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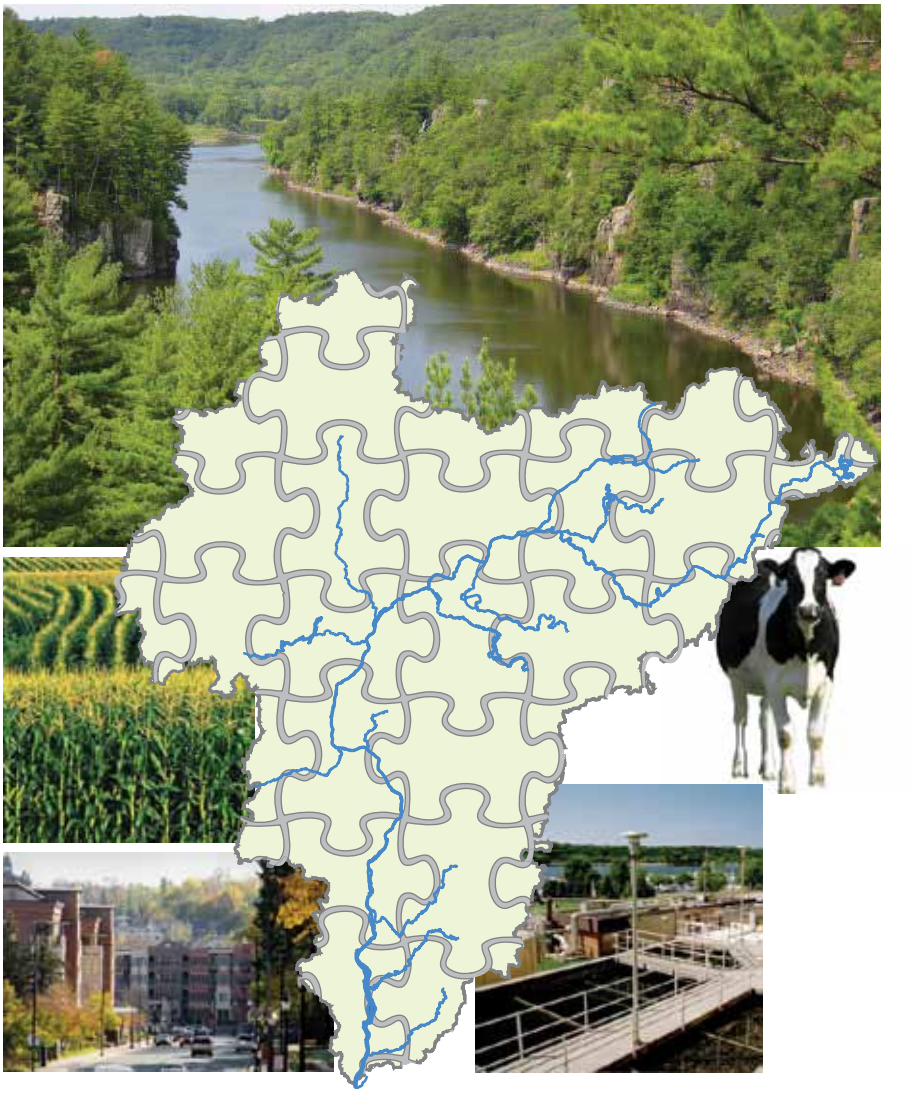

*Putting together pieces of the water-quality puzzle*

St. Croix Watershed Research Station

Science Museum of Minnesota

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

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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 acceptable model fits for both suspended sediment and total phosphorus. 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 two federally endangered mussel species, the winged mapleleaf and the pearly Higgins eye (Coffin and Pfannmuller, 1988). 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 the unit increase in algal productivity (Edlund et al., 2009a).

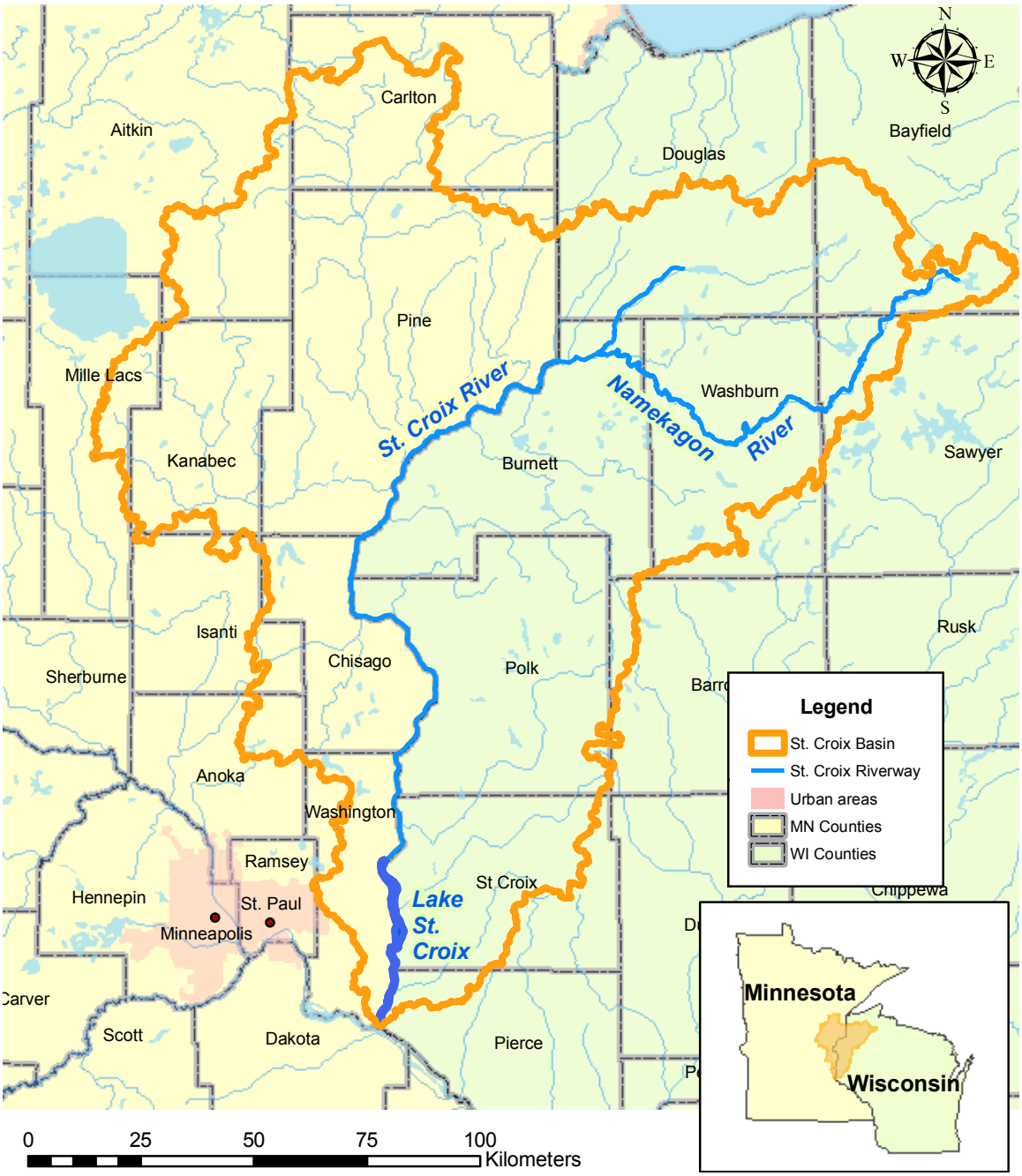


**Figure 1.** The St. Croix River basin in eastern Minnesota and western Wisconsin.

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 and Recreational 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

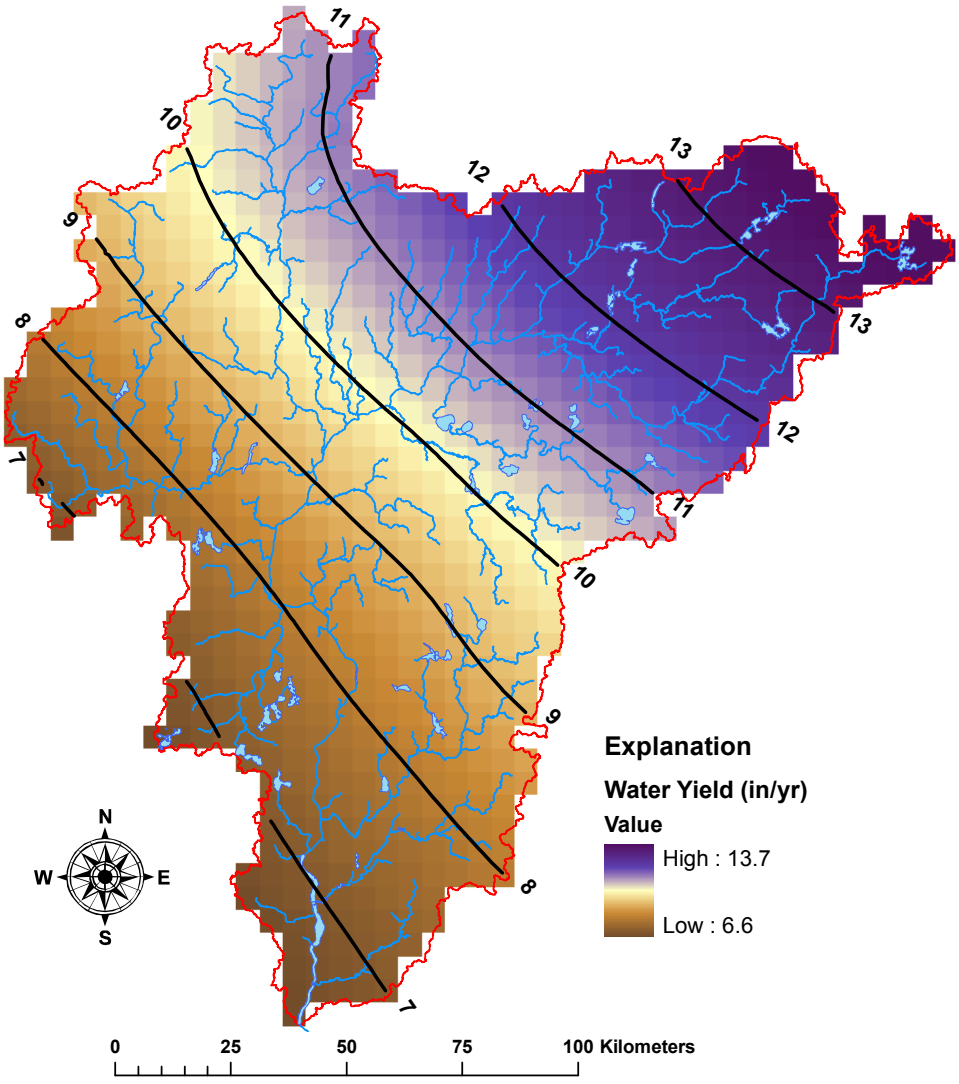


**Figure 2.** Mean annual water yield in the St. Croix basin, inches per year, 1940-2008.

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).

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

**Table 1.** Land-cover types in the St. Croix basin, 1992-2008, from selected dataset 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.

