Constructing a SWAT model of the Sunrise River watershed, eastern Minnesota

TAPwaters St. Croix Watershed Research Station Hydrologic Modeling

Science Museum of Minnesota

Constructing a SWAT model of the Sunrise River watershed, eastern Minnesota

James E. Almendinger
St. Croix Watershed Research Station, Science Museum of Minnesota, Marine on St. Croix, MN 55047

Jason Ulrich
Dept. of Bioproducts and Biosystems Engineering, University of Minnesota, St. Paul, MN 55108

With contributions from
John Nieber
Dept. of Bioproducts and Biosystems Engineering, University of Minnesota, St. Paul, MN 55108

Susan Ribanszky
St. Croix Watershed Research Station, Science Museum of Minnesota, Marine on St. Croix, MN 55047

June 2010

Pursuant to the following projects:

"Manage nonpoint pollutants by watershed modeling of targeted subwatersheds in the St. Croix National Scenic Riverway"
Funding provided by the National Park Service

"Construction and application of a computer model of the Sunrise River watershed to address nonpoint-source pollution loads"
Funding provided by the Minnesota Pollution Control Agency under contract B17140

Contents

Constructing a SWAT model of the Sunrise River watershed, eastern Minnesota

James E. Almendinger
St. Croix Watershed Research Station, Science Museum of Minnesota, Marine on St. Croix, MN 55047

Jason Ulrich
Dept. of Bioproducts and Biosystems Engineering, University of Minnesota, St. Paul, MN 55108

with contributions from
John Nieber
Dept. of Bioproducts and Biosystems Engineering, University of Minnesota, St. Paul, MN 55108

Susan Ribanszky
St. Croix Watershed Research Station, Science Museum of Minnesota, Marine on St. Croix, MN 55047

Abstract

The Sunrise River watershed in eastern Minnesota comprises valued water resources with multiple impairments due at least partially to nonpoint-source pollution. Computer modeling of watershed processes is an important tool to help show where such pollution may originate and which mitigation strategies may be most effective. 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. A SWAT model was constructed from available topographic, hydrographic, soils, land cover, crop cover, livestock, and climate data sets. The model was calibrated to crop yields, stream flow, sediment load, and phosphorus load in the watershed, based on monitoring data from six sites. The monitoring data indicated that the upper subwatershed, probably because numerous lakes and wetlands, was a fairly minor contributor of nonpoint-source sediment and phosphorus. The North Branch subwatershed contributed about 27% of the sediment and 33% of the phosphorus reaching the watershed outlet. However, the lower subwatershed, from below the outlet to Carlos Avery Wildlife Management Area to the village of Sunrise, contributed the most sediment (69%) and nonpoint-source phosphorus (44%) of any such subwatershed. Much of the sediment appeared to be derived from channel erosion or other such riparian source, based on modeled amounts of field erosion. Calculated yields of sediment and phosphorus for the Sunrise watershed were in the same range as for other tributaries in the lower St. Croix basin.

Introduction

Problem

The Sunrise River watershed (Figure 1) comprises highly valued aquatic resources. The lake district that includes North and South Center, North and South Lindstrom, Chisago, and Green lakes provides desired home sites and recreational opportunities within and near the cities of Chisago City, Lindstrom, and Center City. The Sunrise River harbors rich mussel beds along some reaches thus contributing to regional biodiversity. The marshes of the Carlos Avery Wildlife Management Area provide important waterfowl habitat and recreational opportunities for outdoorsmen. The river itself is valued for canoeing and leads to the St. Croix River, a federally designated National Scenic Riverway administered by the National Park Service.

A number of these aquatic resources have become impaired in recent decades as a result of land-use changes. These impairments have triggered several total maximum daily load (TMDL) studies within the watershed, including the North Branch Sunrise River (for fecal coliform), lakes in the Comfort Lake-Forest Lake Watershed District (for excess nutrients), and Martin and Typo lakes (excess nutrients). Despite these efforts focused on distinct problem locations, multiple impairments throughout the watershed have triggered a watershed-wide Sunrise Watershed TMDL in an attempt to provide a more comprehensive assessment of the linkages among problems and potential solutions. About 12 lakes and 10 stream reaches have impairments including eutrophication, low dissolved oxygen, excessive turbidity, harmful pH, and reduced quality of community structure and biodiversity for fish and macroinvertebrates.

Furthermore, the pollutant loads of sediment and nutrients causing these impairments in the Sunrise watershed are passed downstream to the scenic St. Croix River. Such loads from the Sunrise and other tributaries have settled and accumulated in Lake St. Croix, the naturally impounded riverine lake occupying the lowermost 40 km of the riverway. Consequently Lake St. Croix has become more eutrophic from these phosphorus loads and has been listed by both Minnesota and Wisconsin as an impaired water body. To address this problem the interagency St. Croix Basin Water Resources Planning Team (SCBWRPT, or Basin Team) determined a goal to reduce the phosphorus load to the lake by about 20% relative to the 1990s average load, from about 460 metric tons/yr to 360 metric tons/yr (SCBWRPT, 2004). This goal has been included in the Total Daily Maximum Load (TMDL) plan being constructed under the guidance of the Basin Team and funded by the MPCA. Achieving this goal will require reductions in loads from tributary watersheds, including the Sunrise.

Computer models of watersheds can integrate watershed processes, including both point and nonpoint-source 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 nonpoint-source pollution, as well as predict the effectiveness of proposed remediation practices. This report describes in brief the construction of such a computer model of the Sunrise River, to document data inputs and model configuration as a

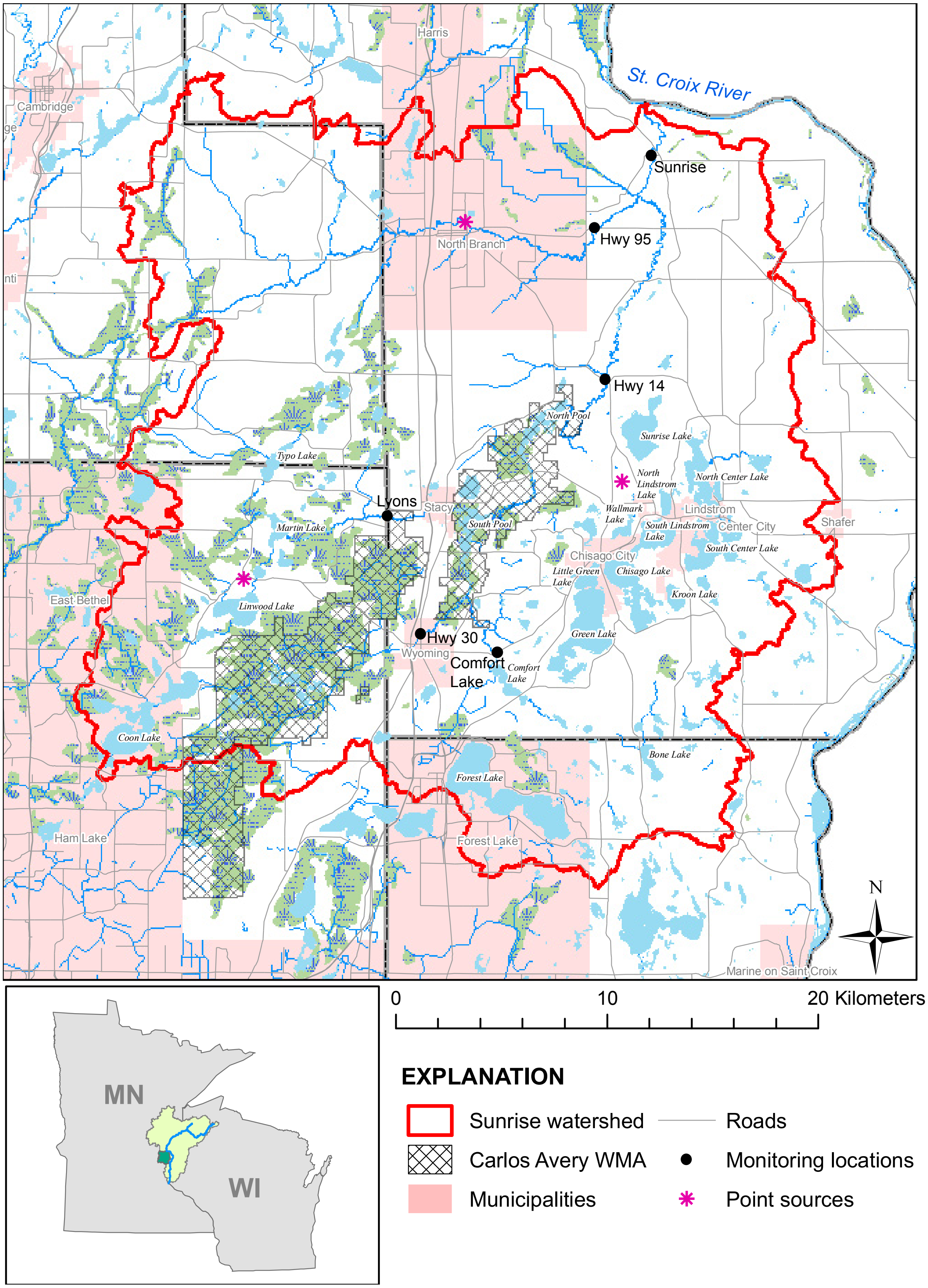


Figure 1. Sunrise River watershed study area.

foundation for applying the model to specific management needs.

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 Sunrise River watershed in eastern Minnesota. This report is written for three different audiences. First, basic background information and terminology are given for a managerial audience with some technical knowledge but without specific experience in modeling. Second, the bulk of the report is aimed at technical experts with enough scientific experience to understand most of the details about how the model was constructed. Third, a subset of those experts with enough modeling experience 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 our office will assist potential users as needed.

Modeling Basics

Model Terminology

A watershed model is a computer program that simulates selected hydrological processes within a study watershed. Watershed here refers to the directly contributing landscape surface 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 spatially referenced geographic data specific to a study watershed, including topography, soils, and land cover. The model is further configured by providing specific characteristics of these geographic features. Such information includes the geometries of reservoirs and other landscape depressions that can modify runoff hydraulics and pollutant transport. 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.

Once constructed, a model is run by providing an input file of weather over a selected period of time. The model then calculates how much water infiltrates, evapotranspires, or runs off to the receiving channel; the mass of 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.

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 ArcSWAT, an interface with ArcGIS geographic information systems (GIS) software. ArcSWAT 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 2). Hence, the subbasin is the smallest unit with spatial meaning in SWAT; within a subbasin, the spatial relations among different land uses and soils are 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. In other words, the SWAT program views the world as consisting of large fields (HRUs) of uniform soil and vegetation sloping directly to a stream channel, whereas in the real world the flow path from field to stream is quite a bit more complicated. For the Sunrise SWAT model, the watershed was divided into 142 subbasins (about 7 km^2 on average), with 1642 HRUs (about 11-12 per subbasin on average).

SWAT runs on a daily time step, requiring input of daily precipitation and daily minimum and maximum temperatures. Missing weather data are created on the fly by a weather generator

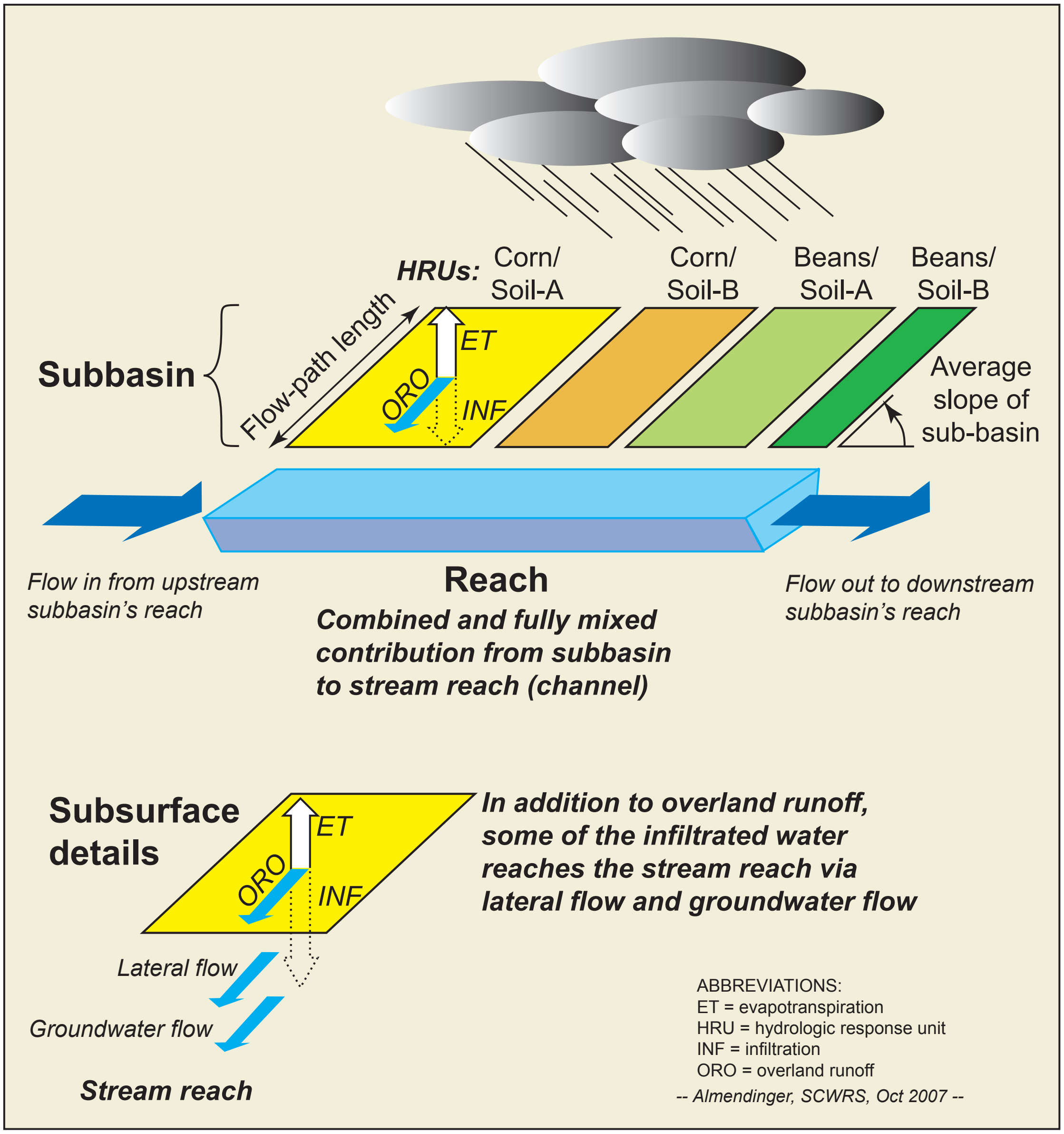


Figure 2. Conceptual subbasin in SWAT with four hydrologic response units (HRUs).

program embedded within SWAT that statistically mimics data from nearby weather stations. 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 a user-supplied baseflow recession constant. Overland runoff transports sediment and nutrients to the channel based on soil erodibility, land cover, peak flow velocity, and solubility (partition coefficient) considerations. The model allows some runoff from each subbasin to be intercepted by depressional storage, called ponds or wetlands in SWAT, 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. All on-channel lakes, whether natural or human-made, are called reservoirs in the model; they greatly influence peak flows and can trap significant quantities of sediment and nutrients.

Model output consists of flows and transported constituents at selected spatial and temporal scales. Output is available for each HRU, subbasin, and reservoir and can be summarized as daily, monthly, or annual averages for selected years of the model run.

Model Construction

This section reviews the data sets used to construct the SWAT model of the Sunrise River watershed, including spatial data and temporal data. Table 1a lists the spatial data sets 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 1b lists the temporal data sets, which include weather and point-source input data sets as well as monitoring data sets used later during the calibration process.

Topographic and Hydrographic Data

Subbasin Delineation

Topography and hydrography are inseparable because the shape of the land (topography) determines the location of surface-water features (hydrography). We began with the 10-m DEM (digital elevation model) data set available from the USGS. Within ArcGIS, ArcSWAT is linked to the ArcHydro extension so that the watershed, subbasins, and channels can be automatically delineated from the DEM alone. While such results are generally acceptable for constructing watershed models the size of the Sunrise, the DEM can miss some drainage features, especially man-made structures, and the automated delineation algorithm may make incorrect choices where the topography is relatively flat and flow directions are ambiguous. Fortunately, the MDNR has done an extensive survey of channels, drainage features, and watershed boundaries across much of Minnesota, including the Sunrise watershed, and they have constructed spatial data sets of hydrologically corrected flow networks and minor watershed boundaries (Sean Vaughn, MDNR, personal communication, 2009). We used a high-density flow network from the MDNR to "burn in" the channel locations in the DEM, which forced the automated delineation routine in ArcSWAT to create channels and subbasins that corresponded closely to the hydrologically

Table 1. Principal datasets for constructing the SWAT model of the Sunrise River watershed.

Item	Agency	Dataset	Format
(a) SPATIAL DATASETS			
Watershed base	MDNR	Hydrologically corrected minor subwatershed delineations	Polygon shapefile
Stream channels	MDNR	Hydrologically corrected high-density flow network	Polyline shapefile
Open water	MDNR	Open Water (24K Hydrography)	Polygon shapefile
Lake geometry	MDNR	Lake basin morphology	Polygon shapefile
Topography	USGS	Digital Elevation Model (DEM), 10-m resolution	Grid
Soils	USDA/NRCS	STATSGO (State Soil Geographic Database)	Polygon shapefile
Soils	USDA/NRCS	SSURGO (Soil Survey Geographic Database)	Polygon shapefile
Land cover	USDA/NASS	Crop Data Layer (CDL), 2006-08	Grid
Land cover	USGS	National Land Cover Dataset (NLCD), 1992 and 2001	Grid
Land cover	UM	Land cover classification, 2000 (statewide) and 2007 (St. Croix Basin)	Grid
(b) TEMPORAL DATASETS			
Precipitation	NCDC	Cooperative Network weather stations	Tabular, time series
Temperature	NCDC	Cooperative Network weather stations	Tabular, time series
Point sources	MPCA	Various, compiled by Edlund (2004), Magdalene (2009), and Steve Weiss (MPCA, personal communication, 2010)	Tabular, time series
Flow and loads	USGS	Sunrise River at Sunrise, water year 1999. Flows were mean daily; loads for suspended sediment and total phosphorus were monthly totals.	Tabular, time series
Flow	MDNR	Sunrise River at Sunrise, 2006-08	Tabular, time series
Flow	MPCA	North Branch at hwy 95, 2005-08	Tabular, time series
Loads	Chisago County SWCD	Sunrise River at Sunrise, 2006-08; and North Branch at hwy 95, 2006-07. Loads for suspended sediment and total phosphorus were annual totals.	Tabular, time series
Flow and loads	USACE	Sunrise River at hwy 14; west branch at Lyons; south branch at hwy 30; and outlet from Comfort Lake, 2008-09. Flows were mean daily and loads of suspended sediment and total phosphorus were monthly totals.	Tabular, time series
Agricultural data	USDA/NASS	Crop yields and harvested acreages; livestock populations. Annual countywide data, collected here for Chisago County.	Tabular

NOTES:
MDNR, Minnesota Department of Natural Resources; MPCA, Minnesota Pollution Control Agency; NASS, National Agricultural Statistics Service; NCDC, National Climatic Data Center; NRCS, Natural Resources Conservation Service; SWCD, Soil and Water Conservation District; USACE, U.S. Army Corps of Engineers; USDA, U.S. Department of Agriculture; USGS, U.S. Geological Survey; WDNR, Wisconsin Department of Natural Resources

corrected delineations determined by the MDNR, regardless of the scale of discretization (number of subbasins) selected.

The Chisago Lakes Improvement District (LID) has two possible outlets, a culvert out of the north end of Chisago Lake and another out of Little Green Lake (Figure 1), both of which are included in the MDNR flow network. However, the north culvert outlet from Chisago is rarely functional (Bud Kapell, Chisago Lakes Improvement District, personal communication, 2009). Instead, Chisago drains through another outlet on its southwest side to Green Lake, making the outlet from Little Green Lake the principal outlet for the LID. Consequently we manually edited the MDNR flow-network shapefile in ArcGIS to remove the north Chisago outlet and to create a channel connection from Chisago to Green Lake.

ArcSWAT will automatically create subbasin outlets only at the branch points (confluences) in the stream network. However, the user can force the creation of subbasin outlets at other points along the stream network as needed. We input an additional 14 points to correspond to selected monitoring station locations, so that SWAT output could be obtained at those points (Table 2). Points were also input to identify the outlets and inlets to all on-channel lakes, called "reservoirs" in SWAT. The routing algorithm in SWAT assumes all reservoirs are at the terminus of a subbasin, which would incorrectly be the next nearest downstream confluence unless an outlet point is explicitly input by the user. From the open-water spatial data set, we chose the 17 lakes over 100 ha in area, as well as two smaller lakes because of their listing for water-quality impairments (Table 3). Furthermore, when a lake has more than one inlet stream, ArcSWAT will create a branch point in the channel network within the lake area, with subbasin outlets also within the lake. Parts of the directly contributing area for the lake will be assigned to the tributary subbasins. While this does not necessarily compromise SWAT's calculations, the contributions of each inlet will not be cleanly separable from other runoff to the lake. Consequently we also created subbasin outlets at the point where each inlet entered a reservoir (and deleted the interior branch-point outlets) so that the contribution of each inlet to a reservoir could be examined separately, should the need arise in the future.

Given the branch points created by the automatic watershed delineation process, the monitoring station locations, and reservoir inlets and outlets, ArcSWAT created a total of 142 subbasins total within the Sunrise watershed (Figure 3). The outer watershed boundary was compared to that of the MDNR and edited in a few places to make the two congruent.

Lake Configuration: SWAT Reservoirs

The reservoirs (on-channel lakes) needed further configuration to account for their hydraulic influence on streamflow. For the most prominent lakes, volumes and areas were obtained from the MDNR lake morphology data set. In addition, lake bathymetry was available for many lakes from the MDNR "Lake Finder" web pages or from the topographic quadrangle maps. We hand-digitized the lake-depth contours, created TINs (triangular irregular networks) in ArcGIS, and recalculated lake geometry. Not only did this provide a check on the available data,

Table 2. Monitoring stations included in the SWAT model of the Sunrise River watershed.

Provisional Site Name	Agency Site Name	Agency	UTM Easting	UTM Northing	Latitude	Longitude	SWAT Subbasin
Sunrise_atSunrise		MPCA/MDNR/ USGS/USACE/SWCD	511022	5043425	45.5443	-92.8588	5
NBr_at95	MPCA North Branch	MPCA/USACE/SWCD	508341	5039994	45.5134	-92.8932	24
Sunrise_at95		MPCA/USACE	511434	5039981	45.5133	-92.8536	35
Sunrise_aboveKost	USACE Cty 14	USACE	508839	5032834	45.4490	-92.8870	47
SEBranch_belowLID		MPCA	507343	5029641	45.4202	-92.9061	56
WBr_nrStacy	USACE Lyons	USACE/ISANTI	498528	5026375	45.3909	-93.0188	75
SBr_atWyoming	USACE Cty 30	USACE	500114	5020799	45.3407	-92.9985	103
Sunrise_belowComfortLk	USACE Big Comfort	CLFLWD/USACE	503734	5019928	45.3328	-92.9523	111
Sunrise_aboveComfortLk		CLFLWD	503580	5018798	45.3227	-92.9543	121
Sunrise_aboveDitch1		CLFLWD	501942	5017398	45.3101	-92.9752	124
ComfortCk_belowBirch		CLFLWD	507306	5016556	45.3025	-92.9068	127
ComfortCk_aboveBirch		CLFLWD	508863	5016090	45.2983	-92.8870	130
Sunrise_belowDitch2		CLFLWD	501285	5015924	45.2968	-92.9836	128
Sunrise_belowForestLk		CLFLWD	501740	5015346	45.2916	-92.9778	132

NOTES: Agency abbreviations: CLFLWD, Comfort Lake-Forest Lake Watershed District; MDNR, Minnesota Department of Natural Resources; MPCA, Minnesota Pollution Control Agency; SWCD, Chisago County Soil and Water Conservation District; USACE, U.S. Army Corps of Engineers; USGS, U.S. Geological Survey.

