May 11, 2009

Mr. Corey Hanson
Water Quality Coordinator
Red Lake Watershed District
102 North Main Avenue
PO Box 803
Thief River Falls, MN 56701

Dear Mr. Hanson:

Subject: EERC Final Report Entitled "Development of the Soil and Water Assessment Tool (SWAT) to Assess Water Quality in the Clearwater River Watershed"
EERC Fund 9698

Please find enclosed the subject report. 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 A. Kurz
Senior Research Manager

BAK/jre

Enclosure

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

Final Report

(for the period October 9, 2007, through April 30, 2009)

Prepared for:

Corey Hanson
Red Lake Watershed District
102 North Main Avenue
PO Box 803
Thief River Falls, MN 56701

Prepared by:

Bethany Kurz

Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

2009-EERC-05-02

May 2009

EERC DISCLAIMER

TABLE OF CONTENTS

LIST OF FIGURES

Continued . . .

LIST OF FIGURES (continued)

Continued . . .

LIST OF FIGURES (continued)

Continued . . .

LIST OF FIGURES (continued)

LIST OF TABLES

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

1.0 INTRODUCTION

Water quality issues in the Red River Basin (RRB) are of great concern, and many of the waterways of the region are impaired with respect to turbidity, nutrient, fecal coliform (FC), and dissolved oxygen levels. 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. 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 (DO) 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 sometimes 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 complimentary 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, which was overseen by the Red Lake Watershed District (RLWD) and funded by the Minnesota Pollution Control Agency (MPCA), was to assess the factors that contribute to the water quality impairments identified within the Clearwater River Watershed and to identify target areas for implementation of beneficial management practices (BMPs) using the Soil and Water Assessment Tool (SWAT). SWAT is a hydrologic model developed by the U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) to predict the impact of land management practices on water, sediment, and agricultural chemical yields in watersheds over long periods of time. It has widely been used throughout the United States to evaluate sediment and nutrient water quality impairments and to aid in the development of total maximum daily loads (TMDLs) (Gassman et al., 2007, and references therein).

The Clearwater River SWAT model developed through this project focused on long-term (i.e., 18 year) simulations of water, sediment, nutrient, and FC loading at multiple points of interest within the watershed. The modeling results will be used to gain a better understanding of water quality issues within the watershed and to aid the RLWD in development of TMDLs for the impaired reaches.

2.0 BACKGROUND

The Clearwater River Watershed (Figure 1) is located in northwestern Minnesota and is a tributary to the Red Lake River at Red Lake Falls. As defined by the U.S. Geological Survey (USGS) 8-digit hydrologic unit code (HUC), the drainage area of the Clearwater River Watershed (HUC 09020305) is 3398 km^2 (1312 mi^2). The major tributaries contained within the watershed include the Lost, Poplar, and Hill Rivers; Silver and Badger Creeks; and Walker Brook (Figure 1). As of 2008, there were a total of 17 impairments in the watershed, including nine DO impairments, four FC impairments, three turbidity (T) impairments, and seven mercury impairments (Figure 2).

The watershed is contained within four ecological regions – the Lake Agassiz Plain, the North Central Hardwood Forests, the Northern Lakes and Forests, and the Northern Minnesota Wetlands (Figure 3). 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 [CEC], 1997).

Approximately 61% of the watershed is contained within the Lake Agassiz Plain, which is characterized by thick beds of clay and silt which comprised 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, was very poorly drained. The native tallgrass prairie of the region has been replaced by intensive row crop agriculture. The North Central Hardwood Forest ecoregion comprises approximately 17.5% of the watershed. This ecoregion is characterized as a transition zone between the predominantly forested Northern Lakes and Forests to the north and the agricultural ecoregions to the south, and contains a patchwork of vegetation and land use, including forests, wetlands and lakes, cropland agriculture, pasture, and dairy operations (U.S. Environmental Protection Agency, 2008). Another 15% of the watershed is characterized by the Northern Lakes and Forests ecoregion. This ecoregion comprises glacial soils, coniferous and northern hardwood forests, numerous ponds and potholes, and a variety of hummocky features formed by glaciers (U.S. Environmental Protection Agency, 2008). While the soils in the region are generally thicker than those to the north, they typically lack the arability of soils in adjacent ecoregions to the south (U.S. Environmental Protection Agency, 2008). The remaining 6.5% 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).

The hydrology of the watershed is somewhat unique from most other watersheds in the RRB, primarily as a result of past periods of glaciation that deposited a varied mixture of sands, gravels, and glacial tills. The glaciers also affected the topography of the watershed, which ranges from quite hilly and hummocky in glacial moraine areas, to very flat in areas that previously comprised proglacial lakes. Numerous groundwater seeps and fens exist in the upper reaches of the watershed, which undoubtedly contribute base flow to the streams and rivers of the region.

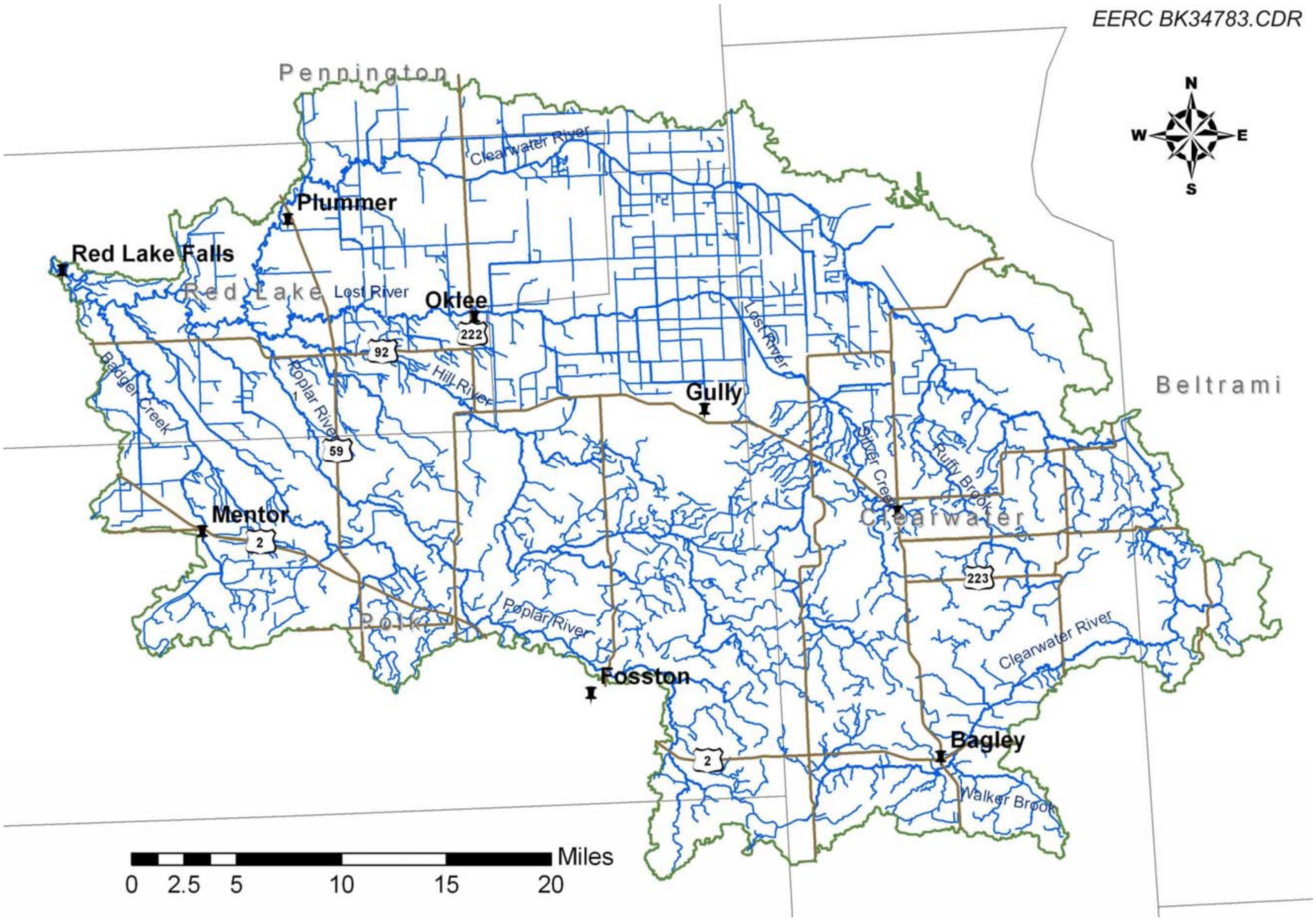

Figure 1. The Clearwater River Watershed and its major tributaries.

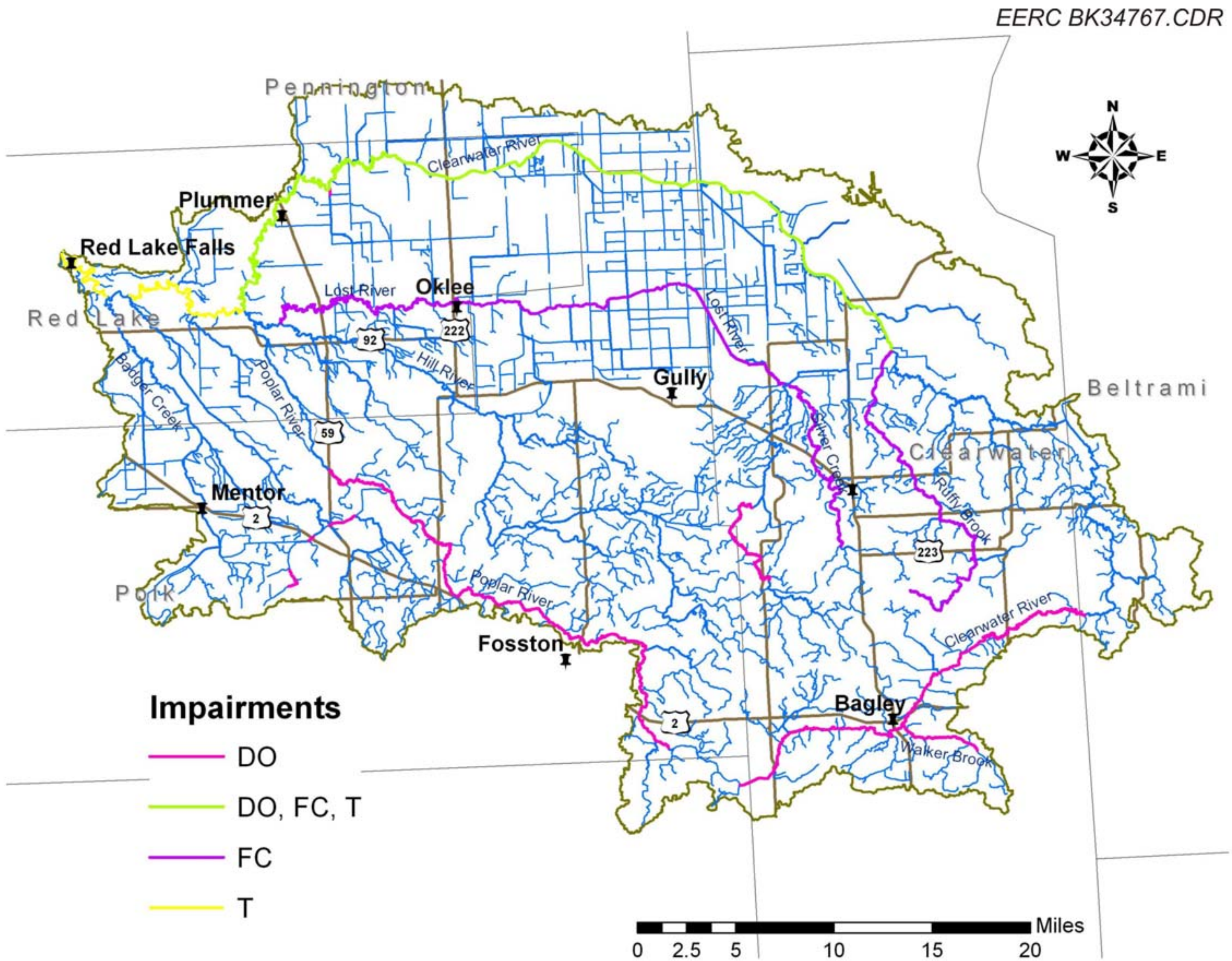

Figure 2. The location of water quality impairments within the Clearwater River Watershed.

EERC BK34763.CDR

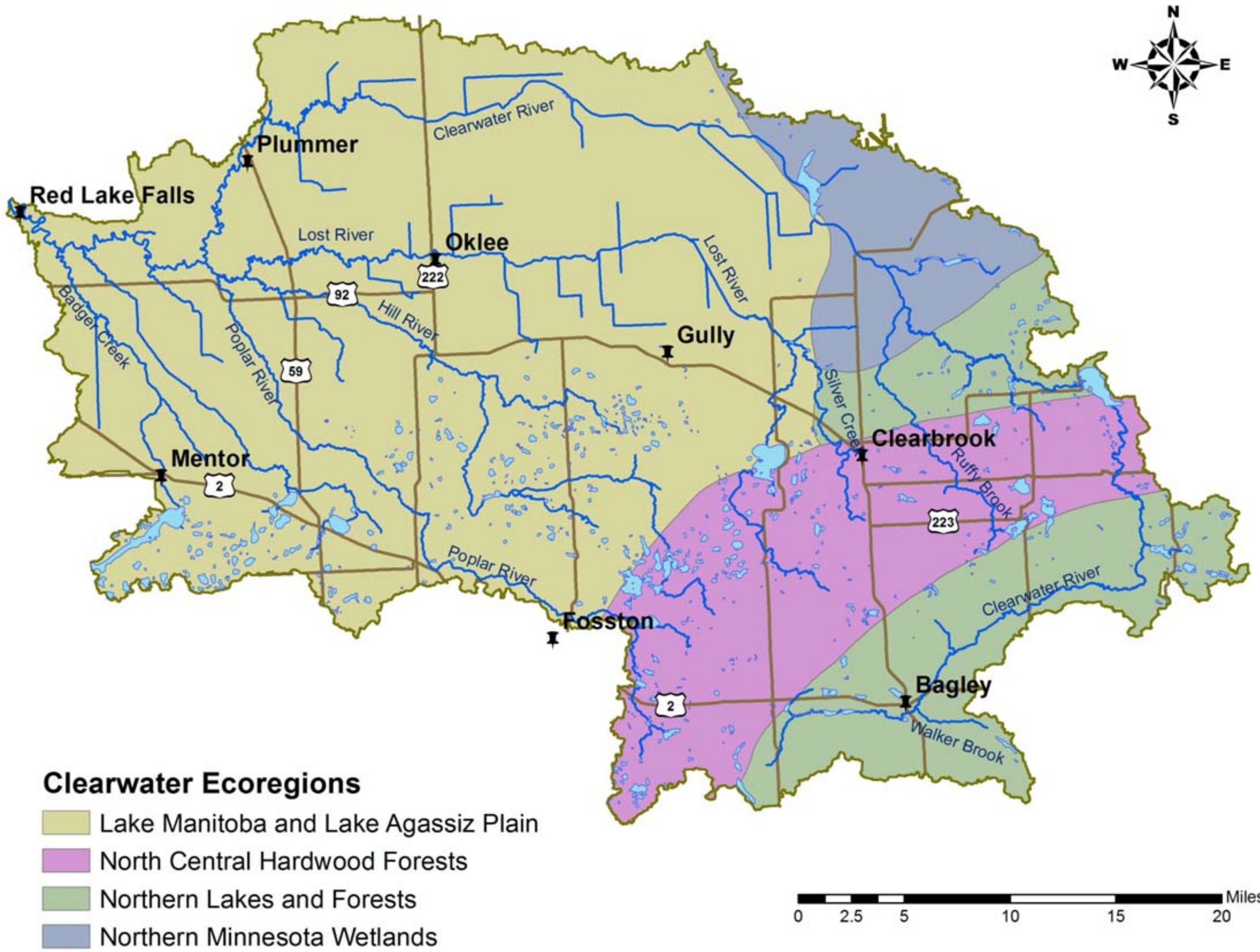

Figure 3. The ecoregion zones contained within the Clearwater River Watershed.

3.0 OVERVIEW OF THE SWAT MODEL

The SWAT is a hydrologic model developed by USDA ARS. 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 be used to answer questions such as the following:

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

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

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

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

5. How do 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 SWRRB model (Simulator for Water Resources in Rural Basins); however, it also incorporates components from CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems), GLEAMS (Groundwater Loading Effects on Agricultural Management Systems), and EPIC (Erosion-Productivity Impact Calculator) (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, humidity) is used to predict the interaction of precipitation (snowfall or rainfall) with the landscape and estimate the amount of runoff, infiltration, evaporation, transpiration, aquifer recharge and base flow (Figure 4) 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,

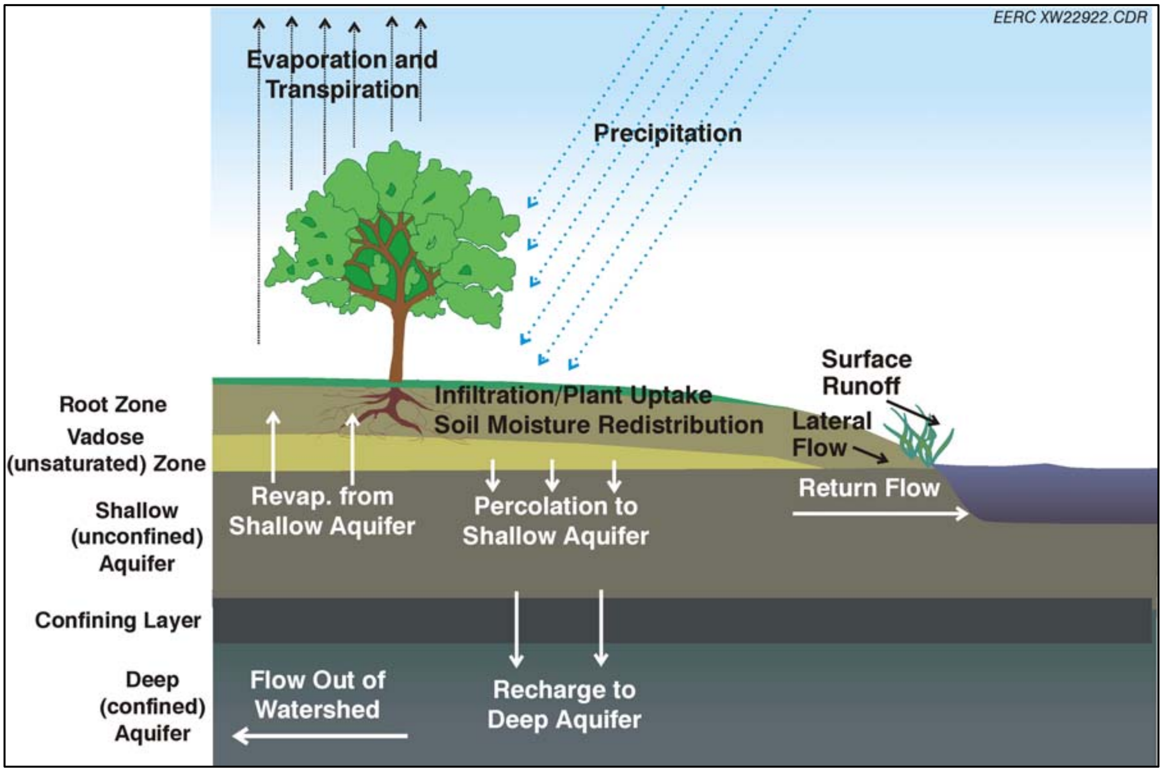

Figure 4. The hydrologic factors modeled within SWAT (modified from Neitsch et al., 2002, http://ftp.brc.tamus.edu/pub/swat/doc/swat2000theory.pdf).

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 5).

To help organize and track all of the various processes that are modeled, SWAT is subdivided into three major components, namely, the 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, 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.

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 (G-A) infiltration method. The SCS curve number method uses empirical equations to estimate the

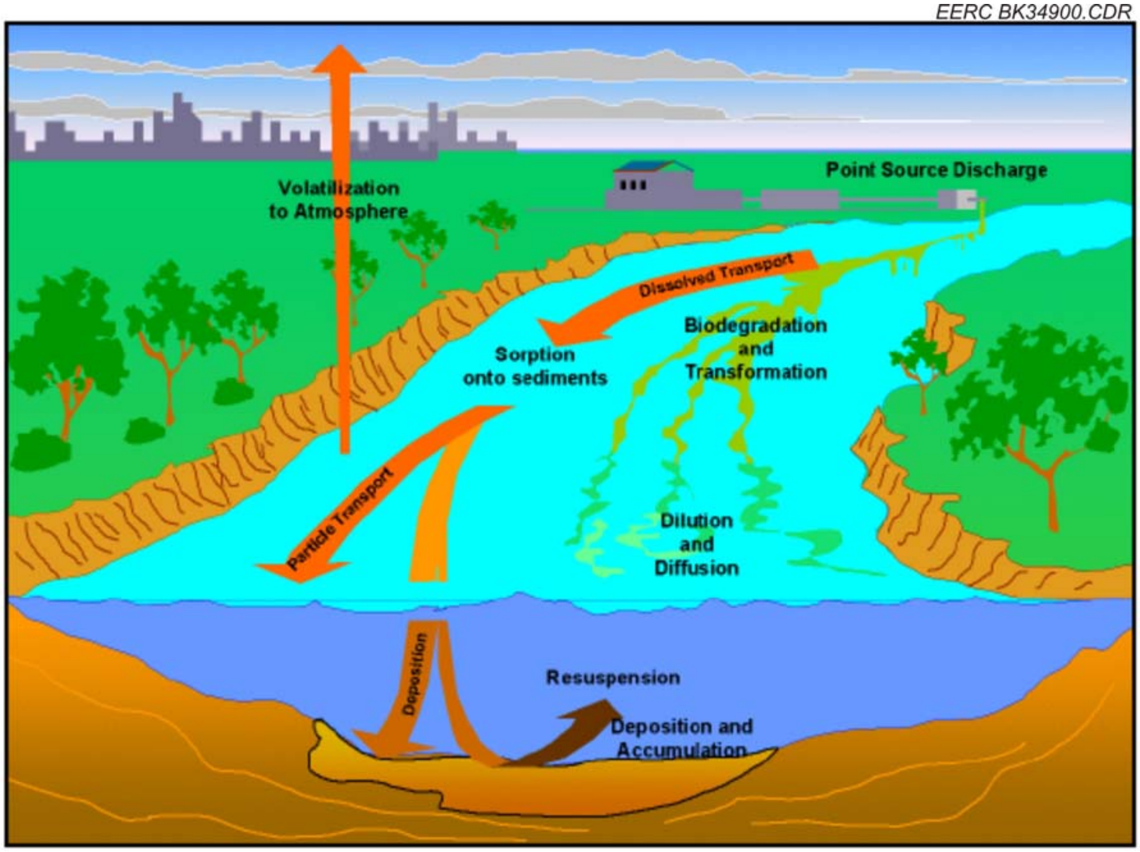

Figure 5. The routing phase of the SWAT model (Neitsch et al., 2002).

amounts of runoff under varying land use and soil types, whereas, the G-A 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 G-A method assumes a saturation excess mechanism. The G-A method requires subdaily (e.g., hourly) weather data, but the SCS curve number method requires only daily data. In addition, SWAT provides three methods, including Penman–Monteith, Priestley–Taylor, and Hargreaves, for estimating the evapotranspiration. Where 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.

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 snow-melting 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).

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 flow attenuation. Because of its ability to differentiate flow attenuation rates during high and low periods, the Muskingum method was deemed more appropriate for the study area.

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 intercepts only a certain percentage of the runoff. The remaining runoff is considered to bypass the storage feature. As with a channel reach, these storage features attenuate the inflow hydrographs and thus reduce peak runoff. Further, translation losses (e.g., seepage and evaporation) are considered for both channel and storage routing.