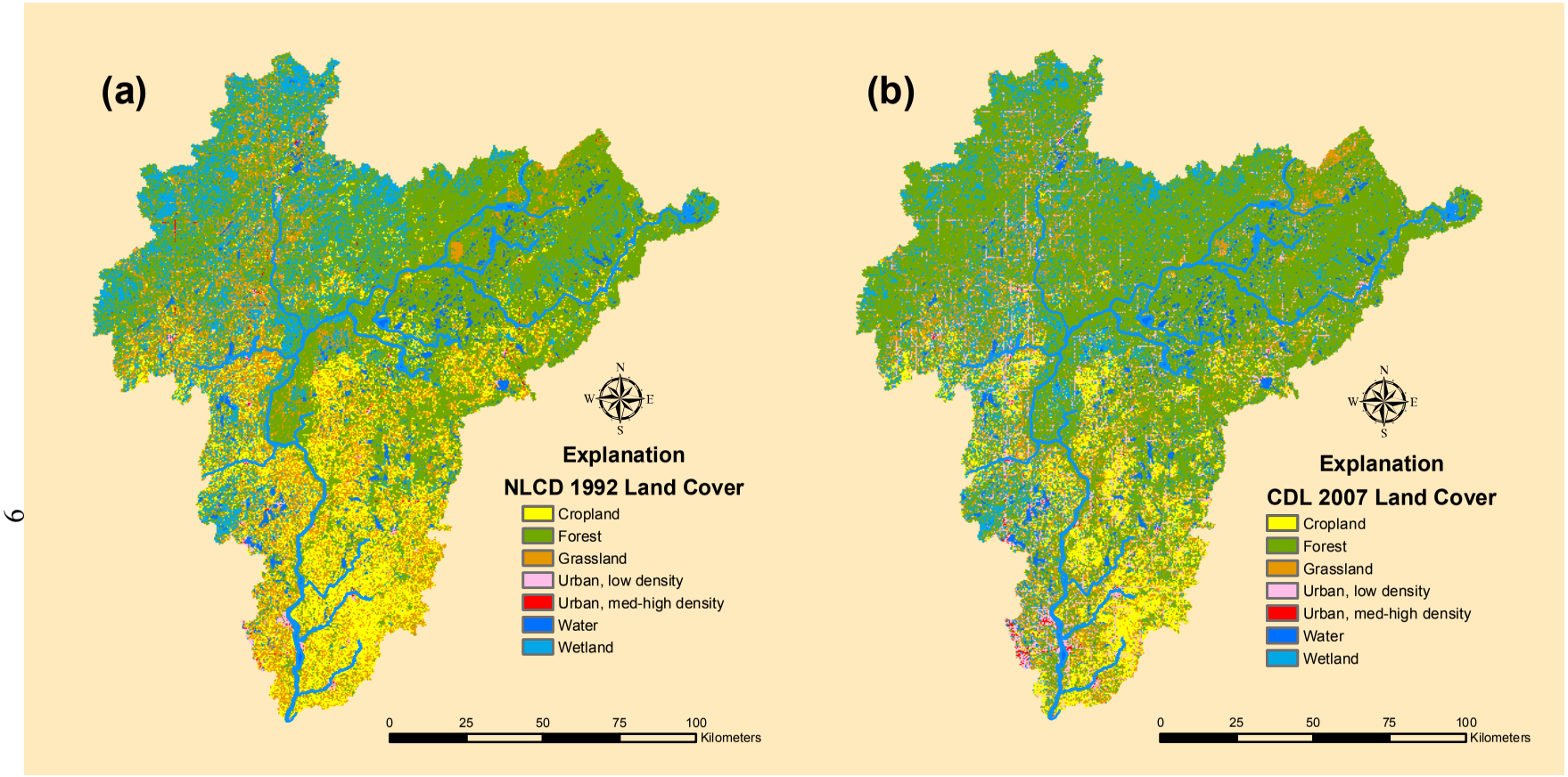


**Figure 3.** Land cover in the St. Croix basin for (a) 1992 and (b) 2007.

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).

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

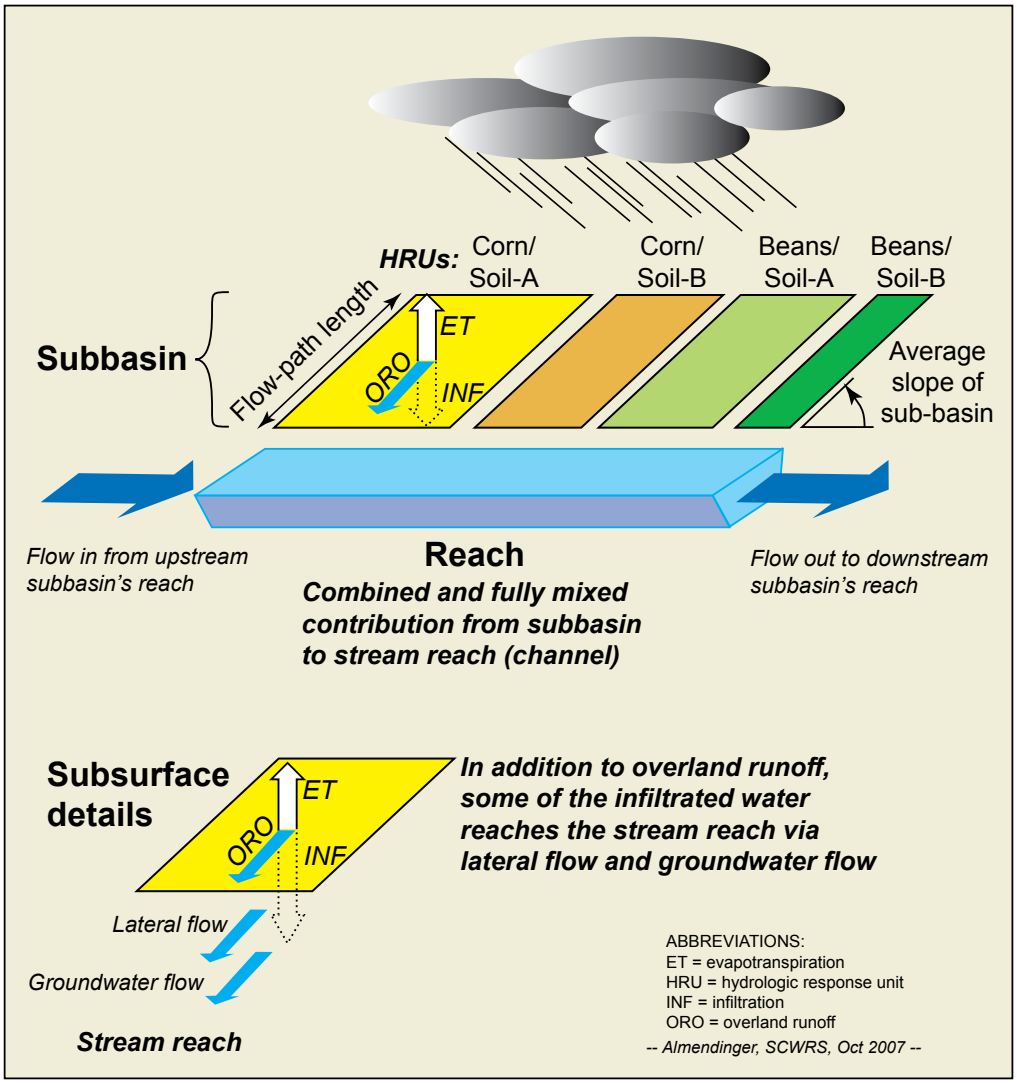


**Figure 4.** Conceptualization of hydrological response units (HRUs) within subbasins in a SWAT model.

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

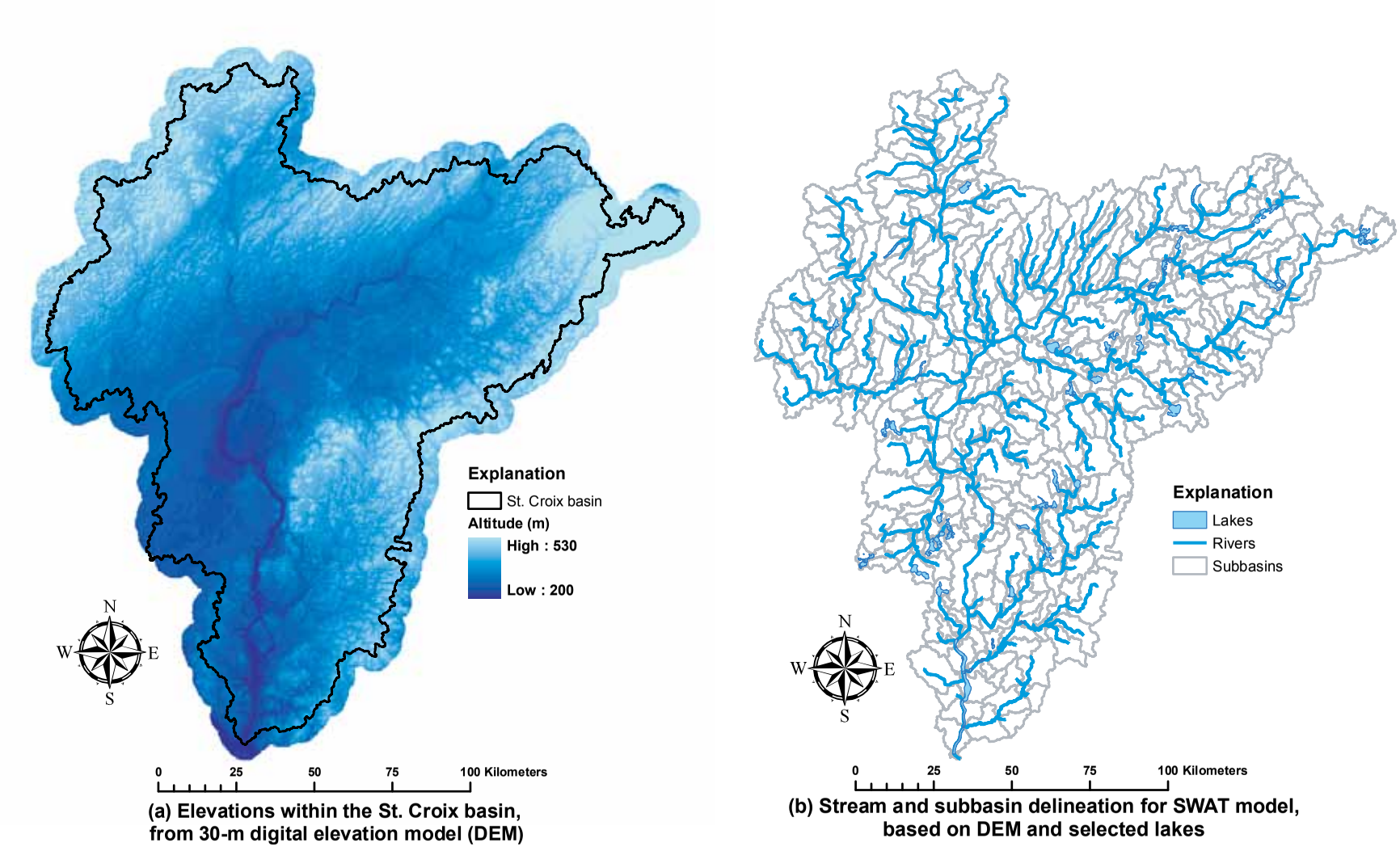


**Figure 5.** (a) Topography of the St. Croix basin and (b) the lakes, stream network, and subbasin delineation in the SWAT model.

force the creation of extra subbasin outlets at other points along the stream network as needed. 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).