Table 3. Data summary for on-channel lakes included as reservoirs in the SWAT model of the Sunrise River watershed.

Name	ID Code	SWAT Subbasin	SWAT ID	Area (ha)			Volume (ha-m)			Mean Depth (m)	SWAT NSED (mg/L)
				Mapped	Principal	Emergency	Mapped	Principal	Emergency		
Bone	res01	131	14	111	94	128	385	349	421	3.48	8
Chisago	res02	98	11	403	349	458	892	744	1039	2.21	20
Comfort	res03	113	16	136	114	158	562	519	606	4.13	6
Coon	res04	120	13	632	557	706	1237	986	1487	1.96	26
Forest	res05	140	15	913	818	1007	2988	2603	3373	3.27	9
Green	res06	99	12	694	614	773	2200	1921	2480	3.17	10
Kroon	res07	92	10	75	65	85	187	159	214	2.49	16
Linn	res08	88	3	63	56	70	63	38	88	1.00	100
Linwood	res09	91	8	262	223	301	683	594	771	2.61	15
Martin	res10	82	9	124	105	144	293	253	333	2.36	18
North_Center	res11	65	5	373	321	424	813	679	946	2.18	21
North_Lindstrom	res12	72	6	70	61	78	292	265	318	4.18	6
North_Pool	res13	57	18	196	165	227	358	295	422	1.83	30
South_Center	res14	80	4	411	355	466	1628	1478	1779	3.97	6
South_Lindstrom	res15	84	7	208	176	241	1033	965	1102	4.96	4
South_Pool	res16	74	17	265	225	305	265	175	355	1.00	100
Sunrise	res17	49	1	308	263	352	350	243	457	1.14	77
Typo	res18	64	2	113	96	131	111	74	148	0.98	104

NOTES: Areas and volumes include those of any smaller upstream on-channel lakes. In particular, this affected metrics of the following lakes: Bone, Comfort, Linwood, Martin, North Center, South Center, and South Pool (which includes Mud Lake here). Other lakes had fairly minor additions, if any. Little Green Lake is included here as part of Green Lake. NSED (model equilibrium sediment concentration) values calculated as a function of mean depth (see text).

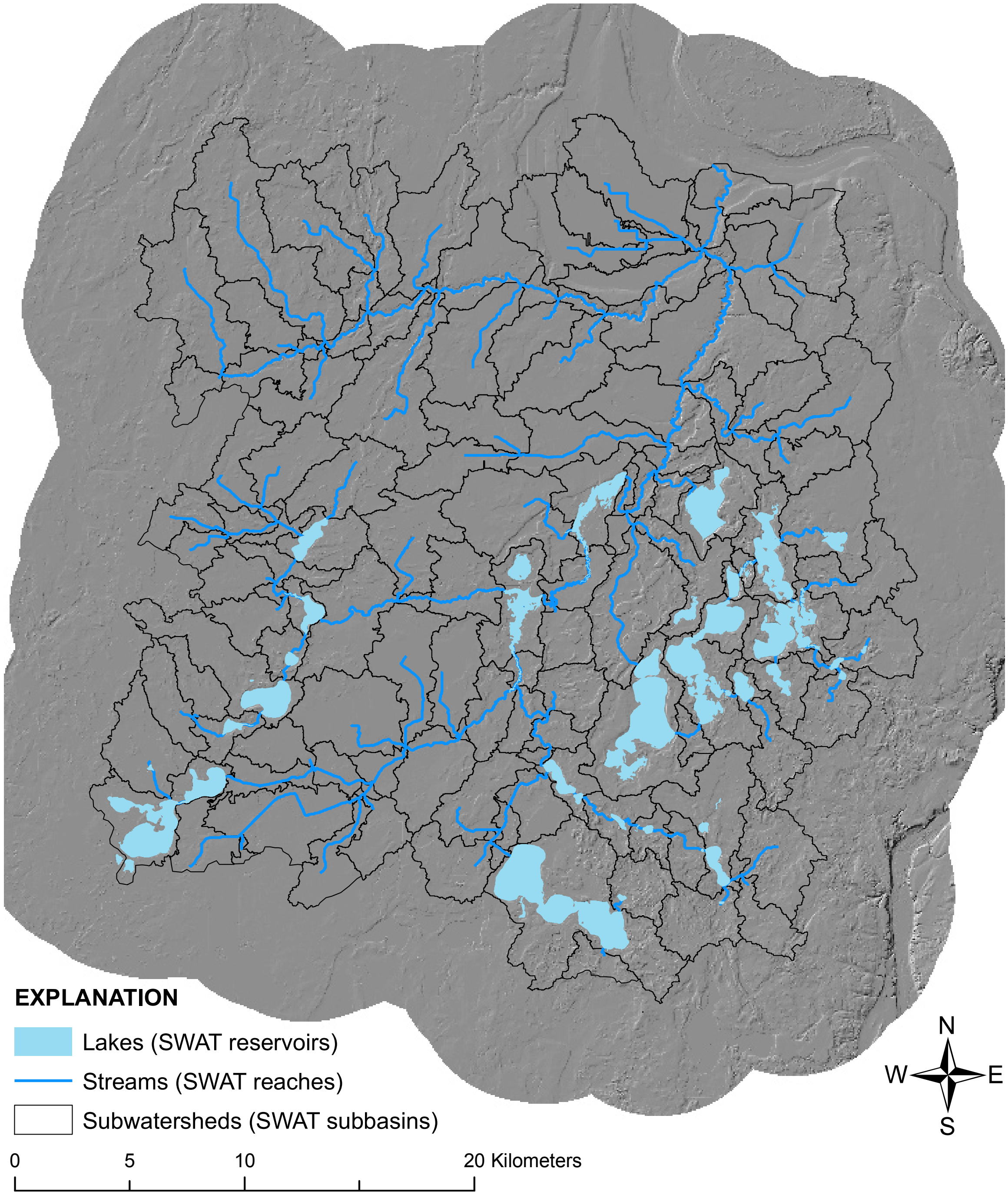


Figure 3. Topography and hydrography (streams and lakes) in the Sunrise watershed and resultant subbasin delineation in SWAT.

it also provided an objective method of calculating the changes in volume and area with lake level for littoral and near-shore regions. Comparable data were already available for a few of the lakes in the Comfort Lake-Forest Lake Watershed District from previous studies (CLFLWD 2008).

Smaller on-channel lakes were not explicitly included as reservoirs in the model, yet they may affect system hydrology. To address this concern, we identified these smaller open-water bodies upstream of each lake in the model and included their area and volume (assuming a 1-m depth) as part of the modeled lake. Thus the lakes in the model are aggregations of a main water body plus nearby smaller lakes that drain to it. Consequently many of the area and volume values given in Table 3 will be a little larger than values reported, for example, by the MDNR or other agencies.

SWAT requires that each reservoir be given a principal volume and area (below which the reservoir will not spill) and an emergency volume and area (above which all water will be released downstream). To estimate these values, we needed some way of estimating how lake volume and area change as lake level rises and falls. For the eleven lakes for which we had such bathymetric data, we developed the following relations:

(1) "Area change factor" = change in lake area (delta A) per change in lake water level (delta H):

Area change factor = 7.8761 * sqrtA – 48.669

(N = 11, r^2 = 0.91)

(2) "Volume change factor" = change in lake volume (delta V) per change in lake water level (delta H):

Volume change factor = 1.2074 * sqrtA^2 – 13.755 * sqrtA + 83.369

(N = 11, r^2 = 0.99)

where lake area A is given in hectares (ha) and sqrtA is the square root of A. As might be expected, a unit change in lake level (1 m, for example) would produce a larger change in area and volume for a large lake than a small lake. Hence the functions were built based on lake size, represented here by lake area, of which we took the square root to get a simpler linear metric. To use the functions, multiply the change factor by a selected change in lake level (delta H, in meters). The result is the change in area or volume resulting from that change in lake level. Volume is returned in units of hectare-meters (ha-m), which is equivalent to a 1-m thick slice covering 1 ha (or 10,000 m^3). These units happen to be what the SWAT model uses; the ha-m unit is conceptually similar to acre-feet.

Each lake has a unique range of lake-level changes, based on catchment topography and outlet (threshold) configuration (if the lake has an outlet). However, for simplicity we assumed that 1 m was the maximum rise of lake level over the outlet threshold during snowmelt or stormflow events. Further we assumed each lake was approximately at the mid-point of this range as mapped, as a starting point. So for each lake, the principal (threshold) area was calculated as the starting area *minus* 0.5 m times the area change factor; likewise the principal volume was calculated as the starting volume *minus* 0.5 m times the volume change factor. The emergency areas and volumes were calculated by *adding* the same changes to the starting values.

Because the changes in area and volume were related to lake size, the changes were, on a percentage basis, relatively similar among lakes. The average percent changes for the 11 lakes examined are given in Table 4. That is, a unit (1-m) rise in lake level would cause an average increase in lake volume of 36% (range 16-66%) and an average increase in lake area of 26% (range 14-50%). While these relations are certainly inexact, they are also simple to use and provide an objective measure where no site-specific data are otherwise available.

Table 4. Estimated change in volume and area of surface-water bodies in the Sunrise River watershed as a function of water-level change.

Change in Water level (m)	Change in Volume (%)	Change in Area (%)
+1	+36%	+26%
+0.5	+18%	+13%
+0.25	+9%	+6%
0	0	0
-0.25	-9%	-6%
-0.5	-18%	-13%
-1	-36%	-26%

Lakes are natural sediment traps, and SWAT assumes that all sediment above a selected “equilibrium sediment concentration” will settle and not be passed downstream. The theory assumes that wind mixing of lakes will maintain a suspended sediment concentration, which presumably would be greater in shallow lakes, where turbulence could re-suspend lake sediment. In modeling practice, however, the equilibrium sediment concentration parameter (NSED in SWAT) is a calibration parameter that is adjusted to whatever value helps the model meet the available monitoring data. In the Sunrise watershed, there are so many lakes and wetlands in the mid- and upper watershed that very little sediment is passed downstream of the North Pool. Hence almost any NSED value would appear to work in the model. To help make a more objective decision about how to set the NSED values, we created a relation based on our experience modeling the Willow River watershed in western Wisconsin (Almendinger and Murphy, 2007). This watershed includes two reservoirs, the New Richmond Flowage and Little Falls Reservoir. Based on their calibrated NSED values we derived the following relations:

(a) $NSED = 80 * D^{-1.85}$

or, after rounding for simplification:

(b) $NSED = 100 * D^{-2}$

where D is the mean depth of the reservoir in meters. We used the simpler equation, (b), in estimating the NSED values given in Table 3. These equations are extremely tentative, being based on only two reservoirs which themselves had little data for proper calibration. Yet they at least provide a starting point for application to other systems, such as here for the Sunrise watershed model.

Landscape Depression Configuration: SWAT Ponds and Wetlands

Depressions on the landscape -- of all sizes at all scales -- can have a large influence on runoff and infiltration processes, in turn influencing transport of sediment and nutrients.

However, few modeling studies acknowledge the problem and fewer still attempt to quantitatively incorporate an appropriate configuration to simulate the influence of these depressions. SWAT allows for depressional storage on the landscape with two very similar features called Ponds and Wetlands. Each model subbasin may have one Pond and one Wetland, and the user specifies what fraction of each subbasin's water yield (overland and subsurface flows) is routed to the Pond or Wetland. Ponds and Wetlands can trap sediment and nutrients at user-specified rates and then pass water, sediment, and nutrients downgradient to the receiving channel reach. The only difference between Ponds and Wetlands in SWAT is that Ponds allow for slightly more user-control of surficial outflow, much like that from a reservoir.

In the Sunrise SWAT model, we used the ArcHydro extension to ArcGIS to identify depressions and their drainage areas on the landscape from the DEM. For each depression we calculated the amount of runoff required to cause the depression to spill, by dividing the depression volume by its drainage area. We arbitrarily selected a 1-cm runoff depth as break point: depressions that required more than 1 cm of runoff to spill were deemed significant, and depressions that spilled with less than 1 cm of runoff were deemed insignificant and excluded from further consideration. We note that further research is needed to better quantify the influence of depressions on runoff, yet this research is beyond the scope of the current project. We recognize that our 1-cm runoff fill-depth is an arbitrary value, but we also believe that accounting for at least the largest depressions is better than ignoring all of them.

The so-designated significant depressions were placed in two categories. Those whose drainage areas intersected the modeled channel network were called "open," and those whose drainage areas had no obvious outlet were called "closed." For each subbasin we aggregated the areas and volumes of open depressions to create a composite SWAT Pond with an aggregate drainage area. Likewise, we aggregated closed depressions to create a SWAT Wetland in each subbasin. ArcHydro measures depression volumes from the existing surface up to where the depression would begin to spill; if the depression contains water, then the volume below the water surface is not counted. To account for this "hidden" volume, we assumed a 0.5-m depth, multiplied this by the depression areas, and added this volume to the ArcHydro-estimated volumes for both Ponds and Wetlands.

As for reservoirs, SWAT requires a principal (minimum) and emergency (maximum) volume and area for each Pond and Wetland. For Wetlands (closed depressions on the landscape), we used the aggregate depression volume and area as calculated by ArcHydro for each subbasin as the principal volume and area, below which the depression would not spill. The maximum (emergency) volume and area were then calculated as for a water level 0.5 m higher, according to Table 4:

For SWAT Wetlands (closed depressions):

Principal Volume and Area = ArcHydro aggregate depression volume and area

Emergency Volume = 1.18 * Principal Volume

Emergency Area = 1.13 * Principal Area

For Ponds (open depressions on the channel network), we assumed a similar 0.5-m range in level, but that they are already spilling and so begin from a midpoint of that range. So, from the aggregate ArcHydro depression area and volume for each subbasin, we calculated a principal volume and area based on a 25 cm drop in level, and an emergency volume and area based on a 25 cm rise in level (i.e., 50 cm above the principal level), according the same level-volume-area relations in Table 4:

For SWAT Ponds (open depressions):

Principal Volume = 0.91 * ArcHydro aggregate depression volume

Principal Area = 0.94 * ArcHydro aggregate depression area

Emergency Volume = 1.18 * Principal Volume

Emergency Area = 1.13 * Principal Area

Table 5 summarizes the statistics of areas, volumes, and drainage-area fractions for the Ponds and Wetlands in the 142 subbasins of the Sunrise SWAT model.

Depressions on the landscape influence not only overland runoff but groundwater recharge as well. Depressions can be sites of focused groundwater recharge and hence can be important drivers of groundwater contributions to baseflow in streams. Unfortunately, the current releases of the SWAT computer code have significant errors that result in all water infiltrating in Ponds and Wetlands being lost from the system. This loss of a large portion of groundwater recharge is unacceptable for simulating the hydrology of rivers such as the Sunrise, whose hydrology is dominated by groundwater discharge to baseflow. Consequently we spent considerable effort in revising the SWAT FORTRAN computer code to correct these errors. This code is available for download from the Science Museum of Minnesota's TAPwaters website (www.smm.org/scwrs/tapwaters/).

Table 5. Summary statistics for depressional features (Ponds and Wetlands in SWAT) included in the 142 subbasins of the Sunrise watershed SWAT model.

Feature	Units	Average	Std Dev	Median	Max	Min
Subbasin Area	(km^2)	6.98	5.73	5.90	33.61	0.002
Ponds (open depressions)						
Contributing drainage area	(% of subbasin)	17%	20%	13%	100%	0%
Principal surface area	(% of subbasin)	2.7%	6.2%	0.9%	53.3%	0.0%
	(ha)	19.0	35.1	2.9	201.2	0.0
Principal volume	(ha-m)	22.7	50.5	1.8	262.8	0.0
Wetlands (closed depressions)						
Contributing drainage area	(% of subbasin)	21%	19%	16%	80%	0%
Principal surface area	(% of subbasin)	5.8%	6.7%	3.5%	33.8%	0.0%
	(ha)	49.4	81.2	23.3	555.3	0.0
Principal volume	(ha-m)	80.9	168.2	24.4	889.1	0.0

NOTES: For all statistics, N= 142 (the number of subbasins in the SWAT model). For Wetlands, SWAT documentation uses the term "normal" rather than "principal."

Soils Data

Two soil spatial datasets were available for the Sunrise 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 2008a, 2008b). The SSURGO data set is much more detailed and thus should improve model accuracy, provided the added detail does not greatly hinder model run efficiency. SSURGO data sets were available for Anoka, Chisago, and Washington counties; however, at the time of model construction only the STATSGO data set was available for Isanti County.

The principal soil parameter that affects model hydrology is the hydrologic soil group (HSG), which ranges from group A for sandy, well-drained soils to group D for fine-grained poorly drained soils. To retain the spatial detail of these HSGs, yet also simplify the soils data so that the model would run efficiently, we created four composite soils in the Sunrise watershed, one for each of the four HSGs, plus a fifth category for non-soil open water (Figure 4). All soils were limited to three layers, and all soil properties for each layer were set to median values of the component soils. During the aggregation process, for SSURGO polygons with more than one component soil, the properties of the dominant soil were assumed to be representative of the entire polygon. If the dominant soil type had no definable properties (as for some urban lands), then the next-most dominant soil type was used. Some soils had a split HSG designation, such as A/D or B/D, where a soil that is normally well-drained (A or B) may in fact be wet because of a high water table. If such a soil polygon had cropland on it, we presumed it was well-drained and assigned it to its principal HSG, either A or B; otherwise the HSG was set to D.

Land-Cover and Land-Use Data

Land Cover: Base Data Assessment

A variety of land-cover data sets were compared to assess which might be most representative for use in the model, especially with regard to cropland areas. Spatial data sets were all derived from satellite imagery and include the National Land Cover Datasets (NLCD) for 1992 and 2001, University of Minnesota (UM) land cover data sets for 2000 and 2007, and the Crop Data Layers (CDL) for 2006-08. All of these data sets give agricultural land cover areas; the CDL data set has the advantage of identifying some crop types. However, a commonly used data source for quantifying crop areas is the National Agricultural Statistics Service (NASS), which produces annual summaries of yields and harvested acres of crops for each agricultural county in the USA. Because the NASS data are countywide summaries, the spatial data sets had to be clipped to county boundaries to provide comparable information. Consequently we

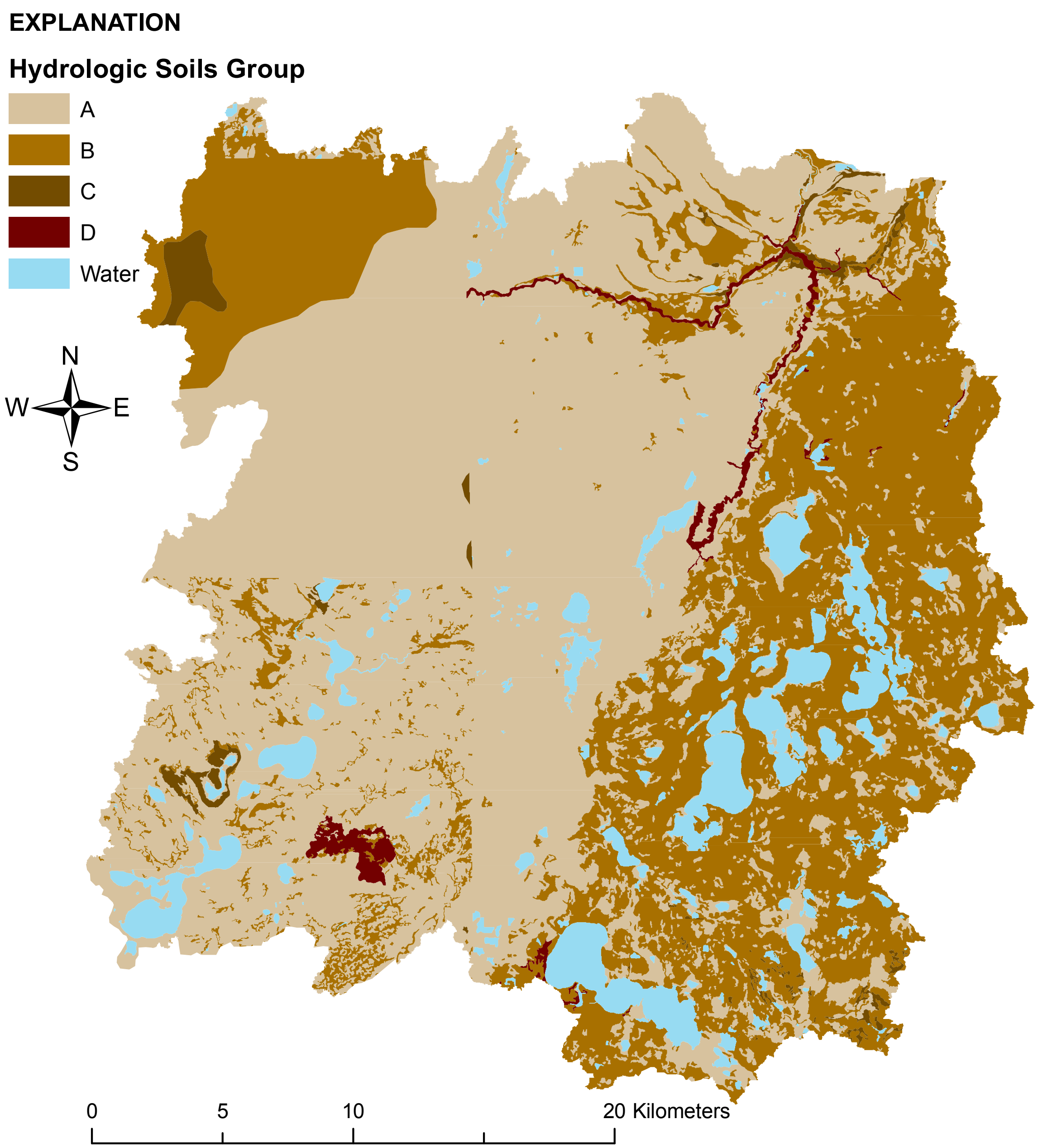


Figure 4. Soil polygons in the Sunrise watershed aggregated by hydrologic soil group (HSG).

clipped the spatial data sets to the Chisago County boundary, which encompasses the bulk of the Sunrise watershed. Because the different data sets defined land cover in different ways, we combined detailed categories from the different data sets into three general categories that were approximately comparable: cropland, undeveloped land, and developed land (Table 6). Trends in land-use change are not quantifiable in detail from these data sets, but in general the spatial data sets suggested that agricultural lands have declined while developed lands have increased.

In contrast, the NASS data suggested that cropland has actually increased, from about

Table 6. Percent areal extent of selected land-cover categories among available data sets for Chisago County, MN, 1992-2008.

