairy manure	4.39	kg/ha/day	BMEAT = 9.15 kg/ha/day BMTRMP = 1.83 kg/ha/day
	20-May	Graze start	Beef manure	4.04	kg/ha/day	BMEAT = 11.88 kg/ha/day BMTRMP = 2.83 kg/ha/day
	1-Nov	Graze end	Dairy			
	1-Nov	Graze end	Beef			

Table A 2. C1S1 cash-crop rotations.

Rotation Name:		c1s1_a				
Year	**Date**	**Operation**	**Item**	**Rate**	**Units**	**Notes**
Year 1	20-Apr	Till	Chisel			
	25-Apr	Auto-fert initialize	46-0-0			NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	30-Apr	Till	Disk			
	7-May	Plant	Corn-Grain			CNOP=74.7, HEATUNITS=1300
	7-May	Fertilize	9-23-30	225	kg/ha	ID=06-24-24, LY1 = 0
	10-Jun	Till	Cultivate			
	15-Oct	Harvest&Kill	Corn-Grain			
Year 2	20-Apr	Till	Chisel			
	10-May	Fertilize	9-23-30	225	kg/ha	ID=06-24-24, LY1 = 0
	15-May	Till	Disk			
	20-May	Plant	Soybeans			CNOP=76.5, HEATUNITS=1300
	15-Oct	Harvest&Kill	Soybeans			

NOTES:
Rotations are all fundamentally CORN-SOYB (C1S1) rotations. Two rotations (c1s1_a and b) were created with the initial year being either corn or soybeans, to maintain spatial coverage of crops in the basin in any one year. Curve numbers (CNOPs) were changed to reflect the crop planted that year. Note that the CNOP value given above are just examples and would differ among the different soil types. SWAT did not allow us to add a fertilizer to its fertilizer data base, so we changed an existing fertilizer with ID = 06-24-24 to have the desired 09-23-30 content.

Table A 3. C2A3 rotations receiving seasonal manure applications.

Rotation Name:		c2a3_a				
Year	**Date**	**Operation**	**Item**	**Rate**	**Units**	**Notes**
Year 1	15-Apr	Auto-fert initialize	46-0-0			NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	30-Apr	Till	Disk			
	7-May	Plant	Corn-Grain			CNOP=74.7, HEATUNITS=1300
	7-May	Fertilize	9-23-30	225	kg/ha	ID=06-24-24, LY1 = 0
	10-Jun	Till	Cultivate			
	15-Oct	Harvest&Kill	Corn-Grain			
	1-Nov	Fertilize	Manure-Dairy	3148	kg/ha	LY1 = 1
	1-Nov	Fertilize	Manure-Beef	328	kg/ha	LY1 = 1
	5-Nov	Till	Chisel			
Year 2	15-Apr	Auto-fert initialize	46-0-0			NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	25-Apr	Fertilize	Manure-Dairy	3148	kg/ha	LY1 = 1
	25-Apr	Fertilize	Manure-Beef	328	kg/ha	LY1 = 1
	30-Apr	Till	Disk			
	7-May	Plant	Corn-Silage			CNOP=74.7, HEATUNITS=1300
	7-May	Fertilize	9-23-30	112	kg/ha	ID=06-24-24, LY1 = 0
	10-Jun	Till	Cultivate			
	15-Sep	Harvest&Kill	Corn-Silage			
Year 3	20-Apr	Till	Chisel			
	30-Apr	Till	Disk			
	7-May	Plant	Alfalfa			CNOP=64.8, HEATUNITS=1000
	10-Sep	Harvest	Alfalfa			
Year 4	25-Jun	Harvest	Alfalfa			
	10-Aug	Harvest	Alfalfa			
	10-Sep	Harvest	Alfalfa			
Year 5	25-Jun	Harvest	Alfalfa			
	10-Aug	Harvest	Alfalfa			
	10-Sep	Harvest&Kill	Alfalfa			
	1-Nov	Till	Moldboard plow			

NOTES:

Rotations are all fundamentally CORN-CSIL-ALF-ALF-ALF (C2A3) rotations. Five rotations (c2a3_a through e) were created with the initial year being one of the five years given above, to maintain spatial coverage of crops in the basin in any one year. Curve numbers (CNOPs) were changed to reflect the crop planted that year. Note that the CNOP value given above are just examples and would differ among the different soil types. SWAT did not allow us to add a fertilizer to its fertilizer data base, so we changed an existing fertilizer with ID = 06-24-24 to have the desired 09-23-30 content. All C2A3 HRUs received seasonal manure applications, except for those receiving daily-haul manure.

