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June 30, 2011

Mr. Mike Vavricka
Minnesota Pollution Control Agency
714 Lake Avenue, Suite 220
Detroit Lakes, MN 56501

Dear Mr. Vavricka:

Subject: EERC Final Reports Entitled "Development of the Soil and Water Assessment Tool (SWAT) to Assess Water Quality in the Red Lake River Watershed" and "Development of the Soil and Water Assessment Tool (SWAT)" in the Lower Red River Watershed"; EERC Fund 9946

Please find enclosed the subject reports. If you have any questions, please contact me by phone at (701) 777-5050, by fax at (701) 777-5181, or by e-mail at bkurz@undeerc.org.

Sincerely,

Bethany Kurz

Bethany A. Kurz
Senior Research Manager

BAK/sah

Enclosures

DEVELOPMENT OF THE SOIL AND WATER ASSESSMENT TOOL (SWAT) TO ASSESS WATER QUALITY IN THE RED LAKE RIVER WATERSHED

Final Report

(for the period of September 1, 2008, through June 30, 2011)

Prepared for:

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2011-EERC-06-27

June 2011

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1.0 INTRODUCTION

Water quality issues in the Red River Basin (RRB) (Figure 1) are of great concern, especially with regard to sediment and nutrient (e.g., phosphorus) transport. The highly erodible soils of the region, coupled with intensive agriculture, extensively modified drainage, and loss of wetlands and their natural storage capacity, have resulted in a landscape that is especially prone to sediment erosion and nutrient transport. Excess quantities of sediment and nutrients in rivers and lakes can adversely affect aquatic life, drinking water, and recreation. Nutrients such as phosphorus can be especially problematic by exacerbating algal growth, sometimes to the point of widespread eutrophication such as is occurring within Lake Winnipeg and other water bodies of the region. Eutrophication can lower dissolved oxygen levels within waterways, which adversely affects aquatic life, such as fish.

While many water quality impairments have been identified in the streams and waterways of the RRB, identifying the source of a particular impairment can be problematic. The most reliable means of identifying problem areas is through long-term water quality monitoring; however, the repeated collection and analysis of water samples at multiple locations throughout the RRB is time-consuming and expensive. Another option is to use tools such as hydrologic models to gain a more comprehensive understanding of the various processes occurring in a watershed that can affect water quality. Hydrologic modeling is not a replacement for water quality monitoring; rather it is a complementary effort that utilizes the flow and water quality data already collected for model calibration. This helps improve the accuracy of the model in predicting the impact of land management changes and/or climate on runoff, water quality, and nutrient and sediment transport. As the availability of monitoring data increases, models can be updated for improved accuracy.

The goal of this project was to assess the factors that contribute to the water quality impairments identified within the Red Lake River Watershed (RLRW) and to identify target areas for implementation of beneficial management practices (BMPs) using hydrologic models. The RLRW is impaired for turbidity and dissolved oxygen, which affects the designated use of aquatic life along 195.2 river miles of the RLRW. The focus of this project was to evaluate the source of the turbidity impairments affecting the aquatic life.

To better understand the source of turbidity impairments within this watershed, the Energy & Environmental Research Center (EERC) developed and calibrated a hydrologic model for the RLRW using SWAT. The model was used to conduct long-term (i.e., 15- to 30-year) simulations of water and sediment loading at multiple points of interest within the watershed. The modeling results were used to gain a better understanding of water quality issues within the watershed and to aid the Minnesota Pollution Control Agency (MPCA) in development of total maximum daily loads (TMDLs) for the impaired reaches.

Figure 1. Locations and boundaries of the watersheds located on the U.S. side of the RRB.

2.0 BACKGROUND

As defined by the U.S. Geological Survey (USGS), the RLRW includes an area of approximately 1450 square miles (Figure 2). However, the SWAT-generated watershed drainage was approximately 1417 square miles (Figure 3). The difference in boundaries is most likely caused by the difference in spatial resolution between the elevation data that were used in the SWAT model versus the USGS-derived watershed boundaries. The RLRW is bordered by the Grand Marais, Snake River, Thief River Watersheds to the north; Sandhill–Wilson and Clearwater Watersheds to the south; and the Red Lakes Watershed to the east. According to the 2008 303d list, the RLRW has turbidity and dissolved oxygen impairments affecting the designated use of aquatic life.

The RLRW lies in the humid continental climate zone, with average annual precipitation of 20.72 inches (based on Crookston, Minnesota, climate data). The continental climate produces extreme annual temperature swings, with very cold winters and warm-to-hot summers.

The RLRW lies within two ecological regions: Lake Agassiz Plain and Northern Minnesota Wetlands (Figure 4). An ecological region—or ecoregion—can be defined as a region that is characterized by a unique combination of geology, landforms, soils, vegetation, climate, wildlife, hydrology, and human factors (Commission for Environmental Cooperation, 1997).

Approximately 72% of the watershed is contained in the Lake Agassiz Plain, which is characterized by thick beds of clay and silt that made up the floor of former glacial Lake Agassiz approximately 10,000 years ago (U.S. Environmental Protection Agency, 2008). Because of the environment in which it was formed, the Lake Agassiz Plain is extremely flat and, historically, poorly drained. The native tallgrass prairie of the region has been replaced by intensive row crop agriculture. The remaining 28% of the watershed is contained within the Northern Minnesota Wetlands ecoregion. This region is characterized by boreal forests and numerous marshes and swamps that reside in what were previously glacial lakes. Most of these areas are sparsely inhabited by humans (U.S. Environmental Protection Agency, 2008).

3.0 MATERIALS AND METHODS

3.1 Description of SWAT

SWAT is a hydrologic model developed by the U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS). The essential function of the model is to predict the impact of land management practices on water, sediment, and agricultural chemical yields in watersheds over long periods of time. The model is increasingly being used in a variety of applications such as assessment of point and non-point sources of pollution, establishment of TMDLs, evaluation of climate change impacts on groundwater supplies and surface water flows, and watershed-scale investigations of flood and drought mitigation measures (Gassman et al., 2007, and references therein). The SWAT model can address the following:

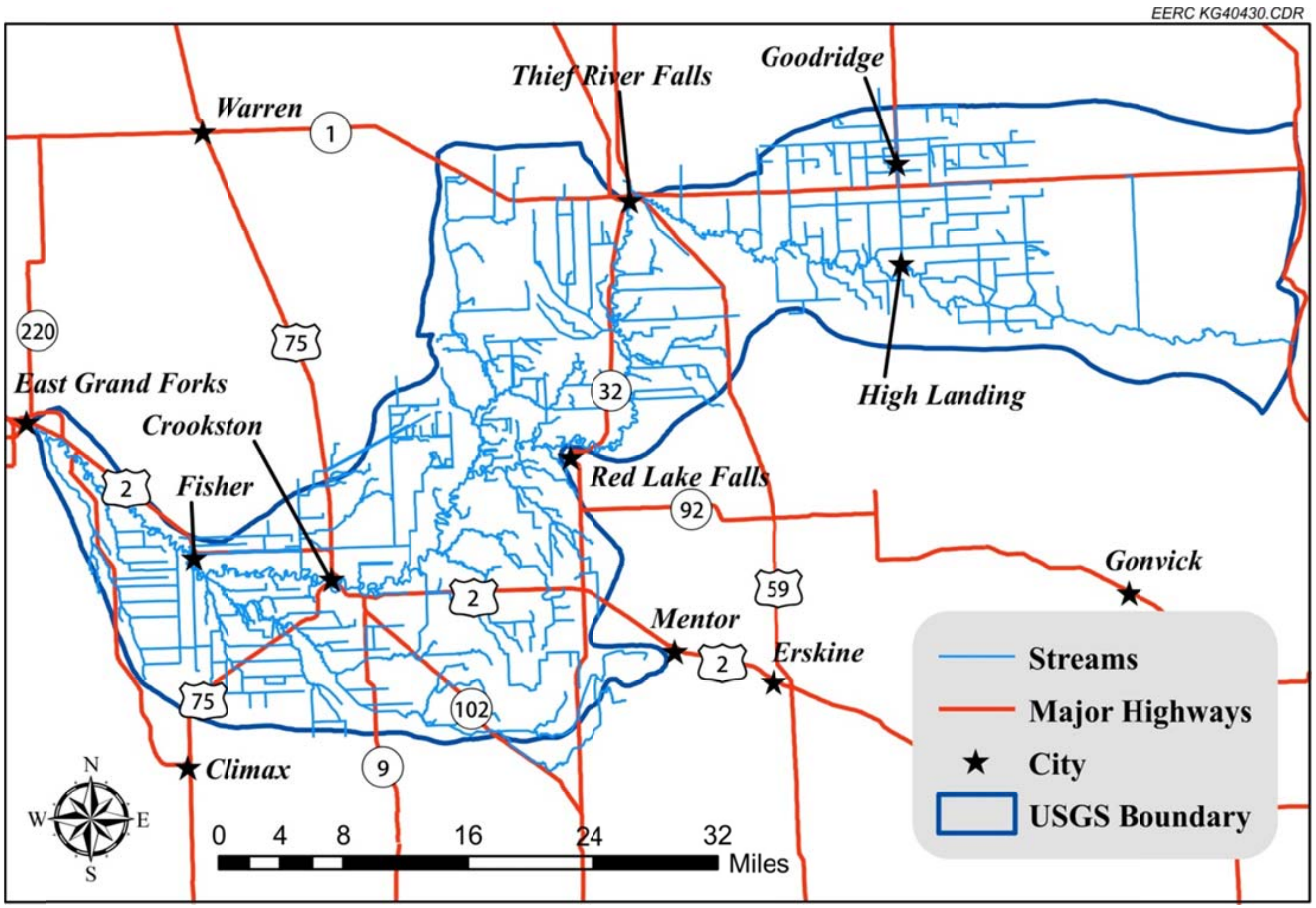

Figure 2. RLRW base map.

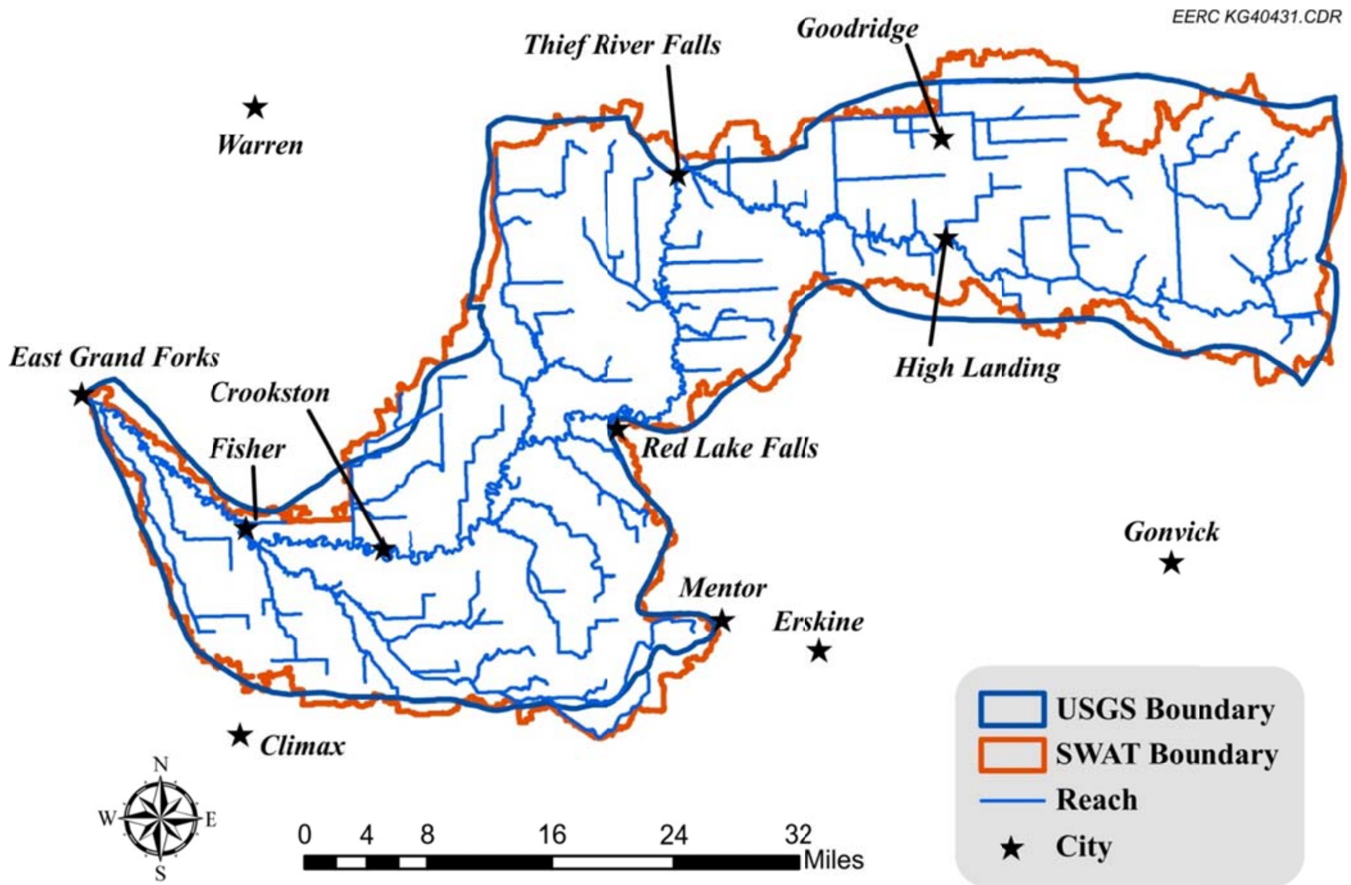

Figure 3. Comparison of the USGS and SWAT-generated watershed boundaries.

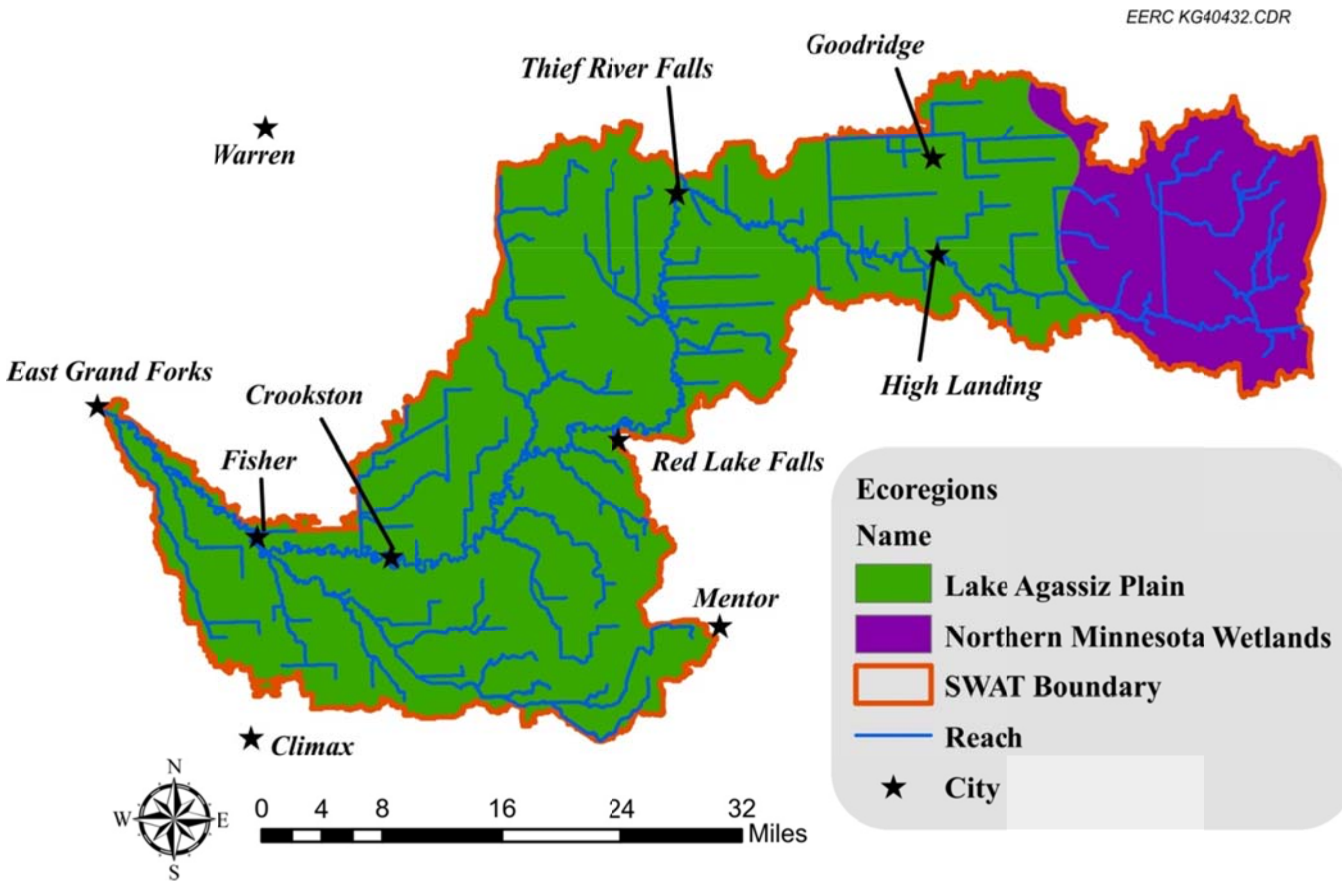

Figure 4. Ecological regions found within the RLRW.

1. How much runoff can be generated from a precipitation event

2. What the loading of constituents is at a particular location within a watershed

3. Where the major contributors to sediment and nutrient loading are located

4. What changes in flow or loading can be expected from adopting alternative land uses and watershed practices

5. How climate conditions affect loading

The SWAT model is physically based, meaning that it uses physically based data sets, such as topography, vegetation, land management practices, soil type, and climate, to predict water and sediment movement, crop growth, nutrient cycling, and a host of other processes associated with hydrology and water chemistry (Neitsch et al., 2002). The model can operate and produce output on a daily, monthly, or yearly time step for simulation periods up to 100 years.

SWAT is a compilation of several ARS models, some of which have been in development since the 1970s. It is a direct outgrowth of the Simulator for Water Resources in Rural Basins (SWRRB) model; however, it also incorporates components from Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS), Groundwater Loading Effects on Agricultural Management Systems (GLEAMS), and Erosion-Productivity Impact Calculator (EPIC) (Neitsch et al., 2002).

SWAT uses topography and the location of waterways to subdivide a watershed into a number of subbasins for modeling purposes. Each subbasin delineated within the model is simulated as a homogeneous area in terms of climatic conditions, but additional subdivisions are used within each subbasin to represent different land use, soils, and slope types. Each of these individual areas is referred to as a hydrologic response unit (HRU) and is assumed to be spatially uniform in terms of soils, land use, and topography.

The hydrologic cycle is the driving force in model simulations. The weather data input to the model (including precipitation, air temperature, wind speed, and humidity) is used to predict the interaction of precipitation (snowfall or rainfall) with the landscape and estimate the amount of runoff, infiltration, evaporation, and transpiration (Figure 5) that occurs in each subbasin. Based on the estimated runoff and the physical characteristics of the landscape (such as soils, topography, and land use), SWAT calculates the amount of sediment, nutrient, and pesticide loading to the main channel in each subbasin. The model then predicts the movement of water, sediment, nutrients, and other water quality components through the channel network of the watershed to the outlet (Figure 6).