Source:	NLCD		UM		CDL			CDL Avg	NASS
Year:	1992	2001	2000	2007	2006	2007	2008	2006-08	2000-08
Land Cover Type	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
Cropland	*26.4%*	*25.6%*	*37.3%*	*15.6%*	*17.2%*	*16.0%*	*13.1%*	*15.1%*	*22.8%*
Agriculture			37.3%						
Cultivated crops		25.6%							
Row crops	25.6%			14.4%					
Corn					7.6%	8.5%	6.4%	7.4%	8.9%
Soybeans					8.3%	6.1%	6.1%	6.7%	8.3%
Small grain	0.7%			0.2%	0.3%	0.2%	0.4%	0.3%	
Other crop				0.0%	0.0%	0.0%	0.0%	0.0%	
Alfalfa				0.9%	1.0%	1.1%	0.3%	0.8%	4.1%
Other hay									1.4%
Undeveloped	*71.9%*	*67.4%*	*51.5%*	*80.5%*	*71.2%*	*73.8%*	*78.4%*	*75.7%*	
Pasture / hay	31.9%	24.1%			18.7%	4.6%	33.7%	18.6%	
Grassland / herbaceous	0.1%	4.7%	3.8%	21.9%		14.1%	2.5%	8.1%	
Forest	18.1%	24.9%	27.7%	34.9%	30.4%	29.3%	27.8%	28.6%	
Wetland	16.2%	8.1%	14.9%	18.1%	16.3%	20.1%	8.9%	14.8%	
Water	5.5%	5.6%	5.1%	5.5%	5.8%	5.6%	5.5%	5.5%	
Developed	*1.8%*	*7.0%*	*11.2%*	*3.9%*	*11.6%*	*10.2%*	*8.5%*	*9.2%*	
Urban/developed			11.2%		11.6%				
Urban, low density	1.2%	6.0%		1.8%		9.6%	7.9%	8.6%	
Urban, med-high density	0.5%	0.9%		2.1%		0.7%	0.6%	0.6%	
Total	100%	100%	100%	100%	100%	100%	100%	100%	

NOTES:
Area of Chisago County = 1,146 km^2.
Data sources:
NLCD, National Land Cover Datasets compiled by the U.S. Geological Survey.
CDL, Cropland Data Layer, compiled by the National Agricultural Statistics Service of the U.S. Department of Agriculture
UM, University of Minnesota, compiled by the Remote Sensing Laboratory in the Department of Forestry.
Data aggregation assumptions:
"Forest" included deciduous, evergreen, and mixed forests; "Wetland" included both woody and herbaceous wetlands; "Urban, low density" included (depending on the dataset) residential open space, recreational lands, turfgrass, and urban land with <25% impervious cover. Barren lands and gravel pits were small areas that were considered partially developed and thus included with the "Urban, low density" category. "Urban, med-high density" included urban land with >25% impervious cover and commercial/transportation designations. In the CDL dataset, "Small grains" included all crops harvested for seeds, besides corn and soybeans; "Other crops" included vegetables and fruits; "Pasture / hay" included CDL grass/pasture and NLCD pasture/hay categories; "Grassland / herbaceous" included clover/wildflowers, seed/sod grass, and fallow cropland categories.
Averaging anomalies
Note in averaging the CDL data, differences in categories resulted in the sum of the average quantities being greater than the actual county area; the percentage coverage is based on this larger total.

19.8% of the county in 1990 to 23.4% in 2008 (Table 7 and Figure 5). One would think that trends over time are better examined in the NASS data set than in the spatial data set, as the NASS data are produced annually with relatively consistent methods from year to year. However, given a 69% increase in population in Chisago County from about 30,500 in 1990 to 51,500 in 2009 (U.S. Census Bureau, www.census.gov), it seems more likely that cropland area was reduced, at least a little, and replaced by developments. Nonetheless, the NASS data sets are useful for defining relative areas of crops, which is critical information for constructing representative crop rotations in the model. Note that the crops were dominated by corn, soybeans, and alfalfa. Small grains were identified as occupying just a fraction of a percent of land in the spatial data sets (Table 6). In the NASS annual tabular data, oats were identified but

Table 7. Annual harvested areas of cropland in Chisago County, MN, according to the National Agricultural Statistics Service (NASS), 1990-2008.

	Harvested area (km²):					
Year	**Corn, grain**	**Corn, silage**	**Soybeans**	**Alfalfa**	**Hay, other**	**Total**
1990	106.5	9.3	48.6	62.8	22.7	249.8
1991	110.1	8.1	51.8	66.8	14.6	251.4
1992	118.2	9.7	57.1	40.9	34.8	260.7
1993	92.7	21.1	46.6	46.6	35.2	242.1
1994	114.6	12.6	55.5	49.8	38.5	270.9
1995	99.2	11.7	53.4	43.7	41.3	249.4
1996	113.8	22.3	63.2	38.9	37.2	275.3
1997	109.3	10.9	69.6	43.7	44.9	278.5
1998	122.7	10.5	74.5	39.7	34.8	282.2
1999	92.7	13.4	90.3	49.0	24.3	269.6
2000	100.4	13.4	90.7	50.2	20.2	274.9
2001	68.4	14.2	100.0	44.9	17.4	244.9
2002	90.7	6.9	94.7	44.9	14.6	251.8
2003	74.1	23.1	100.4	43.3	15.8	256.7
2004	93.9	10.9	88.3	46.6	14.2	253.8
2005	85.8	10.5	91.5	48.6	16.6	253.0
2006	83.0	10.5	104.0	47.4	17.4	262.3
2007	112.6	9.7	85.0	44.1	17.4	268.8
2008	97.6	7.7	105.3	57.5	15.8	283.8
Average areas (km²):						
1990-2008	99.3	12.4	77.4	47.9	25.1	262.1
1990-99	108.0	13.0	61.1	48.2	32.8	263.0
2000-08	89.6	11.9	95.5	47.5	16.6	261.1
Average percent area, of total cropland (%):						
1990-2008	38%	5%	30%	18%	10%	100%
1990-99	41%	5%	23%	18%	12%	100%
2000-08	34%	5%	37%	18%	6%	100%

NOTES: Oats amounted to about 2% of cropland and hay area from 1990-2008, if its area were counted separately. We ignore that small area here, because oats is commonly planted with alfalfa whose acreage is already included in the table.

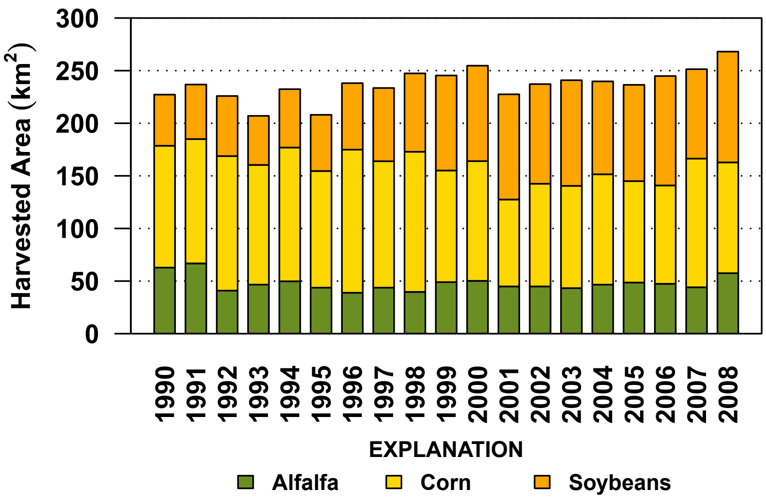


Figure. 5. Crop-harvested areas for alfalfa, corn, and soybeans in Chisago County, MN, 1990-2008, according to the National Agricultural Statistics Service (NASS).

still occupied such a small area that they were ignored in the model (Table 7; see footnotes). Consequently, only corn, soybeans, and alfalfa were considered for inclusion in modeled crop rotations. (Other crops could be added back into the model as an alternative model scenario in the future, if desired.)

Given these data sets with significant variability among them, we chose the CDL 2007 data set for several reasons. First, its values for the broad categories of cropland, undeveloped land, and developed land were mid-range, and thus perhaps representative of average conditions during the last decade (Table 6). Second, the CDL data sets had the advantage of distinguishing among crops, thereby providing a check on relative crop areas. Third, these crop areas corresponded reasonably well to the proportions of crops suggested in the NASS data set. The exception was alfalfa, which the NASS data listed as about 4% of the county, whereas the CDL 2007 data set gave about 1% (Table 6).

The CDL 2007 data layer was then clipped to the watershed boundary to characterize land cover for input to the model (Figure 6 and Table 8). Within the watershed, cropland covered about 13%, somewhat less than in Chisago County as a whole. Table 8 also shows how the CDL categories were translated into the land-cover categories recognized by the SWAT model.

Manure Quantities

The location, timing, and spreading rate (mass per area) of manure applications are important influences on nonpoint-source contributions of nutrients to receiving waters. The first step in assessing manure applications was to calculate the quantity of manure being produced in the watershed, assuming all that is produced will eventually be applied. The National Agricultural Statistics Service (NASS) produces annual reports of livestock numbers for each agricultural county in the USA. Livestock numbers can be converted to manure quantities by applying standard manure production rates per animal unit. We used livestock numbers for Chisago County as the basis for estimating livestock numbers in the Sunrise watershed, adjusted with advice from Chisago County SWCD personnel. Average annual livestock populations for

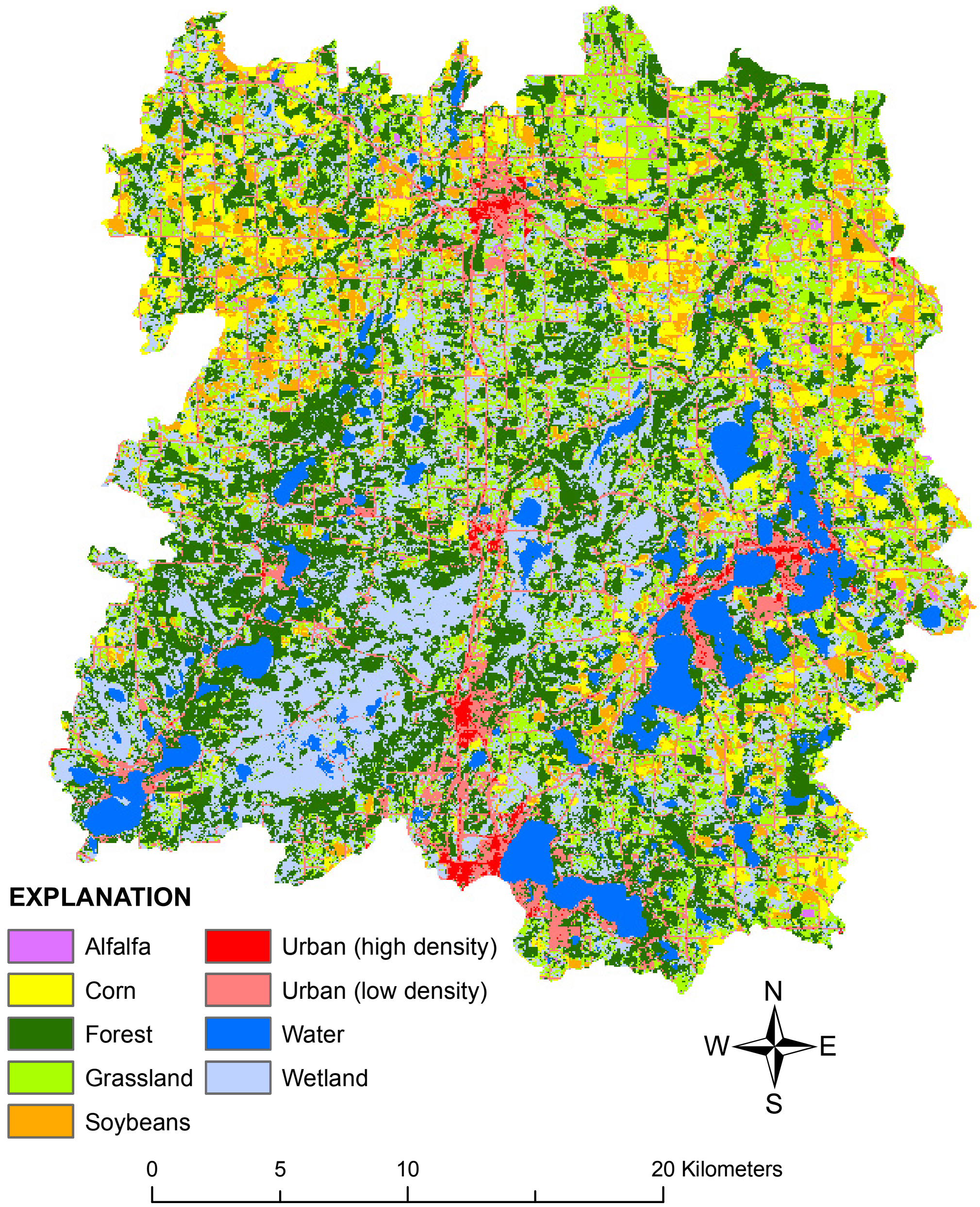


Figure 6. Land cover in the Sunrise River watershed according to the Crop Data Layer (CDL) for 2007.

Table 8. Land cover in the Sunrise River watershed derived from the 2007 Crop Data Layer.

Category	Area (km^2)	Percent (%)
General land-use types		
Water and Wetland	313.9	31.7%
Forest	287.0	29.0%
Grassland	158.9	16.0%
Agriculture (cropland)	128.1	12.9%
Developed	103.5	10.4%
Total watershed area	*991.4*	
SWAT land-use types		
WATR (Water-open)	69.6	7.0%
WETN (Wetland-nonforested)	244.3	24.6%
FRSD (Forest-deciduous)	273.1	27.5%
FRSE (Forest-evergreen)	13.9	1.4%
BROS (Brome-smooth)	133.9	13.5%
BLUG (Bluegrass sod)	25.0	2.5%
AGRR (Agriculture-cropland)	128.1	12.9%
URLD (Urban-low density)	95.0	9.6%
URHD (Urban-high density)	8.5	0.9%
Total watershed area	*991.4*	
Cropland types		
Corn	66.2	51.7%
Soybeans	54.0	42.2%
Alfalfa	5.7	4.4%
All others	2.1	1.6%
Total cropland area	*128.1*	

NOTES: Because of their small aggregate areas, forested wetlands were lumped with nonforested wetlands, mixed forest with deciduous forest, shrubland with grassland (brome), and medium density urban with high density urban lands. Grassland was modeled as smooth brome, and sod as bluegrass.

2000-09 were dominated by cattle, with about 6,700 beef cattle and 5,700 dairy cows (adults plus calves; Table 9). The phosphorus production in manure was also dominated by beef cattle, with about 45% of the total, followed by dairy cows producing about 40% of the total. However, dairy cows produced more raw manure (49%) than beef cattle (39%) because of the greater moisture content of dairy manure. In total, we calculated nearly 178,000 short tons per year of raw manure and 241 short tons of phosphorus per year produced by a combination of dairy cows, beef cattle, hogs, sheep, bison, red deer, and horses (Table 9).

For constructing the SWAT model, we wanted to keep agricultural practices as representative as possible without undue complexity. To that end we decided to focus on only three livestock types: beef cattle, dairy cows, and horses. While horses were calculated to produce only 6.5% of the current total phosphorus load, their numbers seem likely to increase in the future. To account for manure production by other livestock types, we created equivalency tables between different animals based on their phosphorus production (Tables 10 and 11) and converted the excluded livestock types to one of the three included types. Based on the nature of the animal and how its manure is ultimately spread, we chose to convert bison to beef cattle equivalents, hogs to dairy cow equivalents, and sheep and red deer to horse equivalents.

Livestock populations and manure production in the Sunrise watershed (Table 12) were then calculated by scaling the resulting livestock equivalent numbers for Chisago County by the ratio of the watershed area (991 km^2) to the county area (1,145 km^2). Because the Sunrise watershed contains large tracts of non-agricultural lands, the values scaled from Chisago County as a whole would probably overestimate actual livestock populations in the watershed. Consequently the initial population estimates were reduced by 10% to address this possible bias (Chisago County SWCD personnel, personal communication, 2009). The end result for the SWAT model was that a total of 187 short tons of phosphorus are produced annually by beef cattle (47%), dairy cows (46%), and horses (7%).

Table 9. Typical manure characteristics and calculated quantities for Chisago County, 2000-09.

	(a) Manure characteristics				(b) Manure in Chisago County						(c) Nutrients from manure		
Livestock Type	**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)	**Numbers of Animals**	**Animal Est'd Wt** (lbs)	**Animal Units**	**Raw Manure** (short T/yr)	**Total Solids (Dry Wt)** (metric T/yr)	**Percent of Total** (%, raw manure)	**Nitrogen** (short T/yr)	**Phosphorus** (short T/yr)	**Percent of Phosphorus** (%)
Dairy cattle, adult	86	12	0.45	0.094	2,400	1,350	3,240	50,852	6,451	28.6%	266	56	23.1%
Dairy calf	86	12	0.45	0.094	3,300	700	2,310	36,255	4,599	20.4%	190	40	16.5%
Beef cattle, adult	58	8.5	0.34	0.092	2,800	1,200	3,360	35,566	4,738	20.0%	208	56	23.4%
Beef calf	58	8.5	0.34	0.092	3,900	800	3,120	33,025	4,400	18.6%	194	52	21.7%
Hogs	84	11	0.52	0.18	2,600	175	455	6,975	830	3.9%	43	15	6.2%
Sheep	40	11	0.42	0.087	200	100	20	146	37	0.1%	2	0	0.1%
Bison	58	8.5	0.34	0.092	300	1,100	330	3,493	465	2.0%	20	6	2.3%
Red deer	40	11	0.42	0.087	300	110	33	241	60	0.1%	3	1	0.2%
Horses	51	15	0.3	0.071	1,200	1,000	1,200	11,169	2,986	6.3%	66	16	6.5%
Totals								177,722	24,567	100%	991	241	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.

Notes:
Manure charactistics obtained from American Society of Agricultural Engineers (1998), as cited by Neitsch et al. (2002). Numbers of cattle, hogs, and sheep (rounded to nearest 100) for Chisago County obtained from the National Agricultural Statistics Service web data, 2000-09. Calves apportioned to dairy and beef according to the proportions of adult cattle. Unreported numbers for hogs (2007-09) and sheep (2004-09) assumed to be essentilally zero. Bison numbers estimated by Chisago County SWCD staff; bison weight from the National Bison Association web page. Red deer number estimated by Chisago County SWCD staff; red deer weight from North Dakota State University web page by T. Golz and D. Aakre, 1993, Alternative Agriculture Series Number 9. In terms of manure characteristics, bison were assumed to be similar to beef cattle, and red deer to sheep. Horse numbers estimated as 10% of cattle numbers by Chisago County SWCD staff.

Table 10. Equivalent animal numbers, in terms of daily phosphorus production in manure.

One of these animals ...	*... equals this many of these animals:*									*... based on these data:*	
	Dairy cow	**Beef cow**	**Hog**	**Sheep**	**Horse**	**Bison**	**Red deer**	**Chicken**	**Turkey**	(lbs P/day/ 1000-lb animal unit)	(typical wt, lbs)
Dairy cow	1	1.149	4.029	14.586	1.787	1.254	13.260	105.750	19.705	0.094	1350
Beef cow	0.870	1	3.505	12.690	1.555	1.091	11.536	92.000	17.143	0.092	1200
Hog	0.248	0.285	1	3.621	0.444	0.311	3.292	26.250	4.891	0.18	175
Sheep	0.069	0.079	0.276	1	0.123	0.086	0.909	7.250	1.351	0.087	100
Horse	0.559	0.643	2.254	8.161	1	0.702	7.419	59.167	11.025	0.071	1000
Bison	0.797	0.917	3.213	11.632	1.425	1	10.575	84.333	15.714	0.092	1100
Red deer	0.075	0.087	0.304	1.100	0.135	0.095	1	7.975	1.486	0.087	110
Chicken (layer)	0.009	0.011	0.038	0.138	0.017	0.012	0.125	1	0.186	0.3	4
Turkey	0.051	0.058	0.204	0.740	0.091	0.064	0.673	5.367	1	0.23	28

Notes: All animals assumed to be adults.

Table 11. Equivalent animal unit numbers, in terms of daily phosphorus production in manure.

One of these animal units ...	*... equals this many of these animal units:*									*... based on these data:*
	Dairy cow	**Beef cow**	**Hog**	**Sheep**	**Horse**	**Bison**	**Red deer**	**Chicken**	**Turkey**	(lbs P/day/ 1000-lb animal unit)
Dairy cow	1	1.022	0.522	1.080	1.324	1.022	1.080	0.313	0.409	0.094
Beef cow	0.979	1	0.511	1.057	1.296	1.000	1.057	0.307	0.400	0.092
Hog	1.915	1.957	1	2.069	2.535	1.957	2.069	0.600	0.783	0.18
Sheep	0.926	0.946	0.483	1	1.225	0.946	1.000	0.290	0.378	0.087
Horse	0.755	0.772	0.394	0.816	1	0.772	0.816	0.237	0.309	0.071
Bison	0.979	1.000	0.511	1.057	1.296	1	1.057	0.307	0.400	0.092
Red deer	0.926	0.946	0.483	1.000	1.225	0.946	1	0.290	0.378	0.087
Chicken (layer)	3.191	3.261	1.667	3.448	4.225	3.261	3.448	1	1.304	0.3
Turkey	2.447	2.500	1.278	2.644	3.239	2.500	2.644	0.767	1	0.23

Table 12. Annual manure production in the Sunrise River watershed, 2000-09.

	(a) Manure in Sunrise watershed						(b) Nutrients from manure		
Livestock Type	Animal Numbers	Animal Est'd Wt	Animal Units	Raw Manure	Total Solids (Dry Wt)	Percent of Total	Nitrogen	Phosphorus	Percent of Phosphorus
		(lbs)		(short T/yr)	(metric T/yr)	(%, raw manure)	(short T/yr)	(short T/yr)	(%)
Dairy cattle, adult	3,700	1,350	4,995	78,397	9,945	54.6%	410	86	45.8%
Beef cattle, adult	4,400	1,200	5,280	55,889	7,446	38.9%	328	89	47.3%
Horses	1,000	1,000	1,000	9,308	2,489	6.5%	55	13	6.9%
Totals				143,593	19,879	100%	793	187	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.
Notes:
See Table 9 for data on manure characteristics and livestock numbers for Chisago County. Livestock numbers for Sunrise watershed based on Chisago County numbers scaled to the watershed:county area ratio, and reduced by 10% to account for slightly lower animal density in the watershed relative to the county. Based on annual production of phosphorus in manure by different livestock types (see Tables 10 and 11), hogs were converted to equivalent dairy cattle, bison to equivalent beef cattle, and sheep and red deer to equivalent horses, to simplify agricultural management schemes to only three livestock types. Similarly, based on relative manure production, calves were converted to an equivalent number of adult cattle.

Crop Rotations

There are several challenges in constructing crop rotations in SWAT. First, plausible crop rotations must be constructed that are representative of typical rotations (i.e., the temporal sequence) and areal coverage of crops in the watershed. Second, the area of each crop should remain about the same for each year of the model run, so that differences between model runs are unlikely to be an artifact of which year in a rotation a model run is started or stopped. This means that each crop rotation should be split into subrotations that begin in different years of the rotation. For example, for a simple corn-soybean rotation, half the area should begin with corn in the first year, and half the area should begin with soybeans. Third, the annual quantities of manure produced by livestock in the watershed each year must be applied within selected rotations in a way that is realistic and representative of the variety of application rates and methods. We include grazing as an agricultural “rotation” for the purposes of describing agricultural management scenarios within SWAT.

The areas of corn, soybeans, and alfalfa in the Sunrise watershed (see Tables 7 and 8) could adequately be represented by two simple rotations, Cg1S1 (corn-grain and soybeans) and Cs3A3 (three years of corn-silage, followed by three years of alfalfa). Of cropland area identified in the CDL 2007 data set (Table 8), we assigned 85% as Cg1S1 and 15% as Cs3A3. A 90:10% split between the two rotations would have given similar representation, but the added 5% to the Cs3A3 rotation gave more options for trying different manure application rates in the model. We constructed only one Cg1S1 rotation, which received only inorganic fertilizer (i.e., no manure). Four rotations were constructed for the Cs3A3 rotation, based on the amount of manure received: no manure, spring and fall applied manure, daily-hauled manure at low rates, and daily-hauled manure at high rates (56%, 11%, 25%, and 8% of the total Cs3A3 area, respectively). All of the manure applied to the Cs3A3 rotations was from dairy cows, which disposed of all the dairy manure produced in the watershed. The “daily haul” scenarios were actually modeled as a “monthly haul” that occurred on the 15th of each month, to facilitate scheduling the operation in

SWAT (see Appendix tables A3 and A4). All crop rotations on hydrologic soil group A (sandy) soils were tilled only in the spring, whereas those in groups B and C (loamy) soils were chisel-plowed in the fall.

In contrast to dairy manure, the beef manure was applied mostly to grassland, with a small portion going to woodland. We assumed half of the beef manure was applied by grazing; of this half, 80% was applied to grassland and 20% to woodland. Each grazing beef was allotted 3 acres of grassland or 6 acres of woodland, resulting in application rates of about 2 short tons/acre per year in grassland and 1 short ton/acre per year in woodland. Grazing was allowed for 169 days each year, from 12 May to 28 October. The other half of beef manure was applied in the spring time (to dispose of accumulated manure over the winter) to grassland cut as hay, resulting in an application rate of about 12 short tons/acre per year. All beef manure applications were restricted to grassland units that co-occurred in subbasins that had also had cropland.

