LAND USE AND CLIMATE IMPACT ON SEDIMENT AND NUTRIENT LOADS INTO LAKE ASHTABULA, NORTH DAKOTA, USA

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MASTER OF SCIENCE

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ABSTRACT

Lake Ashtabula continues to be listed as impaired water body by the USEPA due to excessive nutrients. A Soil and Water Assessment Tool (SWAT) model was developed for the Lake Ashtabula watershed to estimate the sediment and nutrient loads entering the lake under different land use and climate scenarios. Impacts of flows from the Devils Lake outlets flowing into the lake Ashtabula via Sheyenne River were also included. The study showed that biofuel cropland expansion and increases in precipitation would generate higher streamflow, sediment, and nutrient loads into Lake Ashtabula. However, decreases in precipitation would decrease sediment and total phosphorus loads, but not necessarily total nitrogen loads. Flow from Devils Lake had the most significant impacts on both streamflow and nutrient loads. This well-calibrated and validated watershed model can be used for developing nutrients and sediment Total Maximum Daily Load (TMDL) program for the Lake Ashtabula.

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1. INTRODUCTION

Nonpoint source pollution represents the most common cause of surface water impairment due to nitrogen and phosphorus loads leading to dysfunctional surface water bodies, such as streams, natural lakes and artificial reservoirs (USEPA, 2008a). USEPA established the Total Maximum Daily Load (TMDL) program under the Clean Water Act to alleviate threats to water quality of nation's waters.

Since 2012, Lake Ashtabula in North Dakota has been listed as impaired due to excess nutrients and eutrophication. It is one of the lakes in North Dakota in need of developing a TMDL reduction strategy for nutrients (Dalrymple and Dwelle, 2012). Lake Ashtabula water quality is not supporting its designated uses according to recent three years nutrients indicators reported by North Dakota Department of Health (NDDoH.gov). Agricultural crop production is listed as one of the probable sources contributing to Lake Ashtabula nutrient impairments (USEPA.gov). Numerous nitrogen species have detrimental impacts on water quality. Nutrient phosphorus has the most effect on algal growth, which leads to depletion of dissolved oxygen in water bodies (Borah et al., 2006). The Upper Sheyenne and part of Middle Sheyenne River watershed above the Baldhill Dam contribute to Lake Ashtabula and are of concern for this study. Also of concern is the flow from the outlets of Devils Lake into Lake Ashtabula via Sheyenne River. Devils Lake is located in northeastern North Dakota nearby the upstream of Sheyenne River (Fig. 1 and 13). Two outlets are currently operating to discharge lake water into Sheyenne River for flood control purposes. The outlet from the west end of Devils Lake started to operate in 2007 to reduce the rate of lake water level rise (Vecchia, 2008; Galloway, 2011). The second outlet from east Devils Lake completed in 2012 was used to release more water in response to continuous rising lake water level (Vecchia, 2011). Two outlet alternative scenarios that include maximum operation capacities of a

250 ft^3/s (7.08 m^3/s) west end outlet combined with a 350 ft^3/s (9.91 m^3/s) east end outlet (W250E350); and average operation capacities calculated based on real-time Devils Lake outlet data of a 131 ft^3/s (3.71 m^3/s) west end outlet combined with a 266 ft^3/s (7.53 m^3/s) east end outlet (W131E266) were used in this study to evaluate effects of outlet discharges from Devils Lake on downstream water quality. Devils Lake water was considered as "impaired due to nutrient pollution" before 2012. North Dakota Department of Health (NDDoH) delisted it from 2012 TMDL impaired water report because lake water attained applicable water quality standard within the eutrophic range, however, according to current real-time water quality data obtained from NDDoH, the nutrient concentration in Devils Lake water appears to be high. Therefore, the diversions from Devils Lake to Sheyenne River have the potential to adversely affect the water quality of Lake Ashtabula. The loads delivered to Lake Ashtabula could be more than loads from the Upper and partial Middle Sheyenne River watershed alone due to Devils Lake inputs. It is important to consider the fact that Lake Ashtabula serves as a multipurpose reservoir used for rural and municipal water supply for several regions and therefore, the public health and water quality issues of Lake Ashtabula are of great concern.

The primary focus of this study is to evaluate the impact of land use and climate changes on the nutrient loads that may be delivered to Lake Ashtabula by the Upper and Middle Sheyenne River watershed. Impact of the flows from the Devils Lake outlets is another important part of this study. The Soil and Water Assessment Tool (SWAT) model is used in this study to estimate nutrient loads from contributing areas under conditions before and after major land use changes and future climate scenarios. SWAT is a continuous, physically-based, semi-distributed, watershed scale model. It is capable of estimating runoff, sediment and nutrient loads from watersheds and has been widely accepted and in use for TMDL purposes (Shoemaker et al., 2005).

1.1. Objectives

1. To develop a calibrated SWAT model for the Lake Ashtabula watershed;
2. To investigate impacts of biofuel crops expansion and climate change scenarios on sediments and nutrient loads into Lake Ashtabula; and
3. To investigate impact of flows from the Devils Lake outlets on nutrient loads entering Lake Ashtabula.

2. LITERATURE REVIEW

Surface water quality impairment is of great concern for watershed and water resource management agencies. A total maximum daily load (TMDL) under Section 303(d) of the U.S. Clean Water Act is the maximum amount of pollutant that a water body can assimilate without violating applicable water quality standards. A TMDL is the allowable load of any pollutant that a stream can receive and still meet applicable water quality standards and support its designated uses. It comprises loads from permitted point, nonpoint, and natural background sources (Shoemaker et al., 2005; USEPA, 2008b; Langseth and Brown, 2011). The U.S. Environmental Protection Agency (USEPA) requires all states identify and list those waters within their boundaries that are water quality limited, to prioritize them, and to develop Total Maximum Daily Loads (TMDLs) for the pollutants of concerns.

TMDL development studies are being considered for several watersheds in the State region, and the nation. There are thousands of TMDLs already developed, being developed, or that will be developed throughout U.S., and models are used in most of them. Watershed modeling is a key component in the process of TMDL development and it involves water quality assessments, i.e., to calculate the pollutant loading entering the water body from every source; to identify all sources of the pollutant contributing to the water quality impairment (USEPA, 2008b).

Modeling process involves multi-steps to improve the prediction uncertainty. Sensitivity analysis is the first step to identify critical input parameters that determine the rate of change in model outputs. Local method was used in this study for sensitivity analysis, and it is the process of changing one parameter at a time with other parameters fixed. Calibration process is based on carefully selected model input parameters that are adjusted to reduce prediction uncertainty until the predictions close to observed data with statistical index such as Nash-Sutcliffe efficiency within satisfactory ranges. Validation is the final step to compares the predictions to observed data in a distinct time period apart from the calibration, but use parameters that have been adjusted during the calibration processes (Arnold et al., 2012).

Soil and Water Assessment Tool (SWAT) model has been used to simulate streamflow, sediment, and water quality in many studies for TMDL purposes (Borah et al., 2006). A recent study indicated that both calibration and validation periods of SWAT model performance resulted in Nash-Sutcliffe efficiency and coefficient of determination values up to 0.93 and 0.94 respectively for monthly streamflow (Hutchinson &Christiansen, 2013). Another nutrient TMDL study in Texas using the SWAT model concluded that SWAT model predictions were satisfactorily close to observed values for the use of assessing sediment and nutrient loadings into a receiving lake from the upstream contributing watersheds (Santhi et al., 2001).

Galloway (2011) reported about effects of Devils Lake outlet discharges on sulfate in-stream concentration along Sheyenne River, and he proposed two connecting locations for Sheyenne River and Baldhill Creek with Lake Ashtabula (Fig. 6). His model is an empirical model based on the past twenty years statistics comprising dry and wet periods. The simulation period of my SWAT model falls within the above statistical data period, and the same locations suggested by Galloway are used in this study for subbasin outlets in SWAT model.

Several studies using SWAT model to evaluate hydrologic and water quality impacts has also been applied on the Red River basin with satisfactory performance on streamflow, sediment, total nitrogen and phosphorus simulations (Lin et al., 2015; Rahman et al., 2014). This study indicated that land use changes incurred from bioenergy policy was of a concern in this area, and results showed that streamflow, sediment, and nutrient loads were affected by the biofuel crop (i.e.

corn and soybean) expansion (Lin et al., 2015). The target watershed in this study is one that extends west of the Red River basin, and has distinct land form and land cover from central plain of Red River basin. The land form of central Red River basin is very flat and is the bottom of glacial Lake Agassiz. However, the Lake Ashtabula watershed in this study is in the gently rolling upland. Corn, soybean, and spring wheat are principal crops in both watersheds. However, the study area does not have several secondary crops such as sugarbeet (beta vulgaris), canola (brassica napus), dry beans (phaseolus), barley (hordeum vulgare), and sunflowers (helianthus). It has mostly nonagricultural lands such as pasture and wetland as secondary land cover.

Another model AnnAGNPS has been used to estimate sediment and nutrient loads from Lake Ashtabula watershed using seven sub-models separately, and AnnAGNPS had difficulties to integrate the loads from individual models because the model could not simulate channel routing process between sub-models (Pease and Hassell, 2011; Pease et al., 2010). However, SWAT is capable to build an integrated model including channel routing. In addition, a comparison on model simulation between AnnAGNPS and SWAT based on a Kansas watershed case study indicated that both SWAT and AnnAGNPS model performed with good correlation for streamflow and sediment with Nash-Sutcliffe efficiency (E_{NS}) of 0.47 to 0.73. However, while SWAT performed well for calibration and validation of total phosphorus (TP) with E_{NS} of 0.63 to 0.68, the performance of AnnAGNPS models were unsatisfactory with E_{NS} of -0.38 to 0.32 (Parajuli et al, 2009).

SWAT version 2009 used in this study has the snowmelt routine incorporated in it to better simulate climate condition in the study area, and the same version has been used in many studies for other snow-dominated watersheds (Ficklin and Barnhart, 2014; Hay et al., 2006). SWAT model has been applied on a Northwestern Minnesota watershed to assess the snowmelt algorithm, and results reported acceptable daily performance and satisfactory monthly statistics (Wang & Melesse, 2005). The snowmelt algorithm was also evaluated in the region with a large snowmelt component, where SWAT model obtained E_{NS} of 0.86 between simulated and measured streamflow (Fontaine et al., 2002). Other studies to assess streamflow simulation under snowmelt and rainfall indicated that snowmelt parameters (i.e. snowmelt base temperature and snowpack temperature lag factor) were the most sensitive parameters for model calibrations in a snow-dominated area (Levesque et al., 2008; Ahl et al., 2008).

In general, the model performance of calibrated SWAT model is usually assessed through visual interpretation of the simulated and observed hydrographs matching on the rising and recession limbs, and the baseflow. Commonly recommended statistical measures of agreement between simulated and observed hydrographs are Nash-Sutcliffe efficiency and coefficient of determination (Ahl et al., 2008). A reasonable procedure for calibration has been described by Santhi et al., 2001. Streamflow would be the first to be calibrated until monthly E_{NS} and R^2 exceed 0.5. Sediment would then be calibrated followed by nutrients (i.e. nitrate, organic nitrogen and phosphorus) (Santhi et al., 2001). A case study on a Great Lakes watershed reported that evapotranspiration parameters were important to the model calibration on snow-dominated watershed in addition to snow-melt parameters. The combination of two parameters (i.e. soil evaporation compensation coefficient and plant uptake compensation coefficient) affects water allocation and streamflow fluctuation in SWAT model (Wu and Johnston, 2007). Some other parameters that have been selected for model calibration include curve number and available soil water capacity (Arnold et al., 2000). Sensitive parameters identified in another Red River basin study were used in this study because the climate condition is similar in the two watersheds (Lin et al., 2015; Rahman et al., 2014).

SWAT model has been widely used for assessing the impact of land use/land cover (LULC) and climate changes on streamflow, sediment and nutrients (Tu., 2009; Nie et al., 2011; USEPA, 2013). The focus of the LULC changes in this study is on biofuel crops expansion. This is based on our findings from National Agricultural Statistics Serve Cropland Data layer (NASS CDL) over the past decade. Many studies have concluded that biofuel crops expansion would affect streamflow and water quality (Kim et al, 2013). Results show that the average surface runoff would increase when the watershed has more cropland covers. The croplands may also generate more sediment yields, and higher nutrients loads (Kimwaga et al, 2012). A recent study using SWAT model to evaluate the impacts of LULC changes selected four water quantity and water quality parameters to show the overall performance of the model. The results of the study indicated monthly streamflow, nitrate, organic nitrogen and phosphorus loads all have increased due to cropland expansions (El-Khoury et al, 2015).

Studies have shown that climate change may have different impacts on streamflow and different water quality indicators (Luo, 2013). A recent study found that increasing projected precipitation would increase streamflow, nitrate loads, and organic phosphorus loads. However, a decrease in organic nitrogen loads was also indicated (El-Khoury et al, 2015).

SWAT model is capable of handling both non-point and point source pollution. In this study, SWAT model's ability to handle point source simulation was helpful to evaluate impacts of west and east Devils Lake outlets. Vecchia (2011) proposed three scenarios to evaluate effects of west and east Devils Lake outlets on water quality in the Sheyenne River. This study adopted one the scenarios that represents maximum operation capacities of a 250 ft^3/s (7.08 m^3/s) west end outlet combined with a 350 ft^3/s (9.91 m^3/s) east end outlet (W250E350) since the outlet operations have already been implemented following this plan determined by North Dakota State Water

Commission; and average operation capacities based on real-time Devils Lake outlet data of a 131 ft^3/s (3.71 m^3/s) west end outlet combined with a 266 ft^3/s (7.53 m^3/s) east end outlet (W131E266) was calculated for the use of this study as a second comparable scenario for the amount of inflow connected to Sheyenne River, and water quality measurements of Devils Lake water bodies were retrieved from NDDoH (https://www.ndhealth.gov/wq/sw/Z8_SWData/viewer.html) as point source inputs for SWAT model.

Many studies indicated that multi-outlets calibration improved the streamflow simulation (Gul and Rosbjerg, 2010; Chien et al., 2013). In a recent study intended to compare changes in streamflow of same SWAT model in three different calibration modes: uncalibrated, single outlet calibrated, and multi-outlets calibrated, land use changes scenario showed that estimations from uncalibrated and single outlet calibrated models were significantly different from those of multi-calibration. In addition, climate changes scenario indicated no significant difference between single calibrated and multi-calibrated models; however, changes in streamflow predicted with uncalibrated model were different from calibrated ones (Niraula et al., 2015). Therefore, based on the literature findings, the multi-site calibration was used for the study on Lake Ashtabula watershed to obtain better simulation of impacts of land use and climate changes.

3. MATERIALS AND METHODS

3.1. Study Area

3.1.1. Geography

Lake Ashtabula watershed comprises of the Upper Sheyenne watershed (HUC 09020202) and partial Middle Sheyenne watershed (HUC 09020203) above the Baldhill Dam. It is situated at eastern North Dakota, intersecting with eleven counties that include McHenry, Sheridan, Peirce, Benson, Wells, Eddy, Foster, Nelson, Griggs, Barnes, and Steele Counties. The watershed under this study has an area of approximately 9806 km^2, with two main contributing streams: Sheyenne River and Baldhill Creek. The watershed outlet is located at the USGS gauging station near Badhill Dam (#05058000), approximately 47.034 ˚N and 98.084 ˚W. Six USGS streamflow and NDDoH water quality gauging stations are used in the study for model calibration. Five stations are located at Harvey, Flora, Bremen, Warwick, and Cooperstown along Sheyenne River, and one is located near Dazey along Baldhill Creek (Fig. 1).

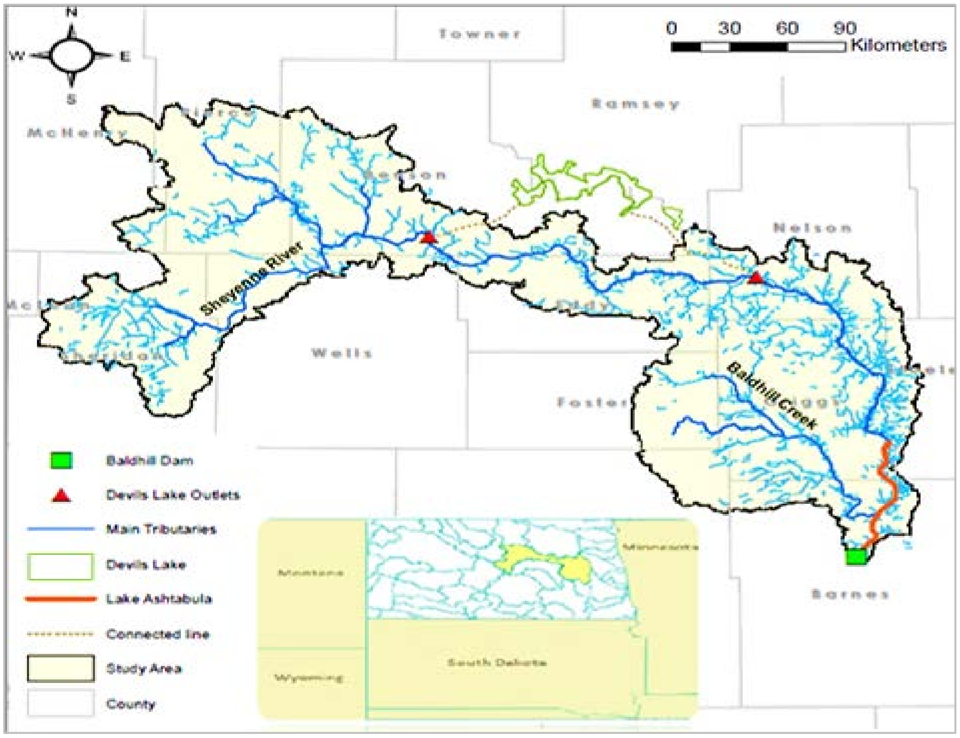


Figure 1. The Lake Ashtabula watershed

3.1.2. Topography and Soils

The study area lies in the gently rolling drift upland areas above Lake Ashtabula in Sheyenne River (NDSWC, 2001). The elevations of the upland areas range from 116 meter to 198 meter from mean sea level. The Sheyenne River within the study area flows through the glacial till that is mixture of silt, clay, and sand. Soils are assigned to hydrologic soil groups (i.e., A, B, C, and D) based on runoff potential of soils (Table 1). About 74% of soils of the study area are placed into hydrologic soil groups A and B that have relatively low runoff potential.

Table 1. Characteristics of hydrological soil groups

Hydrological Soil Groups	Soil Textures	Hydraulic Conductivity	Impacts on Runoff
A	sand, loamy sand, sandy loam	> 144.0 mm/hr	low runoff potential
B	silt loam or loam	< 144.0 to > 36.0 mm/hr	relative low runoff potential
C	sandy clay loam	< 36.0 to >3.6 mm/hr	relative high runoff potential
D	clay loam, silty clay loam, sandy clay, silty clay, or clay	< 3.6 mm/hr	high runoff potential

Notes: USDA NRCS, 2007

3.1.3. Land use

According to 2009 land use developed by National Agricultural Statistics Service (NASS), the dominant land use in the Lake Ashtabula watershed was agriculture with 79% cropland, 6% grassland/pasture, 12% water and wetlands, 1% developed/open space, and the remaining 2 percent fallow/idle cropland or forest. Primary crops in the watershed were corn, soybeans and spring wheat. Land use within the Lake Ashtabula watershed has recently been affected by the bioenergy policies, as with the Red River of the North basin (Lin et al., 2015) and the whole Midwestern region (Wright and Wimberly, 2013). High commodity prices and other incentives provided by biofuel policies since 2006 have caused a significant shift in crop cultivation areas (i.e., more cultivation areas for corn and soybeans and less for spring wheat and sunflowers).

3.1.4. Climate

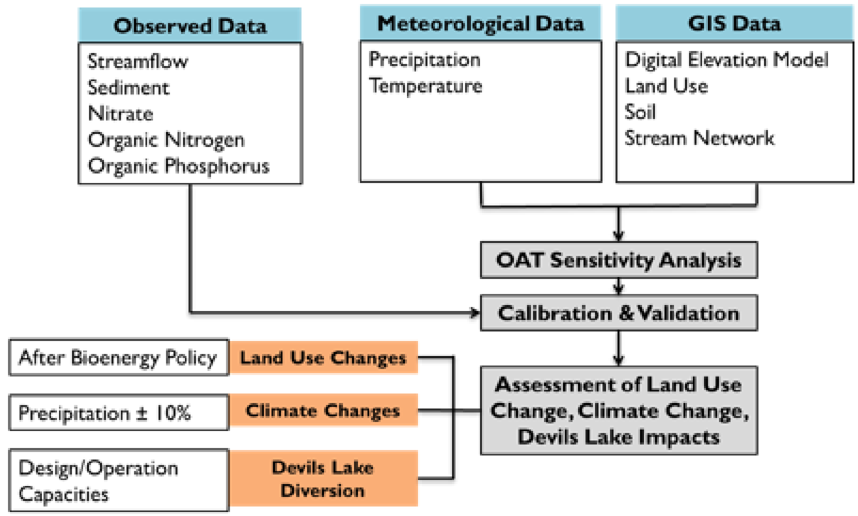
Daily precipitation and temperature data from a combination of 10 North Dakota Agricultural Weather Network (NDAWN) and National Climatic Data Center stations located throughout and surrounding the Lake Ashtabula watershed from January, 1, 2006, to December, 31, 2012, were used in this study. During the selected period for simulation, the mean monthly temperature were -13 °C in January and 22 °C in July, respectively. The average annual precipitation ranged from 447 mm (17.6 inches) in the upper part of the watershed to 517 mm (20.4 inches) in the lower part of the watershed. The region is under the influence of continental climate with cold winters and moderately warm summers. The growing season runs from mid-May through mid-September, ranging from 100 to 140 days (Stoner et al., 1993).