To help organize and track all of the various processes that are modeled, SWAT is subdivided into three major components, namely, subbasin, reservoir routing, and channel routing. Each of these components includes several subcomponents. For example, the subbasin component consists of eight subcomponents: hydrology, weather, sedimentation, soil moisture,

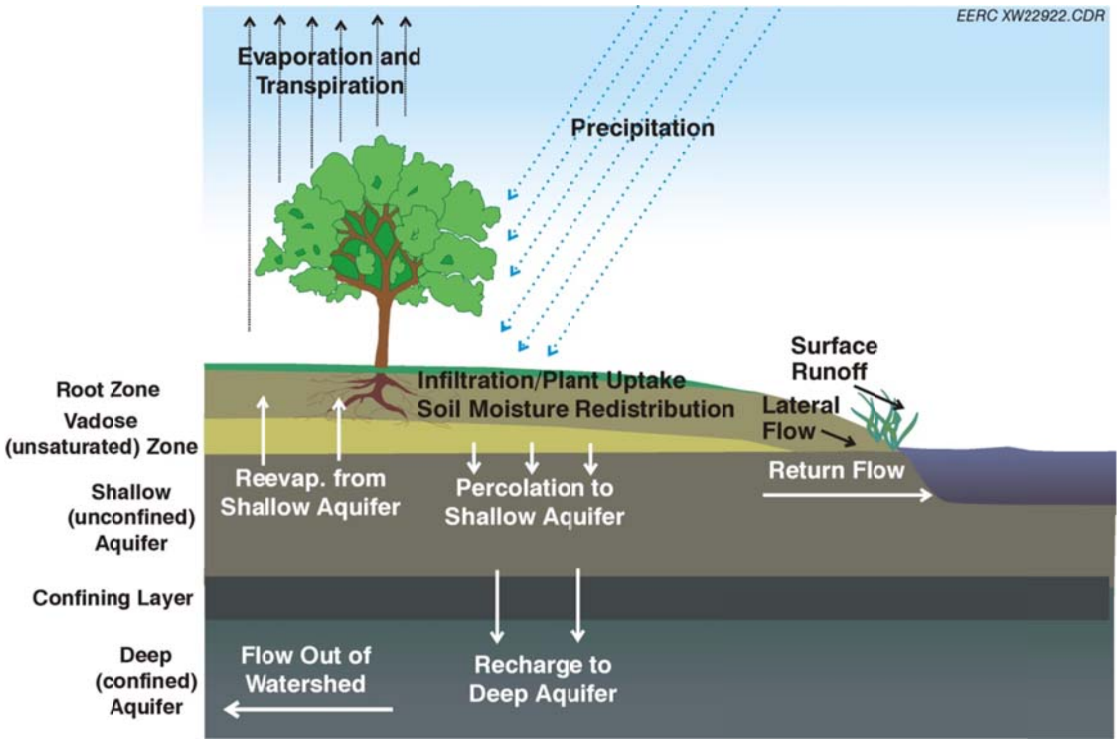

Figure 5. Hydrologic factors modeled within SWAT (modified from Neitsch et al., 2002, ftp://ftp.brc.tamus.edu/pub/swat/doc/swat2000theory.pdf).

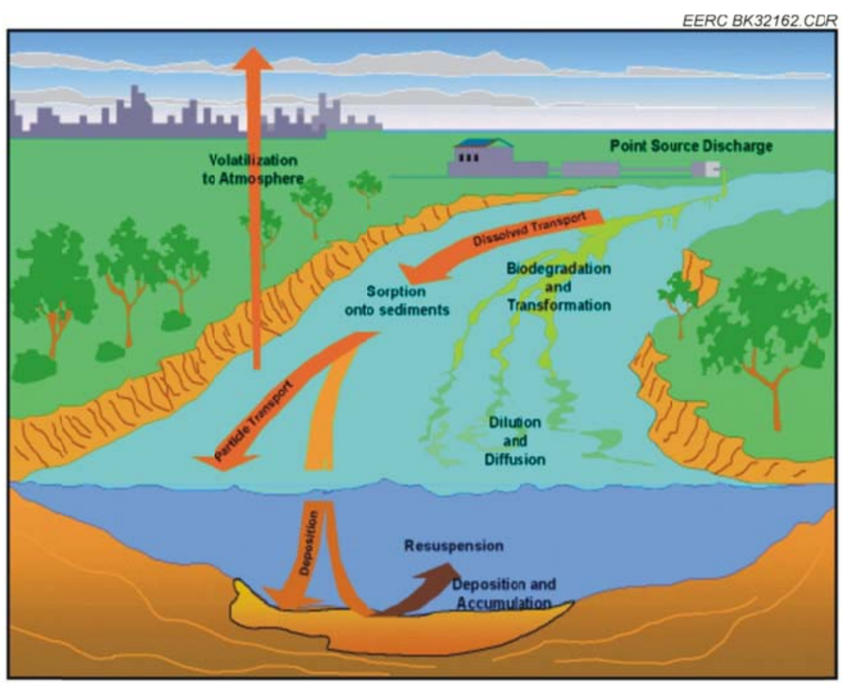

Figure 6. Routing phase of the SWAT model (Neitsch et al., 2002).

crop growth, nutrients, agricultural management, and pesticides. The hydrology subcomponent, in turn, includes surface runoff, lateral subsurface flow, percolation, groundwater flow, snowmelt, evapotranspiration, transmission losses, and ponds. Thus there are many layers of data and detailed calculations that occur for each of the processes modeled by SWAT. Detailed descriptions of the methods used in modeling these components and subcomponents can be found in Arnold et al. (1998), Srinivasan et al. (1998), and Neitsch et al. (2002). Brief descriptions of the main components relevant to this project are provided herein for background information purposes.

3.1.1 Rainfall Runoff Estimation

SWAT provides two methods for estimating surface runoff: 1) the Soil Conservation Service (SCS) runoff curve number method, with the SCS curve number adjusted according to soil moisture conditions, and 2) the Green–Ampt (GA) infiltration method. The SCS curve number method uses empirical equations to estimate the amounts of runoff under varying land uses and soil types, whereas the GA infiltration method is based on the principles of vadose zone hydrology. These two methods have distinct assumptions and data requirements. For example, the SCS curve number method assumes an infiltration excess rainfall runoff mechanism, but the GA method assumes a saturation excess mechanism. The GA method requires subdaily (e.g., hourly) weather data, but the SCS curve number method requires only daily data. In addition, SWAT provides three methods—Penman–Monteith, Priestley–Taylor, and Hargreaves—for estimating evapotranspiration. When available, observed evapotranspiration data can be used as model input as well. Further, SWAT uses a modified rational method to convert estimated surface runoff into corresponding flow rates.

Based on past modeling experience by the EERC and others who have developed SWAT models in the upper Midwest, it is an appropriate choice to use the SCS runoff curve number method along with the Priestley–Taylor method for rainfall runoff estimation. These two methods require a moderate amount of input data but are accurate enough for watershed-level studies.

3.1.2 Rainfall and Snowmelt

Because snowmelt accounts for a large percentage of the annual runoff in the study watersheds, it is imperative to appropriately model snow accumulation and melting processes. In this regard, SWAT is superior to other models.

SWAT classifies precipitation as either rain or snow based on the mean daily air temperature and a specified boundary temperature (i.e., snowfall temperature); the precipitation is classified as snow when the mean daily air temperature is less than the boundary temperature and as rain when the air temperature is greater. The water equivalent of the snow precipitation is then added to the snowpack. The snowpack will increase with additional snowfall and decrease with snowmelt and sublimation. Snowmelt is controlled by the air and snowpack temperatures, the melting rate, and the areal coverage of snow. The snowpack temperature on a given day is estimated as the weighted average of that day’s mean air temperature and the snowpack temperature on the previous day. The weighting includes a specified lag factor, which accounts for the snowpack density, snowpack depth, exposure, and other factors affecting the snowpack temperature. The snowmelt rate is allowed to have a seasonal variation, with the specified maximum and minimum values occurring on the summer and winter solstices, respectively.

The areal coverage of snow correlates well with the amount of snow present in a watershed of interest at a given time because other factors that contribute to variations in the snow coverage, such as drifting, shading, and topography, are usually similar from year to year (Anderson, 1976). This correlation is expressed in SWAT as an areal depletion curve, which is used to describe the seasonal growth and recession of the snowpack as a function of the amount of snow present in the watershed. The areal depletion curve requires a threshold depth of snow above which there will always be 100% cover. The threshold depth depends on factors such as vegetation distribution, wind loading and scouring of snow, interception, and aspect and is unique to the watershed. This snow accumulation and melt phenomenon is modeled using seven parameters in SWAT, which are discussed in detail by Neitsch et al. (2002).

3.1.3 Flow Routing

SWAT provides two methods to route flows through a channel reach: 1) the variable storage routing method and 2) the Muskingum routing method. The first method is based on the continuity equation for the reach and thus does not consider the flow attenuation. On the other hand, the Muskingum routing method uses a continuity equation to consider flow translation and a momentum equation to consider attenuation. Hence, the Muskingum method may be more appropriate for the study watersheds.

In addition, SWAT provides three options, including reservoirs, ponds, and wetlands, to model different types of storage. The reservoir function is intended to model storage that intercepts all runoff generated in its upstream drainage areas, whereas the pond and wetland functions can be used to model storage (e.g., off-line detention ponds and lakes) that may intercept only a certain percentage of the runoff. The remaining runoff will be considered to bypass the storage feature. As with a channel reach, these storage features will attenuate the inflow hydrographs and thus reduce the peaks. Further, translation losses (e.g., seepage and evaporation) are considered for both channel and storage routings.

3.1.4 Erosion and Sediment Transport

SWAT uses the Modified Universal Soil Loss Equation (MUSLE) to compute the erosion caused by rainfall and runoff. When compared to the Universal Soil Loss Equation (USLE), MUSLE uses a runoff factor to improve the sediment yield prediction, eliminate the need for delivery ratios, and allow for application of the equation to individual storm events. The amount of sediment released into a stream reach is estimated based on the surface runoff transport capacity.

Sediment transport in the channel network is a function of two processes, deposition and degradation, operating simultaneously in the reach. Deposition and degradation can be computed using the same channel dimensions for the entire simulation period. For alluvial channels, which are the type found in the proposed study watersheds, SWAT will simulate downcutting and widening of the stream channel and update channel dimensions throughout the simulation period. The maximum amount of sediment transported within a reach is a function of the peak channel velocity, defined by the peak flow rate divided by the cross-sectional area of flow. Deposition will occur when the sediment concentration is greater than the transport capacity; otherwise, degradation will occur. The amount of stream bank erosion is controlled by the channel erodibility factor, which is a function of the stream bank or bed materials. The amount of vegetative cover within each channel reach is also simulated using a channel cover factor.

3.1.5 Simulation of Other Parameters

Once a SWAT model is calibrated and validated in terms of hydrology, it can be expanded to simulate various chemical and biological constituents. In addition to the sediment transport functions discussed above, SWAT can also simulate nutrient (nitrogen and phosphorus) and pesticide loading and predict water quality parameters such as algae and dissolved oxygen. SWAT also allows for the simulation of crop growth and yield.

3.1.6 Simulating the Effects of Watershed Management Practices

SWAT can simulate the effects of various agricultural and watershed management practices. These practices include the following:

- Land use changes
- Agricultural conservation practices (e.g., no-till, reduced-till, and field buffers)
- Tile drainage
- Nutrient management
- Wetland restoration
- Stream restoration
- Riparian buffering (note: depending on the desired level of detail needed to evaluate this option, SWAT may need to be run in conjunction with the Riparian Ecosystem Management Model)

Because options for changing most of the above parameters are built into the model interface and are relatively easy to adjust, the model is especially useful for evaluating options to achieve TMDLs.

3.2 Data Inputs

The following describes the primary data sets used to develop and calibrate the RLRW SWAT model.

Topographic Data: The 30-meter USGS National Elevation Dataset (NED) was used to represent the topography of both subbasins. NED is a raster product assembled and designed to provide national elevation data in a seamless form with a consistent datum, elevation unit, and projection (U.S. Geological Survey, 2006).

Stream Location Data: The USGS National Hydrography Dataset (NHD) is a comprehensive set of digital spatial data that contains information about surface water features such as lakes, ponds, streams, rivers, springs, and wells. This data set was used as the reference surface water drainage network to delineate the subbasins within the watershed.

Land Use Data: The 2006 National Agricultural Statistics Service (NASS) Cropland Data Layer was used to represent land use within the watershed. This data set contains various land use information, including crop-specific data, at a resolution of 56 meters. It was compiled using imagery from the Advanced Wide Field Sensor (AWIFS) equipped on India's ResourceSat-1 satellite.

Conservation Practice Data Layer: A geographic information system (GIS) shape file was obtained from the Minnesota Farm Service Agency (FSA) containing the location of conservation practices that have been implemented in Minnesota through FSA. The data set includes the location of 49 different conservation practices, such as wetland restoration, field buffers, tree plantings, and land enrolled in the Conservation Reserve Program (CRP). This data set was used to update the 2006 Cropland Data Layer for incorporation into the SWAT models.

Soil Data: Soil data for the watershed was incorporated using SSURGO (Soil SURvey GeOgraphic) data, a data set compiled and distributed by the USDA Natural Resources Conservation Service (NRCS). SSURGO is the most detailed geographic soil database available, containing digital data developed from detailed soil survey maps that are generally at scales of 1:12,000, 1:15,840, 1:20,000, 1:24,000, or 1:31,680.

Stream Flow Data: The daily flow data from the USGS gauging station on the Red Lake River at Crookston, Minnesota (05079000), were used for calibration. Flow and sediment data from the Thief River, Red Lakes, and Clearwater Watersheds were incorporated into the model to account for flow and sediment contributions. It is important to note that there were missing data for the Red Lakes flow data during 1994–1999, which significantly affected the accuracy during calibration. These missing flow data also resulted in the Red Lake River USGS gauging station at High Landing near Goodridge, Minnesota, not being used for calibration.

Sediment and Water Quality Data: Water quality information, specifically total suspended solids (TSS) concentration data, was obtained from the MPCA Environmental Data Access Web site. This site contains water quality information collected and compiled by MPCA and other partner agencies such as the Minnesota Department of Natural Resources.

4.0 DEVELOPMENT AND CALIBRATION OF THE RLRW MODEL

The previously described data sets were used to develop and calibrate the RLRW SWAT model. This entailed delineation of the watershed into smaller subbasins and HRUs, incorporation of inlet flow data, point source data, import of the climate data from the weather station used, adjustment of various model parameters to best represent the physical characteristics of the region modeled, and model calibration using observed data. The following sections describe each of the steps taken to develop and calibrate the model.

4.1 Model Development

4.1.1 Watershed Delineation

The first step in model development is watershed delineation, which entails subdividing the watershed into smaller units, called subbasins. The SWAT model predicts discharge, sediment and nutrient loading, and other water quality parameter output for each subbasin defined within the watershed. Thus, for studies such as this one that entail detailed water quality assessment, a higher number of subbasins is desirable. Subbasins were defined based on the topographic information contained within the NED and based on the stream locations defined by the NHD. A trial-and-error approach was used during this step to ensure that the subbasins were relatively similar in size and to ensure that the subbasin outlets were correlated to the USGS gauging stations and most of the MPCA water quality station locations. A total of 215 subbasins with an average area of 17.07 km^2 (6.59 mi^2) were defined within the watershed. The location and number of each subbasin are shown in Figure 7.

4.1.2 HRU Delineation

As previously described, a HRU is a smaller unit defined within each subbasin that is a unique combination of land use, soil type, and slope. Figures 8–10 show the distribution of land use, soils, and slopes used to define the HRUs within the RLRW. Table 1 lists the soil types that make up more than 0.5% of the total watershed area (out of a total of 70 soil types located within the watershed), and Table 2 lists the land uses that comprise more than 0.1% of the total watershed area found in the RLRW.

Once the aforementioned data sets are loaded into the model, the user is able to define the number of HRUs within a watershed based on a specified threshold or degree of sensitivity to soil type, slope, and land use. For example, if a threshold value of 5% is designated for soil type, then any soils that make up less than 5% of a subbasin area will not be included in the formation of HRUs.

Within the RLRW model, the following threshold values were used for each of the three categories:

- Land use: 20%
- Soil type: 10%
- Slope: 10%

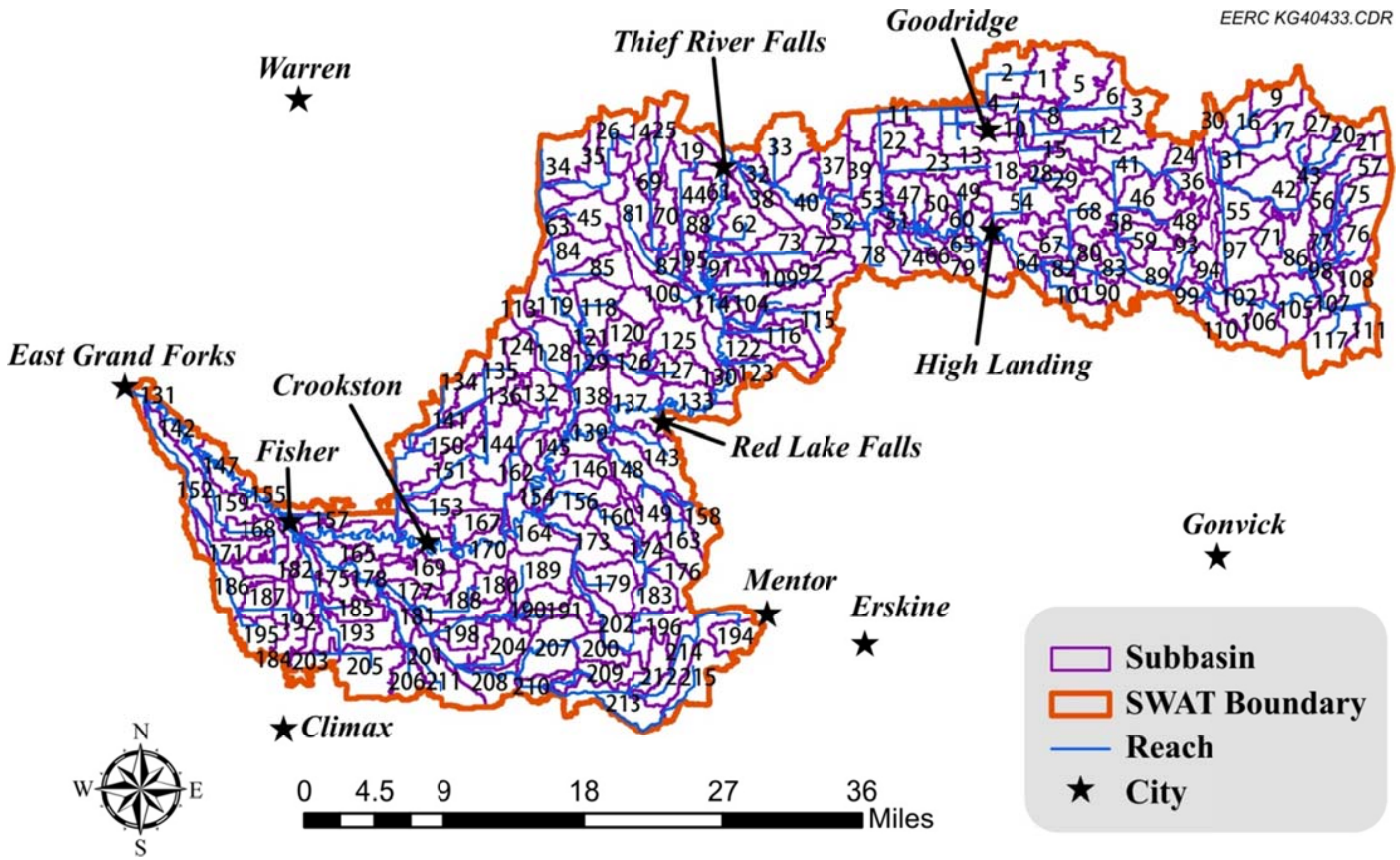

Figure 7. RLRW SWAT-delineated watershed and subbasin boundaries.