Horse manure was applied only to grassland; grassland in subbasins that also had high-density urban units was excluded from receiving horse manure. Of grassland receiving horse manure, two-thirds of the area received manure only from grazing, with a net application rate of about 1.5 short tons/acre per year. The other third of the area also received a springtime application of manure, for an extra 4.7 short tons/acre per year. As for beef, each horse was allotted 3 acres and allowed to graze for 169 days per year, from 12 May to 28 October.

These rotations adequately represented the known areas of corn, soybean, and alfalfa in the watershed, and they disposed of the calculated production of manure in the watershed. The details of these rotations are summarized in the Appendix, Tables A1-A10. Inorganic fertilizer and manure application rates are given in both metric units (as needed by SWAT) and English units (as commonly used by farmers and agronomists in the USA). As can be seen, even with two simple cropland rotations (Cg1S1 and Cs3A3) plus grazing, the various combinations of different crops, manure application rates, livestock types, and soil types resulted in a fairly complicated distribution of agricultural rotations in the SWAT model. The ability of SWAT to consider these many different rotations is one of its greatest strengths.

Point-Source Data

Three waste-water treatment facilities were included in the model as point sources: Chisago Lakes, Linwood Terrace, and North Branch (Figure 1 and Table 13) (Edlund 2004; Magdalene 2009; S. Weiss, MPCA, personal communication, 2009). The Linwood Terrace facility serves a small residential area and discharges much less phosphorus than the other two facilities, which serve major population centers. Substantial upgrades have been implemented in the Chisago Lakes and North Branch facilities in recent years that have reduced their phosphorus loads by 58% and 96%, respectively, relative to loads during the 1990s. Together, these two plants have a remarkable combined reduction in annual load of almost 6 metric tons. These loads were entered in the SWAT model as annual average values from 1990-2009. That is, the loads

Table 13. Point sources included in the SWAT model of the Sunrise River watershed.

Treatment Facility	Coordinates Lon (deg W) *UTM east*	Lat (deg N) *UTM north*	Average Phosphorus Loads 1900-99 (kg/yr)	2000-05 (kg/yr)	2006-09 (kg/yr)	Load Reductions, 1990-99 vs. 2006-09 (kg/yr)	(%)
Chisago Lakes WWTP	92.8755 *509624*	45.4058 *5028018*	4241	5317	1766	-2475	-58%
Linwood Terrace	93.1082 *491715*	45.3633 *5023402*	18	7	8	-10	-57%
North Branch WWTP	92.9706 *502199*	45.5156 *5040280*	3602	2508	133	-3470	-96%

NOTES: Lon, longitude in degrees west; Lat, latitude in degrees north; kg/yr, kilograms per year; UTM, universal transverse mercator zone 15N; WWTP, wastewater treatment plant.

changed each calendar year to match the known trend over time, but within each calendar year the load for each point source was converted to a constant kg/day.

Climate Data

Climate data were ordered from the National Climatic Data Center on CD and DVD. The data set is titled the "Cooperative Summary of the Day" and compiles daily data from weather observers from across the USA, including nearly 300 stations in each of Minnesota and Wisconsin. The five stations in or near the Sunrise watershed are listed in Table 14. In SWAT, each subbasin receives weather inputs from the weather station nearest to its centroid; Figure 7 shows the relation between weather stations and subbasins. Data extracted for four of the stations included daily precipitation (P), minimum temperature (Tmin), and maximum temperature (Tmax); the St. Francis station had only precipitation data. Data for the Cambridge station started in 1948 on the CD (the complete record may be longer), in 1950 for St. Croix Falls, in 1954 for St. Francis, in 1958 for Forest Lake, and in 1990 for Wild River. Over this period of record, the annual average precipitation appears to be increasing at a rate of about 2.7 mm/yr (Figure 8), although there is considerable scatter in the data and different rates could be calculated for different selected windows of time.

Data from the NCDC are not in a form directly readable by SWAT, and considerable effort was put forth to create scripts in Excel VBA (Visual Basic for Applications) that would read, check, and re-format the weather data for use in the SWAT model. The scripts read the data for a selected weather station; extract the P, Tmin, and Tmax data; check for missing days and fill in missing values with a -99 marker value; and put the data in column-ready format for SWAT. SWAT can automatically generate statistically acceptable values for missing climate data (when it finds a -99 value); however, precipitation is so critical to the model that it is unwise to let SWAT generate such values. Instead, filling in missing values from nearby weather stations is preferable. Hence, an additional VBA script was written to identify missing values at one station and fill in those values with those from a nearby selected station. Because processing

Table 14. Weather stations used in the Sunrise River watershed model.

Station Name	Station Number	Longitude (deg W)	Latitude (deg N)	UTM east (m)	UTM north (m)	Altitude (m)	Data
Cambridge 5ESE	211227	93.1264	45.5506	490134	5044121	293	P, T
Forest Lake 5NE	212881	92.9217	45.3428	506855	5020694	293	P, T
St. Francis	217309	93.3653	45.3914	471884	5026092	274	P
Wild River SP	218986	92.7489	45.5231	519610	5041089	287	P, T
St. Croix Falls	477464	92.6464	45.4117	527670	5028744	235	P, T

NOTES: deg, degrees; W, west; N, north; m, meters; UTM, universal transverse mercator zone 15N; P, precipitation; T, temperature. Station names and numbers as reported by the National Climatic Data Center. Most recent names and locations were used.

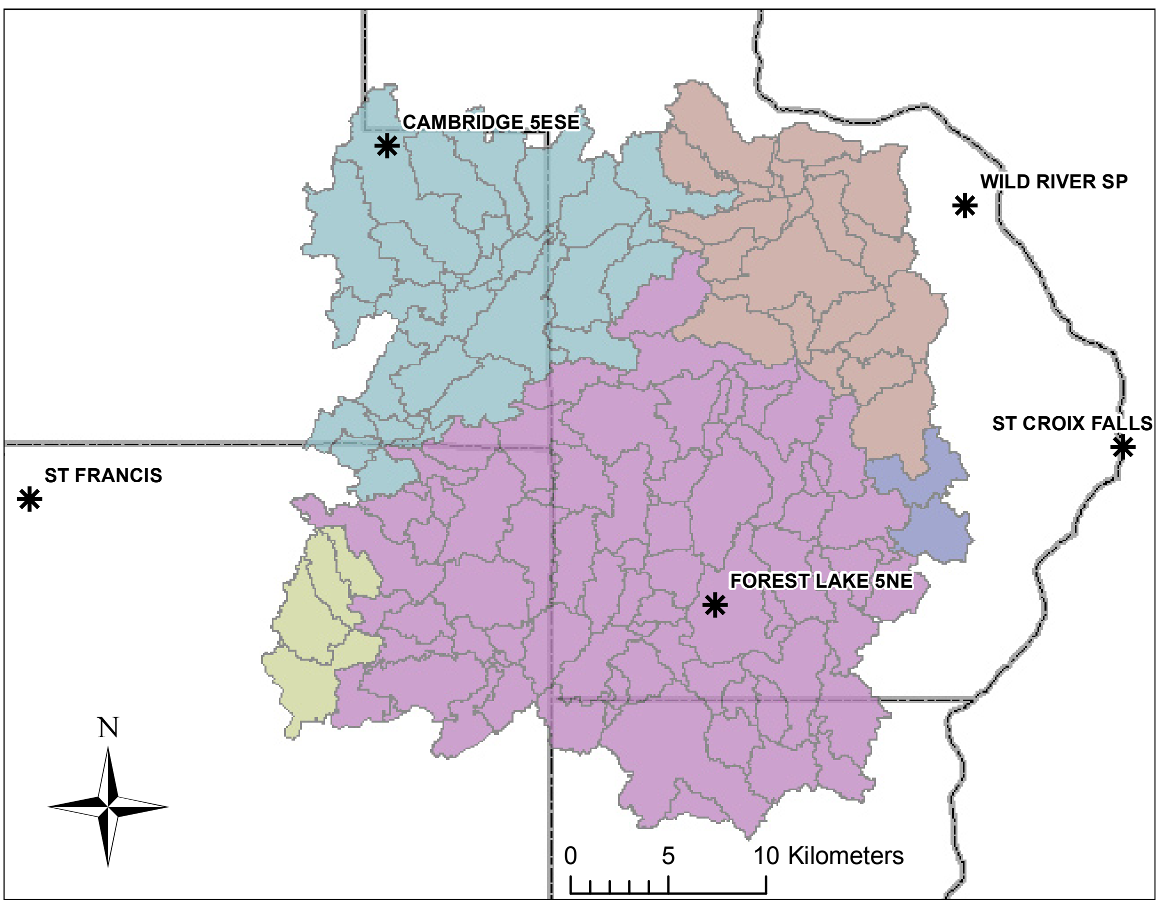


Figure 7. Assignment of subbasins to weather stations in the SWAT model of the Sunrise River watershed.

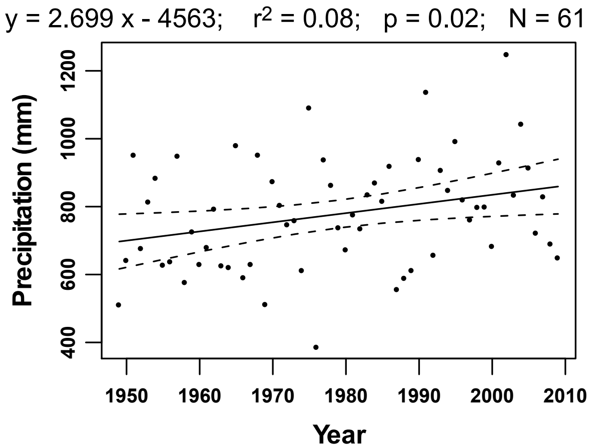


Figure 8. Trend in average annual precipitation for the five weather stations included in the SWAT model, 1948-2009.

climate data is a task needed by nearly all SWAT models, the scripts to help with this process would be useful to other modelers and have been posted on the Science Museum of Minnesota's TAPwaters website (www.smm.org/scwrs/tapwaters/).

We note here that SWAT had difficulty in handling large daily precipitation values. Once precipitation exceeds about 50-80 mm (2-3 inches), runoff appears to be overestimated in the model. When precipitation was censored to include daily values of only 50 mm or less, fits of model output to hydrograph data were significantly improved during the calibration procedure.

Initial Model Construction

With the above discussed data sets, two models of the Sunrise watershed were finally constructed for interim use. Both versions used the 142-subbasin delineation to appropriately capture lake and monitoring point configurations. A low resolution version, with only 289 HRUs, was constructed to provide a model that would run in a matter of seconds, in order to facilitate initial model calibration. A high resolution version with 1643 HRUs was also constructed and configured, to allow more complete representation of land cover and management practices. The high-resolution model was the principal product of this study.

Model Calibration and Validation

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. Flow itself is the critical variable to calibrate, because flow is both the agent of action (by physical erosion and dissolution) and the mechanism of transport for all nonpoint pollutants. Consequently calibration begins with flow; once flow is calibrated, then sediment loads are calibrated. Once sediment is calibrated, then phosphorus, much of which may be adsorbed to particulates, may in turn be calibrated. We followed that general sequence for the Sunrise SWAT model. For multiple sites, we began with an approximate calibration of the low-resolution model for the main station near the mouth of the watershed to get the big picture about right. Then we used calibrated the high-resolution model, moving from upstream to downstream sites where appropriate.

Goodness of Fit Measure

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 1972):

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

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 considered an E_{NS} of 0.5 or greater to indicate 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.

Crop Yields

Annual yields of corn grain, corn silage, soybeans, and alfalfa were obtained for the period 2000 through 2008 for Chisago County, MN (NASS 2009) and presumed to be representative of those in the Sunrise 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.

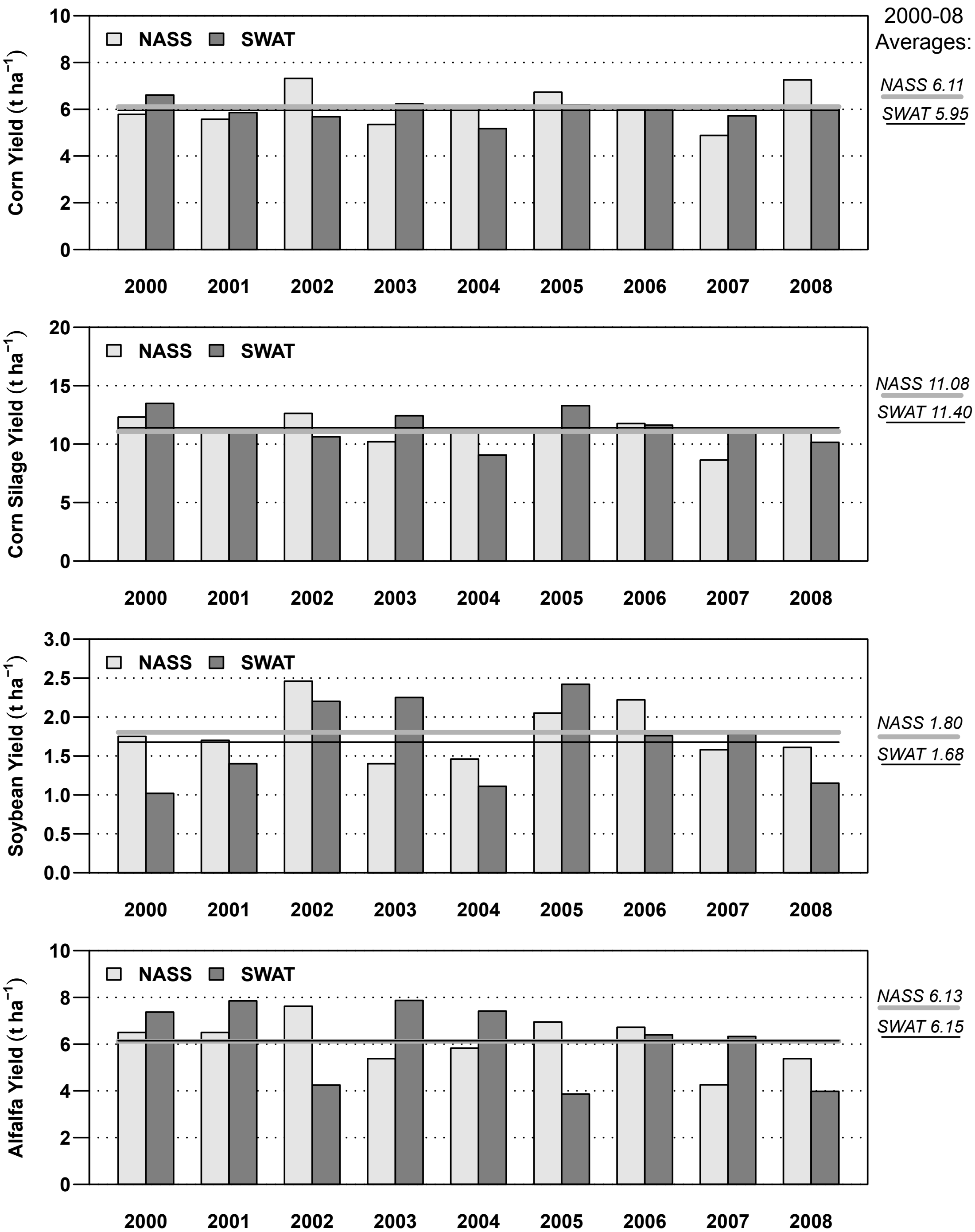
Crop productivity in SWAT was adjusted so that nine-year (2000-08) average annual yields from SWAT matched those reported by NASS to within a few percent (horizontal lines, Figure 9). While over nine years these average values were simulated accurately, the crop yield in any one year could be off by 20-30%, especially for soybeans and alfalfa (bars, Figure 9). Corn-grain and corn-silage yields were simply less variable. Annual crop yields were fit in SWAT principally by adjusting the BIO_E parameter, which controls the amount of biomass produced per unit solar radiation received.

Hydrology

Streamflow data at several points in the Sunrise watershed were collected at times by various agencies from 1998 through 2009 (Figure 1 and Table 2). Daily mean flows near the outlets of many St. Croix tributaries, including the main stem Sunrise River at Sunrise, were reported for water year 1999 by Lenz et al. (2003), in a cooperative study between federal agencies (USGS and NPS) and state agencies (WDNR, MPCA, and MDNR). Though it spans only one year, this data set remains one of the most important benchmarks for model calibration because it includes a full year, and not just the open-water season. In addition, data collection methods were fairly uniform among sites.

Since that study, state and local agencies have continued flow monitoring at selected sites during the ice-free seasons. Daily mean flows were available for 2006-08 for the main stem (G. Flom, MDNR, unpublished digital data, 2009), and for 2005-08 for the North Branch at hwy 95 (C. Klucas, MPCA, and C. Thiel, Chisago SWCD, unpublished digital data). In addition, flows were available for parts of 2008-09 at four other sites: Sunrise at hwy 14, Sunrise at Comfort Lake, West Branch Sunrise at Lyons, and South Branch Sunrise at hwy 30 (E. Stefanik, USACE, unpublished digital data, 2009; site names are here consistent with USACE working files; see Table 2).

The calibration procedure for stream flow in the Sunrise watershed began with an approximate calibration for the principal site near the watershed outlet, the main stem of the Sunrise River at the village of Sunrise. This initial calibration set the whole-basin context within which the other five sites were eventually calibrated. Subwatersheds were then calibrated from upstream to downstream, ending with a final (small) adjustment of parameters at the starting point, the main stem site at Sunrise. Only the final parameter sets are given for each of the subwatersheds (see Appendix Table B1).



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 9. Crop yields in the SWAT model compared to NASS-reported yields in Chisago County, 2000-08.

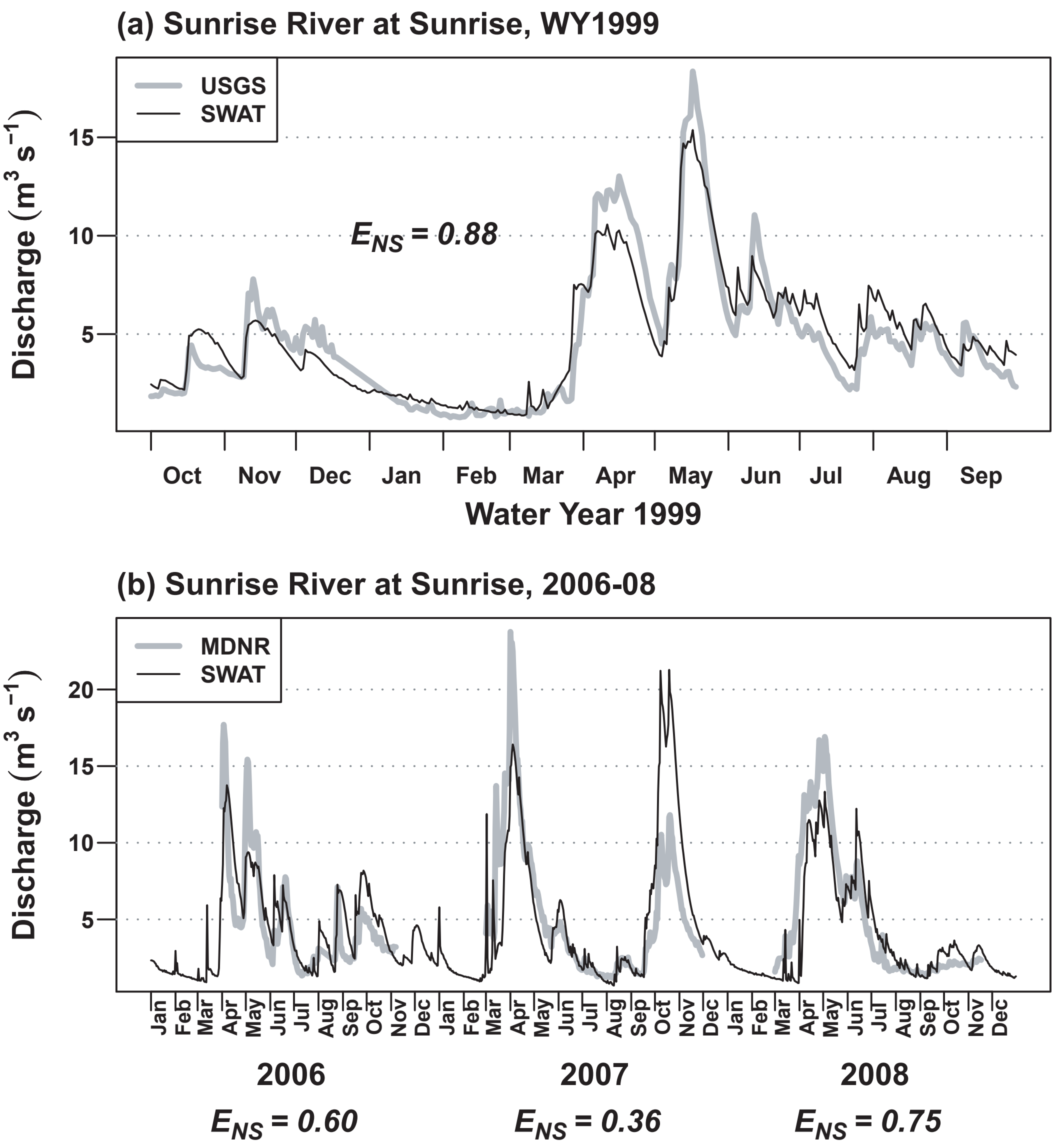


Figure 10. Modeled versus measured daily mean discharge of the Sunrise River at Sunrise, MN, for water year 1999 and calendar years 2006-08.

Sunrise River at Sunrise

The model simulated daily mean flow during water year 1999 with excellent accuracy, resulting in a Nash-Sutcliffe Coefficient of Efficiency (E_{NS}) of 0.88 (Figure 10a). The principal parameter changes to achieve this fit included curve numbers (CN2 and CNOP), groundwater parameters (GW_DELAY and RCHRG_DP), days to reach reservoir target volume (NDTARGR), and snowmelt parameters (SFTMP and SMTMP, among others). Curve numbers were reduced by 75% uniformly across the watershed to promote infiltration rather than overland flow, thereby increasing baseflow at the expense of stormflow. Default curve numbers in SWAT were determined from plot-scale studies which do not account for increased opportunity for infiltration in real-world landscapes, where depressions and flow barriers may trap or otherwise limit overland flow. Groundwater delay (GW_DELAY), conceptually the time between infiltration and groundwater recharge (i.e., the time of travel through the vadose zone), was set to 15 days to provide a seasonal signal to baseflow. Days for reservoirs to reach target volume (NDTARGR) was set to 2 days for all reservoirs to start with, to fit the general shape of hydrograph peaks. Once the amount and seasonality of baseflow was adjusted, and the shape of hydrograph peaks was reproduced, then overall water balance was adjusted using the RCHRG_DP parameter to carry away any excess water. The final value for RCHRG_DP was 0.35 for much of the watershed, which means that 35% of infiltrated water is lost to a deep aquifer whose discharge is not the Sunrise, presumably here the St. Croix. Because of the depth and proximity of the St. Croix River relative to the Sunrise watershed, such a large loss of infiltrated water is conceivable. However, we are skeptical of this large value and suspect that the water balance in SWAT may be incorrect elsewhere; namely, it is possible that modeled evapotranspiration is too low. Snowfall and snowmelt parameters were adjusted to allow some melting over winter and early in the spring; otherwise, spring snowmelt volumes peaked at values much higher than observed.

For validation, model output was compared to flows in 2006-08 (Figure 10b). As can be seen, some seasonal flow peaks are underestimated and some are overestimated. This was a reasonable compromise, and the resulting E_{NS} values were 0.60, 0.36, and 0.75 for the years 2006-08.

North Branch Sunrise River at Hwy 95

The flow calibration (2005-06) and validation (2007-08) periods for the North Branch Sunrise River (Figure 11a and 11b) likewise were well-simulated by the model. The model fit coefficients (E_{NS}) were 0.45, 0.72, 0.69, and 0.62 for the years 2005-08. The North Branch sub-watershed had no reservoirs (on-channel lakes), and so hydrograph shape was a more direct result of overland runoff and baseflow processes. Consequently, effects of altering snowmelt parameters could be seen more easily in the North Branch than in other subwatersheds. The water balance of the North Branch subwatershed was such that the model required no loss of groundwater to a deep aquifer, as was required over the rest of the Sunrise watershed. Such differences in losses to deeper aquifers should be expected among different subwatersheds.