Table A 4. C2A3 rotations receiving daily-haul manure applications, simulated as monthly hauls.

Rotation Name: c2a3dhaul_a

Year	Date	Operation	Item	Rate	Units	Notes
Year 1	15-Jan	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Feb	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Mar	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Apr	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Apr	Auto-fert initialize	46-00-00			NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	30-Apr	Till	Disk plow			
	7-May	Plant	Corn-grain			CNOP=74.7, HEATUNITS=1300
	7-May	Fertilize	9-23-30	225	kg/ha	ID=06-24-24, LY1 = 0
	10-Jun	Till	Field cultivator			
	15-Oct	Harvest&kill				
	5-Nov	Till	Chisel plow			
	15-Nov	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Dec	Fertilize	Dairy	260	kg/ha	LY1 = 1
Year 2	15-Jan	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Feb	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Mar	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Apr	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Apr	Auto-fert initialize	46-00-00			NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	30-Apr	Till	Disk plow			
	7-May	Plant	Corn-silage			CNOP=74.7, HEATUNITS=1300
	7-May	Fertilize	9-23-30	225	kg/ha	ID=06-24-24, LY1 = 0
	10-Jun	Till	Field cultivator			
	15-Sep	Harvest&kill				
	15-Nov	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Dec	Fertilize	Dairy	260	kg/ha	LY1 = 1
Year 3	15-Jan	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Feb	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Mar	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Apr	Fertilize	Dairy	260	kg/ha	LY1 = 1
	20-Apr	Till	Chisel plow			
	30-Apr	Till	Disk plow			
	7-May	Plant	Alfalfa			CNOP=64.8, HEATUNITS=1000
	10-Sep	Harvest only	Alfalfa			
	15-Nov	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Dec	Fertilize	Dairy	260	kg/ha	LY1 = 1
Year 4	15-Jan	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Feb	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Mar	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Apr	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-May	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Jun	Fertilize	Dairy	260	kg/ha	LY1 = 1
	25-Jun	Harvest only	Alfalfa			
	15-Jul	Fertilize	Dairy	260	kg/ha	LY1 = 1
	10-Aug	Harvest only	Alfalfa			
	15-Aug	Fertilize	Dairy	260	kg/ha	LY1 = 1
	10-Sep	Harvest only	Alfalfa			
	15-Sep	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Oct	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Nov	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Dec	Fertilize	Dairy	260	kg/ha	LY1 = 1
Year 5	15-Jan	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Feb	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Mar	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Apr	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-May	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Jun	Fertilize	Dairy	260	kg/ha	LY1 = 1
	25-Jun	Harvest only	Alfalfa			
	15-Jul	Fertilize	Dairy	260	kg/ha	LY1 = 1
	10-Aug	Harvest only	Alfalfa			
	15-Aug	Fertilize	Dairy	260	kg/ha	LY1 = 1
	10-Sep	Harvest only	Alfalfa			
	15-Sep	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Oct	Fertilize	Dairy	260	kg/ha	LY1 = 1
	1-Nov	Till	Moldboard plow			
	15-Nov	Fertilize	Dairy	260	kg/ha	LY1 = 1
	15-Dec	Fertilize	Dairy	260	kg/ha	LY1 = 1

NOTES:

Rotations are all fundamentally CORN-CSIL-ALF-ALF-ALF (C2A3) rotations. Five rotations (c2a3dhaul_a through e) were created with the initial year being one of the five years given above, to maintain spatial coverage of crops in the basin in any one year. Curve numbers (CNOPs) were changed to reflect the crop planted that year. Note that the CNOP value given above are just examples and would differ among the different soil types. These application rates correspond to about 10 short tons of manure per acre during years with alfalfa, and about 5 short tons per acre during years when corn is planted, because during those years fields are available for spreading only about half the time. SWAT did not allow us to add a fertilizer to its fertilizer data base, so we changed an existing fertilizer with ID = 06-24-24 to have the desired 09-23-30 content.