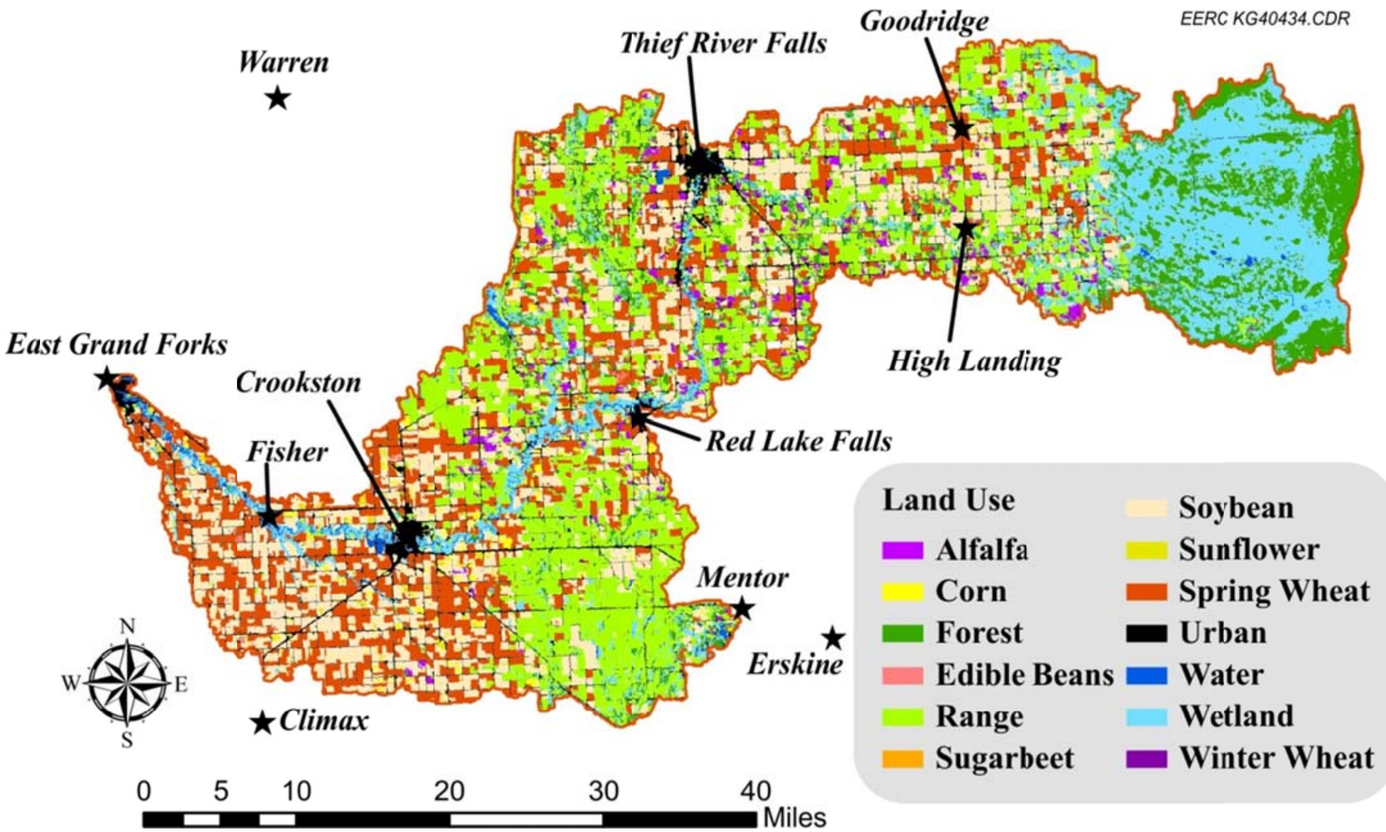

Figure 8. Land use distribution within the RLRW.

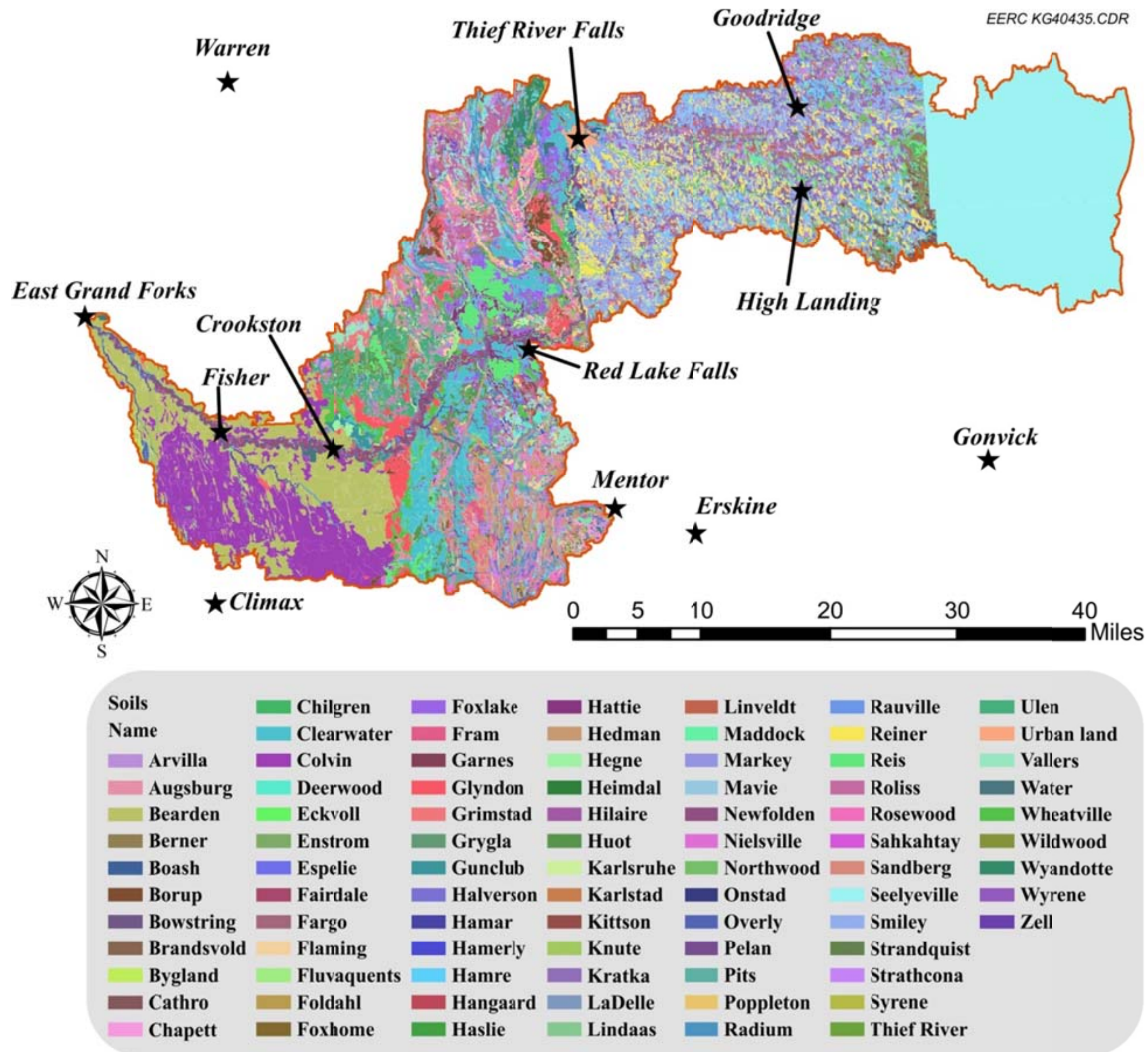

Figure 9. Soil distribution within the RLRW.

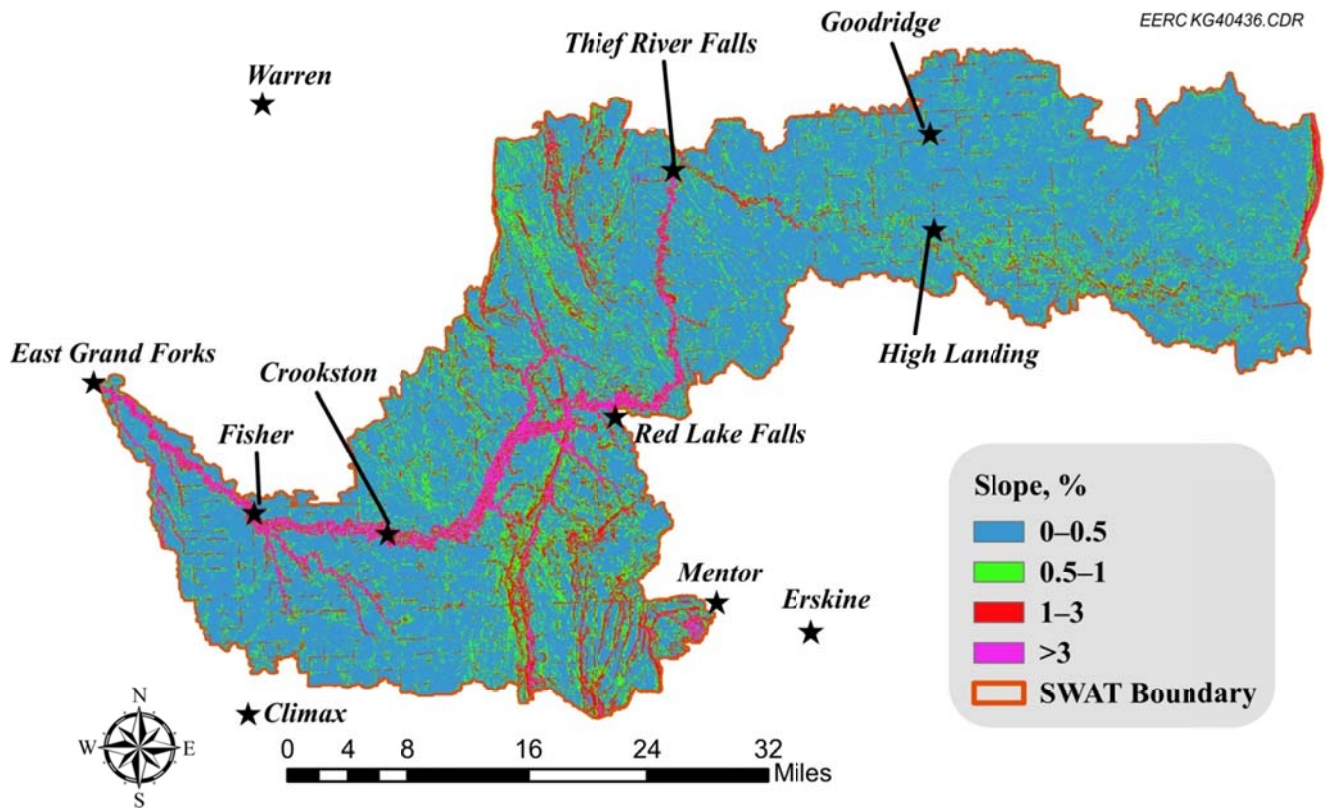

Figure 10. Slope distribution within the RLRW.

Table 1. Soil Types in the RLRW

Soil Name	Area, acres	Percent of Watershed Area
Seelyeville	145,539	16.05
Kratka	104,279	11.50
Smiley	79,401	8.75
Clearwater	69,590	7.67
Colvin	68,029	7.50
Bearden	66,337	7.31
Reiner	41,252	4.55
Ulen	22,426	2.47
Rosewood	21,485	2.37
Glyndon	19,435	2.14
Roliss	18,525	2.04
Fram	18,098	2.00
Hamre	14,887	1.64
Huot	14,770	1.63
Grimstad	12,753	1.41
Fairdale	11,919	1.31
Wheatville	11,863	1.31
Linveldt	11,405	1.26
Northwood	11,156	1.23
Vallers	10,868	1.20
Flaming	8653	0.95
Borup	8380	0.92
Hattie	7864	0.87
Eckvoll	7276	0.80
Hilaire	6740	0.74
Fluvaquents	6700	0.74
Wyandotte	6264	0.69
Thief River	5573	0.61
Cathro	5459	0.60
Syrene	5135	0.57
Water	4999	0.55
Deerwood	4931	0.54
Foldahl	4719	0.52
Mavie	4634	0.51

This resulted in the formation of 1953 HRUs throughout the entire watershed, or an average of 9.08 HRUs per subbasin.

4.1.3 Climate Data

Two weather stations were used to provide precipitation and temperature data input to the model. These stations included Crookston (211891) and Red Lake Falls (216787) (Figure 11). The period of record of climate data incorporated into the model ranges from January 1, 1970, to December 31, 2008.

Table 2. Land Use in the RLRW

Land Use	Area, acres	Percent of Watershed Area
Range	220,064	24.26
Soybean	187,540	20.68
Spring Wheat	161,698	17.83
Wetland	137,466	15.16
Forest	96,639	10.65
Urban	60,192	6.64
Alfalfa	17,141	1.89
Water	8672	0.96
Corn	7384	0.81
Sunflower	5632	0.62
Edible Beans	1343	0.15
Winter Wheat	1312	0.14

For the purposes of this project, a 4-year warm-up period was used at the beginning of the model simulation. This allows the model to equilibrate and estimate the initial value of certain parameters, such as soil moisture, before it starts generating results. Thus, including the warm-up period, the total simulation period of the model is January 1986 to December 2008.

4.2 Flow Calibration

4.2.1 Calibration Parameters

The RLRW model was calibrated using the USGS measured flows on the Red Lake River at Crookston, Minnesota (Station 05079000). The model was calibrated from January 1, 1990, to December 31, 2008.

Table 3 lists the various model parameters that were adjusted to calibrate the model, including the default and calibrated parameter values. The calibration parameters were adjusted to reflect conditions most appropriate for the RRB and the RLRW. Appropriate ranges for most of the sensitive SWAT model parameters had been previously determined through extensive SWAT modeling work conducted by the EERC (Kurz et al., 2007; Wang and Melesse, 2005, 2006; Wang et al., 2006). The RLRW SWAT model used ArcSWAT Version 2.0.0, which was released February 29, 2008. More information on each parameter, such as the assumptions and equations used to determine the parameter, can be found in the SWAT Input/Output File Documentation (Neitsch et al., 2005) available online at http:/swatmodel.tamu.edu.

4.2.2 Measures of Model Performance

Overall, the predicted flows matched the measured flow rates fairly well throughout the calibration period (Figure 12). In general, the timing of the peaks matched well; however, some of the peaks were underestimated by SWAT. Some of this discrepancy can be attributed to the

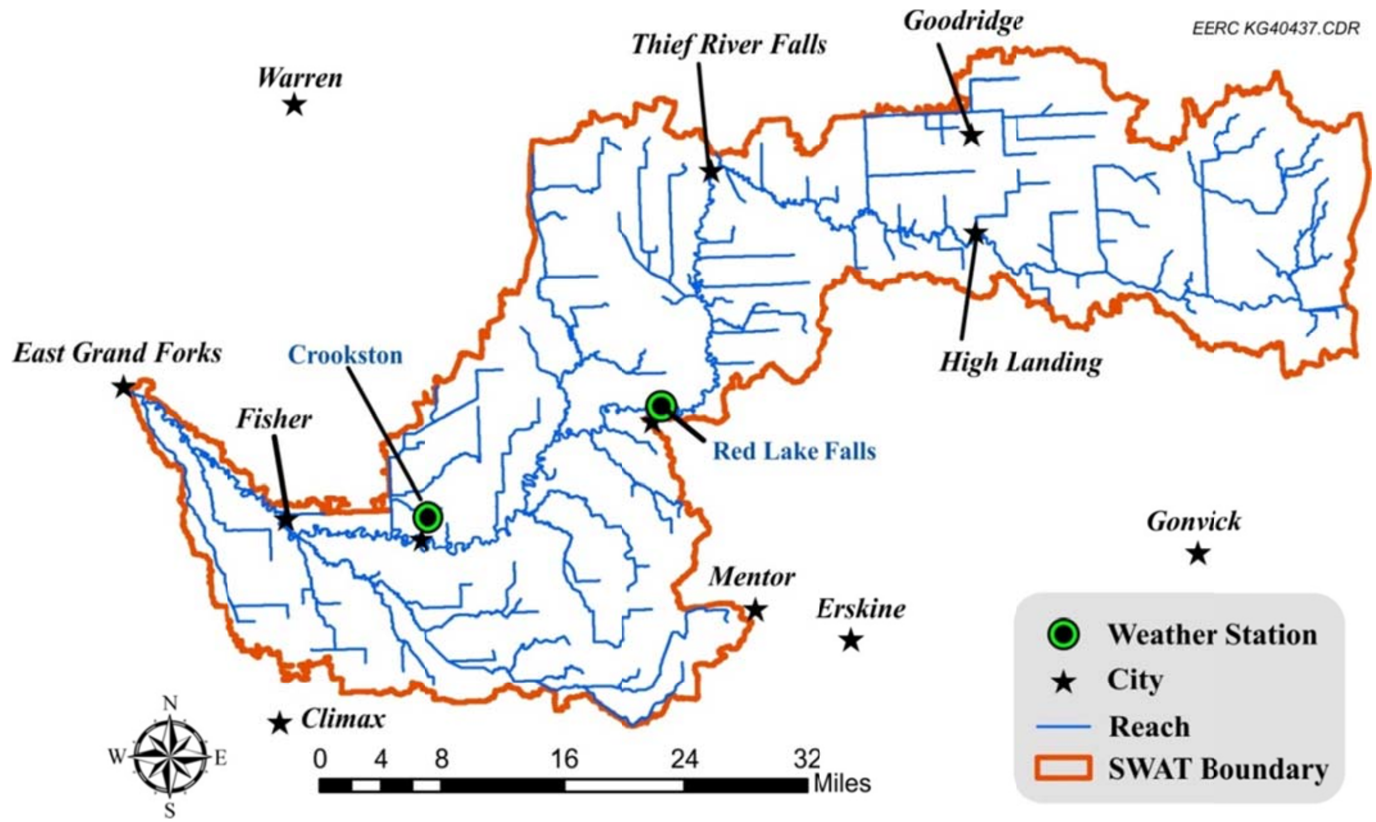

Figure 11. Location of climate stations used to provide temperature and precipitation data to the SWAT model.