Sunrise River at Hwy 14 and West Branch at Lyons

The monitoring station at hwy 14 on the Sunrise River is important because it includes flow from the entire upper watershed, which comprises the Chisago Lake Improvement District, the Comfort Lake-Forest Lake Watershed District, Carlos Avery Wildlife Management Area, and another region of lakes and wetlands further to the west and south. (A station on the Sunrise at hwy 95 would serve a similar function.) This station allows the influence of the upper watershed to be distinguished from that of the lower watershed and North Branch. The monitoring station on the West Branch Sunrise River at Lyons captures the inputs from the west, to allow distinction between those and inputs from the lake districts and associated urban areas.

Calibration of the flows of the West Branch Sunrise River at Lyons (Figure 12b) went

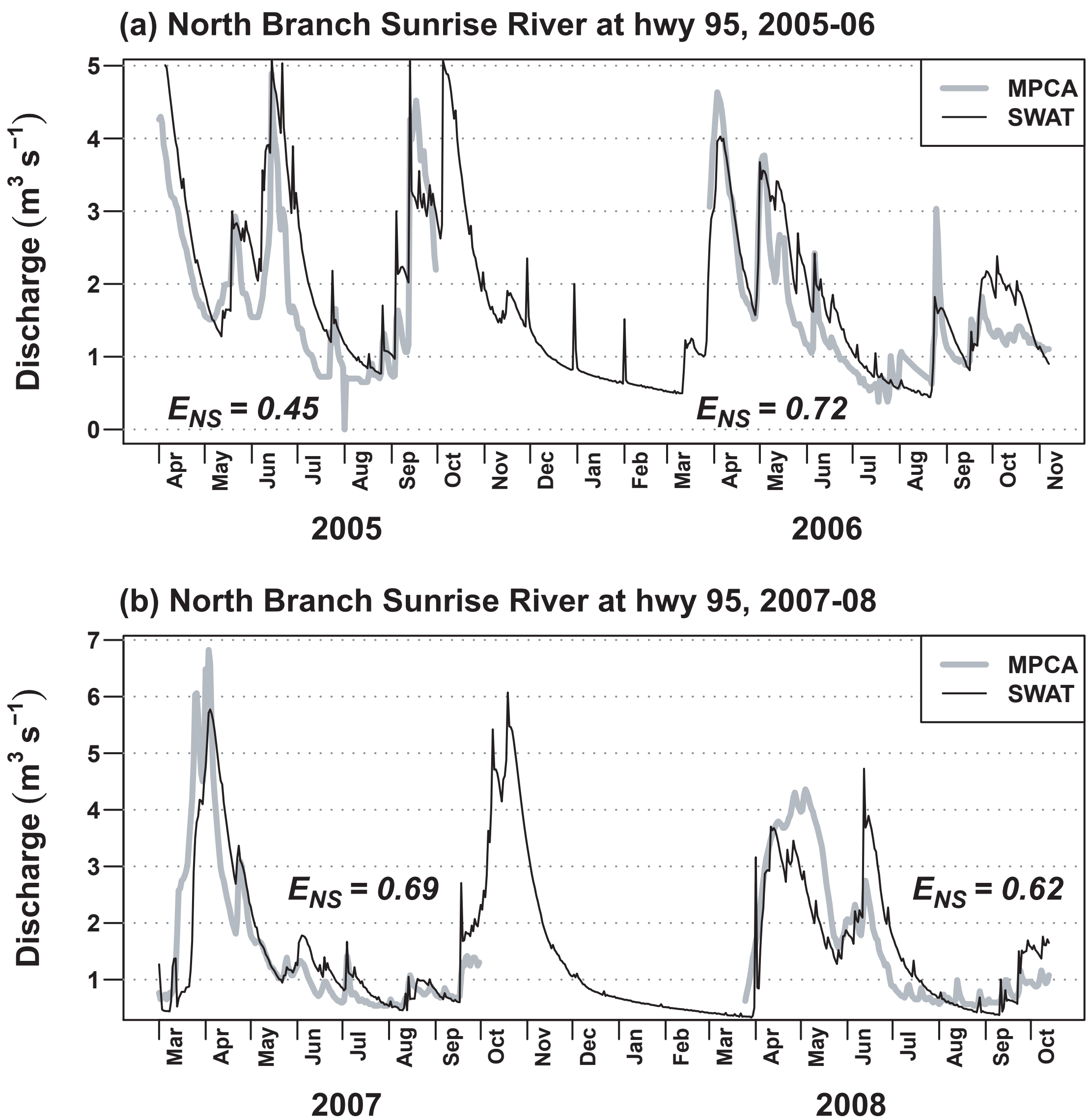


Figure 11. Modeled versus measured daily mean discharge of the North Branch Sunrise River at highway 95 for parts of 2005-06 and 2007-08.

reasonably well, with a very high E_{NS} of 0.85, though this is only for part of 2009. The largest changes from the basin as a whole were that the GW_DELAY parameter was set to 100 days (rather than 15), to smooth baseflow annually, and the reservoir NDTARGR parameter was set to 10 days (rather than 2), to smooth outflow from on-channel lakes.

Calibration of flows at the hwy 14 site (Figure 12a) did not go as well. Flows were overestimated during 2008 and underestimated during 2009, although the monitoring data for 2008 were fairly limited. The calibration data set was nearly identical as for the Lyons site; here, GW_DELAY was set to 90 days rather than 100, but still much more than the 15 days set for most of the rest of the basin.

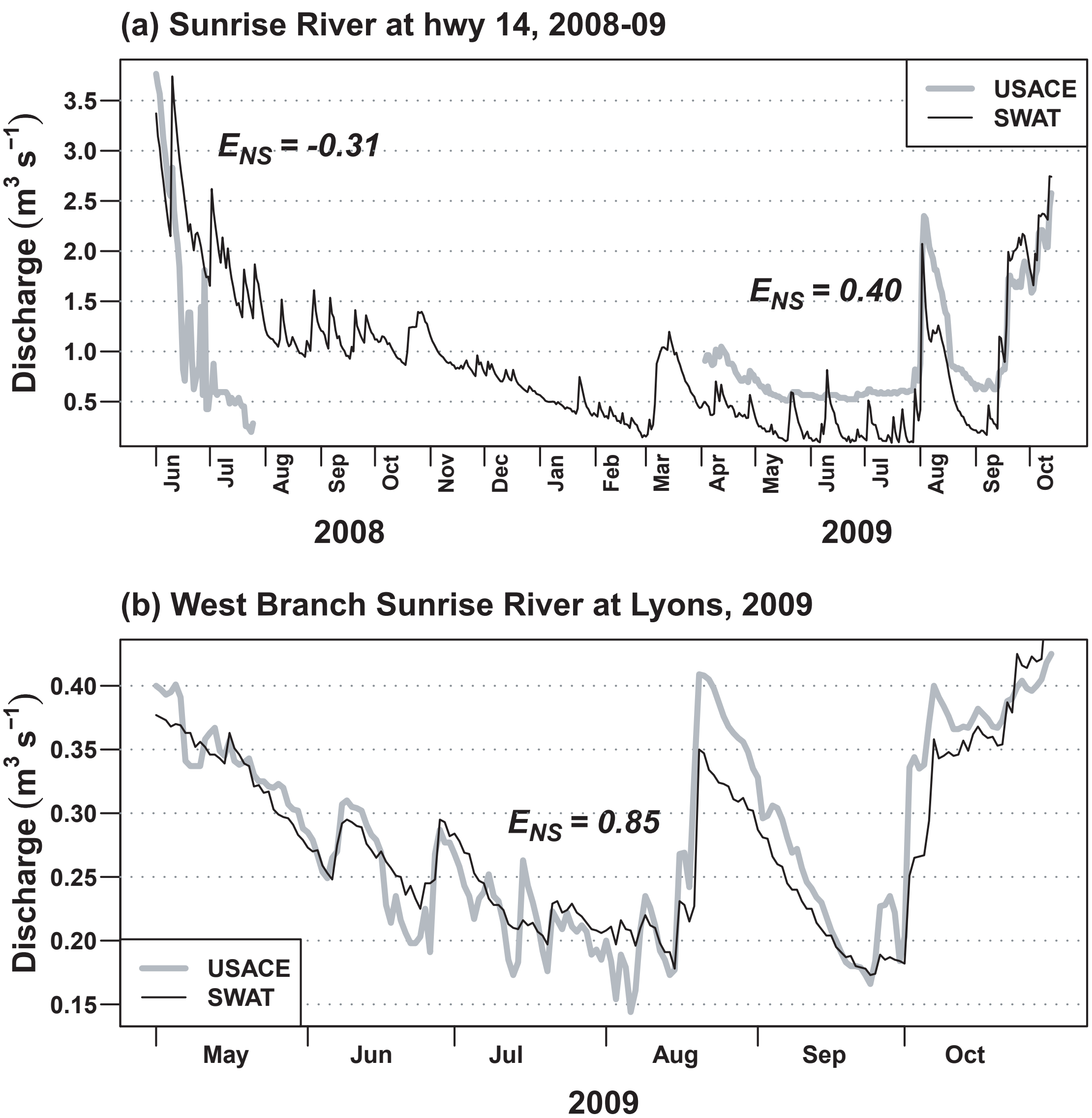


Figure 12. Modeled versus measured daily mean discharge of the Sunrise River at highway 14 and the West Branch Sunrise River at Lyons station, for parts of 2008-09.

South Branch at Hwy 30 and Sunrise River at Comfort Lake

These two sites capture flow from the uppermost regions of the watershed. The model simulated flow reasonably during some times, e.g., during 2009 at hwy 30 and during 2008 at the Comfort Lake outlet (Figure 13a and b). At other times, when the flow data were more fragmentary, model performance was difficult to assess. Some pond and wetland parameters were adjusted in attempting to fit modeled Comfort Lake outflow to the data; it may have been better to keep such parameters consistent with the rest of the basin rather than to try to fit data that may be too fragmentary. Outflow from a lake that drops below its threshold is somewhat problematic; in trying to model small flow values, large percentage errors must be expected.

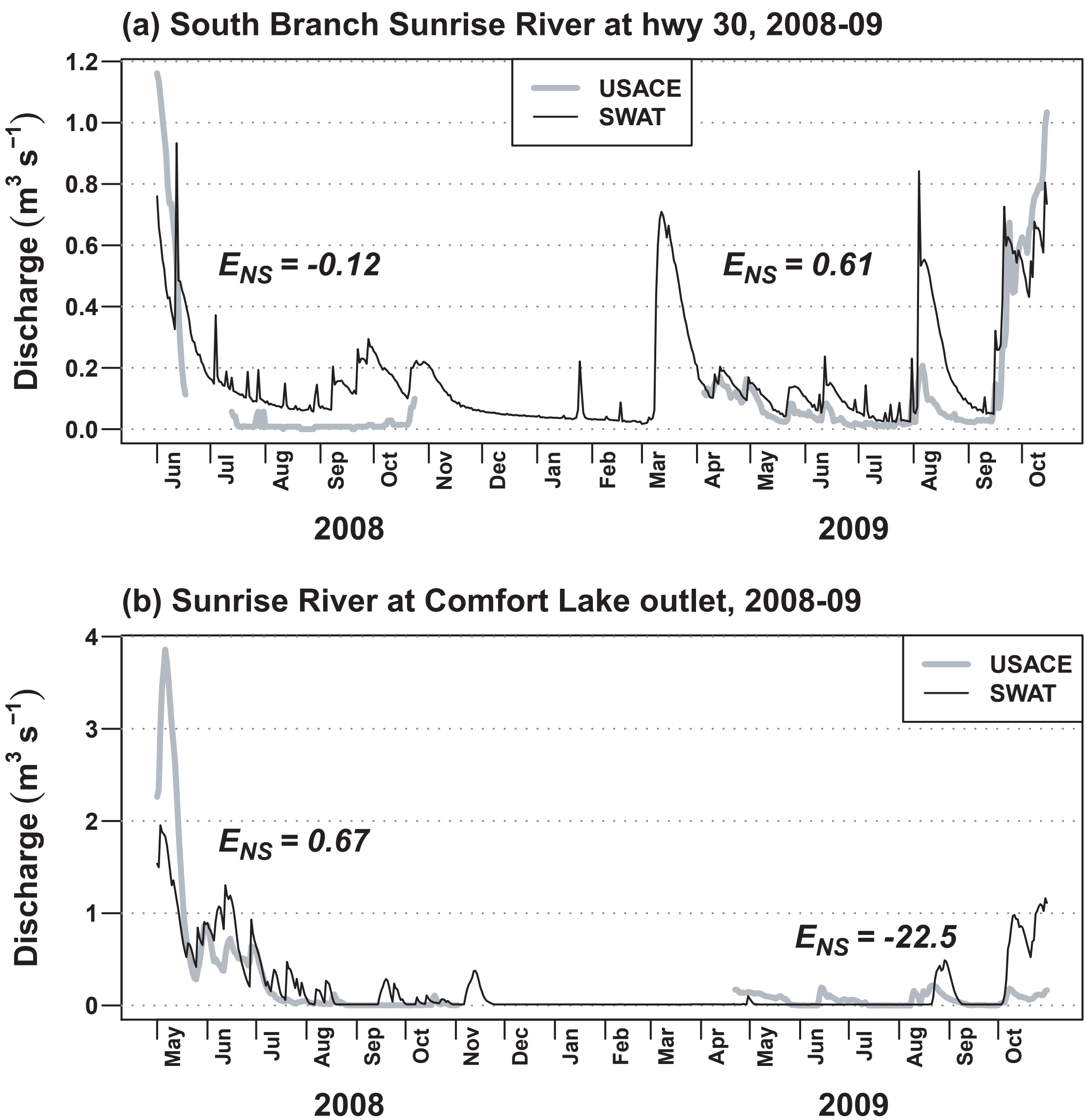


Figure 13. Modeled versus measured daily mean discharge of the South Branch Sunrise River at highway 30 and the Sunrise River at Comfort Lake, for parts of 2008-09.

Sediment

Sediment Load Data

Sediment calibration for any watershed with many lakes and wetlands is problematic because of all the possible sediment traps between uplands and the watershed outlet. The Sunrise watershed offers a prime example of such complications. As it was for flow, the principal data set for sediment load calibration was for water year (WY) 1999 and reported by the USGS in Lenz et al. (2003). Although only average annual data were summarized in that report, monthly values were made available for this study (B. Lenz, D. Robertson, H. Garn, and D. Hanson, USGS, WI and MN Districts, electronic communications, 2005-07). In addition to WY1999, annual loads for the same station were calculated for 2006-08 (C. Thiel, Chisago SWCD, electronic communication, 2009). If these data from near the watershed outlet were all that was available, then predicting sediment transport in the rest of the watershed would be fairly uncertain.

Fortunately, further data were available, specifically annual load data for the North Branch for 2006-07 (C. Thiel, Chisago SWCD, electronic communication, 2009) and for the Sunrise at hwy 14 for part of 2008-09, below most major impoundments (E. Stefanik and W. James, USACE, electronic communication, 2009). The North Branch data were particularly important, because there were no major impoundments to confound the sediment transport downstream. The calculated loads at the hwy 14 station were important to confirm that the upper watershed contributes very little sediment, because of all the lakes and wetlands. In addition, the USACE had similar load estimates for the upper watershed stations at Lyons, hwy 30, and Comfort Lake. We considered only the mineral matter measured at the USACE stations, to avoid loads due to algal production in the lakes.

From these calculated loads, at these six sites, we inferred loads during unmeasured periods, to create as complete an estimate of sediment loads as possible for comparison with model results (Table 15). In Table 15, only the few cells that are shaded are actually supported by

Table 15. Total suspended solids (TSS) loads in the Sunrise River watershed, 1999 and 2006-09. Data supported by some measurements are shaded; all other values inferred by ratio or difference.

	Total Suspended Solids (TSS, mineral)			
	WY 1999		Averages, 2006-09	
Station	**(met T)**	**(%)**	**(met T)**	**(%)**
Upper Watershed				
Comfort Lake outlet	22	*1%*	13	*1%*
South branch at hwy 30	57	*2%*	30	*2%*
West branch at Lyons	305	*8%*	169	*8%*
All flow from upper watershed passes through main stem site at hwy 14, below				
Lower Watershed				
Main stem at hwy 14	164	*4%*	89	*4%*
North Branch at hwy 95	986	*27%*	527	*27%*
Lower watershed (remainder)	2539	*69%*	1392	*69%*
Main stem at Sunrise (total)	3689	*100%*	2008	*100%*
	(C.I. for 1999: 139 - 7,269)			

NOTES:
Abbreviations: TSS, total suspended solids; WY, water year; met T, metric ton; C.I., 95% confidence interval; hwy, highway.
Original data sources: U.S. Geological Survey, for WY1999 loads at main-stem Sunrise station; Chisago County Soil and Water Conservation District, for CY2006-08 annual loads at North Branch and main-stem Sunrise station; and U.S. Army Corps of Engineers, for partial CY2008-09 loads at upper watershed and hwy 14 stations. All other values summarized here were inferred by assuming that percentage loads at each site were representative for times when data were lacking from that site.

data collected during that tine. The several years with overlapping data from all six sites allowed us to calculate the percentage of sediment load attributable to each site. We then applied these same percentages to the data from WY1999 to estimate loads at these sites during that year. We recognize possible significant errors in such a method and therefore relied principally on the measured, rather than the inferred, data.

This data set (Table 15) provided critical context for understanding sediment transport in the Sunrise watershed. First, total sediment load was fairly variable from year to year, as it was nearly 3700 metric tons in WY1999 but averaged only about 2000 metric tons during 2006-08. Second, only 4% of the sediment load came from the upper watershed, i.e., measured at the hwy 14 station. However, note that the three upper watershed sites tallied sediment loads amounting to 11% of the total -- which meant that the 7% difference was trapped between these stations and the hwy 14 station. Hence, the part of the watershed between these three stations and the hwy 14 station -- which broadly comprises the Carlos Avery WMA -- was a net sediment sink, and not a source. Third, the North Branch contributed about 27% of the total sediment load (30% in 2006 and 24% in 2007). Fourth, the remaining part of the lower watershed, below the North Branch and hwy 14 stations and above the Sunrise station, therefore delivered nearly 70% of the sediment load, yet its subwatershed area is not much different from that of the North Branch.

The large sediment contribution from the lower watershed demanded explanation: was it from land uses that destabilized soil on steep slopes, or was it from a different source, such as channel erosion? Model calibration helped answer this question.

Sediment Load Calibration

We began sediment-load calibration with data from the North Branch, because it was unencumbered by significant trapping by in-channel lakes. Without invoking any channel erosion, we could reasonably fit sediment loads, though the fit to monthly WY1999 loads was not very good (these estimated monthly loads were calculated as a simple 27% of the monthly loads measured at the outlet, so significant errors in these monthly target loads were possible). However, when we applied the resulting landscape-erosion parameters to the rest of the watershed (essentially a sediment delivery ratio applied to cropland), erosion from the lower watershed was insufficient to match the 70% of the total demonstrated by the loading data. Hence we inferred that land use, and erosion from the landscape surface, was not the source of the large sediment load from the lower watershed. Channel erosion was the next possible source to test.

Consequently we allowed channel erosion in the North Branch by setting the channel erodibility factor (CH_EROD) to 0.001, its lowest possible value in the model. That produced too much sediment, so the amount of channel erosion was reduced by lowering the channel cover parameter (CH_COV) from 1 to 0.6. In this configuration, the goodness of fit parameter, E_{NS}, reached 0.67 for seasonal sediment loads in the North Branch for WY1999 (Figure 14a), and 0.54 for annual loads from 1999 to 2009 (Figure 14b). During the five study years (1999 and 2006-09), the percent of the sediment load in the North Branch from channel erosion ranged from

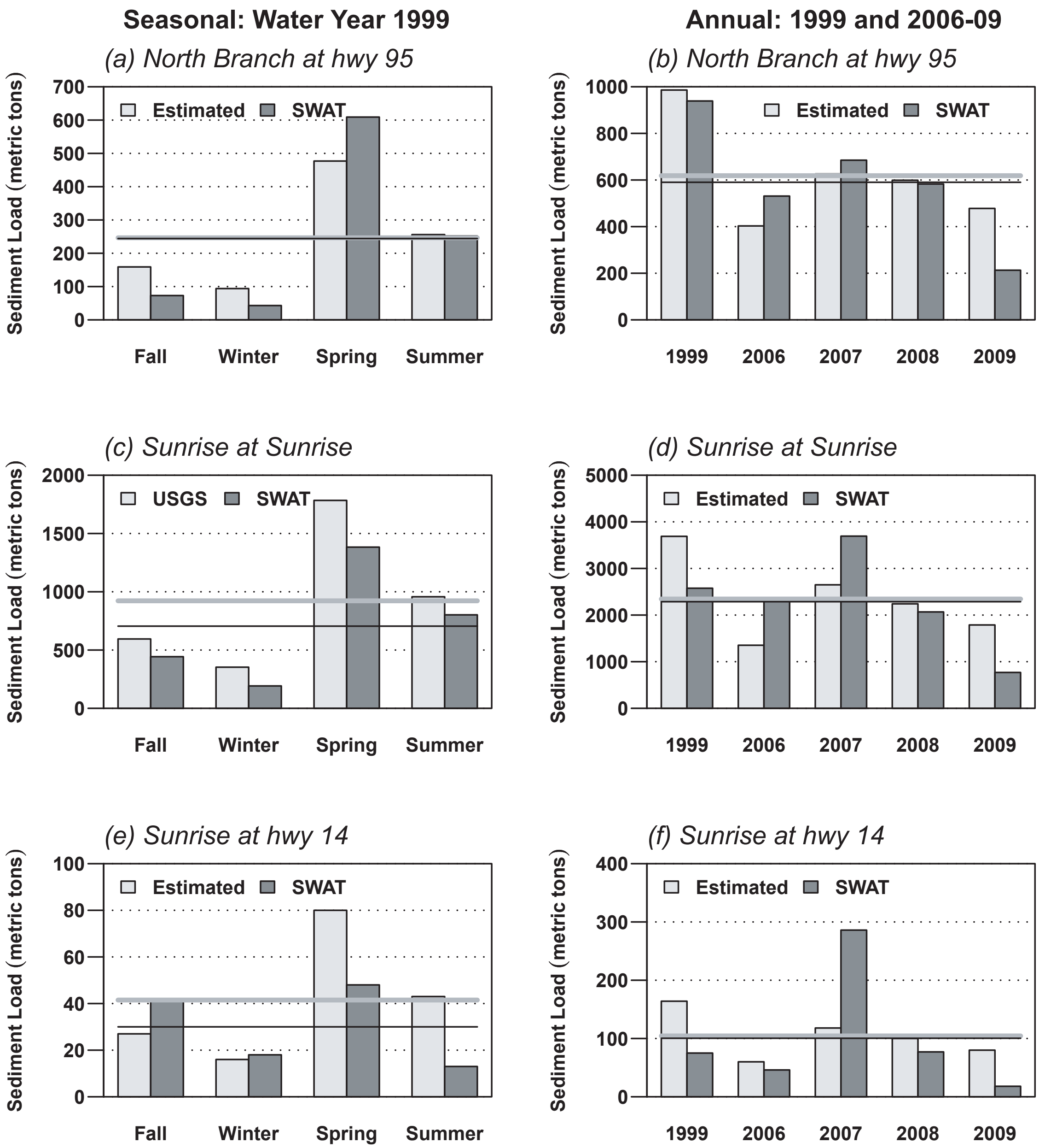


Figure 14. Modeled versus estimated loads of suspended sediment for the North Branch at highway 95, the Sunrise River at Sunrise, and the Sunrise River at highway 14. Seasonal loads shown for water year 1999, and annual loads shown for calendar years 1999 and 2006-09.