## *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) | | | |
|---|---|---|---|---|---|---|---|---|---|
| Name | Lat | Lon | Reported | Principal | Emergency | Reported | Principal | Emergency | Mean D (m) |
| ***Border Pools (upstream to downstream)*** | | | | | | | | | |
| St. Croix Falls Reservoir | 45.426 | -92.648 | 241 | 205 | 278 | 960 | 879 | 1041 | 3.98 |
| Lake St. Croix Pools: | | | | | | | | | |
| Bayport Pool | 45.030 | -92.777 | 1134 | 1026 | 1242 | 7710 | 7215 | 8205 | 6.80 |
| Troy Beach Pool | 44.940 | -92.757 | 1266 | 1150 | 1382 | 13300 | 12739 | 13861 | 10.51 |
| Black Bass Pool | 44.870 | -92.769 | 545 | 477 | 613 | 7360 | 7150 | 7570 | 13.50 |
| Kinnickinnic Pool | 44.788 | -92.791 | 583 | 512 | 654 | 5710 | 5482 | 5938 | 9.79 |
| ***Minnesota Lakes*** | | | | | | | | | |
| Big Marine Lake | 45.219 | -92.859 | 684 | 605 | 762 | 2419 | 2144 | 2693 | 3.54 |
| Coon Lake | 45.305 | -93.168 | 632 | 557 | 706 | 1237 | 986 | 1487 | 1.96 |
| Cross Lake | 45.852 | -92.944 | 374 | 323 | 426 | 1567 | 1432 | 1702 | 4.18 |
| Forest Lake | 45.273 | -92.948 | 913 | 818 | 1007 | 2988 | 2603 | 3373 | 3.27 |
| Green Lake | 45.343 | -92.900 | 694 | 614 | 773 | 2200 | 1921 | 2480 | 3.17 |
| Knife Lake | 45.981 | -93.297 | 510 | 445 | 574 | 1347 | 1153 | 1541 | 2.64 |
| Lindstrom-Chisago Lakes | 45.367 | -92.866 | 681 | 603 | 760 | 2216 | 1943 | 2490 | 3.25 |
| North Center Lake | 45.406 | -92.828 | 373 | 321 | 424 | 813 | 679 | 946 | 2.18 |
| Pine Lake | 46.198 | -93.062 | 314 | 269 | 360 | 1419 | 1309 | 1528 | 4.51 |
| Pokegama Lake | 45.845 | -93.040 | 614 | 540 | 687 | 2148 | 1906 | 2390 | 3.50 |
| Rush Lake | 45.687 | -93.068 | 1239 | 1124 | 1353 | 3857 | 3310 | 4405 | 3.11 |
| South Center Lake | 45.378 | -92.821 | 411 | 355 | 466 | 1628 | 1478 | 1779 | 3.97 |
| Sturgeon Lake | 46.379 | -92.757 | 691 | 611 | 770 | 3897 | 3619 | 4175 | 5.64 |
| Sunrise Lake | 45.428 | -92.865 | 308 | 263 | 352 | 350 | 243 | 457 | 1.14 |
| ***Wisconsin Lakes*** | | | | | | | | | |
| Balsam Lake | 45.465 | -92.426 | 832 | 742 | 921 | 4689 | 4344 | 5034 | 5.64 |
| Bardon Lake | 46.213 | -91.872 | 337 | 289 | 385 | 3080 | 2961 | 3199 | 9.14 |
| Bass Lake | 45.066 | -92.649 | 169 | 142 | 196 | 901 | 846 | 955 | 5.33 |
| Big Round Lake | 45.524 | -92.301 | 411 | 355 | 466 | 1253 | 1102 | 1403 | 3.05 |
| Big Sand Lake | 45.824 | -92.218 | 567 | 497 | 636 | 1555 | 1335 | 1775 | 2.74 |
| Bone Lake | 45.535 | -92.389 | 721 | 640 | 803 | 5055 | 4763 | 5347 | 7.01 |
| Cedar Lake | 45.214 | -92.571 | 448 | 389 | 507 | 1912 | 1746 | 2079 | 4.27 |
| Clam Lake | 45.793 | -92.325 | 625 | 551 | 699 | 2382 | 2135 | 2629 | 3.81 |
| Deer Lake | 45.402 | -92.522 | 327 | 280 | 374 | 2589 | 2475 | 2704 | 7.92 |
| Devils Lake | 45.909 | -92.337 | 405 | 350 | 460 | 1729 | 1581 | 1877 | 4.27 |
| Eau Claire Lakes | 46.294 | -91.513 | 1093 | 987 | 1199 | 7552 | 7078 | 8026 | 6.91 |
| Little Falls Lake | 45.018 | -92.695 | 70 | 61 | 78 | 166 | 139 | 192 | 2.38 |
| Mallalieu | 44.990 | -92.743 | 109 | 92 | 126 | 180 | 144 | 216 | 1.65 |
| McKenzie Lakes | 45.926 | -92.039 | 694 | 615 | 774 | 4127 | 3847 | 4406 | 5.94 |
| Minong Flowage | 46.152 | -91.928 | 633 | 558 | 708 | 1737 | 1486 | 1988 | 2.74 |
| Namekagon Lake | 46.223 | -91.104 | 1306 | 1188 | 1425 | 6371 | 5790 | 6953 | 4.88 |
| Nancy Lake | 46.093 | -91.984 | 306 | 262 | 351 | 1822 | 1715 | 1928 | 5.94 |
| Nelson Lake | 46.093 | -91.470 | 1013 | 912 | 1114 | 3398 | 2963 | 3832 | 3.35 |
| New Richmond Flowage | 45.127 | -92.529 | 96 | 81 | 110 | 102 | 70 | 134 | 1.07 |
| Sand-Birch Island Lakes | 45.932 | -92.161 | 729 | 647 | 811 | 3332 | 3036 | 3628 | 4.57 |
| Shell Lake | 45.733 | -91.899 | 1045 | 942 | 1148 | 7323 | 6873 | 7773 | 7.01 |
| Spooner Lake | 45.840 | -91.824 | 442 | 384 | 501 | 943 | 779 | 1107 | 2.13 |
| St. Croix Flowage | 46.256 | -91.872 | 774 | 689 | 860 | 1652 | 1335 | 1970 | 2.13 |
| Upper St. Croix Lake | 46.357 | -91.803 | 358 | 308 | 409 | 1420 | 1292 | 1548 | 3.96 |
| Wapogasset Lake | 45.328 | -92.425 | 480 | 418 | 542 | 2488 | 2307 | 2669 | 5.18 |
| Yellow Lake | 45.919 | -92.398 | 926 | 830 | 1021 | 5362 | 4971 | 5754 | 5.79 |

**NOTES:** Lat, latitudeof lake centroid; Lon, longitude of lake centroid; ha, hectare; ha-m, hectare-meter (a measure of volume); D, depth; m, meter; "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 * sqrt$A^2$ – 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 that 1 m was the maximum rise of lake level over the outlet threshold during snowmelt or stormflow events. Further we assumed each lake was approximately at the mid-point of this range as reported, as a starting point. So for each lake, the principal (threshold) area was calculated as the starting area *minus* 0.5 m times the area change factor; likewise the principal volume was calculated as the starting volume *minus* 0.5 m times the volume change factor. The emergency areas and volumes were calculated by *adding* the same changes to the 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 assumes that all sediment above a certain suspended sediment concentration will settle and not be passed downstream. This concentration, called the NSED parameter in SWAT, is the maximum concentration of sediment to be passed downstream and is generally larger in small shallow lakes where turbulent mixing can maintain sediment in suspension. Hence, NSED should be inversely proportional to lake depth. In modeling practice, however, NSED is a calibration parameter that is adjusted to whatever value helps the model match the selected monitoring data set, commonly the load of total suspended sediment (TSS). For the construction of the St. Croix SWAT model, we began by setting NSED inversely proportional to the mean lake depth D according to the following equation:

NSED = 100 * $D^{-2}$

This relation reasonably fit the NSED values determined in a previous study that constructed a

SWAT model for the Willow River, another tributary to the St. Croix (Almendinger and Murphy, 2007). For the lakes in the St. Croix basin, the equation gave initial values of NSED ranging from 1 to 88 mg/L, with a median of 6 mg/L. Further work needs to be done to test whether these sediment trapping parameters are realistic; i.e., are the modeled lake-sediment accumulation rates realistic? During calibration, these initial estimates of NSED were adjusted as needed to improve the model fit.

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. These values were initially parameterized as follows. For the part of the year when runoff events are less common and phosphorus delivery to lakes is less likely to be influenced by coincident sediment loads, we assigned all lakes a constant value of 10 m/yr as the *Vs* (PSETLR2 in this case), to match representative rates for natural lakes given in the literature. For the spring snowmelt and rain period (March-May) when sediment delivery is likely to be the greatest, we developed a simple but untested relation to estimate *Vs* (PSETLR1 in this case) from available lake morphometric data. 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. If we assume that residence time is directly proportional to lake volume (*V*), then *s* is likewise inversely proportional to the square root of *V*. Multiplying both sides of the proportionality by *D*, dividing *V* by *D* to obtain lake area (*A*), and rearranging results in the following expression:

$$Vs = D*s = k*\mathrm{SQRT}(D/A) = \mathrm{PSETLR1}$$

where *Vs* (or PSETLR1) is the apparent settling velocity of phosphorus in m/yr; *D* is mean depth of the lake in m; *A* is lake area in ha; and *k* is a constant of proportionality to be determined by fitting the equation to available data, if any. We set the value of *k* to 500 so that the estimated PSETLR1 values then ranged from 25 to 92 m/yr, with a median of 47 m/yr. These values tend to be high for natural lakes but fit within the range for reservoirs, without reaching extreme values. This method appears to be a reasonable way to set provisional *Vs* values that may prove useful when no calibration data exist. More work needs to be done to better predict *Vs* values based on available data. As with the sediment data, these initial parameter estimates for phosphorus settling were adjusted as needed during the calibration process.

## *Landscape Depressions: SWAT Ponds and Wetlands*

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

In the St. Croix SWAT model, we used the NLCD 2001 data set to identify all 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 open-water area, and the Wetland normal area was set to the aggregate wetland area. Each Pond was assumed to have a mean depth of 1.5 m, and each Wetland 1 m. Emergency (maximum) volumes and areas were set to 1.3 times the principal (normal) values, and drainage areas set to 3.3 times the principal surface areas. These Pond and Wetland geometries were determined as averages 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 probably highly variable across the basin, and the St. Croix model could be greatly improved by development of an objective algorithm to systematically identify

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

| Statistic | Subbasin Area | *Percent of subbasin occupied by:* | | | |
|---|---|---|---|---|---|
| | ($km^2$) | Pond | Wetland | Pond Catchment | Wetland Catchment |
| Mean | 47.70 | 2.6% | 11.5% | 8.3% | 36.9% |
| Median | 39.59 | 1.6% | 9.4% | 5.1% | 30.9% |
| Min | 0.01 | 0.0% | 0.0% | 0.0% | 0.0% |
| Max | 205.80 | 17.0% | 52.6% | 56.1% | 100.0% |

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

depressional drainage areas and their relation to existing surface-water bodies (ponds and wetlands). These Ponds and Wetlands influenced a substantial fraction of the St. Croix basin: on average, about 8% of each subbasin drained to a Pond, and 37% to a Wetland (Table 4). That is, runoff from nearly half of the basin (about 45%) was processed by Ponds or Wetlands before being delivered to the channel network.

Both Ponds and Wetlands 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). Seepage from such surface-water bodies can be a substantial portion of groundwater recharge. In prior releases of SWAT, seepage from Ponds and Wetlands was lost from the system. Presumably in the current release of SWAT, this seepage is quantified and contributes to the subbasin reach as baseflow from groundwater discharge. Water-quality parameters for Ponds and Wetlands were initially set similarly as for Reservoirs but modified as needed during calibration. 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 to go with 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, 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 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 (see Figure 6) (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.

