Constructing a SWAT model of the St. Croix River basin, eastern Minnesota and western Wisconsin

Putting together pieces of the water-quality puzzle

Produced by the St. Croix Watershed Research Station, Science Museum of Minnesota

For the National Park Service, Centennial Challenge Program

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Abstract

The biotic integrity and recreational value of the St. Croix National Scenic Riverway depends on its water quality. Both Minnesota and Wisconsin have declared Lake St. Croix, the lowermost 40 km of the Riverway, as impaired due to excessive phosphorus and chlorophyll levels and have agreed to reduce phosphorus loads to the river by 27% over the next several decades. Most of these loads come from diffuse nonpoint sources, and so reducing them will require changing land use and management practices in the 20,000-km^2 contributing basin. A computerized watershed model that simulates rainfall-runoff, erosion, and nutrient-transport processes can help guide decisions about which best management practices are most effective and where to implement them. We here document the construction of such a watershed model for the St. Croix basin using the Soil and Water Assessment Tool (SWAT), a program developed by the USDA to predict nonpoint loads of sediment and nutrients from large basins over long periods of time. Available digital data sets of topography and hydrography were used subdivide the basin into 419 subbasins. The 39 largest lakes intersecting the channel system were modeled explicitly; the many other lakes and wetlands were treated as aggregated surface-water storage in each subbasin. Lake St. Croix was modeled as four separate, sequential pools. Land cover in the model was set to either of two separate decades, the 1990s (1990-99) and the 2000s (2000-09). Agricultural practices were configured to account for crop rotations, tillage practices, livestock grazing, and applications of manure and inorganic fertilizer. Unique combinations of land-cover, soil type, slope, and subbasin resulted in a total of 3,010 hydrologic response units (HRUs), about seven per subbasin. The model was calibrated to observed data for 2000-07 and validated to

data for 1990-99. Calibration of monthly flows was based on data from two main-stem stations (Danbury and St. Croix Falls) and from three tributary stations (Kettle, Snake, and Apple rivers), with excellent model fits. Monthly loads of sediment and nutrients were calibrated based on data at a single main-stem station at Stillwater, MN, with good model fits for suspended sediment, total phosphorus, and total nitrogen. The St. Croix SWAT model offers the most comprehensive whole-basin tool available for identifying where problems exist on the landscape, what new problems may arise as land is developed and climate changes, and which best-management practices are most likely to be effective in reducing nonpoint-source pollution. In short, the model provides an integrated, whole-basin framework for making sound, science-based decisions in how best to restore and protect the St. Croix River, thus securing the nation's investment in the St. Croix National Scenic Riverway.

Introduction

Problem

For its scenic, recreational, biotic, and water-resource values, the upper St. Croix River (Figure 1) was included in the first group of only eight rivers nationwide to be federally designated as a National Scenic and Recreational Riverway by congressional act in 1968. Four years later in 1972, the Riverway was expanded to include the lower St. Croix to its confluence with the Mississippi River (Waters, 1977). The Riverway corridor harbors at least 60 state and federally listed endangered or threatened species (Holmberg et al., 1997), including five federally endangered mussel species: the winged mapleleaf, the Higgins eye pearlymussel, the spectaclecase, the sheepsnose, and snuffbox (Coffin and Pfannmuller, 1988; USFWS, 2014). The river is adjacent to one of the largest population centers in the upper Midwest, the Minneapolis-St. Paul metropolitan area, and is consequently a heavily-used and highly-valued resource, with more than one million visitors annually (NPS, 1995).

However, despite its apparent high quality, the St. Croix River has been significantly impacted by inputs of sediment and nutrients and is far from its original pristine condition. Recent studies have demonstrated that the river receives about four times the natural loads of sediment and phosphorus from its tributaries (Triplett et al., 2009). The increase in loads accelerated after 1940 with the mechanization of agriculture and the widespread application of inorganic fertilizers. As a consequence, during the 1940s the algal community shifted from being benthic-dominated (bottom-dwelling) to planktonic-dominated (free-floating) (Edlund et al., 2009a). Such a shift at the bottom of the food chain has implications for nearly all other aquatic species. Dwindling populations of endangered species, notably mussels, indicates that there have been serious compromises to the health of the river.

Advances in waste-water treatment and soil conservation have held point and nonpoint phosphorus loads in check for the last few decades, but population increases and attendant land-use changes may overwhelm this relative success (Edlund et al., 2009b). The Minneapolis-St. Paul metropolitan area is expanding rapidly into the lower basin of the St. Croix, encouraged by enlarged transportation corridors, planned river crossings, and commercial developments. Higher prices for corn and soybeans will encourage farmers to expand row-crop acreage at the expense of grassland acreage enrolled in conservation reserve programs.

The lowermost 40 km of the Riverway comprises Lake St. Croix, a riverine lake naturally impounded at its confluence with the Mississippi River (Zumberge, 1952; Wright et al., 1998; Blumentritt et al., 2009). Lower velocities, increased hydraulic residence time, and anaerobic hypolimnetic waters promote internal loading of phosphorus from the lake sediments, escalating the eutrophication from increased phosphorus loads. Whereas water-column total phosphorus concentrations increased by a factor of two or three since Euro-American settlement, the flux of biogenic silica (a measure of algal productivity) increased by a factor of 5.5. That is, because of internal recycling of nutrients in the lake, each unit increase in phosphorus resulted in about twice

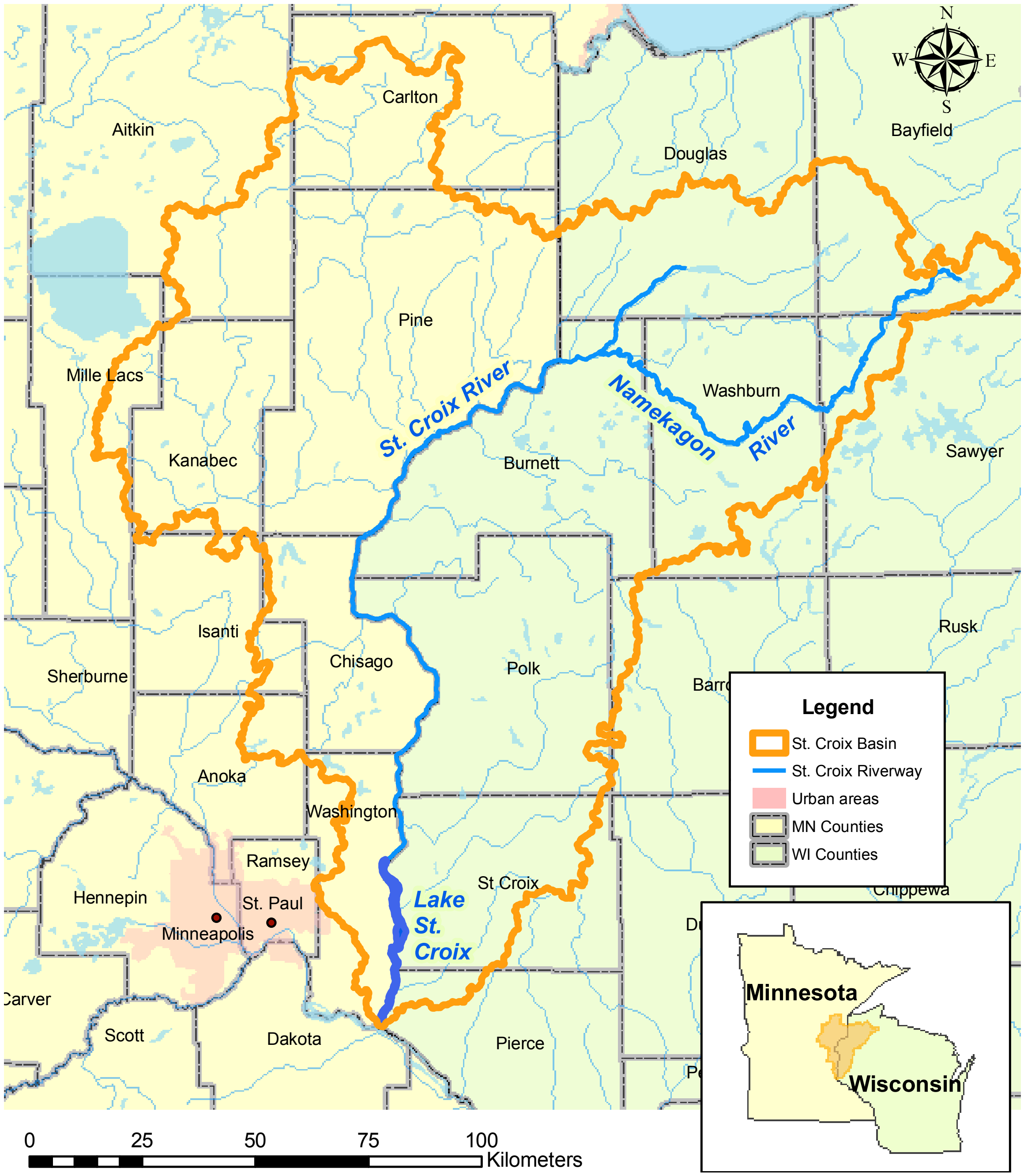


Figure 1. The St. Croix River basin in eastern Minnesota and western Wisconsin.

the unit increase in algal productivity (Edlund et al., 2009a).

In 2008-09, both Minnesota and Wisconsin declared Lake St. Croix to be impaired by eutrophication from excess phosphorus loads, according to section 303(d) of the Clean Water Act. This declaration triggered a total daily maximum load (TMDL) study, which aimed to reduce phosphorus loads by 27% to bring the lake into compliance with Minnesota and Wisconsin standards (MPCA and WDNR, 2012). By accounting for a margin of safety and reserve capacity, the TMDL updated the 20%-reduction goal set in 2004 by the interagency St. Croix Basin Water Resources Planning Team (SCBWRPT, 2004), which was based in part on aiming to return the lake to 1940s conditions, when the lake underwent the ecological transition from benthic- to planktonic-dominated algae (Edlund et al., 2009a). Multiple agencies have shared responsibility for management of land and water resources within the St. Croix basin, which extends over 19 counties in two states, comprising dozens of local units of government (Figure 1). The many players in the watershed emphasize the need for close cooperation between lead state and federal agencies, and for a whole-basin approach to achieve the TMDL recommendations. Local units of government can do their part, but they need to know how their efforts fit within the context of the whole basin.

Previous studies have shown that most of the phosphorus reaching Lake St. Croix comes from nonpoint sources. Based on data from 1988-99, Robertson and Lenz (2002) estimated that in wet years about 87% of the phosphorus load came from nonpoint sources and about 8% from point sources, and in dry years the split was 52% from nonpoint and 29% from point sources (the remainder coming from internal loading from lake sediments). Edlund et al. (2009b) combined historic flow and point-source data with lake-sediment data (from Triplett et al., 2009) to estimate decadal average phosphorus loads to Lake St. Croix and to partition those loads between point, nonpoint, anthropogenic, and natural sources. For the 1990s, they estimated about 12% of the phosphorus load was from point sources and 88% from nonpoint sources; furthermore, the nonpoint sources can be partitioned into about 40% from natural and 48% from anthropogenic sources. Internal loading would only add to these loads. Excluding the natural-source loads, fully 80% of the anthropogenic phosphorus loads were from nonpoint sources, and 20% from point sources. Clearly, to reduce total phosphorus loads to Lake St. Croix, strategies to reduce the nonpoint loads must be part of the solution.

Computer models of watersheds that simulate rainfall-runoff, erosion, and nutrient transport processes are extremely useful tools to help guide watershed managers in the implementation of remediation practices to reduce nonpoint-source pollution (Borah and Bera, 2004). Models can also enhance the value of monitoring data by extending the spatial and temporal scales to which the data apply. Spatially, models can identify subwatersheds and land-use practices within a watershed that may be the principal contributors of pollutant loads monitored at the watershed outlet. Temporally, models can be run for times and climatic conditions beyond the window of monitoring data, thereby providing a context by which the representativeness of the monitoring data can be evaluated. Furthermore, computer models create an objective framework for a whole-basin approach to management of land and water resources. The model provides the overall context for each subunit, wherein the contributions of each unit can be evaluated against the whole. This report describes the construction of such a computer model of the St. Croix River basin to document data inputs and model configuration as a foundation for applying the model to specific management needs.

Study Area and the Origin of Lake St. Croix

The St. Croix River drains a basin of about 20,000 km^2 and extends 250 km from its headwaters to its confluence with the Mississippi River, over which distance it loses only 100 m in altitude (Figure 1). The federally designated St. Croix National Scenic Riverway also includes the 158-km-long Namekagon River in Wisconsin, which joins the St. Croix just upstream of the Minnesota/Wisconsin border. At least 15 other major tributaries contribute to the St. Croix from the basin beyond the narrow Riverway corridor. As noted earlier, the lower 40 km of the Riverway, from Stillwater, MN, to Prescott, WI, is a natural impoundment called Lake St. Croix, dammed at its mouth by sediment from the Mississippi River. Because of the increased hydraulic residence time in Lake St. Croix, the lake suffers from eutrophication that is not always expressed in upstream contributing reaches.

The climate of the St. Croix basin is strongly continental, with cold dry winters and warm humid summers. In Grantsburg, WI, near the basin centroid, the 1971-2000 normal mean temperature is -12.9 deg C (9 deg F) for January and 20.6 deg C (69 deg F) for July. The normal annual precipitation is 808 mm (31.8 inches), 42% of which falls during summer (Jun-Jul-Aug) and only 10% during winter (Dec-Jan-Feb) (NCDC, 2011). Mean annual water yield (also called mean annual runoff) differs across the basin by more than a factor of two, from about 6.6 inches the southwest part of the basin to 13.7 inches in the northeast part, with an average of 9.75 inches (248 mm) over the basin (Figure 2; data from D. Lorenz, U.S. Geological Survey, personal communication, 2010, based on data compiled for Lorenz et al., 2010). This volume equates to a mean annual flow at the outlet of the basin of 157 cms (cubic meters per second; about 5500 cubic feet per second [cfs]). If the mean annual precipitation at Grantsburg is representative of the basin, then mean annual evapotranspiration (ET) would be the difference between precipitation and water yield, or about 560 mm (22 inches).

Most of the land cover in the basin is undeveloped (over 80%), with forest being the single largest category and predominate in the northern half of the basin (Table 1 and Figure 3). According to land use interpreted from satellite imagery, in the early 1990s forest occupied about 46% of the land area, and it appears to have expanded to about 55% by the mid-2000s (meaning 2000-09). Water and wetland areas occupy about 14-19% depending on the data set. While some undeveloped land such as pasture can yield elevated phosphorus loads, the principal sources of anthropogenic nonpoint loads of phosphorus are expected to be tilled cropland and developed urban areas (both residential and non-residential). Cropland is found mostly in the southern half of the basin and has (according to these data sets) declined from about 16% of the basin area in the early 1990s to about 9% in the mid-2000s. Conversely, over the same time period, developed lands have increased from about 2% of the basin area to about 5%. A visual comparison of Figures 3a and 3b will show a general decrease in cropland (yellow) and increase in forest (green), and an expansion of urban areas (red and pink).

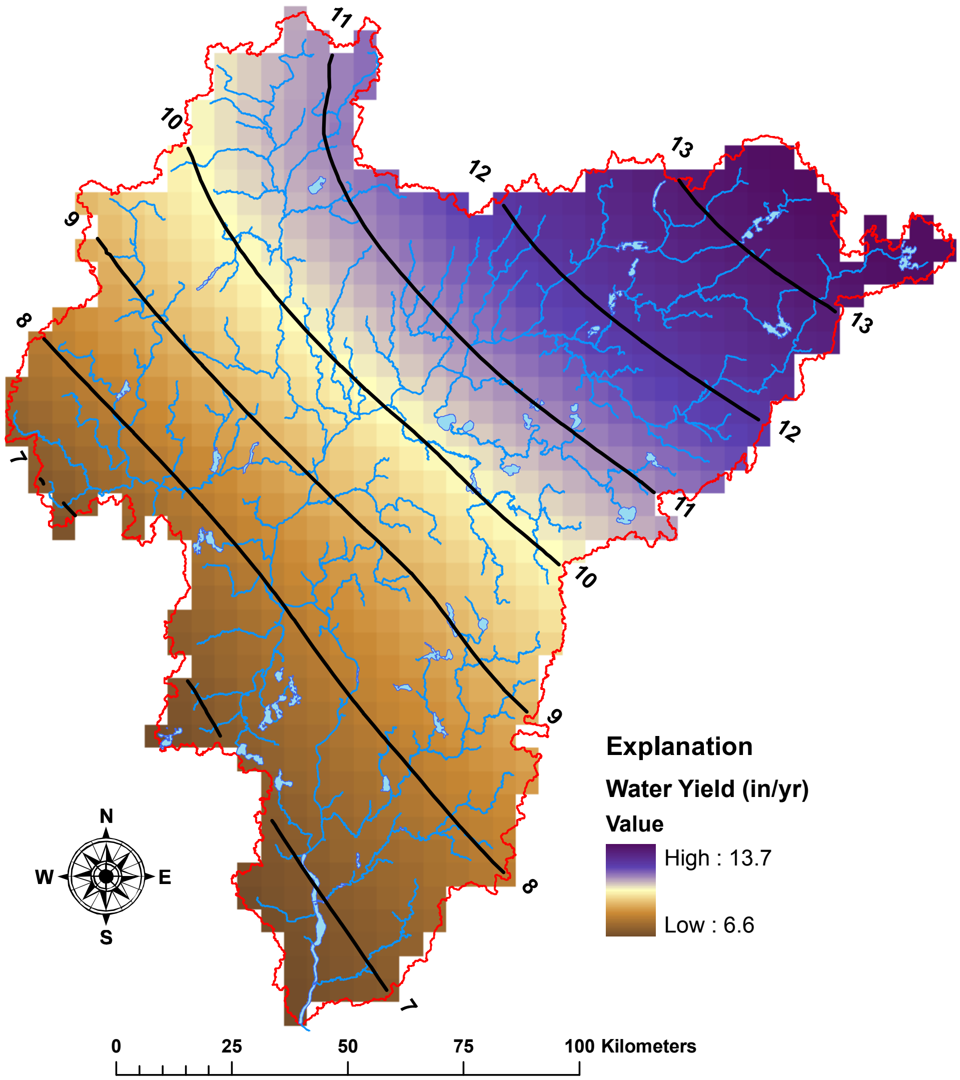


Figure 2. Mean annual water yield in the St. Croix basin, inches per year, 1940-2008.

However, a comparison of values in Table 1 demonstrates the imprecision among the spatial data sets due to different algorithms used to interpret satellite imagery. While the above trends in cropland and urban lands may be qualitatively correct, other data sets should be examined in trying to quantify the trends. In particular, we note that the tabular NASS data sets of cropland area, available for each county for each year, indicated that the percentage area of tilled cropland in the basin went from 11.7% in the 1990s to 11.3% in the 2000s – a nearly insubstantial decline in contrast to the 7% (from 16% to 9%) decline indicated by the spatial data sets (see Land Cover section below).

Table 1. Land-cover types in the St. Croix basin, 1992-2008, from selected digital datasets based on satellite imagery.

	NLCD, 1992		NLCD, 2001		NLCD, 2006		CDL, 2007		CDL, 2008		UM, 2007		Average, 2001-07	
Land Cover Type	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)
Cropland	*3241*	*16.3%*	*1962*	*9.9%*	*1927*	*9.6%*	*1855*	*9.3%*	*1182*	*5.9%*	*1729*	*8.7%*	*1731*	*8.7%*
Row crops	3214	16.1%									1353	6.8%	1429	7.2%
Cultivated crops			1962	9.9%	1927	9.6%								
Corn							923	4.6%	642	3.2%				
Soybeans							491	2.5%	388	2.0%				
Small grain	27	0.1%					62	0.3%	43	0.2%	57	0.3%		
Other crop							20	0.1%	4	0.0%	26	0.1%	71	0.4%
Alfalfa							359	1.8%	104	0.5%	293	1.5%	231	1.2%
Undeveloped	*16307*	*81.9%*	*17026*	*85.5%*	*17019*	*85.2%*	*16866*	*84.8%*	*17688*	*88.9%*	*17728*	*89.0%*	*17265*	*86.7%*
Pasture / hay	3296	16.6%	3013	15.1%	2956	14.8%	1134	5.7%	3746	18.8%			2712	13.6%
Grassland / herbaceous	73	0.4%	812	4.1%	385	1.9%	1093	5.5%	426	2.1%	2295	11.5%	1002	5.0%
Forest	9102	45.7%	10080	50.6%	9312	46.6%	11214	56.4%	10915	54.9%	12149	61.0%	10734	53.9%
Wetland	3098	15.6%	2419	12.2%	3570	17.9%	2715	13.6%	1910	9.6%	2645	13.3%	2652	13.3%
Water	738	3.7%	703	3.5%	796	4.0%	710	3.6%	691	3.5%	638	3.2%	708	3.6%
Developed	*359*	*1.8%*	*919*	*4.6%*	*1038*	*5.2%*	*1171*	*5.9%*	*1027*	*5.2%*	*466*	*2.3%*	*924*	*4.6%*
Urban, low density	281	1.4%	841	4.2%	961	4.8%	1117	5.6%	972	4.9%	173	0.9%	813	4.1%
Urban, med-high density	78	0.4%	78	0.4%	77	0.4%	54	0.3%	55	0.3%	293	1.5%	111	0.6%
Total	19906		19907		19984		19892		19897		19923		19921	

NOTES:
NLCD, National Land Cover Datasets compiled by the U.S. Geological Survey (USGS, 2010)
CDL, Cropland Data Layer, compiled by the National Agricultural Statistics Service of the U.S. Department of Agriculture (NASS, 2011)
UM, University of Minnesota, compiled by the Remote Sensing Laboratory in the Department of Forestry (Dr. Marv Bauer, 2010, personal communication)

Data aggregation assumptions:
"Forest" included deciduous, evergreen, mixed forests, and shrub/scrub; "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, although we inferred that Pasture/hay category for the UM data set was actually representing alfalfa; "Grassland / herbaceous" included clover/wildflowers, seed/sod grass, and fallow cropland categories.

Averaging assumptions:
First, we excluded the 1992 data set from the average because it does not appear to be representative of current land use; we assume the datasets from 2001-07 are essentially representative of current land use with differences among years due primarily to different methods of interpreting the satellite imagery. While average areas of most land-use types could be calculated simply as the mean of the four data sets from 2001-07, the non-uniform cropland categories required some additional effort during the averaging process. First, the average total cropland area for 2001-07 was calculated as the mean of all four data sets. Average areas for alfalfa and other crops (including small grains here) were calculated from those years with data. The resulting "average" row crop area was calculated as the difference between the total cropland area minus the other crop and alfalfa areas.

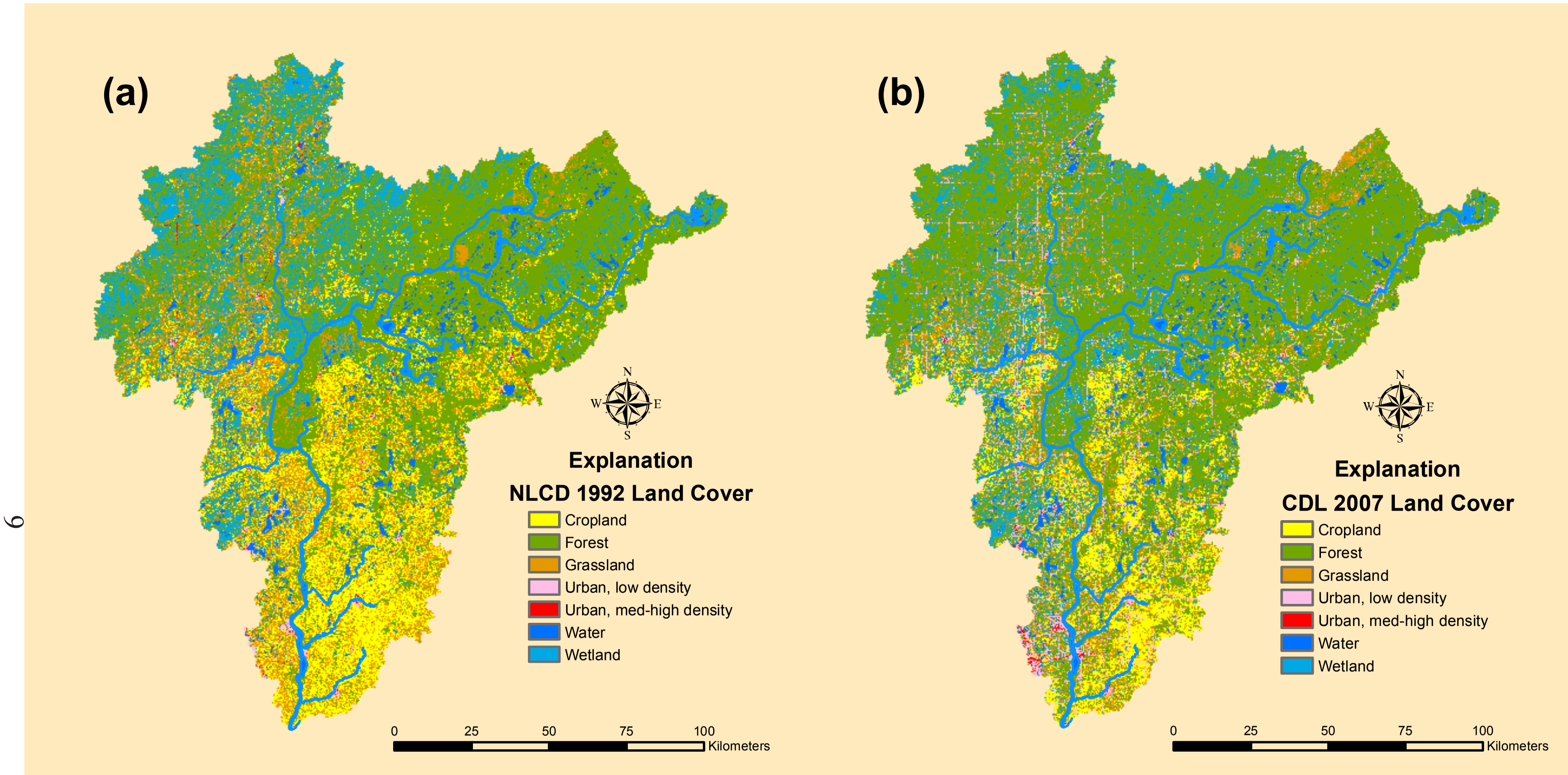


Figure 3. Land cover in the St. Croix basin for (a) 1992 and (b) 2007.

The St. Croix River occupies its ancient bedrock valley, which is a remnant of the North American mid-continent rift system extending southward from Lake Superior. All but the southernmost tip of the basin was overrun by the last (Wisconsinan) glacial advance (Wright, 1972; Hobbs and Goebel, 1982). Consequently the surficial geology is dominated by sandy glacial drift, most of which was deposited by ice from the Superior lobe of the Laurentide ice sheet. This ice lobe retreated from the basin by about 20,000 years ago, leaving behind a hummocky landscape of moraines interspersed with sandy outwash and lacustrine plains, many of which are occupied by peatlands today (about 10-15% of the basin area). These peatlands deliver humic-stained water to the river, giving it a distinctive tea-color. Sometime near 18,000 years ago, an offshoot from the Des Moines ice lobe occupying the Mississippi River valley to the southwest spilled northeasterly into the basin and deposited a tongue of calcareous drift, much of which was outwash, extending to Grantsburg, WI. From these parent materials, soils in the basin tend to be sands to sandy-loams and generally well drained. However, the flat topography can result in poor drainage with shallow water tables despite the coarse soils. The hummocky landscape and fairly permeable surficial deposits result in substantial areas of closed surficial drainage and a strong influence of groundwater discharge on streamflow.