Table A 5. C3S1A3 rotations receiving seasonal manure applications.

Rotation Name:		c3s1a3_a				
Year	**Date**	**Operation**	**Item**	**Rate**	**Units**	**Notes**
Year 1	25-Apr	Auto-fert initialize	46-0-0			NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	30-Apr	Till	Disk			
	7-May	Plant	Corn-Grain			CNOP=74.7, HEATUNITS=1300
	7-May	Fertilize	9-23-30	225	kg/ha	ID=06-24-24, LY1 = 0
	10-Jun	Till	Cultivate			
	15-Oct	Harvest&Kill	Corn-Grain			
	1-Nov	Fertilize	Manure-Dairy	3148	kg/ha	LY1 = 1
	1-Nov	Fertilize	Manure-Beef	328	kg/ha	LY1 = 1
	5-Nov	Till	Chisel			
Year 2	15-Apr	Auto-fert initialize	46-0-0			NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	25-Apr	Fertilize	Manure-Dairy	3148	kg/ha	LY1 = 1
	25-Apr	Fertilize	Manure-Beef	328	kg/ha	LY1 = 1
	30-Apr	Till	Disk			
	7-May	Plant	Corn-Silage			CNOP=74.7, HEATUNITS=1300
	7-May	Fertilize	9-23-30	112	kg/ha	ID=06-24-24, LY1 = 0
	15-Sep	Harvest&Kill	Corn-Silage			
Year 3	20-Apr	Till	Chisel			
	10-May	Fertilize	9-23-30	225	kg/ha	ID=06-24-24, LY1 = 0
	15-May	Till	Disk			
	20-May	Plant	Soybeans			CNOP=76.5, HEATUNITS=1300
	15-Oct	Harvest&Kill	Soybeans			
Year 4	25-Apr	Auto-fert initialize	46-0-0			NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	30-Apr	Till	Disk			
	7-May	Plant	Corn-Grain			CNOP=74.7, HEATUNITS=1300
	7-May	Fertilize	9-23-30	225	kg/ha	ID=06-24-24, LY1 = 0
	10-Jun	Till	Cultivate			
	15-Oct	Harvest&Kill	Corn-Grain			
Year 5	20-Apr	Till	Chisel			
	30-Apr	Till	Disk			
	7-May	Plant	Alfalfa			CNOP=64.8, HEATUNITS=1000
	10-Sep	Harvest	Alfalfa			
Year 6	25-Jun	Harvest	Alfalfa			
	10-Aug	Harvest	Alfalfa			
	10-Sep	Harvest	Alfalfa			
Year 7	25-Jun	Harvest	Alfalfa			
	10-Aug	Harvest	Alfalfa			
	10-Sep	Harvest	Alfalfa			
	1-Nov	Till	Moldboard plow			

NOTES:
Rotations are all fundamentally CORN-CSIL-SOYB-CORN-ALF-ALF-ALF (C3S1A3) rotations. Seven rotations (c3s1a3_a through g) were created with the initial year being one of the seven years given above, to maintain spatial coverage of crops in the basin in any one year. Curve numbers (CNOPs) were changed to reflect the crop planted that year. Note that the CNOP value given above are just examples and would differ among the different soil types. SWAT did not allow us to add a fertilizer to its fertilizer data base, so we changed an existing fertilizer with ID = 06-24-24 to have the desired 09-23-30 content.

Appendix B – HRUs selected for specific applications

Table B 1. Cropland HRUs and corresponding rotations.