3.2. Methodology

One of the important steps for estimating sediment and nutrient loads entering receiving water bodies is modeling the fate and transport of sediments and nutrients by water from where they are generated to the receiving water bodies. There are many watershed models available that can be used in this step. However, SWAT model is one of the most widely used models for this purpose.

In this study, SWAT model version 2009 (Neitsch et al., 2011) was used. The ArcGIS 9.3 extension ArcSWAT 2009 (Neitsch et al., 2011) was used to process model inputs, which include several digital data layers of elevation, land use, soil, and climate. The SWAT Calibration and Uncertainty Programs (SWAT-CUP) version 2009 (Karim, 2013) was used for model calibration against observations of streamflow, sediment, and nutrients after the model was set up in ArcSWAT (Fig. 2).

ArcSWAT includes modules for watershed delineation, hydrologic response unit (HRU) definition, synthetic weather generation; exporting data from geodatabases to prepare SWAT input files, and importing SWAT results from the output files to dynamic geodatabases. The first three modules include spatial analysis using topographic, land use, soil type, and weather data. The other modules connect the SWAT data to SWAT and support hydrologic analysis and model integration (Olivera et al., 2006).



Notes: OAT – One-at-time

Figure 2. Study flow chart

3.2.1. SWAT Modeling

The SWAT model that we developed for the Lake Ashtabula watershed is a continuous simulation model that runs on a daily time step during the study period between January 1, 2006 and December 31, 2012. Two years warm-up period from January 1, 2004 to December 31, 2005 was used in the SWAT model to calculate the initial conditions that were not available (i.e. soil chemical composition) to represent the watershed. The Lake Ashtabula watershed was divided into nineteen subbasins connected through Sheyenne River and Baldhill Creek, two major tributaries to Lake Ashtabula. The subbasins were further divided into 845 HRUs, which are comprised of unique combinations of land uses and soils. Simulations were performed at the HRU level and summarized in each subbasin. The simulated variables, such as streamflow, sediments, and nutrients were routed through the stream network to the watershed outlet, located at the Ballhill Dam.

Hydrologic simulations in SWAT are based on daily water budget, in which water yielded within each subbasin is a sum of surface runoff, lateral subsurface flow, tile drainage, and groundwater baseflow. Water yield can also be calculated by subtracting canopy interception, pond abstraction, evapotranspiration, percolation, and transmission losses from precipitation.

Surface runoff is computed using the SCS curve number method (Eq (3.1-3.3)), and amount of surface runoff reaching the stream channel is computed using an exponential function with a lag coefficient (i.e., *surlag* in Eq (3.4)). Evapotranspiration is computed using Penman-Monteith method in this study. Lateral subsurface flow is computed using a kinematic storage model, and groundwater baseflow is computed using exponential functions. All surface runoff, lateral subsurface flow and groundwater baseflow reaching the stream channels are routed through the channel network using the variable storage coefficient (Neitsch et al., 2011).

$$Q_{surf} = \frac{(P - I_a)^2}{(P - I_a + S)} \tag{3.1}$$

$$I_a = 0.2 * S \tag{3.2}$$

$$S = 25.4 * (\frac{1000}{CN} - 10) \tag{3.3}$$

$$Q'_{surf} = (Q_{surf} + Q_{stor,t-1}) * \left[1 - \exp(\frac{-surlag}{t_{conc}}) \right] \tag{3.4}$$

Where Q'_{surf} is surface runoff discharged to the main channel on a given day (mm H_2O); Q_{surf} is amount of surface runoff generated in the subbasin on a given day (mm H_2O); $Q_{stor,t-1}$ is surface runoff lagged from the previous day (mm H_2O); *surlag* is surface runoff lag coefficient; t_{conc} is time of concentration for the subbasin (hrs); P is rainfall for a given day (mm H_2O); I_a is initial abstractions (mm H_2O); S is retention parameter (mm H_2O); CN is curve number, respectively.

Sediment yield is estimated for each HRU using the Modified Universal Soil Loss Equation (Eq (3.5-3.7)). Sediment is routed through stream channel using a simplified equation based on Bagnold's definition of stream power (Eq (3.8)).

$$sed = 11.8 * (Q_{surf} * q_{peak} * area_{hru})^{0.56} * K_{USLE} * C_{USLE} * P_{USLE} * LS_{USLE} * CFRG \quad (3.5)$$

$$q_{peak} = \frac{C * i * Area}{3.6} \quad (3.6)$$

$$C = \frac{Q_{surf}}{P} \quad (3.7)$$

$$conc_{sed,ch,mx} = c_{sp} * v_{sp,pk}{}^{sp\exp} \quad (3.8)$$

Where *sed* is sediment yield on a given day (tonnes); K_{USLE} is soil erodibility factor; C_{USLE} is cover and management factor; P_{USLE} is erosion control practice factor; LS_{USLE} is topographic factor; *CFRG* is coarse fragment factor; $conc_{sed,ch,mx}$ is maximum concentration of sediment that can be transported in a channel (tonnes/m^3); q_{peak} is peak runoff rate (m^3/s); *C* is runoff coefficient (mm H_2O); *i* is rainfall intensity (mm/hr), and *A* is subbasin area (km^2), c_{sp} is a coefficient defined by the user, $v_{ch,pk}$ is peak channel velocity (m/s), and *spexp* is an exponent defined by the user.

SWAT assumes that nitrate, ammonium, organic nitrogen, organic and mineral phosphorus can be removed from soils. The amounts of nitrate-N contained in the surface runoff and lateral subsurface flow are estimated as products of the volume of water and the average concentration of nitrate in a soil layer (Eq 3.9-3.10). Ammonium can attach to soil particles since it has a positive charge and a soil particle has a negative charge. Ammonium, organic nitrogen, organic and mineral phosphorus attached to soil particles are transported by surface runoff to the main channel, which is calculated by a modified loading function (Eq 3.11-3.12). Nutrient transformations in stream are controlled by the in-stream water quality component of the model. The in-stream kinetics used in SWAT for nutrient routing are adapted from QUAL2E (Gassman et al., 2007). The model tracks nutrients dissolved in the stream and nutrients adsorbed to the sediment. Dissolved nutrients are transported with the water, while those adsorbed to sediments are allowed to settle on streambed (Neitsch et al., 2011).

$$NO_{3,surf} = \beta_{NO_3} * conc_{NO_3,mobile} * Q_{surf} \tag{3.9}$$

$$NO_{3,lat} = \beta_{NO_3} * conc_{NO_3,mobile} * Q_{lat} \tag{3.10}$$

$$sedN_{surf} = \frac{0.001 * conc_{sedN} * sed * \varepsilon_{N:sed}}{area_{hru}} \tag{3.11}$$

$$sedP_{surf} = \frac{0.001 * conc_{sedP} * sed * \varepsilon_{P:sed}}{area_{hru}} \tag{3.12}$$

Where $NO_{3,surf}$, $sedN_{surf}$ and $sedP_{surf}$ are amounts of nitrate, sediments-attached ammonium, organic nitrogen, organic and mineral phosphorus discharged to the main channel from the surface runoff (kg N or Kg P); $NO_{3,lat}$ is amount of nitrate discharged to the main channel from the lateral subsurface flow (kg N); $conc_{NO_3,mobile}$, $conc_{orgN}$ and $conc_{sedP}$ are concentrations of nitrate, sediments-attached ammonium, organic nitrogen, organic and mineral phosphorus; *sed* is sediment yield (tonnes); $area_{hru}$ is HRU area (km^2); β_{NO_3} is nitrogen percolation coefficient; and $\varepsilon_{N:sed}$ and $\varepsilon_{P:sed}$ are nitrogen and phosphorus enrichment ratios, respectively.

3.2.2. Model Data Preparation

The data and their sources that we used for SWAT model development and model calibration for Lake Ashtabula watershed are listed in Table 2.

Table 2. Data and their sources for SWAT model development and calibration

Data	Source	Description
Digital Elevation Model	USGS National Elevation Dataset	30 meter DEM
Landuse	National Agricultural Statistic Service Cropland Data Layer	NASS CDL 2009
Soil	USDA Natural Resource Conservation Service	STATSGO
Stream Network	USGS National Hydrography Dataset	
Meteorology	North Dakota Agricultural Weather Network National Oceanic and Atmospheric Administration	Daily precipitation Daily max & min temperature
Streamflow	USGS National Water Information System	Daily data from 6 gauging stations
Sediment	USGS National Water Information System	Biweekly data from 6 gauging stations (SSC)
Water Quality	North Dakota Department of Health	Biweekly data from 6 gauging stations (NO_3, ON, OP)

Notes: DEM – Digital elevation model; NASS CDL – National Agriculture Statistics Service Cropland Data Layer; STATSGO – State Soil Geographic dataset; SSC – Suspended solid concentration; ON – organic nitrogen; OP – organic phosphorus

- Digital elevation model

Seven digital elevation models (DEMs) were downloaded from the USGS 30-meter National Elevation Dataset (http://nationalmap.gov/elevation.html). A merged DEM was used in this study after preprocessing with data management tool in ArcGIS 9.3. The MASK option in SWAT model was used to define the extent of Lake Ashtabula watershed, which was generated by using BASINs 4.0 (http://www.epa.gov/exposure-assessment-models/basins-tutorials-and-training) to merge the Upper and partial Middle Sheyenne River watershed above the Baldhill Dam that created Lake Ashtabula (Fig. 3).

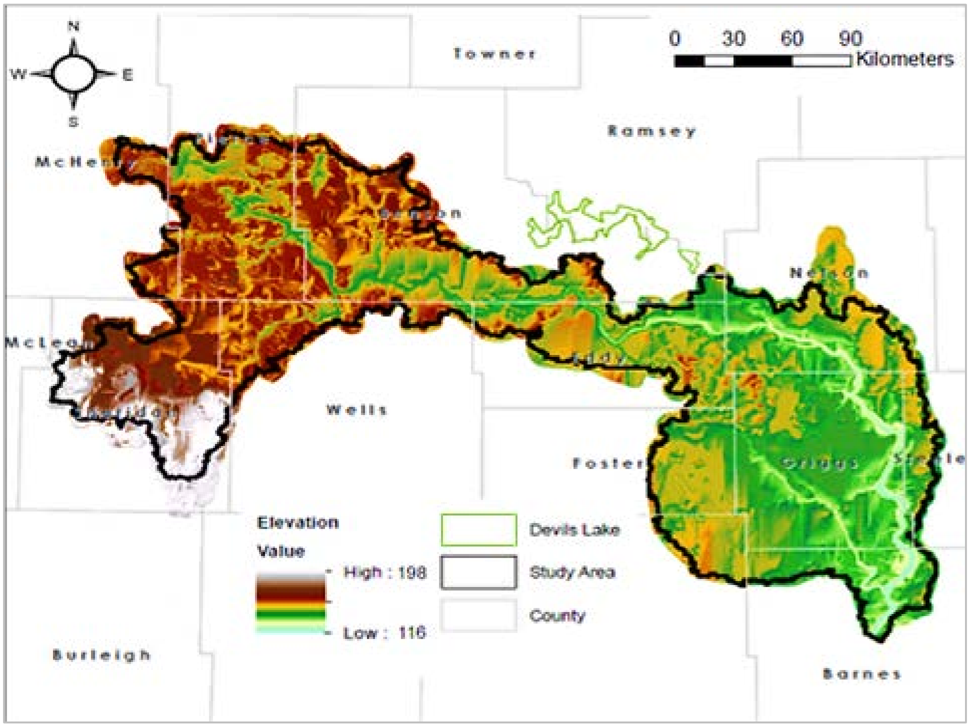


Figure 3. Digital elevation model (DEM) of the Lake Ashtabula watershed

- Stream network

Digital stream networks for the Lake Ashtabula watershed were derived from the USGS National Hydrography Datasets (NHD, 2013). The BURN-IN option using the NHD stream networks was applied to generate the digital streams for the watershed.

- Climate data

SWAT requires at least three meteorological parameters, including daily precipitation, maximum daily temperature, and minimum daily temperature. In this study, daily precipitation and temperature time series recorded at the ten meteorological stations located in or nearby the watershed were used (Table 3). The primary source for these weather data is North Dakota Agricultural Weather Network (NDDAWN). Supplemental data from National Oceanic and Atmospheric Administration (NOAA) were also used to fill the missing data. Solar radiation, wind speed, and relative humidity were generated by SWAT based on historic weather statistics for the region. An initial model run revealed that the weather stations assigned by ArcSWAT were not representative for some subbasins. Therefore we manually adjusted the weather station assignment for these subbasins. The ten weather stations are also shown in Fig. 4.

Table 3. Weather stations for the Lake Ashtabula watershed

ID	Name	Latitude	Longitude	Elevation (m)	Data Used
hop0pcp	Southern Pierce	48.354	-99.992	143.99	precipitation and temperature
hop1pcp	Northwestern Sheridan	47.795	-100.585	159.81	precipitation and temperature
hop2pcp	Southeastern McHenry	48.047	-100.310	142.13	precipitation and temperature
hop3pcp	Middle Sheridan	47.480	-100.444	179.01	precipitation and temperature
hop4pcp	Northwestern Foster	47.508	-99.121	144.93	precipitation and temperature
hop5pcp	Middle Wells	47.645	-99.620	150.51	precipitation and temperature
hop7pcp	Middle Benson	48.078	-99.265	179.01	precipitation and temperature
hop8pcp	Near Dazey	47.241	-98.584	140.76	precipitation only
hop9pcp	Near Harvey	47.808	-99.875	149.66	precipitation and temperature
tmp 1007	Eastern Benson	47.980	-98.907	136.58	temperature only

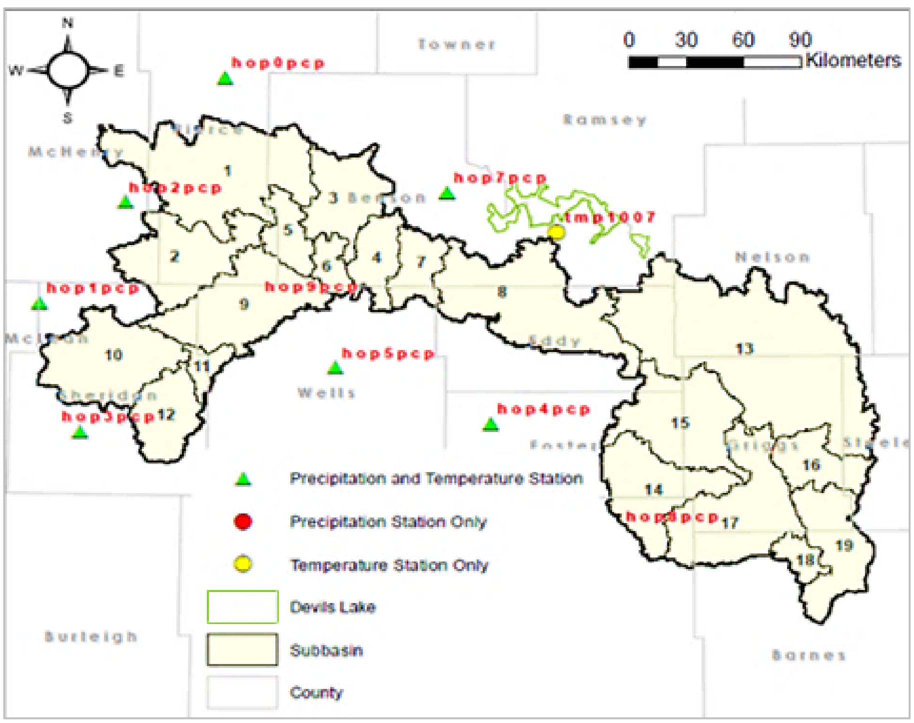


Figure 4. Lake Ashtabula watershed weather stations

- Land use/land cover

Land use/land cover (LULC) was derived from National Agricultural Statistics Service Cropland Data Layer (NASS CDL, 2009). The CDL's LULC categories expanded to more specific sub-groups from 2006 to 2012. For instance, the developed class representing urban area in 2006 was further divided into high, medium and low density residential areas in 2012. In order to account for the difference in LULC classification in the original CDL datasets, we regrouped the original CDL LULC classes into sixteen SWAT land use classes (shown in Table 4).

Table 4. Regrouped land use/land cover classes and their distribution in the Lake Ashtabula watershed (2009)

NASS Crop Data Layer land use classes	**SWAT land use classes**	**Area (km^2)**	**Percent of watershed**
1 Corn	CORN	348.33	4%
5 Soybeans	SOYB	1,507.63	15%
6 Sunflowers	SUNF	157.61	2%
4 Barley	BARL	92.78	1%
21-24 Spring/Winter/Durum Wheat; 25 Small Grains; 255 Double Crop	SWHT	1,816.44	19%
27-29 Oats; Rye; Millet	OATS	13.05	0%
31-35 Canola; Flaxseed; Mustard	CANA	81.10	1%
36 Alfalfa	ALFA	46.08	0%
41 Sugar beets; 43 Potatoes; 246 Reddish	SGBT	2.96	0%
42 Dry Beans	PTBN	107.54	1%
61 Fallow/Idle Cropland; 53 Peas	FPEA	90.17	1%
141-143 Deciduous/Evergreen/Mixed Forest; 152 Shrubland	FRSD	59.73	1%
121-124 Developed/Open Space/Low/Medium/High Intensity; 131 Barren	URBN	573.07	6%
190/195 Woody/Herbaceous Wetlands	WETN	773.54	8%
111 Open Water	WATR	408.65	4%
176 Pasture/Grass; 37 Non Alfalfa	PAST	3,712.39	38%

Notes: NASS – National Agriculture Statistics Service

As shown in Table 4, the major land uses are pasture (38%), wheat (19%), soybeans (15%), wetlands (8%), urban (6%), water (4%), and corn (4%), which account for 94 percent of the study area. An inspection of Fig. 5 shows that sugar beets and pasture spread out across the study area. Wheat was mostly seen in the upper and lower parts of the watershed, but not much in the middle part of the watershed. Soybeans were mostly cultivated in the lower part of the watershed, and corns were found in the subbasins draining to Baldhill Creak. Water and wetlands were mostly located in subbasin 1, and along with the boundary between subbasin 13 and 15.

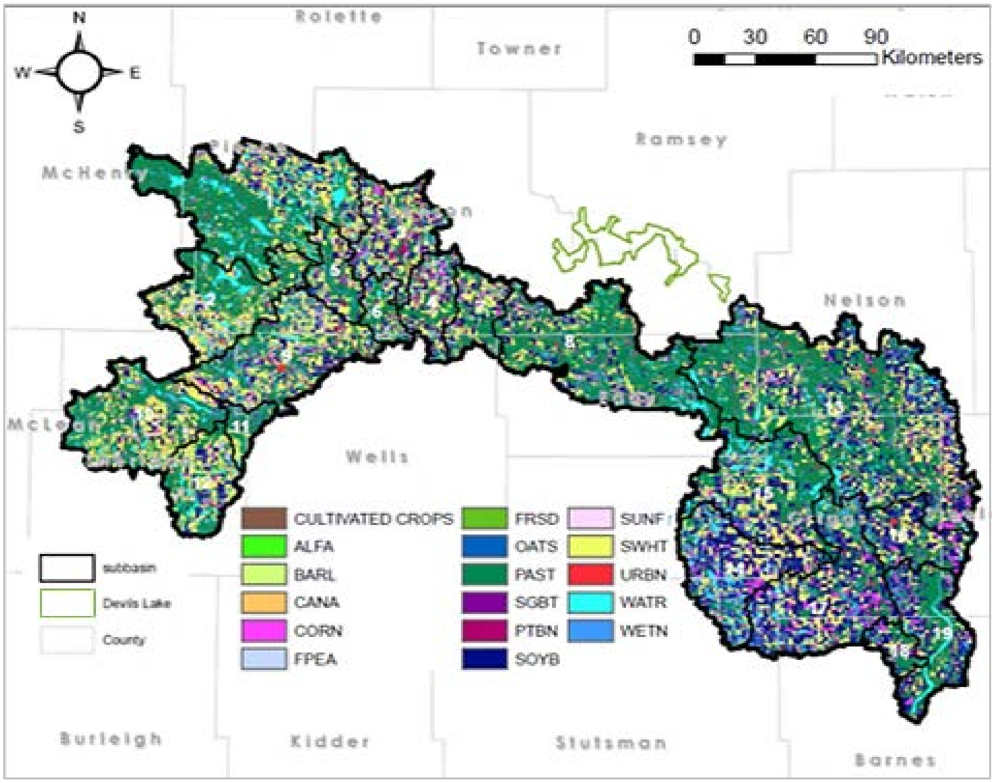


Figure 5. Land uses in the Lake Ashtabula watershed (2009)

- Soils

STATSGO classifies soils into four hydrologic soil groups (i.e., A, B, C, and D) in terms of surface runoff generation potential. A soils have the lowest runoff potential, whereas D soils have the highest runoff potential. The watershed under study has thirty-five soil mapping units. About 63% of them are B soils, 14% D soils, and 11% A, and 11% C soils.