Table 3. The Parameters Adjusted to Calibrate the RLRW SWAT Model

Parameter	Default Value	Calibration Value	Description
SFTMP	1	2	Snowfall temperature, °C
SMTMP	0.5	–0.5	Snowmelt base temperature, °C
SMFMX	4.5	7	Melt factor for snow on June 21 (mmH_2O/°C/day)
SMFMN	4.5	2	Melt factor for snow on December 21 (mmH_2O/°C/day)
TIMP	1	0.2	Snowpack temperature lag factor
SNOCOVMX	1	30	Minimum snow water content that corresponds to 100% snow cover (mmH_2O)
SNO50COV	0.5	0.2	Fraction of snow volume represented by SNOCOVMX that corresponds to 50% snow cover
IPET	1	0	Potential evapotranspiration (PET) method: 0 – Priestley–Taylor method; 1 – Penman–Monteith method; 2 – Hargreaves method; 3 – manually input PET values
ESCO	0.95	0.5	Soil evaporation compensation factor
SURLAG	4	1.5	Surface runoff lag coefficient
SPCON	0.0001	0.0009	Linear parameter for calculating the maximum amount of sediment that can be reentrained during channel sediment routing
SPEXP	1	1.5	Exponent parameter for calculating sediment reentrained in channel sediment routing
ALPHA_BF	0.048	0.03	Baseflow alpha factor (days)
GWQMIN	0	100	Threshold depth of water in the shallow aquifer required for return flow to occur (mmH_2O)
GW_REVAP	0.02	0.08	Groundwater reevaporation coefficient
REVAPMN	1	80	Threshold depth of water in the shallow aquifer for reevaporation or percolation to the deep aquifer to occur (mmH_2O)
RCHRG_DP	0.05	0.7	Deep aquifer percolation fraction
CH_K1	0.5	20	Effective hydraulic conductivity in tributary channel alluvium (mm/hr)
CH_N1	0.014	0.04	Manning's "n" value for the subbasin tributary channels
CH_K2	0	2	Effective hydraulic conductivity in main channel alluvium (mm/hr)
CH_N2	0.014	0.04	Manning's "n" value for the main channel in each subbasin
CH_EROD	0	0.001–0.4	Channel erodibility factor
CH_COV	0	0.2	Channel cover factor
OV_N	Varies	0.14 (crops)	Manning's "n" value for overland flow
OV_N	Varies	0.1 (forest)	Manning's "n" value for overland flow
OV_N	Varies	0.15 (range)	Manning's "n" value for overland flow

climate data. Precipitation tends to have high spatial variability, and rainfall within the watershed may be significantly different between rain gauge locations. Having an increased network of rainfall measurements would help generate better results in calibration. There was a gap from 1994 to 1999 in the Red Lakes flow data, which significantly decreased flows during that time period since those flows could not be accounted for in the model.

While visually comparing the predicted versus observed peak shapes, volume, and timing is a good qualitative measure of model performance, a quantitative evaluation using statistics eliminates human subjectivity. Besides visualization, two statistics, the Nash–Sutcliffe efficiency coefficient (NSE) and volume deviation (D_{vj}) were also used to determine model performance in this study. These statistics can be applied for daily, monthly, seasonal, and annual evaluation time steps. In this project, the statistics were computed for the daily time step, which requires greater model accuracy to achieve acceptable statistical parameters.

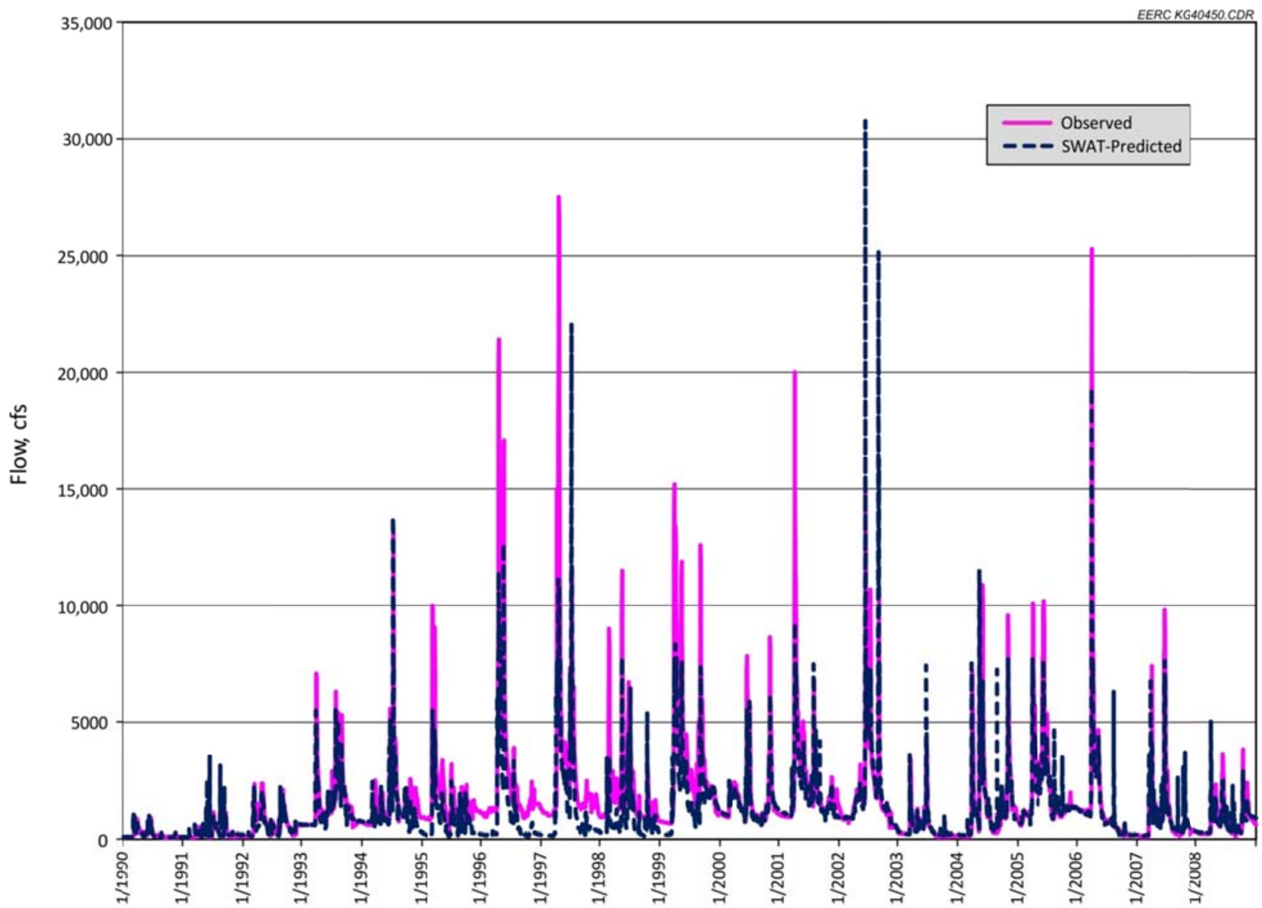

Figure 12. Comparison of the USGS-observed versus model-predicted flow for the calibration period for the Red Lake River at Crookston, Minnesota.

The NSE measures the overall fit of the modeled hydrograph to that of an observed flow hydrograph (Nash and Sutcliffe, 1970). The NSE is computed as:

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n_j} (\mathrm{Q}_{\mathrm{obs}i}^{j} - \mathrm{Q}_{\mathrm{sim}i}^{j})^2}{\sum_{i=1}^{n_j} (\mathrm{Q}_{\mathrm{obs}i}^{j} - \mathrm{Q}_{\mathrm{mean}}^{j})^2}$$

Where $\mathrm{Q}_{\mathrm{sim}i}^{j}$ and $\mathrm{Q}_{\mathrm{obs}i}^{j}$ are the simulated and observed stream flows, respectively, on the *i*th time step for station *j*, and $\mathrm{Q}_{\mathrm{mean}}^{j}$ is the average of $\mathrm{Q}_{\mathrm{obs}i}^{j}$ across the n_j evaluation time steps. The NSE value can range from -∞ to 1.0. A value of 1 indicates that the predicted flows perfectly match measured flows, while negative values indicate that the annual average of the observed flow is more reliable than the model-predicted flow for any given day of the year. While there is no particular value above which a model's performance is considered acceptable, a review of values used within the literature suggests that values above 0.3 to 0.4 for daily-based calibrations generally indicate acceptable model performance (Gassman et al., 2007).

While the Nash–Sutcliffe coefficient is an appropriate indicator of how closely the predicted hydrograph matches the shape of the observed hydrograph, it is not necessarily an appropriate measure for use in evaluating the accuracy of the volume predictions. To test whether the volume of an observed hydrograph is appropriately predicted, a statistical parameter referred to as the deviation in volume is used. This parameter is computed by integrating the flow hydrograph over the evaluation period.

The D_{vj} is a measure of how the predicted annual discharge differs from the measured annual discharge. It is computed as:

$$D_{vj} = \frac{\sum_{i=1}^{n_j} Q^j_{simi} - \sum_{i=1}^{n_j} Q^j_{obsi}}{\sum_{i=1}^{n_j} Q^j_{obsi}} \times 100\%$$

D_{vj} is typically reported in % deviation, with a 0% deviation indicating that the volumes are perfectly matched, a positive deviation indicating that the model underpredicts the flow, and a negative deviation indicating that the model overpredicts the flow.

As seen in Table 4, the NSE values for the calibration period of the RLRW model range from −1.58 to 0.81, with an average of 0.49. The average annual D_{vj} for the calibration period of the RLRW is 22.18%. Calibration gave the best and most accurate results possible. As mentioned previously, improvement in precipitation data would most likely improve model performance. The poor volume deviation results from 1994 to 1999 are a direct result of missing Red Lakes flow data.

4.2.3 Validation

The predicted versus observed flows for the validation period of the RLRW model are shown in Figure 13. SWAT was validated during the years 1984–1989 at the Red Lake River at Crookston, Minnesota (USGS Site 05079000). These dates were utilized based on data availability over the designated years. Other sites were not selected because of lack of data availability.

The model-predicted flows matched well with the observed flows. The timing of peak flows tended to correspond well; however, amplitude of the peaks was a challenge. Dry years tended to be overpredicted, and some of the higher-flow events tended to be underpredicted. The volume deviation values (Table 5) averaged 9.48% over the validation period, which is in an acceptable range. Nash–Sutcliffe values averaged 0.63 over the validation period which is acceptable.

4.3 Sediment Comparison

As previously described, the SWAT model predicts the amount of sediment eroded from the landscape into the waterways of each subbasin, and it also predicts the amount of sediment

Table 4. Statistical Parameters Used to Evaluate the RLRW SWAT Model During the Calibration Period

Year	Measured Annual Q, ft^3/year	SWAT-Predicted Annual Q, ft^3/year	Volume Deviation, %	Nash–Sutcliffe Values
1990	5,911,660,800	5,875,615,208	0.61	0.41
1991	7,850,736,000	10,839,554,714	–38.07	–1.58
1992	19,951,056,000	18,257,986,940	8.49	0.73
1993	46,244,563,200	42,951,332,862	7.12	0.72
1994	46,996,588,800	36,896,451,392	**21.49***	0.61
1995	51,599,721,600	23,701,342,643	**54.07***	0.38
1996	81,800,496,000	39,538,767,943	**51.66***	0.66
1997	92,907,648,000	51,691,660,664	**44.36***	0.52
1998	59,158,339,200	29,393,844,806	**50.31***	0.26
1999	94,604,544,000	63,569,749,484	**32.80***	0.66
2000	52,980,912,000	47,803,837,739	9.77	0.81
2001	73,359,648,000	63,257,683,675	13.77	0.76
2002	63,987,926,400	70,923,958,728	–10.84	0.34
2003	14,901,148,800	14,985,115,251	–0.56	0.46
2004	47,143,468,800	45,146,011,929	4.24	0.77
2005	66,157,344,000	60,375,617,809	8.74	0.81
2006	45,242,236,800	40,547,007,095	10.38	0.69
2007	27,862,272,000	28,467,056,735	–2.17	0.76
2008	24,971,328,000	24,523,058,544	1.80	0.60
Total/Average	923,631,638,400	718,745,654,163	22.18	0.49

***** Because of a gap in the Red Lakes flow data record, the model underpredicts the discharge for these years.

transported within each subbasin reach. The sediment transported within each subbasin reach is reported by SWAT as the amount of sediment into and out of the reach (in metric tons) as well as the sediment concentration. Because the RLRW model was run on a daily time step, these values are reported for every day of the simulation period for each of the 215 stream reaches and can be used for comparison with measured water quality data.

Ten MPCA sites (Table 6) were selected for model sediment calibration because of their location and relatively long data record. The model was calibrated for sediment from January 1, 1994, to December 31, 2008. There was one caveat with using the data from this station for model calibration. The site was sampled for TSS, while the SWAT model predicts suspended sediment. TSS accounts for any physical material entrained in the water column such as sediment, bits of detritus (i.e., leaves, vegetation), and algae, while SWAT is only able to predict sediment. Thus the sediment values predicted by SWAT may be lower than the TSS values, particularly during the later summer months when algae content in the waterways may be elevated.

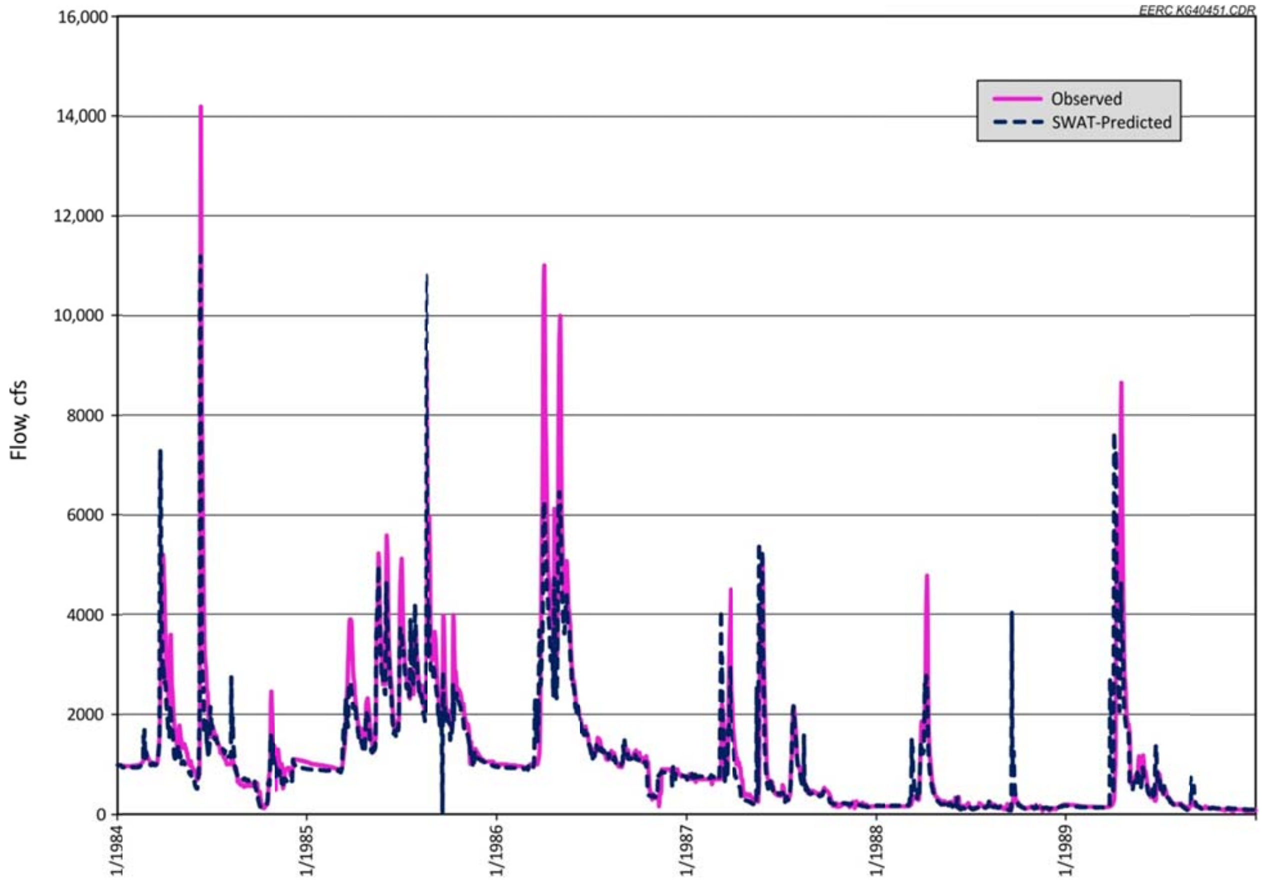

Figure 13. Comparison of the USGS-observed versus model-predicted flow during validation period 1984–1989 for the Red Lake River at Crookston, Minnesota.

Table 5. Statistical Parameters Used to Evaluate the RLRW SWAT Model During the Validation Period

Year	Measured Annual Q, ft^3/year	SWAT-Predicted Annual Q, ft^3/year	Volume Deviation, %	Nash–Sutcliffe Values
1984	43,113,686,400	38,019,901,739	11.81	0.55
1985	68,830,560,000	61,982,993,640	9.95	0.76
1986	57,636,144,000	50,368,549,993	12.61	0.82
1987	23,135,760,000	22,058,643,562	4.66	0.61
1988	9,398,764,800	9,233,827,505	1.75	0.63
1989	16,704,921,600	16,421,620,580	1.70	0.41
Total/Average	218,819,836,800	198,085,537,018	9.48	0.63

Table 6. MPCA Station Identifications and Descriptions Used in Sediment Calibration

Station ID	Station Description
S002-098	Red Lake River at CSAH-220, 3.5 miles east of East Grand Forks
S000-013	Red Lake River downstream of MN-220 bridge in East Grand Forks
S000-031	Red Lake River at bridge on CSAH-15 at Fisher
S003-944	Red Lake River bridge crossing on 420th Ave SE, 27 miles southeast of Thief River Falls
S003-947	Red Lake River Kratka bridge on CSAH-22, 9 miles southeast of Thief River Falls
S002-077	Red Lake River on CSAH-24 bridge, 7 miles south of Goodridge
S002-076	Red Lake River on first bridge in Thief River Falls
S003-942	Red Lake River at St. Hilaire bridge on SCAH-3, 6 miles south of Thief River Falls
S002-080	Red Lake River Sampson bridge in Crookston
S002-132	Black River on CSAH-18 before confluence with Red Lake River, 6 miles west of Red Lake Falls

The suspended sediment concentrations predicted by SWAT versus the measured TSS concentrations for the evaluation locations are shown in Figures 14–24. SWAT values compared well to the measured TSS values consistently throughout the time period. While it is difficult to compare a limited number of sample measurements, the model sediment concentrations matchedwell with the measurements. It is important to keep in mind that because sediment concentrations are highly correlated with stream flow, any inaccuracies in prediction of the peak flow magnitude or timing will also affect sediment concentrations. Thus if the timing of peak flows from a storm event is predicted 3 or 4 days late, the highest sediment concentrations may occur 3 or 4 days later. For this reason, when observed versus measured sediment data are compared, it is acceptable to compare the predicted sediment values from within 3 days before and after the observed date (Raghavan Srinivasan, personal communication, January 2008).

5.0 WATER QUALITY EVALUATION AND IMPLEMENTATION OF HYPOTHETICAL BMPs

The following section describes the predicted distribution of sediment loading within the watershed and presents the results of the BMP scenarios. For reporting purposes, the impacts of the various BMP implementation scenarios were assessed at the outlet of the RLRW (Subbasin 131); however, the data generated by the project allow for evaluation of the results within any subbasin or subbasin reach.