During glacial recession, the ice front retreated far enough north to create pro-glacial lakes Agassiz and Duluth, and meltwaters spilling from these lakes scoured the valleys of the three major rivers of the upper Midwest: the Minnesota (designated as Glacial River Warren when carrying meltwater), the Mississippi, and St. Croix rivers. When meltwater flows ceased, alluvial fans from tributaries dammed flow at points along these rivers, creating a series of riverine lakes. In particular, about 10,300 years ago the alluvial fan of the Chippewa River dammed the Mississippi River, about 100 km southeast of present-day Minneapolis-St. Paul. This created Lake Pepin, which at that time extended all the way north to St. Paul and up the St. Croix valley as well (Blumentritt et al., 2009). Hence the origin of Lake St. Croix is about contemporaneous with the origin of Lake Pepin, although similar alluvial-fan dams within the St. Croix valley may have created local pools prior to the formation of Lake Pepin. Gradually the delta of the Mississippi River at the head of Lake Pepin prograded downstream, thus shortening the lake. When the delta prograded past the confluence with the St. Croix River, the resulting sediment plug at the mouth of the St. Croix thereafter became the functional outlet threshold for Lake St. Croix. The scouring of the St. Croix valley by late-glacial meltwaters resulted in tributary outlets being abandoned high in the valley walls. Where these walls are bedrock, the tributaries now spill down rock gorges. Where the valley walls are glacial drift, however, tributaries may still be downcutting to achieve gradient equilibrium with the lowered base level of the St. Croix.

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 St. Croix River basin in eastern Minnesota and western Wisconsin. The level of detail in this documentation is aimed principally to give technically trained agency personnel enough information to understand the strengths and weakness of the model. This understanding will help resource managers to interpret model output in realistic ways that are most useful to them. Some introductory material regarding watershed modeling is included to help those readers with less technical backgrounds and to standardize some of the modeling terminology as used in this report.

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 a 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 the following: 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. A newly constructed model must commonly 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 further 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. 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" (Neitsch et al. 2011, p. 1). 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 (Winchell et al., 2013), an interface with ArcGIS geographic information systems (GIS) software (ESRI, 2012). ArcSWAT uses the topographic data to delineate the watershed into subbasins and to characterize slopes. Within each subbasin, the interface calculates the total area for each unique combination of land cover, soil type, and slope class, which are three critical factors determining the hydrologic (rainfall-runoff) response of a landscape unit. Each unique combination is defined as a "hydrologic response unit" (HRU), whose aggregate area in each subbasin is modeled as a contiguous land area with uniform soil, land cover, and slope that drains to the subbasin's channel (Figure 4). Including all possible HRUs, many of which may be small and hydrologically insignificant, can add undue complexity to the model and make run-times inefficient. Consequently, the ArcSWAT interface helps the user select the principal land cover types, soil types, and slope categories to use in determining the HRUs to include in the model. Thresholds of percent of subbasin area can be set for each factor, below which data are ignored. For example, if a 10% threshold is selected for land cover, only land-cover categories with areas greater than 10% of the subbasin area will be considered. The modeler faces significant trade-offs in this step, balancing model complexity against efficiency.

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

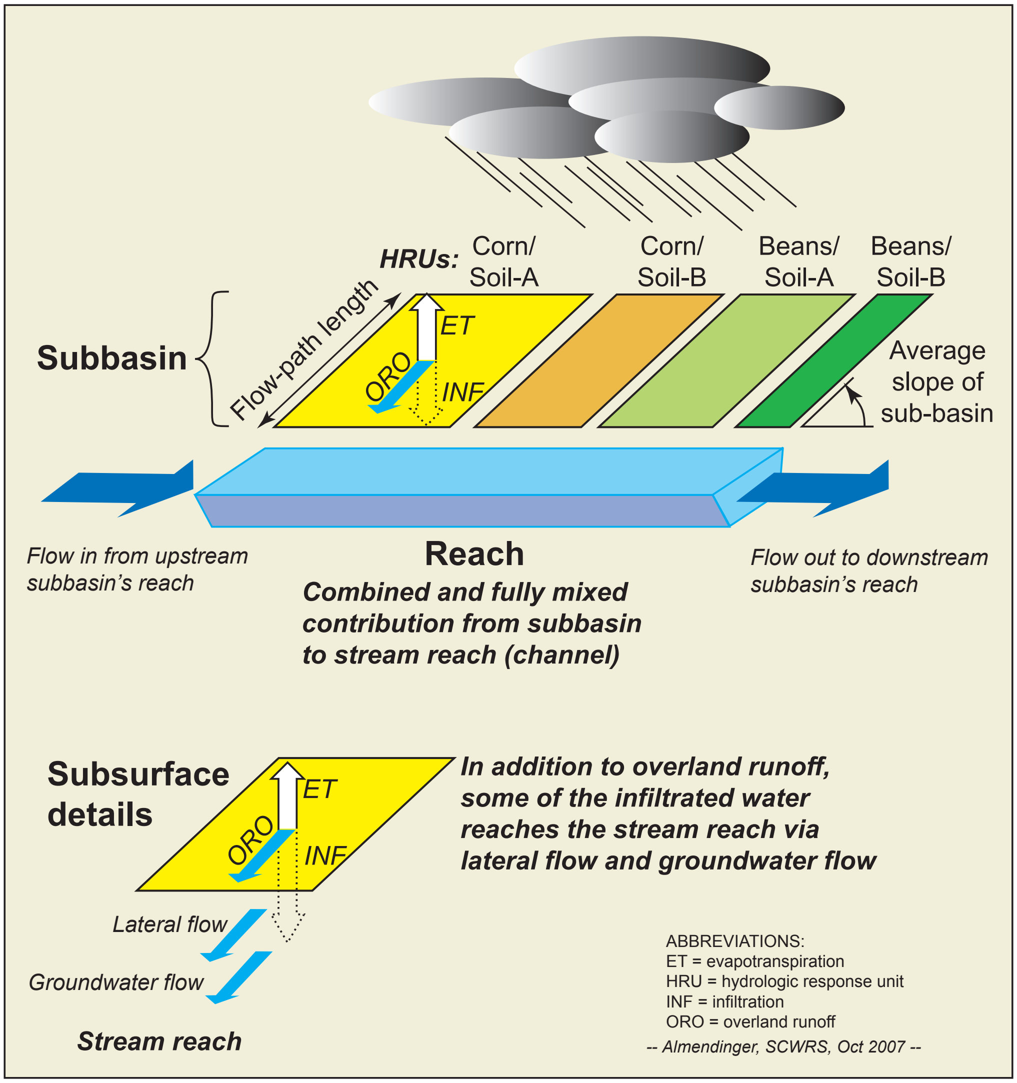


Figure 4. Conceptualization of hydrological response units (HRUs) within subbasins in a SWAT model.

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 usually quite a bit more complicated. For the St. Croix SWAT model, the watershed was divided into 419 subbasins (about 50 km^2 on average), with 3010 HRUs (about seven 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 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 St. Croix River basin, including spatial data and temporal data. Table 2a 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 2b 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.

Stream Network and Subbasin Delineation

ArcSWAT can use the grid-based tools within ArcGIS to automatically delineate the stream network and subbasin boundaries based on a digital elevation model (DEM) of the area. We used the 30-m DEM data set available from the USGS, which would commonly be adequate for basins the size of the St. Croix (Figure 5a). However, automated watershed delineation routines are error-prone in landscapes like that of the St. Croix basin because the geologically young surface has a poorly developed drainage system, with many closed depressions and large flat areas where drainage direction is ambiguous.

To reduce delineation errors due to errors or ambiguities in the DEM, a known stream network can be “burned” into the DEM to force channels to be delineated in the correct positions, thereby increasing the accuracy of the subbasin boundaries between these channels. Fortunately,

Table 2. Principal datasets for constructing the St. Croix SWAT model.

Item	Agency	Reference	Dataset	Format
(a) SPATIAL DATASETS				
Watershed base	MDNR	(1)	Hydrologically corrected minor subwatershed delineations	Polygon shapefile
Stream channels	MDNR	(1)	Hydrologically corrected high-density flow network	Polyline shapefile
Open water	MDNR	(2)	Open Water (24K Hydrography)	Polygon shapefile
Lake geometry	MDNR	(2)	Lake basin morphology	Polygon shapefile
Topography	USGS	(3)	Digital Elevation Model (DEM), 30-m resolution	Grid
Soils	USDA/NRCS	(4)	STATSGO (State Soil Geographic Database)	Polygon shapefile
Soils	USDA/NRCS	(5)	SSURGO (Soil Survey Geographic Database)	Polygon shapefile
Land cover	USDA/NASS	(6)	Crop Data Layer (CDL), 2006-10	Grid
Land cover	USGS	(3)	National Land Cover Dataset (NLCD), 1992, 2001, 2006	Grid
Land cover	UM	(7)	Land cover classification, 2007	Grid
(b) TIME-SERIES DATASETS				
Precipitation	NCDC	(8)	Cooperative Network weather stations	Tabular, time series
Temperature	NCDC	(8)	Cooperative Network weather stations	Tabular, time series
Point sources	MPCA, WDNR	(9)	Various	Tabular, time series
Loads	MCES	(10)	St. Croix River at Stillwater	Tabular, time series
Flow and loads	USGS	(11)	St. Croix River at Danbury and at St. Croix Falls Major tributaries for WY1999	Tabular, time series
Flow and loads	MPCA	(12)	Major Minnesota tributaries	Tabular, time series
Loads	Chisago SWCD	(13)	Sunrise River at Sunrise, 2006-08	Tabular, time series
Flow and loads	MCES	(14)	Valley Creek, Browns Creek (Minnesota tributaries to Lake St. Croix)	Tabular, time series
Agricultural data	USDA/NASS	(15)	Crop yields and harvested acreages; livestock populations. Annual countywide data, for the 19 counties overlapped by the St. Croix basin.	Tabular

ABBREVIATIONS:
MCES, Metropolitan Council Environmental Services; 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

REFERENCES:
(1) Vaughn 2010 and S.R. Vaughn, MDNR, personal communication, 2010. (2) MDNR 2010. (3) USGS 2010. (4) NRCS 2008a. (5) NRCS 2008b. (6) NASS 2011. (7) Marv Bauer, Remote Sensing Laboratory, Department of Forestry, Univ. of Minnesota, personal communication 2010. (8) NCDC 2010. (9) Edlund 2009b; Magalene 2009; Steve Weiss, MPCA, personal communication, 2010; Kathy Bartilson, WDNR, personal communication, 2010. (10) Karen Jensen, MCES, personal communication 2011. (11) Lenz et al. 2003 and B. Lenz, USGS, personal communication, 2005. (12) Chris Klucas, MPCA, personal communication, 2011. (13) Thiel 2009. (14) MCES 2011. (15) NASS 2009, 2010.

the Minnesota Department of Natural Resources (MDNR) has extensively surveyed the drainage network in the state, and they have constructed spatial data sets of hydrologically corrected flow networks and minor watershed boundaries (Vaughn, 2010). The flow networks from the MDNR were extended across state lines for those watersheds straddling state borders, which consequently included most of the St. Croix basin. The only area missing was the subwatershed of the upper Namekagon River, in the northeastern tip of the basin. We downloaded a current stream network for that subbasin from the Wisconsin Department of Natural Resources (WDNR) and merged it with the MDNR data, to create a complete flow network for the basin. The entire flow network was carefully reviewed and manually edited where necessary to create a continuously connected simple flow network (i.e., with no gaps and no loops). Stream connections were simplified as needed where flow lines converged on virtual confluences within the boundaries of some lake lakes. This was especially important for Lake St. Croix, where in the original data set the nodes (junctions) of tributary flow lines with the main channel were not always close to the tributary mouths.

Given this DEM with the corrected and edited flow network burned in, ArcSWAT delineated the flow network and identified all confluences, or nodes, where the flow network branched. These represented subbasin outlets, except where modified as noted. The user can

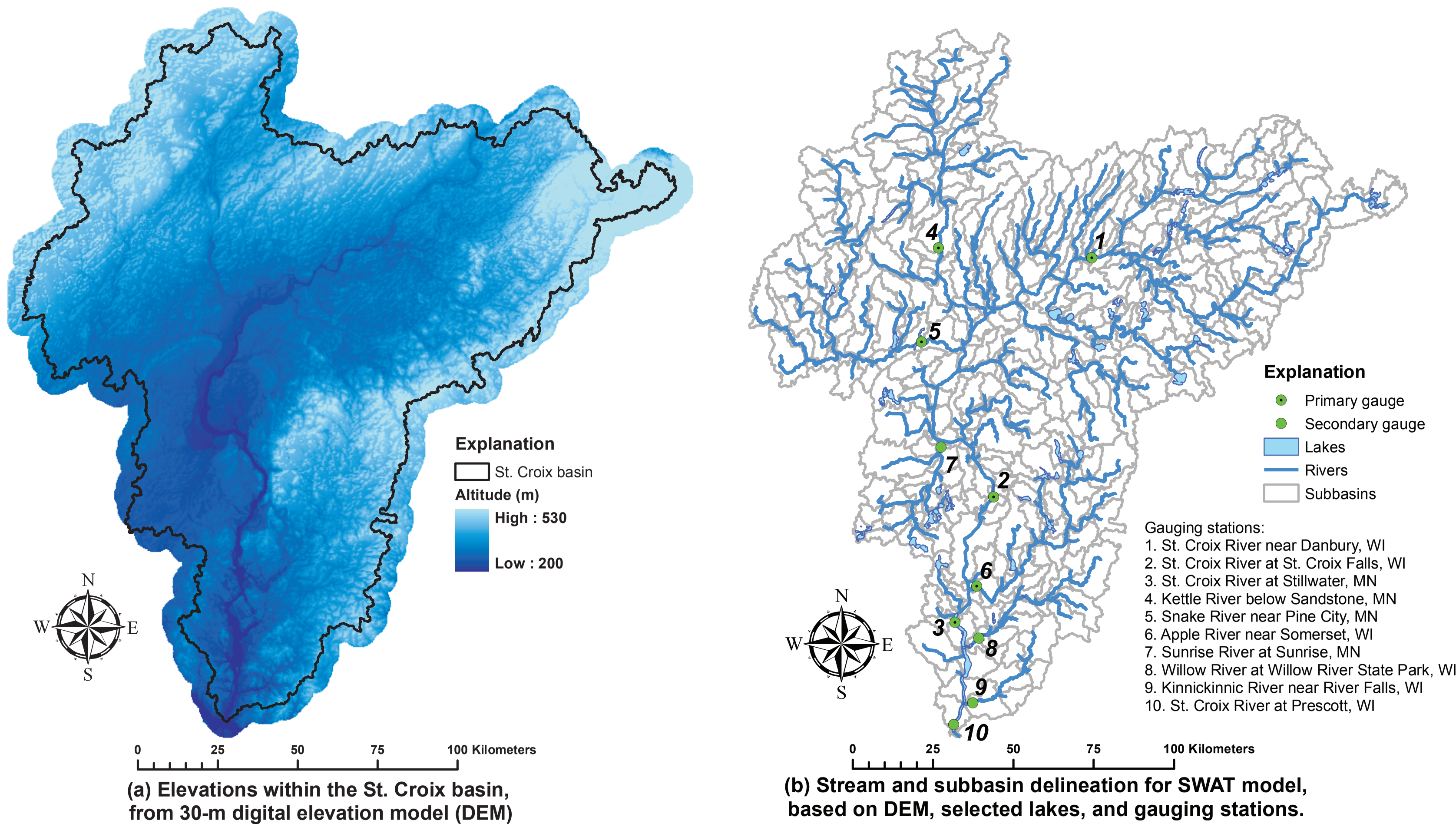


Figure 5. (a) Topography of the St. Croix basin and (b) the lakes, stream network, and subbasin delineation in the SWAT model.

force the creation of extra subbasin outlets at other points along the stream network as needed. In particular, we added points to locate the outlets and inlets to most on-channel lakes included in the model, called “reservoirs” in SWAT, and we deleted any in-lake nodes. The net effect was that we moved in-lake nodes to the lake margin at mouth of each inlet. This added detail assured that the subbasin delineation routine in ArcSWAT would make each lake outlet coincide with a subbasin outlet, and that each inlet would have a distinct subbasin, separate from the direct drainage area of the lake.

The St. Croix basin has far more lakes than can be included individually in the model. We arbitrarily chose to consider lakes with surface areas larger than 200 ha (about 500 acres), which resulted in about 40 lakes. We included a few smaller lakes of particular interest based on previous studies (namely, thee reservoirs in the Willow River watershed, western Wisconsin). We also separated Lake St. Croix into four pools, to correspond to previous studies (Robertson and Lenz, 2002; Triplett et al., 2009; Edlund et al., 2009a and b). A total of 45 lakes were identified by this process for possible inclusion, 39 of which were selected for this version of the model. The remaining open-water bodies were simulated as Ponds, which are conceptual aggregations of water bodies in each subbasin (see SWAT Ponds and Wetlands section below).

Finally, given the DEM, the channel network with branch points (nodes), and the reservoir inlets and outlets, the delineation routine within ArcSWAT created a total of 419 subbasins within the St. Croix basin (Figure 5b). Also shown in Figure 5b are the gauging stations used for flow and water-quality calibration.

Lakes: SWAT Reservoirs

The reservoirs (on-channel lakes) included in the model needed further configuration to account for their hydraulic influence on streamflow (Table 3). For lakes on the Minnesota side of the basin, reported areas and volumes were available as attributes attached to the lake morphology spatial data set posted by the MDNR. For Wisconsin lakes, reported areas and volumes were taken from WDNR (2009). If volume was not reported, it was calculated from lake area and mean depth; if mean depth was not reported, it was estimated as half the maximum depth.

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 is released downstream). These data are not commonly available for lakes, and estimating their values would require knowledge of how lake volume and area change as lake level changes. In a previous study in the Sunrise River watershed, one of the principal tributaries to the St. Croix, we used bathymetric data for 11 lakes to construct the following relations between lake area (which is commonly known), and how area and volume change with a change in lake level:

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

Area change factor = 7.8761 * sqrt*A* – 48.669

($N = 11$, $r^2 = 0.91$)

Table 3. Data summary for on-channel lakes included as reservoirs in the SWAT model of the St. Croix River basin.

			Area (ha)		Volume (ha-m)			SWAT Parameters			
Name	Lat	Lon	Princ	Emerg	Princ	Emerg	Mean Depth (m)	NSED (mg/L)	D50 (um)	PSETLR1 (m/yr)	NSETLR1 (m/yr)
Border Pools (upstream to downstream)											
St. Croix Falls Reservoir	45.426	-92.648	205	352	879	1,202	3.98	0.36	7.2	223.6	10
Lake St. Croix Pools											
Bayport Pool	45.030	-92.777	1,026	1,459	7,215	9,194	6.80	0.47	9.4	85.9	10
Troy Beach Pool	44.940	-92.757	1,150	1,614	12,739	14,984	10.51	0.32	6.5	103.1	10
Black Bass Pool	44.870	-92.769	477	748	7,150	7,990	13.50	0.16	3.2	178.5	10
Kinnickinnic Pool	44.788	-92.791	512	795	5,482	6,393	9.79	0.23	4.6	148.5	10
Minnesota Lakes											
Big Marine Lake	45.219	-92.859	605	920	2,144	3,242	3.54	0.70	13.9	8.1	10
Cross Lake	45.852	-92.944	323	530	1,432	1,971	4.18	0.43	8.6	62.1	10
Forest Lake	45.273	-92.948	818	1,197	2,603	4,143	3.27	0.87	17.5	5.7	10
Green Lake	45.343	-92.900	614	932	1,921	3,039	3.17	0.78	15.6	7.3	10
Knife Lake	45.981	-93.297	445	704	1,153	1,929	2.64	0.80	16.0	14.1	10
Lindstrom-Chisago Lakes	45.367	-92.866	603	917	1,943	3,037	3.25	0.75	15.1	7.0	10
North Center Lake	45.406	-92.828	321	528	679	1,214	2.18	0.82	16.4	6.5	10
Pine Lake	46.198	-93.062	269	451	1,309	1,748	4.51	0.36	7.3	14.0	10
Pokegama Lake	45.845	-93.040	540	833	1,906	2,873	3.50	0.66	13.3	13.8	10
Rush Lake	45.687	-93.068	1,124	1,581	3,310	5,500	3.11	1.08	21.5	6.4	10
South Center Lake	45.378	-92.821	355	577	1,478	2,079	3.97	0.48	9.5	6.5	10
Wisconsin Lakes											
Balsam Lake	45.465	-92.426	742	1,099	4,344	5,725	5.64	0.48	9.7	12.3	10
Bardon Lake	46.213	-91.872	289	481	2,961	3,437	9.14	0.19	3.7	15.7	10
Big Round Lake	45.524	-92.301	355	578	1,102	1,704	3.05	0.62	12.4	10.1	10
Big Sand Lake	45.824	-92.218	497	775	1,335	2,215	2.74	0.81	16.3	5.5	10
Bone Lake	45.535	-92.389	640	965	4,763	5,932	7.01	0.36	7.2	9.5	10
Cedar Lake	45.214	-92.571	389	625	1,746	2,412	4.27	0.46	9.2	16.0	10
Clam Lake	45.793	-92.325	551	848	2,135	3,123	3.81	0.62	12.3	31.3	10
Deer Lake	45.402	-92.522	280	467	2,475	2,933	7.92	0.21	4.2	12.2	10
Devils Lake	45.909	-92.337	350	570	1,581	2,173	4.27	0.44	8.8	7.7	10
Eau Claire Lakes	46.294	-91.513	987	1,411	7,078	8,975	6.91	0.45	9.1	20.0	10
Little Falls Lake	45.018	-92.695	61	95	139	245	2.38	0.33	6.6	56.8	10
Mallalieu	44.990	-92.743	92	160	144	287	1.65	0.58	11.7	38.8	10
Minong Flowage	46.152	-91.928	558	858	1,486	2,490	2.74	0.86	17.2	27.9	10
Namekagon Lake	46.223	-91.104	1,188	1,661	5,790	8,117	4.88	0.71	14.1	10.2	10
Nelson Lake	46.093	-91.470	912	1,317	2,963	4,701	3.35	0.90	18.0	9.4	10
New Richmond Flowage	45.127	-92.529	81	138	70	198	1.07	0.85	16.9	25.9	10
Sand-Birch Island Lakes	45.932	-92.161	647	975	3,036	4,220	4.57	0.56	11.1	5.8	10
Shell Lake	45.733	-91.899	942	1,354	6,873	8,673	7.01	0.44	8.8	10.0	10
Spooner Lake	45.840	-91.824	384	618	779	1,435	2.13	0.92	18.4	8.5	10
St. Croix Flowage	46.256	-91.872	689	1,030	1,335	2,606	2.13	1.23	24.6	23.9	10
Upper St. Croix Lake	46.357	-91.803	308	509	1,292	1,803	3.96	0.44	8.9	15.4	10
Wapogasset Lake	45.328	-92.425	418	666	2,307	3,031	5.18	0.39	7.9	22.7	10
Yellow Lake	45.919	-92.398	830	1,213	4,971	6,536	5.79	0.50	10.0	30.5	10

NOTES: Lat, latitude of lake centroid; Lon, longitude of lake centroid; princ, Principal; Emerg, emergency; ha, hectare; ha-m, hectare-meter (a measure of volume); m, meter; mg/L, milligrams per liter; NSED, equilibrium suspended sediment concentration; D50, median grain size of suspended sediment; PSETLR1, phosphorus apparent settling velocity during March-October; NSETLR1, nitrogen apparent settling velocity during March-October. "Principal" refers to lake area and volume at the level of the lake's threshold. "Emergency" refers to the area and volume at the level the lake is unlikely to rise above. See text for explanations of how Principal values, Emergency values, NSED, and PSETLR were estimated. Reported areas and volumes for Minnesota lakes were taken from the attribute table of the lake morphology spatial data set posted by the Minnesota Department of Natural Resources. Reported areas and volumes for Wisconsin lakes were taken from WDNR, 2009, Wisconsin Lakes, Publication PUB-FH-800, 180 pp. Volume was calculated, as necessary, from reported lake area and mean depth; if mean depth was not reported, it was assumed to be half the maximum depth.

(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 * sqrt*A* + 83.369

(N = 11, r^2 = 0.99)

where lake area *A* is given in hectares (ha) and sqrt*A* 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 each lake was normally about 0.5 m above its threshold, and could rise another 1.5 m during extreme snowmelt or stormflow events (i.e., up to 2 m above the threshold). 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* 1.5 m times the area and volume change factors to the reported (starting) values (Table 3). The percentage of lake area and volume that changes with a unit change in lake level is inversely proportional to lake area. That is, according to these relations, for a 1-m change in lake level, the *relative* change in lake area and volume would be much greater for a small lake than for a large lake. For the 45 lakes explored in the St. Croix basin, a 1-m rise in lake level would increase lake area by an average of 24% and increase lake volume by an average of 22%. 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.

Lakes are natural sediment traps, and SWAT makes two key assumptions in its sediment-trapping algorithm. The first is that because of wind-driven turbulence, lakes (or reservoirs in SWAT's terminology) sustain a minimum "equilibrium" sediment concentration (NSED, in mg/L). In other words, the sediment concentration in the lake is not allowed to fall below this minimum value. While some shallow reservoirs with ample access to fine sediment may have an appreciable NSED value, most natural lakes with well-washed shorelines should have a low NSED value, very near zero. Because suspension of fine sediment by wind-driving turbulence in lakes should be proportional to lake area (increasing wind fetch) and inversely proportional to lake depth (reducing access to the fine sediment), we created a simple function to calculate possible NSED values:

NSED = *a* * sqrtA / D

where sqrtA is the square root of the lake area (ha), D is the mean lake depth (m), and *a* is a constant. With *a* set to 0.1, this equation gave NSED values ranging from 0.16 to 1.23 mg/L, with an average of 0.58 mg/L. If NSED is set too large, then the lakes become sources, rather than sinks, of sediment. Nine lakes were sediment sources with NSED values calculated as above, which was not likely. For these lakes, the NSED was lowered to 0.1 mg/L to make these lakes either net sinks or only negligible sources of sediment.

The second assumption SWAT makes about sediment in lakes is that any sediment above the NSED concentration settles according to Stokes' Law, which makes the median grain size (D50) a sensitive calibration parameter. While the sediment grain size delivered to a lake depends on many factors, the sediment that passes through a lake comprises only the fine grains that remain in suspension. We reasoned that a lake's D50 value may thus be proportional to its NSED value, since both depend on factors maintaining sediment in suspension. Consequently D50 was set to a simple factor of NSED:

$$D50 = b * NSED$$

where *b* is a constant, set here to 20. This results in D50 values ranging from 3-25 µm and averaging 12 µm, in the fine-silt range. During calibration, the coefficients (*a* and *b*) of both NSED and D50 were adjusted so that the amount of sediment trapped was reasonable. On average, with a sediment depositional area of 80% of the principal area for each lake and with a sediment bulk density (dry wt per wet volume) of about 0.5 g/mL, the 39 lakes included in the model trapped an average of 71% of incoming sediment and deposited a 2-mm layer of sediment each year.

Likewise, lakes also trap some of the phosphorus load in their sediments. SWAT simulates the loss of phosphorus to lake sediments by using an apparent settling velocity *Vs* (called PSETLR in SWAT, with units of m/yr), in accordance with a well-used algorithm originally put forth by Vollenweider (1975, 1976). The *Vs* is not a true settling velocity for particles, but a lumped, black-box parameter that represents the net result of all processes that trap (or release) phosphorus to (or from) lake sediments. Because these many processes are not explicitly addressed and unlikely to be perfectly covariant, values for *Vs* reported in the literature vary widely. For natural lakes *Vs* ranges from about 1 to 100 m/yr but more frequently falls between 5 to 20 m/yr (Chapra, 1997). Reservoirs tend to have higher values (Panuska and Robertson, 1999) and wider ranges, from -90 to 269 m/yr in one study (Higgins and Kim, 1981).

SWAT allows the user to set two values for *Vs*, PSETLR1 for the runoff-prone part of the year and PSETLR2 for the rest of the year. For months with runoff (March-October), when sediment delivery and settling of sediment-bound phosphorus is likely to be the greatest, we developed a simple but untested relation to estimate *Vs* (PSETLR1 in this case). The *Vs* parameter is defined as the product of the mean depth (*D*) of the lake times a rate constant (*s*) (Vollenweider, 1975). Brett and Benjamin (2008) demonstrate that the rate constant *s* is inversely proportional to the square root of hydraulic residence time. Consequently a simple relation could be formulated as the following:

$$\text{PSETLR1} = Vs = s * D = c * T_r^{-d} * D$$

where *Vs* (or PSETLR1) is the apparent settling velocity of phosphorus in m/yr; *s* is the rate constant; *D* is mean depth of the lake in m; *c* is a constant of proportionality; T_r is lake hydraulic residence time in days; and *d* is an exponent. Hydraulic residence time T_r was determined for each lake as an 18-year average from the SWAT model following hydrologic calibration (lake volume divided by mean flow). With *c* set to 50 and *d* set to 0.5, the estimated PSETLR1 values then ranged from 5 to 224 m/yr, with an average of 34 m/yr and median of 14 m/yr. These values are larger than those commonly found for natural lakes but lie within the range for reservoirs. This method appears to be a reasonable way to set provisional *Vs* values that may prove useful when no calibration data exist. The four pools of Lake St. Croix were slight exceptions to the above equation, because applying such settling losses sequentially to immediately adjacent pools would result in overestimated trapping. Hence the PSETLR1 values for the Lake St. Croix pools were reduced to 60% the value as calculated above, which allowed the model to match the phosphorus trapping for the 1990s as estimated by the sediment coring work.