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; however, for alluvial channels, which are the type found in the study watershed, SWAT simulates downcutting and widening of the stream channel and updates the 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, and degradation will occur otherwise. 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.

Nutrient Simulation. SWAT is capable of simulating five pools of nitrogen (N) and six pools of phosphorus (P). The soil N pools include two inorganic (ammonium and nitrate) and three organic (active, stable, and fresh). Various interactions and transformations between different N pools are simulated, such as mineralization, decomposition, immobilization, nitrification, denitrification, and ammonia volatilization (Chaubey et al., 2006). Additional processes, such as N uptake by plants, organic N transport with sediment, and removal of nitrate and organic N via water, are also considered (Neitsch et al., 2002). Within each HRU, SWAT estimates how much of each type of N compound is transported into the respective reach. Once the nitrogen enters a stream reach, it is portioned between four pools – organic N, ammonia N, nitrite N, and nitrate N. Various transformations between N compounds within the stream reaches are estimated using algorithms adapted from the QUAL2E model (Chaubey et al., 2006).

The various pools of soil P considered in SWAT include three inorganic (solution, active, and stable) and three organic (fresh, active, and stable) (Chaubey et al., 2006). Various compounds contribute to the organic P pool, including crop residue, microbial biomass, humic matter, and manure. Contributors to inorganic P pools include fertilizer, manure, and mineral forms of P contained within soils. Common transformations between pools that are considered in SWAT include mineralization, decomposition, and immobilization. As with N, SWAT estimates the amount of P leached into the subsurface, absorbed by plants, or transported with water or sediment into stream reaches. Once in a stream reach, P is partitioned between organic P and mineral P, as well as P adsorbed to stream sediment.

Simulating 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 relatively easy to adjust, the model is especially useful for evaluating options to achieve TMDLs. While SWAT estimates many parameters by default, such as nutrient application rates for different crop types, it is advisable to incorporate more detailed data for practices that are of particular interest. As with any model, the accuracy of the output is a function of the accuracy and detail of the input data.

4.0 DEVELOPMENT AND CALIBRATION OF THE CLEARWATER RIVER WATERSHED MODEL

The Clearwater River SWAT model was developed using several data sets that represent the physical characteristics of the watersheds, such as climate, topography, land use, and soil data. These data sets were used to delineate the watershed into smaller subbasins and HRUs, which allow the user to better represent the physical characteristics of the landscape. Once the model was delineated, additional information was incorporated, such as discharge information from point sources, withdrawal and discharge data from wild rice farming operations, the location of cattle operations and feedlots, general farm management operations, and manure inputs from waterfowl. The hydrology and water quality components of the model were calibrated by adjusting various model parameters to best represent the physical and chemical characteristics of the watershed and through comparison with measured discharge and water quality data. The following sections describe each of the steps taken to develop and calibrate the model.

4.1 Model Development

4.1.1 Data Inputs

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

Topographic Data: The 30-meter USGS National Elevation Data set (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 Data set (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 the 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 were 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.

Climate Data: A total of six weather stations were used to provide precipitation and temperature data input to the model. Three of the stations are maintained by the National Weather Service (NWS) and contain both precipitation and temperature data. The data for these sites were downloaded from the National Climate Data Center. The data from the other three stations contained only precipitation data, which were collected through the High Spatial Density Precipitation Network (HSDPN). The HSDPN data were collected through a network of volunteers that report to the local Soil and Water Conservation Districts (SWCD). In some instances, volunteers have been collecting data for close to 30 years. The data collected through the HSDPN is available through the Minnesota Climatology Working Group Web site (http://climate.umn.edu). The station name, number or location, and period of record is listed in Table 1, and the location of the stations within the watershed is shown in Figure 6. Missing values at individual stations were estimated based on data available at nearby stations using linear interpolation. While other climate stations may exist in or near the watershed, they were not used because of gaps in the data record or because of their proximity to an existing station.

While there were enough data available to run the model for a 30-year simulation period, based on the period of record of other data included in the model, such as point source inputs from wastewater treatment plants (WWTPs) and water withdrawals from wild rice paddy operations, 22 years of weather data (from 1986 to 2007) were incorporated into the model. 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 values of certain parameters, such as soil moisture, before generating results. Thus the total simulation period of the model is January 1990 to December 2007.

Stream Flow Data: The daily flow data from three USGS gaging stations were used in model development and calibration. These stations were located on the Clearwater River at Plummer (USGS Gage 05078000), the Clearwater River at Red Lake Falls (USGS Gage

Table 1. The Location of the Stations Used to Provide Climate Data to the Model

Station Name	NWS ID Number	HSDPN Observer Location	Period of Record
Red Lake Falls	216787	NA	1948 – present
Fosston	212916	NA	1948 – present
Red Lake	216795	NA	1943 – June 2007
"Bagley"*	NA	T147N R37W 20	1974 – present
"Oklee"*	NA	T151N R40W 18	1978 – present
"McIntosh"*	NA	T149N R41W 11	1980 – present

* The names of these stations are not official and were used only for descriptive purposes within the model.

05078500), and the Lost River at Oklee (USGS Gage 05078230). The location of these gages is shown in Figure 7.

Sediment and Water Quality Data: Water quality information, including total suspended solids (TSS), total phosphorus, nitrate-N, nitrite-N, and FC concentration data, were 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 RLWD and Minnesota Department of Natural Resources. Additional water quality and flow data were also provided by the RLWD. The water quality data were used to calibrate the model for sediment, FC, and nutrient loading. The location of some of the key water quality station locations used to evaluate and calibrate the SWAT model output are shown in Figure 7.

Non-Point Source Inputs: While SWAT automatically estimates the amount of sediment and nutrient transport from the land as a result of agricultural practices or natural land use, it does not automatically estimate the contribution of non-point sources of pollution from grazing, feedlot operations, or wildlife. In order to account for these operations in the model, the following assumptions were used.

Cattle Operations: To account for the numerous grazing and feedlot operations within the watershed (Figure 8), data on the location and size of registered feedlots were obtained from MPCA and the Clearwater County SWCD. These data contained information on the number and type of animal units (AUs) within Clearwater, Red Lake, and Polk Counties. While there are a handful of swine, sheep, and poultry operations within the watershed, only the cattle operations were included in the model.

Based on the location of each operation and the number of AUs, grazing operations were included in the model on rangeland adjacent to each operation. It was assumed that the cattle grazed from April to September and then moved to a different holding area during the winter months. Within the model, the summer grazing operations account for the amount of manure produced, biomass consumed, and biomass trampled per animal unit. During the winter months, manure was applied to the landscape, but no biomass consumption or biomass trampling was accounted for. The following assumptions were used in estimating the amount of manure applied within the model to simulate cattle operations:

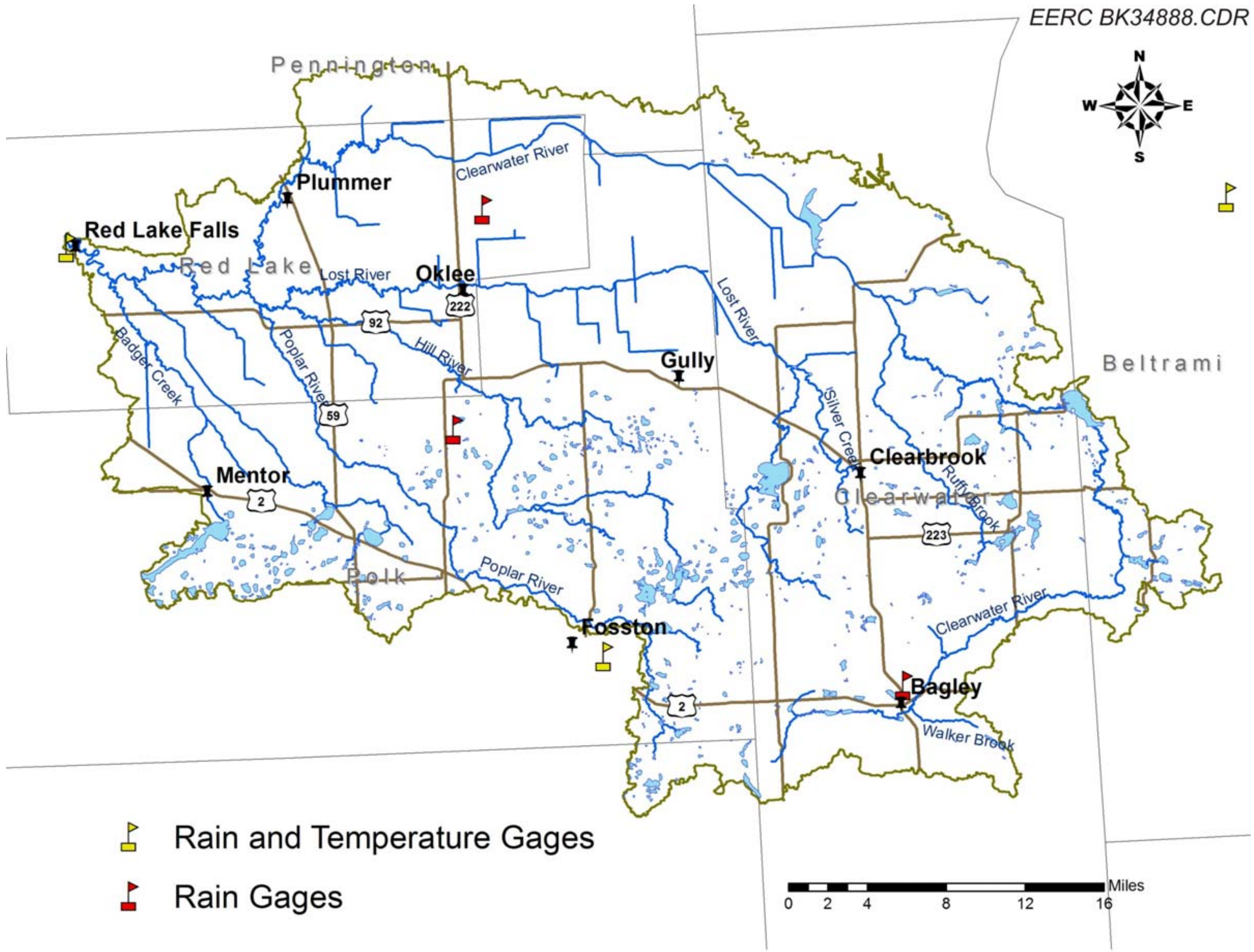

Figure 6. The location of climate gages used to provide temperature and precipitation data to the model.

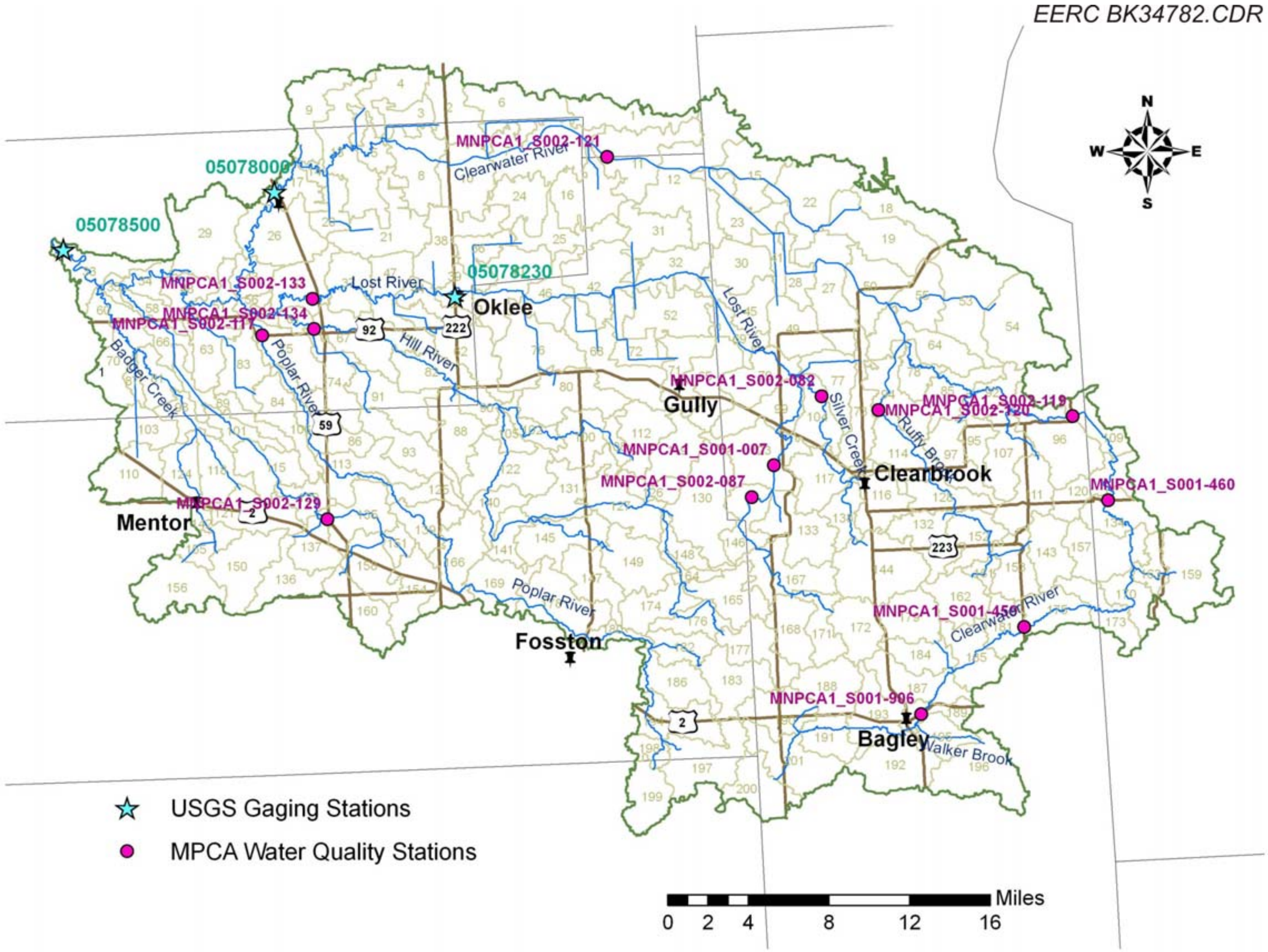

Figure 7. The location of the USGS stream-gaging stations and select MPCA water quality-monitoring stations used to calibrate the model.

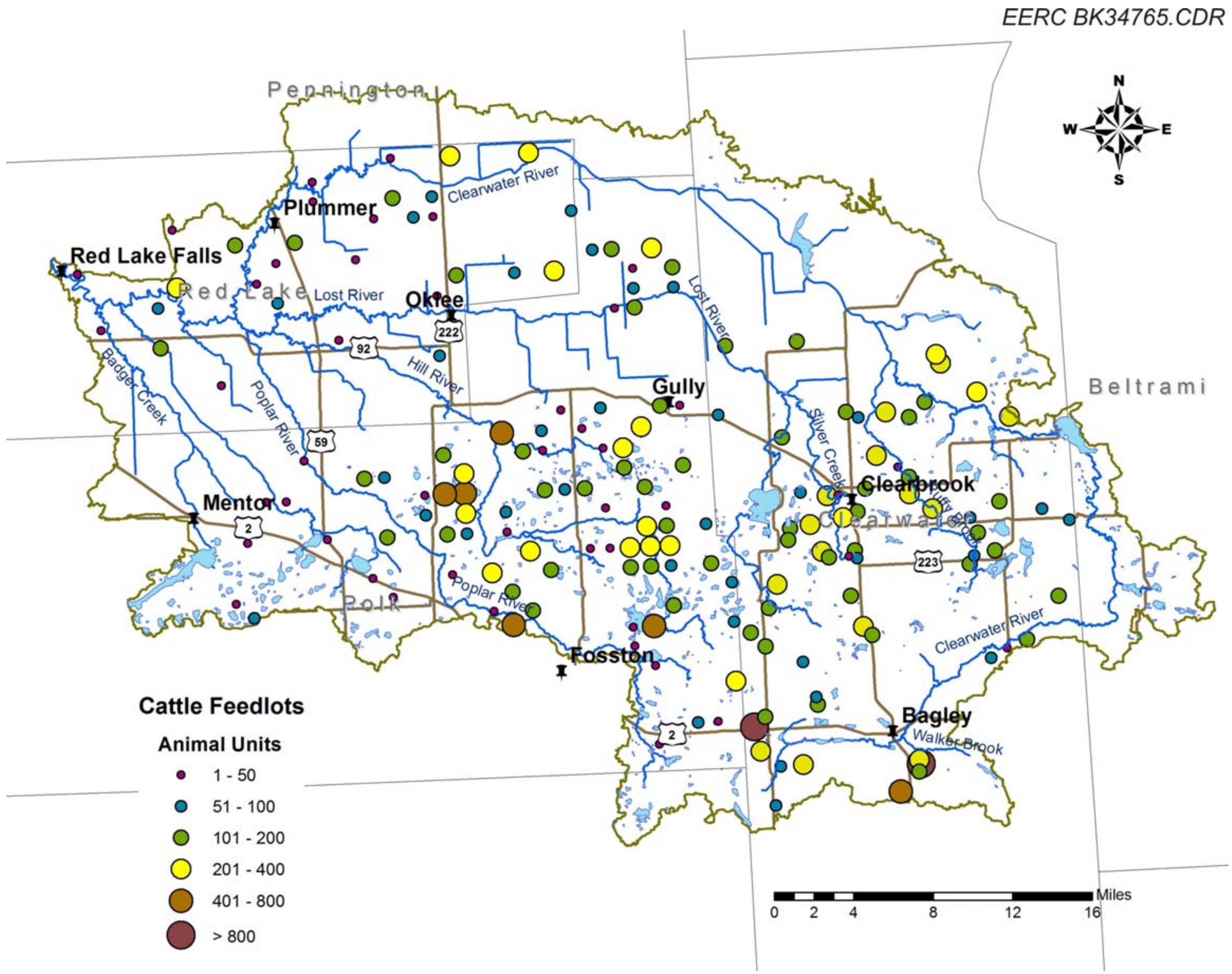

Figure 8. The location of feedlots within the Clearwater River Watershed.

- Assumed two animals per acre, or 4.94 AU per hectare (based on input from the TMDL stakeholder advisory group).

- MPCA defines one beef AU as 1000 pounds, or 454 kilograms.

- Based on manure production and characteristic data published by the American Society of Agricultural Engineers (ASAE, 2003), the amount of wet manure produced per 1000 kg of beef is 58 kg. This translates to 26.3 kg of wet manure per beef AU (or 3.68 kg of dry manure per AU based on ASAE manure moisture content data).

The FC content of 1 g (dry weight) of manure was estimated at 4.10×10^7 colonies (based on ASAE data).

Wildlife Inputs: At the TMDL stakeholder meeting, members suggested that manure inputs from waterfowl and deer may be significant within the watershed. Of particular concern were the number of ducks, geese, and swans that reside in wild rice paddies during the migration. A study conducted by Jay Huseby in the early 1990s (Huseby, 1998) documented the number of migrating and breeding waterfowl in 1491 hectares (4683 acres) of wild rice paddies along the Clearwater River. Huseby found that over a 3-year period ranging from 1993 to 1995, an average of 20 migrating and two breeding waterfowl per paddy-hectare were found in the region. During the migration, approximately 20% of these birds were geese.

These numbers, as well as duck and goose manure production data from ASAE and data provided by RLWD on the size and location of rice paddies in the watershed (Figure 9), were used to estimate the amount of manure applied to wild rice paddies in the watershed. It was assumed that the migrating waterfowl were present for 6 weeks in March and April and again for 6 weeks in September and October. Since it was difficult to estimate how much of the FC or nutrients in the rice paddies are actually transported from the rice paddies to the waterways of the basin, and detailed information on individual paddy drainage practices was not available, the manure was applied directly to the rice paddies within the model. However, in reality, it is unlikely that all of the nutrients and bacteria are transported to the stream reaches; therefore, a 5-meter vegetative buffer was applied to the paddy areas (represented as wetland land use within the model) to reduce the direct input of bacteria and nutrients to the stream reaches.

To account for waterfowl inputs throughout the rest of the watershed, waterfowl breeding population survey data from the Minnesota DNR were used (Minnesota Department of Natural Resources, 2008). Based on these surveys, the average density of breeding ducks in east central Minnesota was 0.04 ducks per hectare. Since no estimates of migrating waterfowl density in the region were found, Huseby's relationship of 10 times the amount of migrating ducks to breeding ducks was used to estimate an average of 0.4 migrating ducks per hectare. The equivalent amount of manure and resulting FC concentrations were estimated using ASAE data and applied throughout the watershed.

While deer manure inputs were considered for incorporation into the model, the average deer density of six animals per square mile estimated by Grund (2008) was so small that the

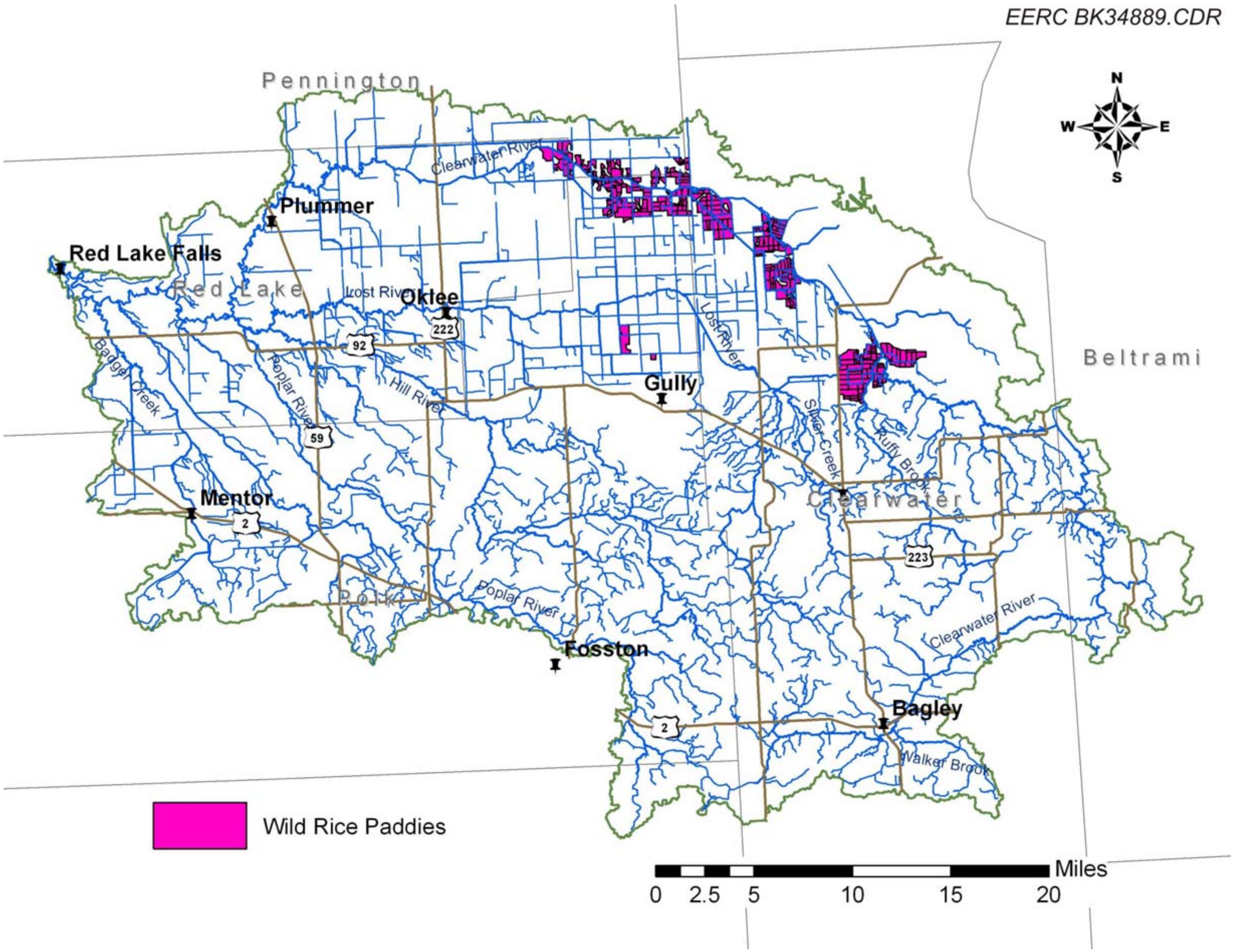

Figure 9. The location of wild rice paddies within the Clearwater River Watershed (data provided by the RLWD).

manure inputs would have been too small to enter into the SWAT model. Therefore, deer manure inputs were not considered in the model.