5.1 Sediment Erosion and Loading Results

The predicted average annual sediment erosion from the subbasins and the predicted sediment output, or loading, from the respective stream reaches within the RLRW are shown in Figures 25 and 26. It is important to note that the subbasins with the highest overland sediment-erosion rates do not necessarily contain stream reaches with the highest sediment-loading rates. This indicates that not all of the sediment that is eroded from the landscape and into the subbasin

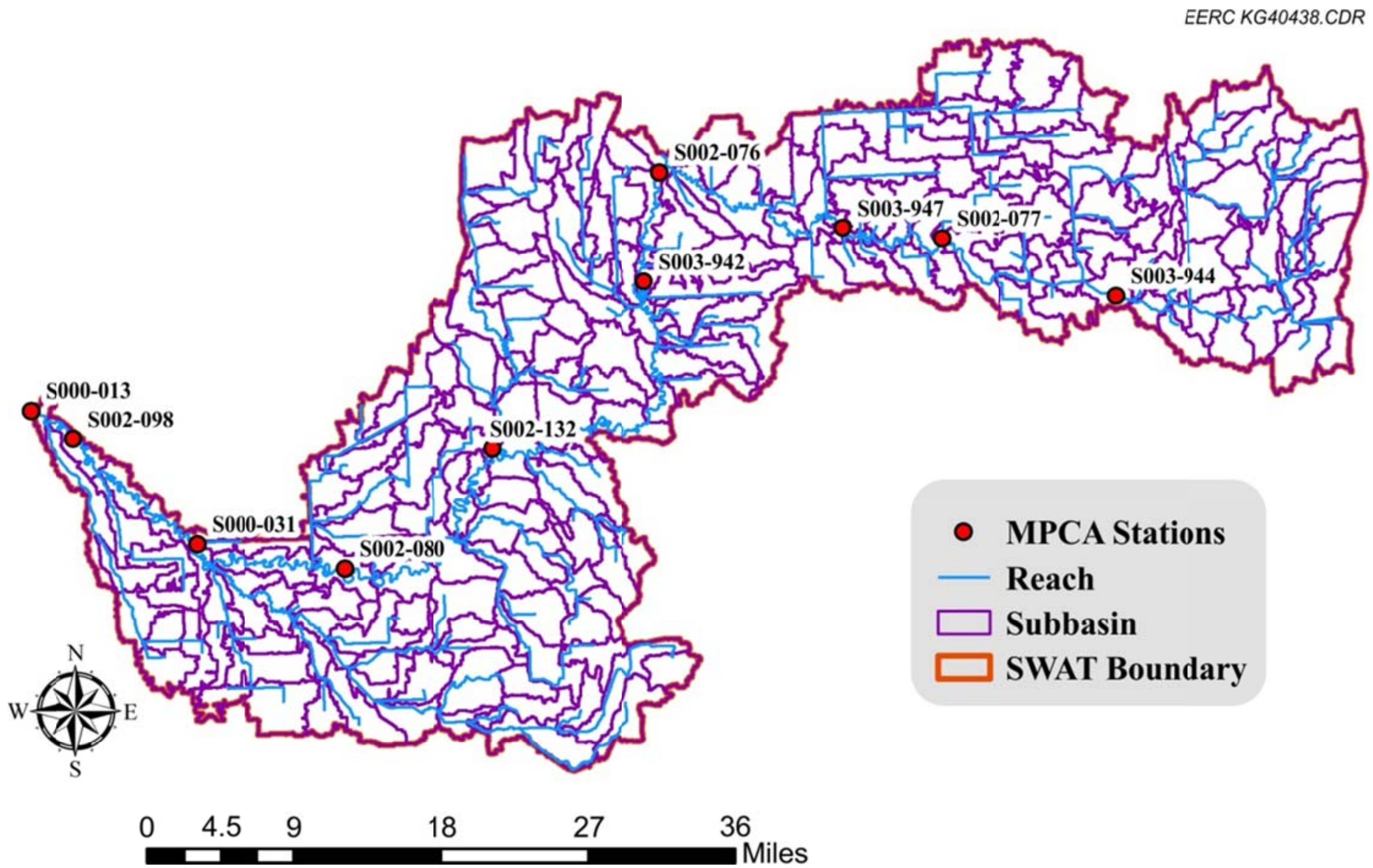

Figure 14. MPCA water quality-sampling site locations utilized for sediment calibration.

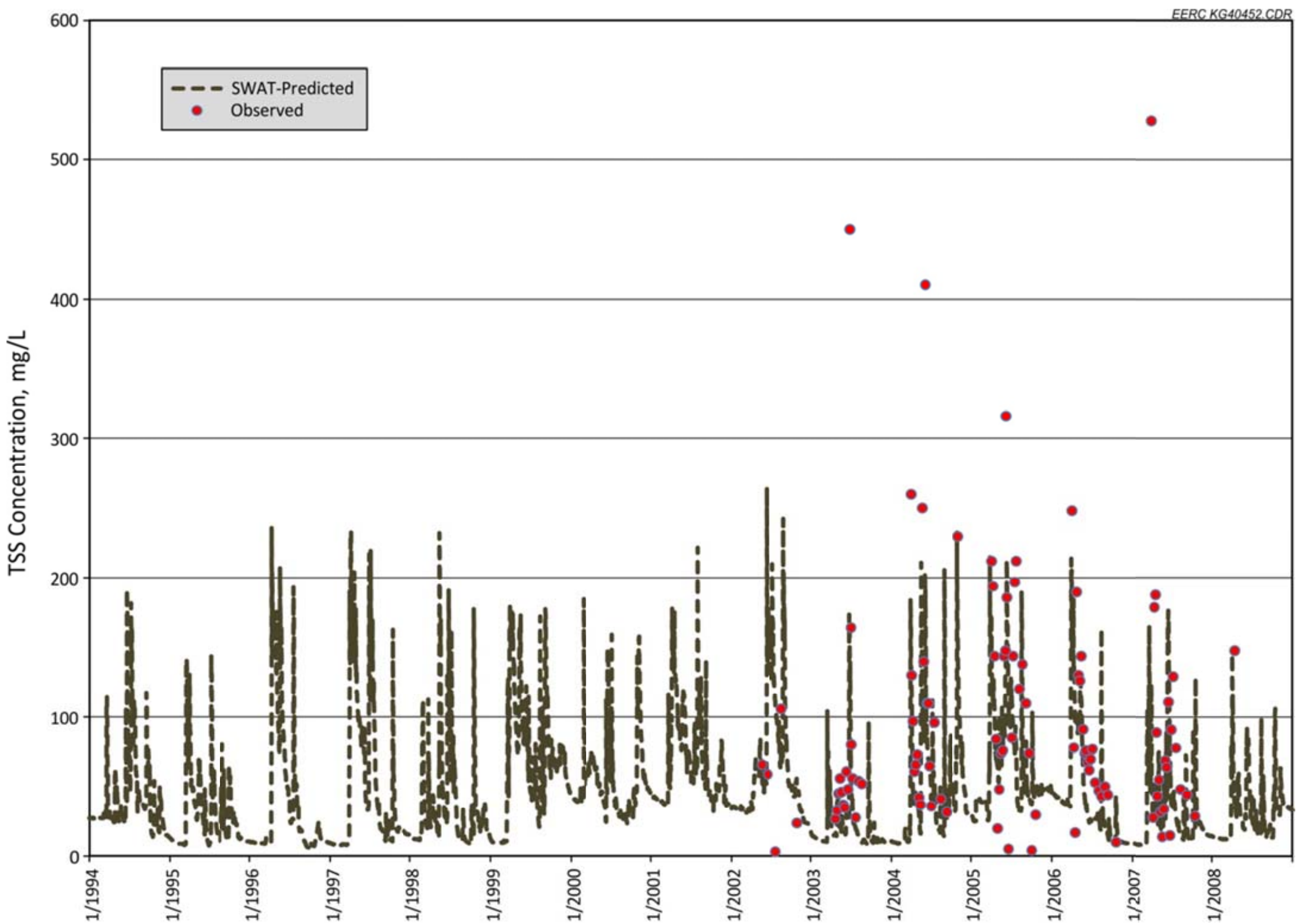

Figure 15. Comparison of observed versus SWAT-predicted sediment concentrations at the Red Lake River at CSAH-220, 3.5 miles east of East Grand Forks (S002-098).

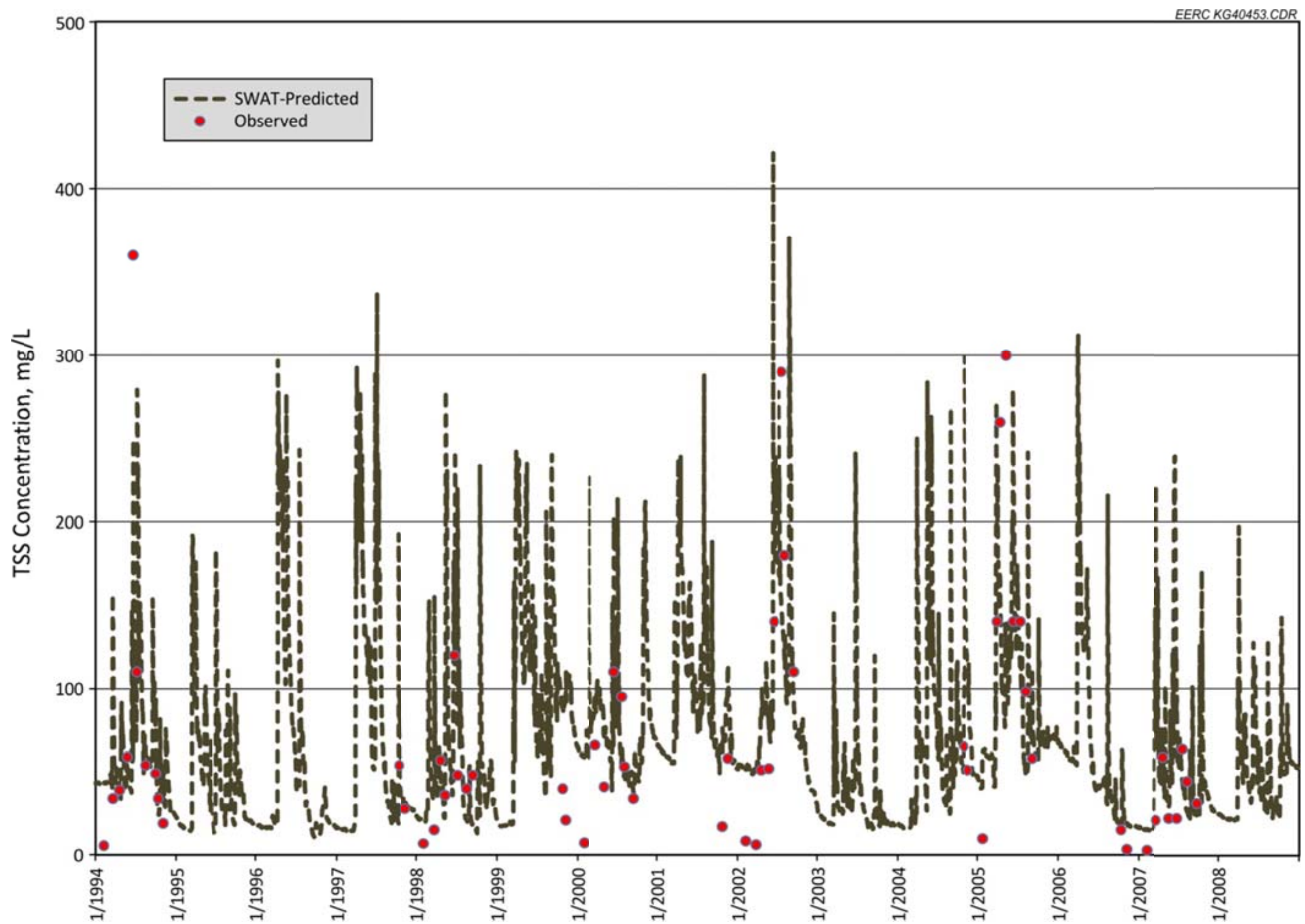

Figure 16. Comparison of observed versus SWAT-predicted sediment concentrations at the Red Lake River downstream of MN-220 bridge in East Grand Forks (S000-013).

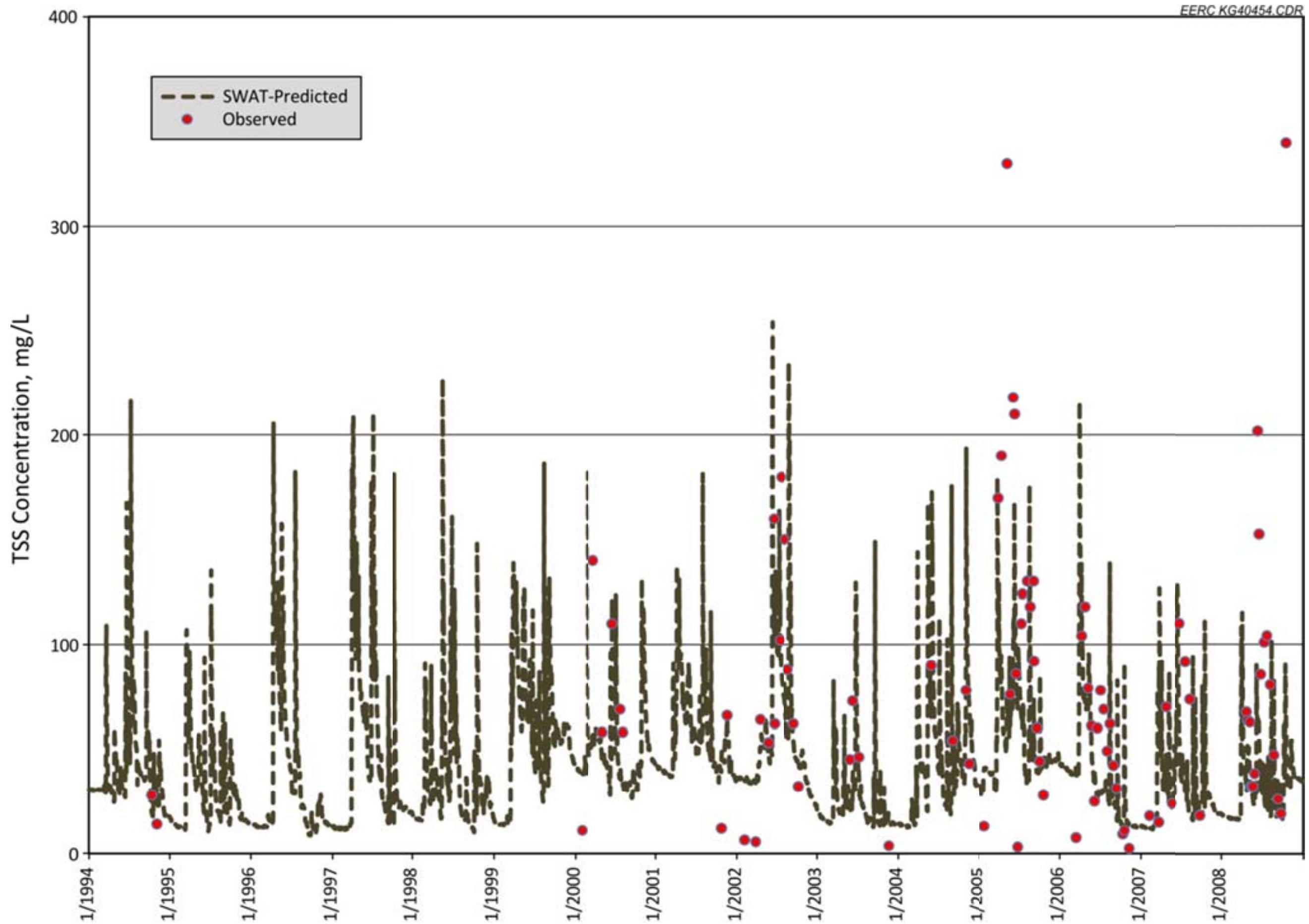

Figure 17. Comparison of observed versus SWAT-predicted sediment concentrations at Red Lake River at bridge on CSAH-15 at Fisher (S000-031).

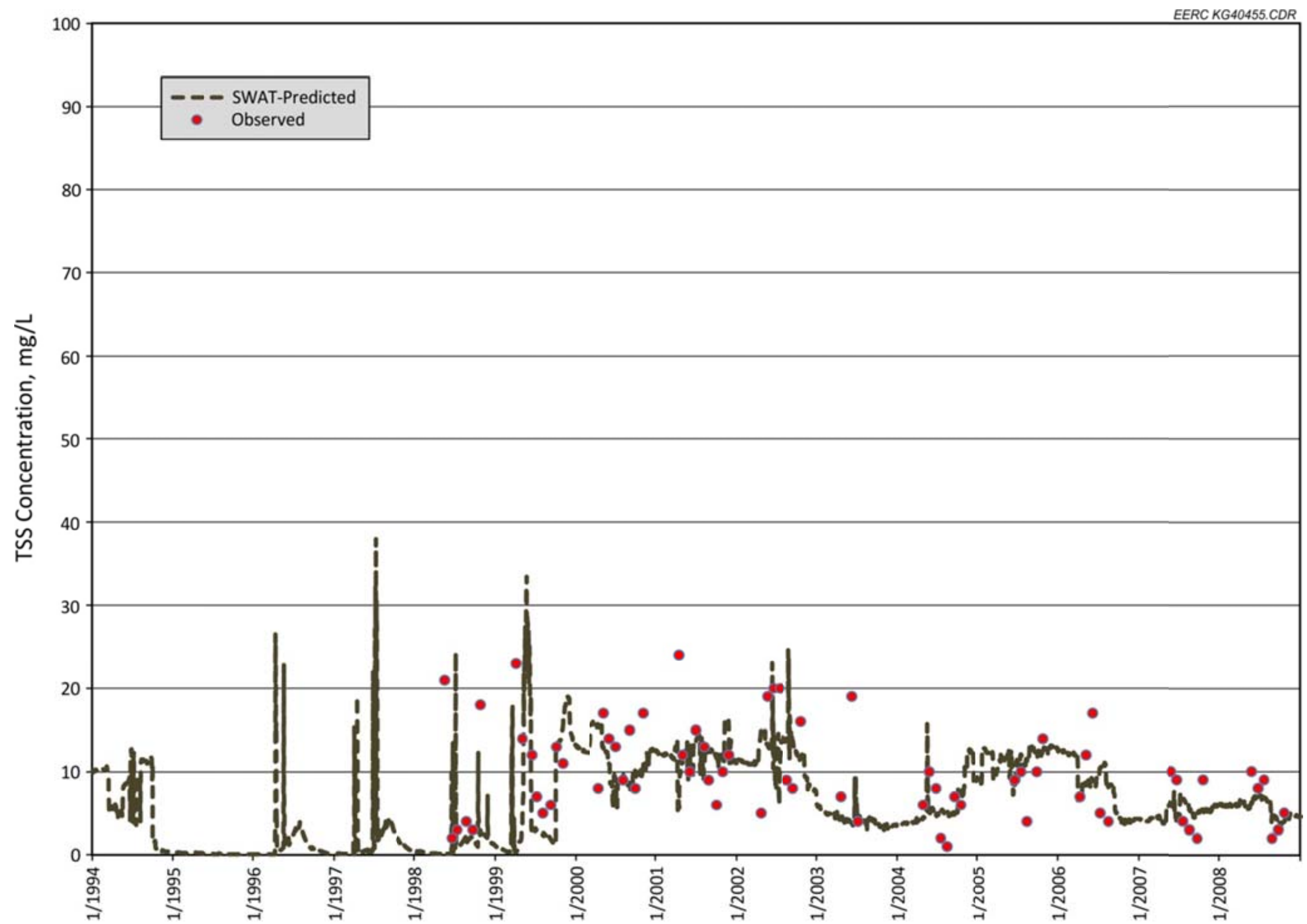

Figure 18. Comparison of observed versus SWAT-predicted sediment concentrations at Red Lake River bridge crossing on 420th Avenue SE, 27 miles southeast of Thief River Falls (S003-944).