A soils cover parts of Upper Sheyenne River watershed and the upper and middle parts of Baldhill Creek watershed. C soils were mostly situated in the Upper Sheyenne River watershed and areas near Lake Ashtabula. D soils stretched along the Sheyenne River from the Middle Sheyenne River watershed to the basin outlet (Fig. 6).

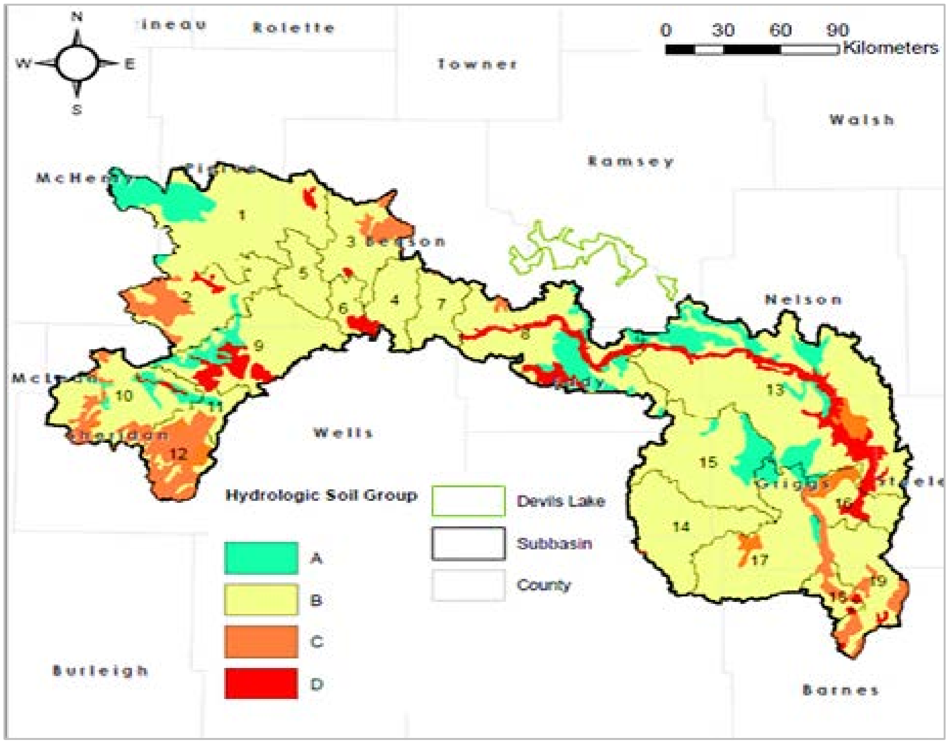


Figure 6. Hydrological soil groups in the Lake Ashtabula watershed

3.2.3. Model Development

A watershed outlet right above the Baldhill Dam and eighteen subbasin outlets were defined in this study. Six subbasin outlets were set at the same locations as the USGS streamflow gauging stations for model calibration and validation purposes (Fig. 7). Two subbasin outlets were added at the same locations as defined in Galloway (2011) to calculate the sediment and nutrient loadings to Lake Ashtabula from its two major tributaries – Sheyenne River and Baldhill Creek. Other subbasin outlets were generated by ArcSWAT. For HRU definition, the threshold values set for land uses and soils were 1% and 4 %, respectively, and 845 HRUs were defined in this study.

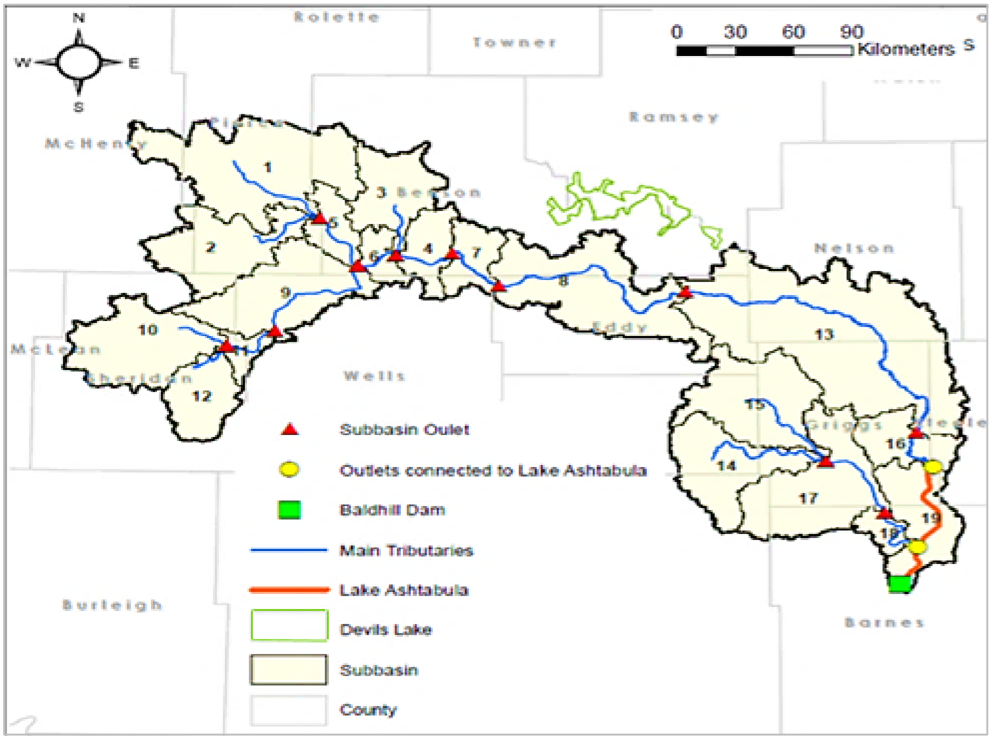


Figure 7. Lake Ashtabula watershed subbasins

3.2.4. Sensitivity Analysis

The SWAT model parameters can be adjusted at three levels: the watershed or basin level in the .bsn and .wwq files, the subbasin level in the .sub, .swq, and .rte files, and the HRU level in the .hru, .mgt, .gw, .sol, and .chm files. The model simulations with default parameter values are usually significantly different from the observations because default parameter values do not necessarily represent the characteristics of the watershed under study. Before model calibration, the OAT (one-at-time) sensitivity analysis was conducted to identify the most influential parameters for various hydrologic, sedimentation, and nutrient cycling processes. In the OAT method, users adjust one parameter at a time while keeping the values for other parameters unchanged. In this study, the values for the parameters in question were increased or decreased by 25% each time.

Thirty-three parameters were identified for streamflow, sediment, and nutrient calibrations (Table 5). In principle, CN2, SURLAG, and SLSUBBSN govern the processes of surface runoff generation; SOL_AWC, SOL_K, and SOL_BD govern the processes of soil water movement; GW_DELAY, ALPHA_BF, GWQMN, GW_REVAP, and RCHRG_DP govern groundwater dynamics; ESCO, EPCO, and GW_REVAP evapotranspiration; CH_N2 and CH_K2 water routing; USLE_K, SPCON, SPEXP, PRF, ADJ_PKR, CH_COV1, and CH_COV2 soil erosion and in-stream sediment transport; and RS2, RS3, RS4, RS5, BC1, BC2, BC3 and BC4 nitrogen and phosphorus cycles in streams (Fig. 8).

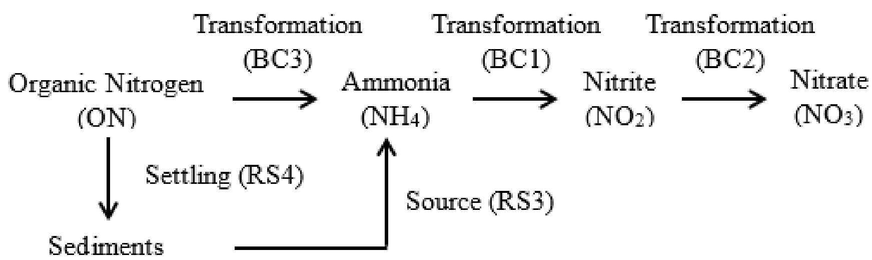


Figure 8. Nitrogen and phosphorus cycles in streams

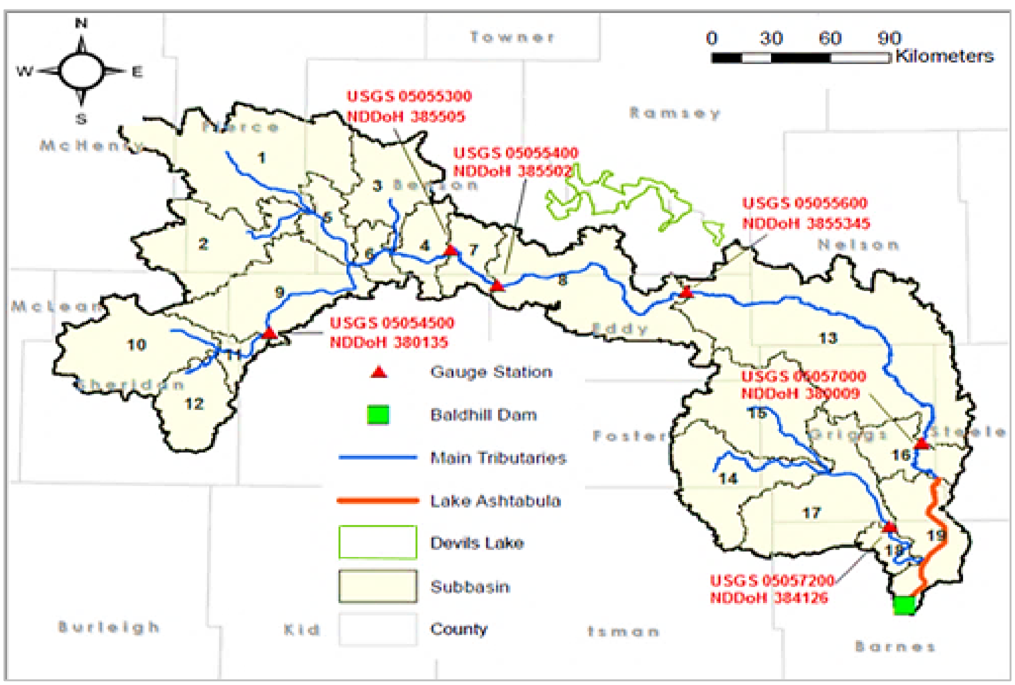
3.2.5. Model Calibration

Streamflow and water quality data measured at the five USGS gauging stations along the Sheyenne River at Harvey, Flora, Bremen, Warwick, and Cooperstown, and one station at Baldhill Creek near Dazey were used for model calibration and validation (Table 5 and Fig. 9). The five-year calibration period for daily streamflow is from January 1, 2006 to December 31, 2010, and the two-year validation period is from January 1, 2011 to December 31, 2012. Sediment load estimates (tonnes/day) and in-stream concentration measurements (mg/l) are also available at four USGS stations at the downstream of Sheyenne River and Baldhill Creek (see Appendix B1-B8 for graphical comparisons). Instantaneous in-stream concentration measurements for three water quality variables (i.e., nitrate, organic nitrogen and organic phosphorus) were also retrievable from six NDDoH gauging stations (see Appendix C1-C18 for graphical comparisons). For model calibration and validation purposes, these in-stream water quality concentrations were converted into daily loads by multiplying their concentrations by flow volumes.

Table 5. Streamflow and water quality gauging stations in the Lake Ashtabula watershed

Agency	Station Name	ID	Hydrology Calibration	Sediment Calibration	Nutrient Calibration
USGS	Sheyenne River above Harvey, ND	05054500	√		
NDDoH		380135			√
USGS	Sheyenne River above Devils Lake outlet Near Flora, ND	05055300	√		
NDDoH		395505			√
USGS	Sheyenne River below Devils Lake outlet near Bremen, ND	05055400	√	√	
NDDoH		385502			√
USGS	Sheyenne River near Warwick, ND	05056000	√	√	
NDDoH		385345			√
USGS	Sheyenne River near Cooperstown, ND	05057000	√	√	
NDDoH		380009			√
USGS	Baldhill Creek near Dazey, ND	05057200	√	√	
NDDoH		384126			√

Notes: USGS – U.S. Geological Survey; NDDoH – North Dakota Department of Health



Notes: USGS – U.S. Geological Survey; NDDoH – North Dakota Department of Health

Figure 9. The USGS and NDDoH gauging stations in the Lake Ashtabula watershed

The SWAT model calibration was set up using SWAT-CUP version 2009. Six time series datasets between January 1, 2006 and December 31, 2010 were generated in the SWAT model for calibration purposes. Daily simulated streamflow (FLOW_OUT), sediment loads (SED_OUT), in-stream sediment concentration (SEDCONC), nitrate loads (NO3_OUT), organic nitrogen loads (ORGN_OUT), and organic phosphorus loads (ORGP_OUT) were compared with observed data collected at these gauging stations (Table 6).

Table 6. SWAT parameters adjusted for hydrology and water quality calibration

Parameters	**Description**	**Suggested Range**	**Default Value**	**Calibrated Value**	**SWAT File**	**Adjusted Level**
Hydrology Calibration						
SFTMP	snowfall temperature (°C)	[-5,5]	1.0	0	*.bsn	Basin
SMTMP	snow melt base temperature (°C)	[-5,5]	0.5	3	*.bsn	Basin
TIMP	snow pack temperature lag factor	[0,1]	1.0	0.3	*.bsn	Basin
SURLAG	surface runoff lag time (days)	[0.05,24]	4.0	0.3	*.bsn	Basin
ESCO	soil evaporation compensation factor	[0,1]	0.95	0.3	*.hru	HRUs
EPCO	plant uptake compensation factor	[0,1]	1.0	0.8	*.hru	HRUs
SLSUBBSN	average slope length (m)	[10,150]	Varies	Varies	*.hru	HRUs
SOL_AWC	available water capacity (mm H_2O/mm soil)	[0,1]	Varies	Varies	*.sol	HRUs
SOL_K	saturated hydraulic conductivity (mm/hr)	[0,2000]	Varies	Varies	*.sol	HRUs
ALPHA_BF	baseflow aplha factors (days)	[0,1]	0.048	0.5	*.gw	Subbasins
GW_DELAY	groundwater delay (days)	[0,500]	31	50	*.gw	Subbasins
GWQMN	threshold water depth in the shallow aquifer for flow (mm)	[0,5000]	0	10	*.gw	Subbasins
GW_REVAP	groundwater revep coefficient	[0.02,0.2]	0.02	0.1	*.gw	Subbasins
RCHRG_DP	deep aquifer percolation fraction	[0,1]	0.05	0.2	*.gw	Subbasins
CN2	SCS CN II value	[35,98]	Varies	Varies	*.mgt	HRUs
CH_N2	manning's n value for main channel	[0,0.3]	0.014	0.01	*.rte	Subbasins
CH_K2	channel effective hydraulic conductivity (mm/hr)	[0,500]	0	10	*.rte	Subbasins

Table 6. SWAT parameters adjusted for hydrology and water quality calibration (continued)

Parameters	Description	Suggested Range	Default Value	Calibrated Value	SWAT File	Adjusted Level
ALPHA_BNK	baseflow alpha factor for bank storage (days)	[0,1]	0	0.3	*.rte	Subbasins
Water Quality Calibration						
SPCON	linear parameter for sediment reentrainment	[0.0001,0.01]	0.0001	0.001	*.bsn	Basin
SPEXP	exponential parameter for sediment reentrainment	[1,2]	1	1	*.bsn	Basin
PRF	peak rate adjustment factor for main channel	[0,2]	1	1.2	*.bsn	Basin
ADJ_PKR	peak rate adjustment factor for subbasins	[0.5,2]	0	0.7	*.bsn	Basin
CH_COV1	channel erodibility factor	[0,0.6]	0	0.01	*.rte	Subbasins
CH_COV2	channel cover factor	[0,1]	0	0.01	*.rte	Subbasins
USLE_K	MUSLE equation soil erodibility k factor	[0,0.65]	Varies	Varies	*.sol	HRUs
RS2	benthic source rate for dissolved P (mg dissolved P /m^2day)	[0.001-0.1]	0.5	0.05	*.swq	Basin
RS3	benthic source rate for NH4-N (mg NH4-N /m^2day)	[0,1]	0.5	0.1	*.swq	Basin
RS4	coefficient for organic N settling (day^{-1})	[0.001,0.1]	0.05	0.35	*.swq	Basin
RS5	coefficient for organic P settling (day^{-1})	[0.001,0.1]	0.05	0.1	*.swq	Basin
BC1	rate constant for biological oxidation of NH_4 to NO_2 (day^{-1})	[0.1,1]	0.55	0.5	*.swq	Basin
BC2	rate constant for biological oxidation of NO_2 to NO_3 (day^{-1})	[0.2,2]	1.1	1.1	*.swq	Basin
BC3	rate constant for hydrolysis of organic N to NH_3 (day^{-1})	[0.2,0.4]	0.21	0.03	*.swq	Basin
BC4	rate constant for mineralization of organic P to dissolved P (day^{-1})	[0.01-0.7]	0.35	0.01	*.swq	Basin

3.2.6. Statistical Measures

Besides graphical comparisons (see Appendix A), coefficient of determination (R^2, Eq. 3.13) and Nash-Sutcliffe efficiency (E_{NS}, Eq 3.14) were used to measure the goodness-of-fit between the model-simulated and observed streamflows at the six USGS gauging stations. E_{NS} is a measure of how well the simulated values agree with the observed values. The closer the E_{NS}'s value is to one, the better the prediction of the model is. Moriasi et al. (2007) suggested that the model performance is satisfactory if the E_{NS} for monthly average streamflow comparison is greater or equal to 0.50. The R^2 is the squared value of the coefficient of correlation R that is a measure of the strength and direction of the relationship between two variables. The closer the R^2 value is to one, the stronger the relationship is. A value of 0.50 for R^2 was considered satisfactory by Gassman et al. (2007) when comparing monthly average streamflows in multiple studies.

$$R^2 = \left[\frac{\sum_{i=1}^{N} (O_i - \bar{O})(S_i - \bar{S})}{\sqrt{\sum_{i=1}^{N} (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^{N} (S_i - \bar{S})^2}} \right]^2 \qquad (3.13)$$

$$E_{NS} = 1 - \frac{\sum_{i=1}^{N} (O_i - S_i)^2}{\sum_{i=1}^{N} (O_i - \bar{O})^2} \qquad (3.14)$$

Where O_i and S_i are observed and simulated values (m^3/s); $\bar{O}$ and $\bar{S}$ are average observed and simulated values (m^3/s), respectively.

In addition, percent bias (PBIAS) is usually used to measure average tendency of over or under prediction of model performance (Eq (3.15)).

$$PBIAS = \frac{\sum_{i=1}^{N} (S_i - O_i)}{\sum_{i=1}^{N} O_i} \qquad (3.15)$$

3.2.7. Scenario Analysis

The calibrated SWAT model was then used to simulate the impacts of land use change, climate change and the Devils Lake diversion on water quality in Lake Ashtabula under eight different scenarios. These scenarios include a baseline scenario, one land use change scenario, two climate change scenarios, and four Devils Lake diversion scenarios. The definitions of these scenarios are shown in Table 7.

Table 7. Definition of scenarios

Scenarios	LULC	Precipitation	Devils Lake Outlet	Analysis
Baseline scenario	NASS CDL 2009	Real observations	Without diversion	Land use changes
LULC 2013 scenario	NASS CDL 2013	Real observations	Without diversion	Land use changes
Increased precipitation scenario	NASS CDL 2009	10% increase	Without diversion	Climate changes
Decreased precipitation scenario	NASS CDL 2009	10% decrease	Without diversion	Climate changes
Devils Lake design capacity under current climate scenario	NASS CDL 2009	Real observations	With both west and east diversions	Devils Lake outlet impacts
Devils Lake operation capacity under current climate scenario	NASS CDL 2009	Real observations	With both west and east diversions	Devils Lake outlet impacts
Devils Lake design capacity under future climate scenario	NASS CDL 2009	10% increase	With both west and east diversions	Devils Lake outlet impacts
Devils Lake operation capacity under future climate scenario	NASS CDL 2009	10% increase	With both west and east diversions	Devils Lake outlet impacts

Notes: LULC – Land use and land cover, NASS CDL – National Agriculture Statistics Service Cropland Data Layer; DL – Devils Lake

4. RESULTS AND DISCUSSION

4.1. Model Calibration and Validation

Table 8 lists model calibration results for streamflow. As shown in Table 8, the statistics for monthly average streamflow comparisons are greater than those for daily streamflow comparisons. R^2 values for monthly average flow comparisons at all six USGS gauging stations were greater than 0.60 during both calibration and validation periods. E_{NS} values for monthly average flow comparison were greater than 0.50 at the Bremen, Warwick, Cooperstown, and Baldhill Creek stations (see Appendix A5-A12 for graphical comparisons), but they were not good at the Harvey and Flora stations (see Appendix A1-A4 for graphical comparisons).