Point Source Inputs: Point source inputs into the model were considered from two key areas – the WWTPs located within the watershed and also direct stream inputs from cattle operations located adjacent to stream reaches. There are a total of five WWTPs that discharge to the Clearwater River or its tributaries (Figure 10), including the Bagley, McIntosh, Oklee, Fosston, and Plummer WWTPs. Average monthly discharge data for each WWTP was obtained from MPCA for incorporation into the model. Most data records extend back to 1989.

The other "point" sources considered in the model were direct cattle manure inputs to the streams. While not typically considered a point source, in order to accurately account for direct manure inputs into the streams they were modeled as such. This approach has been successfully utilized in other hydrologic modeling studies (Baffaut and Benson, 2003; Yagow et al., 1999). Feedlot operations that allowed cattle direct stream access were identified by RLWD using arial photography (Figure 11). These operations were then matched with the MPCA data records to determine the number of animal units in the operation, and it was assumed that 5% of the total manure generated by the cattle was directly input into the respective stream reach. While in actuality this number may be larger or smaller, or vary temporally, without detailed information on the amount of manure directly input into the streams, it seemed to be a reasonable estimate.

Wild Rice Paddy Withdrawal Data: One of the challenges in development of the Clearwater River SWAT model was the incorporation of practices that simulate wild rice production. No literature exists on the modeling of wild rice paddies using SWAT, and based on the limited locations of wild rice production throughout the country, it is reasonable to assume that this is one of the first models that attempts to incorporate such practices.

Throughout the fall and early summer, wild rice paddy operators withdraw water from nearby streams and rivers to flood their paddies. In order to do so, they are required to report their average monthly withdrawals to DNR. These data were obtained from DNR and input into the model as negative point sources. There were a total of 14 withdrawal locations contained along the Clearwater River, and the data records extend back as far as 1988.

While this seems to be an effective means of simulating the withdrawal of water from rice paddies, it does not account for the gradual return of water from the paddies to the reaches through infiltration and base flow, nor does it account for the more rapid release of water from the paddies that occurs just before harvest in late August or early September. While it is impossible to account for the base flow contribution of the paddies without measured data, the drainage of the paddies just before harvest was estimated within the model. It was assumed that by the time water was released from the paddies, an average of 1 in. of water over the entire area of active rice paddies was drained over a 2-week period. According to wild rice paddy operators that are members of the Clearwater River TMDL Stakeholder Group, in any given year approximately 50% to 65% of the paddies are in operation, and at the time of harvest some drain more than an inch of water equivalent and some drain little to no water (personal communication, 2008 and 2009).

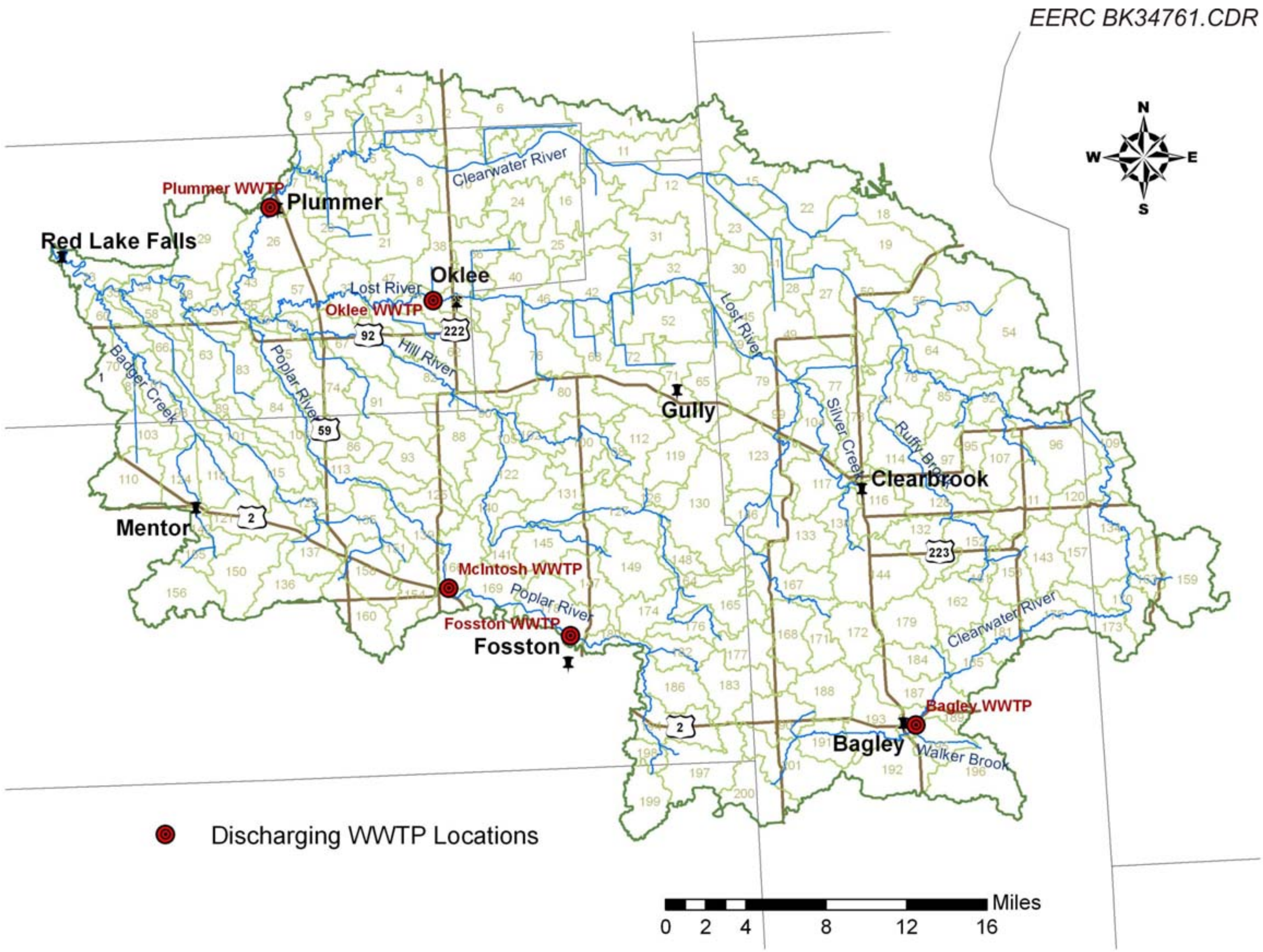

Figure 10.The location of WWTPs that discharge to the Clearwater River Watershed.

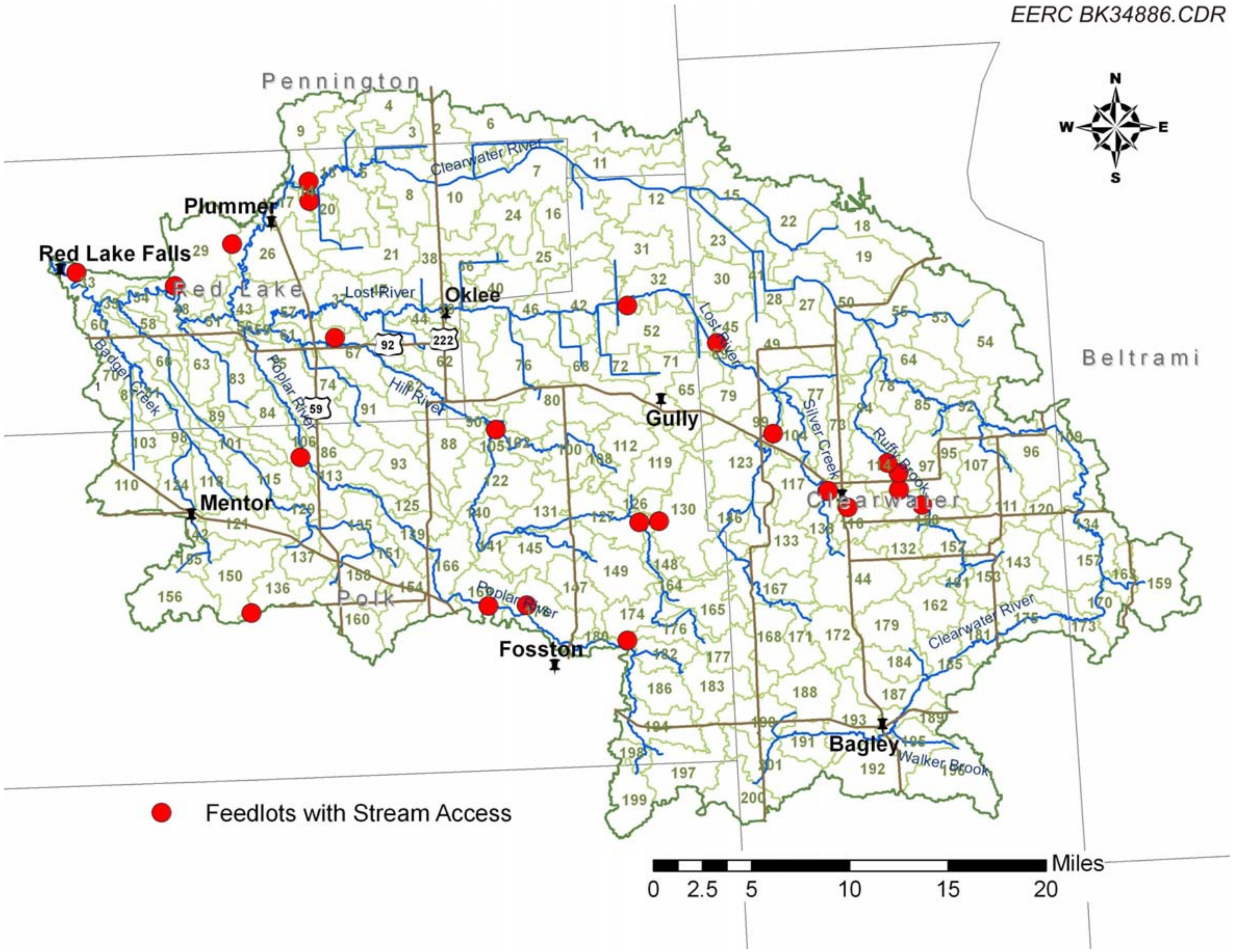

Figure 11. The location of feedlots that have stream access.

4.1.2 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. For studies such as this one which entail a 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 gaging stations and most of the MPCA water quality station locations. A total of 201 subbasins with an average area of 16.8 km^2 (6.5 mi^2) were defined within the watershed. The location and number of each subbasin, as well as the major stream reaches delineated by SWAT, are shown in Figure 12.

4.1.3 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 13–15 show the distribution of land use, soils, and slopes used to define the HRUs within the Clearwater River Watershed. Table 2 shows the percentage of land use within the watershed. Table 3 lists the soil types that comprise more than 0.5% of the total watershed area (out of a total of 102 soil types located within the watershed).

Once the aforementioned data sets were loaded into the model, the number of HRUs within the watershed was defined based on specified thresholds, or degrees 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 comprise less than 5% of a subbasin area will not be included in the formation of HRUs. While the land area would still be represented, it would be proportionately divided into the remaining HRUs based on the percent distribution of soils that comprise greater than 5% of the subbasin area.

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

- Land use: 7%
- Soil type: 18%
- Slope: 20%

This resulted in the formation of 2181 HRUs throughout the entire watershed, or an average of almost 11 HRUs per subbasin. Typically, no more than 10 HRUs are needed per subbasin; however, given the more detailed land use and soil data sets used for this project, a larger number of HRUs was necessary to better capture the variability within each subbasin.

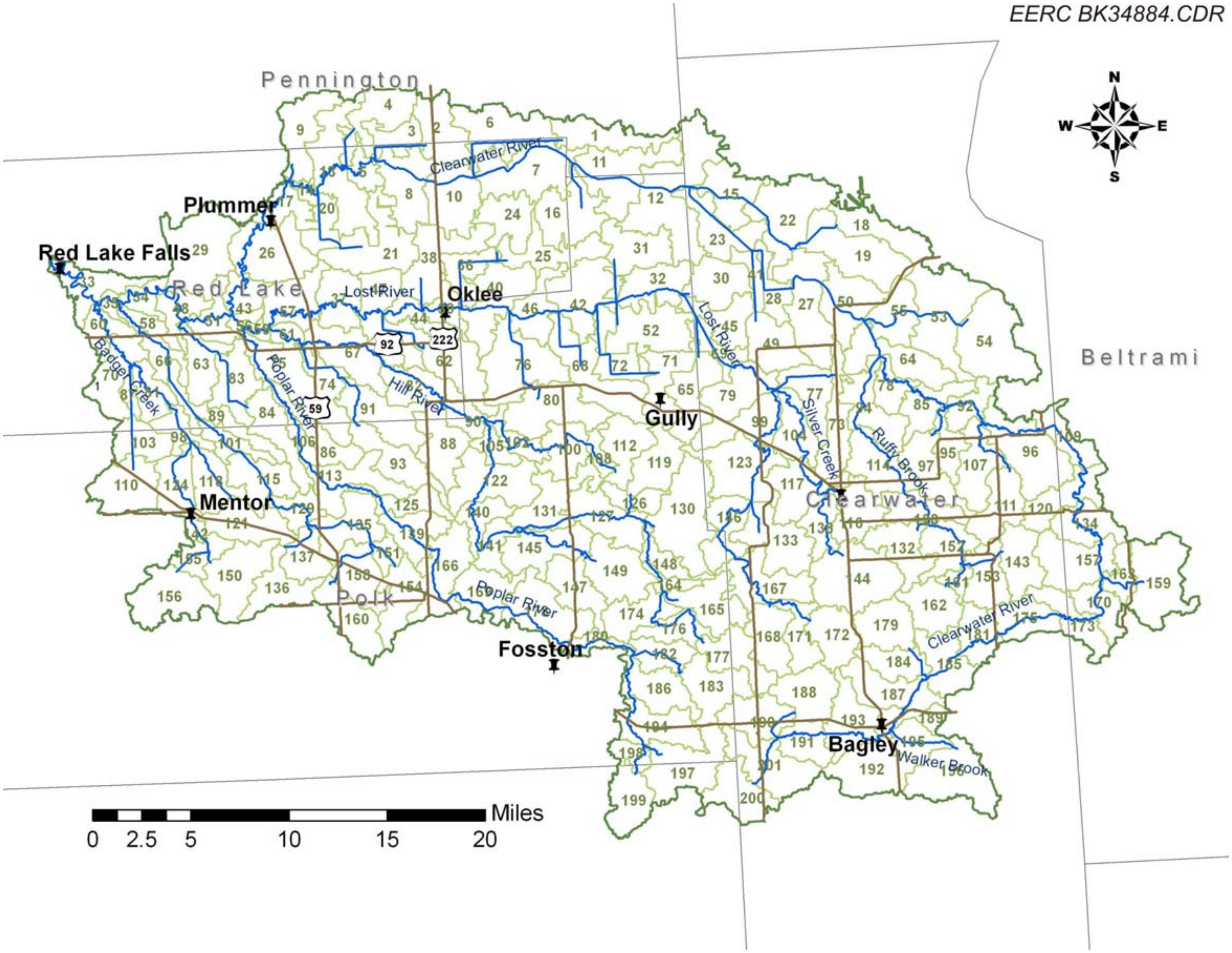

Figure 12. The subbasins and major stream reaches delineated by SWAT within the Clearwater River Watershed.

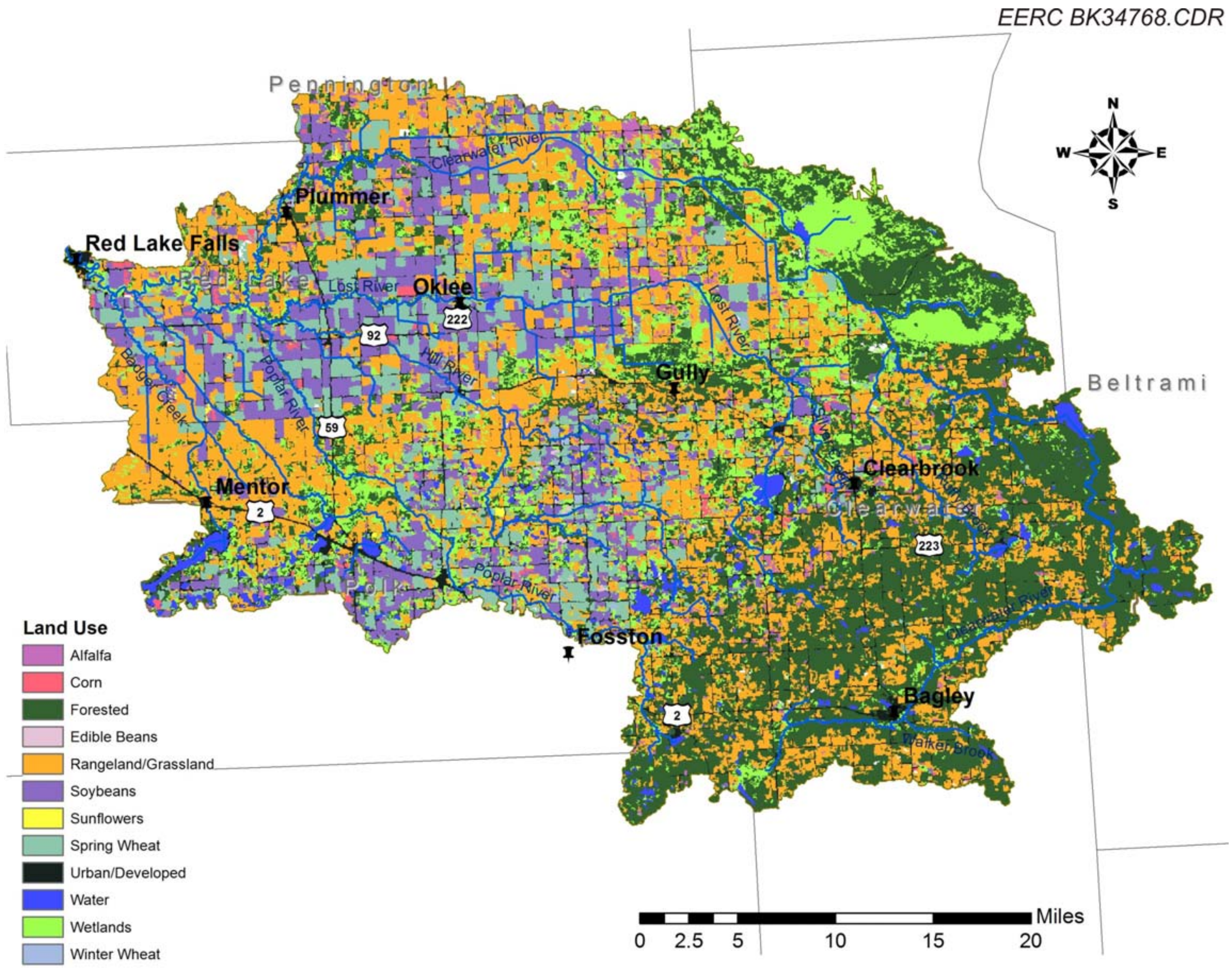

Figure 13. The distribution of land use within the Clearwater River Watershed.

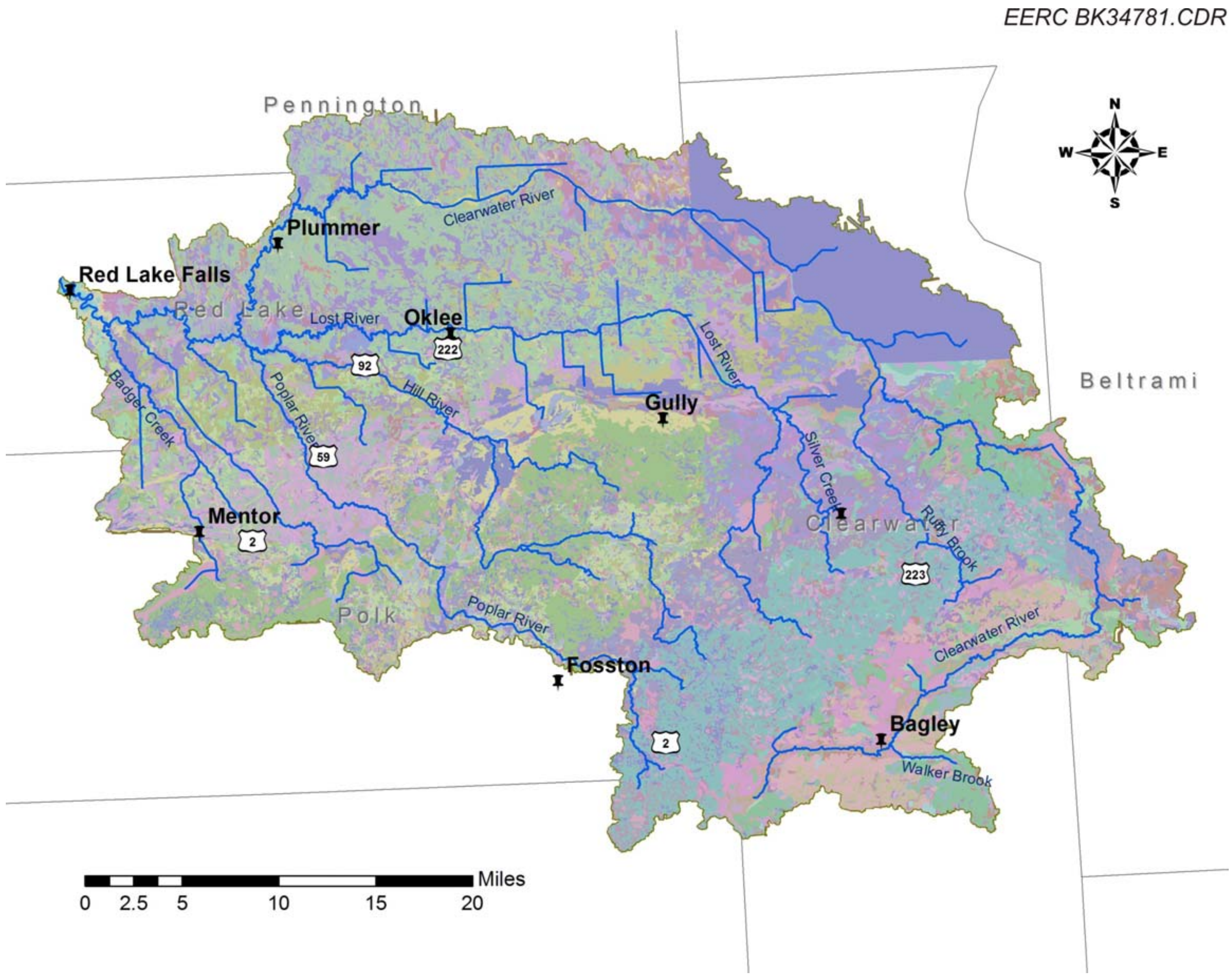

Figure 14. The distribution of soil types located within the Clearwater River Watershed (note that detailed soil data were not available for the Red Lake Nation).