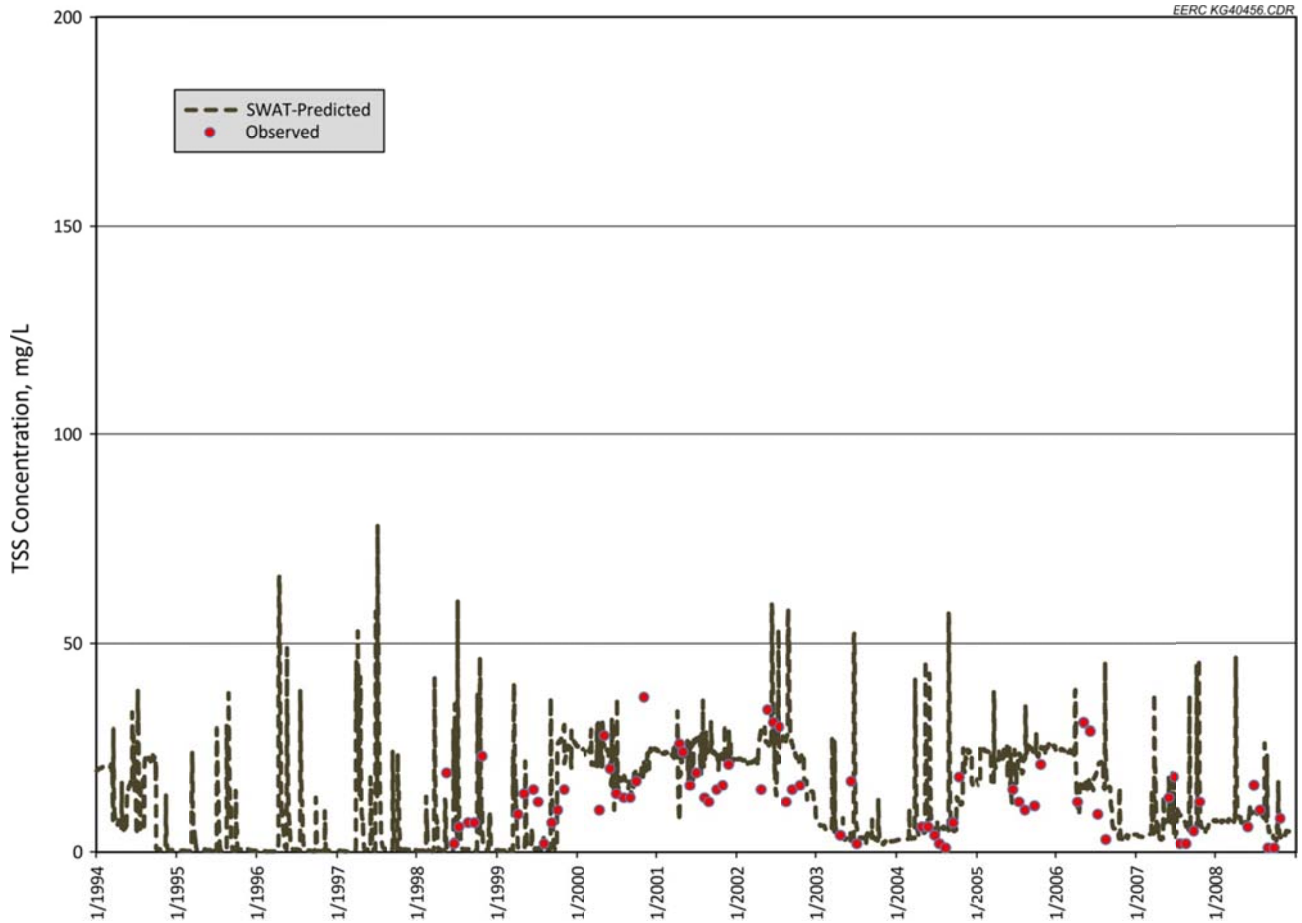

Figure 19. Comparison of observed versus SWAT-predicted sediment concentrations at Red Lake River Kratka bridge on CSAH-22, 9 miles SE of Thief River Falls (S003-947).

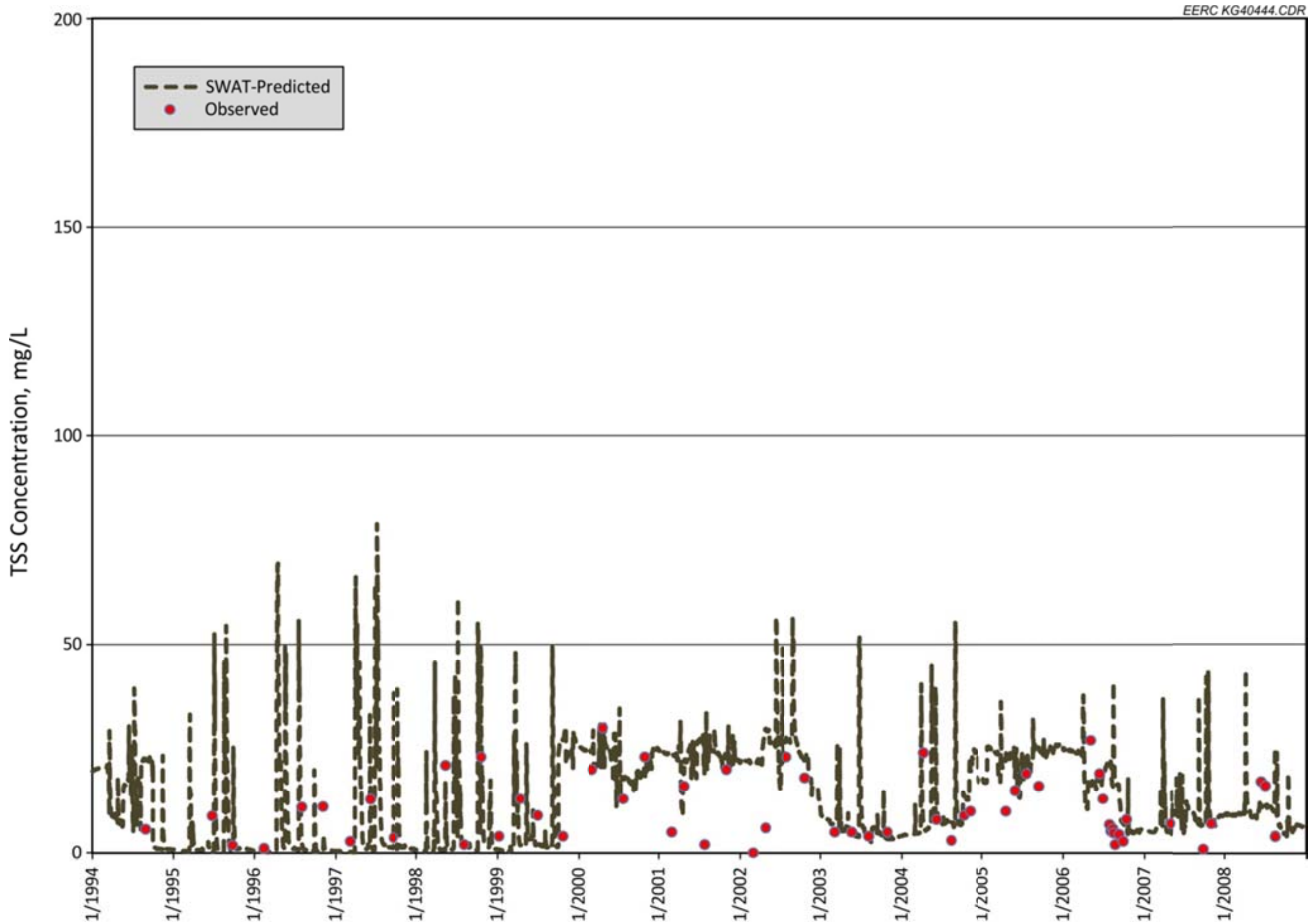

Figure 20. Comparison of observed versus SWAT-predicted sediment concentrations at Red Lake River on CSAH-24 bridge, 7 miles south of Goodridge (S002-077).

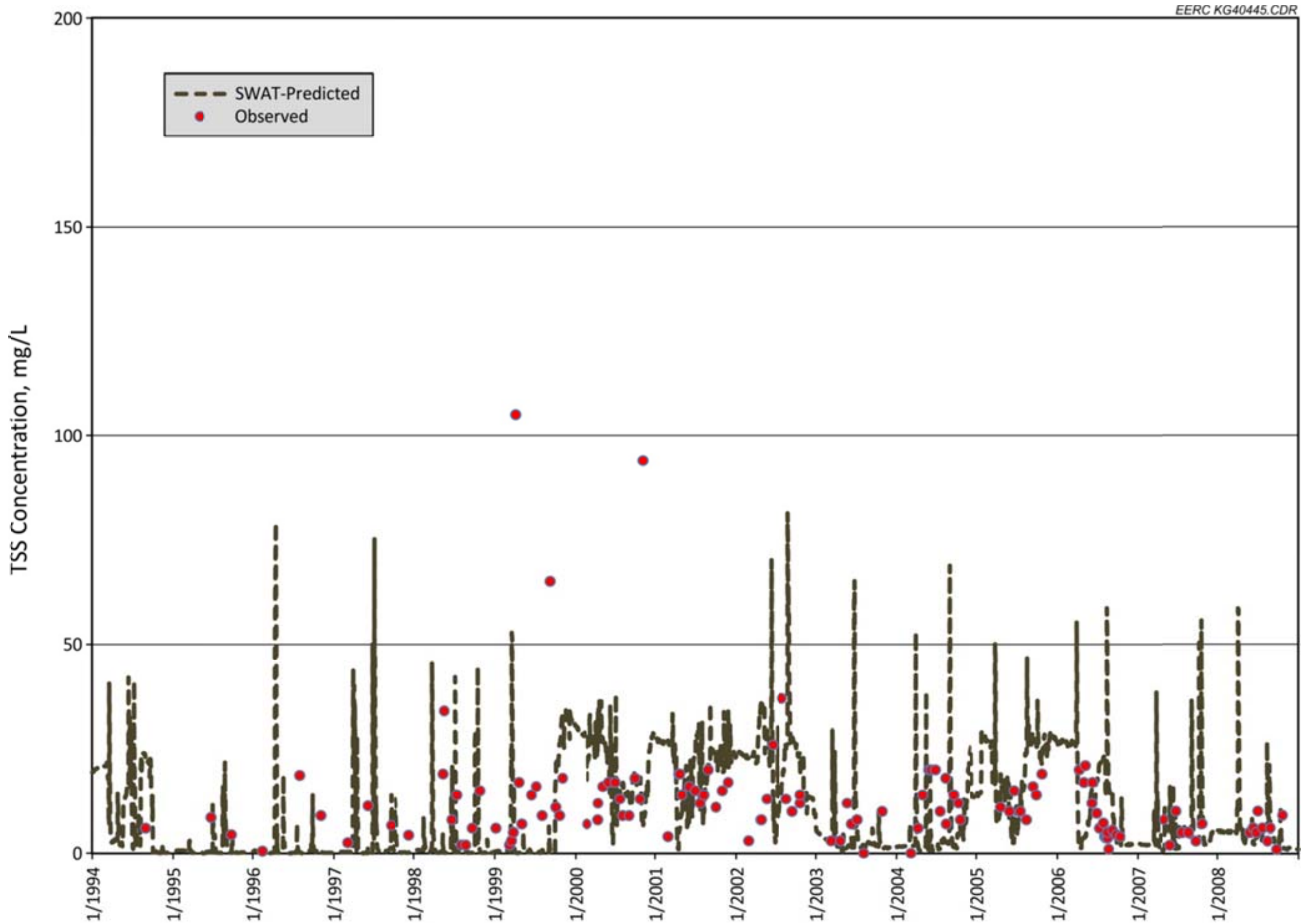

Figure 21. Comparison of observed versus SWAT-predicted sediment concentrations at Red Lake River on 1st bridge in Thief River Falls (S002-076).

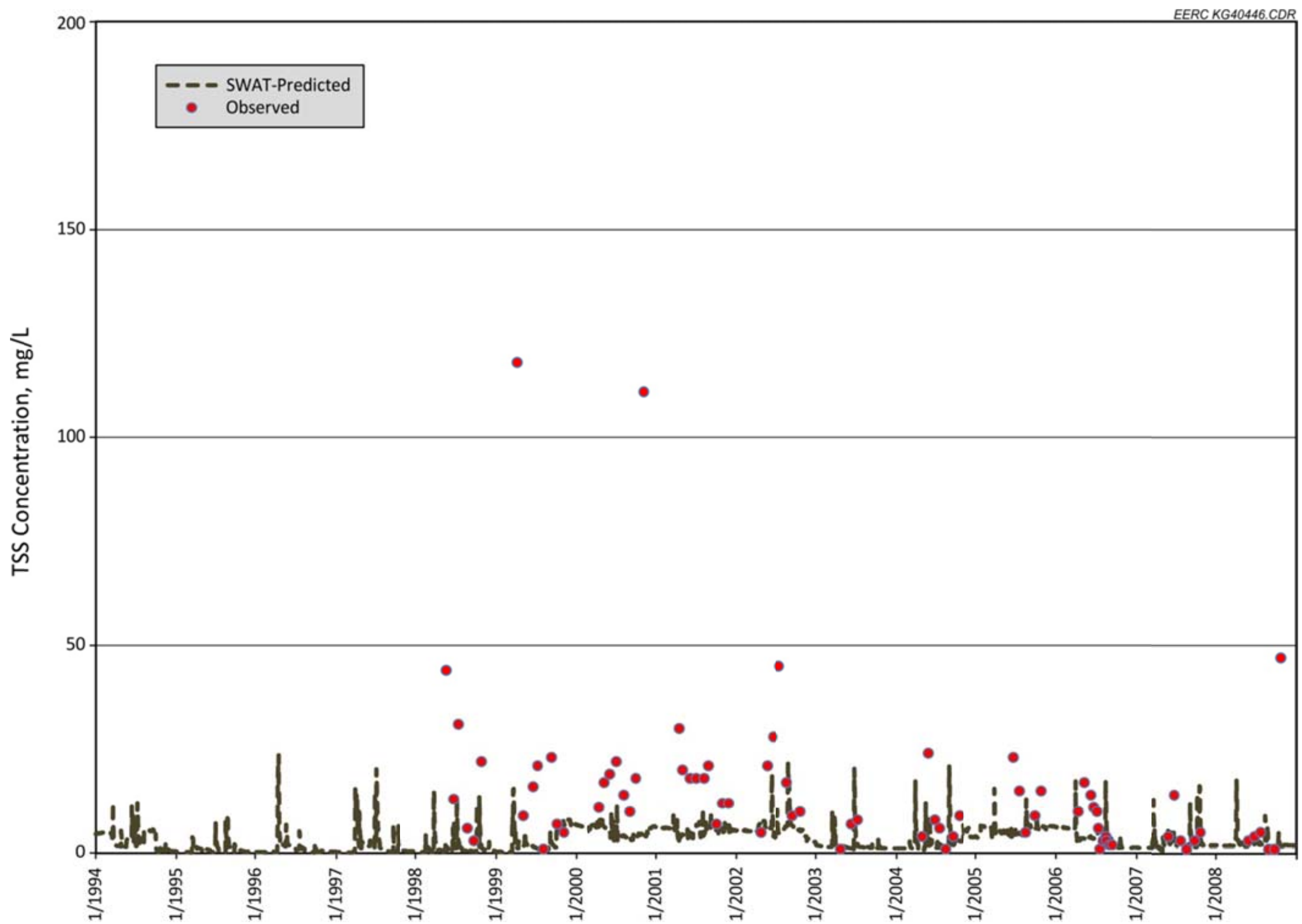

Figure 22. Comparison of observed versus SWAT-predicted sediment concentrations at Red Lake River at St. Hilaire bridge on CSAH-3, 6 miles south of Thief River Falls (S003-942).

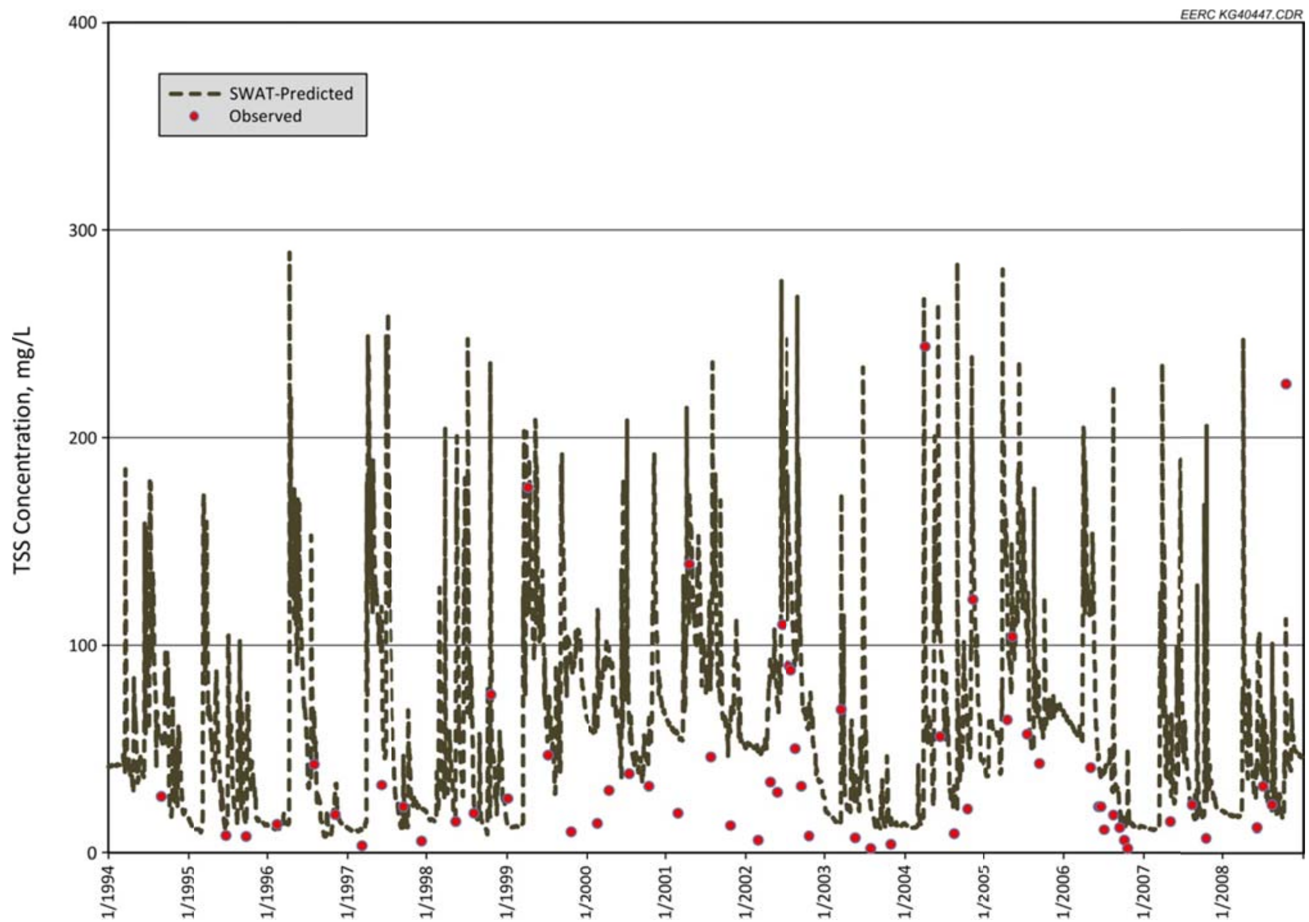

Figure 23. Comparison of observed versus SWAT-predicted sediment concentrations at Red Lake River Sampson Bridge in Crookston (S002-080).