For the non-runoff prone months (November through February), modeled phosphorus levels were too low relative to estimated loads, and hence PSETLR2 values were set to zero to minimize any trapping by lakes. Calibration would have been improved if SWAT allowed release of phosphorus from the lake sediment during winter (i.e., negative PSETLR2 values). Release of sediment-bound phosphorus from lakes during winter is conceivable but unknown at present.

SWAT allows similar settling parameters for nitrogen in reservoirs. Because nitrogen loads are not an identified problem in the St. Croix, calibration for total nitrogen was not pursued as rigorously as for sediment and phosphorus. The runoff-season (March-October) settling rate (NSETLR1) was set to 10 m/yr to approximately match the observed total nitrogen annual loads at the Stillwater, MN gauge site, and the non-runoff season settling rate (NSETLR2) was set to zero, similar to the phosphorus settling rates.

Lowland Depressions: SWAT Ponds and Wetlands

Lowland 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 lowlands 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 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. Because of the similarity of these features and to keep the St. Croix model as simple as possible, we used only the Pond feature because of its slightly greater capability.

In the St. Croix SWAT model, we used the NLCD 2001 data set to identify all lowlands, namely, open-water and wetland (wooded and emergent) grid cells (excluding those open-water grid cells representing the 39 reservoirs). For each subbasin, the Pond principal area was set to the aggregate lowland area, and Pond depth was set to 1.5 m, giving a principal volume (in ha-m) of 1.5 times its area. Emergency volumes and areas were set to 1.3 times the principal values, and drainage areas set to 3.3 times the principal surface areas. This Pond geometry was determined as an average from a more detailed analysis of depressions and drainage areas in the Sunrise River watershed, one of the principal tributaries to the St. Croix (Almendinger and Ulrich 2010). However, in reality these parameters are undoubtedly highly variable across the basin, and the St. Croix model could be greatly improved by development of an objective algorithm to systematically identify depression drainage areas and their relation to existing lowland land covers (open water and wetland). In the St. Croix model, Ponds influenced a substantial fraction of the St. Croix basin: on average, lowlands occupied 14% of each subbasin and received drainage from 45% of each subbasin (Table 4). That is, runoff from nearly half of the basin (about 45%) was processed by Ponds before being delivered to the channel network.

Ponds were allowed to spill at a rate of one-tenth their volume above principal each day (i.e., the NDTARG parameter was set to 10 days). At volumes below principal, no surface outflow occurs. Evaporation was set equal to the potential evapotranspiration (PET) for each day (rather than the default of 0.6*PET). Lowland depressions can have substantial groundwater interaction. In prior releases of SWAT, seepage from Ponds and Wetlands was lost from the system, rather than contributing to stream baseflow as it should. Because it was unclear if this water-balance error had been corrected in the current code, and because it seems likely that most lowlands in the St. Croix are dominated by groundwater discharge and not recharge (out-seepage), such seepage was disallowed by setting the Pond hydraulic conductivities to zero and forcing all Pond outflow to occur as surficial outflow.

Water-quality parameters for Ponds were set similarly as for Reservoirs but modified as needed during calibration. Because of the shallowness of Ponds and their proximity to erosional sources, Pond sediment

Table 4. Summary of Pond areas in the subbasins of the St. Croix SWAT model.

Statistic	Subbasin Area (km^2)	*Percent of subbasin occupied by:* Lowlands	Lowland Catchments
Mean	47.70	14.1%	45.2%
Median	39.59	12.7%	41.8%
Min	0.01	0.1%	0.2%
Max	205.80	61.5%	100.0%

NOTES: Data are for 419 subbasins. "Lowlands" refers to the sum of open water plus emergent and woody wetlands from the 2001 NLCD data set. Catchments were calculated as 3.3 times the lowland areas, a factor estimated for the Sunrise River watershed, a tributary in the southwest quadrant of the St. Croix basin.

parameters were set to larger values than those for reservoirs. Namely, NSED was set to 9 mg/L and D50 to 62.5 µm (near the silt-sand boundary). The nutrient settling season was set the same as for reservoirs (March through October), and the phosphorus settling rate (PSETLP1) was set at 100 m/yr, about three times the average reservoir rate, which trapped about 10% of the incoming phosphorus. We had no data to test this trapping efficiency, but it is of the appropriate magnitude to mesh with the overall budget of transported phosphorus, from what appears to be reasonable phosphorus loads from uplands and reasonable losses in floodplains and lakes on the way to the gauging station at Stillwater. Nitrogen settling rates (NSETLP1) were simply set to the same values as for reservoirs, which helped attain the overall total nitrogen loads at Stillwater. Again, further work needs to be done to better parameterize these features objectively.

Soils

Two soil spatial datasets were available for the St. Croix basin, 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 in theory should improve model accuracy for selected localities within the basin; however, the trade-off is that the added detail reduces the model run efficiency for large modeled areas (Geza and McCray, 2008). Given the large size of the St. Croix basin, we chose the coarser STATSGO soils data to make model runs tractable.

In SWAT, the principal soil parameter that affects the rainfall-runoff process is the hydrologic soil group (HSG), which ranges from coarse well-drained soils (HSG type A) to fine poorly-drained soils (HSG type D). According to the STATSGO data set (Figure 6), about 75% of the basin area has well drained soils, of either HSG type A (29%) or type B (46%). Type A soils have low runoff potential, with commonly >90% sand and <10% clay. Type

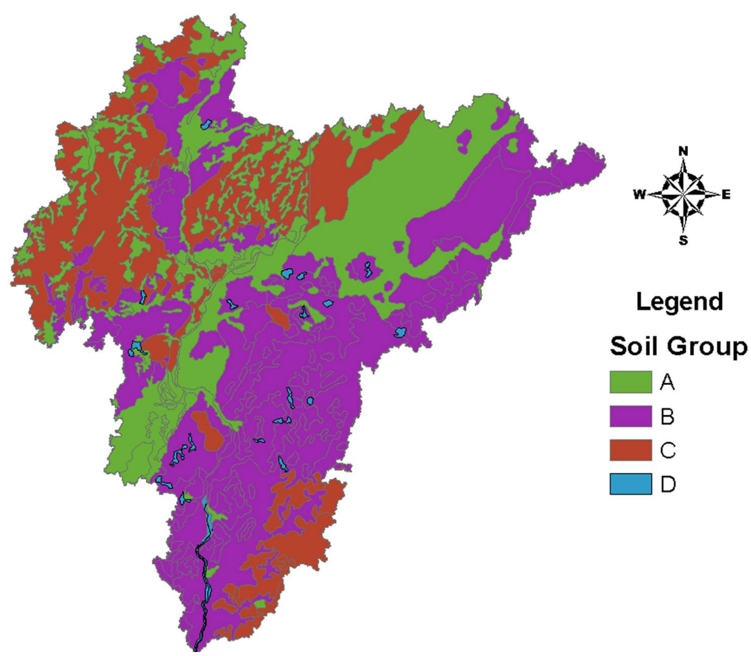


Figure 6. Hydrologic soil groups in the St. Croix basin, based on the STATSGO data set.

B soils have moderately low runoff potential, with 50-90% sand, 10-20% clay, and loamy sand or sandy loam textures. About 24% of the area has HSG type C soils, with moderately high runoff potential, <50% sand, 20-40% clay, and a variety of loamy textures. Only a small fraction (1%) are designated as type D soils, with high runoff potential and >40% clay (see NRCS 2007 for HSG descriptions). The coarse (A and B) soils were developed on pitted glacial outwash plains or shallow lake plains in the central part of the basin, while the finer (C) soils correspond to terminal or ground moraines in the northern third and extreme southeast part of the basin (Hadley and Pelham, 1976; Cummins and Grigal, 1981; Hobbs and Goebel, 1982). Where the landforms are flat enough to limit drainage, water tables can be high and peatlands can form the surface soils, despite coarse underlying deposits.

Land Cover: Agricultural Land

Cropland Area

At least five post-2000 spatial data sets were considered as input to the SWAT model (Table 1). We chose to begin with the Crop Data Layer (CDL) for 2007 because it appeared to be broadly representative of land use during the 2000-09 decade (the "2000s"), meaning the present-day conditions for the purposes of this report (Figure 3b). The CDL data sets have the advantage of identifying the principal crops individually, whereas the National Land Cover Dataset (NLCD) layers identify only generic cropland.

To more fully characterize the area of tilled cropland, we compared the available spatial data sets with tabular data. Tilled cropland here refers to corn, soybeans, small grains, and alfalfa; pasture and other untilled grassland were excluded. The spatial data included the CDL layers from 2006-10 (NASS 2011), and the tabular data were annual harvested areas for 2000-08 compiled by the National Agricultural Statistics Service for each county (NASS 2009), scaled by the percent of each county within the St. Croix basin. The area of tilled cropland varied from year to year in the CDL data sets, ranging from 1182 km^2 in 2008 to 2199 km^2 in 2006, with an average of 1699 km^2. In contrast, the area of tilled cropland in the NASS tabular data sets was always larger than that in the spatial data, with a 2000-08 average area of 2264 km^2. We hypothesize that the spatial data sets may systematically underestimate the true area of tilled cropland because some areas cropped as hay (and that are part of a tillage rotation) may be incorrectly categorized as grassland or other non-tilled herbaceous vegetation. Consequently, we chose to use the 2264 km^2 value from the NASS tabular data set as the more representative area of cropland during the 2000s for model construction. Of the tilled cropland in the basin, 33% was occupied by corn-grain, 9% by corn-silage, 22% by soybeans, 5% by small grains, and 31% by alfalfa (Table 5, bottom).

Table 5. Crop areas and yields by quadrant and county in the St. Croix basin, 2000-08.

County	Corn-grain		Corn-silage		Soybeans		Small grains		Alfalfa		Hay, other	
	Area (km^2)	Yield (*t/ha*)	Area (km^2)	Yield (*t/ha*)	Area (km^2)	Yield (*t/ha*)	Area (km^2)	Yield (*t/ha*)	Area (km^2)	Yield (*t/ha*)	Area (km^2)	Yield (*t/ha*)
Northwest Quadrant (NW)												
MN-Aitkin	0.83	4.25	0.54	8.32	2.26	1.88	2.24	1.71	4.61	4.67	26.42	3.36
MN-Carlton	0.46	4.94	1.76	7.98	n/a	n/a	0.58	1.61	16.65	4.66	40.46	3.33
MN-Kanabec	44.08	5.20	12.63	9.50	36.27	1.56	13.97	2.10	50.33	6.19	80.10	3.92
MN-Mille Lacs	10.57	5.60	2.79	10.50	8.17	1.79	1.52	1.98	7.36	6.6	10.50	4.14
MN-Pine	44.40	5.63	27.78	9.70	37.89	1.87	21.22	1.91	74.35	6.67	149.73	3.88
Total area & average yield	*100.33*	*5.12*	*45.49*	*9.20*	*84.58*	*1.77*	*39.55*	*1.86*	*153.30*	*5.76*	*307.21*	*3.73*
Percent of tilled area	*23.7%*		*10.7%*		*20.0%*		*9.3%*		*36.2%*			
Southwest Quadrant (SW)												
MN-Anoka	3.64	5.42	0.29	8.50	2.21	1.52	0.73	2.21	2.15	5.48	1.42	3.66
MN-Chisago	88.22	6.12	11.70	11.11	94.68	1.81	3.50	1.60	46.67	6.15	16.42	4.08
MN-Isanti	22.63	5.75	0.91	9.53	21.46	1.52	1.80	1.64	8.51	5.52	2.78	3.66
MN-Ramsey	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
MN-Washington	51.67	7.38	2.91	10.94	38.27	2.09	4.15	1.95	27.04	6.17	10.30	4.13
Total area & average yield	*166.16*	*6.17*	*15.81*	*10.02*	*156.62*	*1.74*	*10.19*	*1.85*	*84.37*	*5.83*	*30.92*	*3.88*
Percent of tilled area	*38.4%*		*3.7%*		*36.2%*		*2.4%*		*19.5%*			
Northeast Quadrant (NE)												
WI-Bayfield	n/a	n/a	n/a	n/a	n/a	n/a	1.25	2.10	9.26	4.07	16.41	3.09
WI-Burnett	40.24	5.23	15.31	10.29	21.60	1.70	5.93	2.16	51.01	4.50	20.16	3.04
WI-Douglas	n/a	n/a	n/a	n/a	n/a	n/a	1.04	1.96	14.39	3.95	30.46	2.86
WI-Sawyer	1.44	4.60	0.83	8.37	0.42	1.45	0.27	2.01	2.73	4.65	2.82	3.47
WI-Washburn	26.11	4.93	13.18	9.33	11.20	1.55	4.92	2.50	38.83	4.36	29.59	3.05
Total area & average yield	*67.79*	*4.92*	*29.32*	*9.33*	*33.22*	*1.57*	*13.40*	*2.15*	*116.22*	*4.30*	*99.44*	*3.10*
Percent of tilled area	*26.1%*		*11.3%*		*12.8%*		*5.2%*		*44.7%*			
Southeast Quadrant (SE)												
WI-Barron	15.00	6.16	4.87	11.61	6.23	2.05	1.84	2.40	15.39	5.04	3.43	3.61
WI-Pierce	26.49	7.52	4.15	13.56	11.67	2.28	2.95	2.68	16.35	5.74	1.25	3.76
WI-Polk	190.40	6.20	49.27	11.60	93.42	1.86	20.24	2.25	181.52	5.00	44.46	3.99
WI-St. Croix	184.99	6.66	49.44	13.67	105.45	2.04	23.46	2.61	144.66	5.51	20.08	4.07
Total area & average yield	*416.88*	*6.63*	*107.74*	*12.61*	*216.78*	*2.06*	*48.49*	*2.48*	*357.92*	*5.33*	*69.23*	*3.85*
Percent of tilled area	*36.3%*		*9.4%*		*18.9%*		*4.2%*		*31.2%*			
Whole Basin												
Total area & average yield	*751*	*5.72*	*198*	*10.28*	*491*	*1.80*	*112*	*2.08*	*712*	*5.27*	*507*	*3.62*
Percent of tilled area	*33.2%*		*8.8%*		*21.7%*		*4.9%*		*31.4%*			
Total tilled area in basin = 2264 km²												

NOTES: County-wide data for 2000-08 from U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) web site (NASS 2009). Areas for each crop have been scaled by the fractional land area of each county within the St. Croix basin. Crop yields refer to dry biomass per unit area. See conversion table for factors to convert reported yields to dry biomass.

General Crop Rotations in Basin Quadrants

Cropland areas and yields are not evenly distributed across a basin as large as that of the St. Croix because of differences in climate, soils, and culture. For example, the growing season is shorter in the northern half of the basin, resulting in smaller crop yields, and dairy farming has been traditionally more important in Wisconsin than in Minnesota. To account for these spatial differences, we divided the St. Croix basin into approximate quadrants (Figure 7), by which crop areas and yields were stratified (Table 5). Yields were converted from the NASS-reported units (bushels per acre) to SWAT-consistent units (metric tons dry biomass per hectare) with the conversion factors given in Table 6.

The relative cropland areas in each quadrant formed the basis for identifying the basic crop rotations in the St. Croix basin. A crop rotation is a sequence of crops planted in the same field, commonly over several years. For example, a 2-year corn-soybean rotation would consist of corn and soybeans being planted in alternate years. In SWAT, crop rotations are applied to cropland HRUs, staggered in time so that they reproduce the reported relative areas of each crop on the landscape, year after year. To simplify crop rotations we added the area of small grains to that of soybeans. Rotations including corn-grain, corn-silage, soybeans, and alfalfa were constructed for each of the four quadrants according to the relative areas of each crop given in

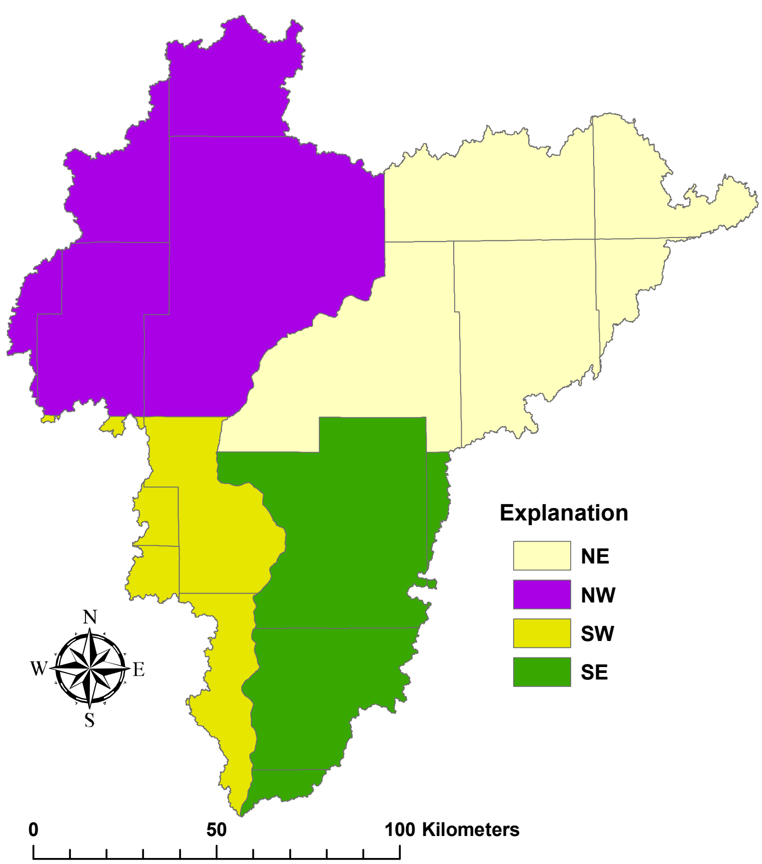


Figure 7. St. Croix quadrants for crop and livestock characterization.

Table 5. Two simple crop rotations could adequately reproduce the NASS-reported crop areas: a 2-yr corn-grain/soybean rotation (CS), and a 6-yr corn-grain/corn-silage/alfalfa (4 yr) rotation (CA). The areas of these two rotations were nearly equal within the basin as a whole: 52% of cropland was CS (1175 km^2) and 48% was CA (1089 km^2). However, the rotations were not distributed evenly across the basin; i.e., the four quadrants of the basin had different proportions of these two rotations (Table 7; see data for 2000s).

Table 6. Factors to convert crop yields as commonly reported in the USA to metric dry biomass units.

Crop	Standard Densities (lb/bushel)	Common Reporting Units in USA	Moisture Content (%)	Conversion Factor to Dry Biomass Yield (metT/ha)
Barley	48	bushels/acre	14.5%	0.0461
Corn	56	bushels/acre	15.5%	0.0531
Oats	32	bushels/acre	14.0%	0.0309
Wheat	60	bushels/acre	13.5%	0.0583
Soybeans	60	bushels/acre	13.0%	0.0586
Rye	56	bushels/acre	14.0%	0.0541
Sunflower	100	bushels/acre	10.0%	0.1010
Flax	56	bushels/acre	9.0%	0.0572
Sorghum	55	bushels/acre	14.0%	0.0531
Corn silage	na	short tons/acre, moist	65.0%	0.3182
Alfalfa, hay	na	short tons/acre, dry	0.0%	0.9091

NOTES: Common grain densities and moisture contents obtained from North Dakota State University (NDSU) Agriculture and University Extension, 1987, Equivalent Weights of Grain and Oilseeds, Publication AE-945, 3 pp. Corn silage (optimal) moisture content from Schroeder, J.W., 2004, Corn silage management, North Dakota State University (NDSU) Agriculture and University Extension, Publication AS-1253.

Table 7. Cropland rotations by quadrant in the St. Croix SWAT model.

Quadrant	1990s: Percent of Cropland	2000s: Percent of Cropland	Rotation
Minnesota			
Northwest Quadrant (NW)	35%	53%	Cg1-S1
	65%	47%	Cg1-Cs1-A4
Southwest Quadrant (SW)	65%	76%	Cg1-S1
	35%	24%	Cg1-Cs1-A4
Wisconsin			
Northeast Quadrant (NE)	15%	36%	Cg1-S1
	85%	64%	Cg1-Cs1-A4
Southeast Quadrant (SE)	30%	46%	Cg1-S1
	70%	54%	Cg1-Cs1-A4
St. Croix Basin	36%	52%	Cg1-S1
	64%	48%	Cg1-Cs1-A4

Total cropland area:	**1990s:**	**2000s:**
-- in km^2	2329 km^2	2264 km^2
-- as % of basin	11.7%	11.3%

NOTES:
Cg1-S1 = 1-yr Corn-gratn / 1-yr Soybeans
Cg1-Cs1-A4 = 1-yr Corn-grain / 1-yr Corn-silage / 4-yr Alfalfa
Northwest quadrant includes Aitkin, Carlton, Kanbec, Mille Lacs, and Pine counties.
Southwest quadrant includes Anoka, Chisago, Isanti, Ramsey, and Washington counties.
Northeast quadrant includes Bayfield, Burnett, Douglas, Sawyer, and Washburn counties.
Southeast quadrant includes Barron, Pierce, Polk, and St. Croix counties.

Spatial Distribution of Rotations within Quadrants

To identify the spatial location of different crop rotations, we overlaid the five CDL data sets from 2006-10 and compared how crops changed from year to year. (In ArcGIS terms, the grids were combined to form a grid identifying all unique sequences of crops.) This process demonstrated significant annual variability in crop locations or errors in identification of crops. The *intersection* of these five data sets identified grid cells that were cropland *every* year from 2006-10 and totaled only 647 km^2, whereas the *union* of the data sets identified grid cells that were cropland in *any* year and totaled 4371 km^2. Neither value is close to any other reported value for cropland area during this time: the intersection underestimates actual cropland area, and the union overestimates it. Further, the divergence between the intersection and union areas increases as data sets are added. Thus, while such combined grids may be useful for identifying the general location and sequence of principal crops, they should not be used to assess the total area of cropland. Again, for total cropland area we adhered to the 2000-08 average area of 2264 km^2 derived from the NASS tabular data.

To distribute the rotations spatially we then began with the union of all CDL cropland from 2006-10 because it included all possible land that was cropland (4371 km^2), out of which we chose 2264 km^2 that represented the most likely location of actual cropland in a "typical" year during the 2000s. Each grid-cell category of the CDL-cropland union was reclassified according to (a) its quadrant and (b) whether its 5-yr crop sequence (from 2006-10) could be best represented by the CS or the CA rotation. To determine the rotations within each quadrant, grid-cell categories were ranked according to years (out of 5) that were corn-grain and soybeans and assigned the CS rotation down to the rank where the cumulative targeted area for CS in that quadrant was achieved. Likewise, grid-cell categories were ranked according to years of corn-silage, alfalfa, and grass and assigned the CA rotation, until the target area for CA in that quadrant was achieved. The remaining grid-cell categories (commonly grassland for three or four years out of five) in each quadrant were assigned to be pasture, under the assumption that land that is occasionally cropped, or mis-identified as cropland because of proximity, is more likely to be pasture than are other grasslands scattered across the basin. The three basic rotations (CS, CA, and pasture) within each of four quadrants resulted in 12 total rotation identifiers. The final CDL-union grid, with all cells reclassified according to these 12 possible rotations, was then overlaid ("mosaicked") back onto the original CDL-2007 grid to form the land-use grid for use by the ArcSWAT interface. In this way, the total cropland area, the relative areas among crops, the temporal rotation of crops, and their spatial distribution across the basin were faithfully reproduced in the model.

Land Cover: Developed Land

The total area of developed land in the St. Croix basin is not large, averaging about 5% of the basin area for the 2001-07 data sets examined (Table 1). Here, by "developed" we mean land with large enough impervious surfaces to be identified as such in the spatial land-use data sets. Roads, cities, and villages would be included, but rural residential areas with low densities would be excluded. In the CDL 2007 data set, the template for land-use input to the model, developed land totaled 5.9%, the sum of NLCD land-cover types 121-124 (Developed/Open Space, Developed/Low Intensity, Developed/Medium Intensity, and Developed/High Intensity). These types were reclassified to the SWAT categories: type 121 to URLD (urban low density), type 122 to URML (urban medium/low density), and types 123-4 to URHD (urban high density). These three categories were chosen because they appeared to correspond to useful distinctions on the ground and for modeling purposes. In the CDL 2007 data set, URHD covered 0.3% of the basin and appeared to correspond to the core of urban areas, surrounded by a fringe of URML that covered 0.9% of the basin. These categories constitute the commercial, industrial, and high-density residential areas of cities in the St. Croix basin. URLD covered 4.7% of the basin and appeared to correspond mostly to the background, section-line road network, although some could be attributed to urban fringes. For our purposes, we considered that the URHD and URML units were where urban growth has occurred in proportion to their population growth, whereas the URLD unit has been established for many years and would increase only slightly with population growth.

The population in these land covers may be roughly estimated, given some assumptions about housing density and household size. We used estimates of household size and density as developed for the Sunrise River watershed, a tributary to the St. Croix in eastern Minnesota (Almendinger and Ulrich, 2012), and assumed they were broadly representative for the St. Croix basin. First, assume the 2005 population (about 465,000; U.S. Census Bureau) is representative for the 2000s period. About 162,000 people, or 35% of the population, live in the URML land-use type, if it represents urban single-family residential areas with a housing density of 3.7 units/ha (1.5 units/acre) with 2.92 persons per household. About 80,000 people, or 17%, live in URHD land-use type, if 22% of it is residential (78% being commercial / industrial) with 25 units/ha (10 units/acre) and 2.92 persons per household. The remaining people, about 224,000 or 48%, apparently live in rural residential settings.

Hydrologic Response Unit (HRU) Determination

As explained earlier, HRUs are determined with the ArcSWAT interface by intersecting spatially referenced (GIS) layers of land cover, soil type, and slope class. Configuration of land cover and soil type data sets are discussed above. During the DEM processing to delineate the watershed (channel hydrography and subbasin boundaries), the ArcSWAT interface also generates a grid of land-slope values that can be divided into user-selected categories and included as a criterion in defining HRUs. We chose two land-slope categories, 0-10% slope, and >10% slope (percent slope = 100*tan of the angle from horizontal).

To avoid undue model complexity, the user sets thresholds for the percent of subbasin area covered by each category in these data layers so that only the dominant categories are included during HRU determination. We chose thresholds of 5% for land use, 10% for soils, and 5% for slope. For example, a land use occupying less than 5% of a subbasin area will be ignored in constructing HRUs for that subbasin. Similarly, soil categories covering less than 10% of the subbasin area, and slope classes covering less than 5%, were ignored in HRU construction. Given these thresholds, ArcSWAT determined a total of 3010 HRUs within the 419 subbasins, or about seven to eight HRUs per subbasin.

We note that these threshold exemptions during HRU construction tend to make small categories of land use, soil, or slope even smaller in the model than in reality. Conversely, dominant categories are expanded. Thus for small land-use categories of interest – such as urban land in the St. Croix basin – it was important to keep the land-use exemption threshold rather low. The 5% threshold was adequate for most land uses, but urban lands were reduced to only 1.5% of the basin area, rather than the 5.9% shown in the CDL 2007 layer. In particular, URHD was reduced from 0.3% to 0.1%, and URML was reduced from 0.9% to 0.3%. To compensate, we expanded all URHD and URML HRUs such that their areal coverage matched the original values. This procedure required simultaneous reductions of grassland or forest HRUs in the same subbasin. However, most of the under-representation of developed land was from URLD being too low in rural subbasins to exceed the threshold for inclusion, such that HRUs for this type were not created in these rural subbasins. And, because such HRUs were not created, the URLD type could not be expanded back up to original, target values.

Land Use: Agricultural Practices

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. We compiled livestock numbers for 2000-09 data for each county in the St. Croix basin (NASS, 2010). Livestock included dairy cows, beef cattle, hogs, sheep, and poultry. Manure from wildlife was not considered. A few herds of bison and red deer are kept in Chisago County (C. Mell, Chisago County Soil and Water Conservation District, personal communication 2009). If a livestock species was not reported at all, we assumed its numbers were negligible in that county. Missing years of livestock numbers were interpolated, assuming data existed before and after the missing year. Livestock numbers were adjusted by the fractional area of each county within the St. Croix basin.