47% to 68% and averaged 60%. The average sediment loads (horizontal lines, Figures 14a and b) were very similar for monitored data and modeled output, for both WY1999 and the five-year annual average loads from 1999 and 2006-09.

We next looked at annual sediment loads at hwy 14 (Figure 14e and f), which were small compared to the North Branch or Sunrise sites. The model did a reasonable job of simulating the monitoring data, though because absolute quantities are small the relative errors appear larger than for other sites. The most important point is that the model could reproduce the annual average sediment load of about 100 metric tons (Figure 14f). Sediment loads at the hwy 14 station were calibrated by adjusting the channel cover parameter (CH_COV) from 0.6, as it was for the North Branch, down to 0.08, while leaving the CH_EROD factor at a constant 0.001. This means that channel erosion in the upper watershed could be about one-seventh that in the North Branch watershed. Because of lower slopes, a lower rate of channel erosion in the upper watershed would not be surprising. However, we note that we could have also achieved calibration by manipulating the sedimentation rates in the reservoirs (on-channel lakes). However, we chose to leave the reservoir NSEDR factors as calculated by the equation presented earlier (dependent on mean depth), and to see if channel erosion could be the critical factor. The conclusion was simply that channel erosion was a larger factor in the North Branch watershed than in the upper watershed.

Given these calibrations for the North Branch and upper subwatersheds, how much channel erosion was necessary to achieve calibration in the lower watershed? For the lower watershed, the CH_COV factor was set at 1 (its full value; see Appendix Table B1), about 1.7 times larger than in the North Branch and more than 10 times larger than in the upper watershed. Greater channel erosion in the lower watershed may be a result of steeper slopes, perhaps resulting from adjustment during postglacial times, as the Sunrise has incised in response to the low base level set by the more deeply incised St. Croix River. Annual average sediment loads over the five years with data (1999 and 2006-09, Figure 14d) were reproduced well in aggregate by the model, though there could be significant error in any one year. Loads during WY1999 (Figure 14c) matched the seasonal pattern, though the annual total was underestimated. Given this configuration, the percent of sediment load in the Sunrise from channel erosion during the five data years (1999 and 2006-09) ranged from 74% to 85% and averaged 77%. Alternate model calibration assumptions that delivered more eroded soil from the landscape surface could reduce the estimate of channel erosion to about 40% of the total sediment load. However these alternate model runs produced more variable sediment output loads that did not match the estimated seasonal and annual loads very well for either the North Branch or main stem at Sunrise. In any case, we concluded that channel erosion was a substantial contributor of sediment to the Sunrise River, and probably the dominant contributor in the lower watershed.

Phosphorus

Phosphorus Load Data

Just as for sediment, calibration of phosphorus loads is problematic for watersheds like the Sunrise, with its many lakes and wetlands. Again, the principal calibration data set was provided by the USGS for the main stem station at Sunrise for WY1999, with annual values reported in Lenz et al. (2003) and with monthly loads provided by USGS personnel (B. Lenz, D. Robertson, H. Garn, and D. Hanson, USGS, WI and MN Districts, electronic communications, 2005-07). Annual loads were also available at the same site for 2006-08 (C. Thiel, Chisago SWCD, electronic communication, 2009). As for other sites, annual phosphorus loads were also estimated for the North Branch for 2006-07 (C. Thiel, Chisago SWCD, electronic communication, 2009) and for the hwy 14, hwy 30, Lyons, and Comfort Lake sites for parts of 2008-09 (E. Stefanik and W. James, USACE, electronic communication, 2009).

These data sets, plus knowledge of point-source inputs from wastewater treatment plants, provided critical context for understanding phosphorus loading and transport within the Sunrise watershed (Table 16). Many of these conclusions were similar to those drawn regarding sediment loading. First, annual variability was significant, with the load from WY1999 being substantially larger than those during 2006-09. Second, point-source loads have been substantially reduced, from 49% of the total load in WY1999 to only 13% during 2006-09. Third, nonpoint loads from the upper watershed (see hwy 14, Table 16) amounted to 10% of the total, yet summed to 15% for the three upper watershed sites. As for sediment, the subwatershed between the three upper sites and the hwy 14 site -- much of which is in Carlos Avery WMA -- was a net phosphorus sink, and not a source. Fourth, the North Branch provided a tiny fraction of the point-source load during 2006-09, down from 20% in WY1999 to about 1% currently. The overall contribution of phosphorus by the North Branch was about 33% of the total during 2006-09, somewhat more than its sediment contribution but in the same range. Fifth, as with sediment, the lower watershed was where most nonpoint-source phosphorus occurred, accounting for 44% of the total phosphorus leaving the Sunrise watershed (Table 16).

What was the source of this phosphorus? Was it from land use practices in the lower watershed, different from those elsewhere? Or was it a consequence of the inferred channel erosion in the lower watershed?

Phosphorus Load Calibration

Phosphorus calibration proceeded similarly to that for sediment. We began with data from the North Branch, because loads there were not obfuscated by reservoir processes. Because sediment loads from runoff were somewhat limited, so too were phosphorus loads. Modeled phosphorus loads from uplands plus point sources could account for only about 30% of the estimated load in the North Branch watershed. However, because of large groundwater contributions to streamflow in the watershed, a tiny concentration of phosphorus in groundwater

Table 16. Total phosphorus (TP) loads in the Sunrise River watershed, 1999 and 2006-09. Data supported by some measurements are shaded; all other values inferred by ratio or difference.

	Total Phosphorus (TP)			
	WY 1999		Averages, 2006-09	
Station	**(kg)**	***(%)***	**(kg)**	***(%)***
Upper Watershed				
Comfort Lake outlet	182	*1%*	146	*1%*
South branch at hwy 30	590	*3%*	440	*3%*
West branch at Lyons	1914	*11%*	1473	*11%*
All flow from upper watershed passes through main stem site at hwy 14, below				
Lower Watershed				
Main stem at hwy 14	6294	*36%*	3157	*23%*
North Branch at hwy 95	6802	*39%*	4392	*33%*
Lower watershed (remainder)	4441	*25%*	5942	*43%*
Main stem at Sunrise (total)	17537	*100%*	13491	*100%*
(C.I. for 1999: 13,049 - 22,025)				
Of the Total Phosphorus reaching Sunrise station:				
Point-Source TP Loads				
Chisago Lakes	5148	*29%*	1766	*12%*
Linwood Terrace	6	*0%*	8	*0%*
North Branch	3484	*20%*	132	*1%*
Total	*8638*	*49%*	*1906*	*13%*
Nonpoint-Source TP Loads				
Main stem at hwy 14	1140	*7%*	1383	*10%*
North Branch at hwy 95	3318	*19%*	4260	*32%*
Lower watershed	4441	*25%*	5942	*44%*
Total	*8899*	*51%*	*11585*	*86%*

NOTES:
Abbreviations: TP, total phosphorus; WY, water year; kg, kilogram; C.I., 95% confidence interval; hwy, highway.
Original data sources: U.S. Geological Survey, for WY1999 loads at main-stem Sunrise station; Chisago County Soil and Water Conservation District, for CY2006-08 annual loads at North Branch and main-stem Sunrise station; and U.S. Army Corps of Engineers, for partial CY2008-09 loads at upper watershed and hwy 14 stations; Minnesota Pollution Control Agency for point-source data. All other values summarized here were inferred by assuming that percentage loads at each site were representative for times when data were lacking from that site.

could account for all of the missing phosphorus. That is, the North Branch subwatershed required only a 0.0008 mg/L (or 0.8 ug/L) concentration of phosphorus in groundwater to achieve calibration. In general, phosphorus concentrations in groundwater tend to be very small, but values of 0.01 to 0.02 mg/L have routinely been found in groundwater beneath agricultural and urban settings (Nolan and Stoner, 2000). The resulting configuration matched the annual loads in the North Branch for 1999 and 2006-09 very well (Figure 15b). The seasonal pattern of phosphorus loading was also matched reasonably well for WY1999 (Figure 15a).

We followed a similar line of reasoning for the upper watershed (above the hwy 14 station), where we also adjusted groundwater-phosphorus concentrations to achieve calibration (Figure 15e and f). The fit for annual totals for 1999 and 2006-09 was quite good, though this was somewhat forced by the point-source input from the upstream Chisago Lakes WWTP. That is, the good fit implied that the model properly inputted known point sources, but provided only limited information about nonpoint sources. The required groundwater phosphorus concentration in the upper watershed was even lower than for the North Branch, only 0.0003 mg/L.

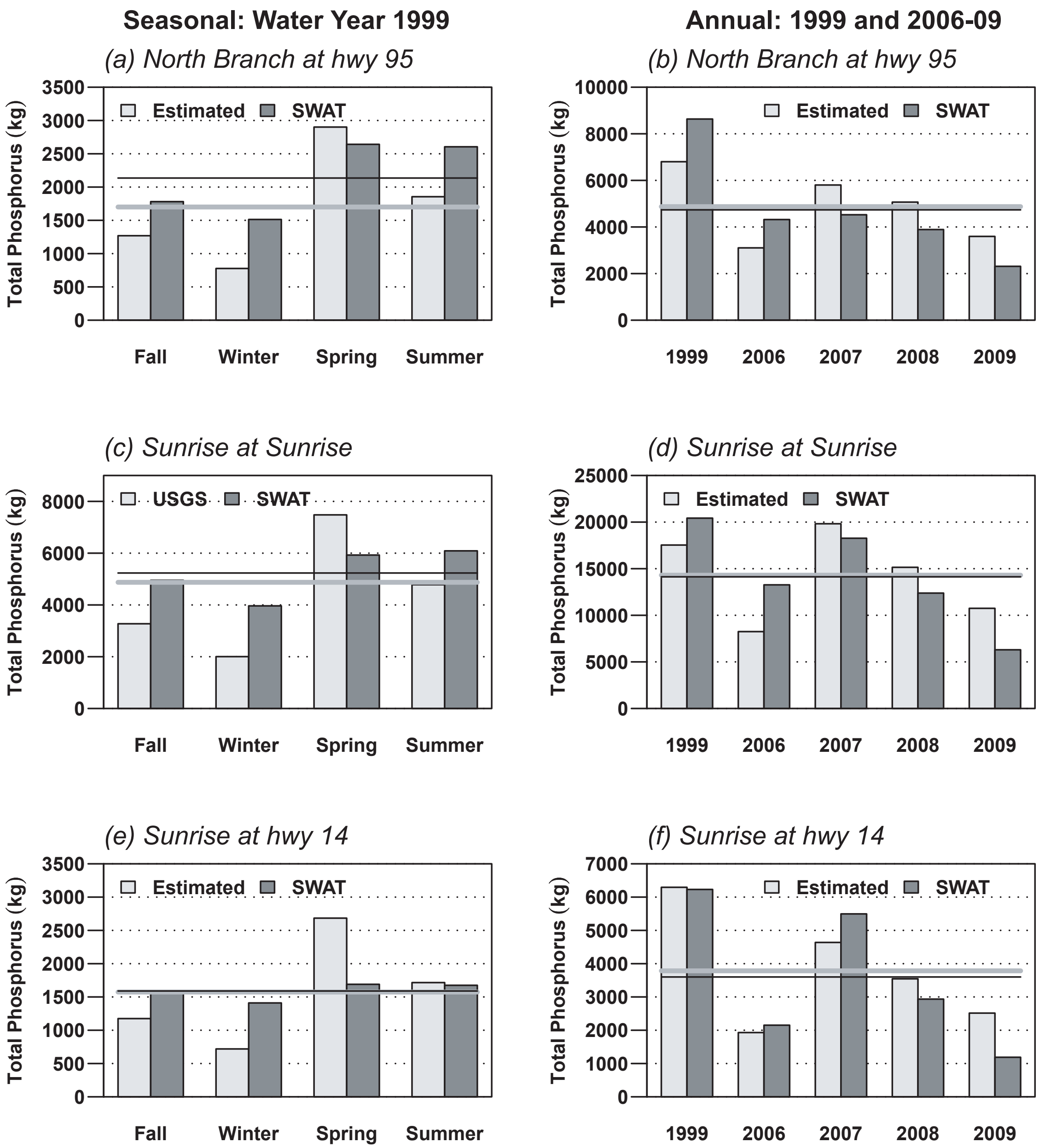


Figure 15. Modeled versus estimated loads of total phosphorus for the North Branch at highway 95, the Sunrise River at Sunrise, and the Sunrise River at highway 14. Seasonal loads shown for water year 1999, and annual loads shown for calendar years 1999 and 2006-09.

Once the North Branch and upper watersheds were parameterized, the phosphorus contribution from the lower watershed could be investigated. First, given the same agricultural parameters as for the North Branch, landscape runoff alone was an insufficient source of phosphorus, accounting for only 36% of the estimated total load. Again, groundwater phosphorus concentrations were manipulated to achieve calibration, resulting in an inferred concentration of 0.012 mg/L, very much in line with values given in Nolan and Stoner (2000). While this concentration is relatively low by most standards, it is more than ten times greater than what was required in the North Branch and upper watersheds. The resulting model output matched the average annual total phosphorus loads from 1999 and 2006-09 (horizontal lines, Figure 15d) quite well.

One may ask whether the eroded channel sediment in the North Branch and lower watersheds was a significant contributor of phosphorus, in addition to (or perhaps instead of) the groundwater contributions inferred by the model. Three stream bed and bank samples from Hay Creek (a tributary to the Sunrise in the lower watershed) had an average sediment total phosphorus (sed-TP) of 289 mg/kg (Corby Lewis, USACE, electronic communication, 2010). If all the eroded channel sediment had this sed-TP concentration, it would have accounted for only about 2% of the total phosphorus load in the North Branch and about 4% in the main stem at Sunrise, leaving groundwater to account for 68% and 60% of the loads in the North Branch and main-stem Sunrise, respectively. So, the contribution of phosphorus from eroded channel sediment was apparently small compared to other sources.

We note incidentally that a fourth sediment sample was of black, fine-grained material interpreted to be derived from soil erosion from nearby fields; this sample had a large sed-TP concentration of 3110 mg/kg (Corby Lewis, USACE, electronic communication, 2010). The SWAT model estimated similarly large sed-TP values from upland soil erosion (not bank sediments): 1660 mg/kg in the North Branch and 2040 in the main-stem Sunrise. Model results for sed-TP were, therefore, relatively consistent with the available field data for both bank and field sediments.

Final Parameter Set

The final parameter set of the calibrated Sunrise River watershed model is given in Appendix Table B1. With a few exceptions, only those parameters with values changed from default during the configuration or calibration processes are included in the table. We remind the reader that any calibrated model is just one example; the model could have been calibrated with equal success by changing other parameters. We believe the parameters we modified to achieve calibration were justified given the available information on the hydrogeologic setting and the known yields of water, sediment, and phosphorus. However, we leave open the possibility that alternative model calibrations might be more appropriate for testing certain future land-management scenarios.

Model Application

The calibrated model was run for 20 years (1990-2009), with output from the last 10 years averaged to estimate typical annual yields (mass per area per year) of sediment and phosphorus from the landscape. Note that these loads are from the upland landscape; they do not include sediment contributions from channel erosion, nor do they include phosphorus contributions from groundwater. These loads are summarized here as subbasin-wide area-weighted average yields from all HRUs (hydrologic response units, which are aggregate areas of uniform land use, soil, and slope) within each subbasin. The maps show the loads generated

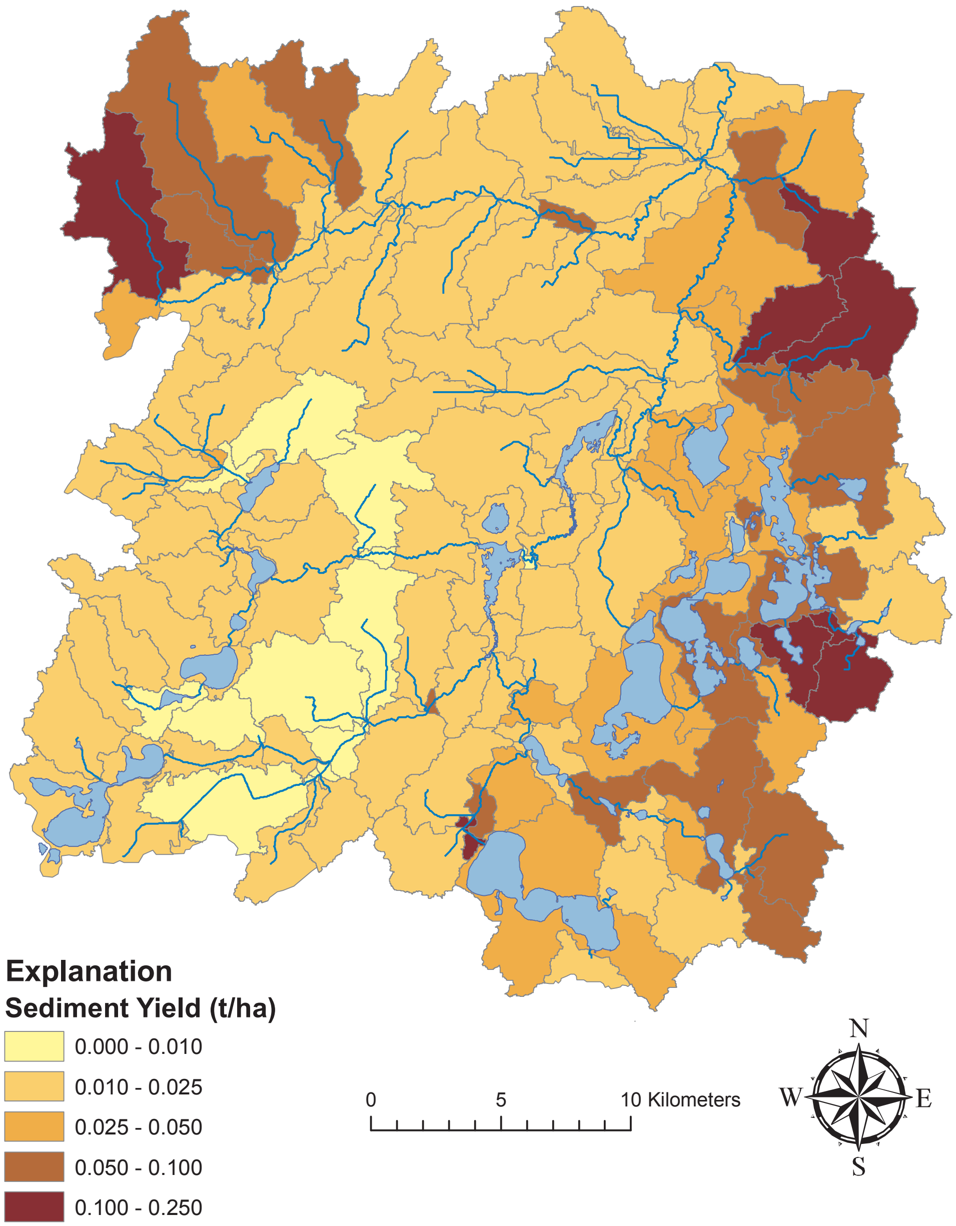


Figure 16. Average modeled subbasin yields of sediment in the Sunrise River watershed, 2000-09.

by each subbasin, not what is delivered to the mouth of the Sunrise. That is, substantial portions of loads from higher-yielding subbasins in the upper watershed may get trapped by lakes and wetlands and never get transported downstream.

Maps of sediment yield (Figure 16) and phosphorus yield (Figure 17) show very similar patterns. The central part of the watershed with low-gradient, sandy soils generate low yields, whereas steeper, finer-grained soils with agriculture generate higher yields in the eastern and northwestern parts of the watershed. Phosphorus yields are also higher in subbasins intersecting the urban areas of Forest Lake, Wyoming, Stacy, and North Branch.

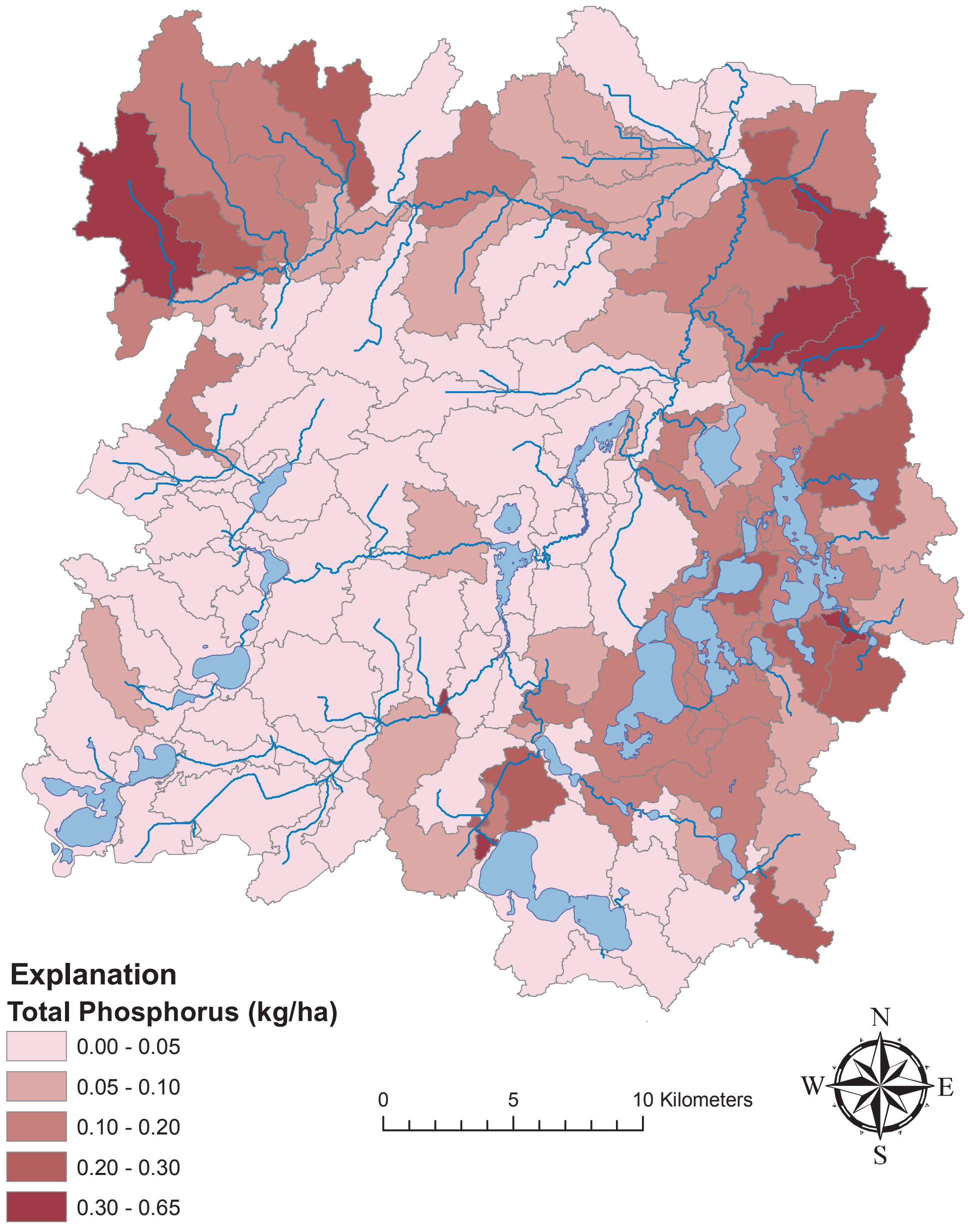


Figure 17. Average modeled subbasin yields of total phosphorus in the Sunrise River watershed, 2000-09.

Summary and Conclusions

The Sunrise River watershed in eastern Minnesota has multiple impairments to its surface waters that may be related to nonpoint-source loads of sediment and nutrients. In response to these impairments, a watershed-wide Sunrise Watershed TMDL has begun in an attempt to provide a more comprehensive assessment of the linkages among problems and potential solutions. A computer watershed model is a quantitative tool that can help provide a watershed-wide perspective by simulating essential physical and biological processes that interconnect the watershed over space and predict system behavior under changed conditions over time.