Table 8. Daily and monthly streamflow calibration and validation at six USGS gauging stations

	USGS 05054500 Sheyenne River above Harvey	**USGS 05055300 Sheyenne River above Devils Lake Outlet near Flora**	**USGS 05055400 Sheyenne River Below Devils Lake Outlet near Bremen**	**USGS 05056000 Sheyenne River near Warwick**	**USGS 05057000 Sheyenne River near Cooperstown**	**USGS 05057200 Baldhill Creek near Dazey**
Calibration (January 1, 2006 to December 31, 2010)						
Monthly E_{NS}	-17.55	0.25	0.51	0.66	0.57	0.70
Daily E_{NS}	-19.45	-0.47	-0.14	0.47	0.50	-0.52
Monthly R^2	0.61	0.67	0.65	0.71	0.67	0.75
Daily R^2	0.41	0.46	0.44	0.60	0.61	0.12
Monthly PBIAS	3.16	0.38	0.06	-0.08	0.49	0.12
Validation (January 1, 2011 to December 31, 2012)						
Monthly E_{NS}	-11.42	0.38	0.51	0.60	0.54	0.41
Daily E_{NS}	-15.49	-1.81	-1.27	-0.11	0.47	0.36
Monthly R^2	0.71	0.76	0.68	0.68	0.73	0.58
Daily R^2	0.41	0.33	0.31	0.21	0.53	0.37
Monthly PBIAS	5.51	1.35	0.56	0.43	0.51	0.22

Notes: USGS - U.S. Geological Survey; E_{NS} – Nash-Sutcliffe Efficiency; R^2 – Coefficient of Determination; PBIAS – Percent bias

The model's poor performance at the Harvey and Flora stations may have been attributed to the fact that there is a dam at the Sheyenne River near Harvey, ND. The design parameters for the Harvey Dam are retrieved from North Dakota Water State Commission (NDWSC) and listed in Table 9 (http://www.swc.state.nd.us/info_edu/map_data_resources/structures/single.php?id=2791&tbl=Dam). The SWAT model has a simplistic approach for modeling a reservoir (Neitsch et al., 2011).

Table 9. Design parameters of Harvey Dam

	Area (km^2)	**Volume (m^3)**
Emergency level	2.84	9,431,188.08
Normal level	1.46	3,330,396.00

4.1.1. Baseline Scenario Water Quality Loads

Once the SWAT model is calibrated and validated, the baseline scenario sediment and nutrient loads into Lake Ashtabula are calculated as the sums from two connecting locations for of the loads from Sheyenne River, Baldhill Creek, and peripheral contribution of the subbasin that Lake Ashtabula is located (i.e., subbasin 19). The baseline scenario water quality loads are listed in Table 10.

Table 10. Estimated sediment and nutrient loads under baseline scenario

	Sheyenne River (at outlet 16)	**Baldhill Creek (at outlet 18)**	**Peripheral (subbasin 19)**	**Total**
Sediment (tonnes/year)	37,848	14,452	136	52,436
Nitrate-N (kg N/year)	17,013	5,367	3	22,383
TN (kg N/year)	1,153,569	177,044	789	1,331,402
TP (kg P/year)	280,610	39,344	108	320,062

Notes: TN – Total Nitrogen; TP – Total Phosphorus

4.2. Land Use Changes

Due to bioenergy policy changes in 2007, among other reasons, croplands in the study area have changed significantly since 2007. This study aims to explore the impact of land use changes by comparing selected years after the policy with the baseline year of 2009. NASS CDL 2013 data layer was used to represent the land use across the Lake Ashtabula watershed after the bioenergy policy change.

A comparison between NASS CDL 2009 and 2013 data indicated that biofuel crops continued to expand in the Lake Ashtabula watershed (Table 11). Corns and soybeans increased by 151% and 40%, resepectively. In contrast, the coverages of sunflower, sugarbeet, oats, and wheat decreased by 91%, 91%, 40%, and 37%, resepectively. The urban area also had a 30% decrease, which might be caused by different land use classificaiton methods. Increases in cropland were found to be about 4% and 15% in Sheyenne River subbasin and Baldhill Creek subbasin (Table 12-13). Most of the land use changes occurred at the downstream Sheyenne River and the subbains near Baldhill Creeks (Fig. 10).

Table 11. SWAT class land use incremental changes using 2009 and 2013 NASS CDL

SWAT land use classes	**NASS CDL 2009**		**NASS CDL 2013**		**Percentage Changes**
	Area (km^2)	**Percent of watershed**	**Area (km^2)**	**Percent of watershed**	
CORN	348.33	4%	872.67	9%	151%
SOYB	1,507.63	15%	2,104.28	21%	40%
SUNF	157.61	2%	14.65	0%	-91%
BARL	92.78	1%	118.56	1%	28%
SWHT	1,816.44	19%	1,152.71	12%	-37%
OATS	13.05	0%	7.79	0%	-40%
CANA	81.10	1%	77.04	1%	-5%
ALFA	46.08	0%	98.05	1%	113%
SGBT	2.96	0%	0.28	0%	-91%
PTBN	107.54	1%	78.11	1%	-27%
FPEA	90.17	1%	335.36	3%	272%
FRSD	59.73	1%	63.43	1%	6%
URBN	573.07	6%	403.39	4%	-30%
WETN	773.54	8%	972.18	10%	26%
WATR	408.65	4%	424.16	4%	4%
PAST	3,712.39	38%	3,068.39	31%	-17%

Notes: NASS CDL – National Agriculture Statistics Service Cropland Data Layer

Table 12. Land use change impacts in Sheyenne River subbasins (NASS CDL 2009 and 2013)

	NASS CDL 2009		NASS CDL 2013		Changes	
	km^2	%	km^2	%	km^2	%
Cropland	2,911.27	39%	3,028.00	41%	116.73	4%
Urban	429.71	6%	302.39	4%	-127.32	-30%
Fellow Land	83.52	1%	322.41	4%	238.89	286%
Forest	41.33	1%	46.99	1%	5.66	14%
Grassland	3,110.65	42%	2,678.80	36%	-431.85	-14%
Water/Wetlands	816.05	11%	1,013.86	14%	197.81	24%

Notes: NASS CDL – National Agriculture Statistics Service Cropland Data Layer

Table 13. Land use change impacts in Bald Creek subbasins (NASS CDL 2009 and 2013)

	NASS CDL 2009		NASS CDL 2013		Changes	
	km^2	%	km^2	%	km^2	%
Cropland	1,035.55	53%	1,192.45	61%	156.90	15%
Urban	118.97	6%	84.66	4%	-34.31	-29%
Fellow Land	6.50	0%	12.39	1%	5.89	91%
Forest	11.44	1%	10.38	1%	-1.06	-9%
Grassland	488.14	25%	347.85	18%	-140.29	-29%
Water/Wetlands	307.86	16%	320.86	16%	13.00	4%

Notes: NASS CDL – National Agriculture Statistics Service Cropland Data Layer

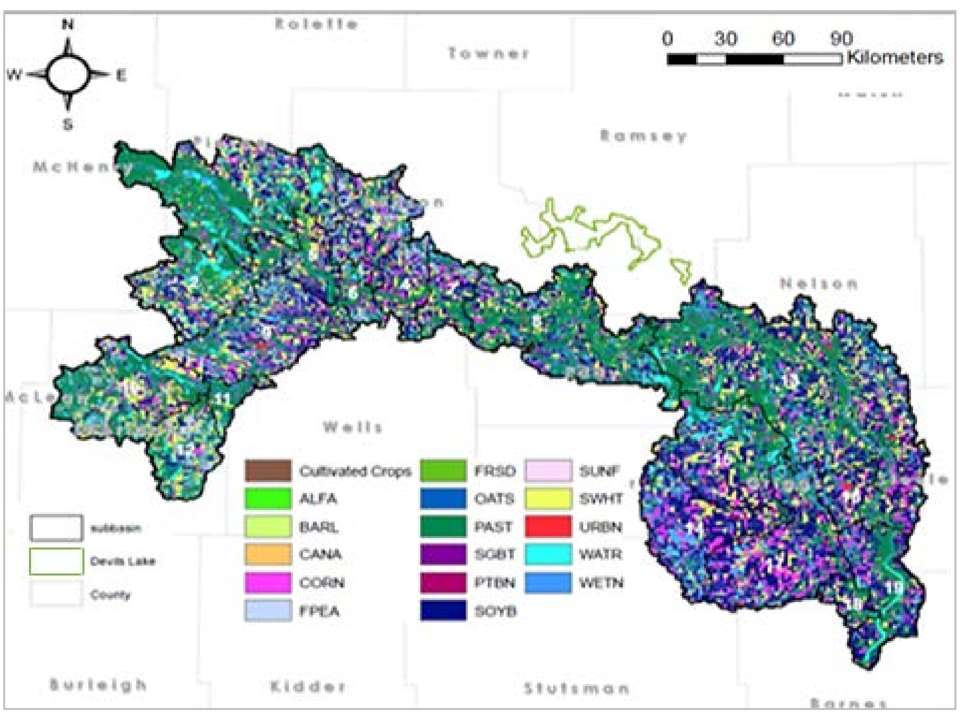
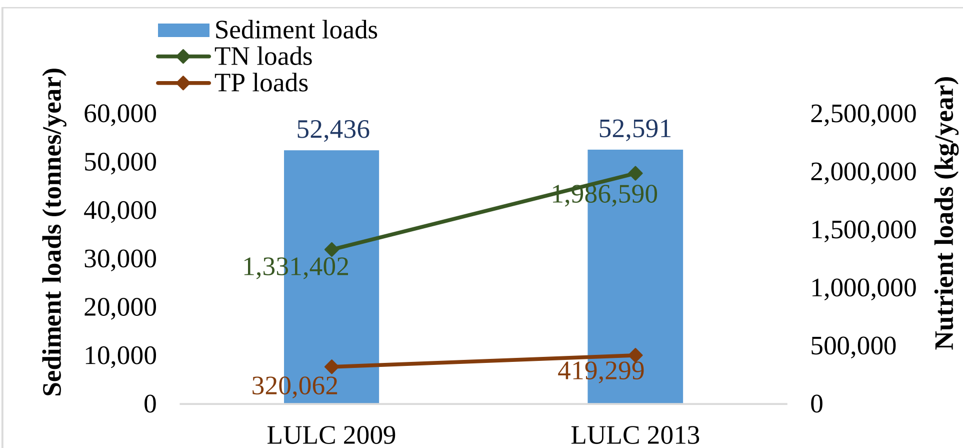


Figure 10. NASS CDL land use map for the Lake Ashtabula watershed (2013)

As shown in Fig. 11, average annual sediment loads between baseline year of 2009 and post-bioenergy policy year of 2013 only increased by 1%; while average annual total nitrogen and total phosphorus loads increased about 49% and 31%, respectively (see also Table 14). Corn requires an average nitrogen fertilization rate of 120 kg/ha; while the average nitrogen fertilization rates for sunflower, oats, and wheat are about half or less than that for corn (Franzen, 2010). The average nitrogen fertilization rate for sugar beet is as high as that for corn; but the planting area for sugar beet is negligible (~0.28 km^2). In contrast, the corn planting areas were about 9% of the entire Lake Ashtabula watershed (872.67 km^2). The phosphorus fertilization aplication rate for corn is also higher than that for other crops.



Notes: LULC – Land use and land cover; TN – Total Nitrogen; TP – Total Phosphorus

Figure 11. Sediment and nutrient loads comparison under LULC changes scenarios

Table 14. Estimated sediment and nutrient loads under LULC 2013 scenario

LULC2013	Sheyenne River (at outlet 16)	Baldhill Creek (at outlet 18)	Peripheral (subbasin 19)	Total
Sediment (tonnes/year)	35,489	16,937	165	52,591
Nitrate-N (kg N/year)	16,778	5,096	3	21,877
TN (kg N/year)	1,768,015	217,617	958	1,986,590
TP (kg P/year)	375,291	43,876	132	419,299

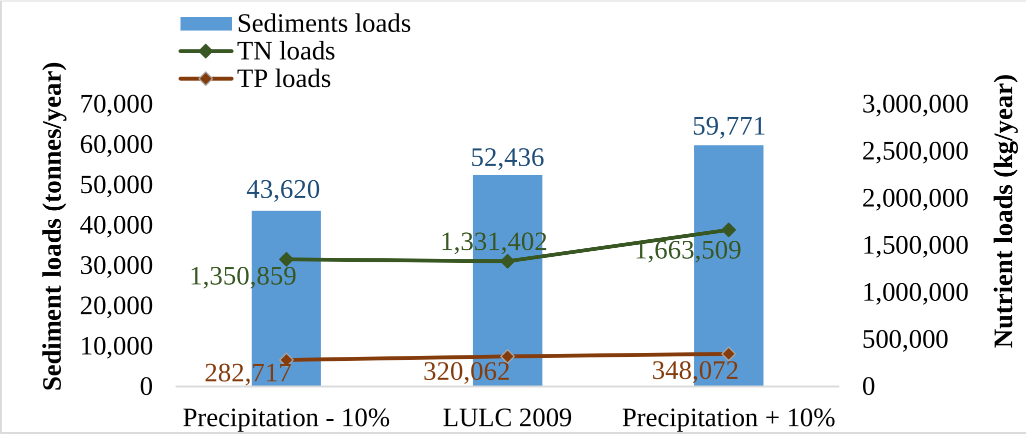
Notes: LULC – Land use and land cover; TN – Total Nitrogen; TP – Total Phosphorus

4.3. Climate Change

Walthall et al. (2012) projected that North-Central U.S. regions could experience an increase of 5 to 15 percent in both summer and winter precipitation over the next 30 to 40 years. Winter precipitation is an important concern in our region, which generates spring snowmelt runoff. This study proposed future climate projection scenario with 10 percent precipitation increase for all year around. All daily precipitation records collected at the nine weather gauging stations were increased by 10 percent to assess climate change impacts on hydrology and water quality in the Lake Ashtabula watershed.

SWCS (2003) reported that there was asymmetric relationship between precipitation and nutrients loads in response to an increase or decrease in precipitation. Sediment and nutrients loads may increase if precipitation increases. However, when precipitation decreases, the results may be complicated. The interactions of plant biomass, runoff, and erosion may reduce the effects of precipitation decreases, and the nutrient loads may either increase or decrease. Therefore, this study also designed a scenario where precipitation decreases 10%.

The analysis shows that, in response to a 10% precipitation increase, the average annual loads for sediment, total nitrogen, and total phosphorus increased about 14%, 25%, and 9%, respectively. In contrast, in response to a 10% precipitation decrease, the average annual loads for sediment and total phosphorus decreased by 17% and 12%, respectively; while the average annual total nitrogen loads increased by 1% (Fig. 12; Table 15-16).



Notes: LULC – Land use and land cover; TN – Total Nitrogen; TP – Total Phosphorus

Figure 12. Sediment and nutrient loads comparison under climate changes scenarios

Table 15. Estimated sediment and nutrient loads under future increased precipitation scenario

Precipitation +10%	**Sheyenne River (at outlet 16)**	**Baldhill Creek (at outlet 18)**	**Peripheral (subbasin 19)**	**Total**
Sediment (tonnes/year)	43,317	16,311	143	59,771
Nitrate-N (kg N/year)	20,320	6,397	3	26,720
TN (kg N/year)	1,457,229	205,420	860	1,663,509
TP (kg P/year)	307,316	40,637	119	348,072

Notes: TN – Total Nitrogen; TP – Total Phosphorus

Table 16. Estimated sediment and nutrient loads under future decreased precipitation scenario

Precipitation -10%	**Sheyenne River (at outlet 16)**	**Baldhill Creek (at outlet 18)**	**Peripheral (subbasin 19)**	**Total**
Sediment (tonnes/year)	31,514	12,013	93	43,620
Nitrate-N (kg N/year)	18,072	5,362	3	23,437
TN (kg N/year)	1,204,431	145,853	575	1,350,859
TP (kg P/year)	253,431	29,206	80	282,717

Notes: TN – Total Nitrogen; TP – Total Phosphorus

4.4. Devils Lake Diversion

The west and east Devils Lake diversion outlets managed by the North Dakota State Water Commission were added in the Lake Ashtabula watershed model to serve as point sources to Sheyenne River to evaluate impacts of Devils Lake diversion. This study proposed two diversion scenarios. The first diversion scenario (i.e., W250E350) is adopted from Vecchia (2011). This scenario is based on design capacities of 250 ft^3/s (7.08 m^3/s) for the western outlet and 350 ft^3/s (9.91 m^3/s) for the eastern outlet. The other diversion scenario (i.e., W131E266) is average operation diversion flow rates calculated based on observed Devils Lake diversion data. The average operational diversion flow rate for the western outlet is 131 ft^3/s (3.71 m^3/s) and that for the eastern outlet is 266 ft^3/s (7.53 m^3/s).

The water quality data for the Devils Lake diversion water were retrieved from the North Dakota Department of Health's website (https://www.ndhealth.gov/wq/sw/Z8_SWData/viewer.html). The water quality data for the west outlet were average values of four Devils Lake monitoring stations (i.e. Stations #384160, #380236, #380221, and #380233) located in the west and main bay. The average values of Stations #380234 and #380235 located in the Devils Lake east bay were used for eastern outlet water quality (Table 17 and Fig. 13). It is worth noting that the Devils Lake diversion outlets are operated only during growing season (May-October).

Table 17. Devils Lake diversion scenarios in the growing season (May – October)

<table>
<tr><th>Outlet Alternatives</th><th>Outlet Capacities</th><th>Ammonia Conc.</th><th>Nitrate Conc.</th><th>Organic Nitrogen Conc.</th><th>Mineralized Phosphorus Conc.</th><th>Organic Phosphorus Conc.</th></tr>
<tr><td>W131E266</td><td>west bay: 3.71 m^3/s; east bay: 7.53 m^3/s</td><td rowspan="2">west bay: 0.060mg/l; east bay: 0.078mg/l</td><td rowspan="2">west bay: 0.065mg/l; east bay: 0.121mg/l</td><td rowspan="2">west bay: 1.307 mg/l; east bay: 1.790mg/l</td><td rowspan="2">west bay: 0.045 mg/l; east bay: 0.035mg/l</td><td rowspan="2">west bay: 0.234 mg/l; east bay: 0.220 mg/l</td></tr>
<tr><td>W250E350</td><td>west bay: 7.08 m^3/s; east bay: 9.91 m^3/s</td></tr>
</table>

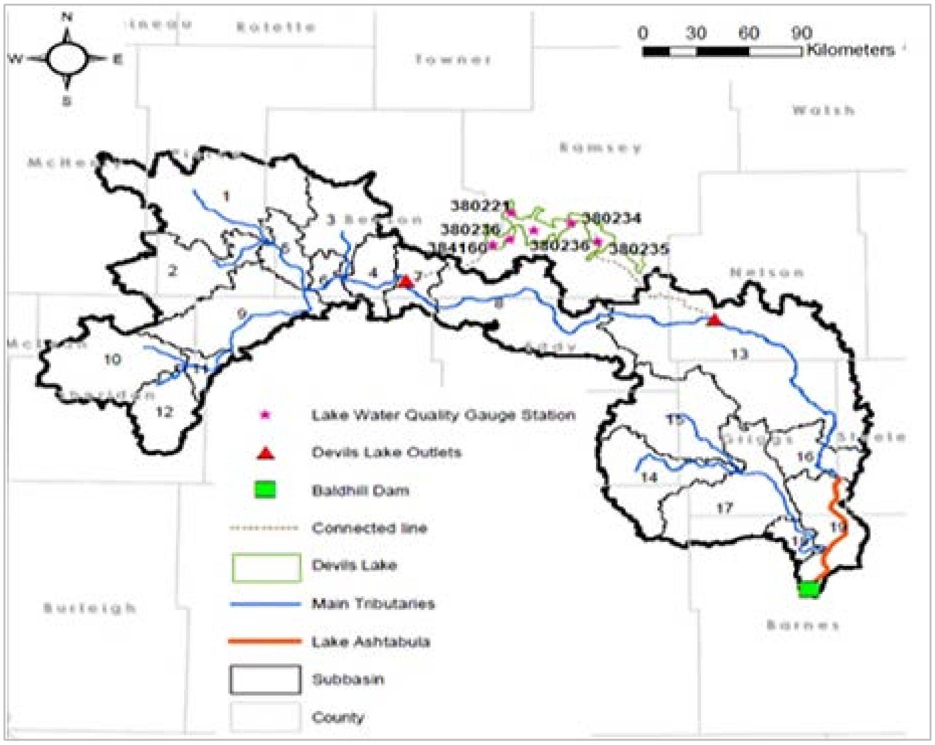
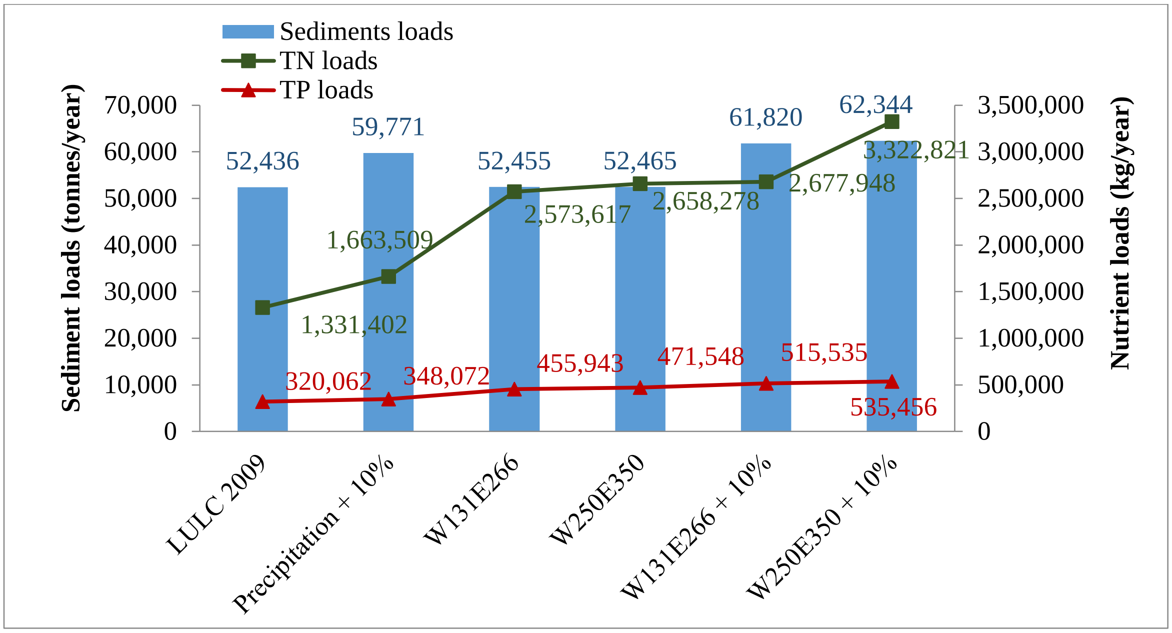


Figure 13. Locations of the eastern and western Devils Lake diversion outlets

The impact of the two Devils Lake diversion scenarios on Lake Ashtabula water quality were evaluated under two climate scenarios: the current climate and future climate with 10% precipitation increase. In other words, four combinations of scenarios were designed to assess the impact of the Devils Lake diversion: (1) operation diversion capacity under current climate (i.e., W131E266), (2) design diversion capacity under current climate (i.e., W250E350), (3) operation diversion capacity under future climate (i.e., W131E266 + 10%), and (4) design capacity under future climate (i.e., W250E350 + 10%).