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 major livestock types: beef cattle, dairy cows, and horses. While horses were calculated to produce only about 5% of the current total phosphorus load in manure in the basin, 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 8 and 9) 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. Thus, while not all animal types were explicitly represented in the model, the total load of phosphorus from manure was preserved. Typical manure characteristics of dairy cows, beef cattle, and horses are given in Table 10, which were used to calculated manure quantities and nutrient loads from reported livestock populations.

For 2000-09, livestock numbers were dominated by dairy cows, with nearly 153,000 animal units in the basin producing about 2.4 million short tons of manure annually, of which 2,620 short tons is phosphorus. (One short ton = 2000 pounds, and one metric ton = 2200 pounds = 1.1 short tons. We use short tons here because agronomists in the USA commonly use these units with regard to manure.) By far, most dairy cows are in the southeast part of the basin, especially in Polk and St. Croix counties in Wisconsin (Figure 8a and Table 11). Beef cattle numbered about 51,000 animal units, producing about 540,000 short tons of manure containing 860 short tons of phosphorus (Table 12), essentially all on the Minnesota side of the basin (Figure 8b). Horses totaled about 16,000 animal units, producing about 150,000 short tons of manure containing 210 short tons of phosphorus (Table 13) and were more common in the southern half of the basin (Figure 8c). In summary, livestock generated a total of 3,690 short tons (3,355 metT) of phosphorus: 71% from dairy cows, 23% from beef cattle, and 6% from horses.

Manure can be applied by grazing in pastures or by mechanical means in crop or hay fields. We assumed that grazing was the principal way of applying horse and beef manure. In contrast, most dairy manure was applied mechanically to crop fields, with a lesser amount spread by grazing. Details of these applications follow in the next two sections.

Table 8. 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.

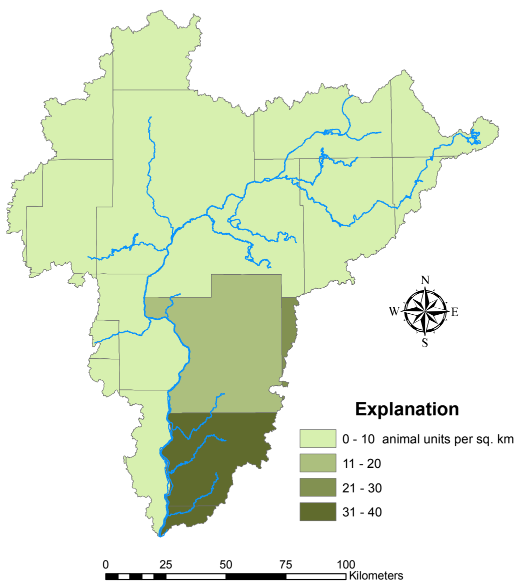
Table 9. Equivalent animal unit numbers, in terms of daily phosphorus production in manure.

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

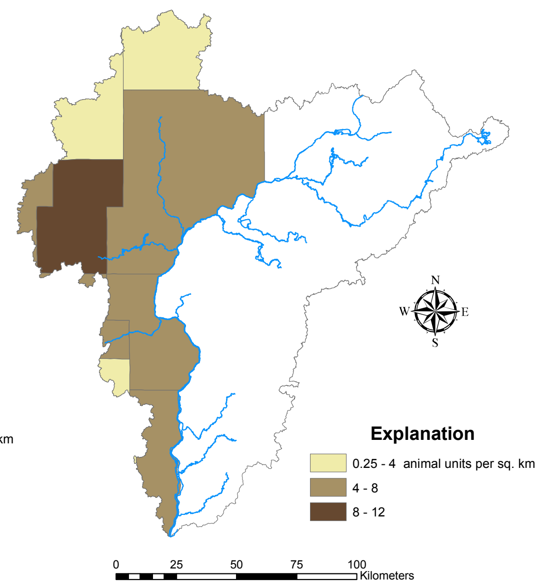
Table 10. Typical manure characteristics for livestoick in the St. Croix SWAT model.

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)
Dairy cows	86	12	0.45	0.094
Beef cattle	58	8.5	0.34	0.092
Horses	51	15	0.3	0.071

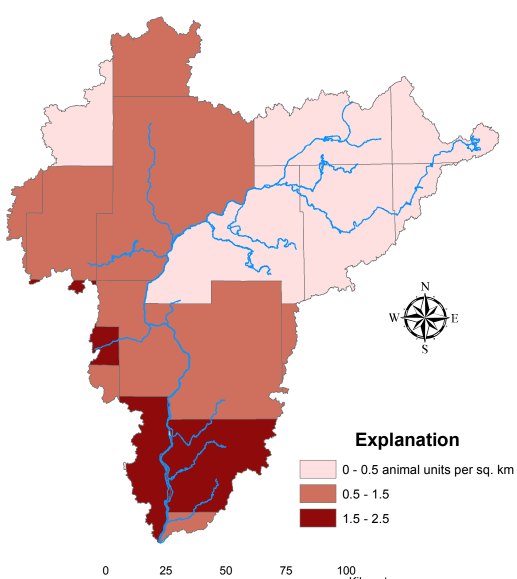
Abbreviations:
Dry Wt, dry weight; lbs, pounds
Notes:
Manure charactistics obtained from ASAE (1998), as cited by Arnold et al. (2011).



(a) Dairy cow animal-unit density, 2000-09



(b) Beef cattle animal-unit density, 2000-09
Beef cattle not listed for Wisconsin; assumed negligible here.



(c) Horse animal-unit density, 2000-09

Figure 8. Animal unit densities of (a) dairy cows, (b) beef cattle, and (c) horses in the St. Croix basin, 2000-09.

Table 11. Dairy cow manure production and associated nutrient loads for portions of counties in the St. Croix basin, 2000-09.

DAIRY COWS	(a) Manure production				(b) Nutrients from manure	
Quadrant / County	Animal Units	Raw Manure	Total Solids (Dry Wt)	Percent of Total	Nitrogen	Phosphorus
		(short T/yr)	(metric T/yr)	(%)	(short T/yr)	(short T/yr)
Northwest Quadrant (NW)						
MN-Aitkin	283	4,436	563	0.2%	23	5
MN-Carlton	1,518	23,823	3,022	1.0%	125	26
MN-Kanabec	6,819	107,029	13,577	4.5%	560	117
MN-Mille Lacs	1,611	25,280	3,207	1.1%	132	28
MN-Pine	12,623	198,111	25,130	8.3%	1,037	217
Totals	*22,853*	*358,679*	*45,498*	*14.9%*	*1,877*	*392*
Southwest Quadrant (SW)						
MN-Anoka	195	3,056	388	0.1%	16	3
MN-Chisago	6,746	105,881	13,431	4.4%	554	116
MN-Isanti	870	13,657	1,732	0.6%	71	15
MN-Ramsey	1	19	2	0.0%	0	0
MN-Washington	1,850	29,040	3,684	1.2%	152	32
Totals	*9,662*	*151,653*	*19,237*	*6.3%*	*794*	*166*
Northeast Quadrant (NE)						
WI-Bayfield	1,731	27,168	3,446	1.1%	142	30
WI-Burnett	10,294	161,564	20,494	6.7%	845	177
WI-Douglas	2,445	38,373	4,868	1.6%	201	42
WI-Sawyer	764	11,987	1,521	0.5%	63	13
WI-Washburn	8,179	128,368	16,283	5.4%	672	140
Totals	*23,413*	*367,462*	*46,612*	*15.3%*	*1,923*	*402*
Southeast Quadrant (SE)						
WI-Barron	4,109	64,491	8,181	2.7%	337	70
WI-Pierce	5,150	80,824	10,252	3.4%	423	88
WI-Polk	44,889	704,535	89,370	29.4%	3,687	770
WI-St. Croix	42,796	671,685	85,203	28.0%	3,515	734
Totals	*96,944*	*1,521,535*	*193,007*	*63.4%*	*7,962*	*1,663*
Basin totals	152,872	2,399,328	304,355	100.0%	12,555	2,623

Abbreviations:
Dry Wt, dry weight; lbs, pounds; short T, short ton = 2000 lb; metric T, metric ton = 1000 kilograms; n/a, not applicable
Notes:
See Table 10 for manure charactistics for each livestock type. Livestock populations obtained from the National Agricultural Statistics Service (NASS, 2010). Calves apportioned to dairy and beef according to the proportions of adult cattle.
Dairy cow AUs here include AU-equivalents of hogs; see Table 9 for conversion factors.

Table 12. Beef cattle manure production and associated nutrient loads for portions of counties in the St. Croix basin, 2000-09.

BEEF CATTLE	(a) Manure production				(b) Nutrients from manure	
Quadrant / County	Animal Units	Raw Manure	Total Solids (Dry Wt)	Percent of Total	Nitrogen	Phosphorus
		(short T/yr)	(metric T/yr)	(%)	(short T/yr)	(short T/yr)
Northwest Quadrant (NW)						
MN-Aitkin	1,837	19,448	2,591	3.6%	114	31
MN-Carlton	3,051	32,293	4,302	6.0%	189	51
MN-Kanabec	15,759	166,806	22,223	30.8%	978	265
MN-Mille Lacs	1,380	14,605	1,946	2.7%	86	23
MN-Pine	18,601	196,894	26,232	36.3%	1,154	312
Totals	*40,628*	*430,046*	*57,295*	*79.4%*	*2,521*	*682*
Southwest Quadrant (SW)						
MN-Anoka	252	2,663	355	0.5%	16	4
MN-Chisago	6,427	68,028	9,063	12.6%	399	108
MN-Isanti	877	9,284	1,237	1.7%	54	15
MN-Ramsey	1	7	1	0.0%	0	0
MN-Washington	2,998	31,735	4,228	5.9%	186	50
Totals	*10,554*	*111,718*	*14,884*	*20.6%*	*655*	*177*
Northeast Quadrant (NE)						
(WI counties of Bayfield, Burnett, douglas, Sawyer, and Washburn)						
Too few beef cattle to include						
Southeast Quadrant (SE)						
(WI counties of Barron, Pierce, Polk, and st. Croix)						
Too few beef cattle to include						
Basin totals	51,182	541,764	72,179	100.0%	3,176	859

Abbreviations:
Dry Wt, dry weight; lbs, pounds; short T, short ton = 2000 lb; metric T, metric ton = 1000 kilograms; n/a, not applicable
Notes:
See Table 10 for manure charactistics for each livestock type. Livestock populations obtained from the National Agricultural Statistics Service (NASS, 2010). Calves apportioned to dairy and beef according to the proportions of adult cattle.

Table 13. Horse manure production and associated nutrient loads for portions of counties in the St. Croix basin, 2000-09.

HORSES	(a) Manure production				(b) Nutrients from manure	
Quadrant / County	Animal Units	Raw Manure	Total Solids (Dry Wt)	Percent of Total	Nitrogen	Phosphorus
		(short T/yr)	(metric T/yr)	(%)	(short T/yr)	(short T/yr)
Northwest Quadrant (NW)						
MN-Aitkin	166	1,542	412	1.0%	9	2
MN-Carlton	581	5,410	1,447	3.6%	32	8
MN-Kanabec	1,676	15,600	4,171	10.3%	92	22
MN-Mille Lacs	243	2,259	604	1.5%	13	3
MN-Pine	2,775	25,826	6,905	17.1%	152	36
Totals	*5,440*	*50,637*	*13,539*	*33.5%*	*298*	*70*
Southwest Quadrant (SW)						
MN-Anoka	198	1,847	494	1.2%	11	3
MN-Chisago	1,677	15,607	4,173	10.3%	92	22
MN-Isanti	429	3,991	1,067	2.6%	23	6
MN-Ramsey	0	1	0	0.0%	0	0
MN-Washington	1,610	14,983	4,006	9.9%	88	21
Totals	*3,914*	*36,430*	*9,741*	*24.1%*	*214*	*51*
Northeast Quadrant (NE)						
WI-Bayfield	168	1,560	417	1.0%	9	2
WI-Burnett	680	6,327	1,692	4.2%	37	9
WI-Douglas	343	3,193	854	2.1%	19	4
WI-Sawyer	48	446	119	0.3%	3	1
WI-Washburn	745	6,938	1,855	4.6%	41	10
Totals	*1,984*	*18,464*	*4,937*	*12.2%*	*109*	*26*
Southeast Quadrant (SE)						
WI-Barron	136	1,270	339	0.8%	7	2
WI-Pierce	224	2,086	558	1.4%	12	3
WI-Polk	2,224	20,702	5,535	13.7%	122	29
WI-St. Croix	2,330	21,687	5,799	14.3%	128	30
Totals	*4,915*	*45,744*	*12,231*	*30.2%*	*269*	*64*
Basin totals	16,253	151,274	40,448	100.0%	890	211

Abbreviations:
Dry Wt, dry weight; lbs, pounds; short T, short ton = 2000 lb; metric T, metric ton = 1000 kilograms; n/a, not applicable
Notes:
See Table 10 for manure charactistics for each livestock type. Horse numbers taken from 2002 Census of Agriculture (USDA, 2004).
Horse AUs here include AU-equivalents of sheep; see Table 9 for conversion factors.

Pasture

Areas of pastureland reported for 2002 and 2007 (USDA, 2009) in each quadrant of the basin were averaged for input to the model. Reported pastureland included cropland, permanent, and woodland, but to avoid undue uncertainty in the model, pastured woodland was converted to a grassland-equivalent area at a ratio of 2:1 (i.e., 2 ha of woodland pasture was replaced by 1 ha of grassland pasture). The resulting area of reported pastureland in the St. Croix basin totaled 1107 km^2.

Two possible grazing densities were assumed: low density at 0.82 AU/ha (animal units per hectare) and medium density at 1.23 AU/ha (1 AU/3 acres and 1 AU/2 acres, respectively). In addition, 5% of the reported pastureland area was reserved for much higher manure application rates under the assumption that winter accumulation of manure was deposited (either by animals or mechanically) in a paddock or barnyard area. We think it is safe to assume that such areas exist in the basin, but we do not know their true areas or locations. Nonetheless, including such areas in the model affords us the opportunity to test their hypothetical impact. Grazing operations included parameters for biomass eaten and trampled, as well as for manure produced (Table 14). Because the number of animal units for each type of livestock was given, and because the grazing densities were made to be uniform in the model across the basin, the modeled grazed area could not be matched exactly with the reported grazed area, especially within each quadrant. Still, for the basin as a whole, modeled area grazed (1103 km^2) was within 1% of the reported area (1107 km^2).

Horse pastureland was assigned first. All horses were assumed to graze at the low density (0.82 AU/ha) for 169 days/yr, thereby depositing 46% of their annual manure load. For the remainder of the year, horses were assumed to be kept in a "paddock" area, presumed to be in or near a barn and set to 5% as large as the horse pastured area. The remainder of the annual manure production (54%) was applied to this area.

Beef pastureland was similarly assigned, but at a higher density of 1.23 AU/ha (1 AU / 2 acres) for 169 days/yr, thus depositing 46% of the annual manure load. This density might be a little high for many beef grazing operations, but some beef feedlot operations do not graze their cattle much at all. The higher density seemed to be a fair compromise to cover both types of beef

Table 14. Daily forage requirements and manure production for animal units (AUs) of grazing livestock.

Animal Unit	Biomass Eaten (kg/AU/d, dry wt)	Biomass Trampled (kg/AU/d, dry wt)	Manure (kg/AU/d, dry wt)	Ratio of Biomass Eaten / Manure
Beef	11.36	2.27	3.86	2.94
Dairy cow	11.36	2.27	5.45	2.08
Horse	11.36	2.27	6.82	1.67

NOTES: One animal unit = 1000 lbs, or 454.5 kg. Biomass eaten set to 2.5% bodyweight, and biomass trampled set to 0.5% bodyweight (UWEX 2002). Manure production from ASAE (1998), as cited by Arnold et al. (2011).

operations, in aggregate. As with horses, paddock areas were set at 5% of beef pastureland, and these paddocks received the remaining 54% of beef manure that presumably accumulates during the non-grazing period (196 days/yr).

Dairy pastureland was assigned at the low animal density of 0.82 AU/ha for 169 days/yr, but under the assumption that only 25% of dairy cows are pastured. A paddock area equal to 5% of the dairy pasture area received 10% of the annual manure production (as if all the cattle spent 10% of their time in this area). The rest of the dairy manure was applied to the CA (corn-alfalfa) rotation either as seasonal (spring and fall) applications or as daily-haul applications. Seasonal applications were applied only to corn fields before planting and after harvest. Daily haul applications were simulated as monthly applications to all fields (corn and alfalfa) except during the months that corn was growing. Of all the land in CA rotation, about 14% received daily-haul applications, 20% received seasonal applications, and 66% received no manure (only inorganic fertilizer).

Specific Crop Rotations

Crop rotations in SWAT are constructed by specifying not only the sequence of crops over a series of years, but also the schedule of all field operations (tillage, planting, fertilizing, and harvesting) within each year of the rotation. We assumed a simple tillage sequence for cropped lands. Generally, prior to planting corn, soybeans, or alfalfa, fields were chisel plowed in the fall or spring and disked in the spring after an initial fertilizer application. When corn followed alfalfa, the alfalfa field was moldboard plowed in the fall and disked in the spring just prior to planting corn. SWAT defaults were initially accepted for depth of tillage and mixing efficiencies for each implement, although some of these were altered during calibration. Planting and harvesting dates for each crop were kept uniform across the basin and from year to year in the model. If necessary, the model could be modified to allow for earlier planting and harvesting in the southern half of the basin or for scheduling operations by plant heat units (growing season degree days).

Crops were fertilized with inorganic fertilizer and manure applications. For corn, inorganic fertilizer was applied at a rate 216 kg/ha (192 lb/acre) nitrogen (N) and 15 kg/ha (13 lb/acre) phosphorus (P). Soybeans received a little starter fertilizer amounting to 20 kg/ha N (18 lb/acre) and 23 kg/ha P (20 lb/acre). Alfalfa did not receive inorganic fertilizer in the model. Even though potassium (K) is often applied to alfalfa, SWAT does not track K and instead assumes that it is not limiting.

Some of the CA rotations received dairy manure in addition to inorganic fertilizer. In these cases the amount of inorganic fertilizer received by corn was reduced by about half, which effectively credited some, but not all, of the additional nutrients from manure. Corn fields in CA rotations with seasonal manure applications received 15 short tons per acre (shT/acre) fresh manure in the spring (pre-planting) and another 15 shT/acre in the fall (post-harvest), resulting in a total of 469 kg/ha N (418 lb/acre) and 90 kg/ha P (80 lb/acre). These rates are substantial; however, at least some of the N content of the fall manure application will be lost to volatilization or denitrification. All fields (corn and alfalfa) in the CA rotations with daily-haul manure applications received manure, except for the months when corn was growing, with an average annual rate of 463 kg/ha N (412 lb/acre) and 95 kg/ha P (84 lb/acre). These rates correspond to an average annual rate of spreading 36 shT/acre of fresh manure (less in years when corn restricts the months of application, and more in years of with alfalfa.)

Pastureland grazed by dairy cows, beef cattle, and horses had much lower application rates of nutrients from manure, about 19-32 kg/ha N (17-29 lb/acre) and 4-9 kg/ha P (3-8 lb/acre). However, the paddock areas, which represent small areas where winter accumulations of manure are spread, had very high application rates, about 438-744 kg/ha N (390-663 lb/acre) and 88-205 kg/ha P (78-182 lb/acre). These values correspond to a fresh-manure application rate of about 33-56 shT/acre. Horses were at the lower end of these ranges, and beef cattle at the higher end.

The basic CS and CA rotations had to be staggered into subrotations with different starting years in order to not have the entire basin change from one crop to another in the same year. For example, for the HRUs assigned to the CS rotation, half were started with corn and the other half started with soybeans, so in any subsequent year in the model run, the total areas of corn and soybeans remained about constant. Further, because curve number is related not only to crop but also (especially) to hydrologic soil group (HSG), separate subrotations also had to be created for each of the four HSGs. All possible combinations of these variables are given in Table 15, resulting in 68 possible rotations as qualified by various subrotations. Table 16 shows the areas of the base rotations plus the three CA subrotation types in the four quadrants of the basin. The details of each of these rotations are laid out in tabular form in Appendix A.

Land Use: Urban Practices

In this version of the model, urban land-use practices were not explored. SWAT default parameters were accepted for urban low-density, urban medium-low density, and urban high-density HRUs (URLD, URML, and URHD, respectively). Later use of the model to investigate urban land-use practices will likely require re-parameterization and recalibration for subbasins with significant areas of urban land.

Table 15. Description of agricultural rotations in the St. Croix SWAT model.

Base Rotation	Subrotation Qualifiers: Type	Subrotation Qualifiers: Hydrologic Soil Group	Subrotation Qualifiers: Sequence	Description
Tilled cropland				
C1-S1 (= "CS")	none	A, B, C, D	a, b	Corn-Soybean rotation
Cg1-Cs1-A4 (= "CA")	no manure seasonal (= "seas") daily haul (= "dh")	A, B, C, D	a, b, c	Corn-grain (1 yr), Corn-silage (1 yr), and Alfalfa (4 yr). Begin sequence a with Corn-grain, b with yr-1 alfalfa, and c with yr-3 alfalfa. Seasonal = spring and fall applications. Daily haul = monthly applications.
Pasture and paddocks				
Dairy_Pasture (= "DPAST")	none	A, B, C, D	none	Pasture, grazed 169 days/yr (46% of annual manure production for 25% of herd) at 0.82 AU/ha (= 1 AU/3 acres)
Dairy_Paddock (= "DPADD")	none	A, B, C, D	none	Pasture, 10% of annual manure production, at 20x grazing density, as 12 equal monthly applications
Beef_Pasture (= "BPAST")	none	A, B, C, D	none	Pasture, grazed 169 days/yr (46% of annual manure production) at 1.23 AU/ha (= 1 AU/2 acres)
Beef_Paddock (= "BPADD")	none	A, B, C, D	none	Pasture, 54% of annual manure production, at 20x grazing density, as 12 equal monthly applications
Horse_Pasture (= "HPAST")	none	A, B, C, D	none	Pasture, grazed 169 days/yr (46% of annual manure production) at 0.82 AU/ha (= 1 AU/3 acres)
Horse_Paddock (= "HPADD")	none	A, B, C, D	none	Pasture, 54% of annual manure production, at 20x grazing density, as 12 equal monthly applications

Table 16. Areas of cropland and grazing rotations by basin quadrant in the St. Croix SWAT model for the 2000-09 decade.

Rotation	Quadrant: NE (km^2)	Quadrant: NW (km^2)	Quadrant: SW (km^2)	Quadrant: SE (km^2)
CS	94.0	224.0	329.0	528.0
CA, no manure	116.2	149.3	78.0	372.0
CA, seasonal applications	24.9	24.9	13.0	155.0
CA, daily haul	24.9	24.9	13.0	93.0
Dairy Pasture	71.4	69.7	0.0	295.6
Dairy Paddock	3.6	3.5	0.0	14.8
Beef Pasture	0.0	330.3	85.8	0.0
Beef Paddock	0.0	16.5	4.3	0.0
Horse Pasture	24.2	66.3	47.7	59.9
Horse Paddock	1.2	3.3	2.4	3.0

Land Cover: Differences between 1990s and 2000s

Land cover during the 1990s was also an important consideration in model development because the TMDL study for the St. Croix basin has set the phosphorus loads to Lake St. Croix during that period as the baseline against which future changes will be measured (MPCA and WDNR, 2012). That is, the clean-water goal for the basin is to reduce phosphorus loads to Lake St. Croix by about 27%, down to about 337 metric tons (metT) from about 460 metT, which was the 1990s decadal average annual load. Hence we needed an accurate land-cover configuration in the model for the 1990s to calibrate model to the known loads during that decade.

For cropland, we again relied on countywide NASS tabular data, averaged from 1990-99 (Table 17) to remain consistent with the tabular data compiled for the 2000s. These data sets indicate that the total area of cropland changed very little from the 1990s to the 2000s, decreasing from 11.7% of the basin to 11.3% of the basin (Table 7, bottom). This is in contrast to the trend indicated by the spatial data sets, where the NLCD 1992 data show about 16% of the basin in tillage, which drops to about 9% in the CDL 2007 data set (Table 1). Imprecision in the spatial data and differences in algorithms to interpret the imagery can make comparisons among spatial data sets problematic for detailed analyses, which further demonstrates the need to use other data sets such as the NASS tabular data as a means of ground-truthing. Even though the cropland area remained relatively constant from the 1990s to the 2000s, there was a large change in areas of tillage rotations. In the 1990s about two-thirds of the cropland was in a forage rotation of corn and alfalfa (CA), with about one-third in a corn-soybean (CS) cash-crop rotation. By the 2000s, these two rotations had become approximately equal (Table 7).

Changes in pasture areas were determined based on differences in livestock populations between the 1990s and the 2000s. Livestock populations for the 1990s were determined as the 1990-99 average of the countywide NASS data sets, scaled by the percent of each county within the basin and summarized for each quadrant. Livestock was more diverse in the 1990s, with more hogs, chickens, and sheep. To remain consistent with our modeled livestock types, hogs and chickens were converted to dairy-cow equivalents, constituting 7% of the resulting dairy-cow AUs. Likewise, sheep were converted to horse equivalents, constituting 9% of the resulting horse AUs. For these AU types over the entire basin, from the 1990s to the 2000s the population of dairy cows dropped by 27% and that of horses increased 10%. Beef population changes were more of a problem, because the tabular data show almost 21,000 beef in Wisconsin in the 1990s, but none in the 2000s. In contrast, in Minnesota beef population increased by about 7,000 AUs, or 16%.

Urban land area was adjusted based on population changes from 1995 to 2005, assuming 1995 was representative of the 1990s and 2005 of the 2000s. U.S. Census Bureau data were tallied for each county and scaled by the percent of each county in the basin and summarized by quadrant. During this time, population increased by 21% over the whole basin (from 385,000 to 465,000), with most growth (28%) occurring in the SE quadrant and least growth (8%) occurring in the NE quadrant.

Table 17. Crop areas and yields by quadrant and county in the St. Croix basin, 1990-99 averages, distributing areasof minor crops among major crops.