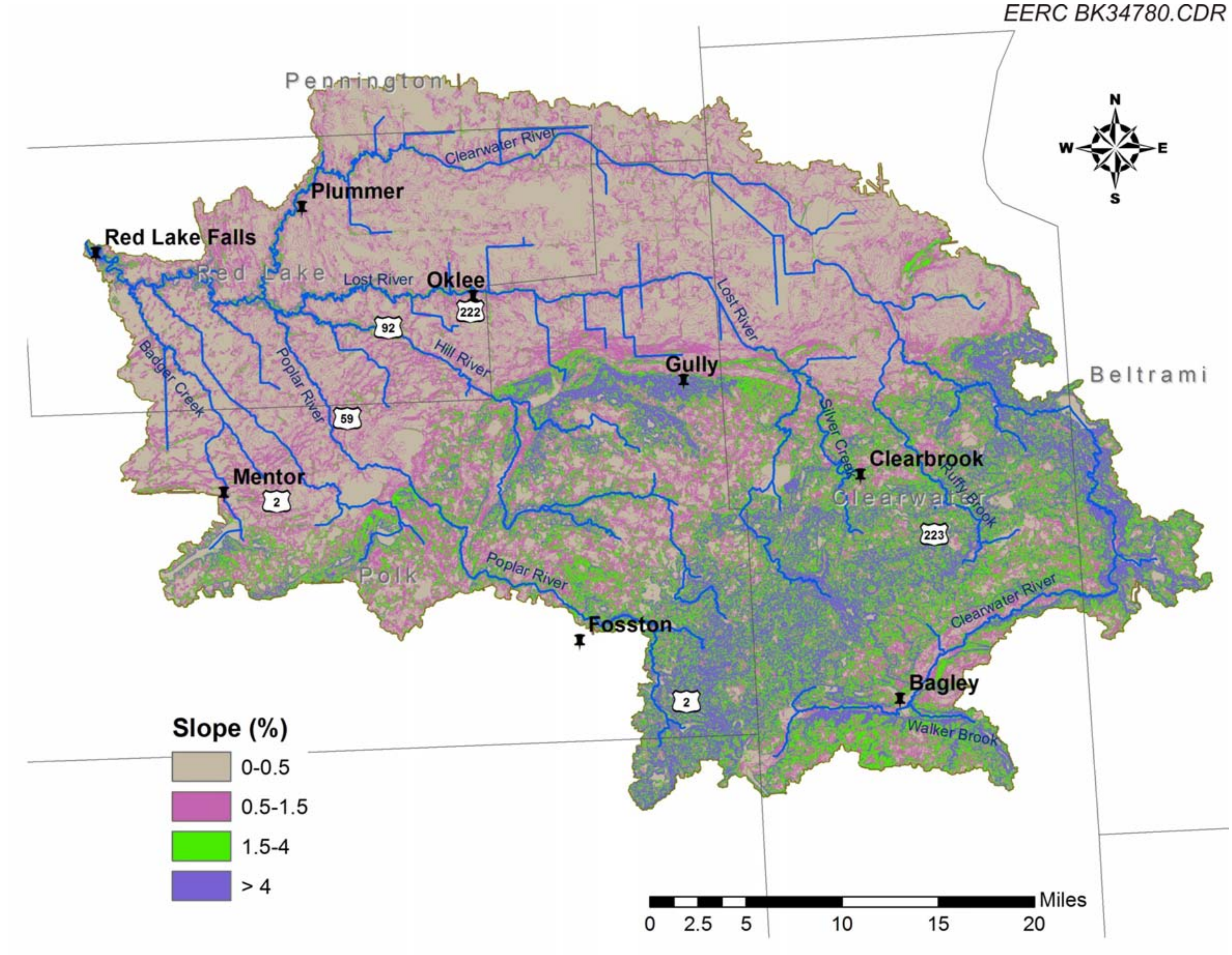

Figure 15. The distribution of different slope classes within the Clearwater River Watershed.

Table 2. The Land Use of the Clearwater River Watershed

Land Use	Area, acres	Percent of Watershed Area
Rangeland/Grassland	234,596	28.14
Forest – Deciduous	230,855	27.69
Wetlands	115,958	13.91
Soybeans	95,479	11.45
Wheat	69,944	8.39
Developed	44,429	5.33
Water	19,277	2.31
Alfalfa	14,070	1.69
Corn	5145	0.62
Winter Wheat	1422	0.17
Beans	551	0.07
Sunflowers	502	0.06
Generic Agricultural Land	441	0.05
Barley	348	0.04
Rangeland – Brush	285	0.04
Oats	252	0.03

4.2 Flow Calibration

4.2.1 Calibration Parameters

As previously mentioned, the hydrology of the Clearwater River model was calibrated using the observed flow data from three USGS gaging stations (Figure 7). These stations were located on the Clearwater River at Plummer (USGS Gage 05078000), the Clearwater River at Red Lake Falls (USGS Gage 05078500) and the Lost River at Oklee (USGS Gage 05078230). The focus of the model calibration was from January 1, 1998, to December 31, 2007, with a model validation period from January 1, 1990, to December 31, 1997.

Table 4 lists the various model parameters that were adjusted to calibrate the model for flow, including the default and calibrated parameter values. The calibration parameters were adjusted to reflect conditions most appropriate for the RRB and the Clearwater River Watershed. 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 et al., 2006; Wang and Melesse, 2006; Wang and Melesse, 2005). 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 www.brc.tamus.edu/swat/doc.html).

4.2.2 Measures of Model Performance

The hydrograph of predicted versus observed flows for the Clearwater River at Plummer, the Clearwater River at Red Lake Falls, and the Lost River at Oklee for the calibration period

Table 3. The Soils That Comprise More Than 0.5% of the Total Watershed Area

Soil Name	Area, acres	Percent of Watershed Area
Smiley	73,459	8.81
Seelyeville	72,709	8.72
Naytahwaush	65,223	7.82
Chapett	55,253	6.63
Cathro	35,545	4.26
Kratka	35,024	4.20
Rosewood	29,672	3.56
Ulen	28,504	3.42
Mavie	26,302	3.16
Grimstad	25,791	3.09
Roliss	22,951	2.75
Waukon	21,663	2.60
Nebish	18,494	2.22
Water	18,330	2.20
Reiner	17,929	2.15
Northwood	17,587	2.11
Flaming	17,177	2.06
Sugarbush	15,721	1.89
Foldahl	14,507	1.74
Maddock	14,510	1.74
Sol	14,502	1.74
Vallers	13,076	1.57
Hamre	12,844	1.54
Heimdal	9179	1.10
Lengby	8850	1.06
Gonvick	8680	1.04
Markey	8672	1.04
Fram	8467	1.02
Knute	7322	0.88
Nary	7246	0.87
Lupton	6975	0.84
Bowstring	6832	0.82
Linveldt	6310	0.76
Arvilla	5601	0.67
Eckvoll	5404	0.65
Andrusia	5254	0.63
Fluvaquents	4676	0.56
Suomi	4617	0.55
Graycalm	4308	0.52
Karlstad	4192	0.50

Table 4. The Parameters Adjusted to Calibrate the Clearwater River SWAT Model

Parameter	Default Value	Calibration Value	Description
SFTMP	1	1.5	Snowfall temperature, °C
SMTMP	0.5	0.8	Snow melt base temperature, °C
SMFMX	4.5	1.5	Melt factor for snow on June 21, mm H_2O/°C-day
SMFMN	4.5	3.5	Melt factor for snow on December 21, mm H_2O/°C-day
TIMP	1	0.25	Snow pack temperature lag factor
SNOCOVMX	1	30	Minimum snow water content that corresponds to 100% snow cover, mm H_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 potential ET values
ESCO	0.95	0.88	Soil evaporation compensation factor
SURLAG	4	1	Surface runoff lag coefficient
SPCON	0.0001	0.0001	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.
IRTE	0	1	Channel water routing method: 0 = variable storage method; 1 = Muskingum routing method
MSK_CO1	0	1.2	Muskingum calibration coefficient used to for normal flow
MSK_CO2	3.5	1.4	Muskingum calibration coefficient used to for low flow
MSK_X	0.2	0.2	Muskingum weighting factor used to control the relative importance of inflow and outflow in determining the storage in a reach
ALPHA_BF	0.048	0.009	Base flow alpha factor, days
GWQMN	0	500	Threshold depth of water in the shallow aquifer required for return flow to occur, mm H_2O
GW_REVAP	0.02	0.09	Groundwater reevaporation coefficient
REVAPMN	1	100	Threshold depth of water in the shallow aquifer for reevaporation or percolation to the deep aquifer to occur, mm H_2O
RCHRG_DP	0.05	0.15	Deep aquifer percolation fraction
GWHT	1	1	Initial groundwater height, m
CN2	Varies	−3.0%	Initial SCS runoff curve number for moisture condition II
CH_K1	0.5	16	Effective hydraulic conductivity in tributary channel alluvium, mm/hr
CH_N1	0.014	0.02	Manning's "n" value for the subbasin tributary channels
CH_N2	0.014	0.02	Manning's "n" value for the main channel in each subbasin
CH_K2	0	20	Effective hydraulic conductivity in main channel alluvium, mm/hr
CH_EROD	0	0.15	Channel erodibility factor
CH_COV	0	0.3	Channel cover factor
ALPHA_BNK	0	0.2	Base flow alpha factor for bank storage, days

and the entire simulation period of the model is shown in Figures 16–21. The flows match fairly well for the Clearwater River stations and are a little more varied for the Lost River. The largest challenge to calibration of the model was the lack of data on groundwater contributions from springs and fens, which appear to affect the base flow quite differently in different portions of the watershed. A base flow separation program that was designed by Arnold et al. (1995) to estimate the percentage of base flow versus surface runoff through the evaluation of measured stream flow data was used to evaluate the base flow at each of the USGS gaging stations. The results (Table 5) show that the base flow conditions along the Lost River are quite different than those along the Clearwater at Plummer and at Red Lake Falls. This is most likely a result of differences in upstream groundwater contributions, or it could be a result of the impacts of the wild rice paddy operations along the Clearwater River. While the rice paddies only contribute directly to surface runoff during the late summer, the continued flooding of the paddies and subsequent infiltration of water into the subsurface may replicate base flow occurring over an extended period of time (hence the long return period estimated by the base flow separator). It should be noted that the base flow conditions at Red Lake Falls are influenced more by the Clearwater River than the Lost River because of the higher proportion of flow in the Clearwater River.

Various parameters were adjusted to replicate the base flow conditions listed in Table 5; however, the amount of base flow that contributes to the waterways of the basin seem to vary not only spatially, but temporally as well. While the SWAT model allows for adjustment of calibration parameters spatially, they cannot vary from year to year. Thus, while the base flow conditions of the Clearwater River Watershed seem to be represented well in the model for some years, they are not so accurate during other years. The model tends to overpredict the base flow following years of relatively high flow, such as 1999 and 2002.

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 (NSE) coefficient and volume deviation (Dvj) 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.

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:

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

where $\mathrm{Q}^j_{\mathrm{sim}i}$ and $\mathrm{Q}^j_{\mathrm{obs}i}$ are the simulated and observed stream flows, respectively, on the ith time step for station j, and $\mathrm{Q}^j_{\mathrm{mean}}$ is the average of $\mathrm{Q}^j_{\mathrm{obs}i}$ across the n_j evaluation time steps. The NSE

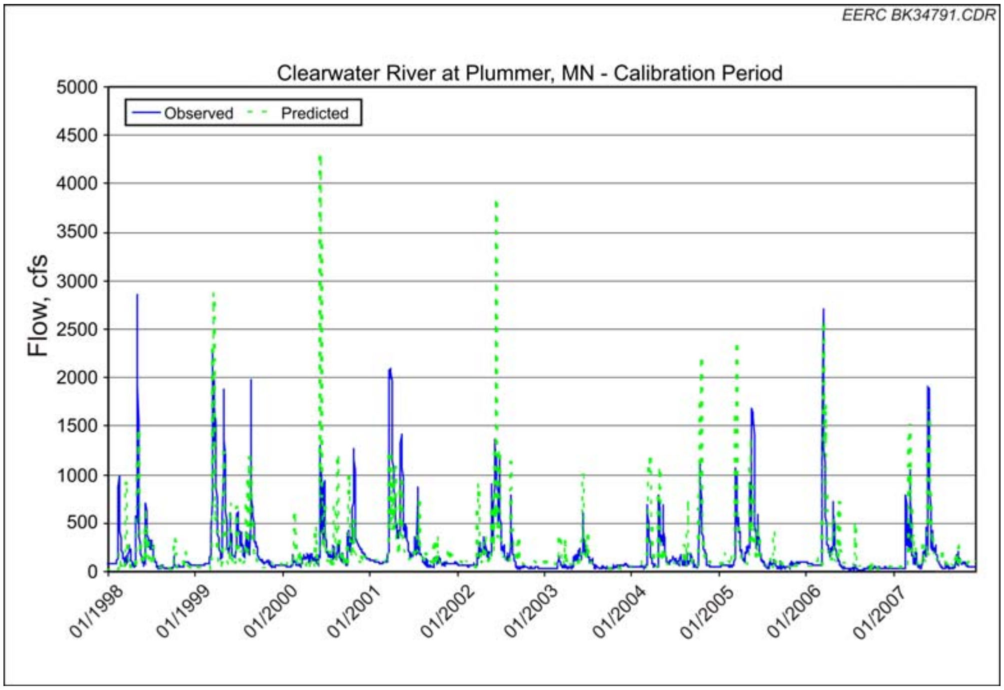

Figure 16. Comparison of the USGS-observed versus model-predicted flow for the calibration period for the Clearwater River at Plummer, Minnesota.

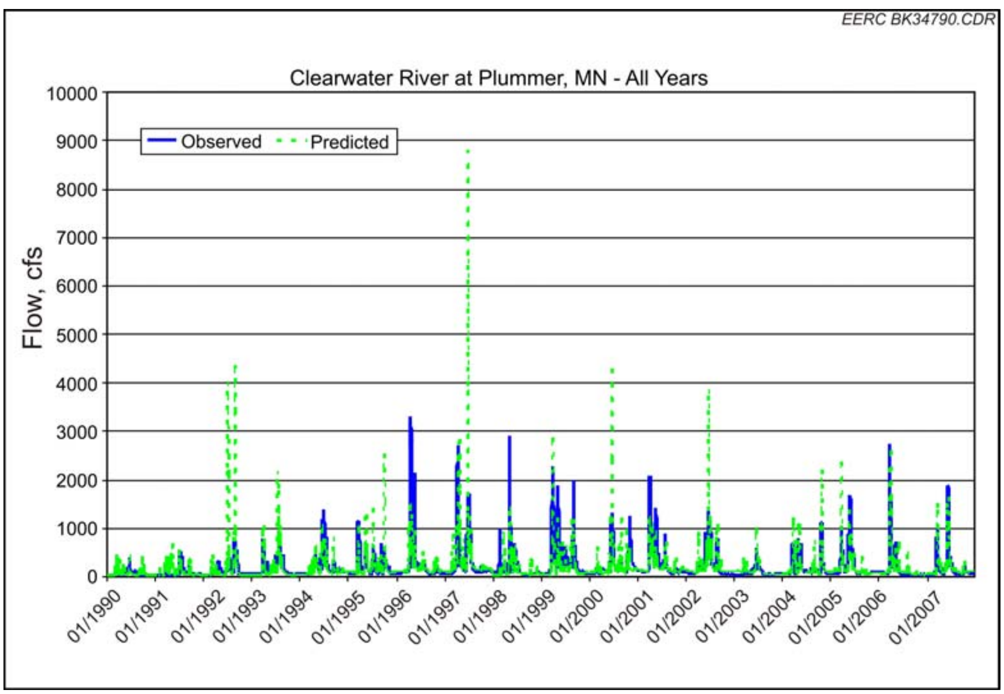

Figure 17. Comparison of the USGS-observed versus model-predicted flow for all years for the Clearwater River at Plummer, Minnesota.

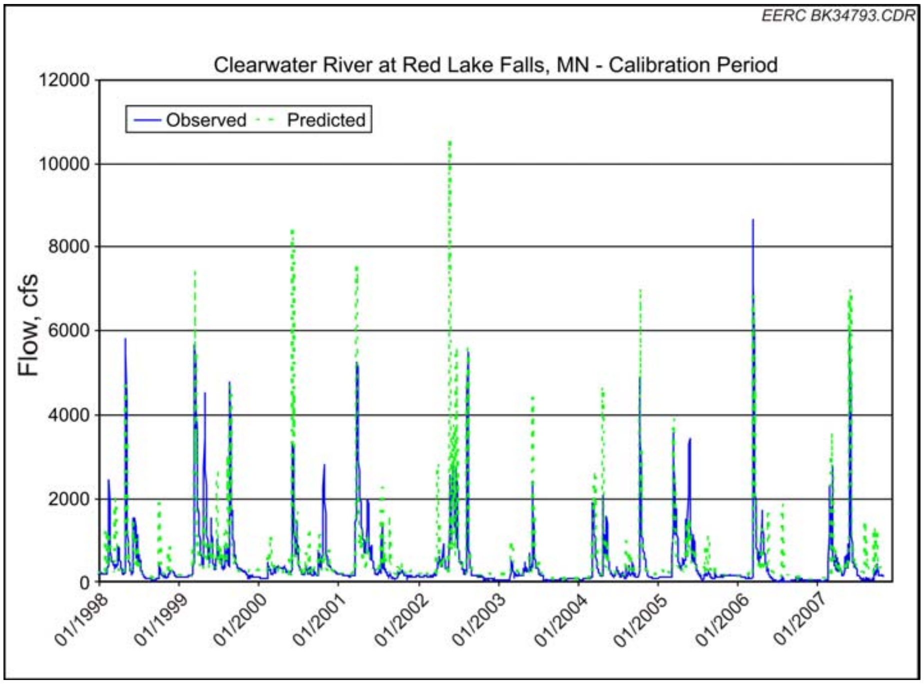

Figure 18. Comparison of the USGS-observed versus model-predicted flow for the calibration period for the Clearwater River at Red Lake Falls, Minnesota.

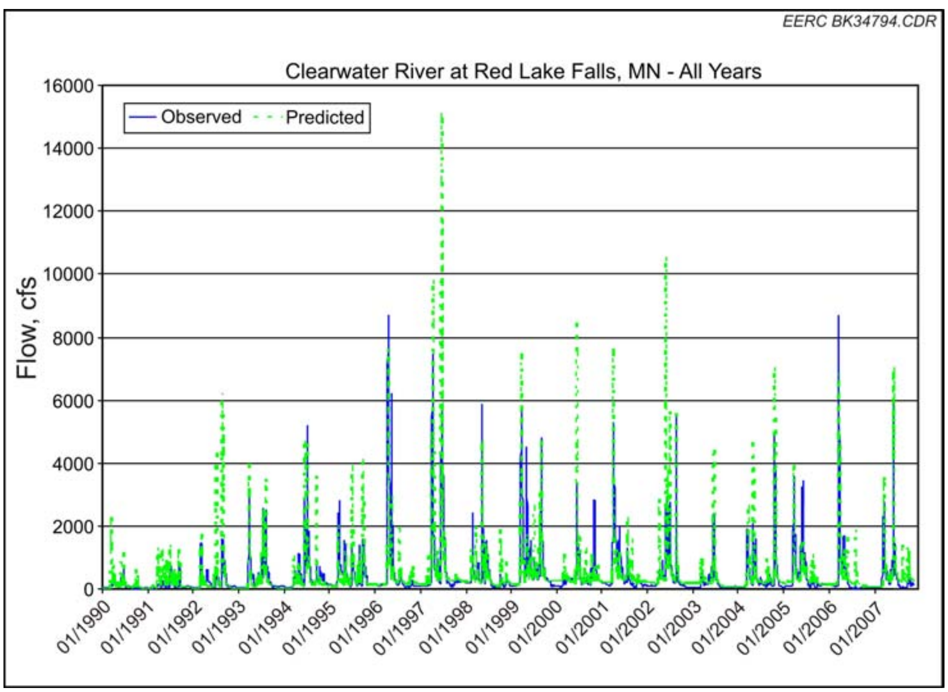

Figure 19. Comparison of the USGS-observed versus model-predicted flow for all years for the Clearwater River at Red Lake Falls, Minnesota.

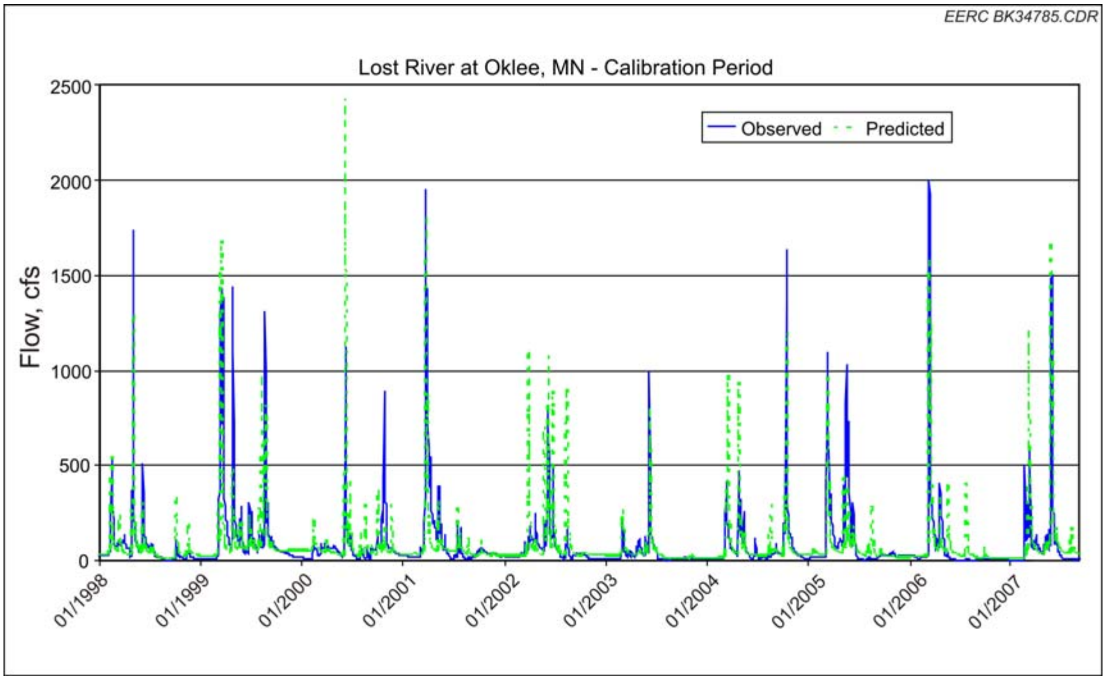

Figure 20. Comparison of the USGS-observed versus model-predicted flow for the calibration period for the Lost River at Oklee, Minnesota.