Subbasin	Within-Subbasin HRU Number	Sequential HRU Number	Satellite-Designated Land Use	Years in Rotation	Rotation	Sub-Rotation
1	1	1	CORN	5	C2A3	a
1	2	2	CORN	2	C1S1	a
1	3	3	CORN	5	C2A3	b
1	4	4	CORN	2	C1S1	b
1	12	12	ALFA	5	C2A3	c
1	13	13	ALFA	5	C2A3	e
1	14	14	ALFA	7	C3S1A3	e
1	15	15	ALFA	5	C2A3	d
1	16	16	ALFA	5	C2A3	b
2	1	31	CORN	2	C1S1	a
2	2	32	CORN	2	C1S1	a
2	3	33	CORN	5	C2A3	e
2	4	34	ALFA	5	C2A3	d
2	5	35	ALFA	5	C2A3	a
2	6	36	ALFA	7	C3S1A3	e
3	1	47	CORN	5	C2A3	d
3	2	48	CORN	7	C3S1A3	b
3	3	49	CORN	5	C2A3	e
3	4	50	CORN	5	C2A3	b
3	5	51	CORN	7	C3S1A3	a
3	6	52	ALFA	5	C2A3	d
3	7	53	ALFA	7	C3S1A3	c
3	8	54	ALFA	5	C2A3	a
3	9	55	ALFA	5	C2A3	c
3	10	56	ALFA	7	C3S1A3	b
4	1	69	SOYB	2	C1S1	b
4	2	70	SOYB	2	C1S1	a
4	3	71	CORN	5	C2A3	e
4	4	72	CORN	7	C3S1A3	c
4	5	73	CORN	5	C2A3	d
4	6	74	ALFA	5	C2A3	d
4	7	75	ALFA	7	C3S1A3	g
4	8	76	ALFA	7	C3S1A3	f
5	1	83	CORN	2	C1S1	a
5	2	84	CORN	7	C3S1A3	a
5	9	91	ALFA	5	C2A3	a
5	10	92	ALFA	5	C2A3	b
5	11	93	ALFA	5	C2A3	e
5	12	94	ALFA	5	C2A3	d
6	1	103	CORN	2	C1S1	a
6	2	104	CORN	7	C3S1A3	f
6	3	105	CORN	5	C2A3	c
6	4	106	ALFA	5	C2A3	e
6	5	107	ALFA	5	C2A3	c
6	6	108	ALFA	7	C3S1A3	f
7	1	117	SOYB	2	C1S1	b
7	2	118	SOYB	2	C1S1	a
7	3	119	SOYB	7	C3S1A3	d
7	4	120	SOYB	2	C1S1	a
7	5	121	CORN	5	C2A3	b
7	6	122	CORN	7	C3S1A3	f
7	7	123	CORN	7	C3S1A3	f
7	8	124	CORN	5	C2A3	e
7	9	125	ALFA	5	C2A3	a
7	10	126	ALFA	7	C3S1A3	e
7	11	127	ALFA	5	C2A3	a
7	12	128	ALFA	5	C2A3	b
7	13	129	ALFA	7	C3S1A3	d