Quadrant/County	Corn-grain		Corn-silage		Soybeans		Alfalfa		Hay, other	
	Area ***(km^2)***	**Yield** ***(t/ha)***	**Area** ***(km^2)***	**Yield** ***(t/ha)***	**Area** ***(km^2)***	**Yield** ***(t/ha)***	**Area** ***(km^2)***	**Yield** ***(t/ha)***	**Area** ***(km^2)***	**Yield** ***(t/ha)***
Northwest Quadrant (NW)										
MN-Aitkin	0.40	4.48	0.84	8.10	0.92	1.49	4.05	6.30	26.01	4.21
MN-Carlton	0.58	4.44	2.27	8.16	n/a	n/a	14.49	5.41	46.60	4.06
MN-Kanabec	62.98	5.10	17.04	9.04	19.73	1.66	41.86	6.80	80.56	4.47
MN-Mille Lacs	14.31	5.29	3.97	9.95	4.66	1.72	9.90	7.66	10.63	4.85
MN-Pine	63.37	5.02	35.72	8.87	20.49	1.70	82.81	7.27	165.85	4.30
Total area & average yield	*141.63*	*4.87*	*59.84*	*8.83*	*45.80*	*1.64*	*153.11*	*6.69*	*329.65*	*4.38*
Percent of tilled area	*35.4%*		*14.9%*		*11.4%*		*38.2%*			
Total tilled area in quadrant	*400.38*									
Southwest Quadrant (SW)										
MN-Anoka	5.92	5.32	0.66	9.23	2.90	1.66	3.39	6.16	1.05	4.27
MN-Chisago	115.04	5.30	13.80	9.43	65.05	1.59	51.33	6.99	32.47	4.89
MN-Isanti	29.78	5.43	1.42	8.76	17.72	1.63	7.57	6.98	3.05	4.45
MN-Ramsey	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
MN-Washington	67.22	6.73	4.05	9.83	41.30	2.26	33.73	7.00	15.22	4.41
Total area & average yield	*217.97*	*5.70*	*19.92*	*9.31*	*126.97*	*1.78*	*96.02*	*6.78*	*51.79*	*4.50*
Percent of tilled area	*47.3%*		*4.3%*		*27.5%*		*20.8%*			
Total tilled area in quadrant	*460.88*									
Northeast Quadrant (NE)										
WI-Bayfield	0.60	5.05	0.84	6.95	0.04	1.33	13.42	4.27	12.78	3.73
WI-Burnett	52.67	5.06	12.89	8.90	11.12	1.47	61.74	5.09	19.60	4.04
WI-Douglas	0.37	4.38	0.41	7.39	n/a	n/a	19.59	4.04	26.51	3.91
WI-Sawyer	1.82	5.20	0.83	8.43	0.22	1.75	3.27	5.25	2.45	3.72
WI-Washburn	25.11	5.30	10.28	9.08	1.49	1.53	60.38	4.84	18.96	4.61
Total area & average yield	*80.58*	*5.00*	*25.24*	*8.15*	*12.87*	*1.52*	*158.41*	*4.70*	*80.30*	*4.00*
Percent of tilled area	*29.1%*		*9.1%*		*4.6%*		*57.2%*			
Total tilled area in quadrant	*277.10*									
Southeast Quadrant (SE)										
WI-Barron	14.92	5.72	4.73	10.48	1.38	2.06	23.52	5.25	3.27	4.86
WI-Pierce	27.51	6.57	4.94	11.94	6.42	2.29	21.74	6.50	1.62	4.70
WI-Polk	195.47	5.92	59.51	10.53	38.19	2.02	256.24	5.39	47.23	5.23
WI-St. Croix	220.85	6.29	46.38	11.84	63.70	2.11	205.50	5.87	23.01	5.00
Total area & average yield	*458.75*	*6.13*	*115.55*	*11.20*	*109.69*	*2.12*	*507.00*	*5.75*	*75.14*	*4.95*
Percent of tilled area	*38.5%*		*9.7%*		*9.2%*		*42.6%*			
Total tilled area in quadrant	*1190.99*									
Whole Basin										
Total area & average yield	*899*	*5.42*	*221*	*9.37*	*295*	*1.77*	*915*	*5.98*	*537*	*4.46*
Percent of tilled area	*38.6%*		*9.5%*		*12.7%*		*39.3%*			
Total tilled area in basin = 2,329 km^2										

NOTES: County-wide data for 1990-99 from NASS (2009). Areas for each crop have been scaled by the fractional land area of each county within the St. Croix basin. Crop yields refer to dry biomass per unit area. See conversion table for factors to convert reported yields to dry biomass.

Table 18 summarizes the changes in the areas of selected land-cover types from the 1990s to the 2000s. The factors in the table show the area of that land cover type in the 2000s relative to the 1990s. For example, the area of the CA rotation in the NW quadrant of the basin in the 2000s was 0.76 (76%) of the area in the 1990s (Table 18, upper left cell of table). In contrast, the area of the CS rotation in that quadrant was 1.61 times larger (61% larger) in the 2000s than in the 1990s.

To implement these changes in the SWAT model, we began with our baseline 2000s land-cover configuration represented by 3010 HRUs. We then expanded or contracted the HRUs of the land-cover types that had changed between the 1990s from the 2000s. Because we were working backwards in time, from the 2000s to the 1990s, we used the inverses of the change factors shown in Table 18. To accomplish these changes, we used a Visual Basic script in Microsoft Access written by a colleague (Jason Ulrich, Dept. of Biosystems and Agricultural Engineering, Univ. of Minnesota, personal communication, March 2011). The script starts with a table of starting HRU areas (as fractions of subbasin areas) and proposed change factors, and the script output is a table of new HRU areas. HRUs with a change factor <1 will be shrunk, with other HRUs in the same subbasin expanding proportionally. HRUs with a change factor >1 will be expanded at the expense of other HRUs in the subbasin. HRUs explicitly given a change factor of 1 will be kept constant in area. We used this option, for example, to preserve the areas of wetlands and open water. All other HRUs – those without specified change factors – were then adjusted to accommodate the requested changes. The script was further constrained by making sure that the total area of each subbasin remained constant, and that no HRU was made smaller than 0.001 of the subbasin area. The script does not change the number of HRUs, only their relative areas. (Changing the number HRUs would require significant changes in SWAT's FORTRAN code.)

Table 18. Land-cover change factors from 1990s to 2000s in the St. Croix basin.

Land Use	**Quadrant of St. Croix Basin**				
	NW	**SW**	**NE**	**SE**	*Average*
Tilled Crop Rotations					
Corn silage / Alfalfa (CA)	0.76	0.65	0.70	0.74	*0.71*
Corn grain / Soybeans (CS)	1.61	1.10	2.27	1.47	*1.61*
Pasture & Paddock					
Dairy	0.55	0.54	0.88	0.79	*0.69*
Beef	1.22	0.96	n/a	n/a	*1.09*
Horse	0.93	1.27	1.34	1.14	*1.17*
Urban Land					
High density	1.19	1.21	1.08	1.28	*1.19*
Medium density	1.19	1.21	1.08	1.28	*1.19*

NOTES: Crop areas determined from countywide NASS data for crops, 1990-99 averages to 2000-08 averages (NASS, 2009). Corn, soybeans, and alfalfa were considered to be the principal crops; areas of minor crops were distributed among these three major crops. Change in pasture and paddock areas were assumed to be proportional to changes in livestock populations, obtained as countywide NASS tables for 1990-99 averages to 2000-09 averages (NASS, 2010). Change in urban land area was assumed to be proportional to change in county populations from 1995 to 2005, from U.S. Census Bureau (2011). All countywide data were area-weighted by the proportion of St. Croix Basin comprised by each county.
NW quadrant: Aitkin, Carlton, Kanabec, Mille Lacs, and Pine counties, Minnesota
SW quadrant: Anoka, Chisago, Isanti, Ramsey, and Washington counties, Minnesota
NE quadrant: Bayfield, Burnett, Douglas, Sawyer, and Washburn counties, Wisconsin
SE quadrant: Barron, Pierce, Polk, and St. Croix counties, Wisconsin

Point-Source Data

Even though most of the phosphorus load to the St. Croix is from nonpoint sources, the load from point sources remains significant and critical to quantify for several reasons. First, point-source loads of phosphorus are one of the few components of phosphorus cycle that can be measured accurately, at least in theory. In practice, reliable calculations of point-source phosphorus loads from wastewater treatment plants were not available prior to 1970 and did not become routine until the 1990s (Edlund et al., 2009b). Nonetheless, these measurements have been valuable in documenting recent changes in phosphorus load due to population growth and treatment technology. Second, knowledge of point-source loads has been critical in allowing inference of the how total load is partitioned into point versus nonpoint-source loads (Edlund et al., 2009b). Third, point sources tend to discharge soluble phosphorus, which is immediately and directly available to stimulate algal growth. Smaller loads of soluble phosphorus from point sources could have a more immediate impact on eutrophication than larger loads of particulate phosphorus from nonpoint sources, at least in the short run.

There are currently about 87 permitted waste dischargers in the St. Croix basin (Edlund et al., 2009b). However, some of these sources either produce negligible phosphorus loads or apply their effluent to land rather than to surface water. Magdalene (2009) identified the 48 principal point sources in the basin discharging to surface water, and these point sources were included in the SWAT model (Table 19 and Figure 9). Nine of these sources are industrial, and 39 are municipal wastewater treatment plants of some sort. Even some of these sources have nearly negligible (or poorly known) current loads but were retained in the model to allow input of future loads as needed.

Edlund et al. (2009b) calculated decadal-average point-source phosphorus loads to the St. Croix from 1900 to 2000, based on demographics and treatment-plant effluent data where available. Magdalene (2009) updated the analysis, adding recent treatment-plant data from 1999-2007. For data entry into the SWAT model, we chose to use the time series of annual average loads for each of the 48 point sources included. For the period 1999-2007 we used the annual loads as calculated by Magdalene (2009). Prior to 1999, we then used the decadal average basin-wide load as given in Edlund et al. (2009b) and distributed it among the point sources based on the proportions of effluent flow volumes during the 1990s. We then applied those loads to the middle year of each decade (e.g., 1995, 1985, and so forth) and interpolated between these values to obtain a time series of average annual point-source loads of phosphorus back to 1900. In this time series, we excluded all industrial point sources (which are a minor component) and all current municipal dischargers that were not operating prior to 1990. This time series is fairly speculative, since most of the treatment plants in the list did not physically exist in the early 1900s. But, including these point sources in the model provides a mechanism to deliver the loads estimated by Edlund et al. (2009b) that is consistent with known population patterns, should we choose to run the model that far back in time.

According to Edlund et al. (2009b), loads peaked in the 1960s-70s but declined in the

Table 19. Permitted point-source dischargers to surface waters in the St. Croix basin.

Model ID	State ID	Name	Type	Geographic coordinates		UTM coordinates		Phosphorus load	
				Longitude (dec deg)	Latitude (dec deg)	Easting (m)	Northing (m)	1990s (kg/yr)	2005-07 (kg/yr)
psmn001	MN0055662	Aitkin agri-peat Inc - Cromwell	I	-92.7820	46.6717	516681	5168685	166	71
psmn002	MN0022616	Askov WWTP	M	-92.7836	46.1785	516701	5113898	166	91
psmn003	MNG580142	Barnum WWTP	M	-92.7969	46.5051	515580	5150185	415	274
psmn004	MN0055808	Chisago Lakes Joint STC	M	-92.8755	45.4058	509624	5028018	4648	3288
psmn005	MN0050636	Cimarron Park WWTP	M	-92.8692	44.9626	510316	4978799	0	0
psmn006	MN0023418	Finlayson WWTP	M	-92.9085	46.1967	507057	5115916	830	4
psmn007	MNG580052	Grasston WWTP	M	-93.1579	45.7916	487731	5070900	166	18
psmn008	MN0050130	Harris WWTP	M	-92.9728	45.5814	502193	5047753	82	82
psmn009	MN0023701	Hinckley WWTP	M	-92.9089	46.0187	507054	5096125	1410	324
psmn010	MN0023809	Isle WWTP	M	-93.4584	46.1254	464646	5108179	114	150
psmn011	MN0057002	Kettle River WWTP	M	-92.5240	46.2930	509364	5148679	166	52
psmn012	MN0054372	Linwood Terrace Co.	I	-93.1082	45.3633	491715	5023402	17	8
psmn013	MN0020699	Moose Lake WWTP	M	-92.7946	46.4419	515852	5143150	1327	1030
psmn014	MN0021156	Mora WWTP	M	-93.3107	45.8767	475901	5080401	1981	2247
psmn015	MN0024350	North Branch WWTP	M	-92.9706	45.5156	502199	5040280	4480	230
psmn016	MN0021997	Ogilvie WWTP	M	-93.4088	45.8318	468260	5075406	498	291
psmn017	MN0021784	Pine City WWTP	M	-92.9386	45.8399	504915	5076255	2074	128
psmn018	MN0021342	Rush City WWTP	M	-92.9495	45.6952	503874	5060102	664	519
psmn019	MN0056910	Sandstone WWTP	M	-92.8303	46.0999	511414	5104579	1161	1408
psmn020	MN0030848	Shafer WWTP	M	-92.7588	45.3907	519040	5026288	166	301
psmn021	MN0051390	Shorewood Park Sanitary District	I	-93.0263	45.6930	497627	5059746	27	50
psmn022	MN0029998	St Croix Valley WWTP	M	-92.7881	45.0392	516693	4987323	1237	2487
psmn023	MN0053309	Taylors Falls WWTP	M	-92.6778	45.3837	525398	5025568	374	240
psmn024	MNG580051	Wahkon WWTP	M	-93.5283	46.0918	459158	5104384	0	181
psmn025	MNG580054	Willow River WWTP	M	-92.8441	46.3175	512002	5129337	0	115
psmn026	MN0000825	Xcel - Allen S King Power Plant	I	-92.7706	45.0294	518032	4986270	0	0
pswi001	WI0031861	Amani	M	-92.6370	45.2496	528489	5010750	24	9
pswi002	WI0020125	Amery	M	-92.3630	45.3005	549943	5016530	743	488
pswi003	WI0039039	Burnett Dairy	I	-92.5812	45.7715	532565	5068750	239	208
pswi004	WI0036706	Clayton	M	-92.1701	45.3488	565009	5022030	233	361
pswi005	WI0023639	Clear Lake	M	-92.2547	45.2452	558490	5010450	2512	129
pswi006	WI0025356	Deer Park	M	-92.3795	45.1699	548762	5002010	108	87
pswi007	WI0060429	Grantsburg	M	-92.6930	45.7797	523869	5069620	1129	1104
pswi008	WI0024279	Hudson	M	-92.7594	44.9664	518971	4979240	6031	1065
pswi009	WI0002836	Lakeside Foods/Chiquita	I	-92.5488	45.1229	535486	4996700	11	23
pswi010	WI0021482	Luck	M	-92.4837	45.5879	540272	5048390	486	423
pswi011	WI0021245	New Richmond	M	-92.5608	45.1153	534546	4995860	1758	631
pswi012	WI0025020	Osceola	M	-92.7174	45.3153	522150	5018020	1859	296
pswi013	WI0029394	River Falls	M	-92.6378	44.8536	528616	4966750	6552	858
pswi014	WI0028835	Roberts	M	-92.5648	44.9699	534316	4979700	42	64
pswi015	WI0028924	Siren	M	-92.3917	45.7776	547291	5069520	497	651
pswi016	WI0030252	Somerset	M	-92.6830	45.1346	524928	4997960	987	137
pswi017	WI0020796	St. Croix Falls	M	-92.6474	45.4067	527596	5028190	1159	1522
pswi018	WI0060984	Star Prairie	M	-92.5446	45.1903	535776	5004200	0	217
pswi019	WI0049191	WDNR GTT Fish Hatchery	I	-91.8988	45.8204	585543	5074690	79	66
pswi020	WI0004197	WDNR Osceola Fish Hatchery	I	-92.6796	45.3496	525100	5021840	184	1
pswi021	WI0004201	WDNR SCF Fish Hatchery	I	-92.6469	45.4064	527634	5028160	160	3
pswi022	WI0028843	Webster	M	-92.3558	45.8657	550000	5079320	315	404

NOTES: Model ID, identification number for the purposes of model development; State ID, identification number assigned by state agencies; Discharger Type, either municipal (M) or industrial (I); dec deg, decimal degree; UTM, Universal transverse mercator projection, Zone 15 North, based on National Altitude Datum (NAD) of 1983; m, meter; kg, kilogram, 1990s refers to the period 1990-99. **REFERENCES:** Edlund 2009b; Magalene 2009; Steve Weiss, MPCA, personal communication, 2010; Kathy Bartilson, WDNR, personal communication, 2010.

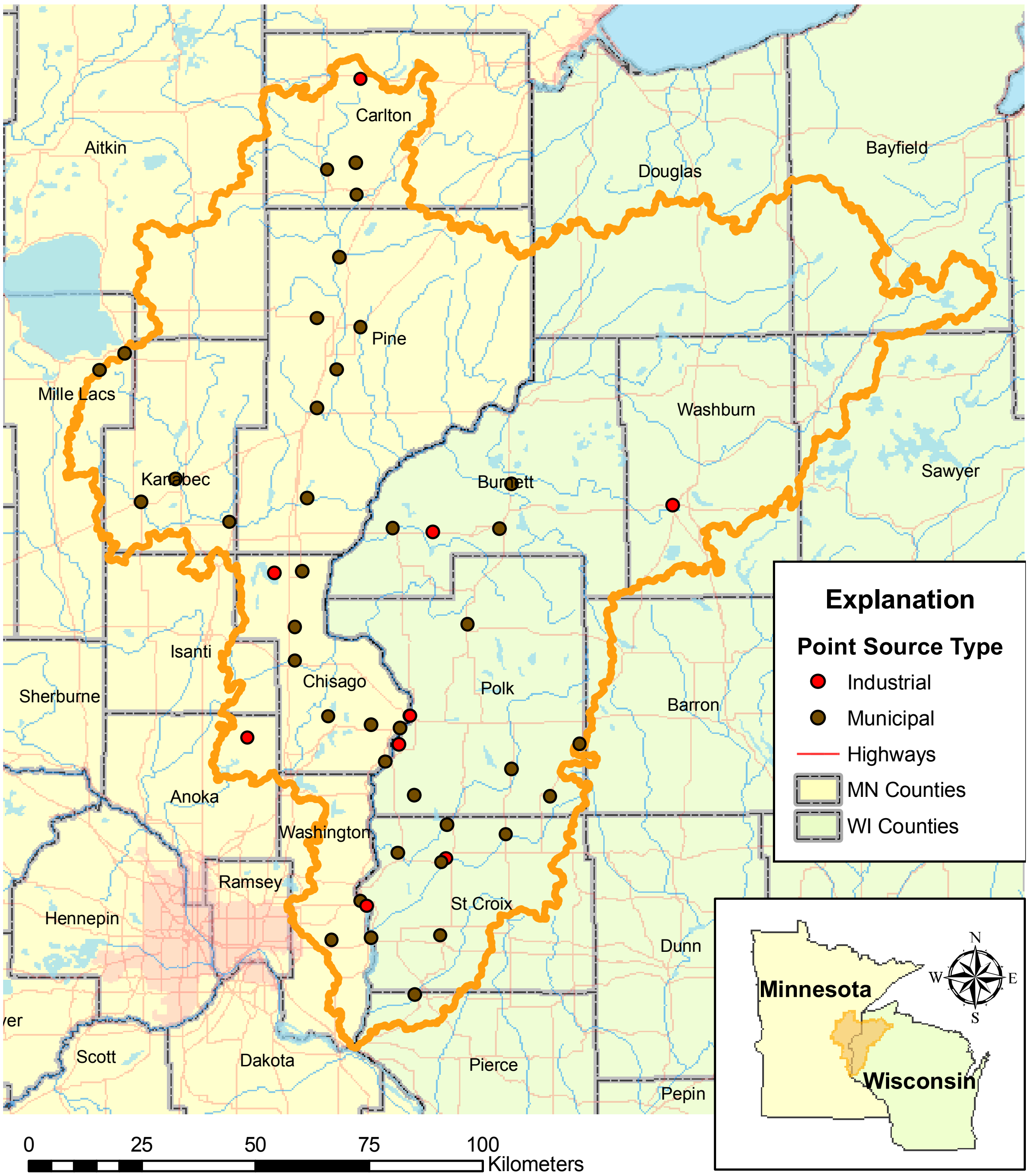


Figure 9. Permitted point sources discharging to surface waters in the St. Croix basin.

1980s after both Minnesota and Wisconsin banned phosphorus in laundry detergent. Loads began rising again, however, during the 1990s in response to population growth in the basin. Point-source loads during the 1990s were estimated at 47.8 metT/yr by Edlund et al. (2009b), at 52 metT/yr by Magdalene (2009), and at 47.3 metT/yr in our analysis (Table 20). About 98% of the load was from municipal, rather than industrial, dischargers, with a little higher loading from Wisconsin (53%) than from Minnesota (47%). By the 2000s, point-source loads dropped to 22.3 metT/yr, down by more than half, because of upgrades to wastewater treatment plants in both Minnesota and Wisconsin. We note the importance of the point-source load estimates for the 1990s, because this is the decade that sets the benchmark against which future phosphorus loads will be measured. Likewise, the load estimate for the 2000s (from data for 2005-07) will form the baseline for "current" conditions in the SWAT model.

Table 20. Summary of point-source phosphorus loads to the St. Croix receiving waters.

Category	**Annual P Load (kg)**		**Percent of basin total**	
	1990s	**2005-07**	**1990s**	**2005-07**
Municipal	46,391	21,904	98.1%	98.1%
Minnesota	*21,958*	*13,460*	*46.4%*	*60.3%*
Wisconsin	*24,433*	*8,445*	*51.7%*	*37.8%*
Industrial	883	431	1.9%	1.9%
Minnesota	*209*	*129*	*0.4%*	*0.6%*
Wisconsin	*674*	*303*	*1.4%*	*1.4%*
Minnesota	22,167	13,588	46.9%	60.8%
Wisconsin	25,107	8,747	53.1%	39.2%
Basin total	**47,274**	**22,335**		

Climate Data

Climate data are one of the foundations required for accurate hydrologic modeling. Yet, within any climate data set, there are spatial gaps between weather stations and temporal gaps when data were not being collected. To fill these gaps, Zhang and Srinivasan (2009) developed a geospatial interpolation scheme that uses only weather stations with data available for a selected day, thus filling temporal gaps from station with missing values. The method then spatially interpolates the data across the watershed between weather stations, thus filling spatial gaps. The result is a continuous time series of daily precipitation and temperature values that are smoothly distributed across the basin in a spatial grid. For application to SWAT, the method then averages the precipitation and temperature grid values within each subbasin polygon delineated by ArcSWAT for each day of the climate data record. In essence, the method creates a weather "pseudo-station" at the centroid of each subbasin polygon with its own continuous daily weather record.

For the St. Croix basin, daily precipitation and temperature observations of 25 weather stations (Table 21 and Figure 10) within or close to the St. Croix basin were obtained from National Climatic Data Center (NCDC, 2010). The methods given in Zhang and Srinivasan (2009) include a number of spatial interpolation options. In this study, we used the ordinary kriging method to spatially interpolate daily weather data from 1960 to 2009, producing basin-wide grids of precipitation and temperature values for each day during this period. As an

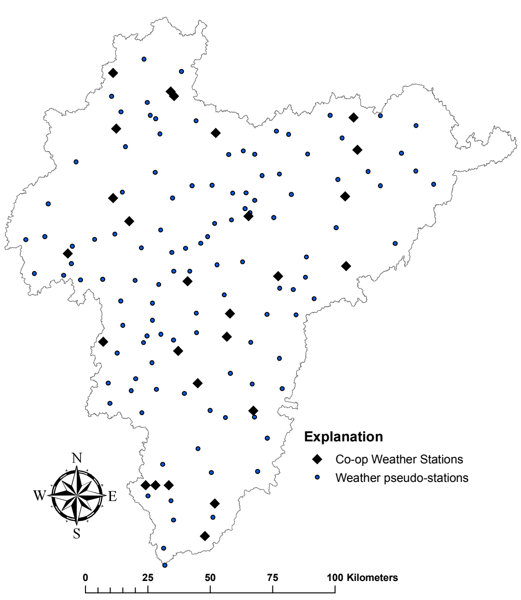


Figure 10. Weather stations in the high-density cooperative network used to generate daily values for each of the pseudo-stations in the SWAT model.

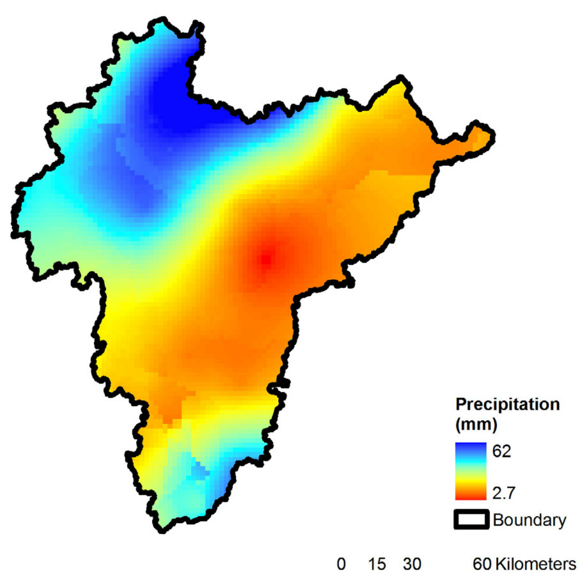


Figure 11. Example of spatially interpolated precipitation for the rain event of 8 August 2008.

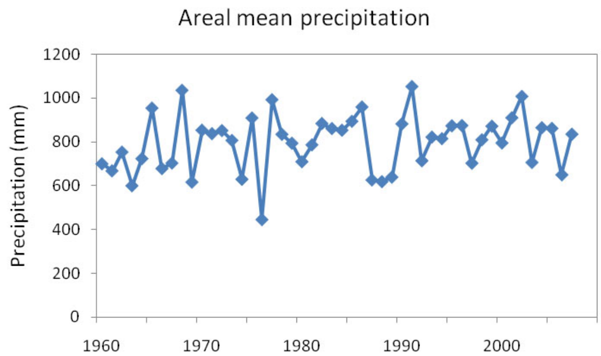


Figure 12. Annual mean precipitation over the St. Croix basin, 1960-2008.

example, the spatial grid of interpolated precipitation on 8 August 2008 is shown in Figure 11. The time series of basin-wide annual areal mean precipitation from 1960-2008, which ranges from 400 mm to 1050 mm, is shown in Figure 12. Rather than apply the method to the full set of 419 subbasins in the SWAT model, we chose to use a slightly simpler delineation with only 114 subbasins. Consequently, each weather pseudo-station provided climate data to three or four subbasins.

Table 21. Weather stations included in the St. Croix SWAT model as sources of daily precipitation, maximum temperature, and minimum temperature.

ID	Name	Altitude (ft)	Geographic coordinates Longitude (dec deg)	Geographic coordinates Latitude (dec deg)	UTM coordinates Easting (m)	UTM coordinates Northing (m)
Minnesota						
210059	Aitkin 2 E	1215	-93.0667	46.5167	494886	5151458
211074	Bruno 7 ENE	845	-92.5333	46.3000	535939	5127486
211227	Cambridge 5 ESE	960	-93.1167	45.5500	490893	5044058
212881	Forest Lake 5 NE	960	-92.9000	45.0333	507877	4986658
213793	Hinckley	1035	-92.9833	45.9833	501291	5092196
214103	Isle 12 N	1285	-93.0500	46.3167	496151	5129234
215598	Moose Lake 1 SSE	1110	-92.7500	46.4333	519206	5142226
215603	Moose Lake RS	1060	-92.7667	46.4500	517920	5144074
215615	Mora	1018	-93.3000	45.8667	476715	5079277
216166	Onamia RS	1260	-93.0667	46.0667	494844	5101457
218037	Stillwater 1 SE	710	-92.7833	45.0333	517067	4986676
218039	Stillwater 2 SW	898	-92.8500	45.0333	511815	4986664
218986	Wild River SP	940	-92.7333	45.5167	520828	5040383
Wisconsin						
470175	Amery	1070	-92.3500	45.3000	550962	5016483
471978	Danbury	950	-92.3667	46.0000	549040	5094242
472934	Frederic	1240	-92.4667	45.6500	541557	5055300
473186	Gordon	1040	-91.8000	46.2333	592527	5120673
473244	Grantsburg	990	-92.6833	45.7667	524623	5068172
474894	Luck	1220	-92.4833	45.5667	540318	5046033
475525	Minong 5 WSW	1075	-91.8667	46.0667	587651	5102079
477226	River Falls	933	-92.6000	44.8500	531608	4966365
477230	Roberts WWTP	977	-92.5500	44.9667	535487	4979346
477464	St. Croix Falls	770	-92.6333	45.4000	528697	5027452
477892	Solon Springs	1130	-91.8167	46.3500	591048	5133616
478027	Spooner Ag Res	1100	-91.8667	45.8167	588046	5074303
479012	Webster 9 SE	1005	-92.2167	45.7833	560892	5070273

SOURCE: NCDC (2010).

Model Construction Summary

The resulting SWAT model of the St. Croix basin had 419 subbasins with 3010 HRUs. A total of 39 lakes were included; these were most of the lakes larger than 200 ha plus four smaller lakes of particular interest from previous studies. Smaller lakes and wetlands were modeled as aggregate units within each subbasin. Agricultural practices included a corn-soybean rotation and a corn-alfalfa rotation, some of which received seasonal or monthly applications of dairy manure. Grazing by horses, beef cattle, and dairy cows was simulated at several densities. The model included 48 point sources with annual data for flow and phosphorus estimated from 1900 to 2007. Daily climate data were compiled from 1960 to 2007.

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.

Goodness of Fit Measures

Both calibration and validation require goodness of fit measures to determine how well the model matches the target data, i.e., to determine the "model performance." An essential first step in model evaluation is to compare plots of observed data with model output (ASCE, 1993). These plots commonly display a time series of flow (e.g., a hydrograph) or transported constituent (e.g., a sedigraph for suspended sediment) at daily, monthly, or annual time steps. Overlaying plots of observed and simulated data can help identify model bias, differences in timing and magnitude of peaks and troughs, and differences in plot shape (e.g., slopes of rises and falls).

To provide more objectivity and quantitative rigor, indices have been developed to measure how closely the model output matches the observed data. In evaluating the St. Croix SWAT model, we used two quantitative statistics recommended by Moriasi et al. (2007): the Nash-Sutcliffe efficiency (NSE), and the percent bias (PBIAS).