The impact of Devils Lake diversion on water quality is not negligible. As shown in Figure 13, the change in average annual sediment loads was mainly due to increase in precipitation. However, the average annual total nitrogen and total phosphorus loads resulted from Devils Lake operation diversion capacity or design diversion capacity under current climate scenarios would increase at least 40%; and the average annual total nitrogen and total phosphorus loads would increase more than 60% under future climate scenarios (Fig. 14; Table 18-21).



Notes: TN – Total Nitrogen; TP – Total Phosphorus

Figure 14. Sediment and nutrient loads comparison under Devils Lake scenarios

Table 18. Estimated sediment and nutrient loads at the designed diversion capacity under current climate scenario

Design Capacity	Sheyenne River (at outlet 16)	Baldhill Creek (at outlet 18)	Peripheral (subbasin 19)	Total
Sediment (tonnes/year)	37,877	14,452	136	52,465
Nitrate-N (kg N/year)	37,274	5,367	3	42,644
TN (kg N/year)	2,480,445	177,044	789	2,658,278
TP (kg P/year)	432,096	39,344	108	471,548

Notes: TN – Total Nitrogen; TP – Total Phosphorus

Table 19. Estimated sediment and nutrient loads at the operational diversion capacity under current climate scenario

Operation Capacity	Sheyenne River (at outlet 16)	Baldhill Creek (at outlet 18)	Peripheral (subbasin 19)	Total
Sediment (tonnes/year)	37,867	14,452	136	52,455
Nitrate-N (kg N/year)	32,798	5,367	3	38,168
TN (kg N/year)	2,395,784	177,044	789	2,573,617
TP (kg P/year)	416,491	39,344	108	455,943

Notes: TN – Total Nitrogen; TP – Total Phosphorus

Table 20. Estimated sediment and nutrient loads at the designed diversion capacity under future climate scenario

Design Capacity +10%	Sheyenne River (at outlet 16)	Baldhill Creek (at outlet 18)	Peripheral (subbasin 19)	Total
Sediment (tonnes/year)	45,890	16,311	143	62,344
Nitrate-N (kg N/year)	37,779	6,397	3	44,179
TN (kg N/year)	3,116,541	205,420	860	3,322,821
TP (kg P/year)	494,700	40,637	119	535,456

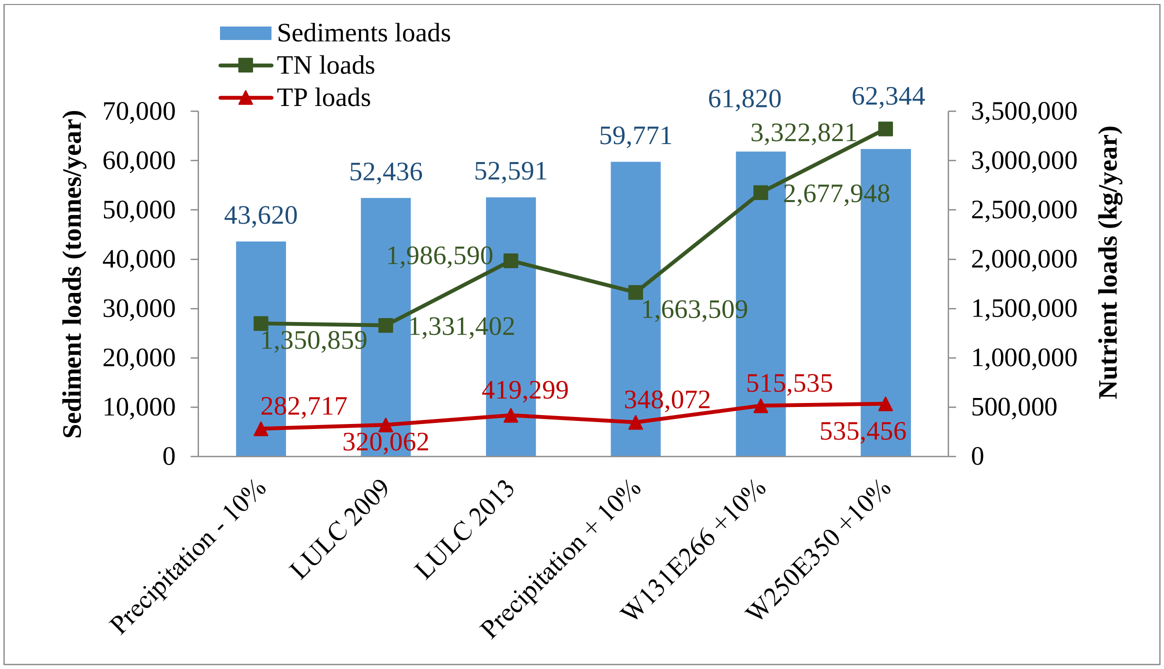
Notes: TN – Total Nitrogen; TP – Total Phosphorus

Table 21. Estimated sediment and nutrient loads at the operational diversion capacity under future climate scenario

Operation Capacity +10%	Sheyenne River (at outlet 16)	Baldhill Creek (at outlet 18)	Peripheral (subbasin 19)	Total
Sediment (tonnes/year)	45,366	16,311	143	61,820
Nitrate-N (kg N/year)	34,071	6,397	3	40,471
TN (kg N/year)	2,471,668	205,420	860	2,677,948
TP (kg P/year)	474,779	40,637	119	515,535

Notes: TN – Total Nitrogen; TP – Total Phosphorus

Above all, Fig. 15 and Table 22 provide a summary of the impacts of land use changes, climate changes, and Devils Lake diversion impacts on Lake Ashtabula water quality.



Notes: LULC – Land use and land cover; TN – Total Nitrogen; TP – Total Phosphorus

Figure 15. Summary of estimated sediment and nutrient loads under all scenarios

Table 22. Percentage changes of sediment and nutrient loads in all scenarios

Scenarios	**Sediment (tonnes/year)**	**Nitrate-N (kg N/year)**	**TN (kg N/year)**	**TP (kg P/year)**
LULC 2009	N/A	N/A	N/A	N/A
LULC 2013	0.30%	-2.26%	49.21%	31.01%
Precipitation - 10%	-16.81%	4.71%	1.46%	-11.67%
Precipitation + 10%	13.99%	19.38%	24.94%	8.75%
W131E266	0.04%	70.52%	93.30%	42.45%
W250E350	0.06%	90.52%	99.66%	47.33%
W131E266 + 10%	17.90%	80.81%	101.14%	61.07%
W250E350 + 10%	18.90%	97.38%	149.57%	67.30%

Notes: LULC – Land use and land cover; TN – Total Nitrogen; TP – Total Phosphorus

5. CONCLUSIONS

Lake Ashtabula, located in Sheyenne River in eastern North Dakota, is a eutrophic lake. Since 2007 it receives diversion water from Devils Lake through Sheyenne River. A SWAT model was developed for the Lake Ashtabula watershed to assess effects of Devils Lake diversion, climate change and land use shift on water quality in the lake. The SWAT model was calibrated and validated using daily and monthly streamflow data and instantaneous water quality measurements observed at six USGS and six NDDoH gauging stations in the watershed – five located in Sheyenne River and one in Baldhill Creek.

Eight scenarios were designed to assess the effects these changes on hydrology and water quality. Land use change impact analysis shows that cropland expansion yields higher sediment and nutrient loads into Lake Ashtabula. Especially, land use changes had significant impacts on Baldhill Creek subbasins because most of corns and soybeans were cultivated in this area. The impacts of increasing and decreasing precipitation had asymmetric relationship with load estimations. The increase in precipitation may increase sediment and nutrient loads; however, decrease in precipitation may decrease sediment and total phosphorus loads, but not necessarily for total nitrogen loads, because the impact on nutrient load depends on the interactions of plant biomass, runoff, and erosion.

Our results also show that, among all scenarios, Devil's Lake diversion has the most significant effects on nutrient loads to Lake Ashtabula, but least effect on sediment load.

This study has resulted in a well-calibrated and validated watershed model that could be used for developing TMDL sediment and nutrients load estimation. This developed model could also identify areas to be targeted by lake water quality improvement projects for load reduction.

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APPENDIX A. STREAMFLOW CALIBRATION AND VALIDATION HYDROGRAPHS

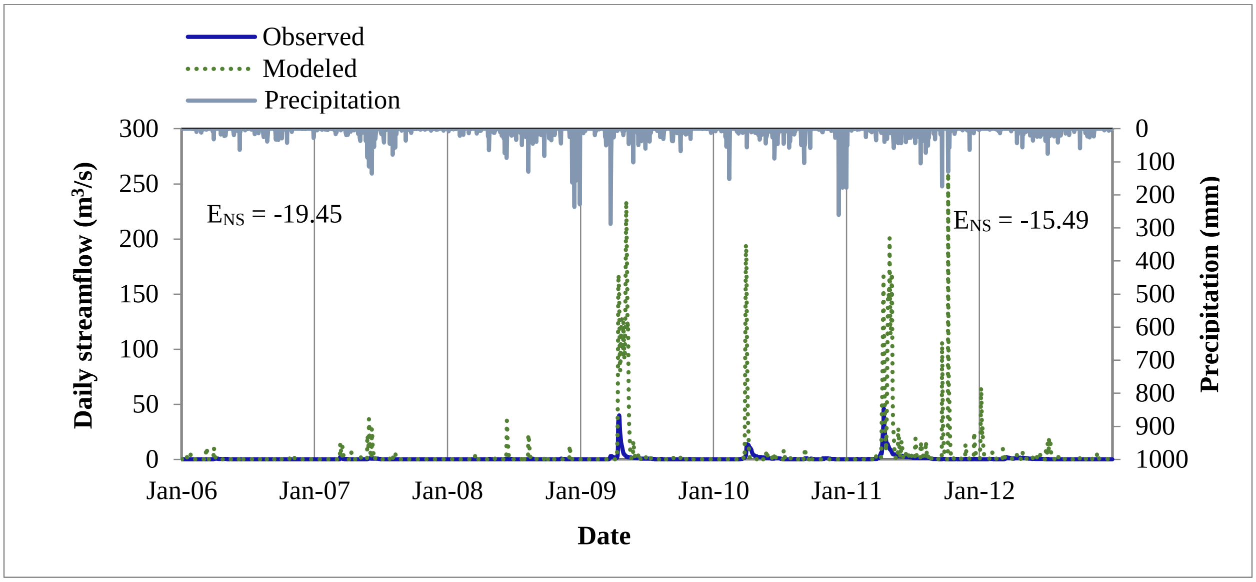

Figure A1. Graphical comparisons of the modeled and the observed daily streamflows in the Sheyenne River above Harvey USGS #05054500 gauging station

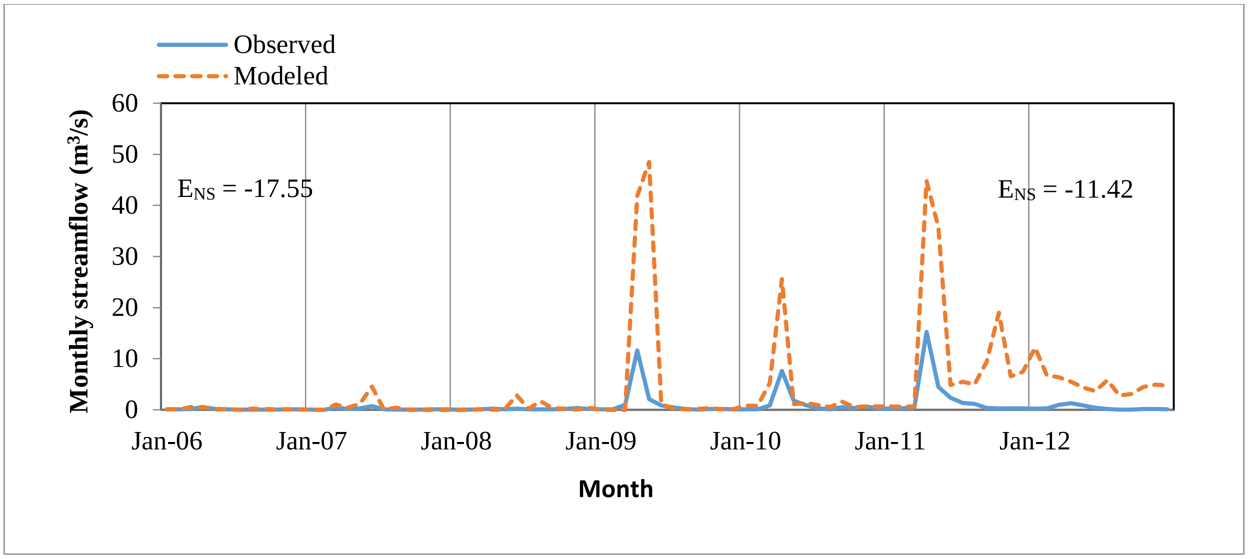

Figure A2. Graphical comparisons of the modeled and the observed monthly average streamflows in the Sheyenne River above Harvey USGS #05054500 gauging station

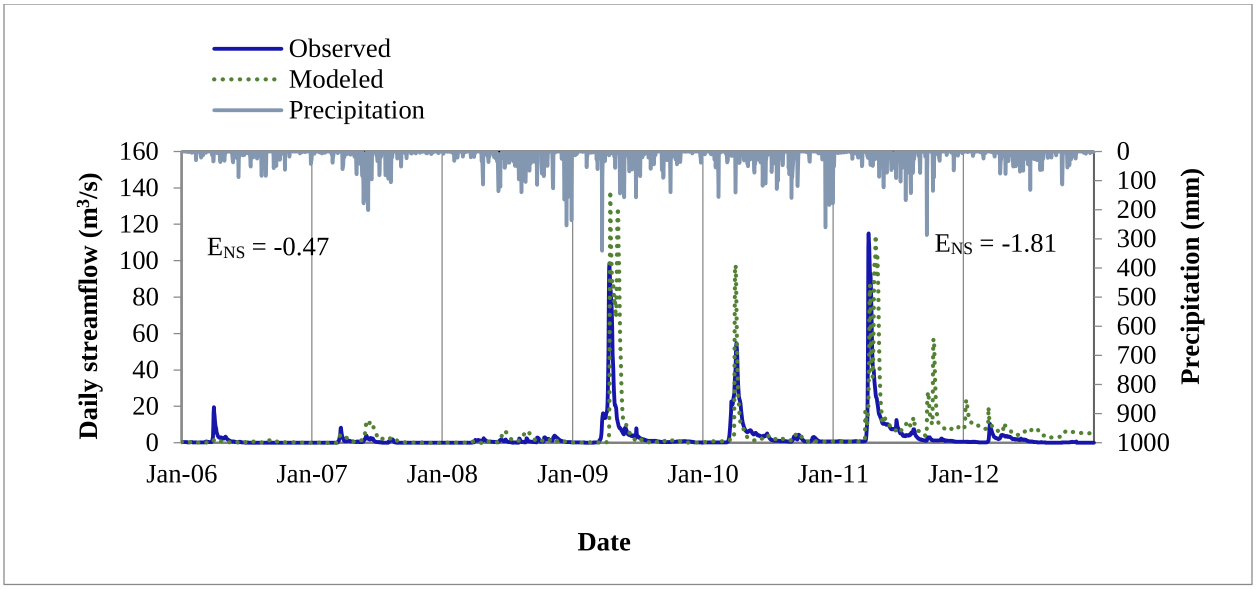

Figure A3. Graphical comparisons of the modeled and the observed daily streamflows in the Sheyenne River above Devils Lake outlet near Flora USGS #05055300 gauging station

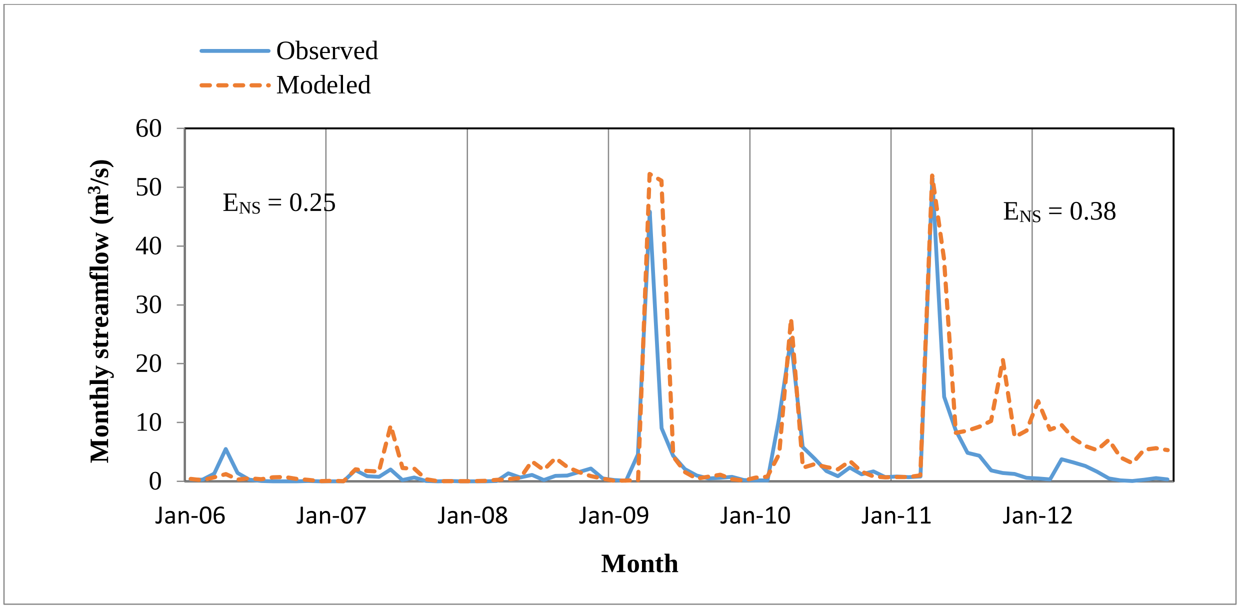

Figure A4. Graphical comparisons of the modeled and the observed monthly average streamflows in the Sheyenne River above Devils Lake outlet near Flora USGS #05055300 gauging station

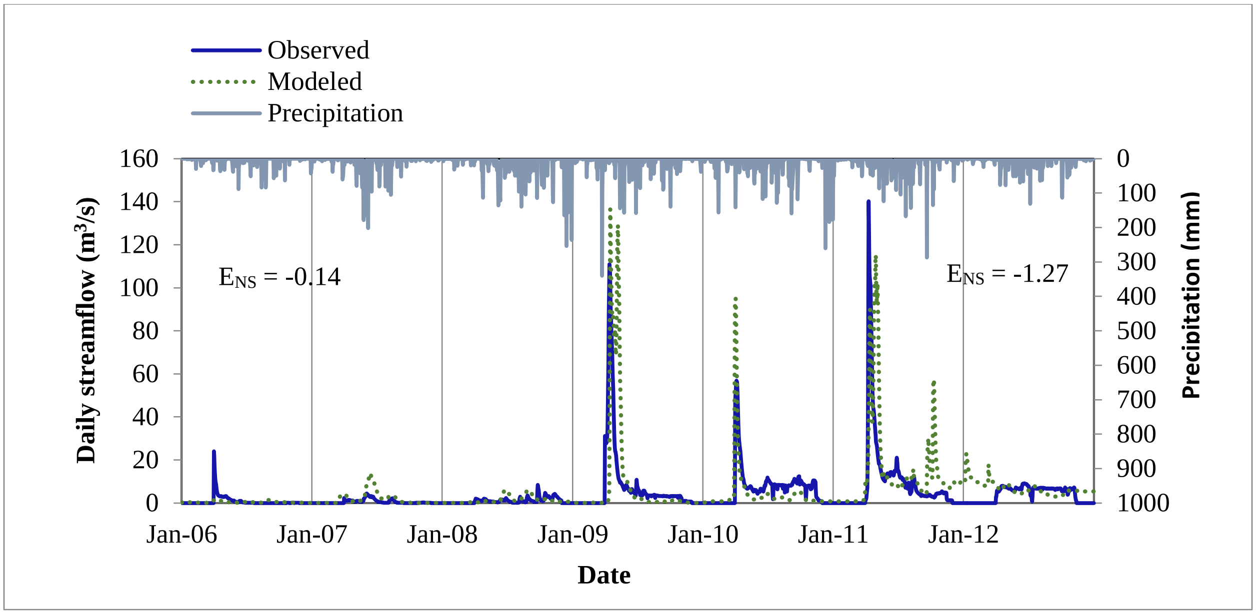

Figure A5. Graphical comparisons of the modeled and the observed daily streamflows in the Sheyenne River below Devils Lake outlet near Bremen USGS #05055400 gauging station