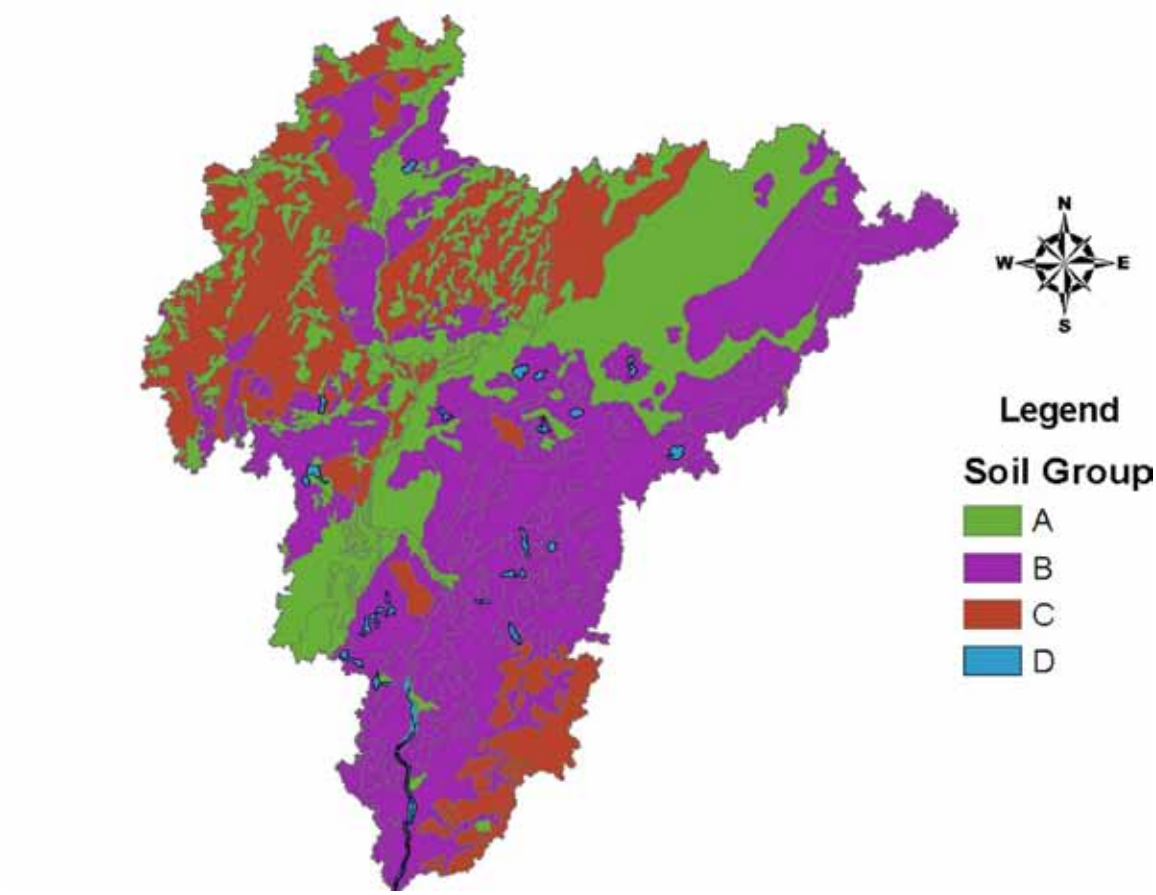


**Figure 6.** Hydrologic soil groups in the St. Croix basin, based on the STATSGO data set.

## *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).

### 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

**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 $km^2$* | | | | | | | | | | | | |

**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.

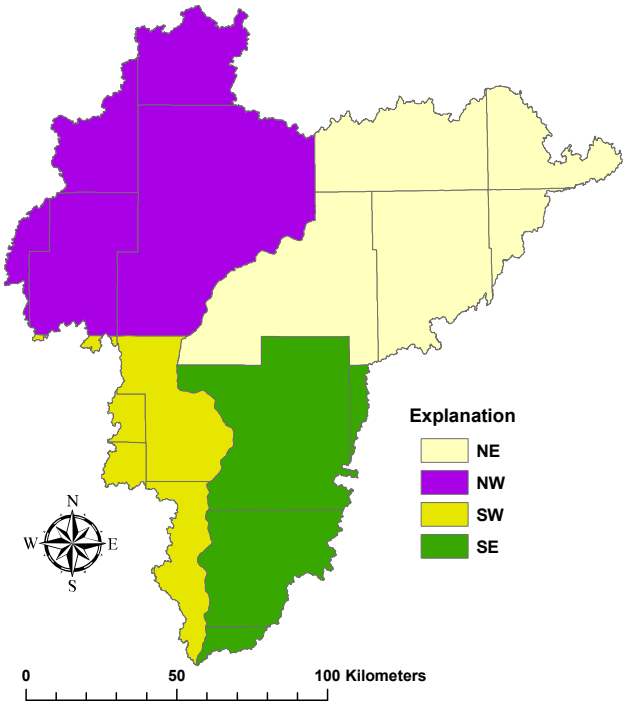


**Figure 7.** St. Croix quadrants for crop and livestock characterization.

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 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.

## 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

**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.

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

**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).

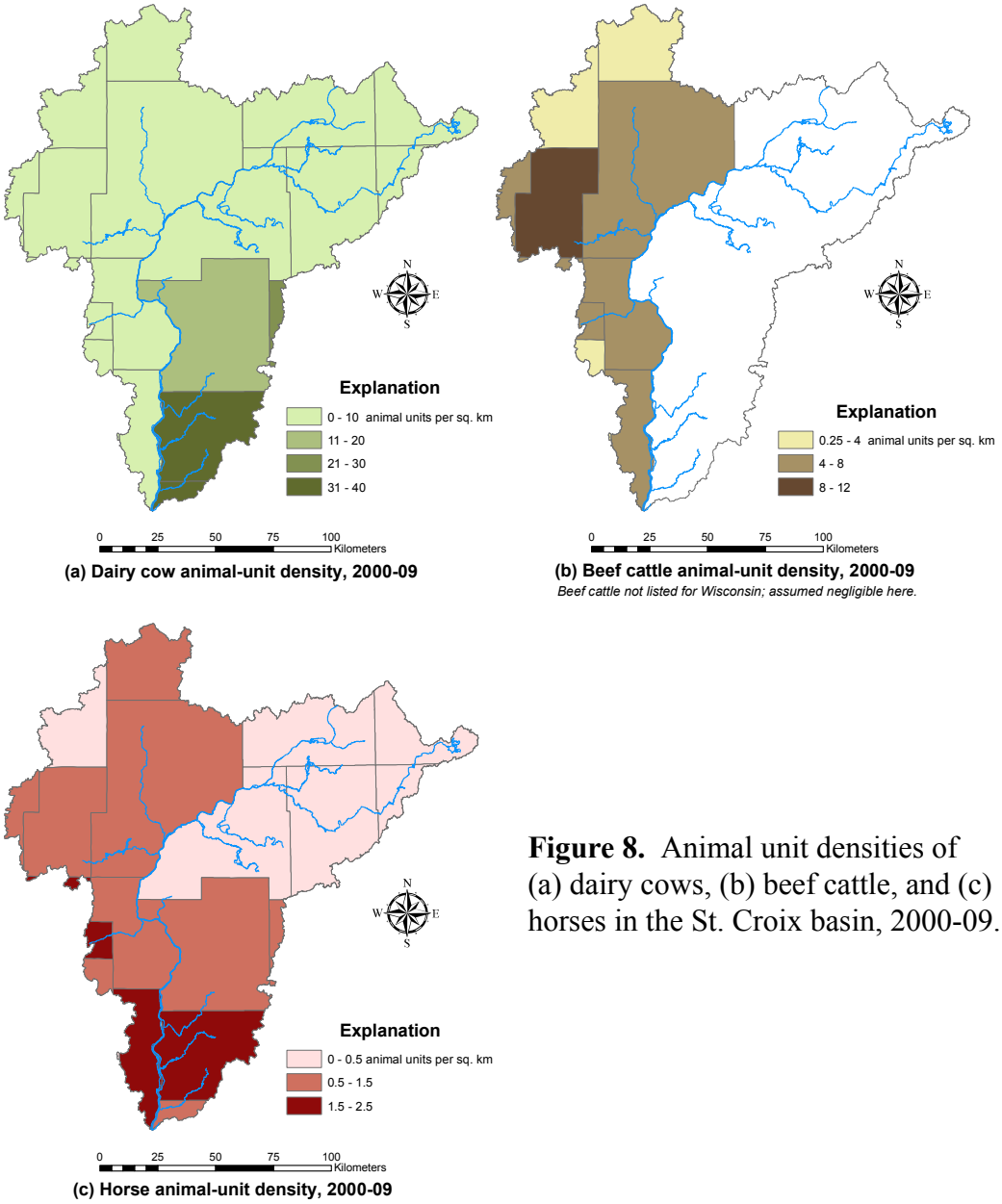


**Figure 8.** Animal unit densities of (a) dairy cows, (b) beef cattle, and (c) horses in the St. Croix basin, 2000-09.

**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** (short T/yr) | **Total Solids (Dry Wt)** (metric T/yr) | **Percent of Total** (%) | **Nitrogen** (short T/yr) | **Phosphorus** (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.

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.

## 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.

**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).

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 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<br>seasonal (= "seas")<br>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.

| | Quadrant | | | |
|---|---|---|---|---|
| Rotation | NE ($km^2$) | NW ($km^2$) | SW ($km^2$) | 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

**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.

465,000), with most growth (28%) occurring in the SE quadrant and least growth (8%) occurring in the NE quadrant.

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

**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

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.)