The Soil and Water Assessment Tool (SWAT) modeling program was chosen as the framework for the model of the Sunrise River watershed. The model was constructed by inputting geographic data specific to the Sunrise. Topographic and hydrographic (stream and lake locations) data were input, as well as known monitoring locations, to subdivide the watershed into 142 subwatersheds spatially linked by the flow network. Land cover was taken from the 2007 USDA Crop Data Layer (CDL), and soils data were generated by simplifying the available SSURGO data into four soils, aggregated by hydrologic group and characterized with median soil properties for each group. Land cover, soils, and slopes were spatially intersected to create hydrologic response units (HRUs) within each subbasin, which is the fundamental unit upon which SWAT operates. A total of 1642 HRUs were created, or about 11-12 per subbasin on average. Furthermore, topographic data were analyzed to identify depressional storage on the landscape, which was entered into SWAT in order to account for the impact of such depressions both on the hydraulics of rainfall-runoff response and on transport of nonpoint-source pollutant loads.

Of the cropland HRUs, 85% were given a simple corn-grain/soybean rotation, and 15% were given a corn-silage/alfalfa rotation. These two crop rotations were sufficient to reproduce the relative percentages of corn, soybeans, and alfalfa on the landscape as determined from the CDL 2007 data set and 2000-08 annual tabular data for Chisago County downloaded from the National Agricultural Statistics Service (NASS). Total livestock in the watershed was inferred from similar annual tabular data for Chisago County downloaded from NASS. All livestock was converted to equivalent animal units of beef cattle, dairy cows, and horses based on phosphorus production in manure. The total manure produced was then distributed in the watershed by grazing livestock in grassland or woodland, seasonal or daily-haul application to corn-silage/alfalfa rotations, or seasonal application to grassland either cut for hay or grazed.

Climate data were obtained from the National Climatic Data Center (NCDC), and scripts were written to check and re-format the data for use by SWAT. Daily total precipitation and minimum and maximum temperatures were extracted for five weather stations within and near the Sunrise watershed for 1948-2009. Point source data from the Minnesota Pollution Control Agency (MPCA) were summarized as annual average values for three sites in the watershed, for

1990-2009. Since about 2005, substantial upgrades have recently been implemented in the two largest plants, the Chisago Lakes and North Branch waste-water treatment facilities, which have reduced their phosphorus output loads by 58% and 96%, respectively, compared to the 1990s.

The model was calibrated to average crop yields over the watershed, flows at six sites, and sediment and phosphorus loads at three sites. Crop yields were adjusted so that the model reproduced the average annual yields of corn-grain, corn-silage, soybeans, and alfalfa for 2000-08. Flow was calibrated principally by manipulating curve numbers, snowmelt parameters, lake outflow, and groundwater parameters. Daily mean flows for the main stem near the watershed outlet (the Sunrise River main stem at the village of Sunrise) and the North Branch (at hwy 95) were fit extremely well to data sets from 1999 and 2005-08, with E_{NS} values averaging above 0.6. Flows at four other sites further upstream in the watershed were not fit as well statistically, but the model did reproduce low flows at these sites when appropriate.

Summary data for loads of sediment and phosphorus at three sites provided critical understanding of sources and transport of these constituents in the watershed. The upper watershed, above the hwy 14 monitoring site, contributed small amounts of nonpoint-source loads, only about 4% of the sediment and 10% of the phosphorus. These small amounts are likely because of the many lakes and wetlands that can trap sediment and nutrients in the upper watershed. The North Branch provided about 27% of the sediment and 33% of the phosphorus. By difference, the lower watershed (below the North Branch and hwy 14 stations, and above the Sunrise station) was the largest contributor of both sediment (69%) and nonpoint-source phosphorus (44%). The majority of sediment transported in this part of the watershed appeared to be from channel or other riparian sources, and much of the phosphorus load was most simply explained as being delivered by groundwater discharge. The model was fit principally to data from these three stations to reproduce the overall, watershed-wide pattern of loading indicated by the data. Average annual loads from 1999 and 2006-09 were targeted, as were seasonal loads during water year 1999 where data were available.

This pattern of loading suggested that reductions in loads to the St. Croix will come primarily from implementation projects in the lower subwatershed, and secondarily in the North Branch subwatershed. Results from remediation efforts will be muted, however, if in fact much of the sediment and phosphorus loads are the result of channel erosion and groundwater discharge, neither of which are easily addressed. Future model runs will be able to provide at least semi-quantitative estimates of the effectiveness of selected remediation efforts.

We concluded that the SWAT model constructed for the Sunrise watershed was adequately calibrated for general testing of how different management scenarios may affect nonpoint-source loads of sediment and nutrients. However, because of the many lakes and wetlands that trap sediment and nutrients in the upper watershed, and because the model was fit principally to monitoring data below these water bodies, we have little constraint on model output in the upper watershed. That is, the model has not been rigorously tested in the upper watershed. Continued data collection and subsequent re-calibration of subwatersheds above selected monitoring sites could be very useful. Such efforts could be targeted to isolate selected land uses (such as urban areas) or to test specific management scenarios. As an initial, simple application of the model, 10-year average (2000-09) subbasin yields of sediment and phosphorus were calculated by the model, showing low yields from the flat, sandy soils in the central watershed and higher yields in the steeper, loamy soils in the eastern and northwestern parts of the watershed.

We further concluded that the yields of sediment and nutrients for the Sunrise presented in Lenz et al. (2003), which identified the Sunrise watershed as the highest-yielding contributor of sediment and phosphorus to the St. Croix River, were significantly overestimated. The overestimate came about primarily from a misunderstanding in assessing watershed area: they used only the central subwatershed area for the main stem of about 439 km^2, whereas the total watershed area, including the North Branch, Lake Improvement District, and West Branch subwatersheds, is really about 991 km^2. Hence, in calculating yields, they divided loads by an area that was much too small, overestimating yields by more than a factor of two. Whereas Lenz et al. (2003) reported watershed-wide yields of 8.4 metric tons/km^2/yr for sediment and 39.9 kg/km^2/yr for phosphorus during water year 1999, more appropriate values would be 3.72 metric tons/km^2/yr for sediment and 17.7 kg/km^2/yr for phosphorus. These values place the Sunrise well within the range of similar tributaries in the lower St. Croix basin. However, even though the loads per unit area (yields) may be reduced by this re-calculation, the loads themselves are not in question, and the loads from the Sunrise – as for nearly all tributaries to the St. Croix – could still be reduced with selected management practices.

Future modeling could help answer some of the following questions. What were the loads of sediment and phosphorus during the 1990s, given the climate and point-source loading at the time? From this baseline, how were loads reduced during the 2000s, given improvements in wastewater treatment methods? What will the Sunrise watershed look like in 10 years, given possible growth in population? Given these changes, how can loads of sediment and phosphorus be realistically reduced? Will remediation efforts on the uplands provide significant reduction in watershed loads, in the face of large loading from the lower watershed? Ultimately, how much will efforts in the Sunrise watershed contribute toward the goal of reducing phosphorus loads to the St. Croix by 20%?

Acknowledgements

We thank the St. Croix Basin Water Resources Planning Team for continued guidance during the course of this project. This interagency team of federal, state, and local agencies is an example of government action and cooperation at its best. In particular -- listed co-equally -- we thank the (federal) National Park Service (Kate Hansen), the (state) Minnesota Pollution Control Agency (Chris Klucas), and the (local) Chisago County (Jerry Spetzman) for their continued patience and confidence. Susan Ribanszky volunteered a day each week for the last two years to help with the data analysis for this project. For technical assistance and insight, we thank the members of the SWAT Midwest America Users Group (SMAUG); identifying model problems and creating solutions to those problems has been a joint effort of this group for the past several years. Discussions with Adam Freihofer (Metropolitan Council Environmental Services), Marylee Murphy (Three Rivers Park District), Pat Oldenburg (Wisconsin Department of Natural Resources), and Paul Baumgart (University of Wisconsin Green Bay) have been especially helpful.

Funding for this project was provided by the National Park Service and the Minnesota Pollution Control Agency.

References

Almendinger, J.E., and Murphy, M.S. 2007. Constructing a SWAT model of the Willow River watershed, western Wisconsin. Final report to the Legislative Commission on Minnesota Resources, National Park Service, and Wisconsin Department of Natural Resources. St. Croix Watershed Research Station, Science Museum of Minnesota. 84 pp.

Arnold, J.G., Williams, J.R., and Maidment, D.R. 1995. Continuous-time water and sediment-routing model for large basins. Journal of Hydraulic Engineering 121(2):171-183.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., and Williams, J.R. 1998. Large area hydrologic modeling and assessment part I: Model development. Journal of the American Water Resources Association 34(1): 73-89.

CLFLWD (Comfort Lake – Forest Lake Watershed District). 2008. Watershed and Lake Water Quality Modeling Investigation for the Development of a Watershed Capital Improvement Plan. Prepared by Wenck Associates, Maple Plain, MN.

Di Luzio, M., Srinivasan, R., Arnold, J.G., and Neitsch, S.L. 2002. ArcView Interface for SWAT2000 User's Guide. USDA Agricultural Research Service; Blacklands Research and Extension Center BRC Report 02-07; Grassland, Soil, and Water Research Laboratory GSWRL Report 02-03; and Texas Water Resources Institute TWRI Report TR-193. 345 pp.

Edlund, M.B. 2004. Historical trends in phosphorus loading to the St. Croix National Scenic Riverway from permitted point source discharges, 1900-2000. Final report to National Park Service, PMIS Project 71951.

Krause, P., Boyle, D.P., and Base, F. 2005. Comparison of different efficiency criteria for hydrological model assessment. Advances in Geosciences 5: 89-97.

Legates, D.R., and McCabe, G.J., Jr. 1999. Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. Water Resources Research 35(1): 233-241.

Lenz, B.N., Robertson, D.M., Fallon, J.D., and Ferrin, R. 2003. Nutrient and suspended-sediment loads and benthic invertebrate data for tributaries to the St. Croix River, Wisconsin and Minnesota, 1997-99: U.S. Geological Survey Water-Resources Investigations Report 01-4162, 57 pp.

Magdalene, S. 2009. Lake St. Croix Total Phosphorus Loading Study. Report to St. Croix Basin Water Resources Planning Team. St. Croix Watershed Research Station, Science Museum of Minnesota.

Nash, J.E., and Sutcliffe, J.V. 1972. River flow forecasting through conceptual models: Part I – A discussion of principles. Journal of Hydrology 10: 282-290.

NASS (National Agricultural Statistics Service). 2009. Data downloaded from the web site: www.usda.gov/nass/

Nolan, B.T., and Stoner, J.D. 2000. Nutrients in groundwaters of the conterminous United States, 1992-95. Environmental Science and Technology 34: 1156-1165.

NRCS (Natural Resource Conservation Service). 2008a. U.S. General Soil Map (State Soil Geographic Database, STATSGO) for Minnesota. U.S. Department of Agriculture. Available URL: http://soildatamart.nrcs.usda.gov.

NRCS (Natural Resource Conservation Service). 2008b. Soil Survey Geographic (SSURGO) Database for Anoka, Chisago, and Washington counties, Minnesota. U.S. Department of Agriculture. Available URL: http://soildatamart.nrcs.usda.gov.

SCBWRPT (St. Croix Basin Water Resources Planning Team). 2004. St. Croix Basin Phosphorus-Based Water-Quality Goals. Prepared by P. J. Davis; printed by Minnesota Pollution Control Agency as report wq-b6-01. 28 pp.

Appendix A. Crop Rotations

Table A1. C1S1 cash-crop rotation.

Rotation Name:		c1s1_a_a				
Year	**Date**	**Operation**	**Item**	**Rate Units**	**Rate Units**	**Notes**
Year 1	16-Apr	Till	Chisel			Spring chisel only on A soils
	21-Apr	Fertilize (or Auto-fert initialize)	46-0-0	337 kg/ha	300 lb/acre	NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	26-Apr	Till	Disk			
	1-May	Plant	Corn-Grain			Set CNOP, HEATUNITS=1300
	1-May	Fertilize	27-15-15	225 kg/ha	200 lb/acre	LY1 = 0
	28-Oct	Harvest&Kill	Corn-Grain			
	15-Nov	*Till*	*Chisel*			*Fall chisel only on B & C soils*
Year 2	18-Apr	Till	Chisel			Spring chisel only on A soils
	5-May	Fertilize	9-23-30	225 kg/ha	200 lb/acre	LY1 = 0
	10-May	Till	Disk			
	15-May	Plant	Soybeans			Set CNOP, HEATUNITS=1300
	15-Oct	Harvest&Kill	Soybeans			
	15-Nov	*Till*	*Chisel*			*Fall chisel only on B & C soils*

NOTES:
Rotations are all fundamentally CORN-SOYB (C1S1) rotations. Two subrotations (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 and hydrologic soil group.

Table A2. Cs3A3 rotation without manure application

Rotation Name:		cs3a3_a				
Year	**Date**	**Operation**	**Item**	**Rate Units**	**Rate Units**	**Notes**
Year 1	21-Apr	Fertilize (or Auto-fert initialize)	46-0-0	337 kg/ha	300 lb/acre	NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	26-Apr	Till	Disk			
	1-May	Plant	Corn-Silage			Set CNOP, HEATUNITS=1300
	1-May	Fertilize	27-15-15	225 kg/ha	200 lb/acre	LY1 = 0
	25-Sept	Harvest&Kill	Corn-Silage			
	5-Nov	Till	Chisel			
Year 2	21-Apr	Fertilize (or Auto-fert initialize)	46-0-0	337 kg/ha	300 lb/acre	NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	26-Apr	Till	Disk			
	1-May	Plant	Corn-Silage			Set CNOP, HEATUNITS=1300
	1-May	Fertilize	27-15-15	225 kg/ha	200 lb/acre	LY1 = 0
	25-Sept	Harvest&Kill	Corn-Silage			
	5-Nov	Till	Chisel			
Year 3	21-Apr	Fertilize (or Auto-fert initialize)	46-0-0	337 kg/ha	300 lb/acre	NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	26-Apr	Till	Disk			
	1-May	Plant	Corn-Silage			Set CNOP, HEATUNITS=1300
	1-May	Fertilize	27-15-15	225 kg/ha	200 lb/acre	LY1 = 0
	25-Sept	Harvest&Kill	Corn-Silage			
	5-Nov	Till	Chisel			
Year 4	30-Apr	Till	Disk			
	7-May	Plant	Alfalfa			Set CNOP, HEATUNITS=1000
	10-Sep	Harvest	Alfalfa			
Year 5	25-Jun	Harvest	Alfalfa			
	10-Aug	Harvest	Alfalfa			
	10-Sep	Harvest	Alfalfa			
Year 6	25-Jun	Harvest	Alfalfa			
	10-Aug	Harvest	Alfalfa			
	10-Sep	Harvest	Alfalfa			
	1-Nov	Till	Moldboard plow			

NOTES:
Rotations are all fundamentally CSIL-CSIL-CSIL-ALFA-ALFA-ALFA (Cs3A3) rotations. Two subrotations (c3a3_a and b) were created with the initial year being either year-1 CSIL or ALFA 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 and hydrologic soil group.

Table A3. Cs3A3 rotation, with daily-haul manure, high rate (simulated here as a once-monthly haul)

Rotation Name:		cs3a3dhhi_a						
Year	**Date**	**Operation**	**Item**	**Rate**	**Units**	**Rate**	**Units**	**Notes**
Year 1	15-Jan	Fertilize	Dairy manure	5222	kg/ha, dry	16.61	sh T/acre, fresh	LY1 = 1
	15-Feb	Fertilize	Dairy manure	5222	kg/ha, dry	16.61	sh T/acre, fresh	LY1 = 1
	15-Mar	Fertilize	Dairy manure	5222	kg/ha, dry	16.61	sh T/acre, fresh	LY1 = 1
	15-Apr	Fertilize	Dairy manure	5222	kg/ha, dry	16.61	sh T/acre, fresh	LY1 = 1
	21-Apr	Fertilize (or Auto-fert initialize)	46-0-0	337	kg/ha	300	lb/acre	NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	26-Apr	Till	Disk					
	1-May	Plant	Corn-Silage					Set CNOP, HEATUNITS=1300
	1-May	Fertilize	27-15-15	225	kg/ha	200	lb/acre	LY1 = 0
	25-Sept	Harvest&Kill	Corn-Silage					
	5-Nov	Till	Chisel					
	15-Nov	Fertilize	Dairy manure	5222	kg/ha, dry	16.61	sh T/acre, fresh	LY1 = 1
	15-Dec	Fertilize	Dairy manure	5222	kg/ha, dry	16.61	sh T/acre, fresh	LY1 = 1
Year 2	15-Jan	Fertilize	Dairy manure	5222	kg/ha, dry	16.61	sh T/acre, fresh	LY1 = 1
	15-Feb	Fertilize	Dairy manure	5222	kg/ha, dry	16.61	sh T/acre, fresh	LY1 = 1
	15-Mar	Fertilize	Dairy manure	5222	kg/ha, dry	16.61	sh T/acre, fresh	LY1 = 1
	15-Apr	Fertilize	Dairy manure	5222	kg/ha, dry	16.61	sh T/acre, fresh	LY1 = 1
	21-Apr	Fertilize (or Auto-fert initialize)	46-0-0	337	kg/ha			NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	26-Apr	Till	Disk					
	1-May	Plant	Corn-Silage					Set CNOP, HEATUNITS=1300
	1-May	Fertilize	27-15-15	225	kg/ha	200	lb/acre	LY1 = 0
	25-Sept	Harvest&Kill	Corn-Silage					
	5-Nov	Till	Chisel					
	15-Nov	Fertilize	Dairy manure	5222	kg/ha, dry	16.61	sh T/acre, fresh	LY1 = 1
	15-Dec	Fertilize	Dairy manure	5223	kg/ha, dry	16.61	sh T/acre, fresh	LY1 = 1
Year 3	15-Jan	Fertilize	Dairy manure	5222	kg/ha, dry	16.61	sh T/acre, fresh	LY1 = 1
	15-Feb	Fertilize	Dairy manure	5222	kg/ha, dry	16.61	sh T/acre, fresh	LY1 = 1
	15-Mar	Fertilize	Dairy manure	5222	kg/ha, dry	16.61	sh T/acre, fresh	LY1 = 1
	15-Apr	Fertilize	Dairy manure	5222	kg/ha, dry	16.61	sh T/acre, fresh	LY1 = 1
	21-Apr	Fertilize (or Auto-fert initialize)	46-0-0	337	kg/ha	300	lb/acre	NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	26-Apr	Till	Disk					
	1-May	Plant	Corn-Silage					Set CNOP, HEATUNITS=1300
	1-May	Fertilize	27-15-15	225	kg/ha	200	lb/acre	LY1 = 0
	25-Sept	Harvest&Kill	Corn-Silage					
	5-Nov	Till	Chisel					
	15-Nov	Fertilize	Dairy manure	5222	kg/ha, dry	16.61	sh T/acre, fresh	LY1 = 1
	15-Dec	Fertilize	Dairy manure	5223	kg/ha, dry	16.61	sh T/acre, fresh	LY1 = 1
Year 4	15-Jan	Fertilize	Dairy manure	5222	kg/ha, dry	16.61	sh T/acre, fresh	LY1 = 1
	15-Feb	Fertilize	Dairy manure	5222	kg/ha, dry	16.61	sh T/acre, fresh	LY1 = 1
	15-Mar	Fertilize	Dairy manure	5222	kg/ha, dry	16.61	sh T/acre, fresh	LY1 = 1
	15-Apr	Fertilize	Dairy manure	5222	kg/ha, dry	16.61	sh T/acre, fresh	LY1 = 1
	30-Apr	Till	Disk					
	7-May	Plant	Alfalfa					Set CNOP, HEATUNITS=1000
	10-Sep	Harvest	Alfalfa					
	15-Sep	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	15-Oct	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	15-Nov	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	15-Dec	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
Year 5	15-Jan	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	15-Feb	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	15-Mar	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	15-Apr	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	15-May	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	15-Jun	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	25-Jun	Harvest	Alfalfa					
	15-Jul	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	5-Aug	Harvest	Alfalfa					
	15-Aug	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	10-Sep	Harvest	Alfalfa					
	15-Sep	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	15-Oct	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	15-Nov	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	15-Dec	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
Year 6	15-Jan	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	15-Feb	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	15-Mar	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	15-Apr	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	15-May	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	15-Jun	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	25-Jun	Harvest	Alfalfa					
	15-Jul	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	5-Aug	Harvest	Alfalfa					
	15-Aug	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	10-Sep	Harvest	Alfalfa					
	15-Sep	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	15-Oct	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	1-Nov	Till	Moldboard plow					
	15-Nov	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1
	15-Dec	Fertilize	Dairy manure	2611	kg/ha, dry	8.31	sh T/acre, fresh	LY1 = 1

NOTES:
Rotations are all fundamentally CSIL-CSIL-CSIL-ALFA-ALFA-ALFA (Cs3A3) rotations. Two subrotations (c3s1a3_a and b) were created with the initial year being either year-1 CSIL or ALFA 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 and hydrologic soil group.

Table A4. Cs3A3 rotation, with daily-haul manure, low rate (simulated here as a once-monthly haul)

Rotation Name:		cs3a3dhlo_a						
Year	**Date**	**Operation**	**Item**	**Rate**	**Units**	**Rate**	**Units**	**Notes**
Year 1	15-Jan	Fertilize	Dairy manure	1741	kg/ha, dry	5.54	sh T/acre, fresh	LY1 = 1
	15-Feb	Fertilize	Dairy manure	1741	kg/ha, dry	5.54	sh T/acre, fresh	LY1 = 1
	15-Mar	Fertilize	Dairy manure	1741	kg/ha, dry	5.54	sh T/acre, fresh	LY1 = 1
	15-Apr	Fertilize	Dairy manure	1741	kg/ha, dry	5.54	sh T/acre, fresh	LY1 = 1
	21-Apr	Fertilize (or Auto-fert initialize)	46-0-0	337	kg/ha	300	lb/acre	NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	26-Apr	Till	Disk					
	1-May	Plant	Corn-Silage					Set CNOP, HEATUNITS=1300
	1-May	Fertilize	27-15-15	225	kg/ha	200	lb/acre	LY1 = 0
	25-Sept	Harvest&Kill	Corn-Silage					
	5-Nov	Till	Chisel					
	15-Nov	Fertilize	Dairy manure	1741	kg/ha, dry	5.54	sh T/acre, fresh	LY1 = 1
	15-Dec	Fertilize	Dairy manure	1741	kg/ha, dry	5.54	sh T/acre, fresh	LY1 = 1
Year 2	15-Jan	Fertilize	Dairy manure	1741	kg/ha, dry	5.54	sh T/acre, fresh	LY1 = 1
	15-Feb	Fertilize	Dairy manure	1741	kg/ha, dry	5.54	sh T/acre, fresh	LY1 = 1
	15-Mar	Fertilize	Dairy manure	1741	kg/ha, dry	5.54	sh T/acre, fresh	LY1 = 1
	15-Apr	Fertilize	Dairy manure	1741	kg/ha, dry	5.54	sh T/acre, fresh	LY1 = 1
	21-Apr	Fertilize (or Auto-fert initialize)	46-0-0	337	kg/ha	300	lb/acre	NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	26-Apr	Till	Disk					
	1-May	Plant	Corn-Silage					Set CNOP, HEATUNITS=1300
	1-May	Fertilize	27-15-15	225	kg/ha	200	lb/acre	LY1 = 0
	25-Sept	Harvest&Kill	Corn-Silage					
	5-Nov	Till	Chisel					
	15-Nov	Fertilize	Dairy manure	1741	kg/ha, dry	5.54	sh T/acre, fresh	LY1 = 1
	15-Dec	Fertilize	Dairy manure	1741	kg/ha, dry	5.54	sh T/acre, fresh	LY1 = 1
Year 3	15-Jan	Fertilize	Dairy manure	1741	kg/ha, dry	5.54	sh T/acre, fresh	LY1 = 1
	15-Feb	Fertilize	Dairy manure	1741	kg/ha, dry	5.54	sh T/acre, fresh	LY1 = 1
	15-Mar	Fertilize	Dairy manure	1741	kg/ha, dry	5.54	sh T/acre, fresh	LY1 = 1
	15-Apr	Fertilize	Dairy manure	1741	kg/ha, dry	5.54	sh T/acre, fresh	LY1 = 1
	21-Apr	Fertilize (or Auto-fert initialize)	46-0-0	337	kg/ha	300	lb/acre	NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	26-Apr	Till	Disk					
	1-May	Plant	Corn-Silage					Set CNOP, HEATUNITS=1300
	1-May	Fertilize	27-15-15	225	kg/ha	200	lb/acre	LY1 = 0
	25-Sept	Harvest&Kill	Corn-Silage					
	5-Nov	Till	Chisel					
	15-Nov	Fertilize	Dairy manure	1741	kg/ha, dry	5.54	sh T/acre, fresh	LY1 = 1
	15-Dec	Fertilize	Dairy manure	1741	kg/ha, dry	5.54	sh T/acre, fresh	LY1 = 1
Year 4	15-Jan	Fertilize	Dairy manure	1741	kg/ha, dry	5.54	sh T/acre, fresh	LY1 = 1
	15-Feb	Fertilize	Dairy manure	1741	kg/ha, dry	5.54	sh T/acre, fresh	LY1 = 1
	15-Mar	Fertilize	Dairy manure	1741	kg/ha, dry	5.54	sh T/acre, fresh	LY1 = 1
	15-Apr	Fertilize	Dairy manure	1741	kg/ha, dry	5.54	sh T/acre, fresh	LY1 = 1
	30-Apr	Till	Disk					
	7-May	Plant	Alfalfa					Set CNOP, HEATUNITS=1000
	10-Sep	Harvest	Alfalfa					
	15-Sep	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	15-Oct	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	15-Nov	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	15-Dec	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
Year 5	15-Jan	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	15-Feb	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	15-Mar	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	15-Apr	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	15-May	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	15-Jun	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	25-Jun	Harvest	Alfalfa					
	15-Jul	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	5-Aug	Harvest	Alfalfa					
	15-Aug	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	10-Sep	Harvest	Alfalfa					
	15-Sep	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	15-Oct	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	15-Nov	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	15-Dec	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
Year 6	15-Jan	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	15-Feb	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	15-Mar	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	15-Apr	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	15-May	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	15-Jun	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	25-Jun	Harvest	Alfalfa					
	15-Jul	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	5-Aug	Harvest	Alfalfa					
	15-Aug	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	10-Sep	Harvest	Alfalfa					
	15-Sep	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	15-Oct	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	1-Nov	Till	Moldboard plow					
	15-Nov	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1
	15-Dec	Fertilize	Dairy manure	870	kg/ha, dry	2.77	sh T/acre, fresh	LY1 = 1

NOTES:
Rotations are all fundamentally CSIL-CSIL-CSIL-ALFA-ALFA-ALFA (Cs3A3) rotations. Two subrotations (c3s1a3_a and b) were created with the initial year being either year-1 CSIL or ALFA 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 and hydrologic soil group.