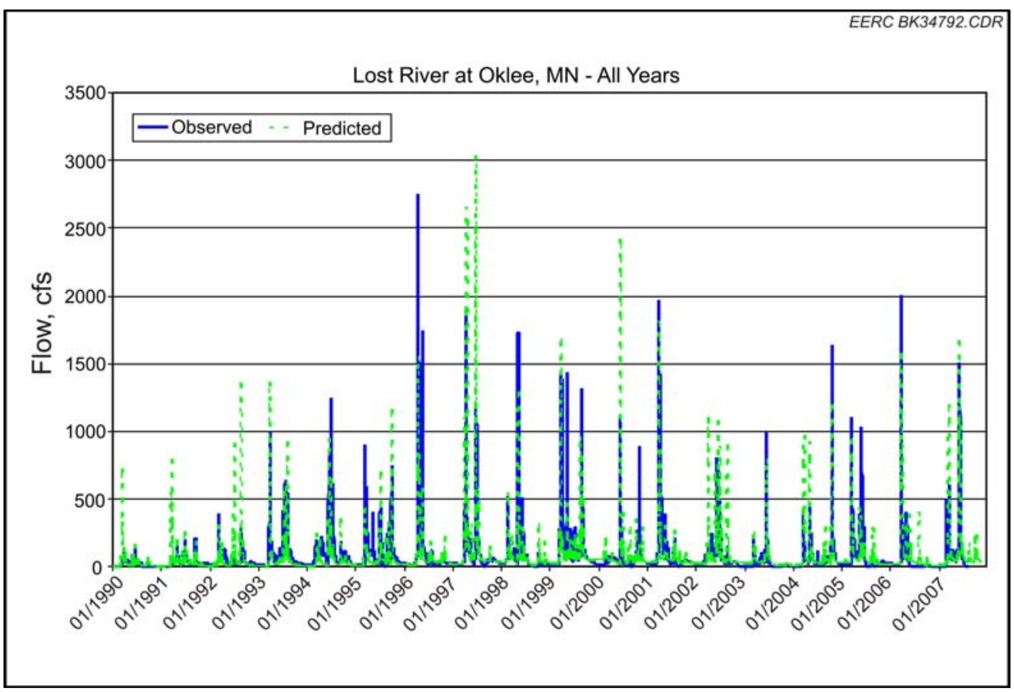

Figure 21. Comparison of the USGS-observed versus model-predicted flow for all years for the Lost River at Oklee, Minnesota.

Table 5. Base Flow Contributions at Each of the USGS Gaging Stations as Estimated by the Base Flow Separator Program

USGS Gaging Station Location	Average Base Flow Contribution, %	Base Flow Recession Time*
Clearwater River at Plummer	55	241
Clearwater River at Red Lake Falls	53	200
Lost River at Oklee	43	80

* The base flow recession time is the amount of time it takes for the flow in the river to return to pre-base flow conditions.

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 NSE 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 Dvj is a measure of how the predicted annual discharge differs from the measured annual discharge. It is computed as:

$$D_{vj} = \frac{\sum_{i=1}^{n_j} Q_{\mathrm{sim}i}^{j} - \sum_{i=1}^{n_j} Q_{\mathrm{obs}i}^{j}}{\sum_{i=1}^{n_j} Q_{\mathrm{obs}i}^{j}} \times 100\%$$

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

As seen in Table 6, the Dvj and NSE values for the calibration period of the Clearwater River are significantly better than the validation period. This is not surprising given the very low flow years experienced during 1990 and 1992. While the model appears to significantly overpredict the flows at Red Lake and at Oklee for these years, it may also be a result of the poor accuracy of gage data at very low flow conditions. Overall, the statistics for the calibration years look good, and the average NSE and Dvj values are well within acceptable ranges for model calibration.

Table 6. Statistical Parameters Used to Evaluate the Clearwater River SWAT Model During the Calibration and Validation Period (the calibration period is highlighted in blue)

Year	Clearwater River at Plummer		Clearwater River at Red Lake Falls		Lost River at Oklee	
	Dvj	NSE	Dvj	NSE	Dvj	NSE
1990	−11.8	−1.36	53.21	−4.25	38.67	−4.24
1991	12.4	−0.45	67.45	−1.43	12.90	−1.63
1992	13.3	−7.95	39.45	−6.36	35.12	−6.54
1993	−19.5	−0.07	−18.28	0.68	−32.82	0.47
1994	−28.8	0.47	−20.67	0.57	−46.85	0.44
1995	-6.0	−0.21	−15.97	−0.03	−34.92	0.18
1996	−28.5	0.54	−27.11	0.63	−48.54	0.49
1997	-1.7	−0.49	5.40	−0.07	15.28	−0.73
1998	2.0	0.56	-4.71	0.69	-9.97	0.81
1999	−25.1	0.54	−23.52	0.58	−28.47	0.45
2000	0.4	−0.34	10.96	−0.15	5.64	0.23
2001	−27.5	0.60	−17.17	0.63	−36.22	0.61
2002	12.9	0.15	26.93	0.12	34.56	−0.68
2003	15.2	0.28	34.60	0.48	11.95	0.88
2004	−13.8	0.02	14.96	0.57	−1.81	0.64
2005	−23.7	0.52	−20.04	0.58	−32.87	0.48
2006	2.6	0.60	5.04	0.80	10.98	0.67
2007	2.8	0.68	16.41	0.63	18.24	0.61
	Average for Calibration Period					
	−1.4	**0.36**	**4.35**	**0.49**	**−2.8**	**0.47**

4.3 Sediment Calibration

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 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 Clearwater River model was run on a daily time step, these values are reported for every day of the simulation period for each of the 201 stream reaches and can be used for comparison with measured water quality data.

While there are several MPCA water quality stations located throughout the Clearwater River Watershed, only stations with relatively long or recent data records were selected for comparison with model-predicted flows. In addition, stations were selected throughout the watershed to ensure that most major stream reaches were included in the evaluation of model performance. There is one caveat with using the data from these stations for model calibration. The sites were 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.

The suspended sediment concentrations predicted by SWAT versus the measured TSS concentrations for five evaluation locations are shown in Figures 22–26. The predicted values appear to match the measured values pretty well, and although some values are over- or under-predicted, most appear to be within the range of measured values, except at the Silver Creek site near Gonvick (Figure 24). The SWAT-predicted sediment concentrations appear to be high, especially for storm events. There is a possibility that the measured data are missing some of the higher-sediment concentrations that occur during high-flow events (as indicated by the one high value shown the summer of 2003), but it is not very likely. It is important to keep in mind that since the 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 are predicted 3 or 4 days late, the highest sediment concentrations may occur 3 or 4 days later. For this reason, when comparing observed versus measured sediment data, 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).

The total predicted annual sediment loading for the calibration period is shown in Table 7. These values are on the low side of the sediment-loading estimates for many of the RRB tributaries (Paakh et al., 2006), but they are still within an acceptable range. Given the relatively low turbidity levels in the Clearwater River and its tributaries, one would expect the predicted sediment loading to be lower than other rivers in the RRB.

4.4 FC Calibration

After calibration of the bacteria-related parameters in SWAT, the model-predicted FC concentrations seem to match reasonably well with measured values (Figures 27–31). Some of the concentrations during higher-flow events may be overestimated; however, it is difficult to determine when comparing with limited observed data. The comparison of the predicted versus measured data at the Clearwater Station near County Road 96 (S002-121) appears to be the least accurate. This may indicate that the contribution of FC bacteria from waterfowl within the wild rice paddies are overestimated. Without having more detailed data on the return flows from the rice paddies, it is difficult to predict the FC bacteria loading from these areas.

4.5 Nutrient Calibration

The nutrient calibration focused on nitrogen (as nitrate- and nitrite-N) and total P. Initially, efforts were made to calibrate the model for DO, since that is one of the primary impairments within the watershed. Unfortunately, the DO output predicted by SWAT is currently unreliable and has not been widely tested. Additional programming is needed to update this component of the model so that it more accurately represents dissolved oxygen output (R. Srinivasan, personal communication, January 2009). Since further calibration of the model for dissolved oxygen was pointless and the focus of this project was on evaluating the sediment and FC impairments within the watershed, less time was spent on the nutrient portion of the model calibration. After adjusting the parameters that control the amount of denitrification that occurs within the subsurface, the comparison of predicted versus measured values for N look quite good

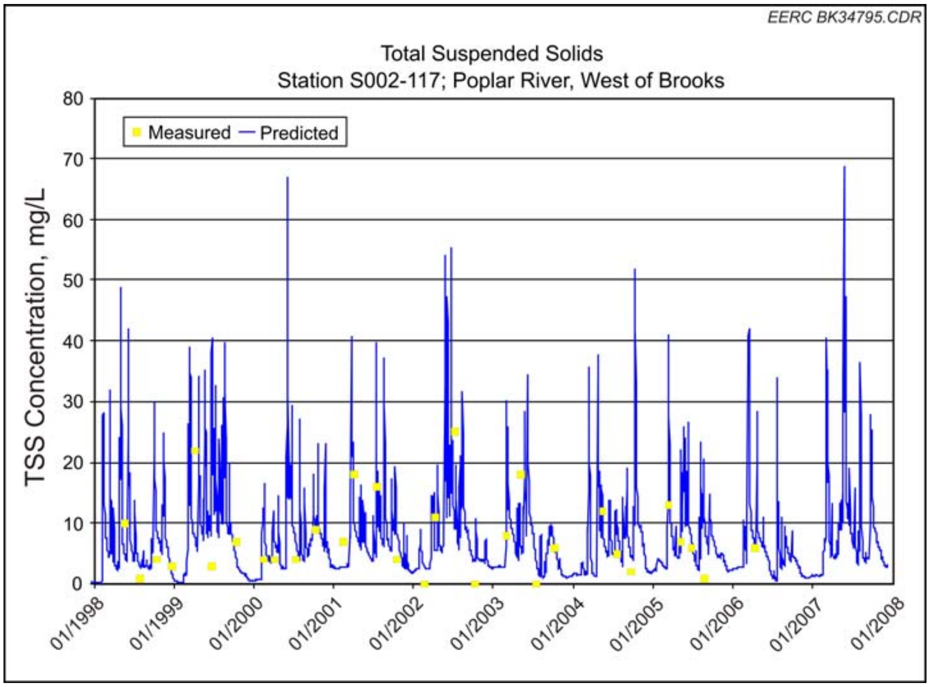

Figure 22. Comparison of measured versus SWAT-predicted sediment concentrations at the Poplar River station west of Brooks.

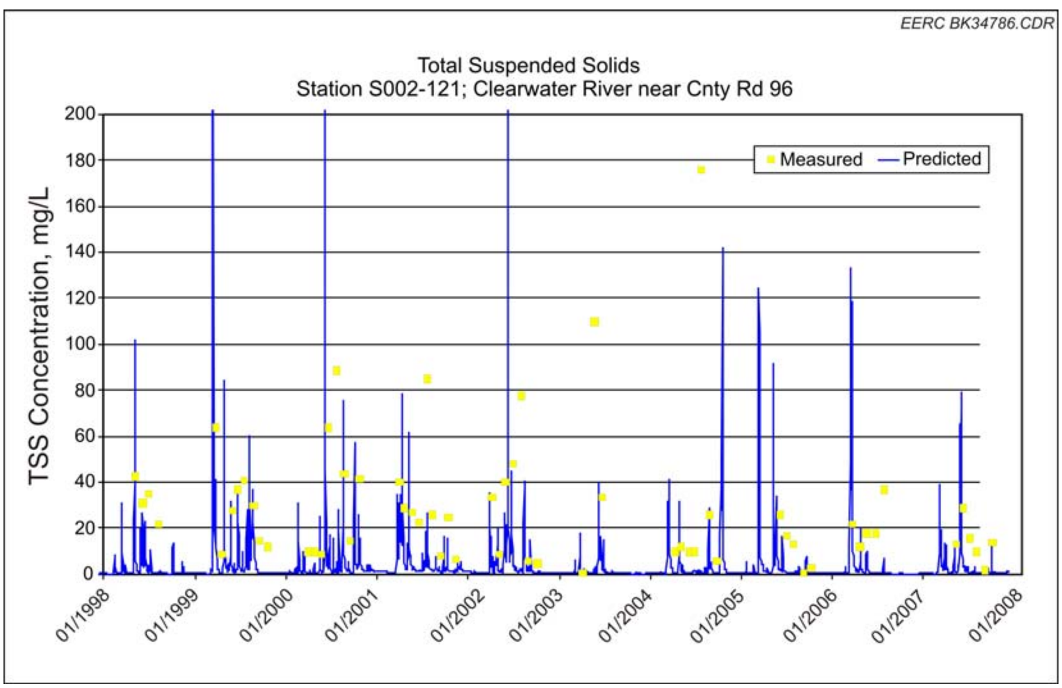

Figure 23. Comparison of measured versus SWAT-predicted sediment concentrations at the Clearwater River station near County Road 96.

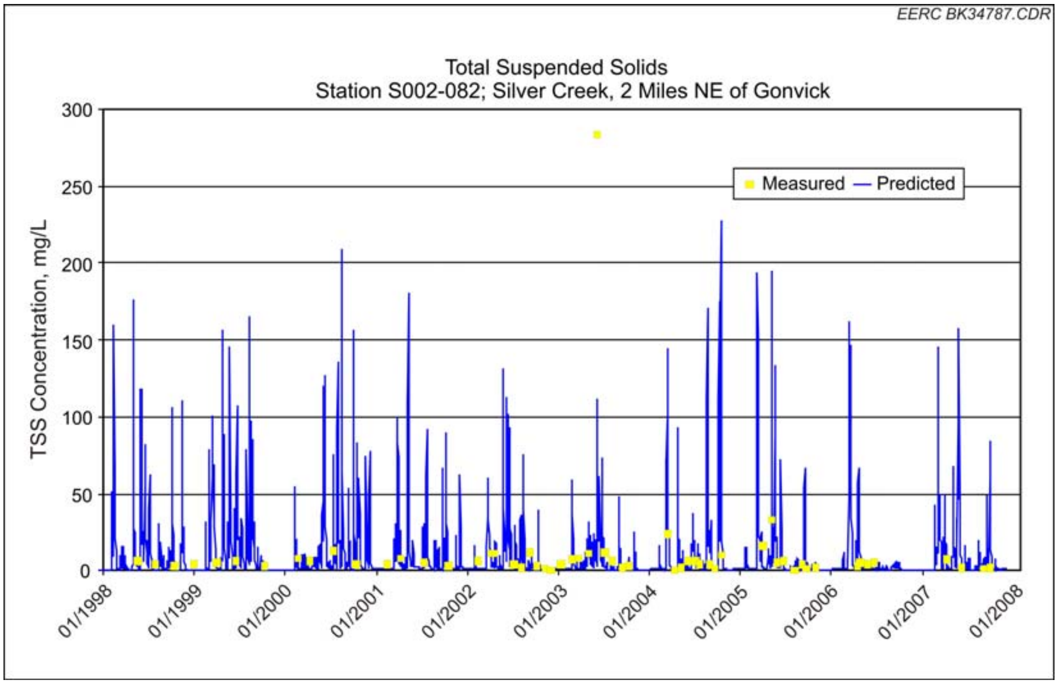

Figure 24. Comparison of measured versus SWAT-predicted sediment concentrations at the Silver Creek station, 2 miles northeast of Gonvick.

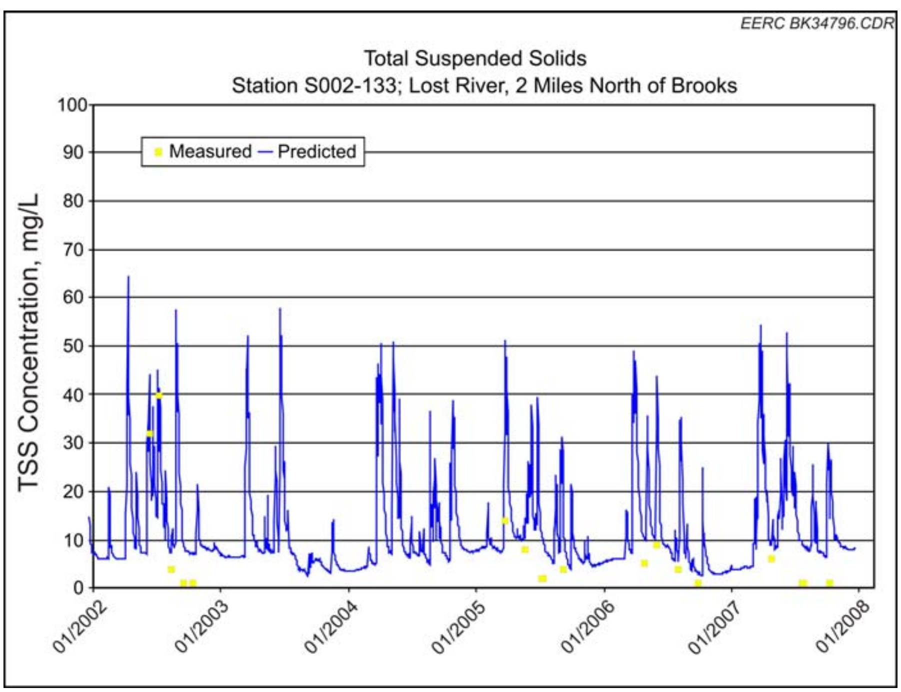

Figure 25. Comparison of measured versus SWAT-predicted sediment concentrations at the Lost River station, 2 miles north of Brooks.

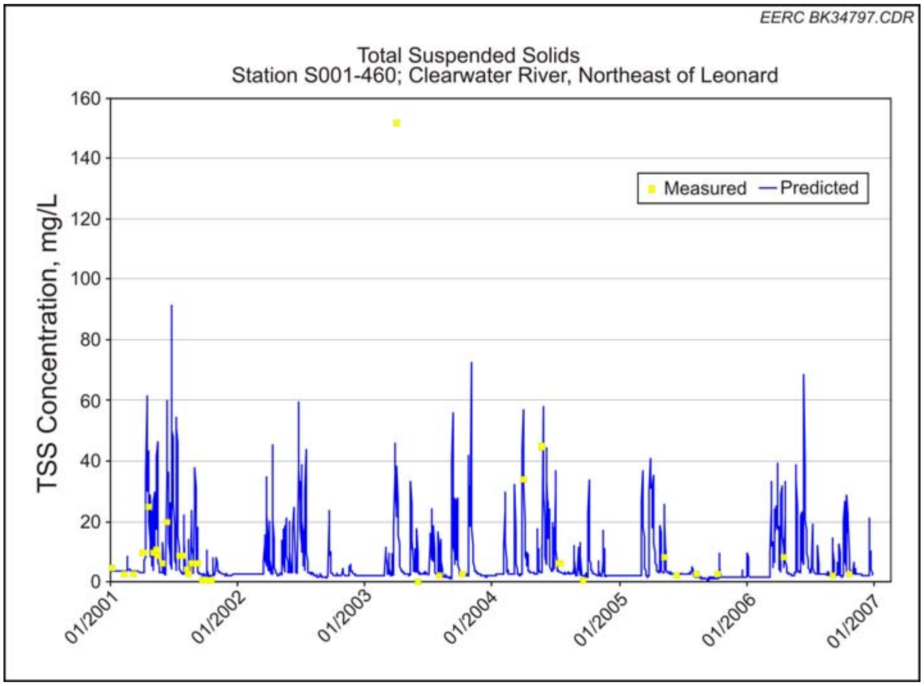

Figure 26. Comparison of measured versus SWAT-predicted sediment concentrations at the Clearwater River station northeast of Leonard.

Table 7. The Predicted Annual Sediment Loading and Average Sediment Concentration at the Outlet of the Watershed

Year	Predicted Sediment Loading, metric tons	Average Annual Sediment Concentration, mg/L
1998	8249	13.8
1999	12,121	14.4
2000	9114	12.8
2001	7734	13.7
2002	17,919	14.4
2003	4386	8.8
2004	9614	11.1
2005	6160	10.3
2006	8192	8.9
2007	11,011	12.0

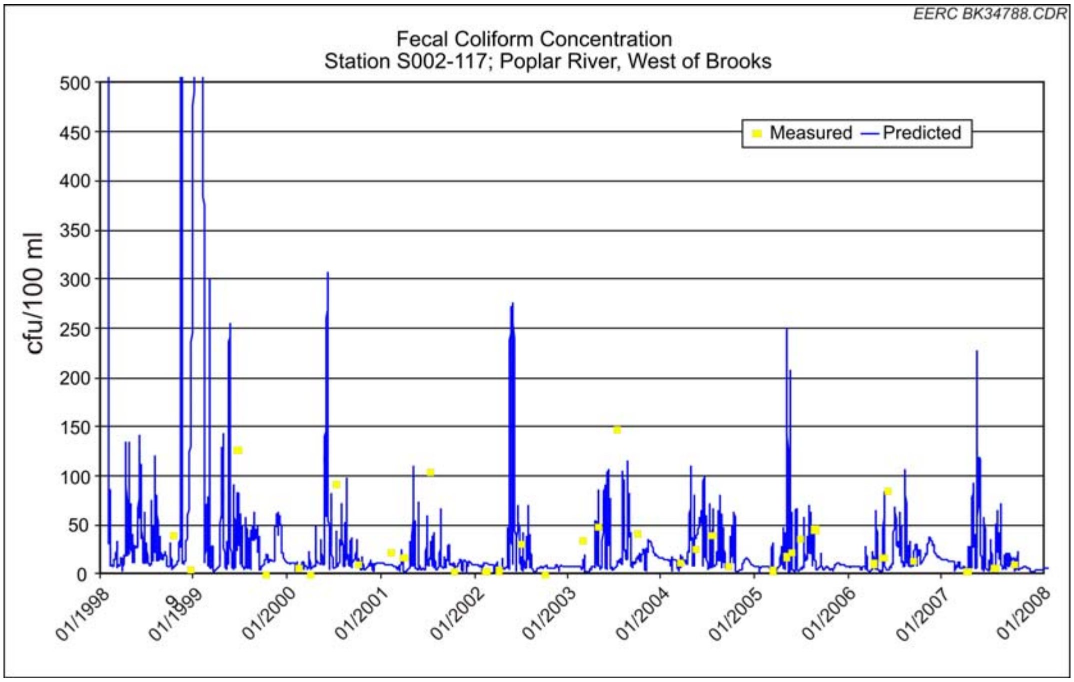

Figure 27. Comparison of measured versus SWAT-predicted FC concentrations at the Poplar River station west of Brooks.

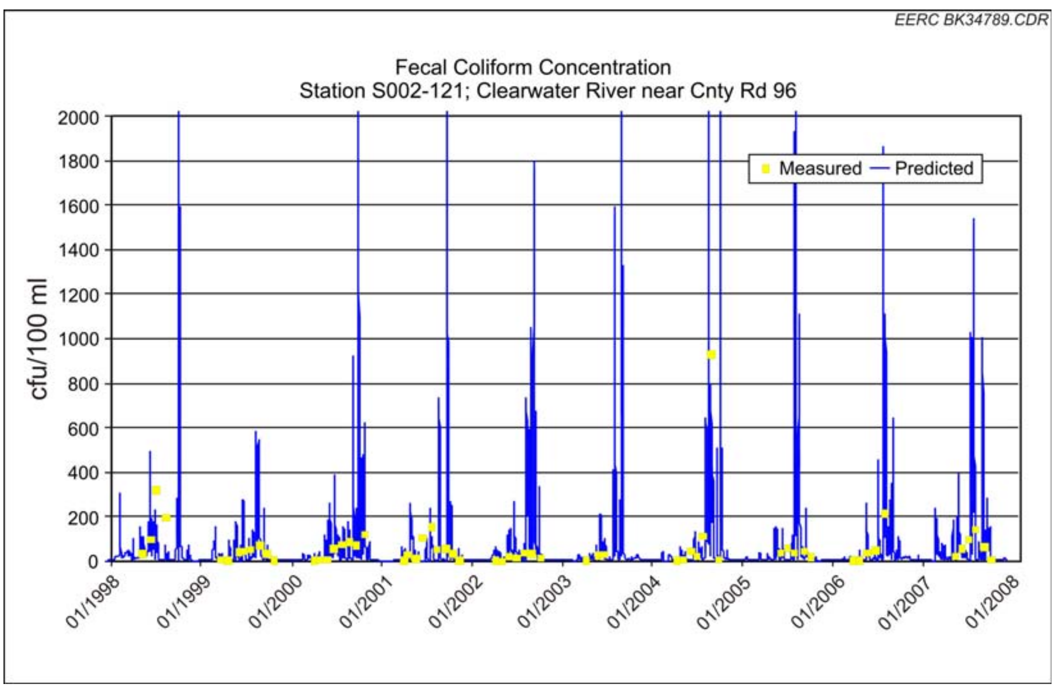

Figure 28. Comparison of measured versus SWAT-predicted FC concentrations at the Clearwater River station near County Road 96.