## *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

**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.

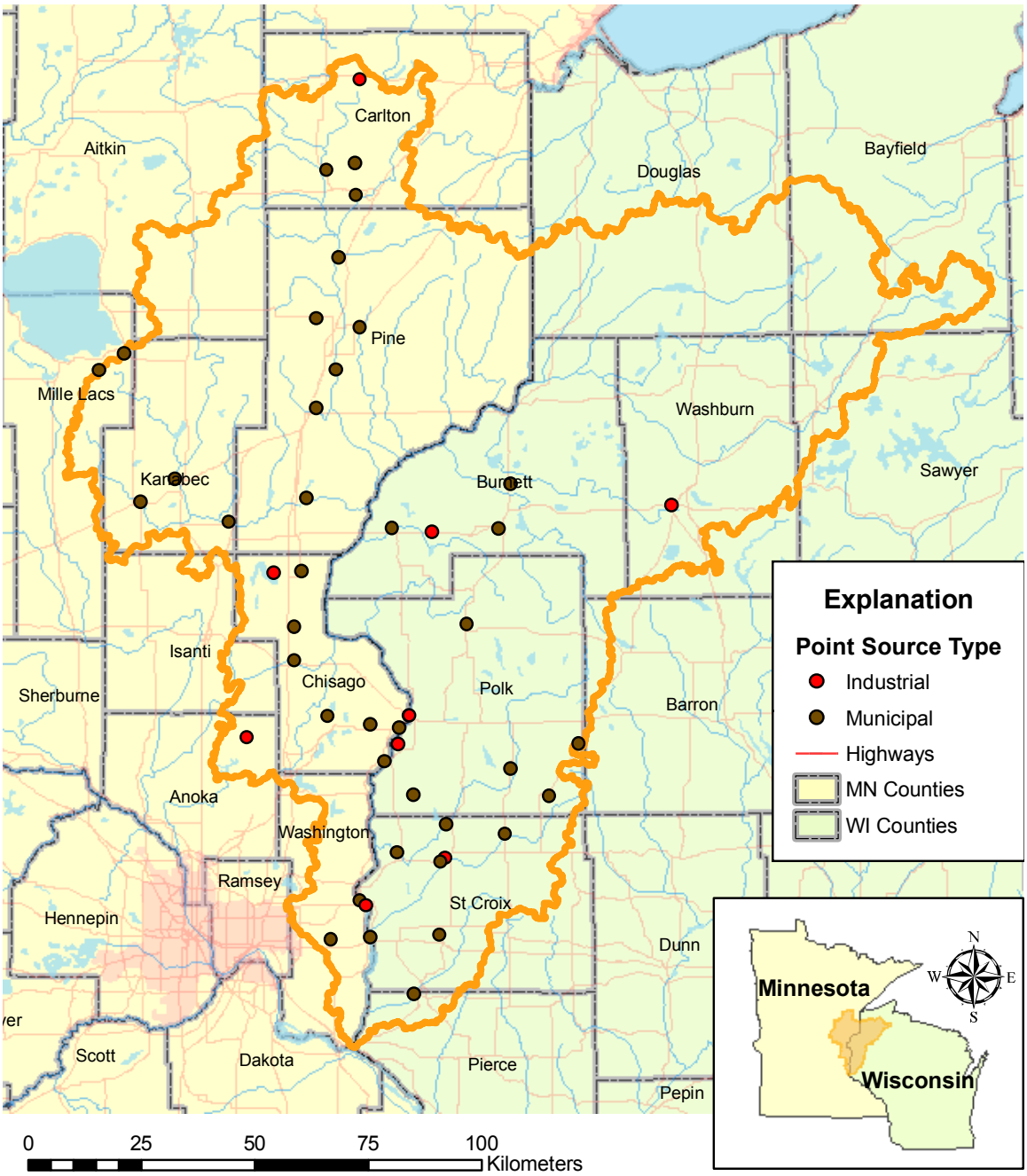


**Figure 9.** Permitted point sources discharging to surface waters in the St. Croix basin.

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 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

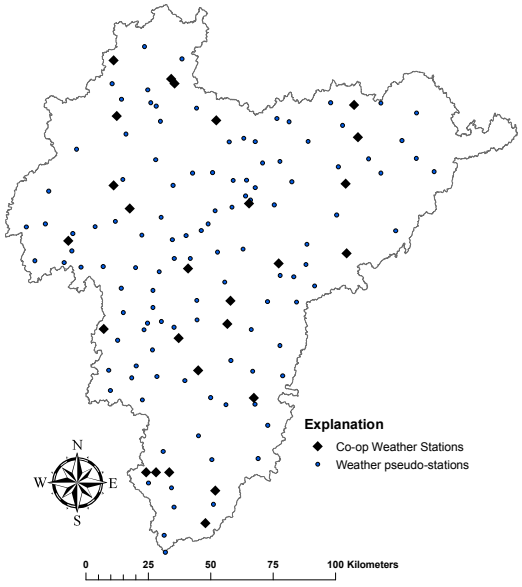


**Figure 10.** Weather stations in the high-density cooperative network used to generate daily values for each of the pseudo-stations in the SWAT model.

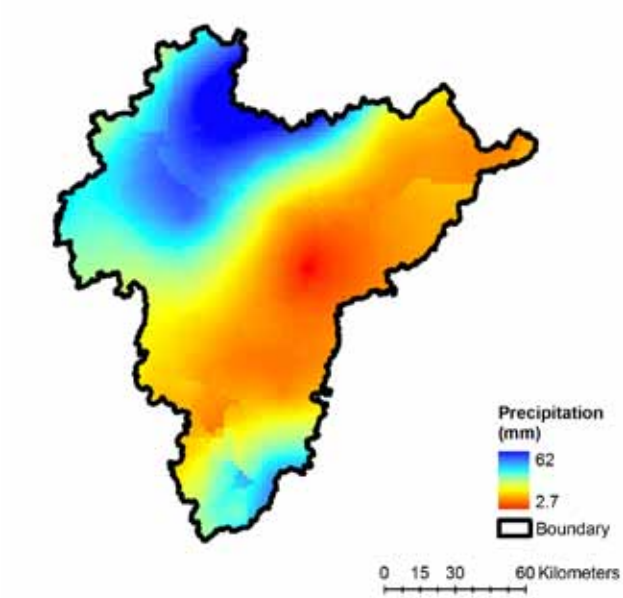


**Figure 11.** Example of spatially interpolated precipitation for the rain event of 8 August 2008.

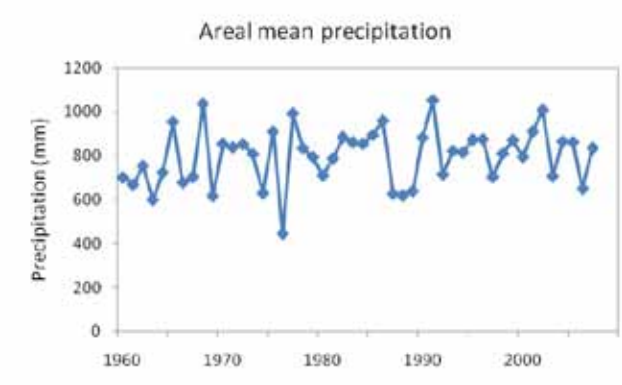


**Figure 12.** Annual mean precipitation over the St. Croix basin, 1960-2008.

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.

| | | | Geographic coordinates | | UTM coordinates | |
|---|---|---|---|---|---|---|
| **ID** | **Name** | **Altitude (ft)** | **Longitude (dec deg)** | **Latitude (dec deg)** | **Easting (m)** | **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 2009.

## 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 three quantitative statistics recommended by Moriasi et al. (2007): the Nash-Sutcliffe efficiency (NSE), the percent bias (PBIAS), and the ratio of the root-mean-square error to standard deviation (RSR).

**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:

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

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 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:

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

**Root-mean-square error to observations standard deviation ratio (RSR):**
Root-mean-square error (RMSE) is one of the commonly used error index statistics (Chu and Shirmohammadi, 2004; Singh et al., 2004; Vasquez-Amábile and Engel, 2005). Although it is commonly accepted that the lower the RMSE the better the model performance, only Singh et al. (2004) have published a guideline to qualify what is considered a low RMSE based on the observations standard deviation. Based on the recommendation by Singh et al. (2004), a model evaluation statistic, named the RMSE-observations standard deviation ratio (RSR), was developed. RSR standardizes RMSE using the observations standard deviation, and it combines both an error index and the additional information recommended by Legates and McCabe (1999). RSR is calculated as the ratio of the RMSE and standard deviation of measured data, as shown in

equation below:

$$\text{RSR} = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_{i=1}^{n}\left(Y_{obs,i} - Y_{sim,i}\right)^2}}{\sqrt{\sum_{i=1}^{n}\left(Y_{obs,i} - Y_{mean}\right)^2}} \qquad [3]$$

RSR incorporates the benefits of error index statistics and includes a scaling/normalization factor, so that the resulting statistic and reported values can apply to various constituents. RSR varies from the optimal value of 0, which indicates zero RMSE or residual variation and therefore perfect model simulation, to a large positive value. A lower RSR indicates a lower RMSE relative to the observed standard deviation and therefore better model performance.

## *Hydrology*

Hydrologic calibration and validation of the St. Croix SWAT model 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, 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, the high-flow to low-flow distribution, storm flows, and seasonal variation. Calibration was performed at the monthly time step for the period 2000-2007, and validation was performed for the time period of 1990-1999.

The parameters altered to achieve hydrologic calibration are given in Table 22. Snowmelt parameters were adjusted to avoid excessive snowmelt peaks in the spring. Soil evaporation, soil available water capacity, and forest canopy parameters were adjusted to increase evapotranspiration over most of the basin, thereby reducing overall water yield. Curve numbers were reduced by 20% to increase infiltration and baseflow. Baseflow was also enhanced by reducing loss of shallow groundwater to evapotranspiration by phreatophytes (plants reaching the water table or near to it). Recession following runoff events was fit by adjusting the baseflow recession (alpha baseflow) 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 0.71 at Danbury (Table 23; Figures 13a and 13b). The fits for the validation period are only slightly lower but still within the acceptable range as defined by Moriasi et al. (2007). The tributaries were fit similarly well, especially the Kettle and Snake rivers. The PBIAS

statistic shows overall water yield at St. Croix Falls fitting within 2% for the calibration period, and within 5% 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.

| | Parameter | | Values | | |
|---|---|---|---|---|---|
| **Files** | **Abbreviation** | **Name** | **Default** | **Calibrated** | **Subbasins applied** |
| BSN | SFTMP | Snowfall temperature (deg C) | 1 | -0.5 | basin-wide |
| BSN | SMTMP | Snow melt base temperature (deg C) | 0.5 | 0 | basin-wide |
| BSN | SMFMX | Snow melt factor, maximum (mm H2O / degC-day) | 4.5 | 4.5 | basin-wide |
| BSN | SMFMN | Snow melt factor, minimum (mm H2O / degC-day | 4.5 | 3.5 | basin-wide |
| BSN | TIMP | Snow pack temperature lag factor (0.01 - 1) | 1 | 0.1 | basin-wide |
| BSN | FFCB | Beginning soil water storage, as fraction of field capacity | 1 | 0.8 | basin-wide |
| GW | GW_DELAY | Groundwater delay time (days) | 31 | 5 | basin-wide |
| GW | ALPHA_BF | Baseflow alpha factor (baseflow recession constant) (days) | 0.048 | 0.182 | Kettle Riverwatershed |
| | | | | 0.2 | Snake River watershed |
| | | | | 0.003 | rest of basin |
| GW | GWQMN | Threshold depth of water in shallow aquifer for groundwater discharge to reach to occur (mm H2O) | 0 | 1 | basin above Danbury |
| | | | | 1 | Apple River watershed |
| | | | | 200 | rest of basin |
| GW | REVAPMN | Threshold depth of water in shallow aquifer for loss to deep percolation or phreatophytic transpiration to occur (mm H2O) | 1 | 600 | basin above Danbury |
| | | | | 500 | rest of basin |
| HRU | CANMX | Maximum canopy storage (mm H2O) | 0 | 2.5 | all FRSD (deciduous forest) in basin |
| HRU | ESCO | Soil evaporation compensaton factor (0.01 - 1) | 0.95 | 0.95 | Kettle River watershed |
| | | | | 0.8 | rest of basin |
| MGT | CN2 | Curve number for SCS moisture condition II | | minus 20% | basin-wide |
| MGT | CNOP | Curve number for SCS moisture condition II, for selected management operation | | minus 20% | basin-wide (for land with agricultural management operations) |
| RES | IFLOOD1R | Beginning month of non-flood season | | 10 | basin-wide |
| RES | IFLOOD2R | Ending month of non-flood season | | 4 | basin-wide |
| RES | NDTARG | Number of days to reach target storage from current storage. | | 3 | basin-wide |
| SOL | SOL_AWC(1) | Available water capacity, soil layer 1 (mm H2O / mm soil) | | plus 5% | basin-wide |

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

| Site | Period | Years | NSE | PBIAS | RSR |
|---|---|---|---|---|---|
| ***Main stem:*** | | | | | |
| St. Croix River at Danbury | Calibration | 2000-07 | 0.71 | 11 | 0.54 |
| | Validation | 1990-99 | 0.46 | 11 | 0.73 |
| St. Croix River at SC Falls | Calibration | 2000-07 | 0.84 | 2 | 0.40 |
| | Validation | 1990-99 | 0.78 | 5 | 0.47 |
| St. Croix River at Stillwater | Calibration | 2000-07 | 0.83 | -1 | 0.41 |
| | Validation | 1990-99 | 0.78 | 2 | 0.47 |
| ***Tributaries:*** | | | | | |
| Kettle River | Calibration | 2000-07 | 0.85 | 14 | 0.38 |
| | Validation | 1990-99 | 0.75 | 7 | 0.50 |
| Snake River | Calibration | 2000-07 | 0.87 | -4 | 0.36 |
| | Validation | 1990-99 | 0.70 | -12 | 0.55 |
| Apple River | Calibration | 2000-07 | 0.54 | -3 | 0.68 |
| | Validation | 1990-99 | 0.31 | 4 | 0.83 |
| ***Averages*** | *Calibration* | *2000-07* | *0.77* | *3* | *0.46* |
| | *Validation* | *1990-99* | *0.63* | *3* | *0.59* |

**NOTES:** Calibration period = 2000-07; Validation period = 1980-99; SC, St. Croix; NSE, Nash-Sutcliffe Coefficient of Efficiency; PBIAS, percent bias; RSR, ratio of root-mean-square-error to standard deviation of observations. See text for explanations and references.