Table A5. Cs3A3 rotation with seasonal manure application to corn.

Rotation Name:		cs3a3seas_a						
Year	**Date**	**Operation**	**Item**	**Rate**	**Units**	**Rate**	**Units**	**Notes**
Year 1	16-Apr	Fertilize (or Auto-fert initialize)	46-0-0	337	kg/ha	300	lb/acre	NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	21-Apr	Fertilize	Dairy manure	4700	kg/ha	14.95	sh T/acre, fresh	
	26-Apr	Till	Disk					
	1-May	Plant	Corn-Silage					Set CNOP, HEATUNITS=1300
	1-May	Fertilize	27-15-15	225	kg/ha	200	lb/acre	LY1 = 0
	25-Sept	Harvest&Kill	Corn-Silage					
	1-Nov	Fertilize	Dairy manure	4700	kg/ha	14.95	sh T/acre, fresh	
	5-Nov	Till	Chisel					
Year 2	16-Apr	Fertilize (or Auto-fert initialize)	46-0-0	337	kg/ha	300	lb/acre	NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	21-Apr	Fertilize	Dairy manure	4700	kg/ha	14.95	sh T/acre, fresh	
	26-Apr	Till	Disk					
	1-May	Plant	Corn-Silage					Set CNOP, HEATUNITS=1300
	1-May	Fertilize	27-15-15	225	kg/ha	200	lb/acre	LY1 = 0
	25-Sept	Harvest&Kill	Corn-Silage					
	1-Nov	Fertilize	Dairy manure	4700	kg/ha	14.95	sh T/acre, fresh	
	5-Nov	Till	Chisel					
Year 3	16-Apr	Fertilize (or Auto-fert initialize)	46-0-0	337	kg/ha	300	lb/acre	NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	21-Apr	Fertilize	Dairy manure	4700	kg/ha	14.95	sh T/acre, fresh	
	26-Apr	Till	Disk					
	1-May	Plant	Corn-Silage					Set CNOP, HEATUNITS=1300
	1-May	Fertilize	27-15-15	225	kg/ha	200	lb/acre	LY1 = 0
	25-Sept	Harvest&Kill	Corn-Silage					
	1-Nov	Fertilize	Dairy manure	4700	kg/ha	14.95	sh T/acre, fresh	
	5-Nov	Till	Chisel					
Year 4	30-Apr	Till	Disk					
	7-May	Plant	Alfalfa					Set CNOP, HEATUNITS=1000
	10-Sep	Harvest	Alfalfa					
Year 5	25-Jun	Harvest	Alfalfa					
	10-Aug	Harvest	Alfalfa					
	10-Sep	Harvest	Alfalfa					
Year 6	25-Jun	Harvest	Alfalfa					
	10-Aug	Harvest	Alfalfa					
	10-Sep	Harvest	Alfalfa					
	1-Nov	Till	Moldboard plow					

NOTES:
Rotations are all fundamentally CSIL-CSIL-CSIL-ALFA-ALFA-ALFA (Cs3A3) rotations. Two subrotations (c3s1a3_a and b) were created with the initial year being either year-1 CSIL or ALFA 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 and hydrologic soil group.

Table A6. Grass hay rotation with spring beef-manure application

Rotation Name: GrassHay

Year	Date	Operation	Item	Rate	Units	Rate	Units	Notes
Year 1	*1-Apr*	*Plant*	*Smooth brome*					*For "plant" option; omit for "peren" option*
	21-Apr	Fertilize	Beef manure	3875	kg/ha	11.74	sh T/acre, fresh	
	1-Jul	Harvest	Grass (smooth brome)					
	1-Sep	Harvest	Grass (smooth brome)					
	1-Nov	*Kill*	*Smooth brome*					*For "plant" option; omit for "peren" option*

Table A7. Grazing rotation for beef cattle in grassland

Rotation Name: GrsBeef

Year	Date	Operation	Item	Rate	Units	Rate	Units	Notes
Year 1	*1-Apr*	*Plant*	*Smooth brome*					*For "plant" option; omit for "peren" option*
	12-May	Graze start	Beef manure	4.10	kg/ha/day, dry wt	2.05	sh T/acre/yr, fresh wt	BMEAT = 12.05 kg/ha/day BMTRMP = 2.41 kg/ha/day
	28-Oct	Graze end	Beef	169	days			(days entered above; end date for info only here)
	1-Nov	*Kill*	*Smooth brome*					*For "plant" option; omit for "peren" option*

Table A8. Grazing rotation for beef cattle in woodland

Rotation Name: WdBeef

Year	Date	Operation	Item	Rate	Units	Rate	Units	Notes
Year 1	*1-Apr*	*Plant*	*Forest-deciduous*					*For "plant" option; omit for "peren" option*
	12-May	Graze start	Beef manure	2.05	kg/ha/day, dry wt	1.03	sh T/acre/yr, fresh wt	BMEAT = 6.02 kg/ha/day BMTRMP = 1.20 kg/ha/day
	28-Oct	Graze end	Beef	169	days			(days entered above; end date for info only here)
	1-Nov	*Kill*	*Forest-deciduous*					*For "plant" option; omit for "peren" option*

Table A9. Grazing rotation for horses in grassland, plus spring manure application (1/3 of horse grazing area)

Rotation Name: GrsHorseHi

Year	Date	Operation	Item	Rate	Units	Rate	Units	Notes
Year 1	*1-Apr*	*Plant*	*Smooth brome*					*For "plant" option; omit for "peren" option*
	21-Apr	Fertilize	Horse manure	3073	kg/ha	4.65	shT/acre	
	12-May	Graze start	Horse manure	6.03	kg/ha/day, dry wt	1.55	sh T/acre/yr, fresh wt	BMEAT = 10.04 kg/ha/day BMTRMP = 2.01 kg/ha/day
	28-Oct	Graze end	Horse	169	days			(days entered above; end date for info only here)
	1-Nov	*Kill*	*Smooth brome*					*For "plant" option; omit for "peren" option*

Table A10. Grazing rotation for horses in grassland (no spring manure application; 2/3 of horse grazing area)

Rotation Name: GrsHorseLo

Year	Date	Operation	Item	Rate	Units	Rate	Units	Notes
Year 1	*1-Apr*	*Plant*	*Smooth brome*					*For "plant" option; omit for "peren" option*
	12-May	Graze start	Horse manure	6.03	kg/ha/day, dry wt	1.55	sh T/acre/yr, fresh wt	BMEAT = 10.04 kg/ha/day BMTRMP = 2.01 kg/ha/day
	28-Oct	Graze end	Horse	169	days			(days entered above; end date for info only here)
	1-Nov	*Kill*	*Smooth brome*					*For "plant" option; omit for "peren" option*

Appendix B. Calibrated Model Parameters

Table B1. Parameter set used for the Sunrise River watershed SWAT model.

NOTES: *Alphabetical by table or file name; tables in project database; dat files in ArcSwat\Databases folder. Parameter values, where HRU or subbasin-specific, were applied only to those HRUs and subbasins upstream from the monitoring point. Blanks designate the same parameter values as for the main monitoring station at Sunrise.*

File & Paramet	Description	units	Default	Sunrise at Sunrise	North Branch at hwy 95	Sunrise at hwy 14	Sunrise at Comfort Lake	West Branch at Lyons	South Branch at hwy 30	Rationale
table bsn										
SFTMP	Snowfall temperature	deg C	1	-2						Limits additions to snowpack (to lower snowmelt event)
SMTMP	Snowmelt base temperature	deg C	0.5	-5						Negative value allows some early melting to avoid large snow build-up and snowmelt event.
SMFMX	Snowmelt melt factor, max	mmH2O/deg-day	4.5	1.5						Lower values slow melt
SMFMN	Snowmelt melt factor, min	mmH2O/deg-day	4.5	0.5						Lower values slow melt
TIMP	Snowpack temperature lag factor	unitless	1	1						Values <1 slow melt.
SNOCOVMX	Snowpack water content at which coverage is 100%	mmH2O	1	10						Assuming 1 mm H2O = 1 cm of snowpack, default seems much too low for 100% snow cover. 20 cm snow (8") seems better; perhaps 10 cm would be enough. Model is not v. sensitive anyway.
SURLAG	Surface runoff lag coefficient	unitless	4	4						Lower values compensate for short (HRU) times of concentration; higher values could go with longer (subbasin) times of concentration. Affects sediment and nutrient transport more than hydrology. Left at default.
SPCON	Linear parameter, channel sediment transport	unitless	0.0001	0.01						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	1						Left at default; used SPCON to stop deposition
CDN	CDN, denitrification parameter	unitless	0 => 1.4	-0.3						Table bsn shows default of 0, but I/O manual says default = 1.4. (Previous versions were negative; use only positive values here.)
SNDCO	SNDCO, soil water denitrification point parameter	unitless	0 => 1.10	0.99						Table bsn shows default of 0, but I/O manual says default = 1.10.
PSP	Phosphorus availability index	unitless	0.4	0.3						Set to achieve realistic total phosphorus concentrations in top layer of agricultural soils, after setting SOL_LABP1 to soil-test phosphorus levels
PHOSKD	Phosphorus soil partitioning coefficient	m^3/T (T = Mg)	175	50						To get more phosphorus in runoff, reduce either PSP (giving less soluble P) or reduce PHOSKD (giving more soluble P).
PPERCO			10	17.5						
RSDCO	Residue decomposition coefficient	unitless	0.05	na						RSDCO ineffective here; change in crop.dat file
table chm										
SOL_LABP1	Soil labile P content, layer 1	ppm	5	For all agricultural HRUs: 25% at 20 ppm; 50% at 40 ppm, and 25% at 60 ppm						Assumed to be soil-test P values. Rural residential HRUs would retain their former STP. Entries of zero in the table actually default to 5 ppm.

Table B1. (continued) Parameter set used for the Sunrise River

NOTES: *Alphabetical by table or file name; tables in project database; dat files in ArcSwat\Databases folder. Parameter values, where HRU or subbasin-specific, were applied only to those HRUs and subbasins upstream from the monitoring point. Blanks designate the same parameter values as for the main monitoring station at Sunrise.*

File & Paramet	Description	units	Default	Sunrise at Sunrise	North Branch at hwy 95	Sunrise at hwy 14	Sunrise at Comfort Lake	West Branch at Lyons	South Branch at hwy 30	Rationale
file crop.dat										
BIO_E for CORN	Radiation use efficiency, or biomass-energy ratio	(kg/ha)/(MJ/m^2)	39	36						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	36						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	11						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	25						Used to adjust crop yields, beyond effects of water and nutrient stresses
HVSTI for CORN	Harvest index (fraction of above-ground biomass removed)	unitless	0.5	0.4						
CPYLD for CORN	Normal fraction of phosphorus in yield for corn-grain	unitless	0.0016	0.0016						Literature indicated value different from default
CPYLD for CSIL	Normal fraction of phosphorus in yield for corn-silage	unitless	0.0016	0.0016						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
WSYF for SOYB	Water-stress yield factor (minimum HVSTI when dry)	unitless	0.01	0.1						
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
USLE_C for BROS	Minimum C_{USLE} for smooth brome	unitless	0.003	0.003						Sunrise: start with default. For the Willow: to make erosion rates from brome about half that from alfalfa
USLE_C for ALFA	Minimum C_{USLE} for alfalfa	unitless	0.01	0.01						Sunrise: start with default. For the Willow: to make erosion rates from alfalfa about 1/3 to 1/4 that from cultivated crops
RSDCO_PL 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_PL for CSIL	Plant residue decomposition coefficient for corn-silage	unitless	0.05	0.15						ditto
RSDCO_PL for SOYB	Plant residue decomposition coefficient for soybeans	unitless	0.05	0.15						ditto
table gw										
GW_DELAY	Groundwater delay time	days	~30	15	15	90		100	10	Large values smooth contribution by groundwater to baseflow
ALPHA_BF	Baseflow recession constant	1/days	~0.1	0.5						Commonly from just above 0 to 1; smaller units have slower (less steep) baseflow recession
RCHRG_DP				0.35	0			0	0.6	
GWSOLP	Phosphorus concentration in groundwater	mg/L	0	0.012	0.0008	0.0003				Values of 0.01-0.02 mg/L found in some studies (Nolan and Stoner)
table hru										
SLSUBBSN	Slope length	m	50 (SWAT), or 90-120 (ArcSWAT)	Default						If no values are entered, SWAT default = 50 m. But, ArcSWAT will calculate values, commonly in the range of 90-120 m.
SLOPE	Slope	m/m (unitless)	by hru	Default						Previously, SWAT used the subbasin-wide slope for all hrus; the current SWAT is improved by calculating a slope for each hru individually.
OV_N	Overland runoff Manning's N	unitless	by hru (about 0.05 to 0.14)	Default						Previous default of 0.014 was too low, but now ArcSWAT seems to assign reasonable values by hru.
SLSOIL	Slope length for lateral flow in soil	m	by subbasin	Default						Same as for SLSUBBSN
ESCO	Soil evaporation compensation factor	unitless	0 => 0.95	Default						Smaller values reduce overall water yield from basin. A table entry of zero (which is default) will result in SWAT using 0.95. The default basin-wide value of ESCO is set in Table bsn; I presume any value here overrides the default for that hru.

Table B1. (continued) Parameter set used for the Sunrise River

NOTES: *Alphabetical by table or file name; tables in project database; dat files in ArcSwat\Databases folder. Parameter values, where HRU or subbasin-specific, were applied only to those HRUs and subbasins upstream from the monitoring point. Blanks designate the same parameter values as for the main monitoring station at Sunrise.*

File & Paramet	Description	units	Default	Sunrise at Sunrise	North Branch at hwy 95	Sunrise at hwy 14	Sunrise at Comfort Lake	West Branch at Lyons	South Branch at hwy 30	Rationale
table mgt1										
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; however note we may be increasing this too much. See WiscoDisco Farms, where no-till did not reduce P yields.
CN2	Curve number, initial, soil moisture condition 2	unitless	by land cover	75% of initial value						Decreasing CN increases infiltration and baseflow, reduces hydrograph spikes
USLE_P	USLE support practice factor, nominally	unitless	1	as needed for sediment calibration						Used as a primary calibration scaling parameter to reduce sediment delivery from subbasins; applied indiscriminately to all HRUs
table mgt2										
CNOP	Curve number for scheduled ag operation	unitless	CN2 above	75% of initial value						CNOP set in rotations each year based on crop, soil hydrologic group, and tillage level.
table pnd										
PND_FR	Pond drainage fractional area in subbasin	unitless	0	from ArcHydro						Fractional area of subbasin land draining to "ponds," here defined as large depressions intersecting channels, excluding lakes modeled as reservoirs. All such identified ponds within a subbasin are aggregated into one composite Pond per subbasin.
PND_PSA	Pond principal surface area	ha	0	0.94*area of "GIS riparian depressions"						Aggregate area of Pond in each subbasin. Here, the 0.94 factor assumes an outlet threshold about 0.25 m lower than mapped water levels.
PND_PVOL	Pond principal volume	ha-m	0	0.91*volume of "GIS riparian depressions"						Aggregate volume of Pond in each subbasin. Here, the 0.91 factor assumes an outlet threshold about 0.25 m lower than mapped water levels.
PND_ESA	Pond emergency surface area	ha	0	1.13*PND_PSA						Area of Pond at emergency (maximum) level, calculated assuming about a 0.5 m rise above the threshold.
PND_EVOL	Pond emergency volume	ha-m	0	1.18*PND_PVOL						Volume of Pond at emergency (maximum) level, calculated assuming about a 0.5 m rise.
NDTARG	Number of days to reach target storage	days	15	5						Days to reach target volume
PND_NSED	Equilibrium sediment concentration	mg/L	1	0						Let Ponds capture all sediment (probably pass some, but no data to parameterize)
PND_K	Pond hydraulic conductivity	mm/hr, to nearest 0.001	~0.5	0.1			0.35			Seepage from Ponds now functions in our version of SWAT.
PSETL1 (for Ponds)	Phosphorus settling rate, settling season 1, ponds	m/yr	1	0						Let Ponds pass all phosphorus (probably capture some -- but no data to parameterize)
WET_FR	Wetland drainage fractional area in subbasin	unitless	0	from ArcHydro						Fractional area of subbasin land draining to "wetlands," defined here as closed drainages in each subbasin. Such closed drainages were identified as large depressions not intersecting channels.
WET_NSA	Wetland normal surface area	ha	0	from ArcHydro						Aggregate area of large depressions not intersecting channels
WET_NVOL	Wetland normal volume	ha-m	0	from ArcHydro						Aggregate volume of large depressions not intersecting channels
WET_MXSA	Wetland maximum surface area	ha	0	1.13*WET_NSA						Area of Wetlands at emergency (maximum) level, calculated assuming about a 0.5 m rise.
WET_MXVOL	Wetland maximum volume	ha-m	0	1.18*WET_NVOL			2X original			Volume of Wetlands at emergency (maximum) level, calculated assuming about a 0.5 m rise.
WET_NSED	Equilibrium sediment concentration	mg/L	1	0						Zero ensures that all sediment gets trapped in Wetlands (closed depressions)
WET_K	Wetland hydraulic conductivity	mm/hr, to nearest 0.001	~0.5	0.25			0.1			Seepage from Wetlands now functions in our version of SWAT.
PSETLW1 (for Wetlands)	Phosphorus settling rate, settling season 1, wetlands	m/yr	15	1000						High rate ensures all phosphorus gets trapped in Wetlands (closed depressions)

Table B1. (continued) Parameter set used for the Sunrise River

NOTES: *Alphabetical by table or file name; tables in project database; dat files in ArcSwat\Databases folder. Parameter values, where HRU or subbasin-specific, were applied only to those HRUs and subbasins upstream from the monitoring point. Blanks designate the same parameter values as for the main monitoring station at Sunrise.*

File & Paramet	Description	units	Default	Sunrise at Sunrise	North Branch at hwy 95	Sunrise at hwy 14	Sunrise at Comfort Lake	West Branch at Lyons	South Branch at hwy 30	Rationale
table res	*(parameters are changed in reservoir dialogue box or lwq text files -- not directly in this dbf file)*									
RES_PSA	Principal area of lake or reservoir	ha		Area at level 0.5 m below mapped level						dA/dH determined from lake hypsometery.
RES_PVOL	Principal volume of lake or reservoir (volume at threshold)	ha-m	user input	Volume at level 0.5 m below mapped level						dV/dH determined from lake hypsometery.
RES_ESA	Emergency area of lake or reservoir	ha		Area at level 0.5 m above mapped level						dA/dH determined from lake hypsometery.
RES_EVOL	Emergency volume of lake or reservoir	ha-m		Volume at level 0.5 m above mapped level						dV/dH determined from lake hypsometery.
RES_NSED	Equilibrium sediment concentration	mg/L	1	By formula (see text), based on mean depth..						Increased to pass more sediment through the reservoirs. Shallower reservoirs should have higher values than deep reservoirs.
RES_K	Reservoir hydraulic conductivity	mm/hr, to nearest 0.1	~0.5	0.1		0.3	0.4	0.3	0.2	Seepage from Reservoirs now functions correctly. (1 dec. place)
IRESCO	Outflow simulation code	unitless	0-3	2						Outflow simulated by target days to reach principal volume
IFLOOD1-2	Beginning and ending month of flood season	uniteless	1							Leave equal to each other for unregulated lakes and reservoirs.
STARG1-12	Monthly target volumes	ha-m	0	Set all to RES_PVOL						For unregulated lakes and reservoirs, set all 12 STARG values to RES_PVOL to force SWAT to use that as its target volume each month. (Otherwise SWAT uses EVOL for non-flood months and soil-moisture-based values below that for flood months.)
NDTARGR	Number of days to reach target storage volume	days	user input	2				10	10	Dramatically affects shape of hydrograph peaks.
PSETLR1	Phosphorus settling rate, season 1, reservoirs	m/yr	10	Default						Could have been used to improve phosphorus calibration
PSETLR2	Phosphorus settling rate, season 2, reservoirs	m/yr	10	Default						Ditto
table rte										
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	0.001	0.001	0.001	0.001	0.001	0.001	Zero precludes any channel erosion
CH_COV	Channel cover factor	unitless	0-1	1	0.6	0.08	0.08	0.08	0.08	Set to one to allow erosion, to simplify interpretation should erodibility be changed in the model
table sol										
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.
table sub										
CH_K1	Tributary channel hydraulic conductivity	mm/hr	~0.5	0.5						Small effect; left at default
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 B1. (continued) Parameter set used for the Sunrise River

NOTES: *Alphabetical by table or file name; tables in project database; dat files in ArcSwat\Databases folder. Parameter values, where HRU or subbasin-specific, were applied only to those HRUs and subbasins upstream from the monitoring point. Blanks designate the same parameter values as for the main monitoring station at Sunrise.*

File & Paramete	Description	units	Default	Sunrise at Sunrise	North Branch at hwy 95	Sunrise at hwy 14	Sunrise at Comfort Lake	West Branch at Lyons	South Branch at hwy 30	Rationale
file swq.dbf										
RS5	Organic phosphorus settling rate	1/day	0.05							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 47 MLDBOARD	Mixing efficiency of moldboard plow	unitless	0.95	Default, to start with						Kept at default
EFTMIX for 48 CHISPLOW	Mixing efficiency of chisel plow	unitless	0.3	Default, to start with						Increased to reduce surface residue to selected levels under different tillage levels
EFTMIX for 50 DISKPLOW	Mixing efficiency of disk plow	unitless	0.85	Default, to start with						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							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.