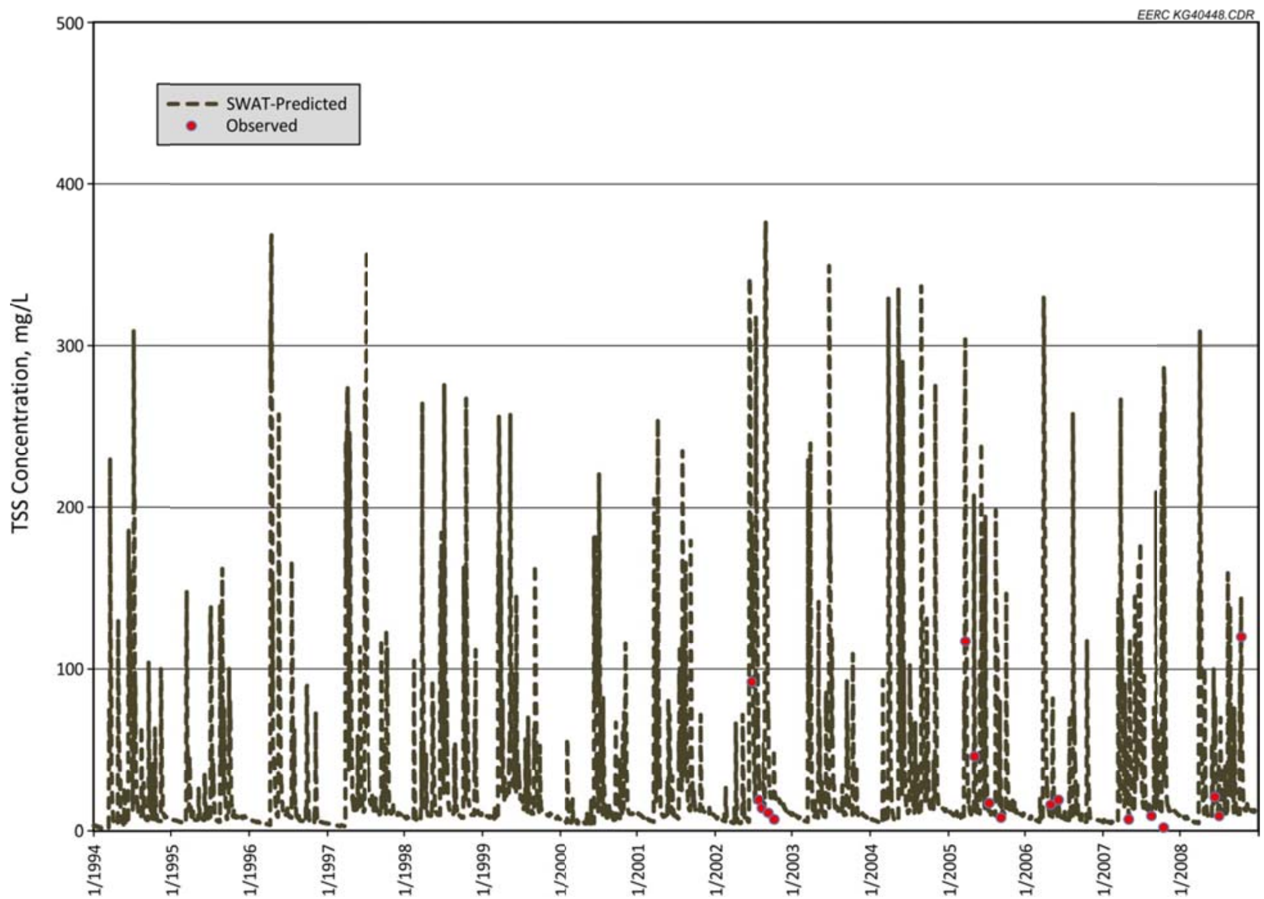

Figure 24. Comparison of observed versus SWAT-predicted sediment concentrations at the Black River on CSAH-18 before the confluence with Red Lake River, 6 miles west of Red Lake Falls (S002-132).

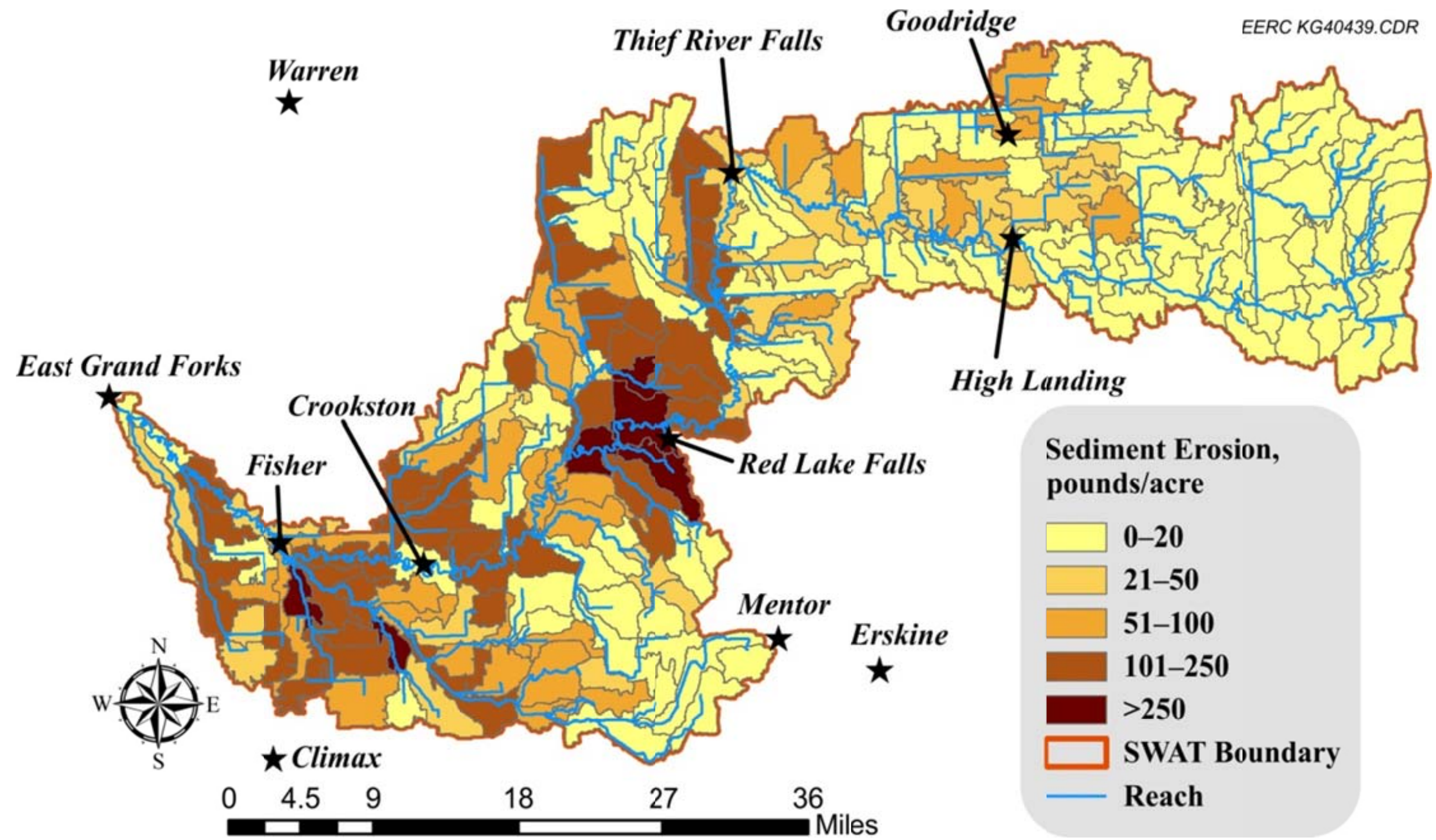

Figure 25. Average annual sediment erosion from the landscape of each subbasin within the RLRW.

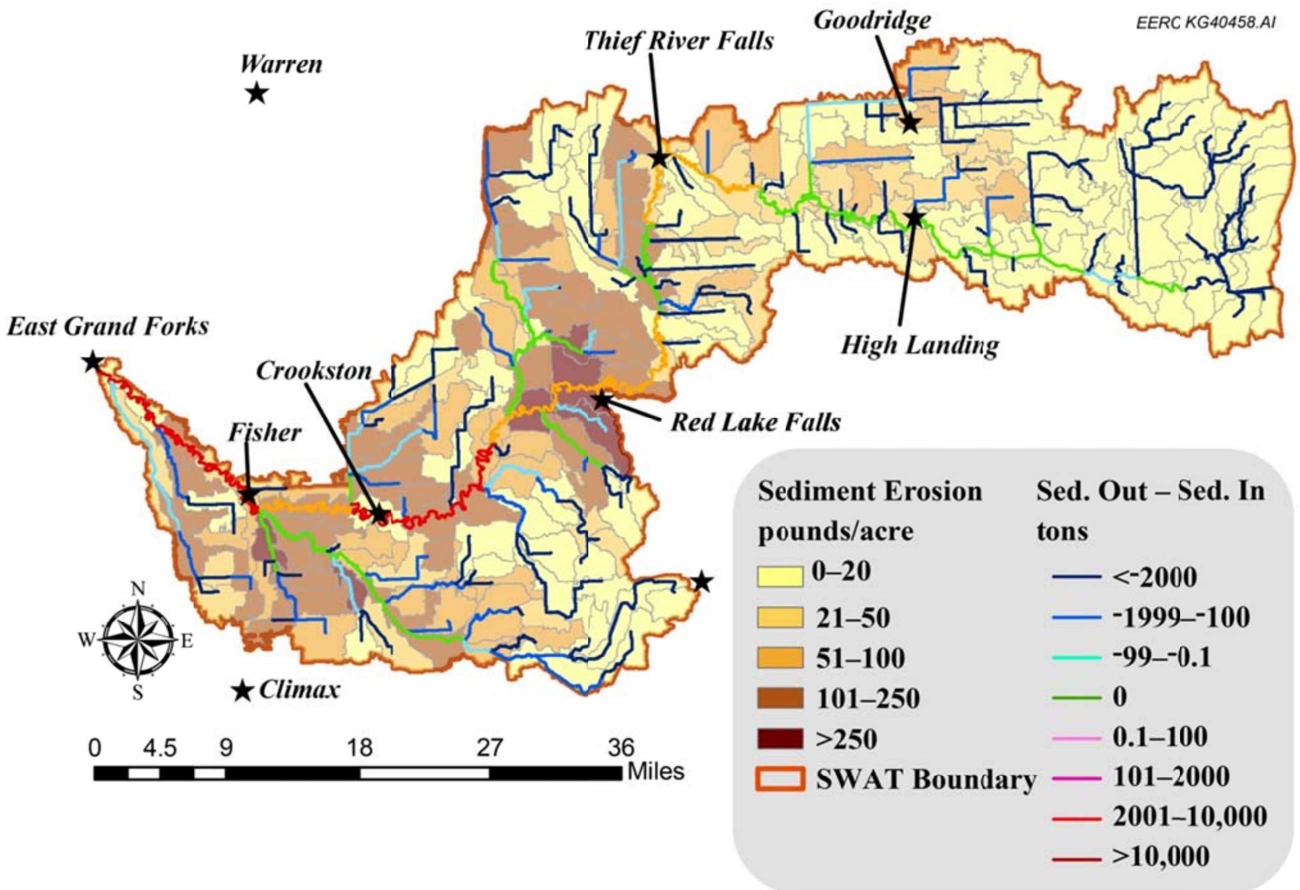

Figure 26. The estimated average annual sediment erosion from the landscape of each subbasin and the estimated average annual sediment loading within each reach of the RLRW.

reaches is transported out of the subbasin. Figure 27 shows the predicted annual net sediment output within each of the subbasin reaches. This was calculated by subtracting the overland sediment erosion and upstream inputs within each subbasin from the total estimated sediment being transported out of the subbasin reach. Negative values indicate that less sediment is leaving the stream reach than is coming in, indicating sediment deposition within the stream reach. Positive values indicate that, on average, more sediment is leaving a particular stream reach than is coming in from upstream loading or from overland erosion within the subbasin.

This suggests that stream bank and/or bed erosion is occurring within the reach. Because sediment transport or deposition within the stream reaches is controlled by flow volume and velocity, during major flood events much of the deposited sediment can be transported out of the stream reaches and eventually out of the watershed.

The highest sediment loading and overland sediment erosion areas are located primarily in the western half of the watershed, roughly downstream from the Thief River Falls area. When the land use for the RLRW is examined, the high overland sediment erosion areas fall within the agricultural and range areas of the watershed. The lower sediment areas are primarily wetlands, water, and forest. In addition to overland erosion contributions, in-stream erosion also appears to be contributing significantly to sediment loading. In-stream erosion incorporates sediment from stream banks and/or stream beds. The SWAT model indicates that the Red Lake River is alternating between erosion and deposition within the stream reaches. This makes sense since a stream can only carry a certain amount of sediment depending on its volume and velocity, so the Red Lake River has to deposit sediment at times, and when a certain threshold is reached, the stream will again be able to erode sediment and carry more of a load. An alternating pattern of deposition and erosion is indicative of this process. In addition to spatial variation, sediment transport varies temporally. Those years and/or months with increased discharge will also have increased sediment transport. For example, as shown in Figure 28, the highest quantities of sediment loading occur during the higher-flow months, such as March, April, May, and June.

5.2 BMP Implementation Evaluation

To evaluate how improvements in sediment loading might be achieved within some of the reaches of the RLRW, a hypothetical evaluation of field buffer strip implementation was evaluated. Field buffers typically range in width from 30 to 120 feet (Natural Resources Conservation Service, personal communication, 2008); therefore, field buffers were implemented to agricultural fields at widths of 50, 80, and 120 feet. For each width, three different scenarios were evaluated by assuming a 25%, 50%, and 75% implementation rate. Subbasins were randomly selected for implementation of field buffer strips. For reporting purposes (Table 7), the effectiveness of buffer strips was evaluated at the outlet of the RLRW (Subbasin 131), although any stream reach could be evaluated if desired.

While the buffer strips were extremely effective (>80% reduction) at limiting sediment erosion coming off the landscape (Figures 29–31), sediment levels in the Red Lake River were not significantly reduced at the outlet (Table 7). This indicates that a significant amount of the sediment is eroding from within stream channel itself. In an effort to reduce sediment loads, two additional BMPs were implemented: grassed waterways and stream bank stabilization. Grassed waterways were implemented in tributary subbasins. The locations were selected based on

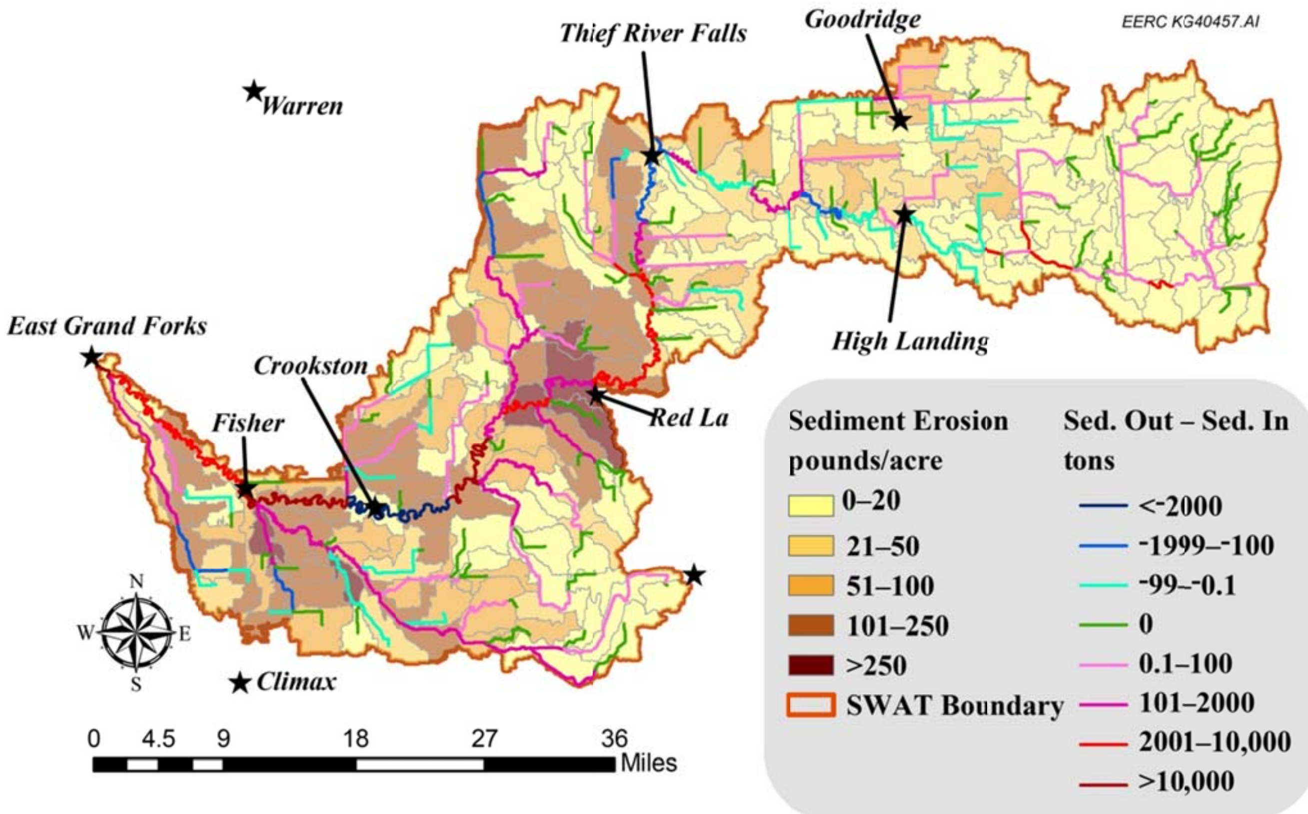

Figure 27. The estimated average annual sediment erosion from each subbasin and the average annual net sediment deposition (output minus input) within the waterways of the RLRW.

Table 7. The Effectiveness of the BMP Implementation Scenarios as Measured at the Red Lake River Watershed Outlet

BMP Scenario	Sediment Concentration Reduction, %	Sediment Loading Reduction, %
Buffer 50 ft – 25% Implementation	0.24	0.35
Buffer 50 ft – 50% Implementation	0.57	0.83
Buffer 50 ft – 75% Implementation	1.06	1.51
Buffer 80 ft – 25% Implementation	0.27	0.40
Buffer 80 ft – 50% Implementation	0.66	0.96
Buffer 80 ft – 75% Implementation	1.26	1.81
Buffer 120 ft – 25% Implementation	0.29	0.43
Buffer 120 ft – 50% Implementation	0.70	1.02
Buffer 120 ft – 75% Implementation	1.34	1.94
Grassed Waterway (20 reaches)	–0.01	0.76
Grassed Waterway (39 reaches)	0.02	1.29
Stream Bank Stabilization (14 sites)	0.52	0.71
Stream Bank Stabilization (21 sites)	20.9	17.2
Stream Bank Stabilization (27 sites)	21.4	17.8
Combined BMPs	22.9	21.2

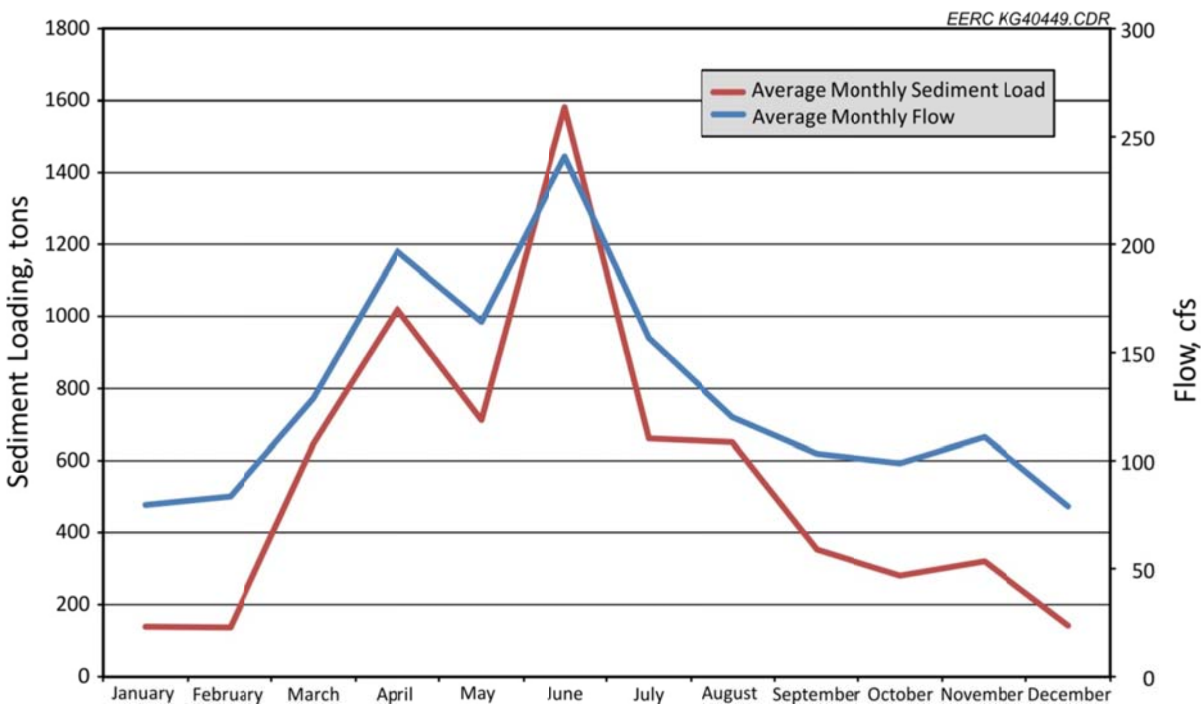

Figure 28. Average monthly flow and sediment loading for all subbasin reaches within the RLRW.