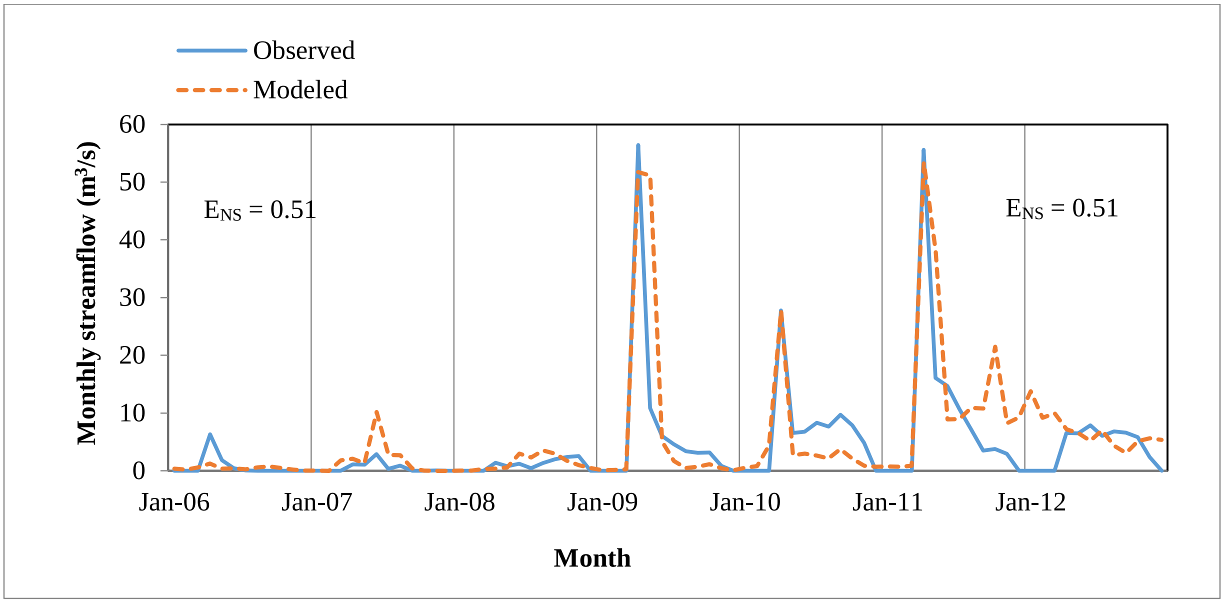

Figure A6. Graphical comparisons of the modeled and the observed monthly average streamflows in the Sheyenne River below Devils Lake outlet near Bremen USGS #05055400 gauging station

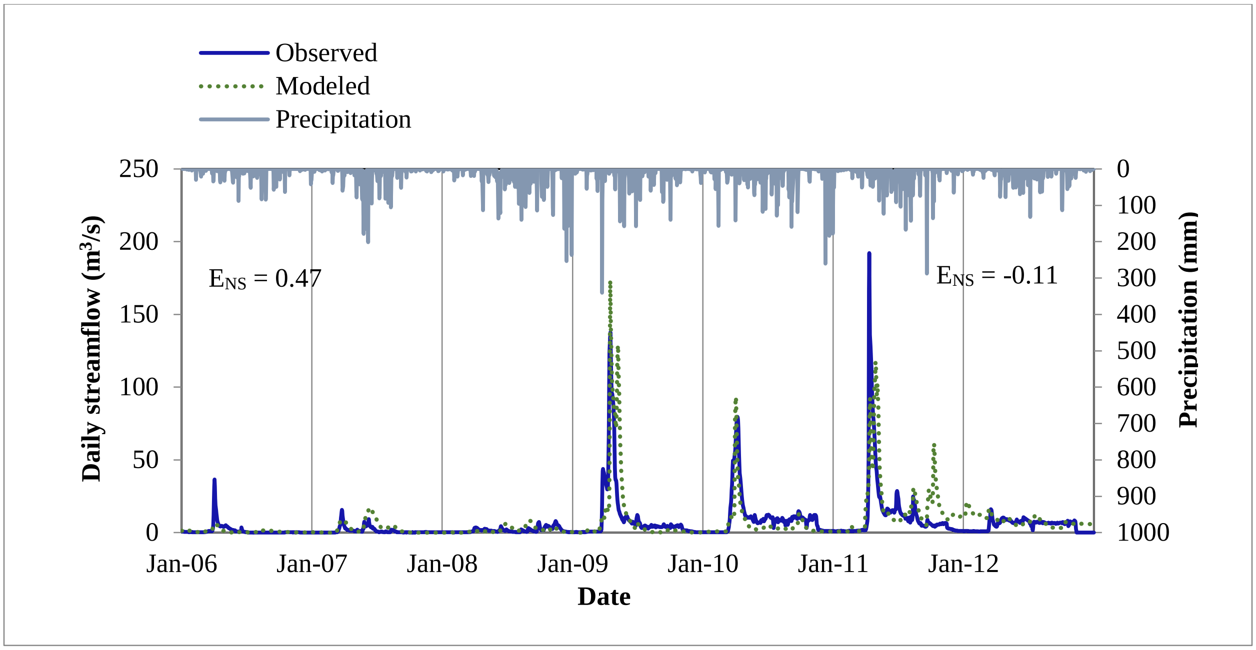

Figure A7. Graphical comparisons of the modeled and the observed daily streamflows in the Sheyenne River near Warwick USGS #05055600 gauging station

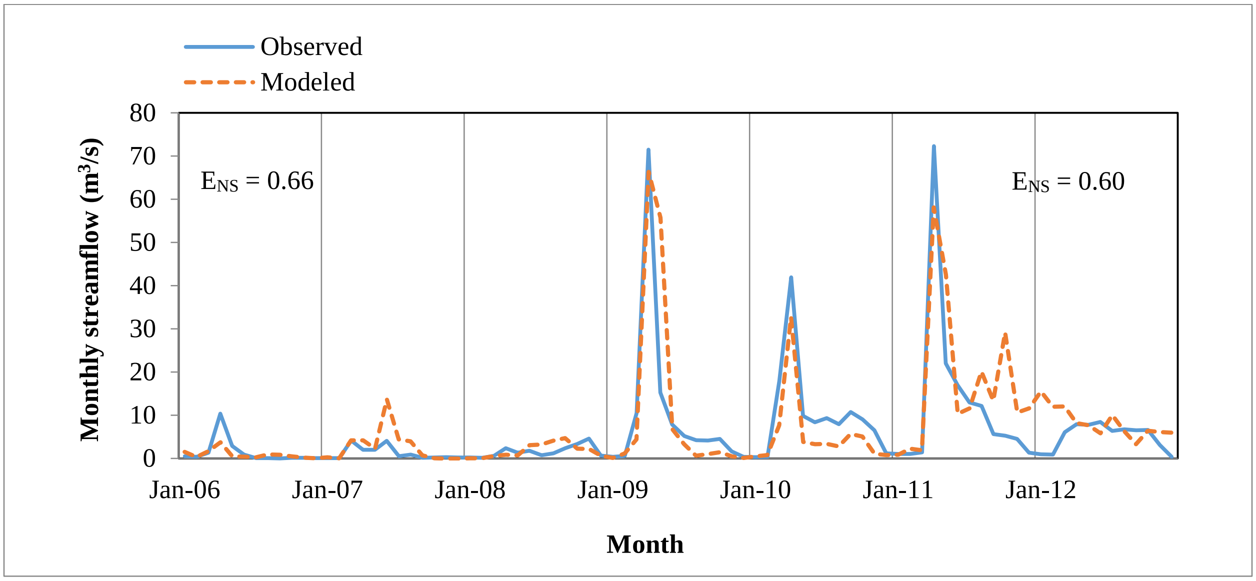

Figure A8. Graphical comparisons of the modeled and the observed monthly average streamflows in the Sheyenne River near Warwick USGS #05055600 gauging station

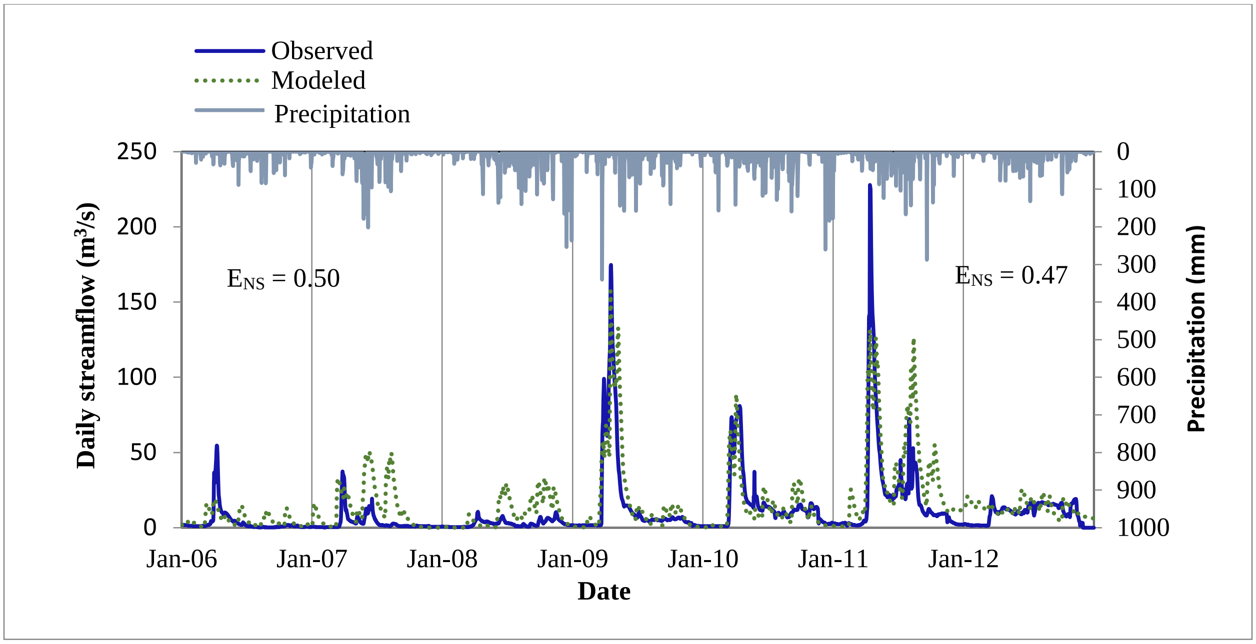

Figure A9. Graphical comparisons of the modeled and the observed daily streamflows in the Sheyenne River near Cooperstown USGS #05055700 gauging station

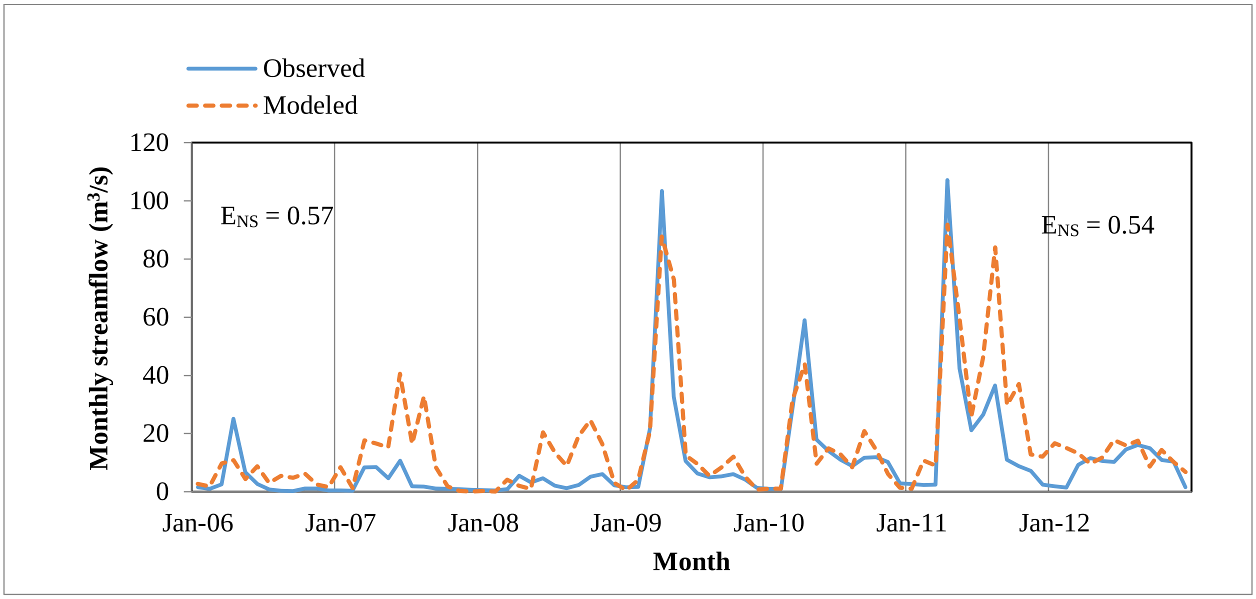

Figure A10. Graphical comparisons of the modeled and the observed monthly average streamflows in the Sheyenne River near Cooperstown USGS #05055700 gauging station

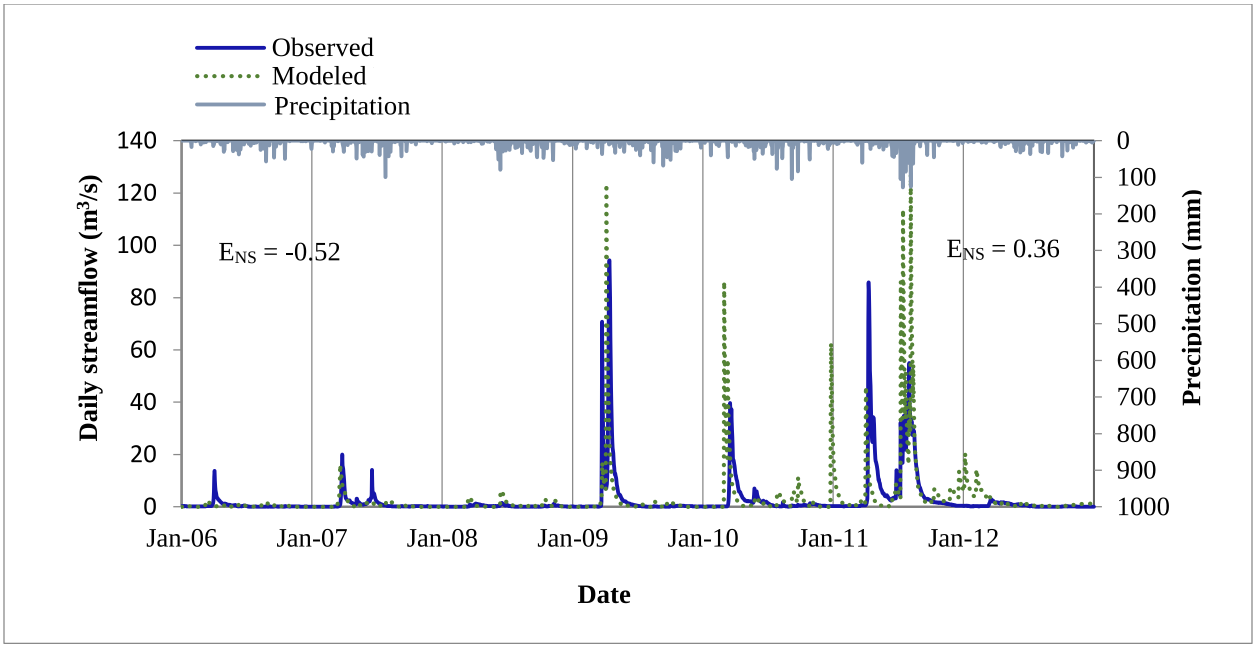

Figure A11. Graphical comparisons of the modeled and the observed daily streamflows in the Baldhill Creek near Dazey USGS #050557200 gauging station

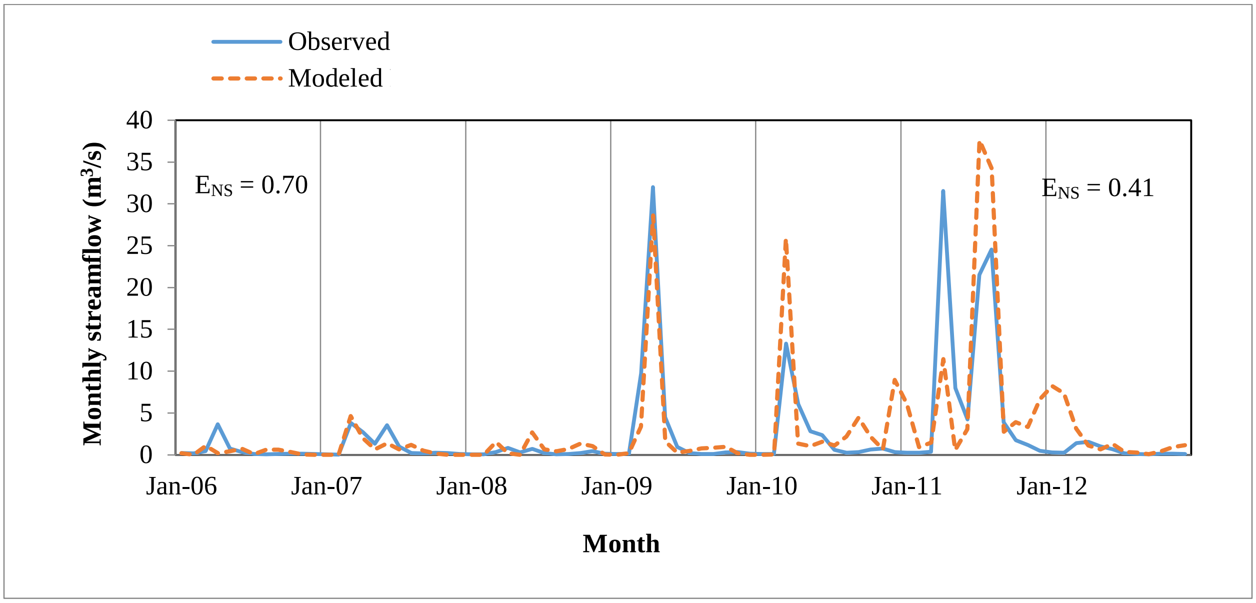

Figure A12. Graphical comparisons of the modeled and the observed monthly average streamflows in the Baldhill Creek near Dazey USGS #050557200 gauging station

APPENDIX B. SEDIMENT CALIBRATION SEDIGRAPHS

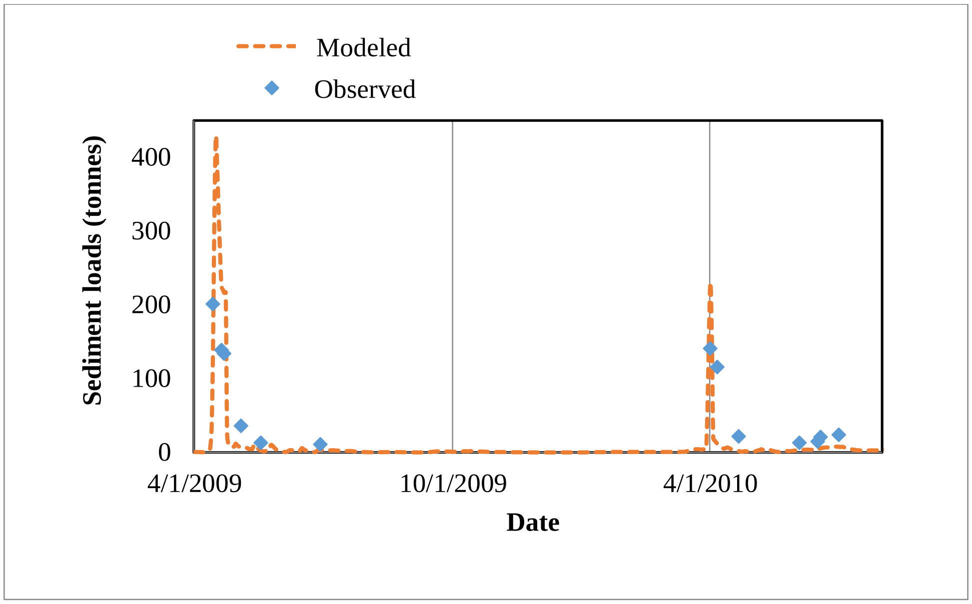

Figure B1. Graphical comparisons of the modeled and the observed suspended solid loads in the Sheyenne River below Devils Lake outlet near Bremen USGS #05055400 gauging station