8	1	140	SOYB	7	C3S1A3	c
8	2	141	SOYB	2	C1S1	a
8	3	142	SOYB	7	C3S1A3	f
8	4	143	CORN	2	C1S1	b
8	5	144	CORN	5	C2A3	e
8	6	145	CORN	2	C1S1	a
8	7	146	ALFA	5	C2A3	d
8	8	147	ALFA	5	C2A3	b
9	1	155	SOYB	2	C1S1	a
9	2	156	SOYB	2	C1S1	a
9	6	160	CORN	7	C3S1A3	g
9	7	161	CORN	2	C1S1	b
9	8	162	ALFA	5	C2A3	d
9	9	163	ALFA	5	C2A3	a
10	1	172	SOYB	2	C1S1	b
10	2	173	SOYB	2	C1S1	a
10	3	174	SOYB	2	C1S1	b
10	4	175	CORN	7	C3S1A3	a
10	5	176	CORN	7	C3S1A3	e
10	10	181	ALFA	5	C2A3	b
10	11	182	ALFA	5	C2A3	e
11	1	192	SOYB	2	C1S1	b
11	2	193	CORN	2	C1S1	a
11	3	194	CORN	2	C1S1	b
11	4	195	ALFA	5	C2A3	d
11	5	196	ALFA	5	C2A3	a
12	6	210	ALFA	5	C2A3	c
12	7	211	ALFA	5	C2A3	c
12	8	212	ALFA	7	C3S1A3	a
13	1	220	SOYB	2	C1S1	a
13	2	221	SOYB	2	C1S1	b
13	3	222	SOYB	2	C1S1	a
13	4	223	CORN	5	C2A3	e
13	5	224	CORN	7	C3S1A3	d
13	6	225	CORN	5	C2A3	e
13	7	226	ALFA	5	C2A3	c
13	8	227	ALFA	5	C2A3	a
13	9	228	ALFA	5	C2A3	b
14	1	236	SOYB	2	C1S1	b
14	2	237	SOYB	7	C3S1A3	b
14	3	238	SOYB	2	C1S1	b
14	4	239	SOYB	7	C3S1A3	g
14	5	240	SOYB	2	C1S1	a
14	6	241	CORN	5	C2A3	e
14	7	242	CORN	2	C1S1	a
14	8	243	CORN	7	C3S1A3	a
14	9	244	CORN	5	C2A3	d
14	10	245	CORN	7	C3S1A3	e
14	11	246	ALFA	5	C2A3	c
14	12	247	ALFA	7	C3S1A3	f
14	13	248	ALFA	5	C2A3	e
14	14	249	ALFA	5	C2A3	a
15	1	261	SOYB	2	C1S1	b
15	2	262	SOYB	2	C1S1	b
15	3	263	CORN	2	C1S1	a
15	4	264	CORN	7	C3S1A3	g
15	5	265	CORN	2	C1S1	a
15	6	266	ALFA	5	C2A3	b
15	7	267	ALFA	5	C2A3	d
15	8	268	ALFA	5	C2A3	a
15	9	269	ALFA	5	C2A3	e