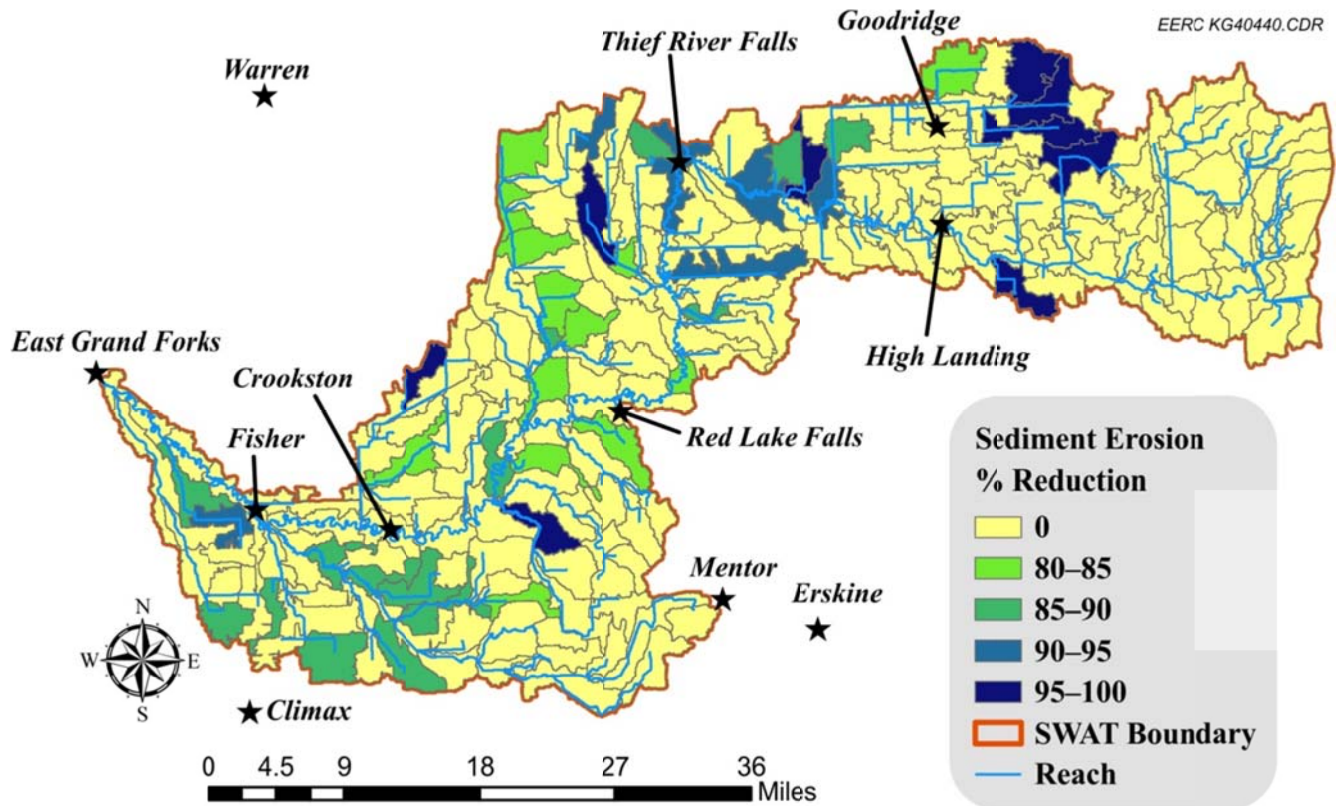

Figure 29. Predicted overland sediment erosion reductions for 50-foot field buffer strip BMP implementation on 25% of crop fields.

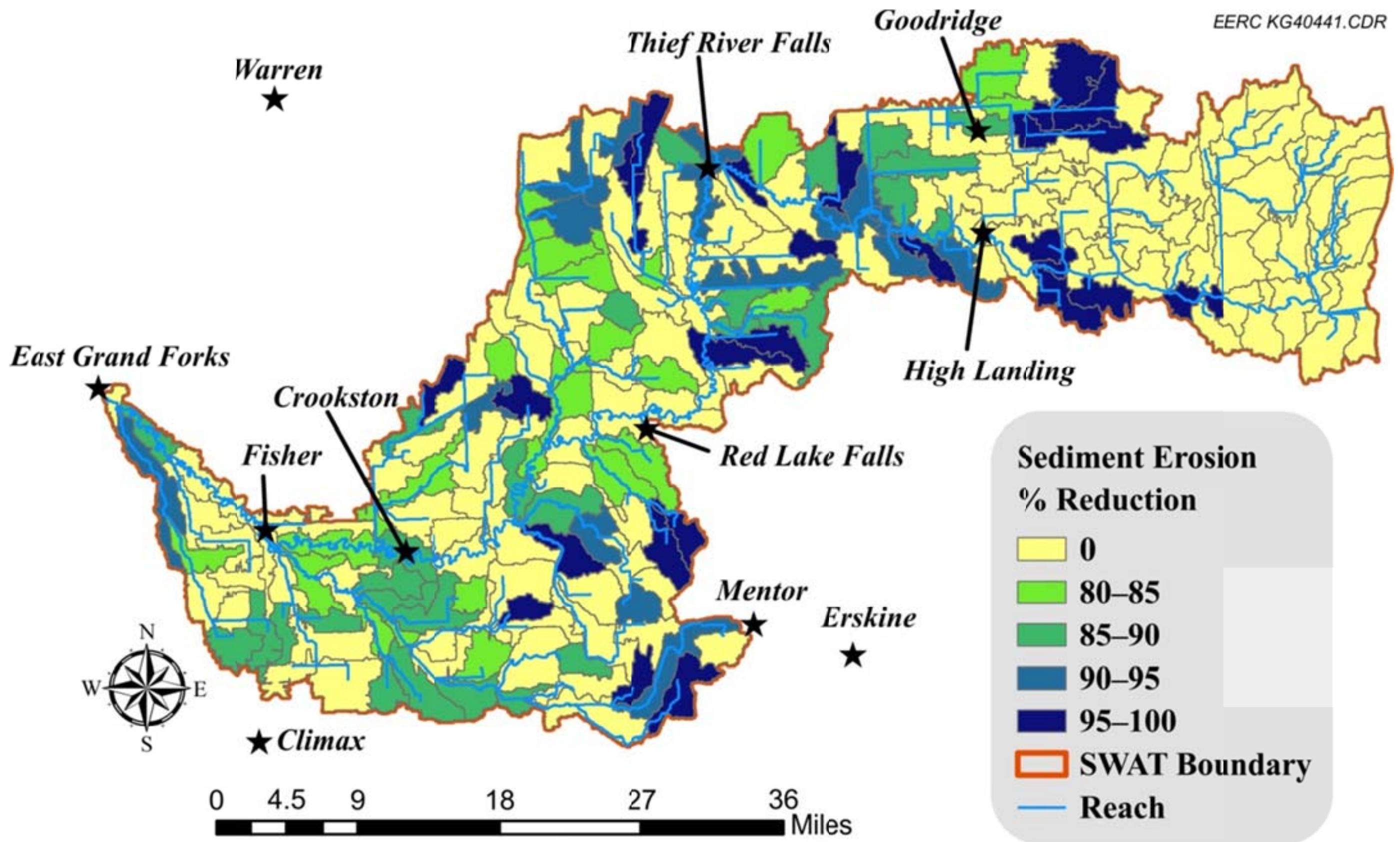

Figure 30. Predicted overland sediment erosion reductions for 50-foot field buffer strip BMP implementation on 50% of crop fields.

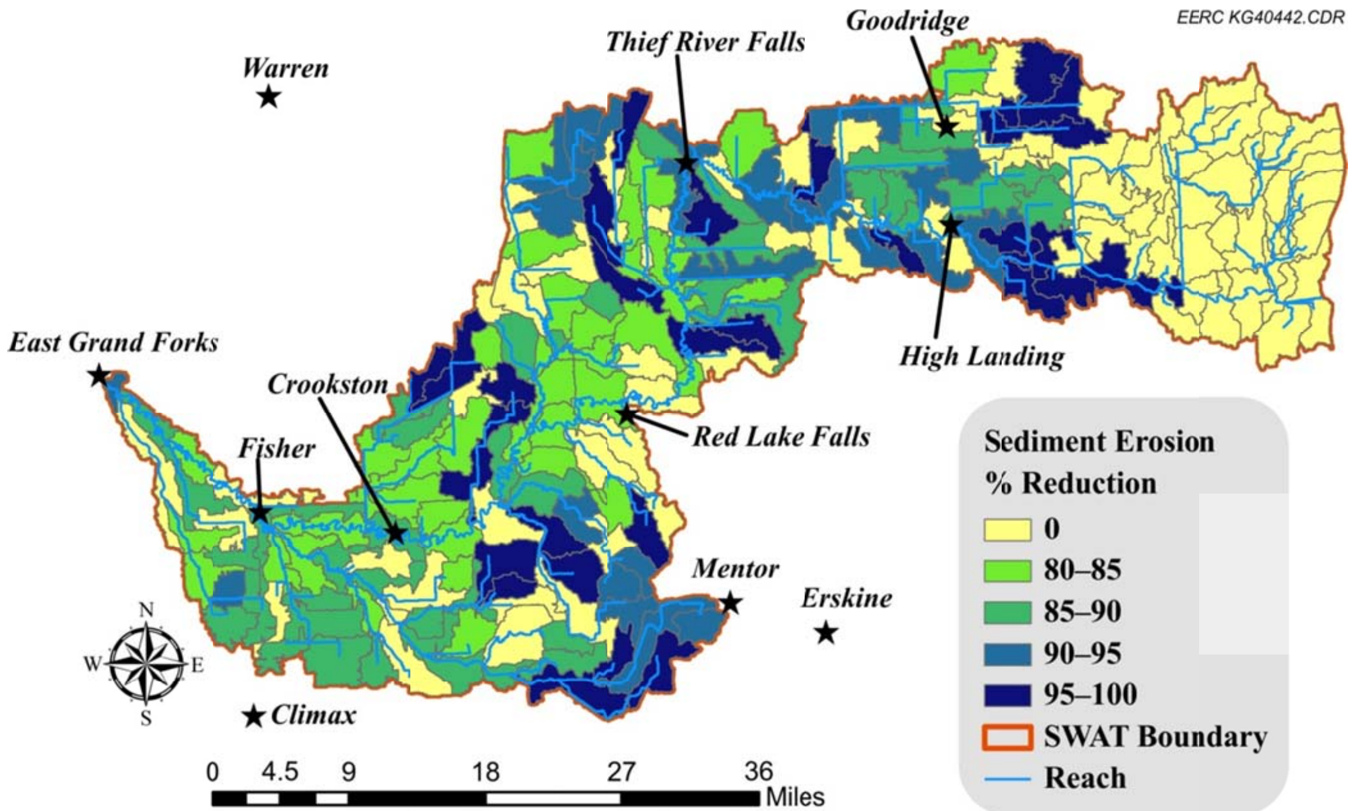

Figure 31. Predicted overland sediment erosion reductions for 50-foot field buffer strip BMP implementation on 75% of crop fields.

subbasins where SWAT indicated a positive net sediment value (indicating more sediment is leaving the subbasin, thus eroding). These locations were separated based on the net amount of sediment leaving a subbasin. This was done in order to be able to randomly select small streams instead of main stem streams for grass waterways and stream bank stabilization. One additional scenario was evaluated that combined the 50-foot buffer/75% implementation, grassed waterways on 39 reaches, and the stream bank stabilization at 27 sites (referred to as combined BMP).

In order to significantly reduce sediment load at the watershed outlet, SWAT indicated that stream bank stabilization would need to be completed on larger tributaries and Red Lake River locations. The grassed waterways had minimal impact on reducing sediment at the watershed outlet. Stream bank stabilization implemented on the larger tributaries or Red Lake River did have reductions of sediment load of about 17% and sediment concentration of about 21%. The combined BMP scenario yielded similar results of 21% sediment load reduction and 23% sediment concentration reduction. When evaluating the BMP scenarios, they all had good sediment reductions in the upstream portions of the watershed. As seen in Figure 32, sediment reductions can be significant in most parts of the watershed when combining the three BMPs.

6.0 CONCLUSIONS

Through this project, a water quality model of the RLRW was developed and calibrated using the best available data. The model was calibrated for flow from January 1990 to December 2008. An evaluation of efficiency statistics for the calibration period of the model indicate that the predicted versus measured discharge match well enough for evaluation of BMP implementation. Additional climate data from more sites within the watershed is needed to improve the model calibration and performance. The model was calibrated for sediment from January 1994 to December 2008. The limited number of measured TSS values appeared to compare well with the SWAT values throughout the watershed.

The model results indicate that the highest sediment erosion occurs primarily in the agricultural and range areas of the RLRW. Sediment-reducing BMPs should be targeted for these agricultural areas. An evaluation of net sediment loading indicates that the RLRW reaches are characterized both by net sediment deposition and net channel erosion from the streambed and/or banks. The predicted overland erosion rates ranged from 0 to 400 pounds/acre/year.

An evaluation of field buffer implementation for agricultural fields in select subbasins revealed that significant reductions in overland sediment erosion are possible. Implementing buffers around the fields in a subbasin could yield sediment erosion reductions greater than 90%. Even buffers applied only to a portion of the fields within a subbasin could yield large reductions. These values are comparable to the sediment retention percentages reported in the literature (Grismer et al., 2006; U.S. Environmental Protection Agency, 1993). However, the model results indicated minimal reductions between 0.23% and 1.34% in sediment concentration and 0.34% and 1.94% in sediment load at the RLRW outlet could be achieved through random implementation of field buffer strips. Therefore, grassed waterways and stream bank restoration scenarios were implemented to attempt to reduce sediment in the Red Lake River. While grassed

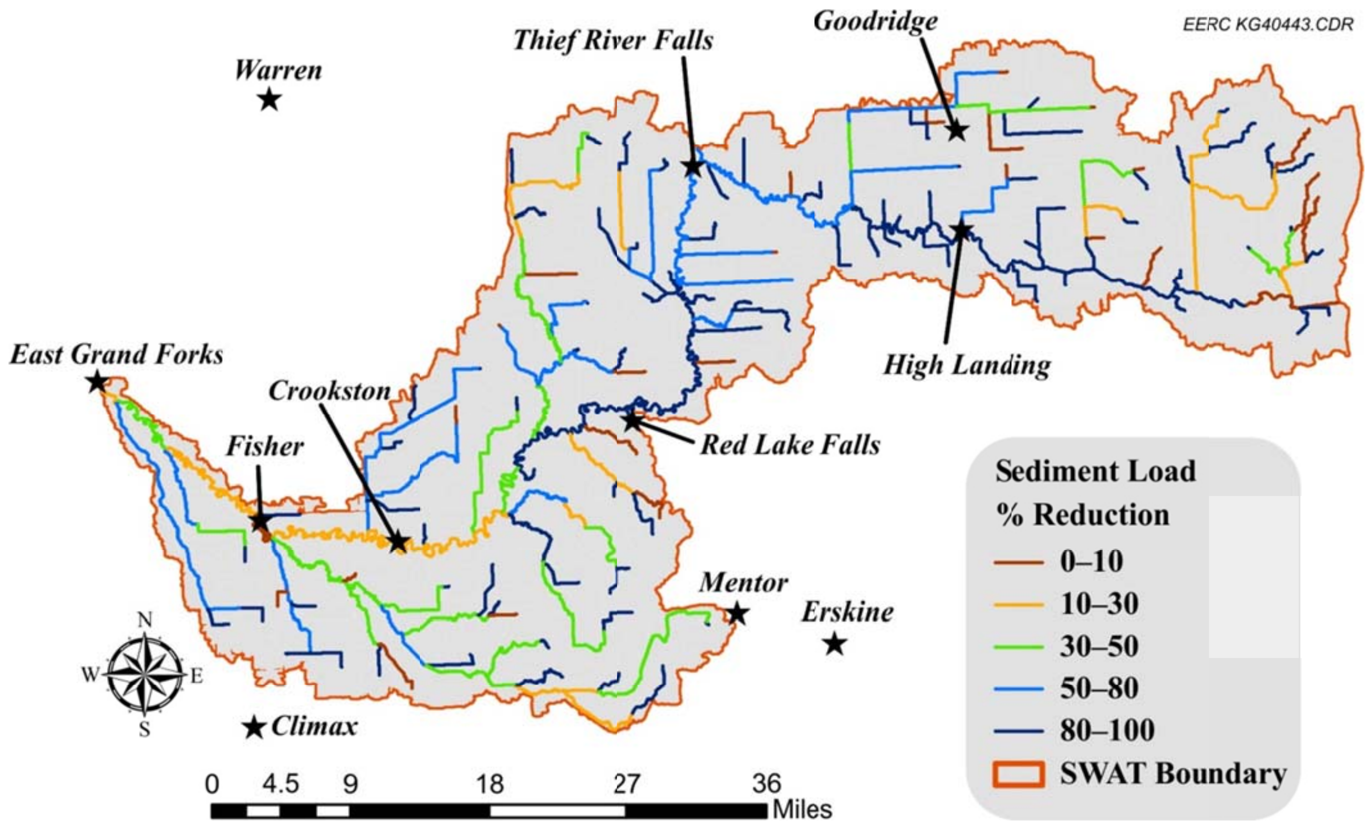

Figure 32. Predicted annual average sediment load reduction for combined BMP scenario.

waterways had minimal impact on sediment concentrations, stream bank stabilization on larger tributaries or the Red Lake River itself could yield reductions in sediment concentration up to 21.4% and reductions in sediment load up to 17.8%. A combined BMP scenario with buffer strips, grassed waterway, and stream bank stabilization could yield reductions in sediment concentration of 22.9% and reductions in sediment load of 21.2%.

The work described here and the models developed through this project will hopefully serve as a base upon which future research and implementation efforts can build. Many more scenarios can be evaluated using these models, especially as target BMPs are identified as a function of implementation likelihood and/or as new federal programs and policies arise to support BMP implementation. In addition, the accuracy of these models can be improved as new data become available and as updates are made to the model programming.

7.0 REFERENCES

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