Nash-Sutcliffe efficiency (NSE): The Nash-Sutcliffe efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information") (Nash and Sutcliffe, 1970). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. NSE is computed as shown in equation 1:

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_{obs,i} - Y_{sim,i}\right)^2}{\sum_{i=1}^{n}\left(Y_{obs,i} - Y_{mean}\right)^2}\right] \quad [1]$$

Where
Yobs,i is the *i*th observation for the constituent being evaluated,
Ysim,i is the *i*th simulated value for the constituent being evaluated,
Ymean is the mean of observed data for the constituent being evaluated,
and *n* is the total number of observations.

NSE ranges between negative infinity and 1.0, with 1.0 being the optimal value (a perfect model fit) and values <0.0 indicating that the mean observed value is a better predictor than the simulated value, thereby demonstrating unacceptable model performance. Good performance is indicated by values >0.5 and acceptable performance by values between 0.0 and 0.5 (Moriasi et al., 2007). NSE is known to be greatly influenced by larger deviations (Legates and McCabe 1999, Krause et al. 2005). Thus, in comparing modeled flows for example, NSE is a better measure of simulating peak flows rather than baseflows. Nonetheless, NSE remains highly recommended (ASCE, 1993; Legates and McCabe, 1999) and widely used, providing extensive information on reported values. Sevat and Dezetter (1991) also found NSE to be the best objective function for reflecting the overall fit of a hydrograph.

Percent bias (PBIAS): Percent bias (PBIAS) is the model deviation expressed as a percentage of the observed value. The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias (Gupta et al., 1999). PBIAS is calculated with equation 2:

$$PBIAS = \frac{\left[\sum_{i=1}^{n}\left(Y_{obs,i} - Y_{sim,i}\right) * (100)\right]}{\sum_{i=1}^{n}\left(Y_{obs,i}\right)} \quad [2]$$

Hydrology

Hydrologic calibration and validation of the St. Croix SWAT model for monthly flows were done where USGS flow data were readily available, at two sites on the St. Croix River main stem (Danbury and St. Croix Falls) and for three tributaries (Kettle River, Snake River, and Apple River). Estimated flows were also available from the Metropolitan Council for the St. Croix River at Stillwater and Prescott, but because these flows were not directly measured they were not used for calibration. Instead, emphasis was given to the St. Croix Falls site as the most downstream gauged site representing the largest part of the basin. Basin-wide parameters were adjusted initially to obtain an approximate calibration to flows at St. Croix Falls. Then parameters were adjusted on a sub-basin basis for the St. Croix above Danbury, the Kettle, the Snake, and the Apple river watersheds, followed by a final small re-adjustment at St. Croix Falls. Key considerations in the hydrology calibration were the overall water balance, storm flows, and seasonal variation in baseflow. Calibration was performed at the monthly time step for the period 2000-2007, and validation was performed for the time period of 1990-1999. In addition, model parameters were then adjusted within three tributary subbasins (Sunrise, Willow, and Kinnickinnic), based on daily flows from water-year 1999 or (for the Kinnickinnic) calendar years 2003-06. Because of the coarseness of the whole-basin model at the scale of these subbasins, model subbasin calibration was not as good as for the whole basin, but nonetheless the result was an incrementally improved model at both subbasin and whole-basin scales.

The parameters altered to achieve hydrologic calibration are given in Table 22. The main parameters adjusted included snowmelt temperature (SMTMP) to avoid excessive snowmelt runoff peaks in the spring; curve numbers (CN2 and CNOP) to promote infiltration and reduce runoff peaks; soil evaporation compensation factor (ESCO) to adjust overall water balance; and groundwater delay (GW_DELAY) to adjust the seasonality of baseflow. In particular, snow melt temperature (SMTMP) was increased to 3 deg C to delay snow melt in the spring. This parameter appears to be spatially variable, as slightly better fits were obtained with lower SMTMP values in the southerly subbasins (Willow and Kinnickinnic), where perhaps sun angle and fewer trees allow a faster melt. However, this parameter is a basin-wide parameter in this version of SWAT and a value of 3 deg C gave the best overall fit. CN values were commonly reduced 20-30%, with the exception of the Snake subbasin where they were increased by 5%. ESCO values were commonly reduced below default (0.95) to increase evapotranspiration and thus reduce water yield to observed values. GW_DELAY was uniformly increased well above the default (30 days) to smooth the baseflow signal and better account for aquifer response times on the order of a year or more. Recession following runoff events was fit by adjusting the baseflow recession (ALPHA_BF) parameter. A full explanation of these parameters is beyond the scope of this report. Interested readers may consult Arnold et al. (2013).

The model fit the St. Croix River flow very well, with a calibrated NSE of 0.84 at St. Croix Falls and 0.77 at Danbury (Table 23; Figures 13b and 13a). The fits for the validation period are only slightly lower but still within the acceptable range as defined by Moriasi et al. (2007). The fit statistics for the St. Croix at Stillwater and Prescott are similarly good as those for St. Croix Falls, since the flows at Stillwater and Prescott are driven largely by the flows at St. Croix Falls. The tributaries were fit similarly well, especially the Kettle (NSE = 0.78) and Snake (NSE = 0.85) rivers (Table 23; Figures 14a and 14b). The PBIAS statistic shows overall water yield at St. Croix Falls fitting within 4% for the calibration period, and <1% for the validation period. Hydrographs for the St. Croix River main stem (Figure 13) and calibrated tributaries (Figure 14) demonstrate the quality of the fit.

Table 22. Parameters altered to achieve hydrologic calibration of the St. Croix SWAT model.

Table	Files	Parameter: Abbreviation	Parameter: Name	Values: Default	Values: Calibrated	Subbasins applied
bsn	bsn	SFTMP	Snowfall temperature (deg C)	1	2.5	basin-wide
bsn	bsn	SMTMP	Snow melt base temperature (deg C)	0.5	2.5	basin-wide
bsn	bsn	SMFMX	Snow melt factor, maximum (mm H2O / degC-day)	4.5	10	basin-wide
bsn	bsn	SMFMN	Snow melt factor, minimum (mm H2O / degC-day	4.5	4	basin-wide
bsn	bsn	TIMP	Snow pack temperature lag factor (0.01 - 1)	1	0.1	basin-wide
gw	gw	GW_DELAY	Groundwater delay time (days)	31	200	basin-wide, except for:
					550	St. Croix above Danbury
					750	Apple
					300	Kettle
					800	Kinnickinnic
					400	Snake
					75	Sunrise
					600	Willow
gw	gw	ALPHA_BF	Baseflow alpha factor (baseflow recession constant) (days)	0.048	0.48	basin-wide
gw	gw	GW_REVAP	Groundwater re-evaporation coefficient	0.02	0.01	Kinnickinnic
					0.05	Sunrise
gw	gw	RCHRG_DP	Fraction of recharge lost to deep aquifer	0.05	0	basin-wide
hru	hru	ESCO	Soil evaporation compensaton factor (0.01 - 1)	0.95	0.8	basin-wide, except for:
					0.9	St. Croix above Danbury
					0.73	Apple
					0.85	Kettle
					0.6	Kinnickinnic
					0.5	Snake
					0.5	Sunrise
					0.6	Willow
hru	hru	SURLAG	Surface runoff lag coefficient	4	0.5	basin-wide, except for:
					0.1	Kinnickinnic
mgt1	mgt	CN2	Curve number for SCS moisture condition II	ArcSWAT	-20%	St. Croix above Danbury
					-25%	Apple
					+20%	Kettle
					-25%	Kinnickinnic
					+5%	Snake
					-30%	Sunrise
					-20%	Willow
mgt2	mgt	CNOP	Curve number for SCS moisture condition II, for selected management operation	ArcSWAT	same as for CN2	same as for CN2
pnd	pnd	IFLOD1	Beginning month of non-flood season	1	12	all ponds
pnd	pnd	IFLOD2	Ending month of non-flood season	1	1	all ponds
pnd	pnd	PND_EVOL	Emergency pond volume	user	2*PND_PVOL	all ponds
pnd	pnd	NDTARG	Days to reach target pond volume	15	3	all ponds
pnd	pnd	PND_K	Pond hydraulic conductivity	0	1	Sunrise
pnd	pnd	PNDEVCOEFF	PET-to-Evaporation coefficient for Ponds	0.6	1	all ponds
res	res	IFLOOD1R	Beginning month of non-flood season	1	12	all lakes
res	res	IFLOOD2R	Ending month of non-flood season	1	1	all lakes
res	res	STARG1-12	Monthly target volumes	0	RES_PVOL	all lakes
res	res	NDTARGR	Days to reach target lake volume	10	3	all lakes
res	res	EVRSV	Evaporation coefficient for reservoirs	0.6	1	all lakes
rte	rte	CH_W2	Main channel width	ArcSWAT	-67%	basin-wide
rte	rte	CH_WDR	Main channel width-to-depth ratio	ArcSWAT	-67%	basin-wide
rte	rte	CH_N2	Main channel roughness	0.014	0.03	basin-wide
sub	sub	CH_K1	Tributary channel hydraulic conductivity	0	1	basin-wide, except for:
					0	Kettle
					5	Kinnickinnic
					5	Willow

NOTES: For non-constant default values, "ArcSWAT" means supplied by ArcSWAT, "user" means supplied by user. Parameters considered but not altered beyond default: ICN, FFCB (bsn); GWQMN, SHALLST, REVAPMN (gw); CANMX (hru); SOL_AWC (sol).

Table 23. Goodness of fit statistics for hydrologic calibration and validation of the St. Croix SWAT model.

Site		Calibration			Validation			Overall		
	Time step	Period	NS	PBIAS	Period	NS	PBIAS	Period	NS	PBIAS
St. Croix River at Danbury	Monthly	2000-2007	0.77	-2.9	1990-1999	0.68	-1.1	1990-2007	0.74	-1.8
St. Croix River at St. Croix Falls	Monthly	2000-2007	0.84	-4.3	1990-1999	0.75	0.0	1990-2007	0.80	-1.8
St. Croix River at Stillwater	Monthly	2000-2007	0.83	-1.8	1990-1999	0.72	1.0	1990-2007	0.78	-0.2
St. Croix River at Prescott	Monthly	2000-2007	0.83	-3.0	1990-1999	0.72	-1.2	1990-2007	0.78	-2.0
Kettle River	Monthly	2000-2007	0.78	2.7	1990-1999	0.75	-0.4	1990-2007	0.77	1.0
Snake River	Monthly	2000-2007	0.85	5.9	1990-1999	0.70	-2.5	1990-2007	0.79	2.0
Sunrise River	Daily	WY1999	0.72	-2.1						
Apple River	Monthly	2000-2007	0.70	-1.8	1990-1999	0.50	2.9	1990-2007	0.62	0.9
Willow River	Daily	WY1999	0.54	2.9						
Kinnickinnic River	Daily	2003-2006	0.33	0.1						

NOTES: NS, Nash-Sutcliffe coeffiecient of efficiency; PBIAS, percent bias, or negative percent error. A negative PBIAS means that the model overestimated flow. See text for definitions. Data sets from the U.S. Geological Survey, in collaboration with the Minnesota Department of Natural Resources and Minnesota Pollution Control Agency.

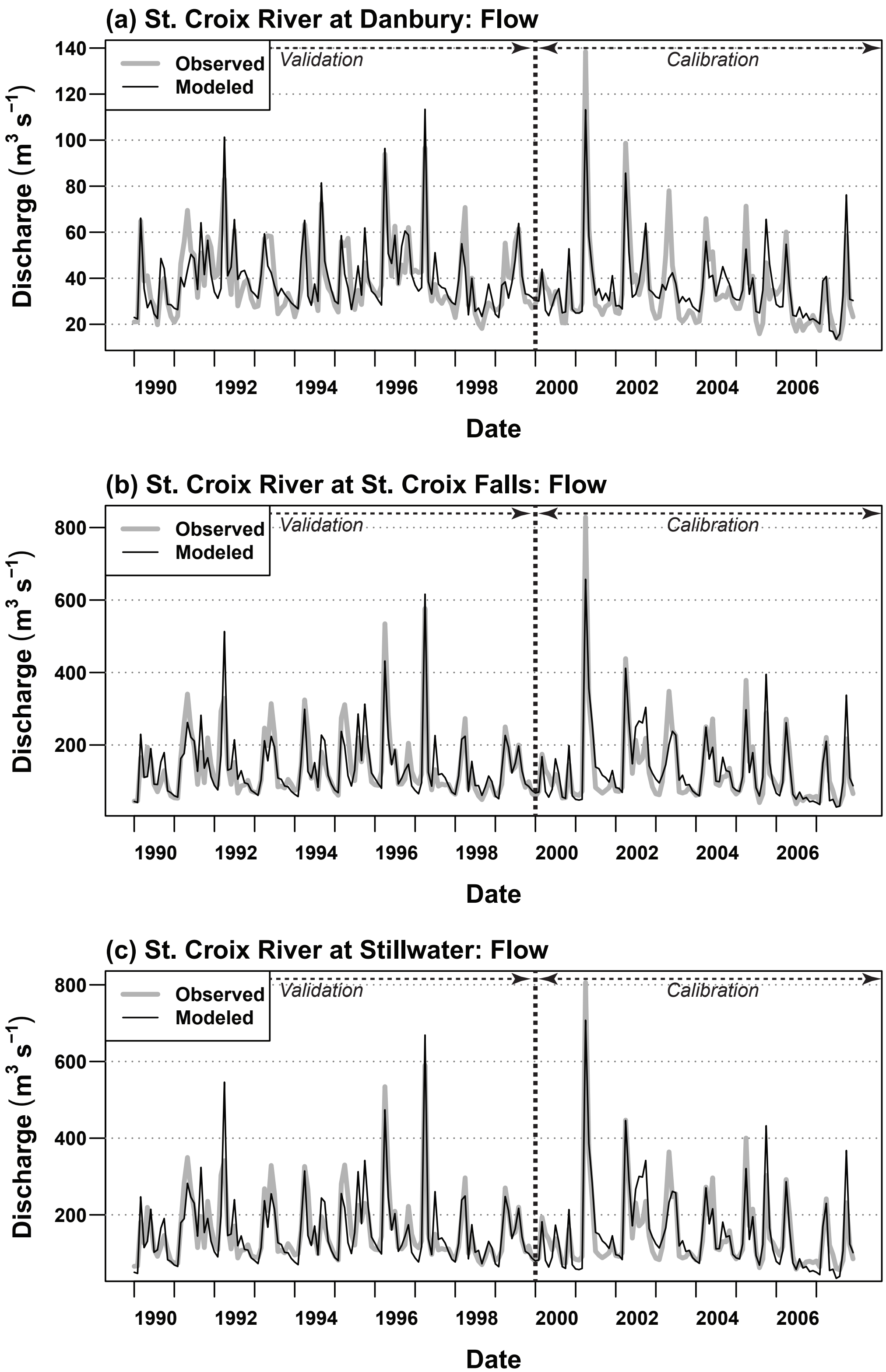


Figure 13. Flow of the main stem of the St. Croix River at (a) Danbury, (b) St. Croix Falls, and (c) Stillwater for calibration (2000-07) and validation (1990-99) periods.

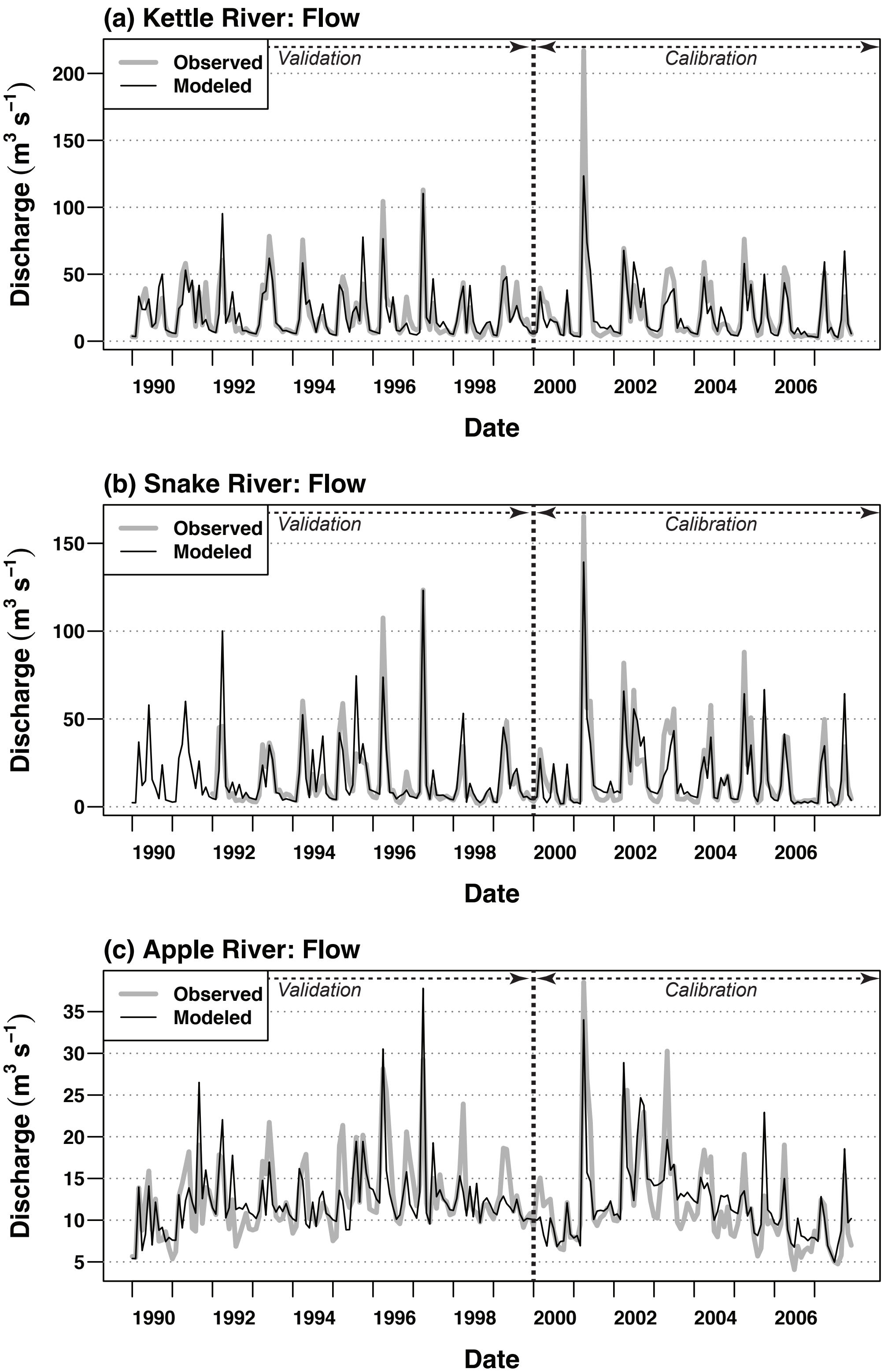


Figure 14. Flow of major tributaries to the St. Croix for calibration (2000-07) and validation (1990-99) periods: (a) Kettle River, (b) Snake River, and (c) Apple River.

Water Quality

Water quality in the SWAT model was calibrated sequentially by constituent. The model was calibrated first to suspended sediment, second to total phosphorus, and last to total nitrogen. All calibration was based on monthly loads at Stillwater as calculated by the Metropolitan Council Environmental Services (MCES 2011; K. Jensen, MCES, personal communication, 2011). All three constituents were fit well during the calibration period (2000-07), with NSE values of 0.76 for sediment, 0.83 for total phosphorus, and 0.69 for total nitrogen (Table 24). During the validation period (1990-99), NSE values for total phosphorus (0.58) and total nitrogen (0.56) remained above the threshold suggested by Moriasi et al. (2007). Sediment validation was somewhat less successful (NSE = 0.24), although PBIAS showed an error of <1% for this time. Monthly time series of these water-quality constituents showed good relation between modeled and observed monthly loads (Figure 15). Note that the sediment loads (Figure 15a) during the validation period appear reasonably close to the observed values, and the modest NSE value must be the result of missing just a few peaks.

As in the rest of the glaciated upper Midwest, sediment calibration in the St. Croix watershed (Figure 15a) was challenging due to the presence of numerous lowlands (ponds and wetlands) and lakes that trap sediment between the uplands and the monitoring point. These depressions are a consequence of the glacial-drift landforms in the St. Croix basin and they reduce subbasin-scale loads below those expected from calculations based on the universal soil-loss equation (USLE), including the modified USLE (MUSLE) used within SWAT. Fortunately, SWAT includes a number of features that allow the net effects of these depressions to be appropriately simulated (Almendinger et al. 2014). As noted earlier (Table 4), on average, all water yield from 45% of each subbasin area was routed through a SWAT pond feature, wherein significant fractions of sediment and nutrients were trapped. On-channel lakes (reservoirs in SWAT) were likewise important sediment traps impacting net yields from all upstream contributing subbasins.

Table 24. Goodness of fit statistics for water-quality calibration and validation of the St. Croix SWAT model.

Parameter and Site		Calibration			Validation			Overall		
	Time step	Period	NS	PBIAS	Period	NS	PBIAS	Period	NS	PBIAS
SEDIMENT										
St. Croix River at Stillwater	Monthly	2000-2007	0.76	6.0	1990-1999	0.24	-0.8	1990-2007	0.64	2.3
Willow River	Monthly	WY 1999	0.68	-4.7						
TOTAL PHOSPHORUS										
St. Croix River at Stillwater	Monthly	2000-2007	0.83	-12.7	1990-1999	0.58	9.3	1990-2007	0.73	0.2
Willow River	Monthly	WY 1999	0.23	4.7						
TOTAL NITROGEN										
St. Croix River at Stillwater	Monthly	2000-2007	0.69	-9.6	1990-1999	0.56	15.5	1990-2007	0.63	4.4

NOTES: NS, Nash-Sutcliffe coeffiecient of efficiency; PBIAS, percent bias, or negative percent error. A negative PBIAS means that the model overestimated a value. See text for definitions. Observed data sets for St. Croix River at Stillwater from the Metropolican Council Environmental Services, and for the Willow River from the U.S. Geological Survey.

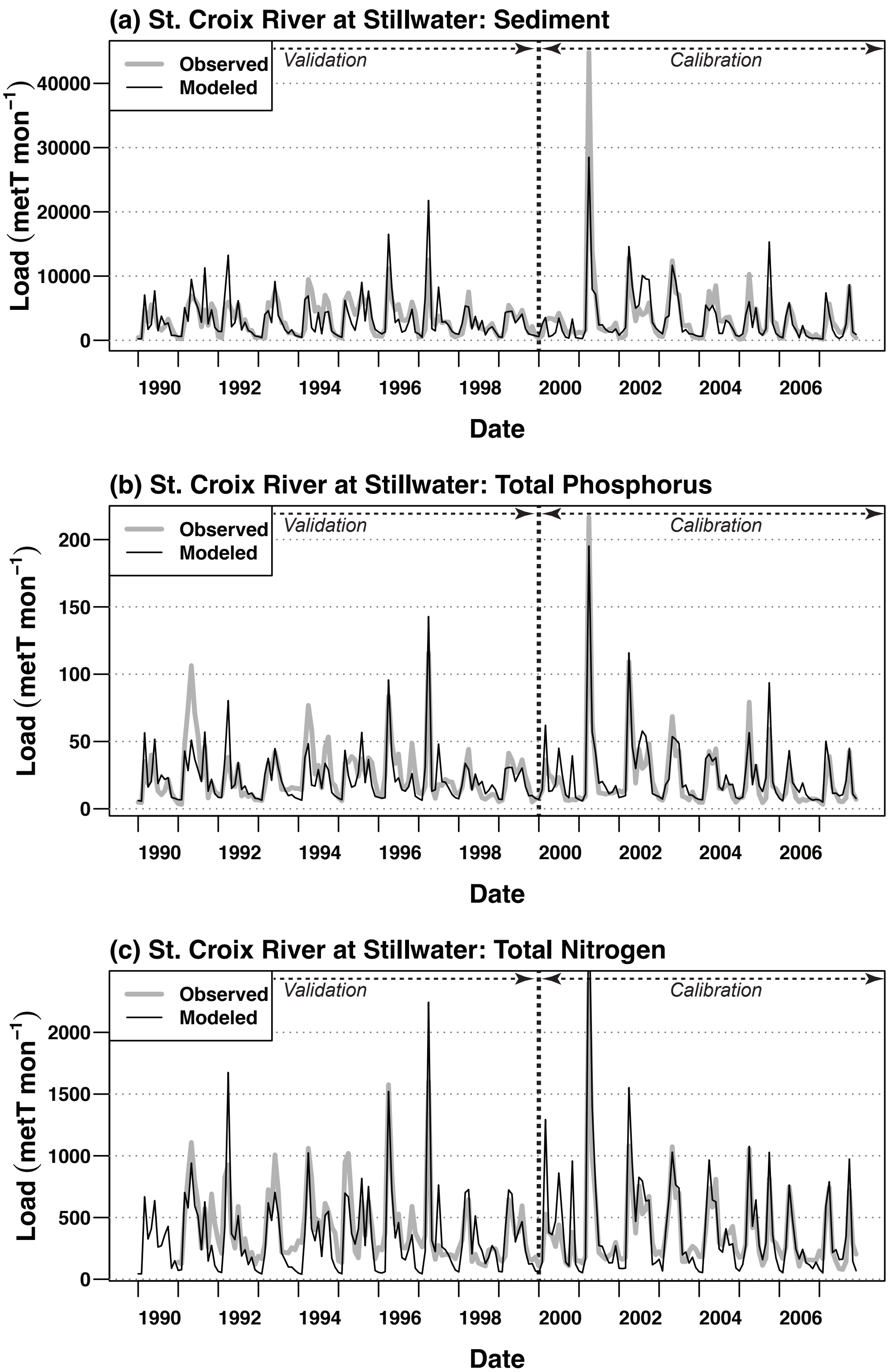


Figure 15. Monthly loads of (a) suspended sediment, (b) total phosphorus, and (c) total nitrogen for the St. Croix River at Stillwater, 1990-2007.

To generate appropriate sediment yields from upland HRUs, parameters were adjusted to alter both the availability and transport of sediment (Table 25). Subbasin slope lengths (SLSUBBSN) were reduced by 8-20%, and cropping practice support factor (USLE_P) was reduced by 20% basinwide to bring HRU-scale sediment yields in line with literature values. Then equilibrium sediment concentration (NSEDs) and median grain sizes (D50s) were adjusted for all Ponds and Reservoirs to reduce loads further and alter their seasonal distribution (see above report sections on Reservoirs and Ponds for explanations for parameter settings). Finally, channel sediment transport processes were adjusted to further smooth seasonal distribution of sediment, reducing peaks and adding some suspended sediment during lower flow months. We used the simplest Bagnold sediment transport algorithm in SWAT, which assumes all transported sediment is silt. Hence, bedload was ignored by the model. This simplification is often justified because many sediment-load observations are based on the suspended fraction and not bedload. This is certainly the case for the St. Croix River at Stillwater, where the station is at a bridge over the upper part of Lake St. Croix, about a mile below where the river enters the lake. Grab samples from this site thus contain only suspended material and no bedload.

Total phosphorus (TP) loads (Figure 15b) are of vital importance to the St. Croix basin: phosphorus is the prime suspect causing the eutrophication impairment of Lake St. Croix. Hence calibrating phosphorus loads in the model is an important first step in understanding the sources of phosphorus and its transport to receiving waters. Once we understand the source and transport of phosphorus, we can develop mitigation efforts to abate these loads. However, phosphorus calibration was likewise complicated by the same source and transport factors that affected sediment, resulting in a large number of parameters that could be adjusted in any number of ways to achieve calibration (Table 26). Our principal "hard-data" target for calibration was the 2000-

Table 25. Parameters altered to achieve sediment calibration of the St. Croix SWAT model.