Table B 1. (continued) Cropland HRUs and corresponding rotations.

Subbasin	Within-Subbasin HRU Number	Sequential HRU Number	Satellite-Designated Land Use	Years in Rotation	Rotation	Sub-Rotation
16	1	280	ALFA	5	C2A3	a
16	2	281	ALFA	5	C2A3	b
16	3	282	ALFA	5	C2A3	e
16	4	283	ALFA	5	C2A3	c
16	5	284	ALFA	5	C2A3	e
16	6	285	ALFA	5	C2A3	a
17	1	303	SOYB	2	C1S1	b
17	2	304	SOYB	2	C1S1	a
17	3	305	SOYB	2	C1S1	a
17	4	306	SOYB	2	C1S1	b
17	5	307	CORN	5	C2A3	e
17	6	308	CORN	2	C1S1	a
17	7	309	CORN	7	C3S1A3	b
17	8	310	CORN	2	C1S1	a
17	9	311	CORN	5	C2A3	b
17	10	312	ALFA	5	C2A3	a
17	11	313	ALFA	5	C2A3	e
17	12	314	ALFA	5	C2A3	c
17	13	315	ALFA	5	C2A3	d
18	1	328	CORN	7	C3S1A3	e
18	2	329	CORN	2	C1S1	b
18	3	330	ALFA	5	C2A3	e
18	4	331	ALFA	7	C3S1A3	b
18	5	332	ALFA	7	C3S1A3	g
18	6	333	ALFA	5	C2A3	d
19	5	347	ALFA	5	C2A3	b
19	6	348	ALFA	7	C3S1A3	e
19	7	349	ALFA	5	C2A3	c
19	8	350	ALFA	5	C2A3	a
20	1	365	CORN	5	C2A3	d
20	2	366	CORN	7	C3S1A3	b
20	3	367	ALFA	5	C2A3	c
20	4	368	ALFA	5	C2A3	d
20	5	369	ALFA	5	C2A3	e
21	1	375	SOYB	2	C1S1	a
21	2	376	SOYB	7	C3S1A3	c
21	3	377	SOYB	2	C1S1	a
21	4	378	CORN	5	C2A3	a
21	5	379	CORN	5	C2A3	d
21	6	380	ALFA	7	C3S1A3	e
21	7	381	ALFA	5	C2A3	c
21	8	382	ALFA	5	C2A3	c
22	1	388	SOYB	2	C1S1	a
22	2	389	SOYB	2	C1S1	b
22	3	390	SOYB	7	C3S1A3	e
22	4	391	SOYB	2	C1S1	a
22	5	392	CORN	7	C3S1A3	a
22	6	393	CORN	5	C2A3	b
22	7	394	ALFA	5	C2A3	c
22	8	395	ALFA	5	C2A3	d
22	9	396	ALFA	5	C2A3	b
22	10	397	ALFA	7	C3S1A3	e
22	11	398	ALFA	5	C2A3	e
23	1	410	SOYB	2	C1S1	b
23	2	411	SOYB	2	C1S1	b
23	3	412	SOYB	2	C1S1	b
23	4	413	SOYB	2	C1S1	b
23	8	417	CORN	2	C1S1	a
23	9	418	CORN	5	C2A3	c
23	10	419	CORN	5	C2A3	c
23	11	420	ALFA	5	C2A3	b
23	12	421	ALFA	5	C2A3	a
23	13	422	ALFA	5	C2A3	a
24	4	435	CORN	2	C1S1	a
24	5	436	CORN	7	C3S1A3	c
24	6	437	CORN	2	C1S1	a
24	7	438	CORN	7	C3S1A3	b
24	8	439	CORN	2	C1S1	b
24	9	440	ALFA	5	C2A3	a
24	10	441	ALFA	5	C2A3	a
24	11	442	ALFA	5	C2A3	c
24	12	443	ALFA	5	C2A3	d
24	13	444	ALFA	5	C2A3	d
24	14	445	ALFA	7	C3S1A3	e
25	1	460	SOYB	2	C1S1	a
25	2	461	SOYB	7	C3S1A3	g
25	3	462	SOYB	2	C1S1	b
25	4	463	SOYB	2	C1S1	a
25	5	464	SOYB	2	C1S1	a
25	10	469	CORN	5	C2A3	e
25	11	470	CORN	2	C1S1	b
25	12	471	CORN	5	C2A3	b
25	13	472	CORN	5	C2A3	e
25	14	473	CORN	7	C3S1A3	e
25	15	474	CORN	2	C1S1	a
25	16	475	ALFA	5	C2A3	d
25	17	476	ALFA	5	C2A3	e
25	18	477	ALFA	7	C3S1A3	g
25	19	478	ALFA	5	C2A3	b
25	20	479	ALFA	5	C2A3	e
25	21	480	ALFA	5	C2A3	e
26	1	492	CORN	2	C1S1	b
26	2	493	CORN	5	C2A3	d
26	3	494	CORN	2	C1S1	a
26	4	495	CORN	5	C2A3	d
26	5	496	ALFA	5	C2A3	b
26	6	497	ALFA	5	C2A3	c
26	7	498	ALFA	7	C3S1A3	e
26	8	499	ALFA	5	C2A3	d
26	9	500	ALFA	7	C3S1A3	e
27	5	517	CORN	2	C1S1	a
27	6	518	CORN	2	C1S1	a
27	7	519	CORN	5	C2A3	d
27	8	520	ALFA	7	C3S1A3	c
27	9	521	ALFA	5	C2A3	a
27	10	522	ALFA	5	C2A3	a

NOTES: ALFA = alfalfa; CORN = corn-grain or corn-silage (CSIL); SOYB = soybeans; C2A3 = corn-grain/corn-silage/alfalfa/alfalfa/alfalfa rotation; C2S1A3A = corn-grain/corn-silage/soybeans/corn-grain/alfalfa/alfalfa/alfalfa rotation; C1S1 = corn-grain/soybeans rotation. Sub-rotation letter designates the year within the rotation (a = 1, b = 2, etc.) initiated in the first year of simualation.