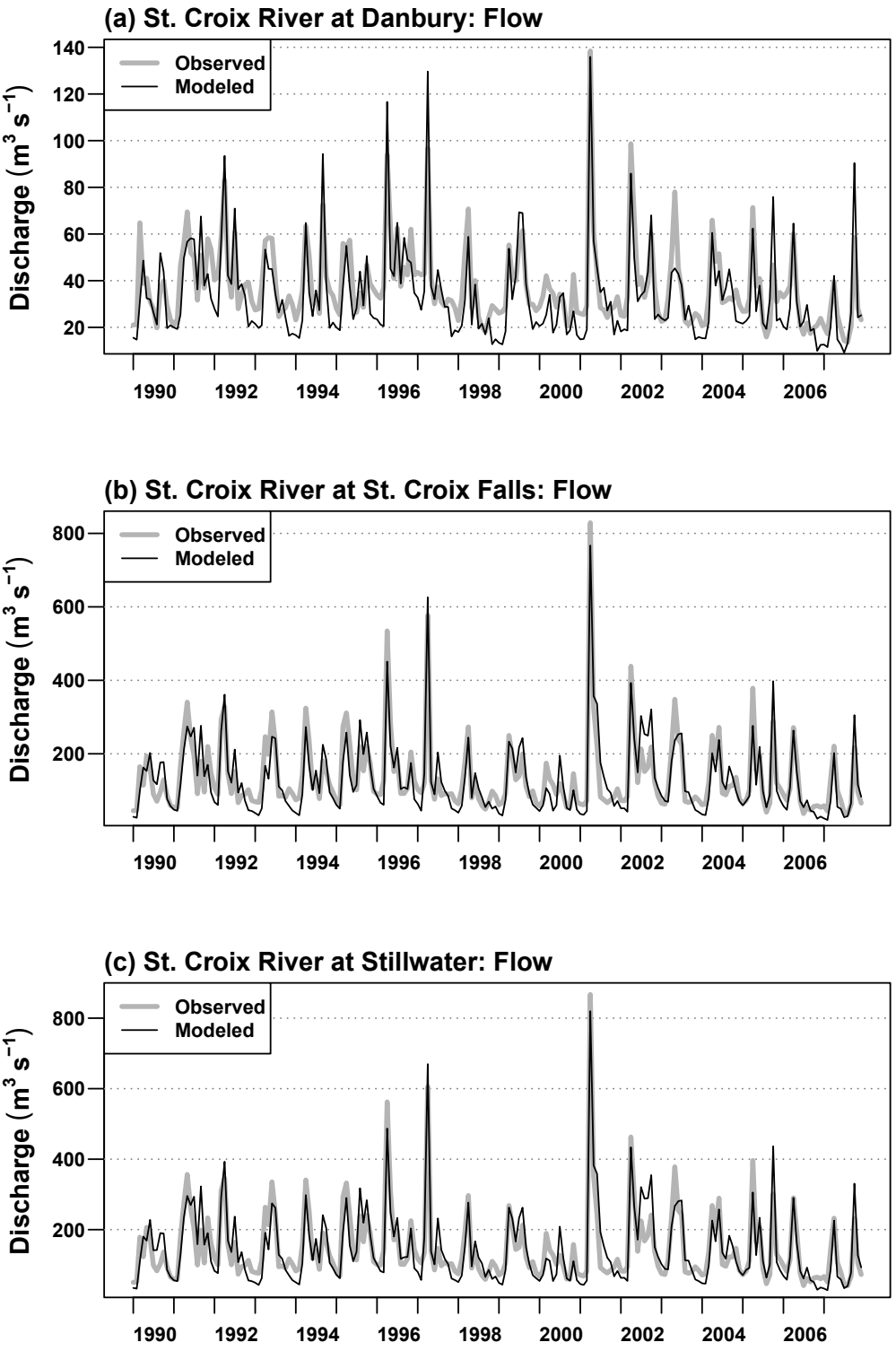


**Figure 13.** Flow of the main stem of the St. Croix River at (a) Danbury, (b) St. Croix Falls, and (c) Stillwater for calibration (2000-07) and validation (1990-99) periods.

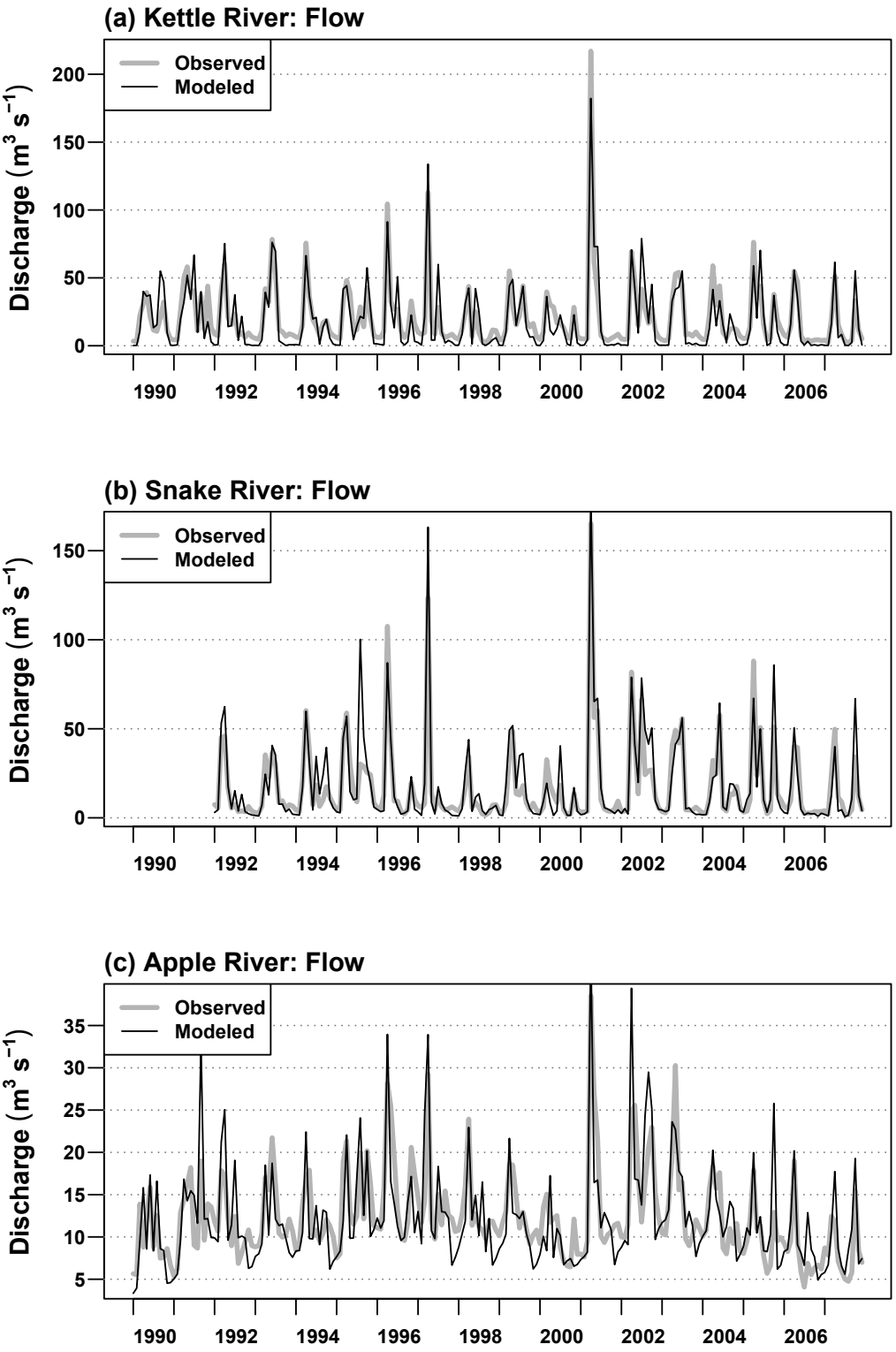


**Figure 14.** Flow of major tributaries to the St. Croix for calibration (2000-07) and validation (1990-99) periods: (a) Kettle River, (b) Snake River, and (c) Apple River.

## *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). Sediment and phosphorus were both fit well, with NSE values exceeding the 0.5 threshold value for the 2000-07 calibration period (Table 24). Total nitrogen was fit less well, with negative NSE values, but with low PBIAS values to assure that annul total loads were approximately correct. Monthly time series of these water-quality constituents showed good relation between modeled and observed monthly loads (Figure 15).

Sediment calibration in the St. Croix watershed was challenging due to the presence of numerous ponds and wetlands that act as a trap 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 37% of each subbasin area was routed through a SWAT wetland feature, and 8% 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. To reduce sediment yields further, parameters were adjusted to alter both the availability and transport of sediment (Table 25). These adjustments included reducing peak flow rates, slope lengths, and soil erosivity below initial values. In addition, the net sediment-trapping effect of small upland depressions was simulated by reducing the support practice factor (USLE_P) to 0.5, and the net effect of vegetated overland flow paths was simulated by adding filter strips to selected land units (Table 25).

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

| Site | Period | Years | NSE | PBIAS | RSR |
|---|---|---|---|---|---|
| Suspended sediment | Calibration | 2000-07 | 0.76 | -8.24 | 0.49 |
| | Validation | 1990-99 | 0.57 | -19.68 | 0.65 |
| Total phosphorus (TP) | Calibration | 2000-07 | 0.62 | 18.30 | 0.62 |
| | Validation | 1990-99 | -0.51 | 28.86 | 1.22 |
| Total nitrogen (TN) | Calibration | 2000-07 | -1.88 | 0.47 | 1.69 |
| | Validation | 1990-99 | -1.34 | 11.01 | 1.52 |

**NOTES:** Calibration period = 2000-07; Validation period = 1990-99; NSE, Nash-Sutcliffe Coefficient of Efficiency; PBIAS, percent bias; RSR, ratio of root-mean-square-error to standard deviation of observations. See text for explanations and references. All model runs were begun five years prior to calibration or validation period to allow for model equilibration (model spin-up).