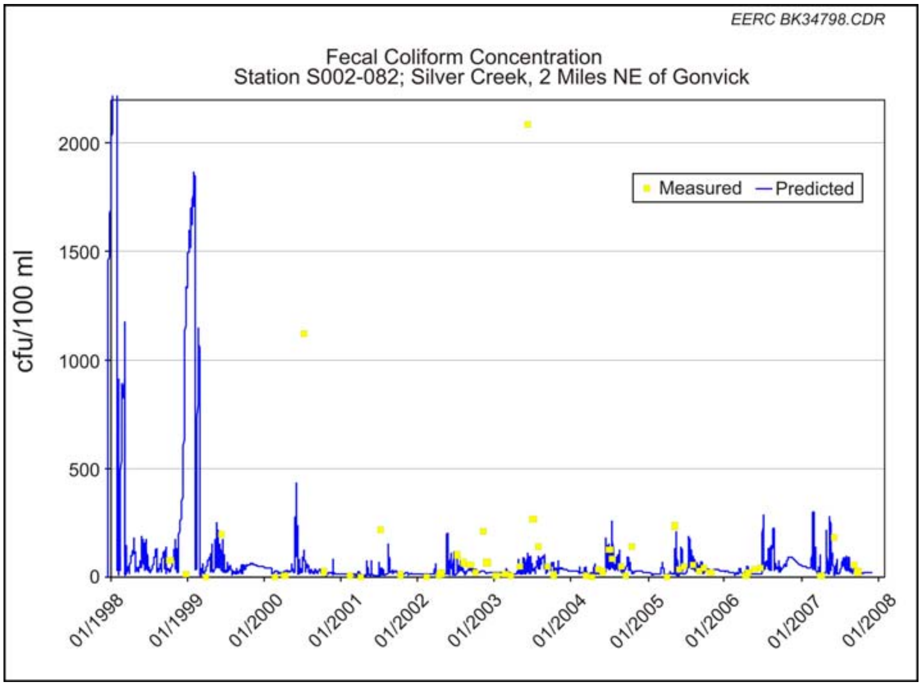

Figure 29. Comparison of measured versus SWAT-predicted FC concentrations at the Silver Creek station, 2 miles northeast of Gonvick.

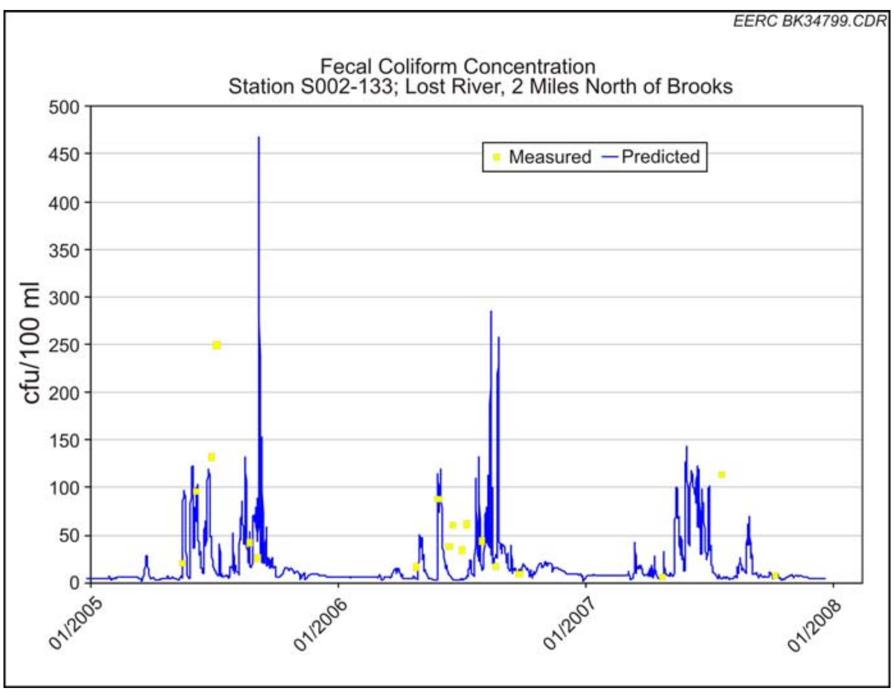

Figure 30. Comparison of measured versus SWAT-predicted FC concentrations at the Lost River station, 2 miles north of Brooks.

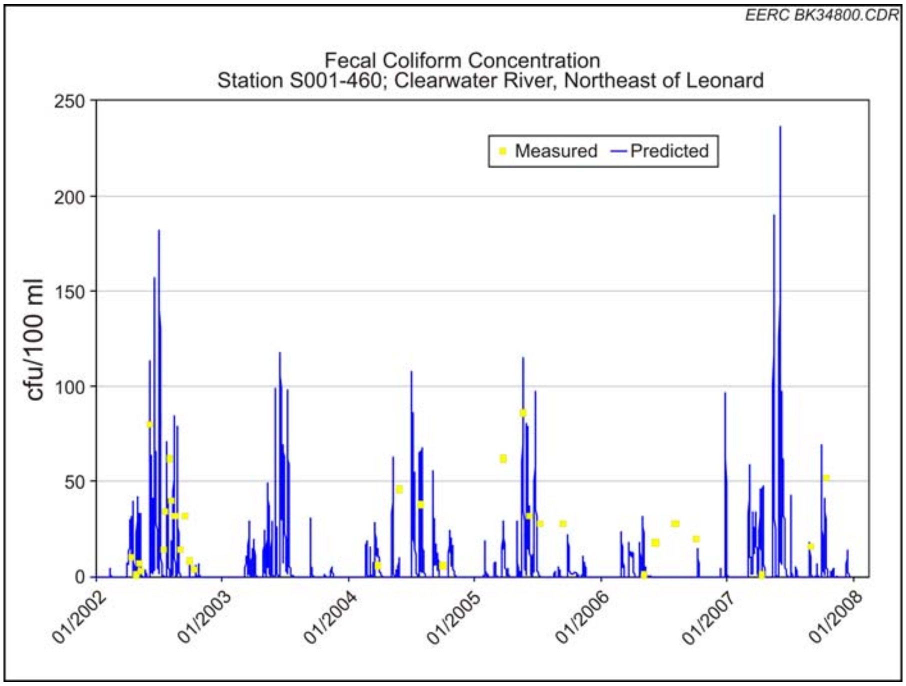

Figure 31. Comparison of measured versus SWAT-predicted FC concentrations at the Clearwater River station northeast of Leonard.

(Figures 32–36). As with the sediment and FC results, some of the concentrations may be overpredicted during storm events, but again, it is difficult to tell with limited observed data.

The P results predicted by SWAT appear to be less accurate (Figure 37–41), and additional calibration is needed for high-flow events. The predicted P concentrations appear acceptable during lower-flow events.

5.0 WATER QUALITY EVALUATION AND IMPLEMENTATION OF HYPOTHETICAL BMPS

The following section describes the predicted distribution of sediment, nutrient, and FC loading within the watershed and presents the results of several BMP implementation scenarios. While it is possible to evaluate a variety of options for BMP implementation, a systematic approach was used that evaluated the implementation of BMPs if implemented in 25%, 50%, and 75% of the Clearwater River subbasins. For reporting purposes, the impacts of the various BMP implementation scenarios were assessed at the outlet of the watershed; however, the data generated by this project allow for evaluation of the results within any subbasin or subbasin reach.

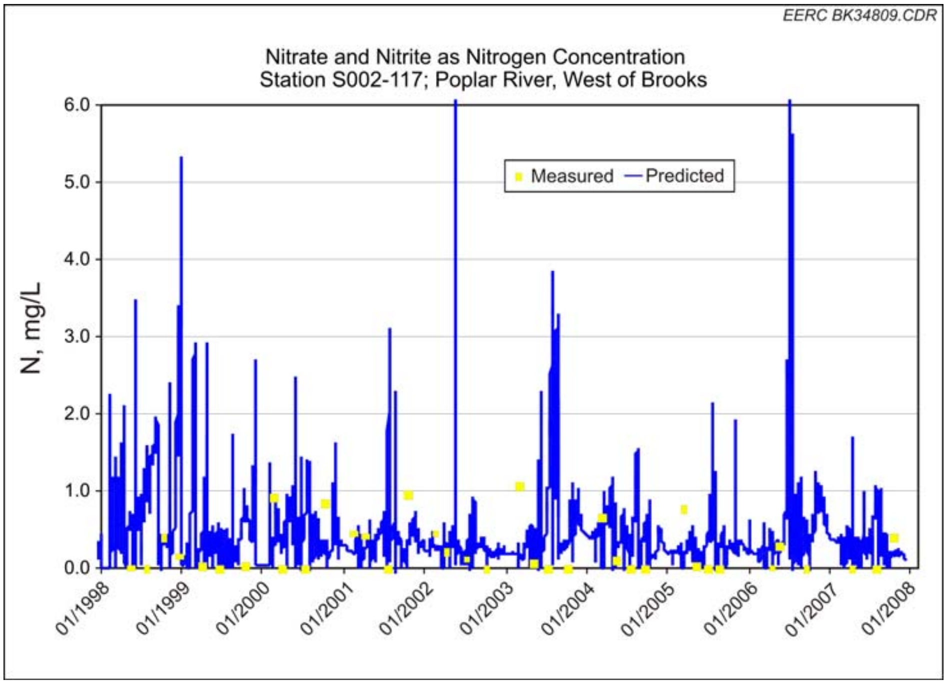

Figure 32. Comparison of measured versus SWAT-predicted nitrate- and nitrite-N concentrations at the Poplar River station west of Brooks.

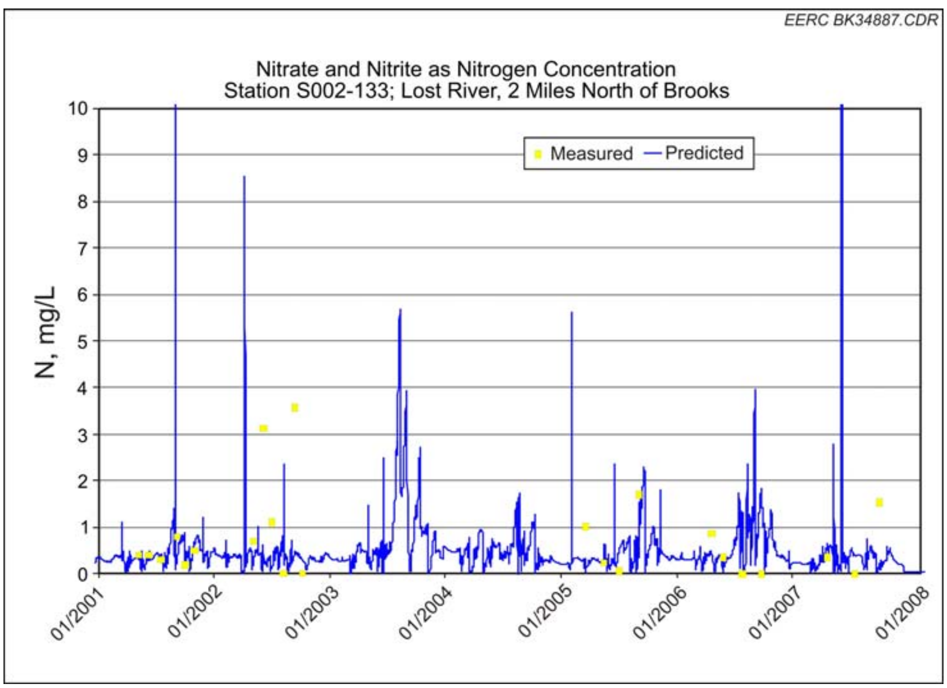

Figure 33. Comparison of measured versus SWAT-predicted nitrate- and nitrite-N concentrations at the Lost River station, 2 miles north of Brooks.

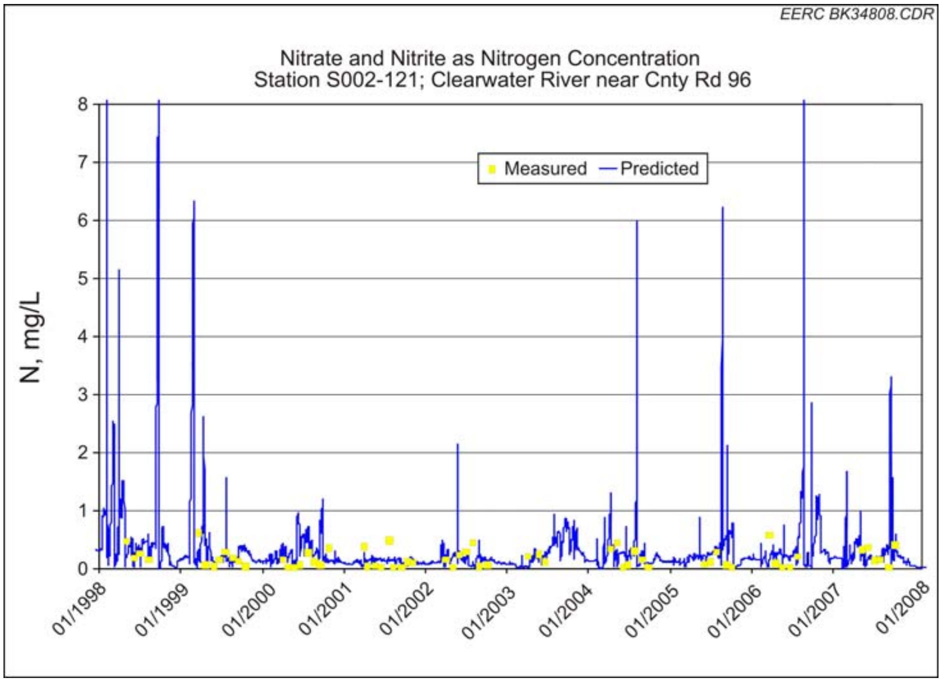

Figure 34. Comparison of measured versus SWAT-predicted nitrate- and nitrite-N concentrations at the Clearwater River station near County Road 96.

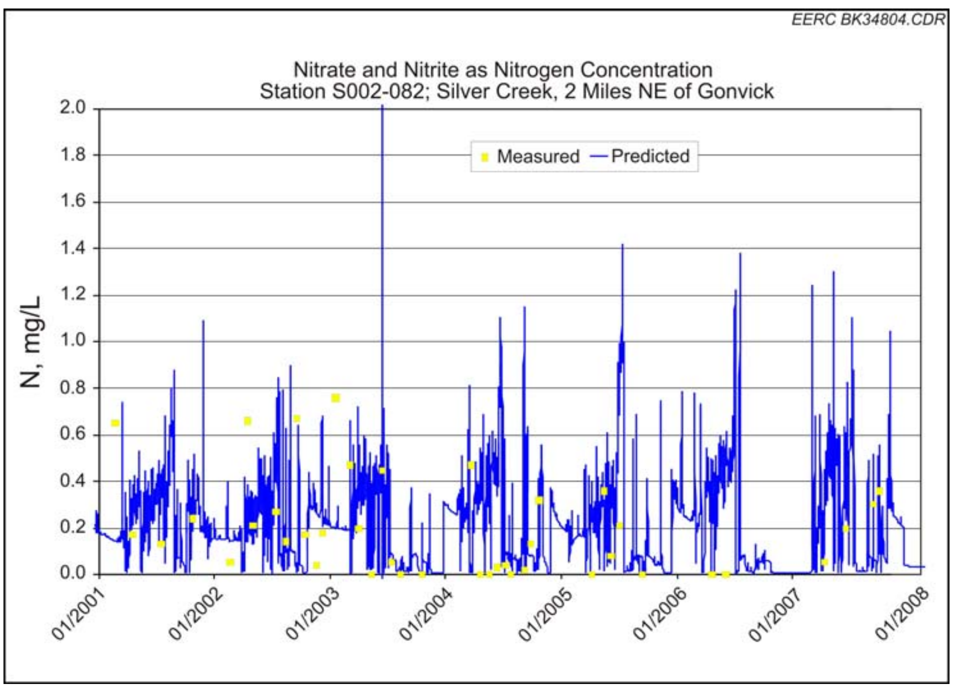

Figure 35. Comparison of measured versus SWAT-predicted nitrate- and nitrite-N concentrations at the Silver Creek station, 2 miles northeast of Gonvick.

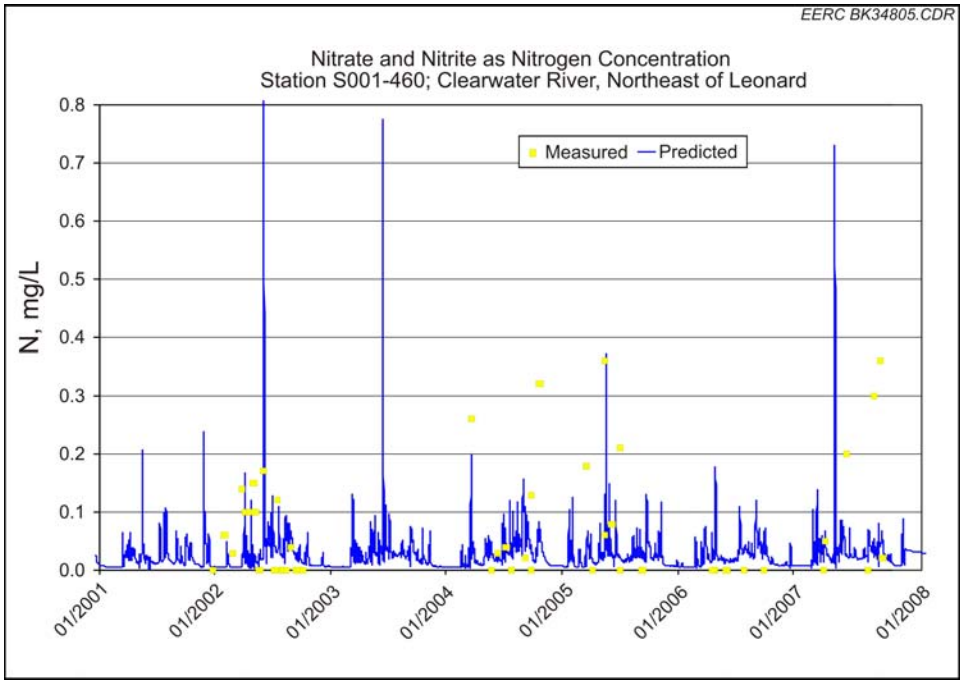

Figure 36. Comparison of measured versus SWAT-predicted nitrate- and nitrite-N concentrations at the Clearwater River station northeast of Leonard.

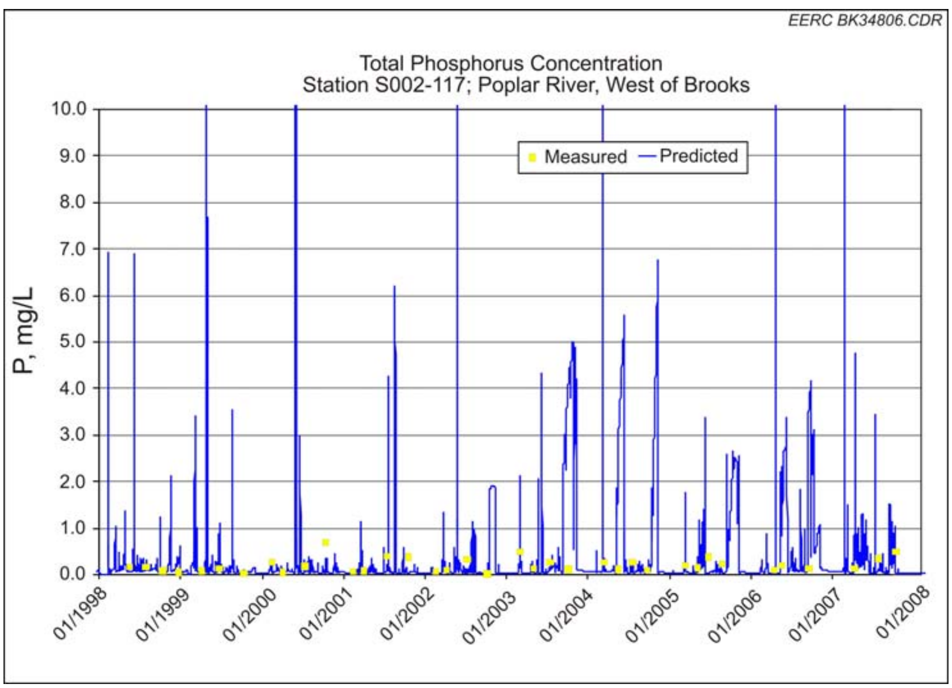

Figure 37. Comparison of measured versus SWAT-predicted phosphorus concentrations at the Poplar River station west of Brooks.

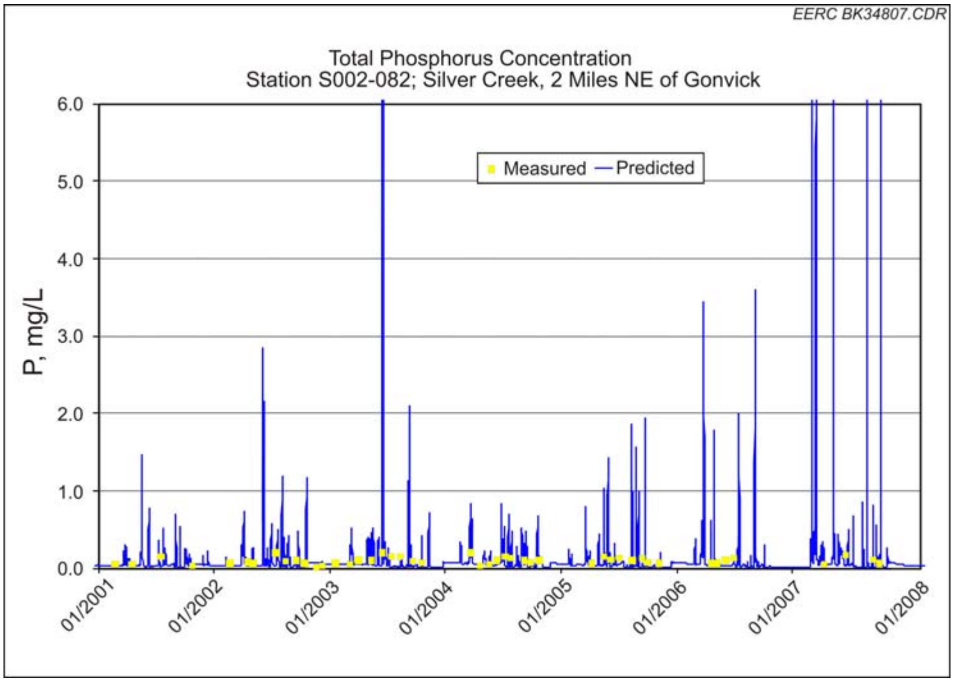

Figure 38. Comparison of measured versus SWAT-predicted phosphorus concentrations at the Silver Creek station, 2 miles northeast of Gonvick.