		Parameter		Values		
Table	Files	Abbreviation	Name	Default	Calibrated	Subbasins applied
bsn	bsn	SPEXP	Exponent parameter for sediment transport capacity in reach	1	1.7	basin-wide
hru	hru	HRU_SLP	Average slope (m/m)	ArcSWAT	0.001	All wetland (WETN) HRUs
hru	hru	SLSUBBSN	Average slope length (m)	ArcSWAT	-8% - 20%	basin-wide, except for: wetland, grassland, and agricultural land
mgt1	mgt	USLE_P	USLE support practice factor	1	0.8	basin-wide
pnd	pnd	PND_NSED	Equilibrium sediment concentration in ponds (mg/L)	0	9	all ponds
pnd	pnd	PND_D50	Median particle diameter of sediment (micro-m)	10	62.5	all ponds
res	res	RES_NSED	Equilibrium sediment concentration in reservoirs (lakes) (mg/L)	0	0.16 to 1.42 = f(lake area, depth)	all lakes
res	res	RES_SED	Initial sediment concentration in reservoirs (lakes)	0	RES_NSED	all lakes
res	res	RES_D50	Median particle diameter of sediment (micro-m)	10	20 * RES_NSED 9 * RES_NSED	all lakes, except for: Willow
rte	rte	CH_COV1	Channel erodibility factor	0	0.04 0.5	basin-wide, except for: Willow
rte	rte	CH_COV2	Channel cover factor	0	0.04 0.5	basin-wide, except for: Willow
sub	sub	CH_S1	Tributary slope	ArcSWAT	0.2 * ArcSWAT value	basin-wide

NOTES: For non-constant default values, "ArcSWAT" means supplied by ArcSWAT, "user" means supplied by user. Parameters considered but not altered beyond default: ADJ_PKR, PRF, SPCON (bsn); FILTERW (mgt); USLE_K (sol); EFFMIX, DEPTIL (till.dat).

Table 26. Parameters altered to achieve nutrient calibration of the St. Croix SWAT model.

Table	Files	Parameter: Abbreviation	Parameter: Name	Values: Default	Values: Calibrated	Subbasins applied
TOTAL PHOSPHORUS						
chm	chm	SOL_LABP1 (also SOL_SOLP1)	Initial labile (soluble) P concentration in soil layer 1 (ppm)	5	0.15 to 9 = f(STP)	Soil-test phosphorus (STP) assigned by land use. See notes below.
chm	chm	SOL_LAB2-10	Initial labile (soluble) P concentration in soil layer 2-10 (ppm)	0	1	all HRUs
gw	gw	GWSOLP	Soluble P concentratioin in groundwater (mg/L)	0	0 to 0.02	Assigned by land use. See notes below.
res	lwq	IRES1	Beginning month of mid-year nutrient settling rate	1	3	all lakes
res	lwq	IRES2	Ending month of mid-year nutrient settling rate	1	10	all lakes
res	lwq	PSETLR1	Season 1 phosphorus settling rate for reservoirs (m/yr)	10	5 to 223 =f(lake depth, residence time)	all lakes
res	lwq	PSETLR2	Season 2 phosphorus settling rate for reservoirs (m/yr)	10	0	all lakes
res	lwq	RES_ORGP	Initial organic phosphorus concentration in reservoirs (mg/L)	0	0.025	all lakes
res	lwq	RES_SOLP	Initial soluble phosphorus concentration in reservoirs (mg/L)	0	0.025	all lakes
pnd	pnd	IPND1	Beginning month of mid-year nutrient settling	1	3	all ponds
pnd	pnd	IPND2	Ending month of mid-year nutrient settling season	1	10	all ponds
pnd	pnd	PSETLP1	Season 1 phosphorus settling rate for ponds (m/yr)	10	100	all ponds
pnd	pnd	PSETLP2	Season 2 phosphorus settling rate for ponds (m/yr)	10	0	all ponds
pnd	pnd	PND_ORGP	Initial concentration of organic phosphorus in pond (mg/L)	0	0.025	all ponds
pnd	pnd	PND_SOLP	Initial concentration of soluble phosphorus in pond (mg/L)	0	0.025	all ponds
swq	swq	RS2	Benthic source of dissolved P (mg/m2/day)	0.05	15 30	all reaches, except for: Willow
swq	swq	RS5	Organic P settling rate coefficient (per day)	0.05	1.4 2	all reaches, except for: Willow
TOTAL NITROGEN						
bsn	bsn	RCN	Concentration of nitrogen in rainfall (mg N/L)	0	1.65	basin-wide (NADP 20014)
bsn	bsn	NPERCO	Nitrogen percolation coefficient	0.2	0.5	basin-wide
res	lwq	IRES1	Beginning month of mid-year nutrient settling rate	1	3	all reservoirs (lakes)
res	lwq	IRES2	Ending month of mid-year nutrient settling rate	1	10	all reservoirs (lakes)
res	lwq	NSETLR1	Season 1 nitrogen settling rate for reservoirs (m/yr)	5.5	10	all reservoirs (lakes)
res	lwq	NSETLR2	Season 2 nitrogen settling rate for reservoirs (m/yr)	5.5	0	all reservoirs (lakes)
pnd	pnd	IPND1	Beginning month of mid-year nutrient settling	1	3	all ponds (and wetlands)
pnd	pnd	IPND2	Ending month of mid-year nutrient settling season	1	10	all ponds (and wetlands)
pnd	pnd	NSETLP1	Season 1 nitrogen settling rate for ponds (m/yr)	5.5	10	all ponds
pnd	pnd	NSETLP2	Season 2 nitrogen settling rate for ponds (m/yr)	5.5	0	all ponds
swq	swq	RS3	Benthic source of dissolved NH4-N (mg/m2/day)	0.5	100	all reaches
swq	swq	RS4	N settling rate coefficient (per day)	0.05	10	all reaches

NOTES: For non-constant default values, "ArcSWAT" means supplied by ArcSWAT, "user" means supplied by user. Parameters considered but not altered beyond default: P_UPDIS, PPERCO, PHOSKD, PSP, N_UPDIS, CDN, SDNCO (bsn); DEPTIL, EFFMIX (till.dat). Soil-test phosphorus (STP) assigned according to land cover: 1 ppm for water & wetlands; 5 ppm for forest & grassland; 10 ppm for pasture; 20 ppm for 25% of cropland; 40 ppm for urban and 50% of cropland; 60 ppm for barnyards and 25% of cropland. Groundwater soluble P assigned by land cover: 0 mg/L for water & wetlands; 0.01 mg/L for forest & grassland; 0.015 for pasture & urban; 0.02 for cropland & barnyard.
RCN calculated with data from NADP (National Atmospheric Deposition Program), 2014. Data downloaded in grid format from National Trends Network website (http://nadp.sws.uiuc.edu/NTN/). Accessed Nov. 2014.

07 total phosphorus load for the St. Croix River at Stillwater. To constrain the parameter values further, we tried to make sure the phosphorus loads were of reasonable magnitude at selected steps along the transport path from field to lake. These additional considerations could be called "soft-data" targets, because they were not measured in the St. Croix basin itself but were taken from the literature.

To calibrate total phosphorus, we first adjust HRU-scale parameters to generate reasonable yields of phosphorus (kg/ha/yr) from croplands (Table 27). This was done principally by adjusting the soil labile phosphorus content, by setting it to a fraction of assigned soil-test phosphorus levels. This generated loads substantially greater than were measured at the

Table 27. Areas of selected landscape units and their average annual loads and yields of sediment, phosphorus, and nitrogen over 18 years of model runs (1990-2007) for the St. Croix SWAT model. Quantities refer to amounts mobilized in the uplands, which are generally larger than what is delivered to receiving waters.

Land Cover	Area		Sediment			Total Phosphorus			Total Nitrogen		
			Load	Percent	Yield	Load	Percent	Yield	Load	Percent	Yield
	(km^2)	(%)	(metT)	(%)	(metT/ha)	(metT)	(%)	(kg/ha)	(metT)	(%)	(kg/ha)
Urban	**488**	**2%**	**1,143**	**1%**	**0.02**	**23**	**5%**	**0.47**	**288**	**5%**	**5.9**
Agriculture	**3,434**	**17%**	**207,872**	**97%**	**0.61**	**383**	**79%**	**1.11**	**2,880**	**52%**	**8.4**
Cropland	**2,296**	**11%**	**186,220**	**86%**	**0.81**	**329**	**68%**	**1.43**	**2,141**	**38%**	**9.3**
by crop:											
Corn-grain	*743*	*4%*	*75,672*	*35%*	*1.04*	*134*	*28%*	*1.86*	*892*	*16%*	*12.3*
Corn-silage	*203*	*1%*	*23,054*	*11%*	*1.12*	*37*	*8%*	*1.83*	*249*	*4%*	*12.0*
Soybeans	*540*	*3%*	*65,651*	*30%*	*1.20*	*122*	*25%*	*2.23*	*805*	*14%*	*14.8*
Alfalfa	*810*	*4%*	*21,843*	*10%*	*0.27*	*36*	*7%*	*0.44*	*195*	*3%*	*2.4*
by rotation:											
Corn-Soybeans (CS)	*986*	*5%*	*117,857*	*55%*	*1.19*	*214*	*44%*	*2.16*	*1,400*	*25%*	*14.1*
Corn-Alfalfa (CA)	*1,310*	*7%*	*68,363*	*32%*	*0.52*	*115*	*24%*	*0.88*	*741*	*13%*	*5.6*
CA, no manure	*860*	*4%*	*50,725*	*24%*	*0.59*	*72*	*15%*	*0.83*	*452*	*8%*	*5.3*
CA, daily-haul manure	*188*	*1%*	*9,733*	*5%*	*0.51*	*29*	*6%*	*1.53*	*171*	*3%*	*9.1*
CA, seasonal manure	*262*	*1%*	*7,905*	*4%*	*0.30*	*15*	*3%*	*0.56*	*118*	*2%*	*4.4*
Pastureland	**1,138**	**6%**	**21,652**	**10%**	**0.19**	**54**	**11%**	**0.47**	**739**	**13%**	**6.5**
Pasture	*1,083*	*5%*	*20,447*	*9%*	*0.19*	*33*	*7%*	*0.31*	*643*	*12%*	*5.9*
Beef	*383*	*2%*	*9,147*	*4%*	*0.24*	*17*	*4%*	*0.45*	*350*	*6%*	*9.1*
Dairy	*516*	*3%*	*8,835*	*4%*	*0.17*	*11*	*2%*	*0.22*	*217*	*4%*	*4.2*
Horse	*184*	*1%*	*2,465*	*1%*	*0.13*	*4*	*1%*	*0.24*	*76*	*1%*	*4.1*
Barnyard	*55*	*0.3%*	*1,205*	*1%*	*0.22*	*21*	*4%*	*3.77*	*96*	*2%*	*17.6*
Beef	*19*	*0.1%*	*668*	*0.3%*	*0.35*	*14*	*3%*	*7.18*	*57*	*1%*	*29.5*
Dairy	*26*	*0.1%*	*371*	*0.2%*	*0.14*	*4*	*1%*	*1.76*	*28*	*0.5%*	*10.9*
Horse	*10*	*0.05%*	*166*	*0.1%*	*0.17*	*2*	*0.4%*	*2.04*	*11*	*0.2%*	*11.2*
Grassland	**1,756**	**9%**	**1,175**	**1%**	**0.007**	**24**	**5%**	**0.14**	**446**	**8%**	**2.5**
Forest	**11,572**	**58%**	**4,214**	**2%**	**0.004**	**36**	**7%**	**0.03**	**1,575**	**28%**	**1.4**
Aquatic	**2,755**	**14%**	**950**	**0%**	**0.003**	**20**	**4%**	**0.07**	**381**	**7%**	**1.4**
Totals	***20,006***	***100%***	***215,355***	***100%***		***485***	***100%***		***5,570***	***100%***	

NOTE: Standard errors of the mean ranged from about 4-42% of load or yield value, and averaged about 11%.

Stillwater site, and so Ponds were parameterized to trap phosphorus at about 20% efficiency, and lakes (reservoirs) to a mean of 48% efficiency, similar to the mean of 45% given in Brett and Benjamin (2008). (See Reservoir section above for the formula used to set phosphorus apparent settling rates, the PSETLR1 parameter.) Finally, channel water-quality processing was activated (the QUAL2E routines) in SWAT to further smooth the annual signal of total phosphorus loads, reducing peaks and increasing loads during lower-flow months. These channel-scale parameters for phosphorus were designed to account for loss of phosphorus to the channel sediment by algal settling, and to allow for phosphorus release from the sediment to the water column by desorption. However, the parameter values were adjusted far beyond suggested ranges for the St. Croix SWAT model, and it is likely that other, larger-scale processes are at play. In particular, we hypothesize that peaks of total phosphorus loading are moderated during storm and other runoff events by temporary storage in floodplain and backwater locations, and that some of this phosphorus later contributes to loads during lower-flow periods. An alternative hypothesis is that the many lakes in the St. Croix basin could release phosphorus from their sediment during the winter months (with effectively negative PSETLR2 values), thereby increasing phosphorus loads during the low-flow winter months. This hypothesis needs testing but could explain why the St. Croix, with its many lakes, may cycle nutrients somewhat differently than other large basins. The pattern is consistent with other SWAT models for tributary watersheds within the St. Croix basin, namely the Willow (Almendinger and Murphy 2007) and Sunrise (Almendinger and Ulrich 2010, 2012) river watersheds. However, we have no data to test this hypothesis, and the current version of SWAT does not allow for negative PSETLR values, which would be a useful addition to the SWAT code.

Calibration of total nitrogen (Figure 15c) can be more problematic than for either sediment or phosphorus, because of the many microbial processes that can alter nitrogen speciation and transport in a basin with as many wetlands and lakes as in the St. Croix. These processes are not well-constrained in SWAT or other such large-basin models. Despite these potential complications, the modeled monthly total nitrogen load had a reasonable NS value (>0.5) with nearly default parameterization. To improve the fit, the total annual load generated was adjusted with the nitrogen percolation coefficient (NPERCO), and trapping by Ponds and Reservoirs was adjusted with the nitrogen settling rate (NSETLR) (Table 26). The settling season was the same as for phosphorus, namely, March through October. Finally, the total nitrogen signal was smoothed slightly by adjusting in-stream setting and release, as was done for total phosphorus. Again, it seems likely that floodplain and backwater processes are helping to modulate the nitrogen signal, blunting peak loads and adding to low-flow loads. Further seasonal smoothing would be useful, and it may be that the model is missing part of the groundwater delivery of nitrate to the channels.

Annualized model output can be analyzed to isolate which land covers and land uses are the principal sources of sediment and nutrients on the landscape (Table 27). Yields in Table 27 represent quantities that are mobilized at the HRU or field scale, prior to any transport processes that may trap (or sometimes add) constituents along the path from field to stream. This table indicates that although agriculture occupies only 17% of the land area in the St. Croix basin, it may be responsible for generating 97% of the sediment, 79% of the phosphorus, and 52% of the nitrogen mobilized on the landscape. We suspect that the influence of agriculture is somewhat exaggerated by these figures, possibly because SWAT was developed principally to simulate agricultural lands and processes, and the non-agricultural land covers (forest, grassland, and urban) may not be as well-constrained. Furthermore, the lake sediment-core studies (Triplett et al., 2009) indicate that current loads of sediment and phosphorus are about four times the natural background loads, which would imply that about 75% of the current loads are due to human activities (agriculture and urban land uses). While the percent of phosphorus mobilized in the model is reasonably similar to this value, the percent sediment generated is much larger. The difference for sediment may simply be channel erosion, which contributes to the downstream loads but is not included in the amounts generated by the HRUs (upland landscape units). In fact, both sediment and phosphorus are so altered by their passage thought lowlands (ponds and wetlands) and lakes that quantifying the relation between yields generated on the landscape and loads delivered to the watershed outlet is a principal challenge in watershed modeling.

The average yields (annual loads per unit area) may be mapped by subbasin to show the net results of the source and transport factors acting across the St. Croix basin. Figures 16-18 show the average annual subbasin yields of sediment, total phosphorus, and total nitrogen, respectively. These maps represent delivery of sediment and nutrients from the landscape, including lowlands, to the stream network. They do not, however, include the trapping of sediment and nutrients by lakes connected to the stream network. These maps can help guide implementation efforts by locating “hot spots” of sediment and nutrient sources and delivery. Because both source and delivery are considered, such maps should be superior to those based on source (land use) alone, where export coefficients are used to translate land use into area-weighted yields and annual loads.

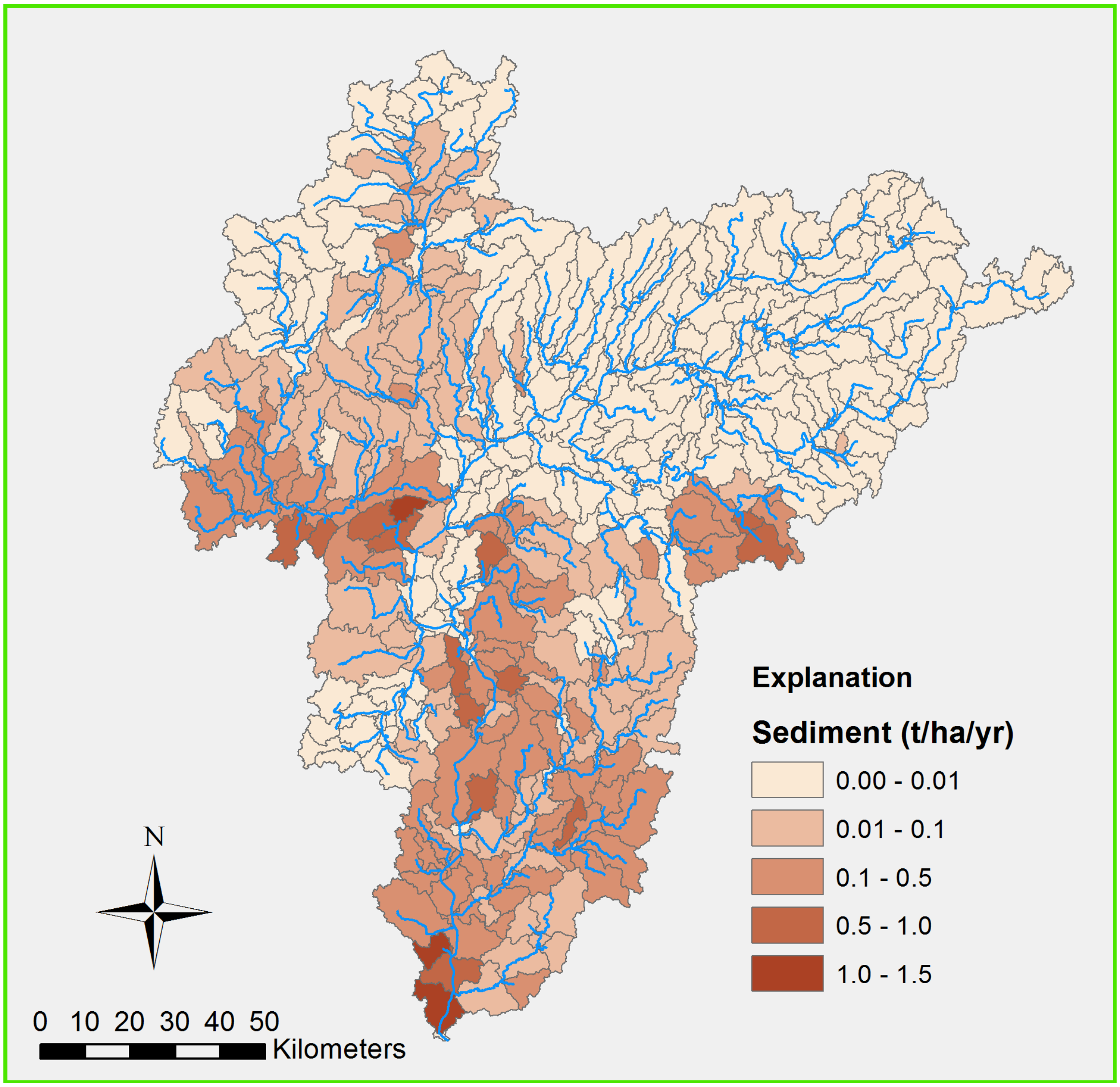


Figure 16. Average annual sediment yield by model subbasin in the St. Croix basin, 2000-07.

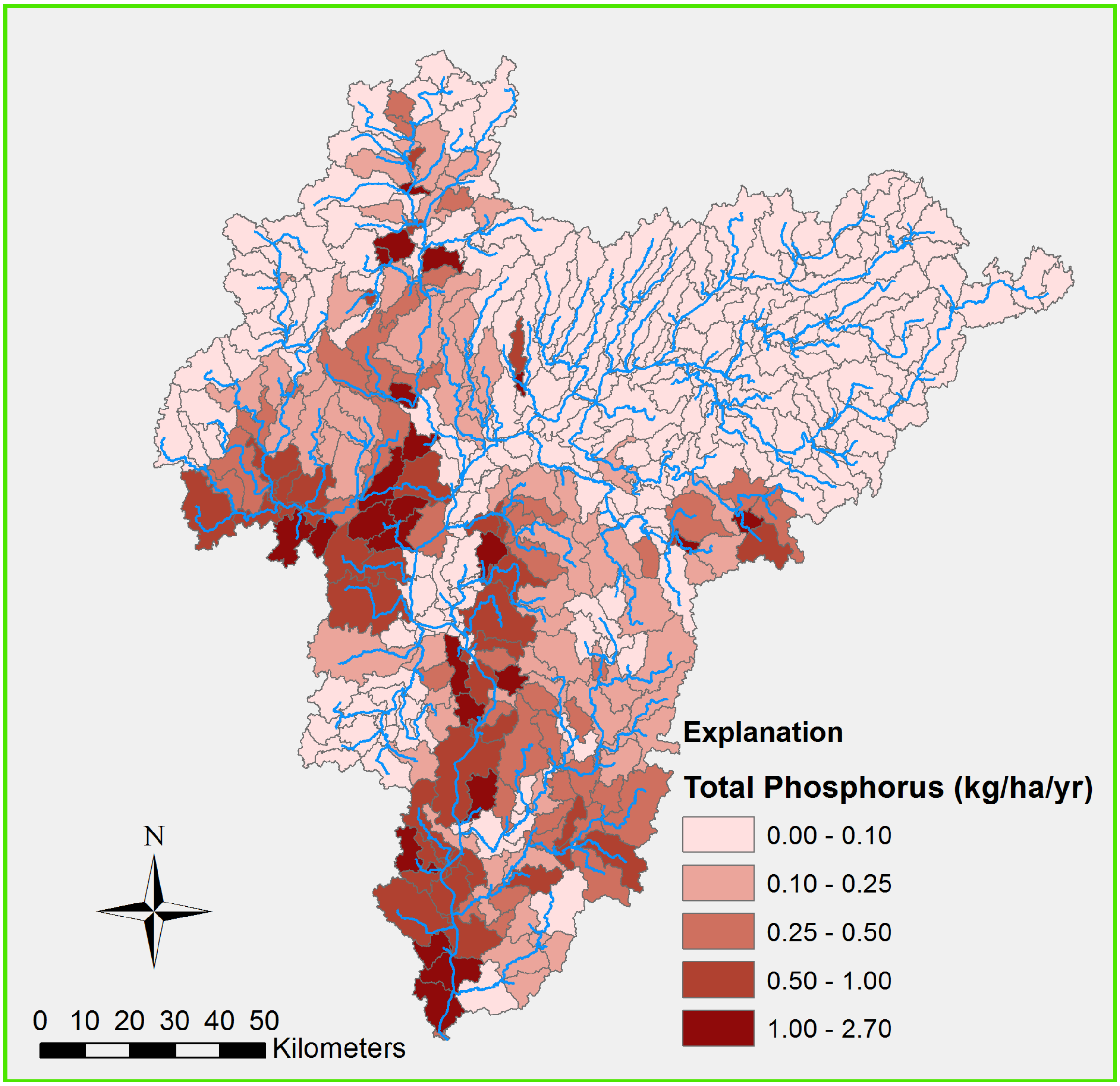


Figure 17. Average annual total phosphorus yield by model subbasin in the St. Croix basin, 2000-07.

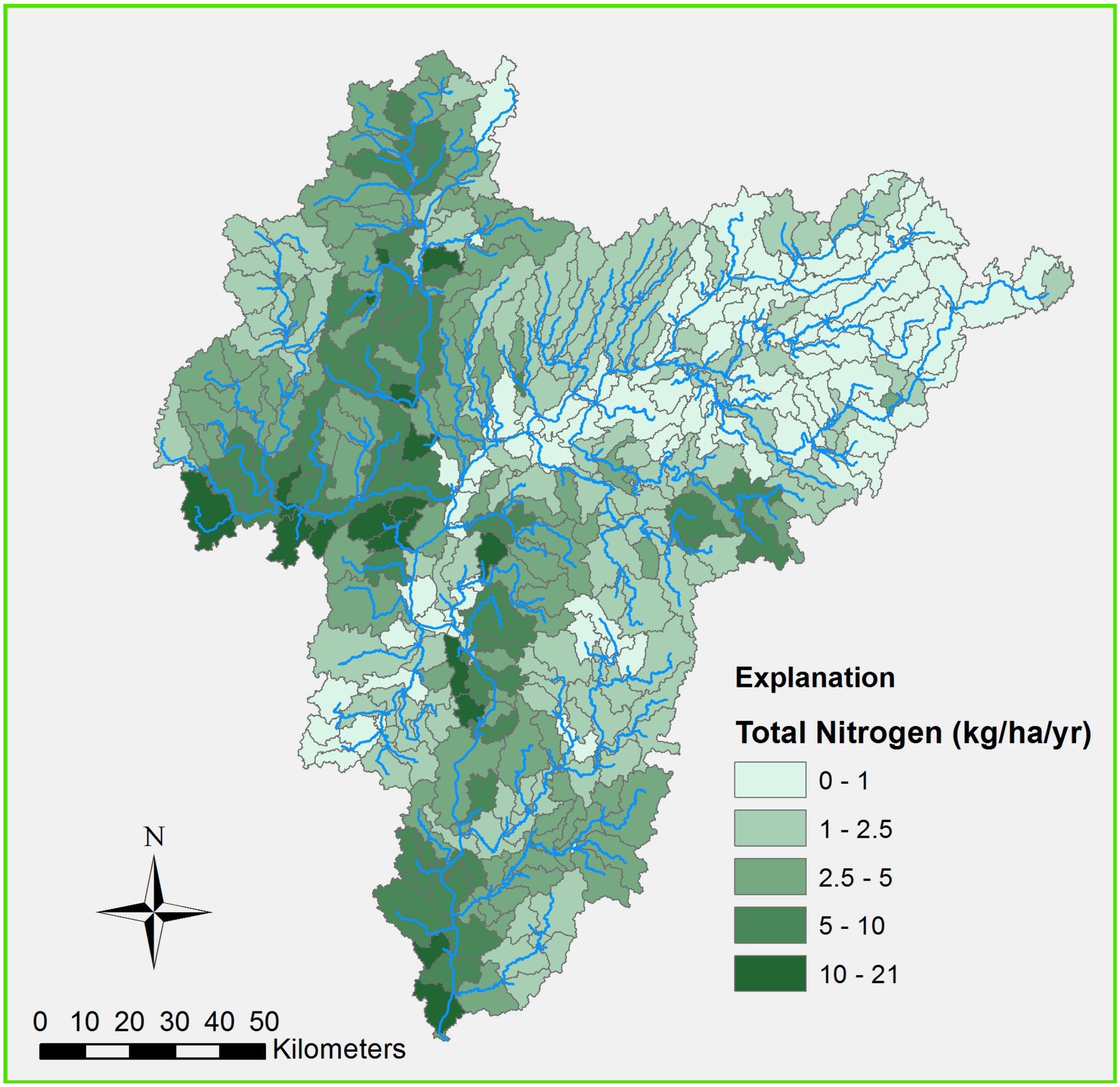


Figure 18. Average annual total nitrogen yield by model subbasin in the St. Croix basin, 2000-07.

Summary and Conclusions

Although the St. Croix National Scenic Riverway remains one of the most scenic and high-quality large rivers systems in the Upper Midwest, its water quality has been degraded by both point- and nonpoint-source pollution from its 20,000-km^2 basin. Lake St. Croix, the lowermost 40 km of the Riverway, has been declared by both Minnesota and Wisconsin to be impaired due to eutrophication from excess phosphorus loads. Previous work has resulted in both states adopting the goal of reducing total phosphorus loads to the lake by 27% relative to loads in the 1990s. A computerized watershed model can provide a whole-basin framework for addressing this goal by integrating all loads from all sources in a mechanistic way. In particular, the model can help identify locations for implementing best management practices that could reduce nonpoint-source loads, which are the largest contributor of phosphorus to the Riverway. We chose to use the SWAT modeling program, which was developed by the USDA to predict nonpoint loads of sediment and nutrients from large basins over long periods of time.