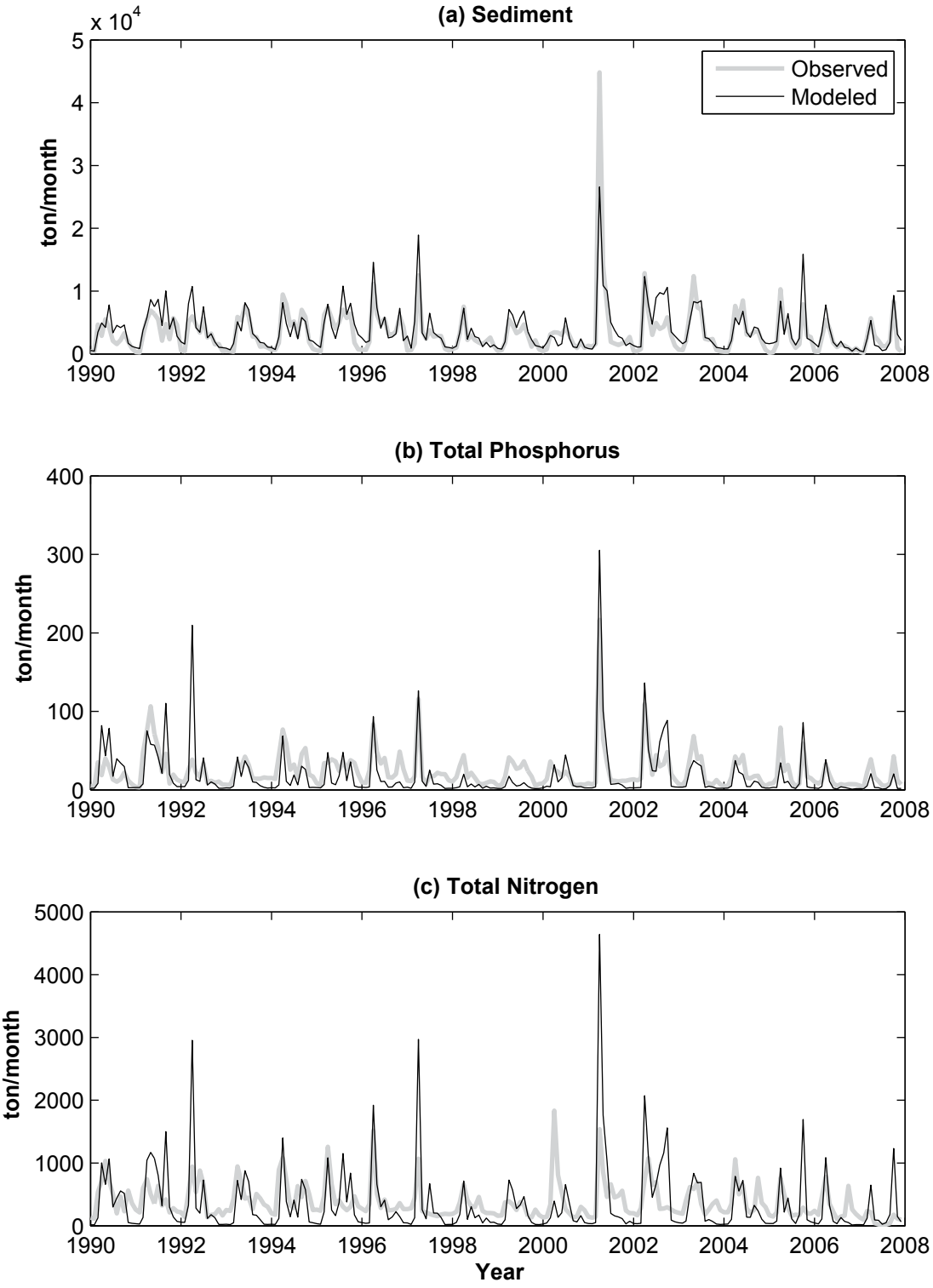


**Figure 15.** Monthly loads of (a) suspended sediment, (b) total phosphorus, and (c) total nitrogen for the St. Croix River at Stillwater, 1990-2007.

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

| Files | Parameter | | Values | | Subbasins applied |
|---|---|---|---|---|---|
| | Abbreviation | Name | Default | Calibrated | |
| bsn | ADJ_PKR | Peak rate adjustment factor for sediment routing in tributary channels (in subbasins) | 1 | 0.869 | basin-wide |
| bsn | PRF | Peak rate adjustment factor for sediment routing in main channel | 1 | 0.10 | basin-wide |
| hru | HRU_SLP | Average slope (m/m) | interface | 0.50% | wetland and grassland with initial slopes >0.5% |
| hru | SLSUBBSN | Average slope length (m) | interface | minus 20% | wetland, grassland, and agricultural land |
| mgt1 | FILTERW | Width of edge-of-field filter strip (m) | 0 | 22.7 | all HRUs |
| mgt1 | USLE_P | USLE support practice factor | 1 | 0.5 | all HRUs |
| pnd | PND_NSED | Equilibrium sediment concentration in ponds (mg/L) | 1 | 0 | all ponds |
| pnd | WET_NSED | Equilibrium sediment concentration in wetlands (mg/L) | 1 | 0 | all wetlands |
| res | RES_NSED | Equilibrium sediment concentration in reservoirs (lakes) (mg/L) | 1 | 0 | all reservoirs (lakes) |
| sol | USLE_K | USLE soil erodibility factor | database | minus 44% | all soils |
| till.dat | DEPTIL | Depth of tillage (mm) | 150 | 100 | moldboard plow |
| | | | 100 | 60 | disk |
| | | | 150 | 100 | chisel plow |
| till.dat | EFFMIX | Efficiency of tillage (fraction mixed) | 0.95 | 0.6 | moldboard plow |
| | | | 0.85 | 0.4 | disk |
| | | | 0.3 | 0.25 | chisel plow |

Total phosphorus (TP) loads 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 transport factors that affected sediment, resulting in a large number of parameter adjustments (Table 26). Total phosphorus loads were reduced as a consequence of the sediment calibration, especially for low-flow months. To help bring loads up to observed values, tillage depth and efficiencies were reduced to keep more phosphorus near the land surface and available for transport by overland runoff. Ultimately, the many surface-water bodies in the St. Croix basin played an apparent major role in mediating the total phosphorus load and the timing of its routing down the stream network. The phosphorus settling parameters for ponds and lakes (reservoirs in SWAT) were adjusted so that water bodies trapped significant amounts during the months with high runoff and suspended sediment loads. However, during the low-flow months some of this phosphorus was released (i.e., a negative settling rate), thereby elevating low-flow phosphorus loads. In short, ponds and lakes smooth the seasonal signal of phosphorus loading, reducing springtime runoff peaks and increasing low-flow loads. 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.

Calibration of total nitrogen was more problematic than for either sediment or phosphorus, which we attribute to 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. The negative NSE values for

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

| | Parameter | | Values | | |
|---|---|---|---|---|---|
| **Files** | **Abbreviation** | **Name** | **Default** | **Calibrated** | **Subbasins applied** |
| bsn | CDN | Exponential rate of denitrification | 1.4 | 0.112 | basin-wide |
| bsn | NPERCO | Nitrogen percolation coefficient | 0.2 | 0.012 | basin-wide |
| bsn | RCN | Concentration of nitrogen in rainfall (mg N/L) | 0 | 13.28 | basin-wide |
| bsn | SDNCO | Denitrification threshold water content | 1.1 | 0.945 | basin-wide |
| lwq | RES_NO3 | Initial concentration of nitrate in pond (mg/L) | 0 | 0.782 | all reservoirs (lakes) |
| lwq | RES_ORGN | Initial concentration of organic nitrogen in reservoir (mg/L) | 0 | 0.576 | all reservoirs (lakes) |
| pnd | NSETLP1 | Season 1 nitrogen settling rate for ponds (m/yr) | 5.5 | -0.4 | all ponds |
| pnd | NSETLP2 | Season 2 nitrogen settling rate for ponds (m/yr) | 5.5 | 0.15 | all ponds |
| pnd | NSETLW1 | Season 1 nitrogen settling rate for wetlands (m/yr) | 5.5 | -0.8 | all wetlands |
| pnd | NSETLW2 | Season 2 nitrogen settling rate for wetlands (m/yr) | 5.5 | 6 | all wetlands |
| pnd | PND_NO3 | Initial concentration of nitrate in pond (mg/L) | 0 | 3.525 | all ponds |
| pnd | PND_ORGN | Initial concentration of organic nitrogen in pond (mg/L) | 0 | 10.37 | all ponds |
| pnd | PND_ORGP | Initial concentration of organic phosphorus in pond (mg/L) | 0 | 0.38 | all ponds |
| pnd | PND_SOLP | Initial concentration of soluble phosphorus in pond (mg/L) | 0 | 2.7 | all ponds |
| pnd | PSETLP1 | Season 1 phosphorus settling rate for ponds (m/yr) | 10 | -15 | all ponds |
| pnd | PSETLP2 | Season 2 phosphorus settling rate for ponds (m/yr) | 10 | 4.8 | all ponds |
| pnd | WET_NO3 | Initial concentration of nitrate in pond (mg/L) | 0 | 20.01 | all ponds |
| pnd | WET_ORGN | Initial concentration of organic nitrogen in pond (mg/L) | 0 | 54.17 | all ponds |
| res | NSETLR1 | Season 1 nitrogen settling rate for reservoirs (m/yr) | 5.5 | -0.4 | all reservoirs (lakes) |
| res | NSETLR2 | Season 2 nitrogen settling rate for reservoirs (m/yr) | 5.5 | 0.15 | all reservoirs (lakes) |
| res | PSETLR1 | Season 1 phosphorus settling rate for reservoirs (m/yr) | 10 | -15 | all reservoirs (lakes) |
| res | PSETLR2 | Season 2 phosphorus settling rate for reservoirs (m/yr) | 10 | 4.8 | all reservoirs (lakes) |
| res | RES_ORGP | Initial organic phosphorus concentration in reservoirs (mg/L) | 0 | 0.7 | all reservoirs (lakes) |
| res | RES_SOLP | Initial soluble phosphorus concentration in reservoirs (mg/L) | 0 | 0.8 | all reservoirs (lakes) |
| till.dat | DEPTIL | Depth of tillage (mm) | 150 | 100 | moldboard plow |
| | | | 100 | 60 | disk |
| | | | 150 | 100 | chisel plow |
| till.dat | EFFMIX | Efficiency of tillage (fraction mixed) | 0.95 | 0.6 | moldboard plow |
| | | | 0.85 | 0.4 | disk |
| | | | 0.3 | 0.25 | chisel plow |
| wwq | P_N | Algal preference factor for ammonia | 0.5 | 0.115 | basin-wide |

nitrogen (Table 24) indicate a mis-match between modeled and observed values, and the plot of monthly values (Figure 15c) show how many peaks are missed and low-flow months tend to be underestimated. Part of the low-flow underestimation may be attributed to the loads of nitrogen associated with dissolved organic carbon, known to be large in the St. Croix, which is not one of the components considered in SWAT. Since the monthly pattern of nitrogen loads was not well-matched, we focused on getting the total load about right, as shown by a low PBIAS value for the calibration period (Table 24).

The average yields (annual loads per unit area) may be mapped on a subbasin-by-subbasin basis to show the net results of the source and transport factors acting across the St. Croix basin. Figures 16-18 show the average annual yields of sediment, total phosphorus, and total nitrogen, respectively. These maps represent delivery of sediment and nutrients from the landscape (including ponds and wetlands) to the stream network; they do not 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.