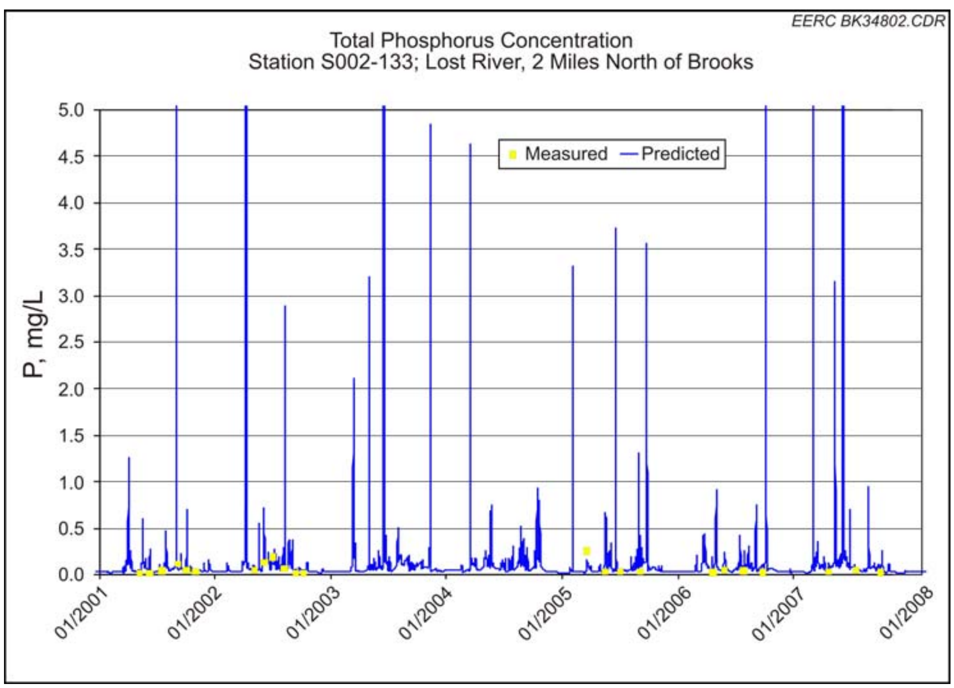

Figure 39. Comparison of measured versus SWAT-predicted phosphorus concentrations at the Lost River station, 2 miles north of Brooks.

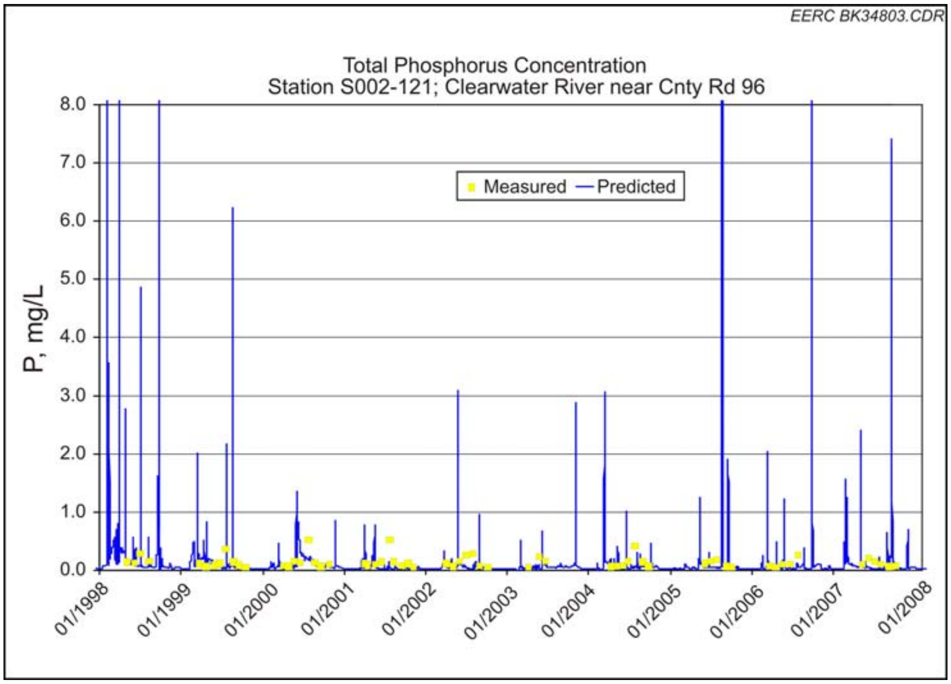

Figure 40. Comparison of measured versus SWAT-predicted phosphorus concentrations at the Clearwater River station near County Road 96.

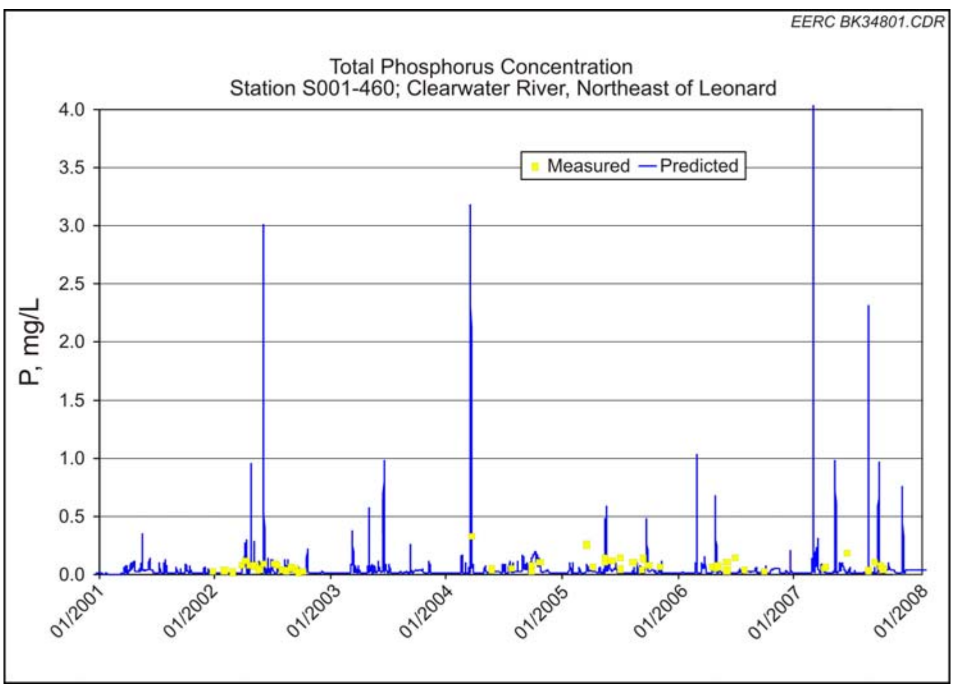

Figure 41. Comparison of measured versus SWAT-predicted phosphorus concentrations at the Clearwater River station northeast of Leonard.

5.1 Sediment and Nutrient Results

The predicted average annual sediment erosion from the subbasins within the Clearwater River Watershed is shown in Figure 42. 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. Also depicted in Figure 42 is the predicted sediment output, or loading, from the respective stream reach. As would be expected, since sediment loading is correlated to stream discharge, the highest amounts of sediment loading occur along the larger reaches with greater discharge. Figure 42 also illustrates that many of the subbasins with high rates of overland erosion have relatively low sediment-loading rates. This indicates that not all of the sediment that is eroded from the landscape and into the subbasin reaches is transported out of the subbasin. Figure 43 shows the predicted net sediment output within each of the subbasin reaches. This was calculated by subtracting the amount of sediment transported out of each reach from the amount of sediment coming in. Positive values indicate that more sediment is being deposited into the reach than is leaving, while negative values suggest 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 predicted sediment-bound P, as well as organic N and P, yield results are depicted in Figures 44–46. As would be expected, the distribution of sediment-bound P yields mirrors that of the sediment yields. The organic P and N yields also follow a pattern similar to as the sediment yields. This is likely a result of the watershed topography, soil properties, and attenuation to sediment and/or soil particles.

For the calibration period of the model (1998 to 2007), the average estimated sediment, organic N, and organic P yields and loads are shown in Table 8. For example, the average annual sediment erosion from Clearwater River Watershed is 0.167 tons/hectare, or 54,437 tons across the entire watershed. The average annual sediment loading at the watershed outlet for the calibration period is 9450 tons. This represents a delivery ratio of 17.3%, which indicates that only 17.3% of the sediment eroded from the landscape is being transported out of the watershed.

5.2 FC Loading Results

The predicted average annual FC concentrations for each reach are shown in Figure 47. The average concentration at the watershed outlet is predicted as 35.5 cfu/100 mL. The higher concentrations predicted by the model (dark blue) tend to be in smaller reaches with lower flows with direct inputs from animal feedlots. The actual FC concentrations in these reaches are probably not as high as indicated. For comparison purposes, Figure 48 shows the predicted average FC concentrations in the stream reaches overlaid with the location of the feedlots in the watershed. While some reaches downstream of areas with a high density of feedlots have elevated FC concentrations (such as along some of the Hill River segments), others reaches downstream of feedlots do not appear impacted (such as along Ruffy Brook).

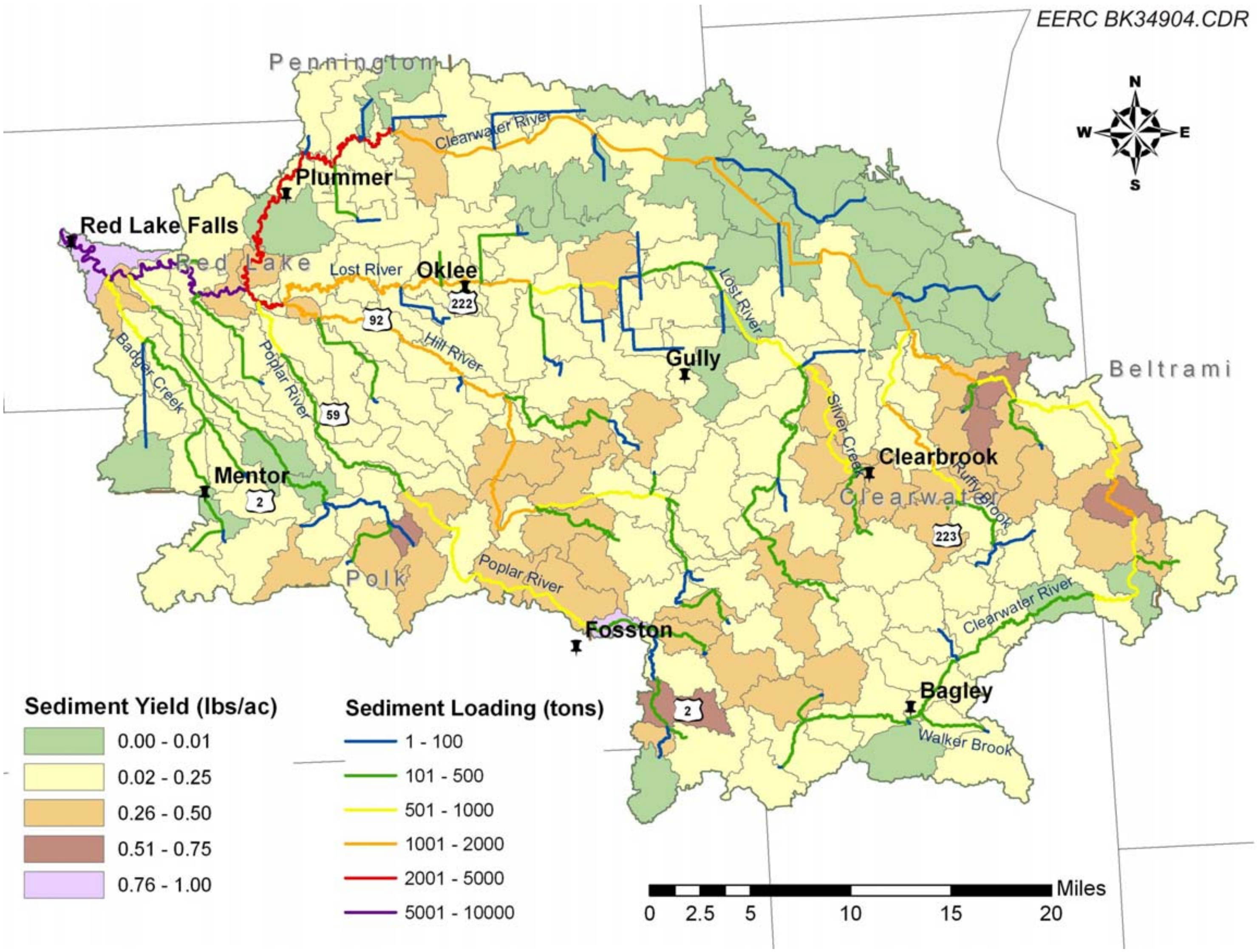

Figure 42. The estimated average annual sediment erosion from the landscape of each subbasin (sediment yield) and the estimated sediment loading within each reach of the Clearwater River Watershed.

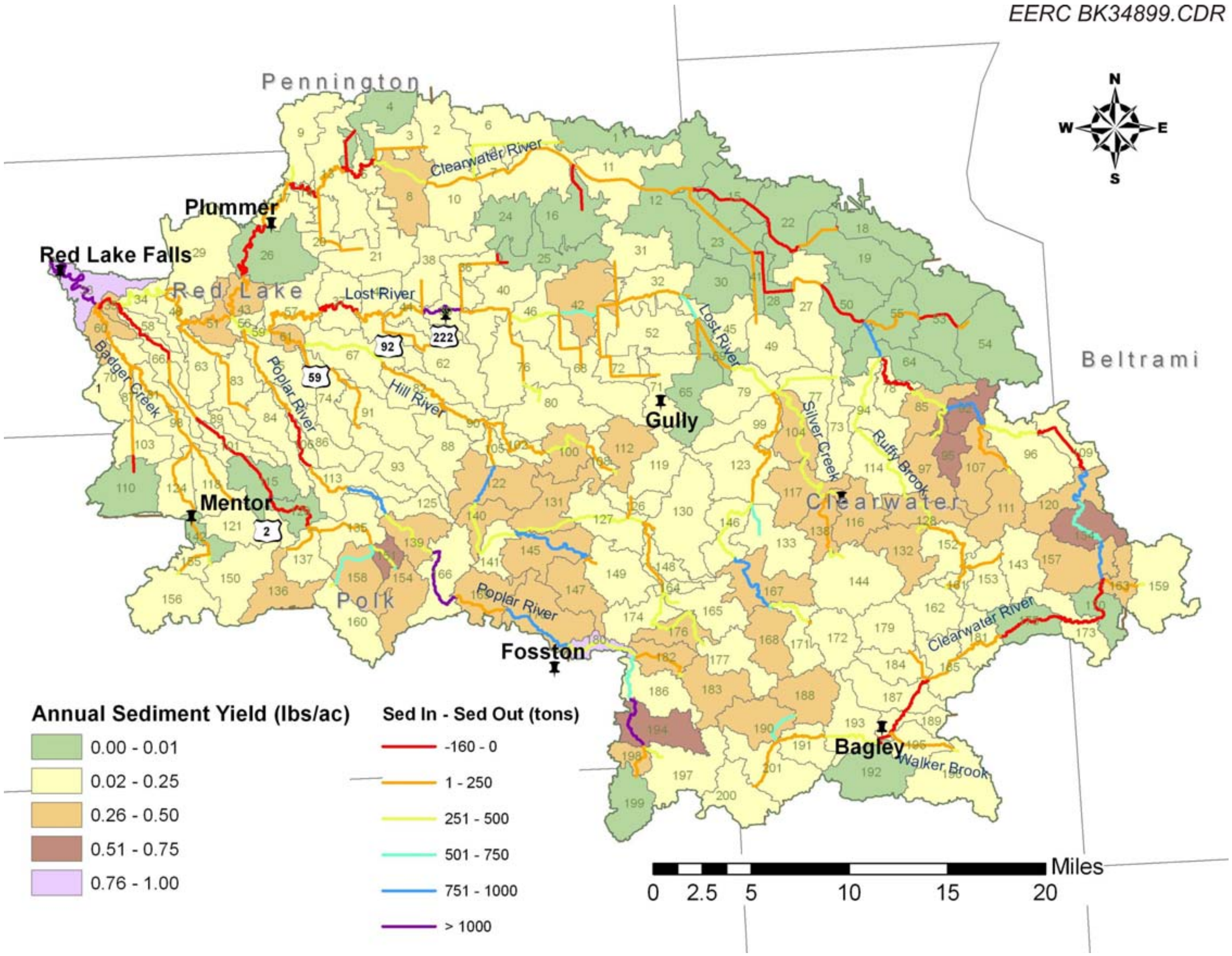

Figure 43. The estimated average annual sediment erosion from each subbasin and net sediment deposition (input minus output) within the waterways of the Clearwater River Watershed.

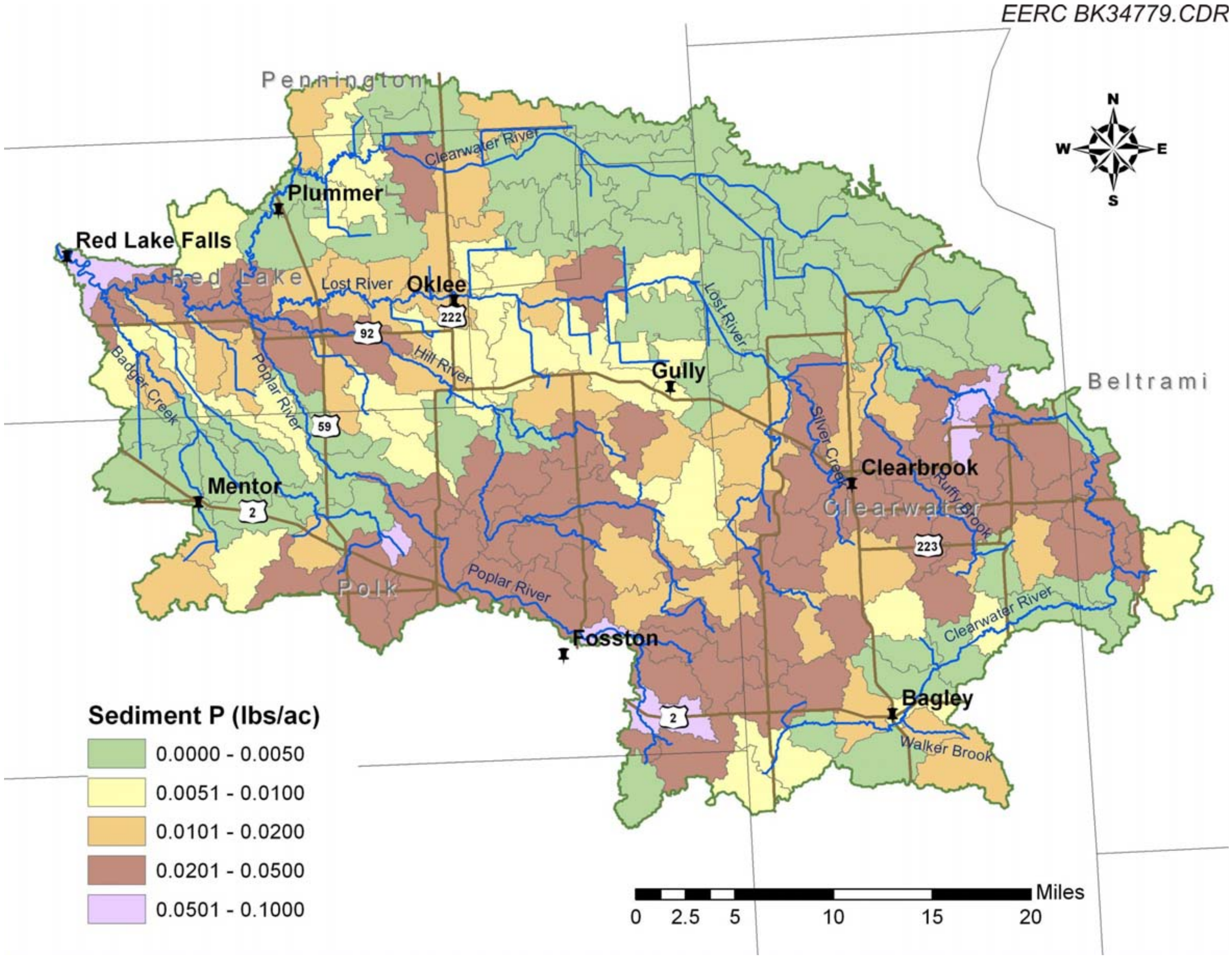

Figure 44. The predicted sediment-bound phosphorus yields within the Clearwater River Watershed.

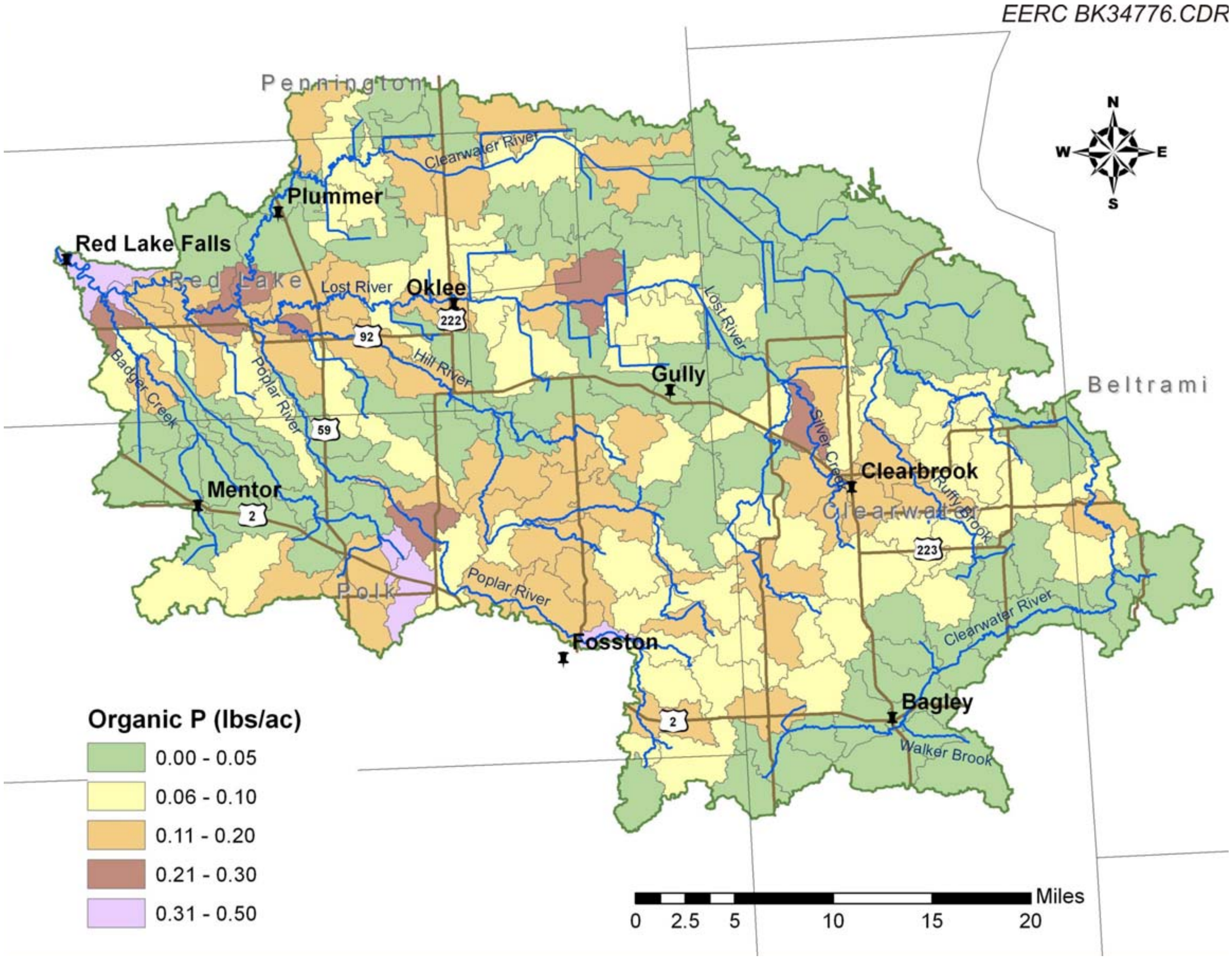

Figure 45. The predicted organic P yields within the Clearwater River Watershed.