Table B 2. HRUs receiving pasture (grazing) rotation.

Sequential HRU Number	Subbasin	Within-Subbasin HRU Number	1999 Area (km^2)
66	3	20	5.97
80	4	12	2.29
81	4	13	3.04
114	6	12	6.33
116	6	14	0.29
139	7	23	0.76
152	8	13	7.51
170	9	16	0.08
189	10	18	3.31
190	10	19	0.47
233	13	14	10.42
258	14	23	1.90
299	16	20	0.10
327	17	25	0.69
429	23	20	0.89
458	24	27	0.15
510	26	19	0.20
		Total area grazed:	***44.38***

Table B 3. HRUs receiving daily-haul rotation, simulated as monthly hauls.

Sequential HRU Number	Subbasin	Within-Subbasin HRU Number	Rotation Name	1999 Area (km^2)
124	7	8	c2a3dhaul_e	0.16
146	8	7	c2a3dhaul_d	5.93
162	9	8	c2a3dhaul_d	1.51
163	9	9	c2a3dhaul_a	1.07
195	11	4	c2a3dhaul_d	4.15
210	12	6	c2a3dhaul_c	0.04
313	17	11	c2a3dhaul_e	1.75
315	17	13	c2a3dhaul_d	0.70
347	19	5	c2a3dhaul_b	0.37
365	20	1	c2a3dhaul_d	1.92
369	20	5	c2a3dhaul_e	0.09
378	21	4	c2a3dhaul_a	6.08
381	21	7	c2a3dhaul_c	4.40
393	22	6	c2a3dhaul_b	1.17
396	22	9	c2a3dhaul_b	1.70
497	26	6	c2a3dhaul_c	0.39
521	27	9	c2a3dhaul_a	0.02
		Total area receiving daily haul manure:		***31.44***

NOTES:
All rotations are variants of C2A3 rotation. Rotation a begins with CORN, rotation b with CSIL, rotation c with year-1 ALFA, rotation d with year-2 ALFA, and rotation e with year-3 ALFA.

Table B 4. Grassland HRUs with modified curve numbers to simulate area of impacted residential and recreational development.

Sequential HRU Number	Subbasin	Within-Subbasin HRU Number	Original Curve Number (CN2)	Impacted Curve Number (CN2)	1999 Area (km^2)	2006 Area (km^2)
Impacted grassland HRUs for calibration to 1999 data						
27	1	27	64.8	71.1	0.81	0.81
65	3	19	53.1	64.8	2.22	2.23
169	9	15	53.1	64.8	5.42	5.43
171	9	17	64.8	71.1	1.34	1.35
325	17	23	64.8	71.1	1.61	1.62
340	18	13	64.8	71.1	1.41	1.41
341	18	14	53.1	64.8	5.97	5.98
359	19	17	53.1	64.8	0.79	0.80
362	19	20	27.9	53.1	0.05	0.05
372	20	8	53.1	64.8	8.32	8.32
373	20	9	53.1	64.8	0.56	0.56
384	21	10	64.8	71.1	9.40	10.75
386	21	12	53.1	64.8	0.49	0.57
409	22	22	64.8	71.1	1.36	1.45
454	24	23	53.1	64.8	0.40	0.42
455	24	24	53.1	64.8	6.59	7.15
488	25	29	53.1	64.8	0.20	0.21
508	26	17	53.1	64.8	6.35	6.55
529	27	17	53.1	64.8	5.46	5.72
		Total area of impacted grasslands, 1999:			***58.75***	
Additional impacted grassland HRUs for validation against WY 2006 data						
371	20	7	64.8	71.1	2.89	2.89
406	22	19	53.1	64.8	0.18	0.19
429	23	20	53.1	64.8	0.89	0.99
491	25	32	27.9	53.1	0.36	0.38
509	26	18	53.1	64.8	0.38	0.40
531	27	19	27.9	53.1	0.32	0.32
			Total area of impacted grasslands, 2006:			***66.57***