We used the ArcSWAT interface to prepare the data sets required by the SWAT program itself. A high-quality, high-density flow network from the Minnesota Department of Natural Resources (MDNR) was used in conjunction with the 30-m digital elevation model (DEM) from the U.S. Geological Survey (USGS) to delineate the St. Croix basin into 419 subbasins. The U.S. Department of Agriculture (USDA) Crop Data Layer (CDL) for 2007 served as the starting land-cover data set. However, it was modified considerably by considering all the CDL layers from 2006-10 and National Agricultural Statistics Service (NASS) tabular data for cropland. This modified land-use grid was intersected with soils from the STATSGO data layer and a slope-class (0-10% and >10%) data layer to create a total of 3010 hydrologic response units (HRUs), approximately seven per subbasin. Each HRU, having uniform land cover, soils, and slope, was modeled to have a uniform rainfall-runoff response that ultimately delivers water, sediment, and nutrients to the channel reach in that subbasin. A total of 39 lakes were explicitly included in the model, comprising most open-water bodies larger than 200 ha in area plus a few smaller reservoirs from earlier studies. Based on limited morphometric data, the lakes were provisionally parameterized to estimate stage-volume relations, sediment suspension capacity, and apparent phosphorus settling rate. Smaller open-water bodies and wetlands were modeled in a general way as aggregated conceptual depressions (SWAT ponds and wetlands) in each subbasin.

Agricultural lands were configured with a combination of spatial and tabular data from the USDA. Crops were dominated by corn, soybeans, and alfalfa, and their relative areas were broadly consistent between the spatial CDL 2007 data set and tabulated data from the National Agricultural Statistics Service (NASS). To allow for regional differences across the St. Croix basin, we divided the basin into four quadrants (NW, NE, SW, and SE). We could replicate the areas of the principal crops with just two rotations in each quadrant of the basin: a simple cash-crop rotation of corn and soybeans, and a livestock-feed rotation of two years of corn (one grain, one silage) followed by four years of alfalfa. Livestock numbers from NASS tables were averaged over 2000-09. Dairy cows, concentrated in the SE quadrant, dominated livestock populations in the basin; second were beef cattle, with horses being a distant third. All other livestock species, including hogs, sheep, and poultry, were converted to animal-unit equivalents of cows, beef, or horses so that their contribution to the total phosphorus load from manure was not lost. Annual quantities of manure produced by each livestock population were calculated and applied to selected crop rotations, hay, or pasture. Application methods included daily-haul spreading, seasonal spreading, and simple grazing during the growing season. Several different application rates were incorporated into the model to allow for differences among farming practices.

Point sources in the model included 26 in Minnesota and 22 in Wisconsin. Of this total, 39 were municipal wastewater treatment plants that contributed 98% of the point-source phosphorus load, the remaining 2% coming from nine industrial dischargers. In aggregate, these wastewater treatment plants have made remarkable improvement in their discharge of phosphorus over the past 20 years. During the 1990s the annual load of total phosphorus from point sources was about 47.3 metT. By 2005-07, the load had dropped by more than half, down to 22.3 metT. Annual loads of phosphorus from wastewater were estimated back to 1900 (with data from Edlund et al., 2009b), should the model be run that far back in time.

Climate data were compiled from data downloaded from the National Climatic Data Center (NCDC) for the 1960-2009 period. Daily precipitation and temperature data from 25 weather stations from in or near the St. Croix basin were spatially interpolated and applied to 114 weather pseudo-stations across the basin, each of which corresponds to three or four subbasins in the SWAT model.

The model was calibrated to observed data for 2000-07 and validated to data for 1990-99. Calibration of monthly flows was based on data from two main-stem stations (Danbury and St. Croix Falls) and from three tributary stations (Kettle, Snake, and Apple rivers), with excellent model fits. Monthly loads of sediment and nutrients were calibrated based on data at a single main-stem station at Stillwater, MN, with good model fits for suspended sediment, total phosphorus, and total nitrogen. The calibrated model represents a whole-basin framework available for understanding the source of nonpoint pollutants in the basin and their transport to receiving waters. It furthermore can estimate changes in the loads of these pollutants caused by changes in land use or climate. In short, the model offers the most comprehensive whole-basin tool available for identifying where problems exist on the landscape, what new problems may arise as land is developed and climate changes, and which best-management practices are most likely to be effective in reducing nonpoint-source pollution. The SWAT model is thus a critical element in management efforts to improve and protect the water resources of the St. Croix basin.

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Appendix A: Specific Crop Rotations

Tables A1 – A10

Table A1. Corn-soybean (CS) cash-crop rotation.

Rotation Name:	CS_a											
Year	**Date**	**Operation**	**Item**	**Rate**	**Units**	**Rate**	**Units**	**N (kg/ha)**	**P (kg/ha)**	**N (lb/acre)**	**P (lb/acre)**	**Notes**
Year 1	21-Apr	Fertilize	46-0-0	337	kg/ha	300	lb/acre	155		138		NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	26-Apr	Till	Disk									
	1-May	Plant	Corn-Grain									CNOP A = 67, B = 77, C = 83, D = 87
	1-May	Fertilize	27-15-15	225	kg/ha	200	lb/acre	61	15	54	13	LY1 = 0
	28-Oct	Harvest&Kill	Corn-Grain									
Year 2	23-Apr	Till	Chisel									
	10-May	Fertilize	9-23-30	225	kg/ha	200	lb/acre	20	23	18	20	LY1 = 0
	15-May	Till	Disk									
	20-May	Plant	Soybeans									CNOP A = 67, B = 78, C = 85, D = 89
	15-Oct	Harvest&Kill	Soybeans									
	31-Oct	Till	Chisel									
Nutrient additions:												
Year 1								216	15	192	13	
Year 2								20	23	18	20	
Annual average								118	19	105	17	

NOTES:
Basic rotation is corn-grain / soybean. Two subrotations (CS_a and CS_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. Subrotations were futher modified to set curve numbers (CNOPs) according to the crop planted that year and hydrologic soil group (A, B, C, or D).

Table A2. Corn-alfalfa (CA) rotation without manure application.

Rotation Name: CA_a

Year	Date	Operation	Item	Rate	Units	Rate	Units	N (kg/ha)	P (kg/ha)	N (lb/acre)	P (lb/acre)	Notes
Year 1	18-Apr	Fertilize	46-0-0	337	kg/ha	300	lb/acre	155		138		NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	26-Apr	Till	Disk									
	1-May	Plant	Corn-Grain									CNOP A = 67, B = 77, C = 83, D = 87
	1-May	Fertilize	27-15-15	225	kg/ha	200	lb/acre	61	15	54	13	LY1 = 0
	28-Oct	Harvest&Kill	Corn-Grain									
	15-Nov	Till	Chisel									
Year 2	18-Apr	Fertilize	46-0-0	337	kg/ha	300	lb/acre	155		138		NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	26-Apr	Till	Disk									
	1-May	Plant	Corn-Silage									CNOP A = 67, B = 77, C = 83, D = 87
	1-May	Fertilize	27-15-15	225	kg/ha	200	lb/acre	61	15	54	13	LY1 = 0
	25-Sept	Harvest&Kill	Corn-Silage									
	5-Nov	Till	Chisel									
Year 3	16-Apr	Till	Disk									
	23 April	Plant	Alfalfa									CNOP A = 31, B = 59, C = 72, D = 79
	5-Sep	Harvest	Alfalfa									
Year 4	25-Jun	Harvest	Alfalfa									
	1-Aug	Harvest	Alfalfa									
	10-Sep	Harvest	Alfalfa									
Year 5	25-Jun	Harvest	Alfalfa									
	1-Aug	Harvest	Alfalfa									
	10-Sep	Harvest	Alfalfa									
Year 6	5-Jul	Harvest	Alfalfa									
	5-Sep	Harvest	Alfalfa									
	1-Nov	Till	Moldboard plow									
Nutrient additions:												
Year 1								216	15	192	13	
Year 2								216	15	192	13	
Year 3								0	0	0	0	
Year 4								0	0	0	0	
Year 5								0	0	0	0	
Year 6								0	0	0	0	
Annual average								72	5	64	4	

NOTES:
Basic rotation is corn-grain / corn-silage / alfalfa / alfalfa / alfalfa / alfalfa. Three subrotations (CA_a, CA_b, and CA_c) were created with the initial year being either corn-grain, year-1 alfalfa, or year-3 alfalfa to maintain spatial coverage of corn versus alfalfa in the basin in any one year. Subrotations were futher modified to set curve numbers (CNOPs) according to the crop planted that year and hydrologic soil group (A, B, C, or D).

Table A3. Corn-alfalfa (CA) rotation with seasonal manure application.

Rotation Name:	CAseas_a											
Year	**Date**	**Operation**	**Item**	**Rate**	**Units**	**Rate**	**Units**	**N (kg/ha)**	**P (kg/ha)**	**N (lb/acre)**	**P (lb/acre)**	**Notes**
Year 1	18-Apr	Fertilize	46-0-0	112	kg/ha	100	lb/acre	52		46		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	179	38	159	33	
	26-Apr	Till	Disk									
	1-May	Plant	Corn-Grain									CNOP A = 67, B = 77, C = 83, D = 87
	1-May	Fertilize	27-15-15	225	kg/ha	200	lb/acre	61	15	54	13	LY1 = 0
	28-Oct	Harvest&Kill	Corn-Grain									
	1-Nov	Fertilize	Dairy manure	4700	kg/ha	14.95	sh T/acre, fresh	179	38	159	33	
	15-Nov	Till	Chisel									
Year 2	18-Apr	Fertilize	46-0-0	112	kg/ha	100	lb/acre	52		46		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	179	38	159	33	
	26-Apr	Till	Disk									
	1-May	Plant	Corn-Silage									CNOP A = 67, B = 77, C = 83, D = 87
	1-May	Fertilize	27-15-15	225	kg/ha	200	lb/acre	61	15	54	13	LY1 = 0
	25-Sept	Harvest&Kill	Corn-Silage									
	1-Nov	Fertilize	Dairy manure	4700	kg/ha	14.95	sh T/acre, fresh	179	38	159	33	
	15-Nov	Till	Chisel									
Year 3	16-Apr	Till	Disk									
	23 April	Plant	Alfalfa									CNOP A = 31, B = 59, C = 72, D = 79
	5-Sep	Harvest	Alfalfa									
Year 4	25-Jun	Harvest	Alfalfa									
	1-Aug	Harvest	Alfalfa									
	10-Sep	Harvest	Alfalfa									
Year 5	25-Jun	Harvest	Alfalfa									
	1-Aug	Harvest	Alfalfa									
	10-Sep	Harvest	Alfalfa									
Year 6	5-Jul	Harvest	Alfalfa									
	5-Sep	Harvest	Alfalfa									
	1-Nov	Till	Moldboard plow									
Manure application rates and nutrient additions:				Manure rate:		Manure rate:		Nutrient totals, inorganic fertilizer plus manure:				
Year 1				9400	kg/ha	30	st T/acre, fresh	469	90	418	80	
Year 2				9400	kg/ha	30	st T/acre, fresh	469	90	418	80	
Year 3				0		0		0	0	0	0	
Year 4				0		0		0	0	0	0	
Year 5				0		0		0	0	0	0	
Year 6				0		0		0	0	0	0	
Annual average				3133	kg/ha	10	st T/acre, fresh	156	30	139	27	

NOTES:
Basic rotation is corn-grain / corn-silage / alfalfa / alfalfa / alfalfa / alfalfa. Three subrotations (CA_a, CA_b, and CA_c) were created with the initial year being either corn-grain, year-1 alfalfa, or year-3 alfalfa to maintain spatial coverage of corn versus alfalfa in the basin in any one year. Subrotations were futher modified to set curve numbers (CNOPs) according to the crop planted that year and hydrologic soil group (A, B, C, or D).

Table A4. Corn-alfalfa (CA) rotation with daily-haul manure applications, simplified as monthly applications (years 1-4 here; continues to years 5-6 on next page).

Rotation Name:		CAdh_a										
Year	**Date**	**Operation**	**Item**	**Rate**	**Units**	**Rate**	**Units**	**N (kg/ha)**	**P (kg/ha)**	**N (lb/acre)**	**P (lb/acre)**	**Notes**
Year 1	15-Jan, Feb, Mar, Apr	Fertilize	Dairy manure	1200	kg/ha, dry	3.82	sh T/acre, fresh	46	10	41	9	LY1 = 1
	18-Apr	Fertilize	46-0-0	112	kg/ha	100	lb/acre	52		46		NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	26-Apr	Till	Disk									
	1-May	Plant	Corn-Grain									CNOP A = 67, B = 77, C = 83, D = 87
	1-May	Fertilize	27-15-15	225	kg/ha	200	lb/acre	61	15	54	13	LY1 = 0
	28-Oct	Harvest&Kill	Corn-Grain									
	5-Nov	Till	Chisel									
	15-Nov, Dec	Fertilize	Dairy manure	1200	kg/ha, dry	3.82	sh T/acre, fresh	46	10	41	9	LY1 = 1
Year 2	15-Jan, Feb, Mar, Apr	Fertilize	Dairy manure	1200	kg/ha, dry	3.82	sh T/acre, fresh	46	10	41	9	LY1 = 1
	18-Apr	Fertilize	46-0-0	112	kg/ha	100	lb/acre	52		46		NSTR=0.99, EFF=2, NMXS=30, LY1=1, NMXA=155.02
	26-Apr	Till	Disk									
	1-May	Plant	Corn-Silage									CNOP A = 67, B = 77, C = 83, D = 87
	1-May	Fertilize	27-15-15	225	kg/ha	200	lb/acre	61	15	54	13	LY1 = 0
	25-Sept	Harvest&Kill	Corn-Silage									
	5-Nov	Till	Chisel									
	15-Nov, Dec	Fertilize	Dairy manure	1200	kg/ha, dry	3.82	sh T/acre, fresh	46	10	41	9	LY1 = 1
Year 3	15-Jan, Feb, Mar, Apr	Fertilize	Dairy manure	1200	kg/ha, dry	3.82	sh T/acre, fresh	46	10	41	9	LY1 = 1
	20-Apr	Till	Disk									
	23-Apr	Plant	Alfalfa									CNOP A = 31, B = 59, C = 72, D = 79
	5-Sep	Harvest	Alfalfa									
	15-Sep, Oct, Nov, Dec	Fertilize	Dairy manure	1200	kg/ha, dry	3.82	sh T/acre, fresh	46	10	41	9	LY1 = 1
Year 4	15-Jan, Feb, Mar, Apr, May, Jun	Fertilize	Dairy manure	1200	kg/ha, dry	3.82	sh T/acre, fresh	46	10	41	9	LY1 = 1
	25-Jun	Harvest	Alfalfa									
	15-Jul	Fertilize	Dairy manure	1200	kg/ha, dry	3.82	sh T/acre, fresh	46	10	41	9	LY1 = 1
	1-Aug	Harvest	Alfalfa									
	15-Aug	Fertilize	Dairy manure	1200	kg/ha, dry	3.82	sh T/acre, fresh	46	10	41	9	LY1 = 1
	10-Sep	Harvest	Alfalfa									
	15-Sep, Oct, Nov, Dec	Fertilize	Dairy manure	1200	kg/ha, dry	3.82	sh T/acre, fresh	46	10	41	9	LY1 = 1

Table A4. Continued (years 5-6)

Rotation Name:		CAdh_a								
Year	**Date**	**Operation**	**Item**	**Rate Units**	**Rate Units**	**N (kg/ha)**	**P (kg/ha)**	**N (lb/acre)**	**P (lb/acre)**	**Notes**
Year 5	15-Jan, Feb, Mar, Apr, May, Jun	Fertilize	Dairy manure	1200 kg/ha, dry	3.82 sh T/acre, fresh	46	10	41	9	LY1 = 1
	25-Jun	Harvest	Alfalfa							
	15-Jul	Fertilize	Dairy manure	1200 kg/ha, dry	3.82 sh T/acre, fresh	46	10	41	9	LY1 = 1
	10Aug	Harvest	Alfalfa							
	15-Aug	Fertilize	Dairy manure	1200 kg/ha, dry	3.82 sh T/acre, fresh	46	10	41	9	LY1 = 1
	10-Sep	Harvest	Alfalfa							
	15-Sep, Oct, Nov, Dec	Fertilize	Dairy manure	1200 kg/ha, dry	3.82 sh T/acre, fresh	46	10	41	9	LY1 = 1
Year 6	15-Jan, Feb, Mar, Apr, May, Jun	Fertilize	Dairy manure	1200 kg/ha, dry	3.82 sh T/acre, fresh	46	10	41	9	LY1 = 1
	5-Jul	Harvest	Alfalfa							
	15-Jul, Aug	Fertilize	Dairy manure	1200 kg/ha, dry	3.82 sh T/acre, fresh	46	10	41	9	LY1 = 1
	5-Sep	Harvest	Alfalfa							
	15-Sep, Oct	Fertilize	Dairy manure	1200 kg/ha, dry	3.82 sh T/acre, fresh	46	10	41	9	LY1 = 1
	1-Nov	Till	Moldboard plow							
	15-Nov,Dec	Fertilize	Dairy manure	1200 kg/ha, dry	3.82 sh T/acre, fresh	46	10	41	9	LY1 = 1
Manure application rates and nutrient additions:				Manure rate:	Manure rate:	Nutrient totals, inorganic fertilizer plus manure:				
Year 1				7200 kg/ha, dry	22.90 sh T/acre, fresh	386	72	344	65	
Year 2				7200 kg/ha, dry	22.90 sh T/acre, fresh	386	72	344	65	
Year 3				9600 kg/ha, dry	30.54 sh T/acre, fresh	365	77	325	68	
Year 4				14400 kg/ha, dry	45.81 sh T/acre, fresh	547	115	487	103	
Year 5				14400 kg/ha, dry	45.81 sh T/acre, fresh	547	115	487	103	
Year 6				14400 kg/ha, dry	45.81 sh T/acre, fresh	547	115	487	103	
Annual average				11200 kg/ha, dry	36 sh T/acre, fresh	463	95	412	84	

NOTES:
Basic rotation is corn-grain / corn-silage / alfalfa / alfalfa / alfalfa / alfalfa. Three subrotations (CA_a, CA_b, and CA_c) were created with the initial year being either corn-grain, year-1 alfalfa, or year-3 alfalfa to maintain spatial coverage of corn versus alfalfa in the basin in any one year. Subrotations were futher modified to set curve numbers (CNOPs) according to the crop planted that year and hydrologic soil group (A, B, C, or D).

Table A5. Grazing rotation for dairy cows in grassland.

Year	Date	Operation	Item	Rate Units	Rate Units	N (kg/ha/day)	P (kg/ha/day)	N (lb/acre/day)	P (lb/acre/day)	Notes
Rotation Name:		DPAST								
Year 1			Pasture (PAST)							Begin with perennial PAST land-cover type
	12-May	Graze start	Dairy manure	4.50 kg/ha/d, dry	28.73 lbs/acre/d, fresh	0.17	0.04	0.15	0.03	BMEAT = 9.36 kg/ha/day BMTRMP = 1.87 kg/ha/day
	28-Oct	Graze end	Dairy	169 days						
Annual manure and nutrient application rates:				Manure rate: (kg/ha/yr, dry)	Manure rate: (sh T/acre/yr, fresh)	Nutrient additions: (kg/ha/yr)	(kg/ha/yr)	(lb/acre/yr)	(lb/acre/yr)	
				761	2.43	29	6	26	5	

Table A6. Rotation for dairy cows in paddock or barnyard area, simplified as monthly applications.

Year	Date	Operation	Item	Rate Units	Rate Units	N (kg/ha)	P (kg/ha)	N (lb/acre)	P (lb/acre)	Notes
Rotation Name:		DPADD								
Year 1	15-Jan	Fertilize	Dairy manure	1100 kg/ha, dry	3.51 sh T/acre, fresh	42	9	37	8	LY1 = 1
	15-Feb	Fertilize	Dairy manure	1100 kg/ha, dry	3.51 sh T/acre, fresh	42	9	37	8	LY1 = 1
	15-Mar	Fertilize	Dairy manure	1100 kg/ha, dry	3.51 sh T/acre, fresh	42	9	37	8	LY1 = 1
	15-Apr	Fertilize	Dairy manure	1100 kg/ha, dry	3.51 sh T/acre, fresh	42	9	37	8	LY1 = 1
	15-May	Fertilize	Dairy manure	1100 kg/ha, dry	3.51 sh T/acre, fresh	42	9	37	8	LY1 = 1
	15-Jun	Fertilize	Dairy manure	1100 kg/ha, dry	3.51 sh T/acre, fresh	42	9	37	8	LY1 = 1
	15-Jul	Fertilize	Dairy manure	1100 kg/ha, dry	3.51 sh T/acre, fresh	42	9	37	8	LY1 = 1
	15-Aug	Fertilize	Dairy manure	1100 kg/ha, dry	3.51 sh T/acre, fresh	42	9	37	8	LY1 = 1
	15-Sep	Fertilize	Dairy manure	1100 kg/ha, dry	3.51 sh T/acre, fresh	42	9	37	8	LY1 = 1
	15-Oct	Fertilize	Dairy manure	1100 kg/ha, dry	3.51 sh T/acre, fresh	42	9	37	8	LY1 = 1
	15-Nov	Fertilize	Dairy manure	1100 kg/ha, dry	3.51 sh T/acre, fresh	42	9	37	8	LY1 = 1
	15-Dec	Fertilize	Dairy manure	1100 kg/ha, dry	3.51 sh T/acre, fresh	42	9	37	8	LY1 = 1
Annual manure and nutrient application rates:				Manure rate: (kg/ha/yr, dry)	Manure rate: (sh T/acre/yr, fresh)	Nutrient additions: (kg/ha/yr)	(kg/ha/yr)	(lb/acre/yr)	(lb/acre/yr)	
				13200	42.13	502	106	447	94	

Table A7. Grazing rotation for beef cattle in grassland.

Year	Date	Operation	Item	Rate	Units	Rate	Units	N (kg/ha/day)	P (kg/ha/day)	N (lb/acre/day)	P (lb/acre/day)	Notes
Rotation Name:		BPAST										
Year 1			Pasture (PAST)									Begin with perennial PAST land-cover type
	12-May	Graze start	Beef manure	4.75	kg/ha/d, dry	28.87	lbs/acre/d, fresh	0.19	0.05	0.17	0.05	BMEAT = 13.98 kg/ha/day BMTRMP = 2.80 kg/ha/day
	28-Oct	Graze end	Beef	169	days							
Annual manure and nutrient application rates:				Manure rate: (kg/ha/yr, dry)		Manure rate: (sh T/acre/yr, fresh)		Nutrient additions: (kg/ha/yr)	(kg/ha/yr)	(lb/acre/yr)	(lb/acre/yr)	
				803		2.44		32	9	29	8	

Table A8. Rotation for beef cattle in paddock or barnyard area, simplified as monthly applications.

Year	Date	Operation	Item	Rate	Units	Rate	Units	N (kg/ha)	P (kg/ha)	N (lb/acre)	P (lb/acre)	Notes
Rotation Name:		BPADD										
Year 1	15-Jan	Fertilize	Beef manure	1550	kg/ha, dry	4.71	sh T/acre, fresh	62	17	55	15	LY1 = 1
	15-Feb	Fertilize	Beef manure	1550	kg/ha, dry	4.71	sh T/acre, fresh	62	17	55	15	LY1 = 1
	15-Mar	Fertilize	Beef manure	1550	kg/ha, dry	4.71	sh T/acre, fresh	62	17	55	15	LY1 = 1
	15-Apr	Fertilize	Beef manure	1550	kg/ha, dry	4.71	sh T/acre, fresh	62	17	55	15	LY1 = 1
	15-May	Fertilize	Beef manure	1550	kg/ha, dry	4.71	sh T/acre, fresh	62	17	55	15	LY1 = 1
	15-Jun	Fertilize	Beef manure	1550	kg/ha, dry	4.71	sh T/acre, fresh	62	17	55	15	LY1 = 1
	15-Jul	Fertilize	Beef manure	1550	kg/ha, dry	4.71	sh T/acre, fresh	62	17	55	15	LY1 = 1
	15-Aug	Fertilize	Beef manure	1550	kg/ha, dry	4.71	sh T/acre, fresh	62	17	55	15	LY1 = 1
	15-Sep	Fertilize	Beef manure	1550	kg/ha, dry	4.71	sh T/acre, fresh	62	17	55	15	LY1 = 1
	15-Oct	Fertilize	Beef manure	1550	kg/ha, dry	4.71	sh T/acre, fresh	62	17	55	15	LY1 = 1
	15-Nov	Fertilize	Beef manure	1550	kg/ha, dry	4.71	sh T/acre, fresh	62	17	55	15	LY1 = 1
	15-Dec	Fertilize	Beef manure	1550	kg/ha, dry	4.71	sh T/acre, fresh	62	17	55	15	LY1 = 1
Annual manure and nutrient application rates:				Manure rate: (kg/ha/yr, dry)		Manure rate: (sh T/acre/yr, fresh)		Nutrient additions: (kg/ha/yr)	(kg/ha/yr)	(lb/acre/yr)	(lb/acre/yr)	
				18600		56.53		744	205	663	182	

Table A9. Grazing rotation for horses in grassland.

Rotation Name: HPAST

Year	Date	Operation	Item	Rate Units	Rate Units	N (kg/ha/day)	P (kg/ha/day)	N (lb/acre/day)	P (lb/acre/day)	Notes
Year 1			Pasture (PAST)							Begin with perennial PAST land-cover type
	12-May	Graze start	Horse manure	5.50 kg/ha/d, dry	16.66 lbs/acre/d, fresh	0.11	0.02	0.10	0.02	BMEAT = 9.36 kg/ha/day BMTRMP = 1.87 kg/ha/day
	28-Oct	Graze end	Horse	169 days						
Annual manure and nutrient application rates:				Manure rate: (kg/ha/yr, dry)	Manure rate: (sh T/acre/yr, fresh)	Nutrient additions: (kg/ha/yr)	(kg/ha/yr)	(lb/acre/yr)	(lb/acre/yr)	
				930	1.41	19	4	17	3	

Table A10. Rotation for horses in paddock or barnyard area, simplified as monthly applications.

Rotation Name: HPADD

Year	Date	Operation	Item	Rate Units	Rate Units	N (kg/ha)	P (kg/ha)	N (lb/acre)	P (lb/acre)	Notes
Year 1	15-Jan	Fertilize	Horse manure	1825 kg/ha, dry	2.76 sh T/acre, fresh	37	7	33	7	LY1 = 1
	15-Feb	Fertilize	Horse manure	1825 kg/ha, dry	2.76 sh T/acre, fresh	37	7	33	7	LY1 = 1
	15-Mar	Fertilize	Horse manure	1825 kg/ha, dry	2.76 sh T/acre, fresh	37	7	33	7	LY1 = 1
	15-Apr	Fertilize	Horse manure	1825 kg/ha, dry	2.76 sh T/acre, fresh	37	7	33	7	LY1 = 1
	15-May	Fertilize	Horse manure	1825 kg/ha, dry	2.76 sh T/acre, fresh	37	7	33	7	LY1 = 1
	15-Jun	Fertilize	Horse manure	1825 kg/ha, dry	2.76 sh T/acre, fresh	37	7	33	7	LY1 = 1
	15-Jul	Fertilize	Horse manure	1825 kg/ha, dry	2.76 sh T/acre, fresh	37	7	33	7	LY1 = 1
	15-Aug	Fertilize	Horse manure	1825 kg/ha, dry	2.76 sh T/acre, fresh	37	7	33	7	LY1 = 1
	15-Sep	Fertilize	Horse manure	1825 kg/ha, dry	2.76 sh T/acre, fresh	37	7	33	7	LY1 = 1
	15-Oct	Fertilize	Horse manure	1825 kg/ha, dry	2.76 sh T/acre, fresh	37	7	33	7	LY1 = 1
	15-Nov	Fertilize	Horse manure	1825 kg/ha, dry	2.76 sh T/acre, fresh	37	7	33	7	LY1 = 1
	15-Dec	Fertilize	Horse manure	1825 kg/ha, dry	2.76 sh T/acre, fresh	37	7	33	7	LY1 = 1
Annual manure and nutrient application rates:				Manure rate: (kg/ha/yr, dry)	Manure rate: (sh T/acre/yr, fresh)	Nutrient additions: (kg/ha/yr)	(kg/ha/yr)	(lb/acre/yr)	(lb/acre/yr)	
				21900	33.16	438	88	390	78	