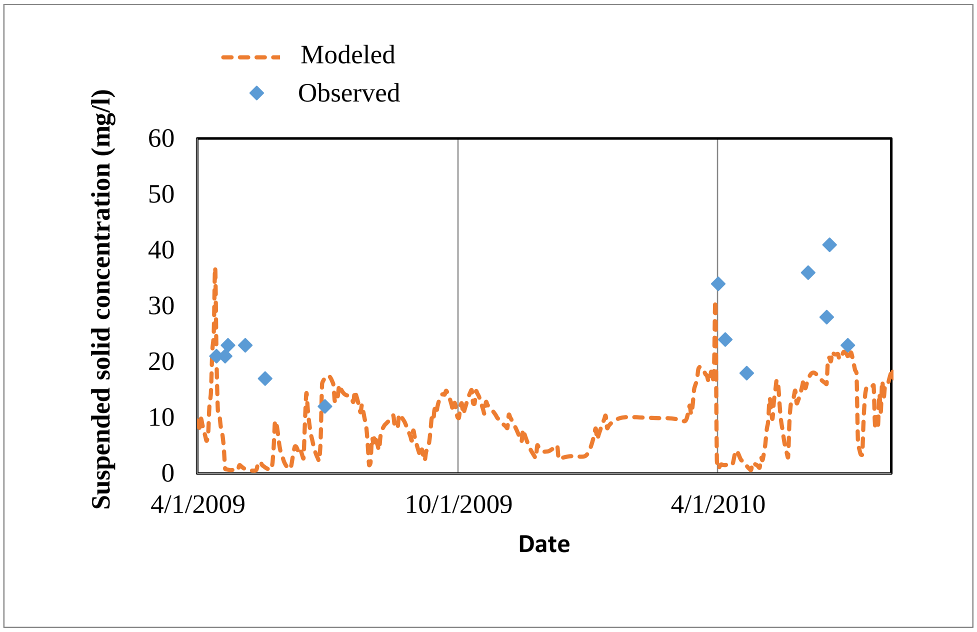

Figure B2. Graphical comparisons of the modeled and the observed suspended solid concentration in the Sheyenne River below Devils Lake outlet near Bremen USGS #05055400 gauging station

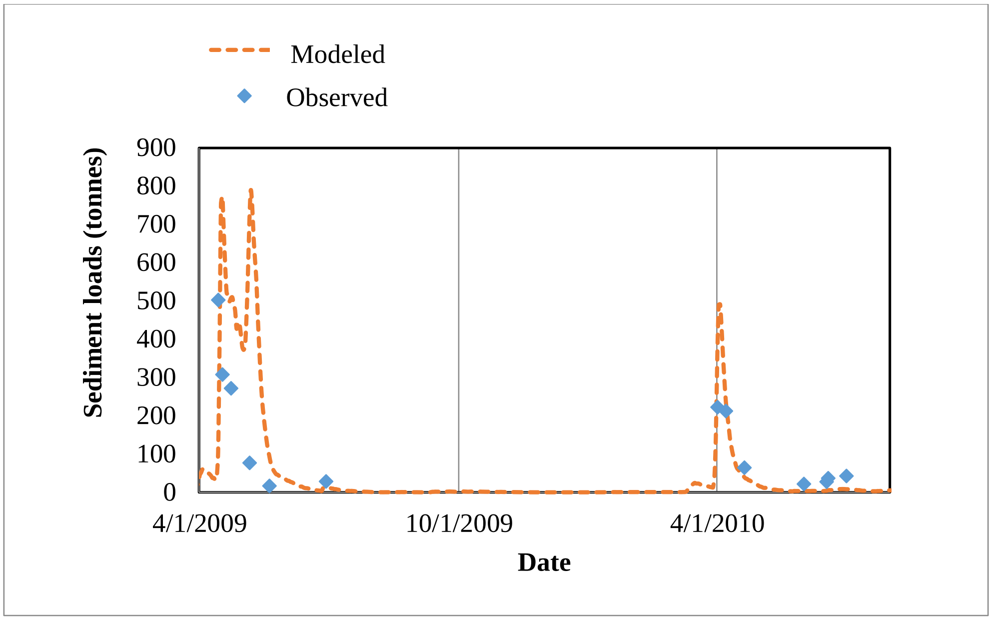

Figure B3. Graphical comparisons of the modeled and the observed suspended solid loads in the Sheyenne River near Warwick USGS #05055600 gauging station

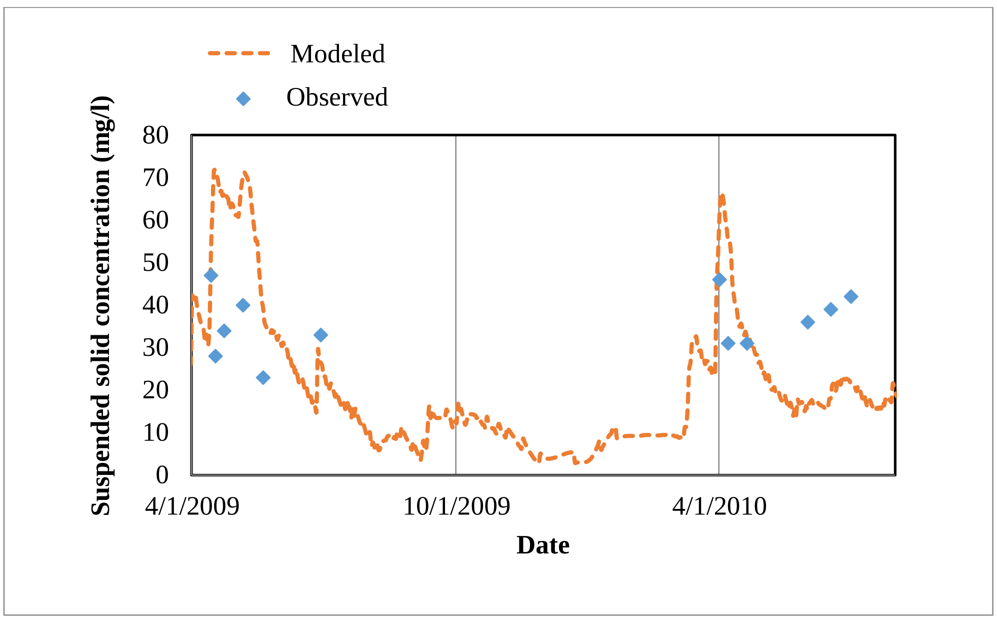

Figure B4. Graphical comparisons of the modeled and the observed suspended solid concentration in the Sheyenne River near Warwick USGS #05055600 gauging station

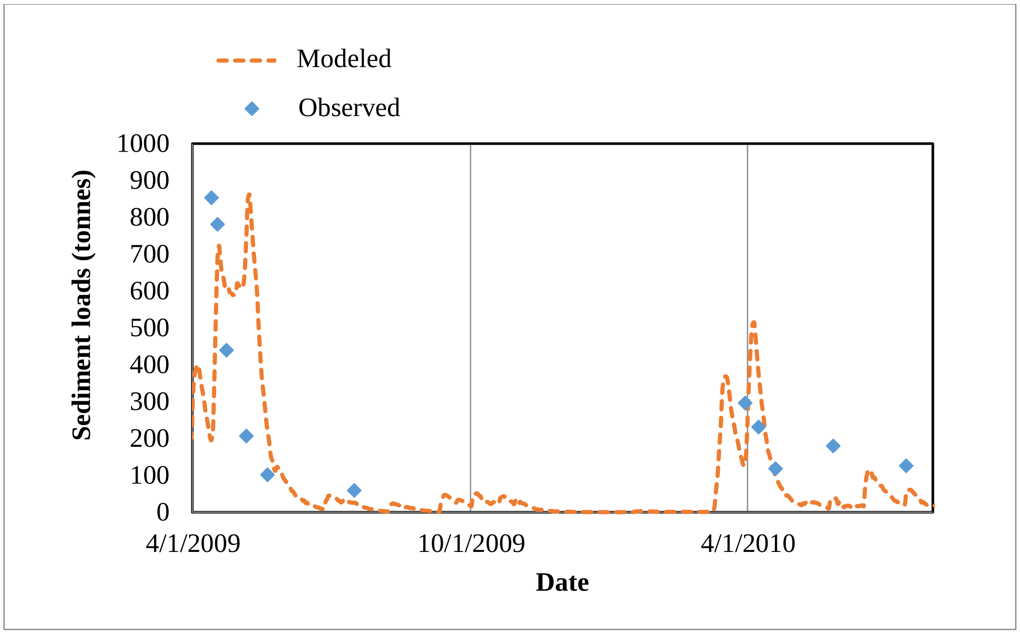

Figure B5. Graphical comparisons of the modeled and the observed suspended solid in the Sheyenne River near Cooperstown USGS #05055700 gauging station

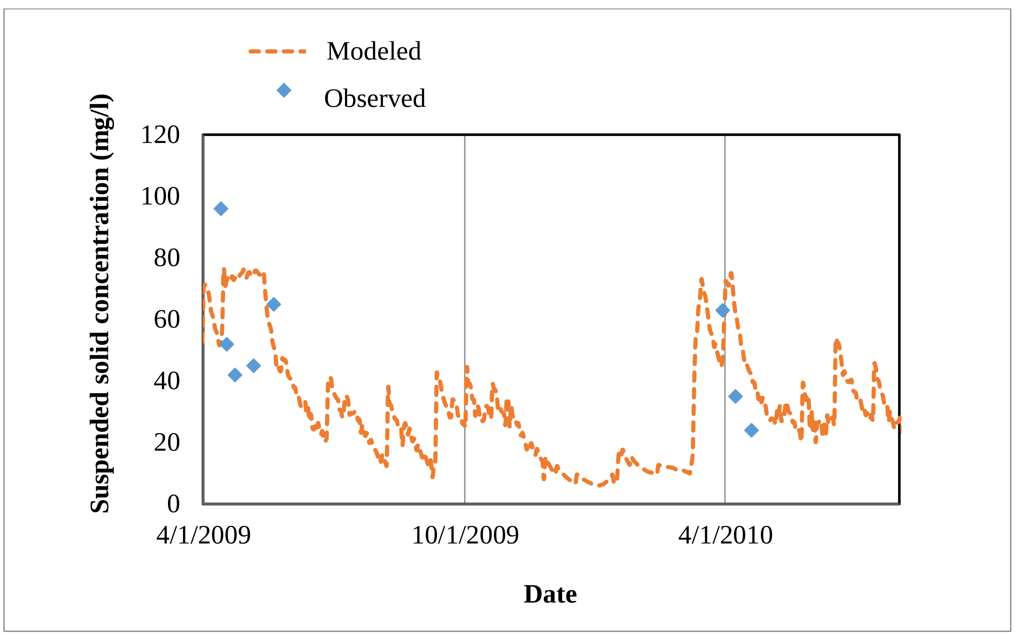

Figure B6. Graphical comparisons of the modeled and the observed suspended solid concentration in the Sheyenne River near Cooperstown USGS #05055700 gauging station

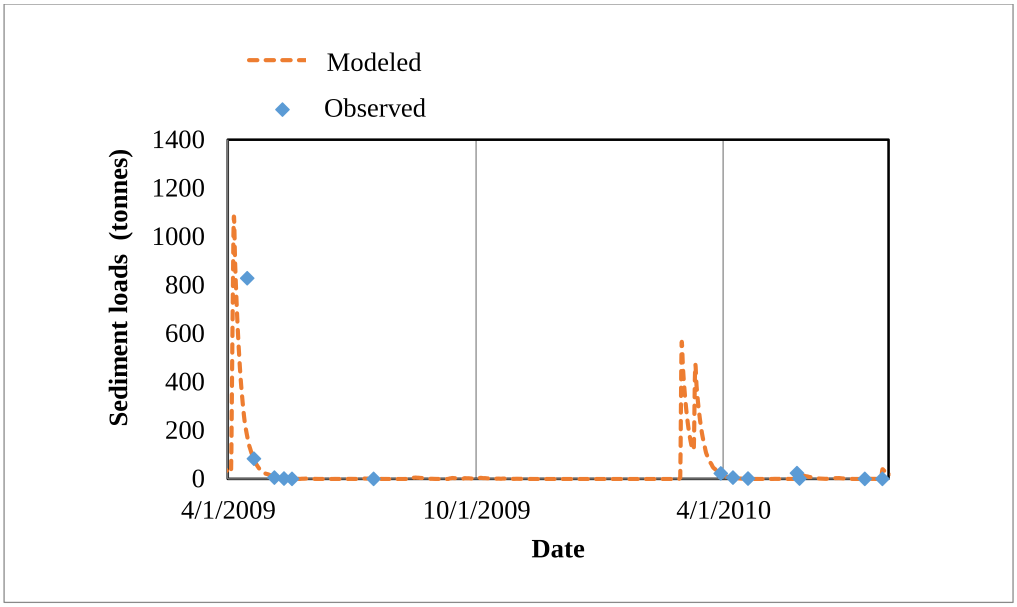

Figure B7. Graphical comparisons of the modeled and the observed suspended solid in the Baldhill Creek near Dazey USGS #050557200 gauging station

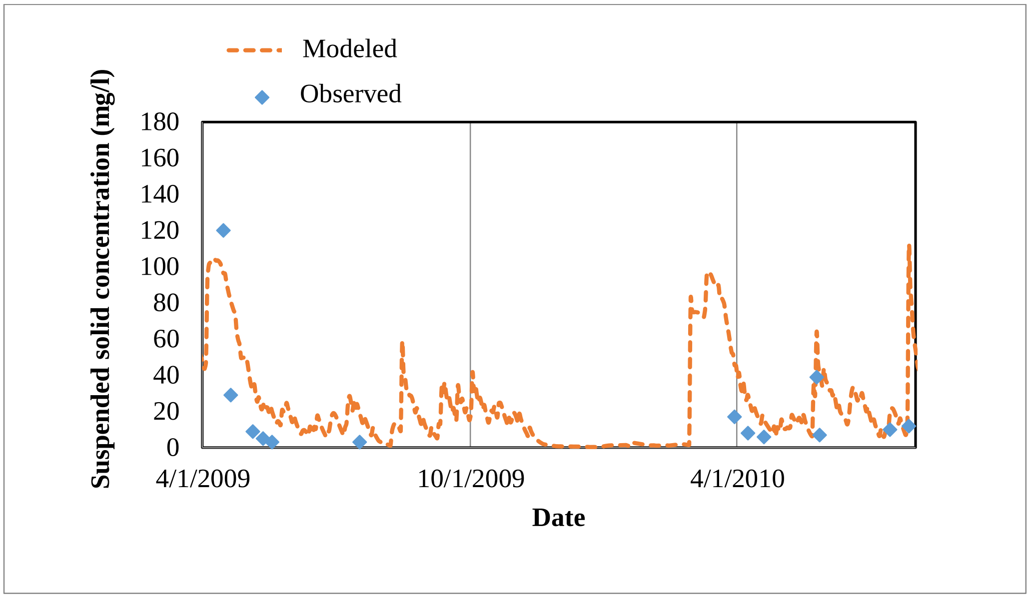

Figure B8. Graphical comparisons of the modeled and the observed suspended solid concentration in the Baldhill Creek near Dazey USGS #050557200 gauging station

APPENDIX C. NUTRIENTS CALIBRATION CHEMOGRAPHS

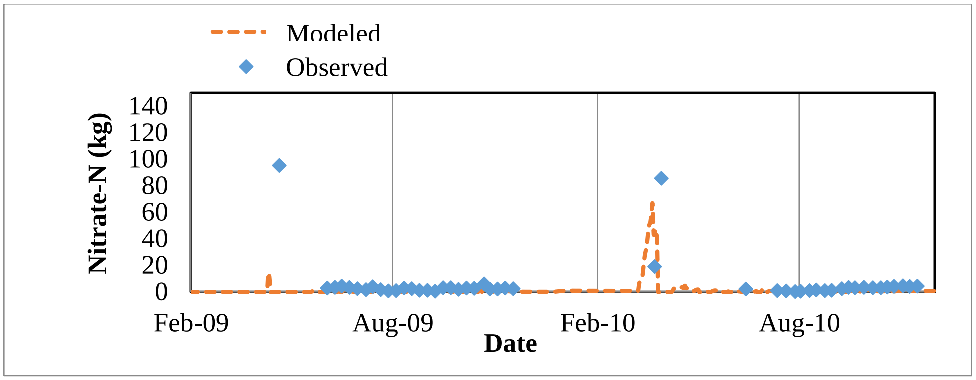

Figure C1. Graphical comparisons of the modeled and the observed nitrate loads in the Sheyenne River above Harvey NDDoH #380135 gauging station

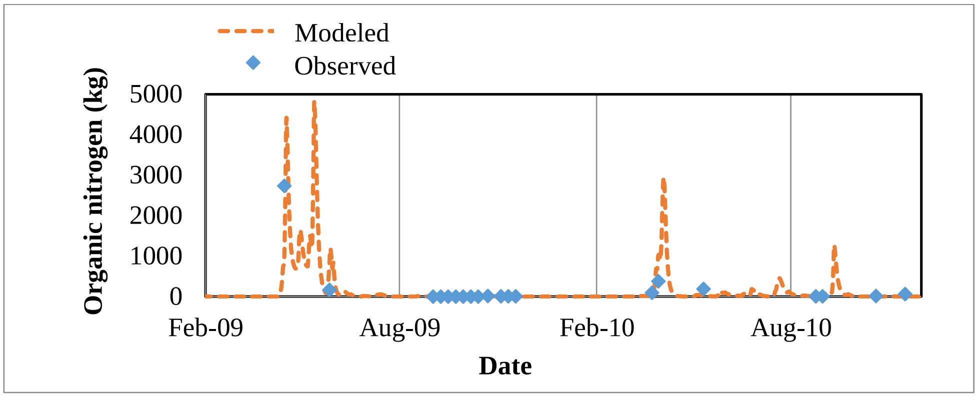

Figure C2. Graphical comparisons of the modeled and the observed organic nitrogen loads in the Sheyenne River above Harvey NDDoH #380135 gauging station

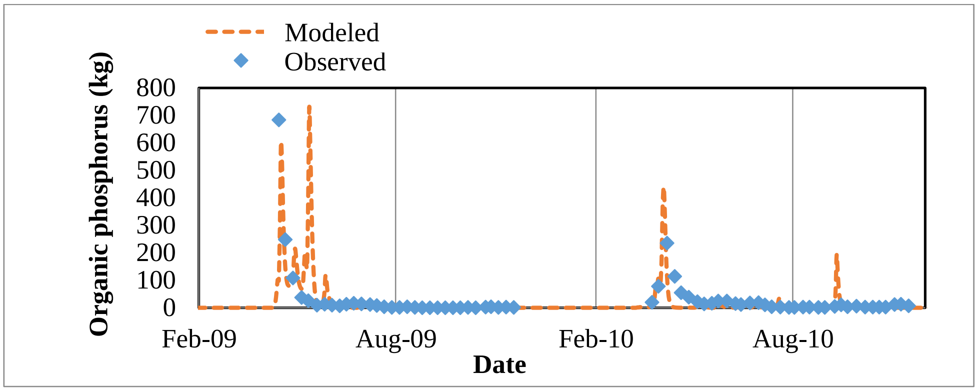

Figure C3. Graphical comparisons of the modeled and the observed organic phosphorus loads in the Sheyenne River above Harvey NDDoH #380135 gauging station

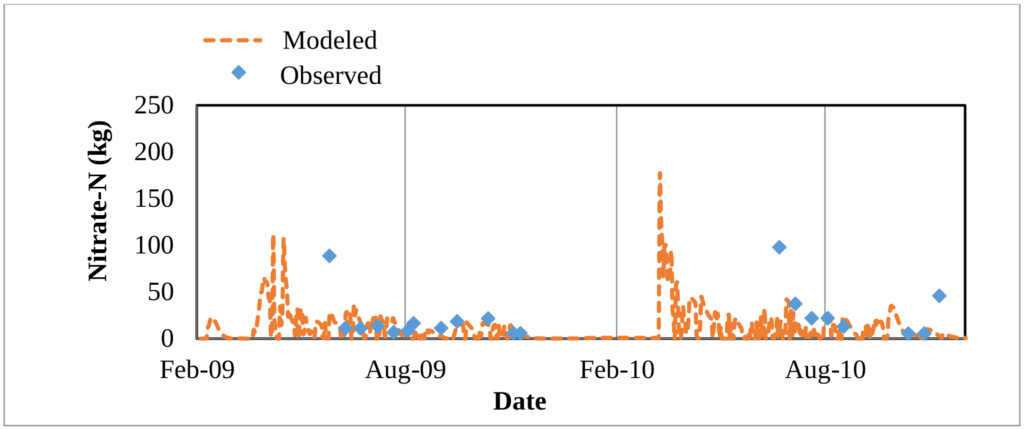

Figure C4. Graphical comparisons of the modeled and the observed nitrate loads in the Sheyenne River above Devils Lake outlet near Flora NDDoH #395505 gauging station