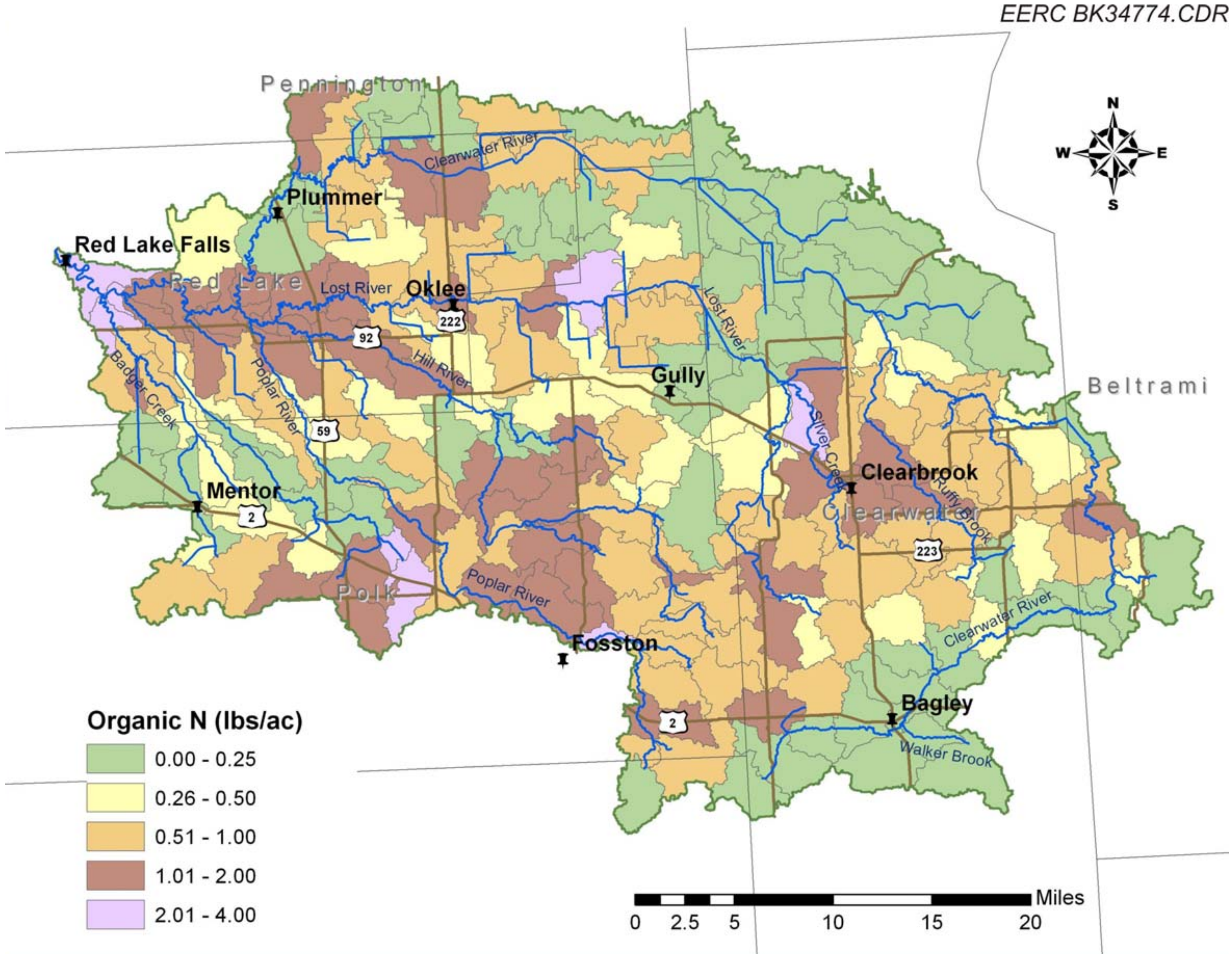

Figure 46. The predicted organic N yields within the Clearwater River Watershed.

Table 8. The Predicted Sediment, Organic N, and Organic P Yields Throughout the Clearwater River Watershed and Loading at the Outlet

Parameter	Yields	Loading Across Entire Watershed (metric tons)	Loading at Outlet (metric tons)	Delivery Ratio
Sediment	0.17 tons/ha	54,440	9450	17.3%
Organic N	0.77 kg/ha	259	507	51.1%
Organic P	0.09 kg/ha	31	60	51.7%

5.3 BMP Implementation

To evaluate how improvements in sediment, nutrient, and FC loading might be achieved within the Clearwater River Watershed, several BMP implementation scenarios were evaluated, including the following:

- Field buffers
- Exclusion of cattle from streams and waterways
- Channel/grade stabilization
- No-till farming
- Grassed waterways
- Rotational grazing
- Residue management
- Riparian buffers
- Stormwater management

For each practice, three scenarios were evaluated by assuming a 25%, 50%, and 75% implementation rate. For reporting purposes, the effectiveness of each measure was evaluated at the outlet of the watershed near Red Lake Falls. A brief description of how each of these practices was implemented in the model is described below.

Field Buffers: Field buffers typically range in width from 30 to 120 feet (Natural Resources Conservation Service, personal communication, 2008). To simulate the implementation of field buffers within the SWAT model, 60-foot (18.3-meter) buffers were applied to the agricultural crops in 25%, 50%, and 75% of the subbasins.

Cattle Exclusion: As previously discussed, the cattle operations with direct stream access were considered as sources of direct nutrient and FC loading. To simulate cattle exclusion practices, 25%, 50%, and 75% of these direct inputs were removed.

Channel/Grade Stabilization: To simulate this practice, the setting for channel erodibility was adjusted so as to limit the amount of erosion in the respective reach to negligible. This was implemented in 25%, 50%, and 75% of stream reaches.

No-Till Farming: The default setting of the model includes a generic spring and fall tillage practice. These practices were removed, and a no-till mixing operation was added to the spring. In addition, the Manning's roughness coefficient for the impacted fields was adjusted to simulate

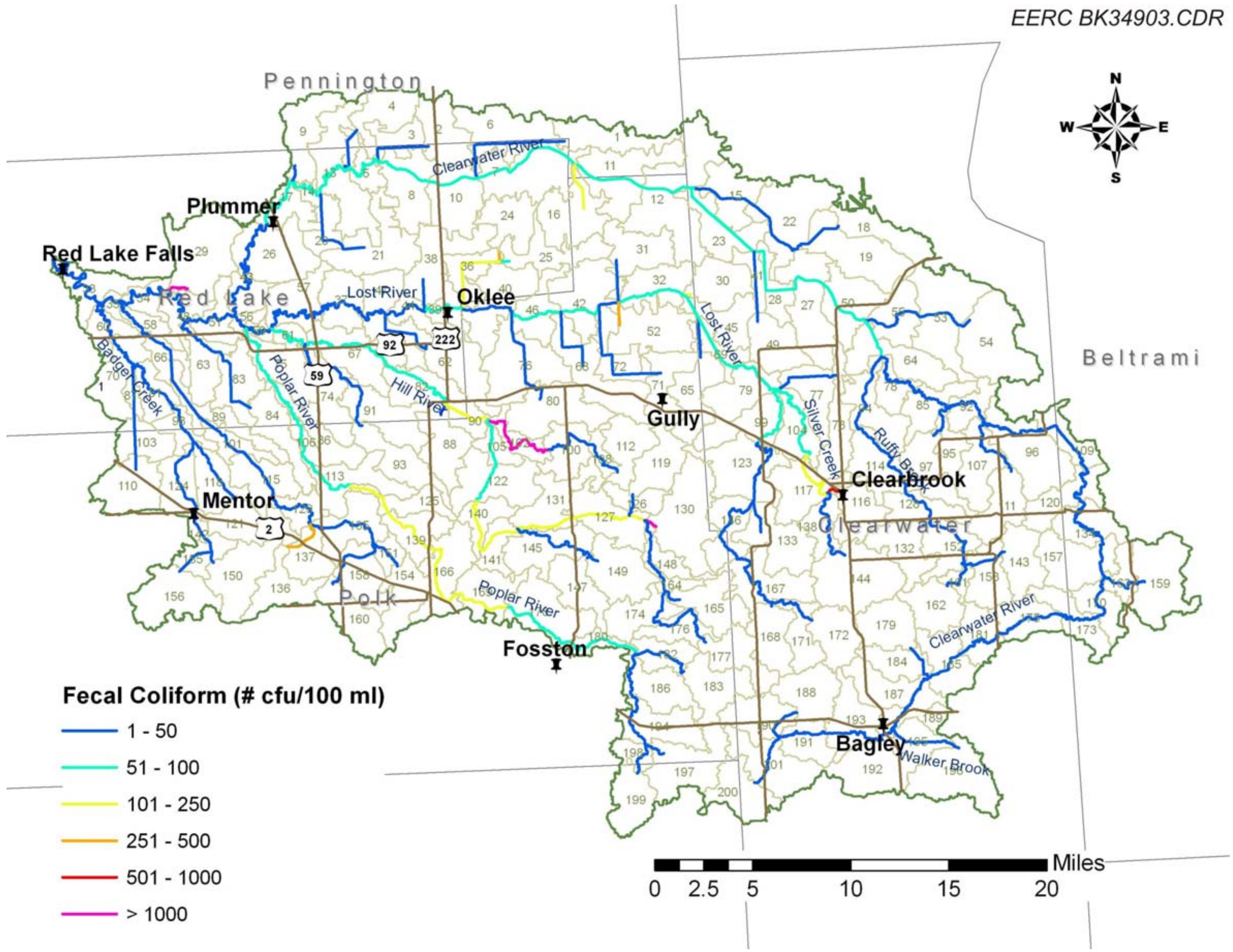

Figure 47. The predicted average annual FC concentrations in individual stream reaches.

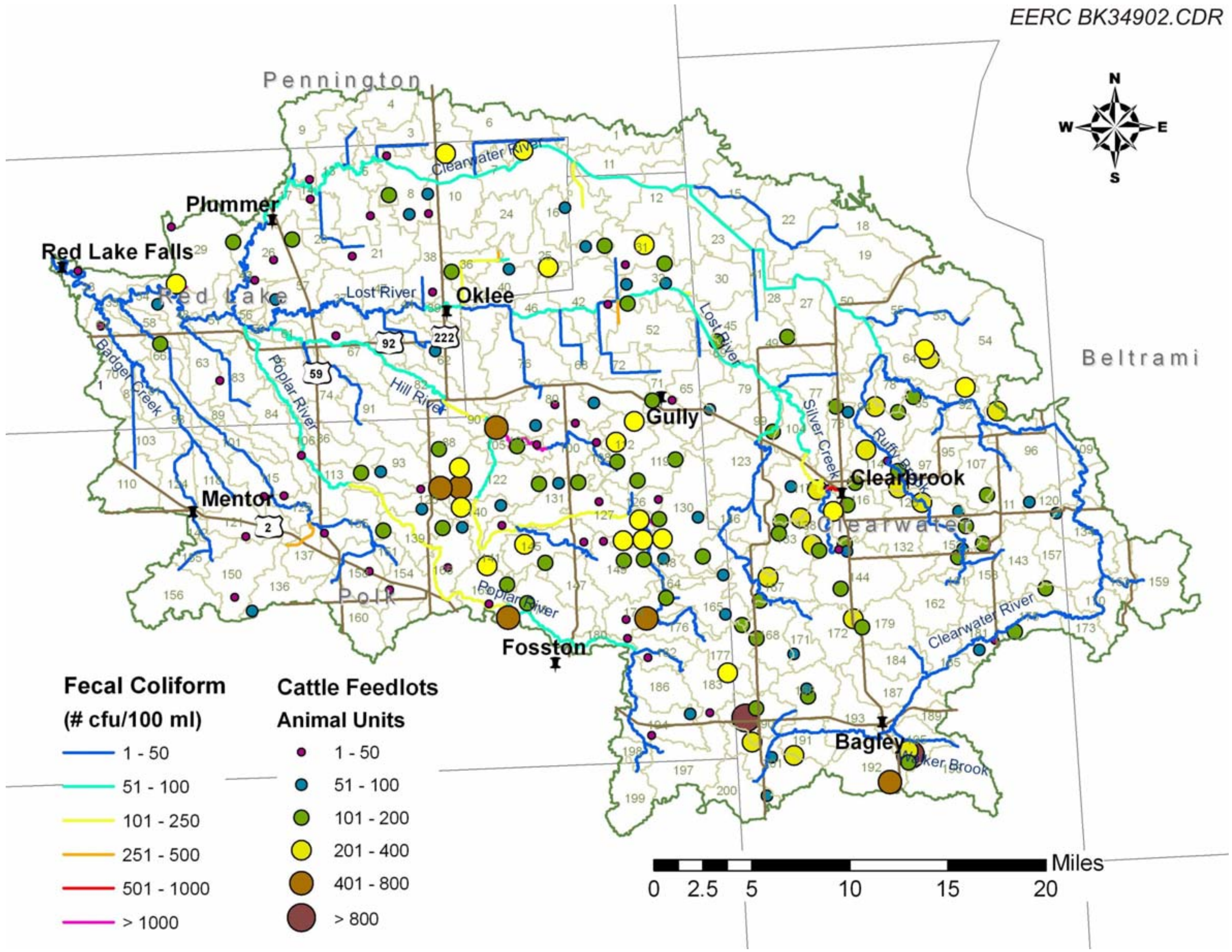

Figure 48. The location of feedlots within the watershed.

the increased crop residue on the surface. This practice was applied to the agricultural crops in 25%, 50%, and 75% of the subbasins.

Grassed Waterways: The settings for channel cover and channel roughness were adjusted to simulate this practice using values found in the literature. This was implemented in 25%, 50%, and 75% of stream reaches.

Rotational Grazing: This was simulated by reducing the amount of biomass consumed and biomass trampled in the grazing operations. It was implemented and applied to 25%, 50%, and 75% of the grazing operations in the watershed.

Residue Management: This practice was simulated by changing the default fall tillage practice to conservation tillage and adjusting the Manning's roughness coefficient of the respective field to a value representative of residue management. This practice was applied to the agricultural crops in 25%, 50%, and 75% of the subbasins.

Riparian Buffers: Riparian buffers were simulated by implementing 5-meter filter strips along rangeland and agricultural fields in the respective subbasin. The relatively small filter strip width was selected to account for the fact that in reality not all fields in the subbasin would contribute sediment and nutrients to the stream reach. This was implemented in 25%, 50%, and 75% of the subbasins.

Stormwater Management: By default, SWAT simulates the sediment, nutrient, and FC inputs from urban areas using a regression equation developed by USGS. To simulate stormwater management, the urban inputs from 25%, 50%, and 75% of the towns in the watershed were systematically excluded.

In addition to each of the scenarios listed above, three additional scenarios were run using the three most effective BMP measures evaluated in SWAT. The selection of the most effective BMP scenarios was somewhat subjective since a certain BMP may be the most effective at reducing sediment, but not as effective at reducing FC loading. Ultimately, a combination of residue management, field borders, and channel stabilization practices were implemented.

5.4 BMP Implementation Results

The results of the BMP implementation scenarios are shown in Table 9. In some cases, the SWAT-predicted nutrient loads increased after implementation of a BMP scenario, such as no-till farming. Where there is an increase in organic N and a decrease in nitrate, it is likely that transformations between N pools occurred, and that N loading decreased overall. Without additional calibration of the model for P, it is difficult to know if the increase in P is a result of inaccuracies in the model, inaccuracies in the way the BMP scenario was modeled, or if the predictions are correct. In the case of no-till farming, the roughness coefficient of the land decreases without residue management when compared to conventional tillage (Arabi et al., 2007), allowing additional surface runoff to occur. While adjustments were made in the model to increase the roughness coefficient of the land to values given in the literature for

Table 9. The Effectiveness of the Various BMP Implementation Scenarios Simulated in SWAT

BMP Implementation Scenarios (percentage of load reduction by parameter, practice, and implementation rate)					
	Sediment	FC	Organic and Mineral Phosphorus	Organic Nitrogen	Nitrate
25% Implementation Rate					
Combination of Three Most Effective	6.6	22.4	10.2	3.1	29.7
Field Border	2.3	5.9	2.4	0.8	2.6
Cattle Exclusion	NA*	5.2	0.7	0.1	8.1
Channel/Grade Stabilization	2.9	12.5	6.9	1.3	32.0
No-Till	0.9	25.2	–8.2	−11.0	35.1
Grassed Waterways	0.4	11.2	4.9	1.2	35.1
Rotational Grazing	0.0	0.0	0.0	0.0	0.0
Residue Management	1.2	14.5	5.0	1.4	27.4
Riparian Buffers	1.3	2.2	1.7	0.6	1.6
Stormwater Management	0.5	7.9	3.5	0.1	31.6
50% Implementation Rate					
Combination of Three Most Effective	17.4	35.0	21.7	6.8	36.9
Field Border	6.5	12.4	5.0	1.8	4.7
Cattle Exclusion	NA*	10.8	1.2	0.1	12.9
Channel/Grade Stabilization	6.1	9.9	10.4	0.0	32.5
No-Till	0.31	19.8	–2.5	−6.6	33.8
Grassed Waterways	1.0	7.9	6.2	2.5	26.8
Rotational Grazing	0.0	0.0	0.0	0.0	0.0
Residue Management	1.5	24.3	4.6	1.9	32.0
Riparian Buffers	3.7	4.5	3.4	1.3	4.0
Stormwater Management	0.5	19.4	4.6	1.6	31.5
75% Implementation Rate					
Combination of Three Most Effective	29.6	34.3	29.7	13.9	36.4
Field Border	15.4	18.5	8.2	3.6	6.4
Cattle Exclusion	NA*	16.7	2.2	0.2	28.1
Channel/Grade Stabilization	9.2	0.1	11.8	−0.6	34.7
No-Till	2.9	25.3	5.5	−0.31	35.0
Grassed Waterways	56.5	29.8	−33.0	−5.9	−39.5
Rotational Grazing	0.0	0.0	0.0	0.0	0.0
Residue Management	2.6	22.7	6.54	−0.23	35.3
Riparian Buffers	8.7	6.7	5.3	2.4	5.4
Stormwater Management	0.7	13.5	10.9	5.6	31.5

***** Sediment was not included as a direct stream input from cattle.

residue management, perhaps the values were not representative of the landscape in the watershed.

6.0 CONCLUSIONS

Through this project, a water quality model of the Clearwater River Watershed was developed and calibrated using the best available data. The model was calibrated from January 1998 to December 2007 and validated from January 1990 to December 1997. An evaluation of efficiency statistics for the calibration period of the model indicates that the predicted versus measured discharge match well.

According to the results of this study, significant reductions in sediment, nutrient, and FC loading can be achieved through implementation of the BMPs evaluated, especially through the implementation of multiple practices throughout the watershed. The results of this evaluation are interesting in that the BMP implementation locations were random and not necessarily located in areas where they are most effective. It is likely that the benefits would be even greater if a targeted approach were taken with respect to BMP implementation.

To better improve the accuracy of the SWAT model developed through this project, additional data are needed to better document groundwater seeps and spring inputs, fertilizer application rates specific to the watershed, the concentration of FC bacteria in water exiting wild rice paddies and contributing water bodies, the location and size of unregistered cattle operations, and the number of cattle that have direct stream access. In addition, the DO simulation component of the SWAT model needs to be updated and improved by the model developers.

The work described here and the model developed through this project will hopefully serve as a base upon which future research and implementation efforts can build. There are many more combinations of BMP implementation scenarios that can be evaluated using this model, 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

Anderson, E.A., 1976, A point energy and mass balance model for snow cover: National Oceanic and Atmospheric Administration technical report NWS 19, Washington, D.C., U.S. Department of Commerce, National Weather Service.

Arabi, M., Frankenberger, J.R., Engel, B.A., and Arnold, J.G., 2007, Representation of agricultural conservation practices with SWAT, Hydrological Processes (2007), DOI: 10.1002/hyp.6890.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., and Williams, J.R., 1998, Large-area hydrologic modeling and assessment: part I. model development: Journal of American Water Resources Association (JAWRA) v. 34, no. 1, p. 73–89.

Chaubey, I, Migliaccio, K.W., Green, C.H., Arnold, J.G., and Srinivasan, R., 2006, Phosphorus modeling in Soil and Water Assessment Tool Model, Published by Texas A& M University, Available at: http://ssl.tamu.edu/media/3133/swat-p%20modeling_3777_c007.pdf (accessed March 2009).

Commission for Environmental Cooperation, 1997, Ecological regions of North America—toward a common perspective: Report published by the CEC, Montreal, Canada, www.cec.org/files/pdf/BIODIVERSITY/eco-eng_EN.pdf 71 p. (accessed April 2008).

Gassman, P.W., Reyes, M.R., Green, C.H., and Arnold, J.G., 2007, The Soil and Water Assessment Tool—Historical development, applications, and future research directions: Transactions of the American Society of Agricultural and Biological Engineers, v. 50, no. 4, p. 1211–1250.

Grund, M.D., 2008, Monitoring population trends of White-Tailed Deer in Minnesota's farmland transition zone – 2008, Farmland Wildlife Populations and Research Group, Minnesota Department of Natural Resources http://files.dnr.state.mn.us/publications/wildlife/populationstatus2008/1_farmland_wildlife.pdf (accessed April 2009).

Huseby, J.T., 1997. Use of cultivated wild rice paddies and associated habitats by migrating and breeding waterfowl in northwest Minnesota: Ph.D. dissertation, University of North Dakota, UMI Number: 9810291.

Kurz, B.A., Wang, X., de Silva, L., Hanson, S.K., Kurz, M.D., Peck, W.D., Simonsen, T.K. and Steadman, E.N., 2007, An evaluation of basinwide, distributed storage in the RRB—the Waffle concept: Draft final report prepared by the Energy & Environmental Research Center for the USDA–NRCA.

Minnesota Department of Natural Resources and U.S. Fish and Wildlife Service, 2008, Minnesota 2008 waterfowl breeding population survey, http://files.dnr.state.mn.us/outdoor_activities/hunting/waterfowl/wf200805.pdf (accessed April 2009).

Nash, J. E., and Sutcliffe, J.V., 1970, River flow forecasting through conceptual models part I—a discussion of principles: Journal of Hydrology, v. 0, no. 3, p. 282–290.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., and King, K.W., 2002, Soil and Water Assessment Tool theoretical documentation, Version 2000: Document produced by the Agricultural Research Service and Blackland Research Center, www.brc.tamus.edu/swat/downloads/doc/swat2000theory.pdf (accessed April 2008).

Paakh, B., Goeken, W., and Halvorson, D., 2006, State of the Red River of the North: Publication of the Minnesota Pollution Control Agency, 104 p., www.pca.state.mn.us/publications/ reports/redriverreport2006.pdf (accessed April 2008).

Srinivasan, R., Ramanarayanan, T.S., Arnold, J.G., and Bednarz, S.T., 1998, Large-area hydrologic modeling and assessment: part II. model application: Journal of American Water Resources Association (JAWRA), v. 34, no. 1, p. 91–101.

U.S. Environmental Protection Agency, Description of Ecoregions. www.epa.gov/naaujydh/pages/ecoregions/level_iii.htm (accessed April 2009).

Wang, X., Melesse, A.M., and Yang, W., 2006, Influences of potential evapotranspiration methods on SWAT's hydrologic simulation in a northwestern Minnesota watershed: Transactions of the American Society of Agricultural and Biological Engineers, v. 48, no. 5, p. 1697–1711.

Wang, X, and Melesse, A.M., 2006, Effects of STATSGO and SSURGO as inputs on SWAT model's snowmelt simulation: Journal of the American Water Resources Association, v. 42, no. 5, p. 1217–1236.

Wang, X., and Melesse, A.M. 2005. Evaluation of the SWAT model's snowmelt hydrology in a northwestern Minnesota watershed: Transactions of the American Society of Agricultural and Biological Engineers, v. 48, no. 4, p. 1359–1376.

Yagow, G., Shanholtz, V., Seale, R., Stephens, R., Johnson, D., and Lunsford, C., 1999, Preliminary fecal coliform assessment in the Blackwater River Watershed. Presented at the 1999 ASAE Annual International Meeting, Toronto, Canada, Paper No. 99-2185.