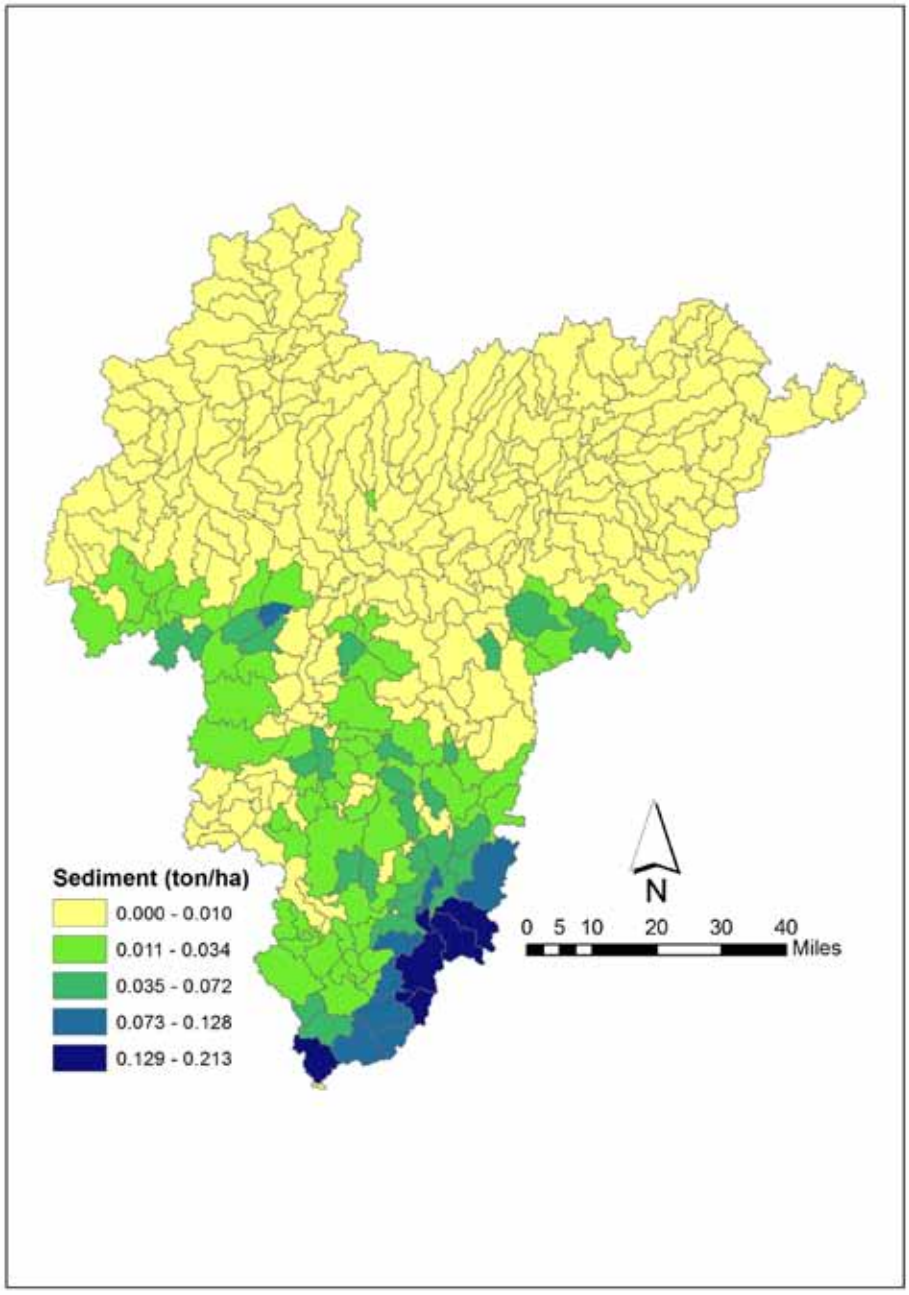


**Figure 16.** Average annual sediment yield by model subbasin in the St. Croix basin, 2000-07.

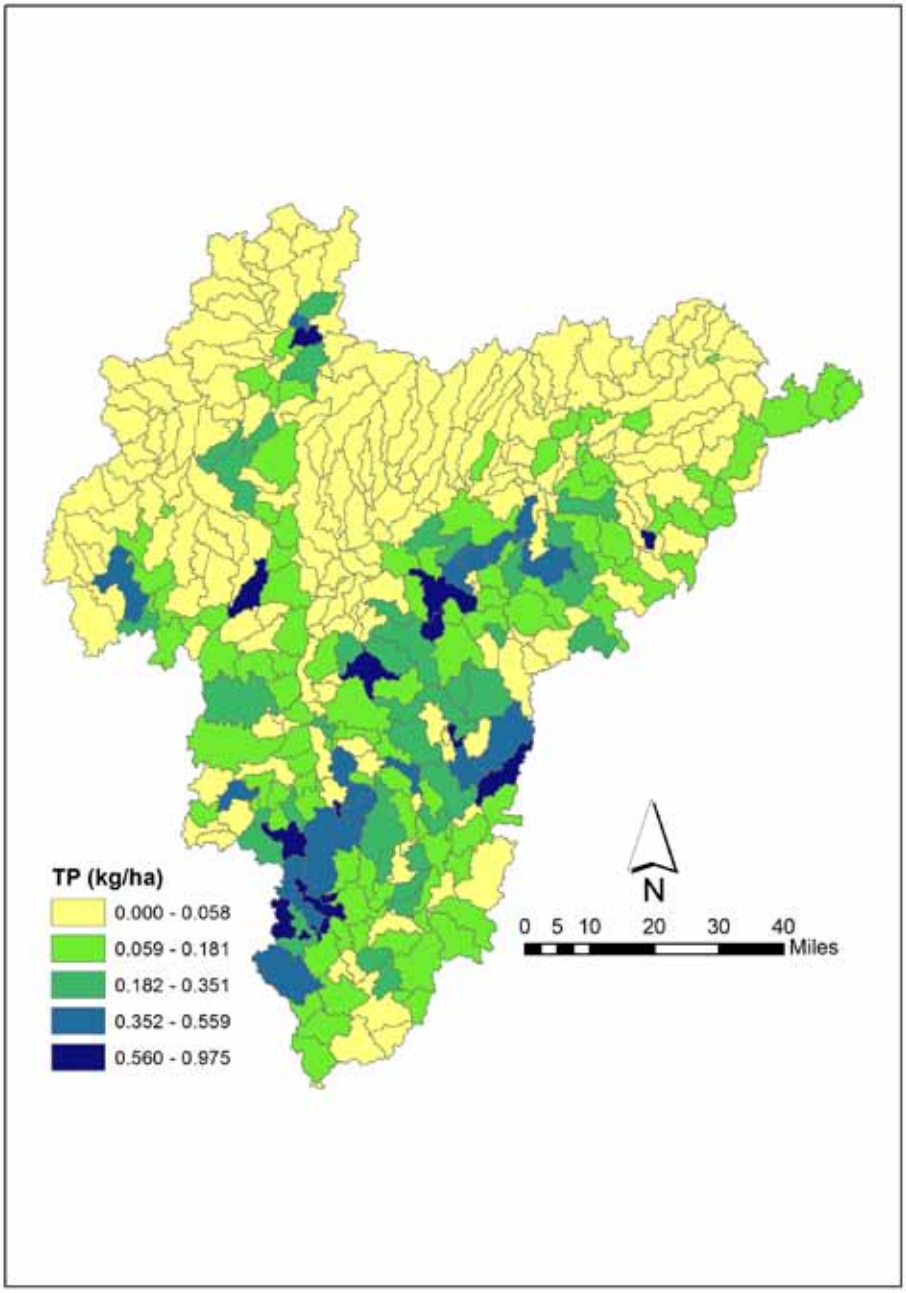


**Figure 17.** Average annual total phosphorus yield by model subbasin in the St. Croix basin, 2000-07.

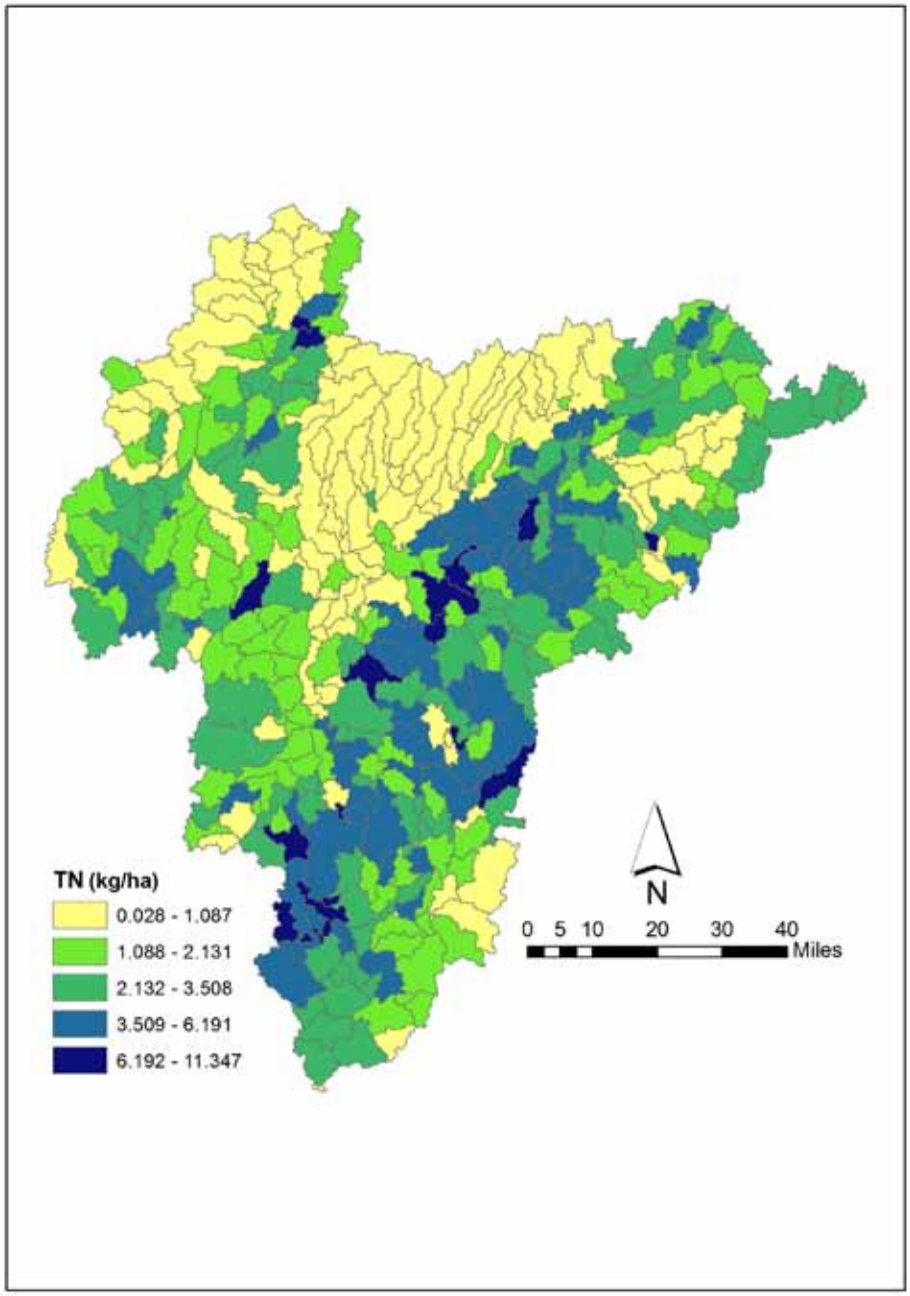


**Figure 18.** Average annual total nitrogen yield by model subbasin in the St. Croix basin, 2000-07.

# 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 20% 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 3028 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, 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 acceptable model fits for both suspended sediment and total phosphorus. 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).

| 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 (yers 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.

| **Rotation Name:** | | DPAST | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **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 | 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 cowws in paddock or barnyard area, simplified as monthly applications.

| **Rotation Name:** | | DPADD | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **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 | 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.

**Rotation Name:** BPAST

| 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 | 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.

**Rotation Name:** BPADD

| 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 | 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 |