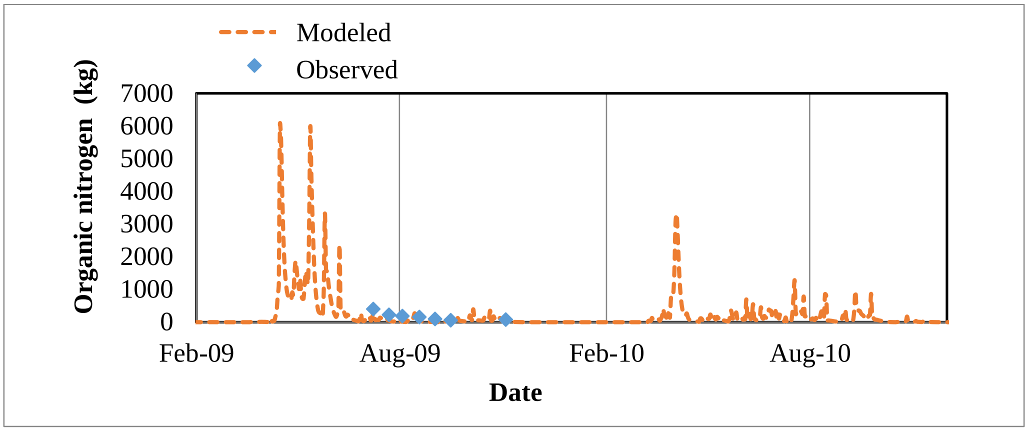

Figure C5. Graphical comparisons of the modeled and the observed organic nitrogen loads in the Sheyenne River above Devils Lake outlet near Flora NDDoH #395505 gauging station

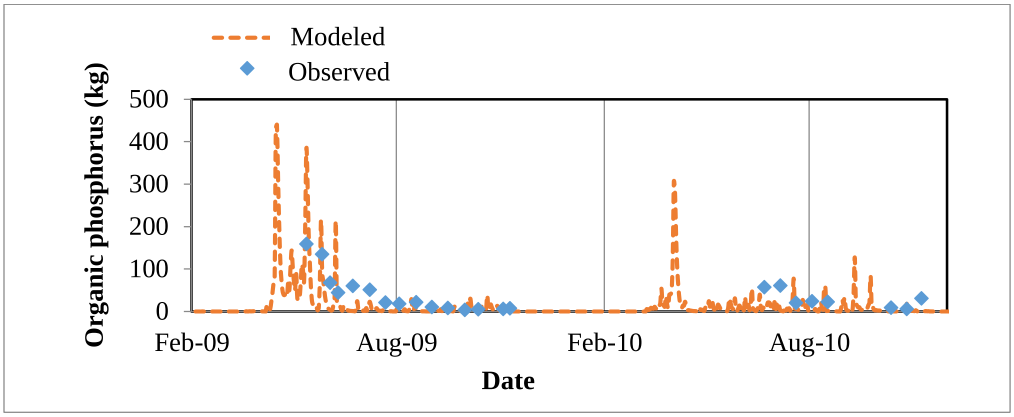

Figure C6. Graphical comparisons of the modeled and the observed organic phosphorus loads in the Sheyenne River above Devils Lake outlet near Flora NDDoH #395505 gauging station

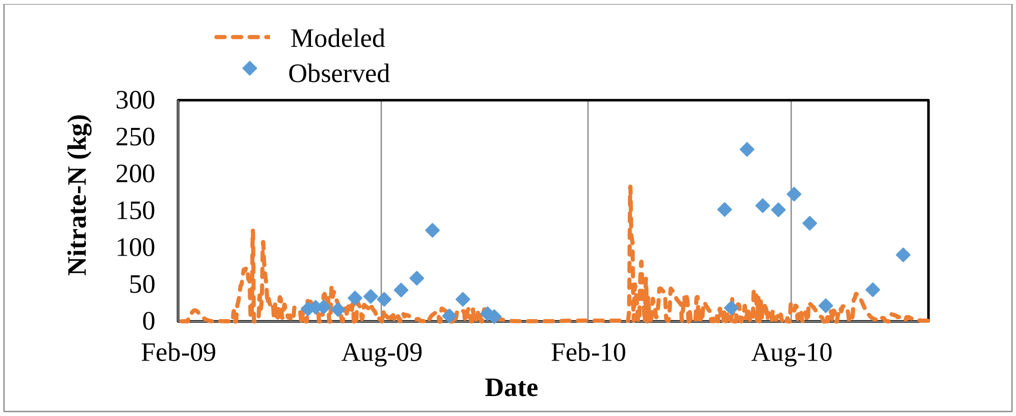

Figure C7. Graphical comparisons of the modeled and the observed nitrate loads in the Sheyenne River below Devils Lake outlet near Bremen NDDoH #385502 gauging station

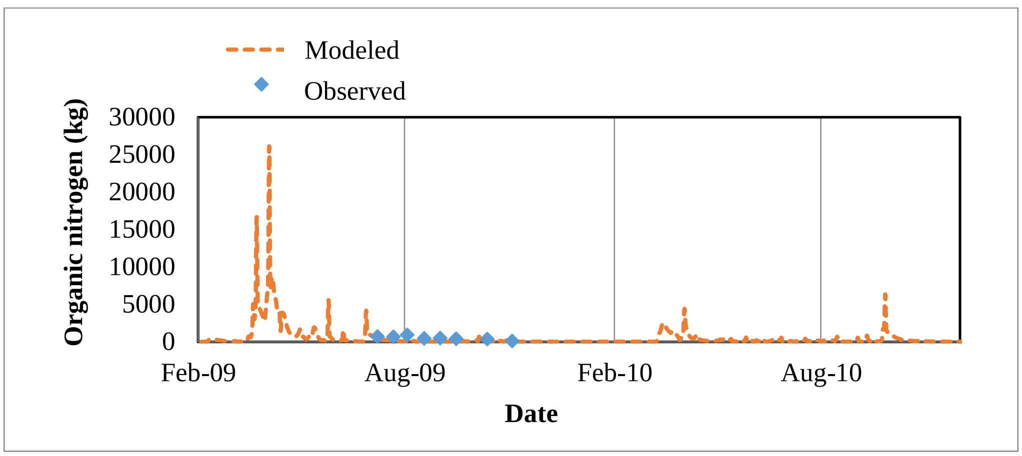

Figure C8. Graphical comparisons of the modeled and the observed organic nitrogen loads in the Sheyenne River below Devils Lake outlet near Bremen NDDoH #385502 gauging station

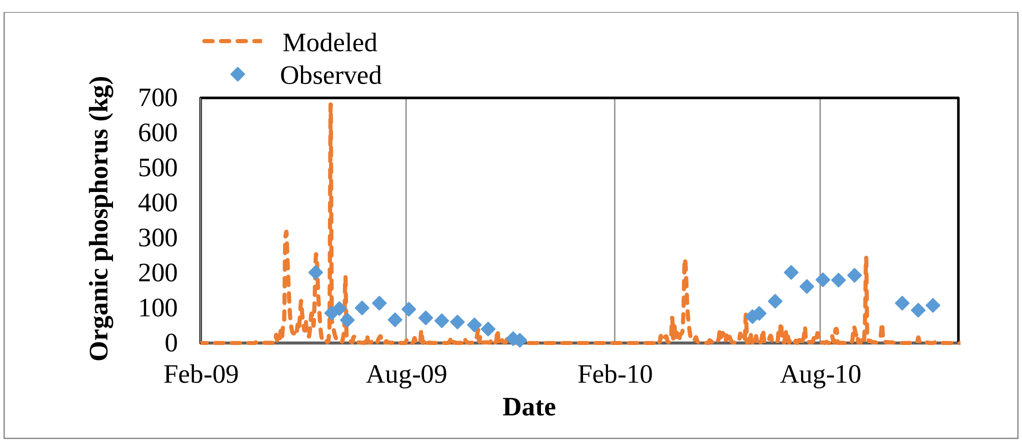

Figure C9. Graphical comparisons of the modeled and the observed organic phosphorus loads in the Sheyenne River below Devils Lake outlet near Bremen NDDoH #385502 gauging station

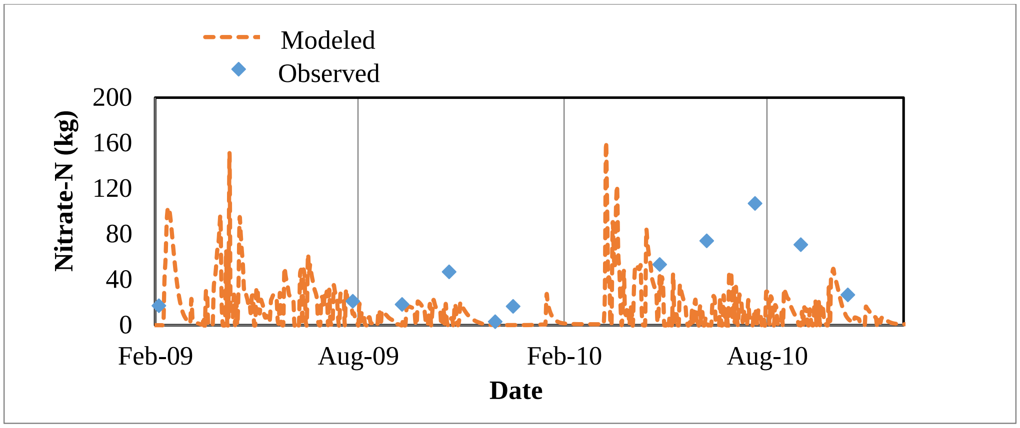

Figure C10. Graphical comparisons of the modeled and the observed nitrate loads in the Sheyenne River near Warwick NDDoH #385345 gauging station

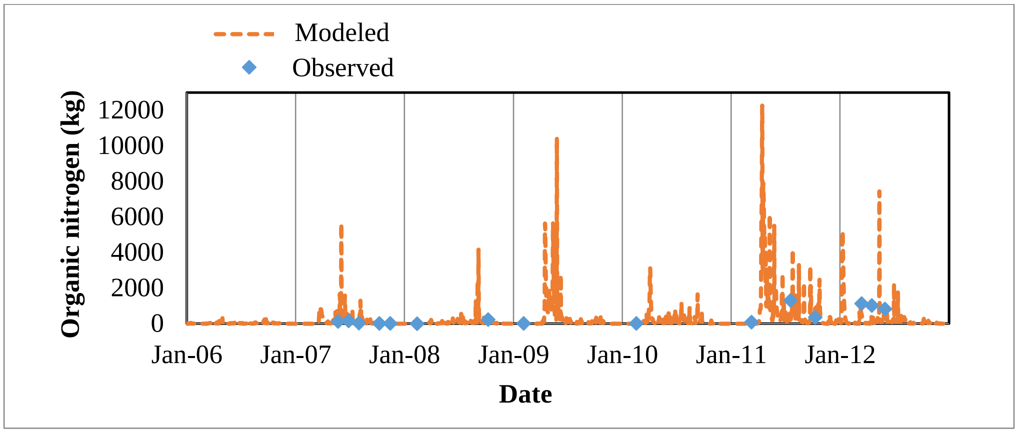

Figure C11. Graphical comparisons of the modeled and the observed organic nitrogen loads in the Sheyenne River near Warwick NDDoH #385345 gauging station

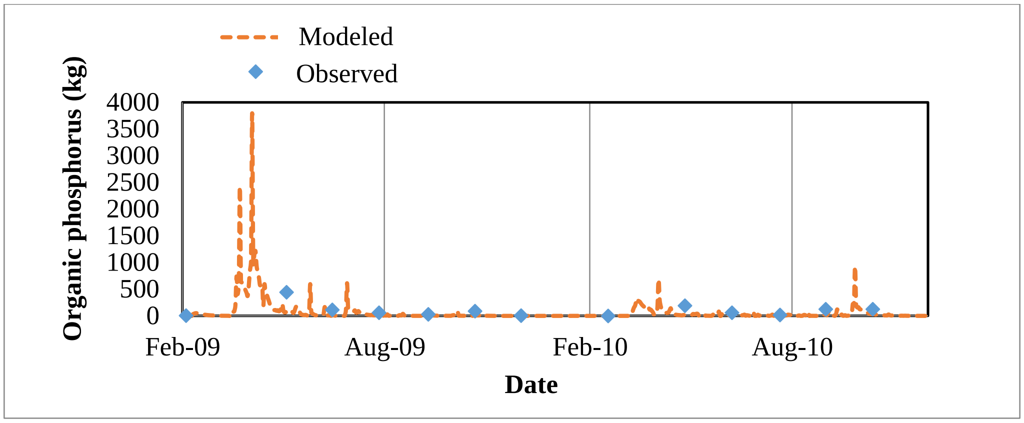

Figure C12. Graphical comparisons of the modeled and the observed organic phosphorus loads in the Sheyenne River near Warwick NDDoH #385345 gauging station

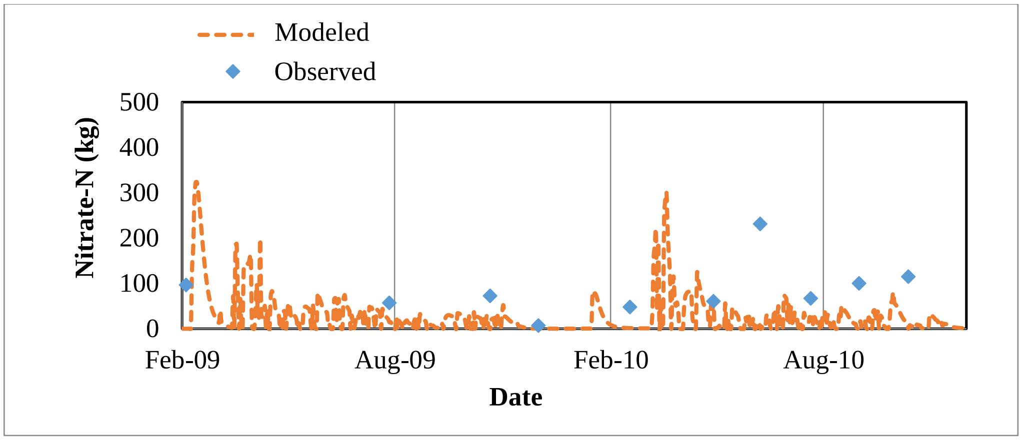

Figure C13. Graphical comparisons of the modeled and the observed nitrate loads in the Sheyenne River near Cooperstown NDDoH #380009 gauging station

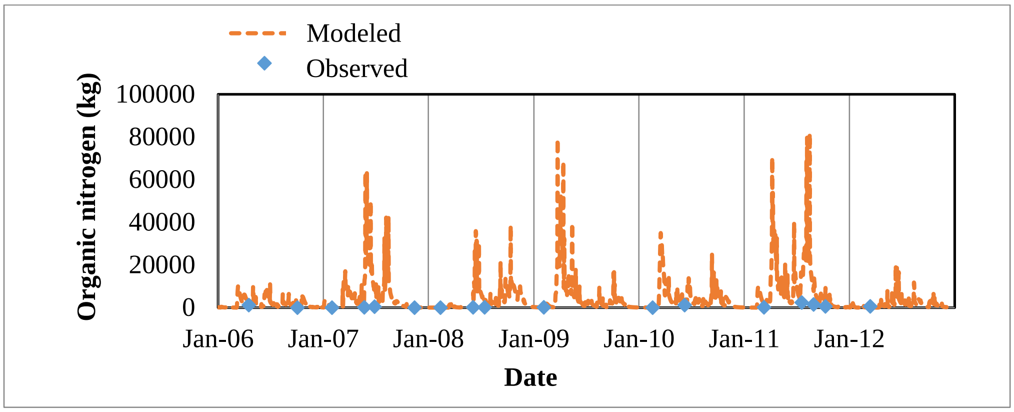

Figure C14. Graphical comparisons of the modeled and the observed organic nitrogen loads in the Sheyenne River near Cooperstown NDDoH #380009 gauging station

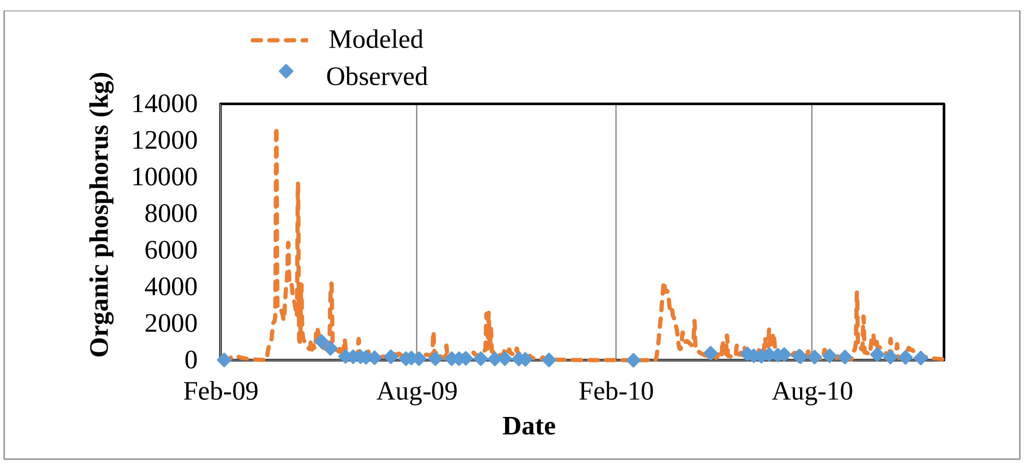

Figure C15. Graphical comparisons of the modeled and the observed organic phosphorus loads in the Sheyenne River near Cooperstown NDDoH #380009 gauging station

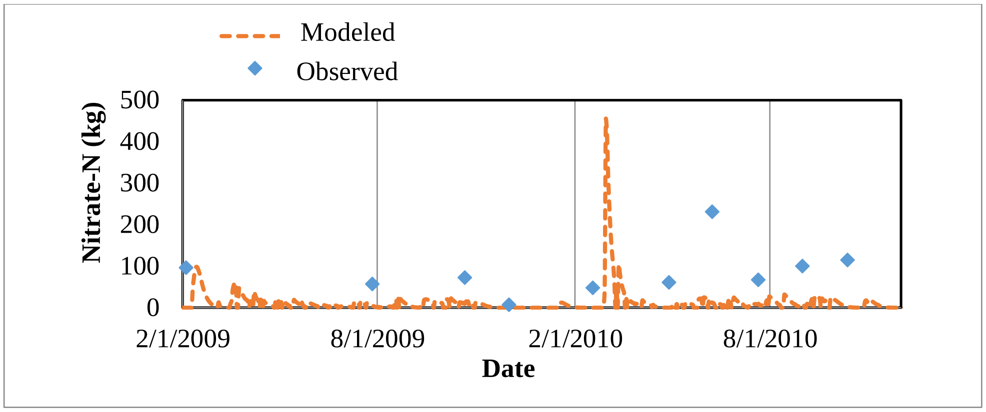

Figure C16. Graphical comparisons of the modeled and the observed nitrate loads in the Baldhill Creek near Dazey NDDoH #384126 gauging station

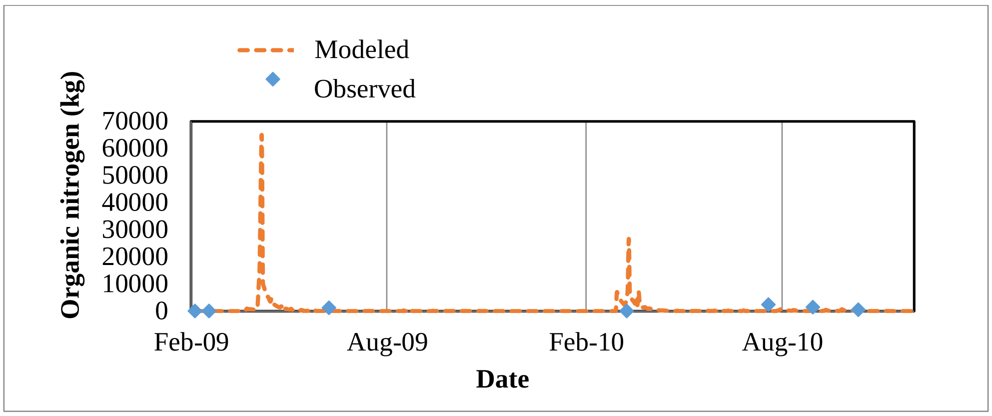

Figure C17. Graphical comparisons of the modeled and the observed organic nitrogen loads in the Baldhill Creek near Dazey NDDoH #384126 gauging station

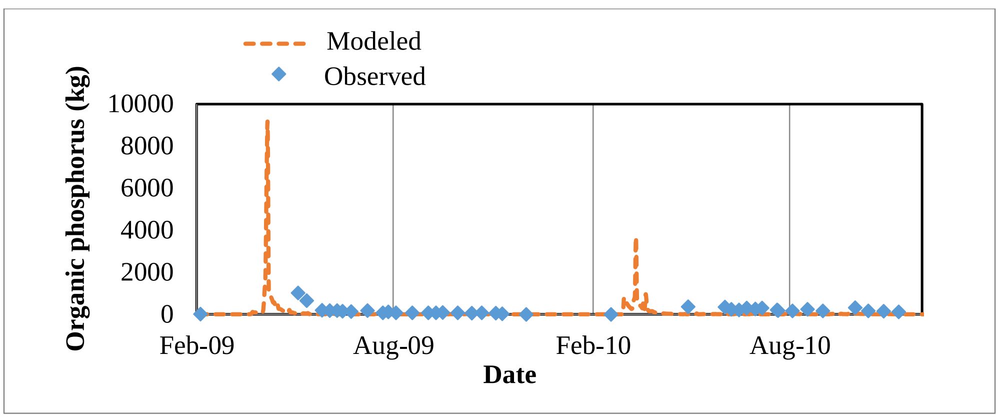

Figure C18. Graphical comparisons of the modeled and the observed organic phosphorus loads in the Baldhill Creek near Dazey NDDoH #384126 gauging station