ERDC/CHL TR-20-3

Coastal and Hydraulics Laboratory

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Nested Physics-Based Watershed Modeling at Seven Mile Creek

Minnesota River Integrated Watershed Study

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US Army Engineer Research and Development Center
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Final report

Prepared for US Army Corps of Engineers, Saint Paul District
Saint Paul, MN 55101

Under USACE MVP; MIPR 138667; “Minnesota River Basin Watershed Study - Nested GSSHA Model Development for the Seven Mile Creek Watershed”

Abstract

The Minnesota River Basin (MRB) Integrated Study Team (IST) was tasked with assessing the condition of the MRB and recommending management options to reduce suspended sediments and improve the water quality in the basin. The Gridded Surface Subsurface Hydrologic Analysis (GSSHA) was chosen by the IST as the fine scale model for the Seven Mile Creek Watershed to help quantify the physical effects from best management practices within the MRB. The predominately agricultural Seven Mile Creek Watershed produces high total suspended solids and nutrients loads, contributing roughly 10% of the total load to the Minnesota River. GSSHA models were developed for a small experimental field research site called Red Top Farms, a Hydrologic Unit Code (HUC)-12 model for the entire Seven Mile Creek Watershed, and a sub-basin of the Seven Mile Creek Watershed. After calibration, the resulting models were able to simulate measured tile drain flows, stream flow, suspended sediments, and to a lesser extent, nutrients. A selected suite of alternative land-use scenarios was simulated with the models to determine the watershed response to land-use changes at the small and medium scale and to test whether the type, size, and spatial distribution of land uses will influence the effectiveness of land management options.

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Preface

This work for performed for the US Army Corps of Engineers, Saint Paul District, under USACE MVP, MIPR 138667; "Minnesota River Basin Watershed Study - Nested GSSHA Model Development for the Seven Mile Creek Watershed." The US Army Corps of Engineers, Saint Paul District, sponsor point of contact was Mrs. Ann Banitt. COL Karl Jansen was the Commander at the time of publication of this report.

At the time of publication of this report, Dr. Hwai-Ping (Pearce) Cheng was Chief, Hydrologic Systems Branch, and Dr. Cary Talbot was Chief, Flood and Storm Protection Division of the US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL). The Deputy Director of ERDC-CHL was Mr. Jeffrey R. Eckstein, and Dr. Ty V. Wamsley was the Director.

COL Teresa A. Schlosser was the Commander of ERDC, and the director was Dr. David Pittman.

1 Introduction

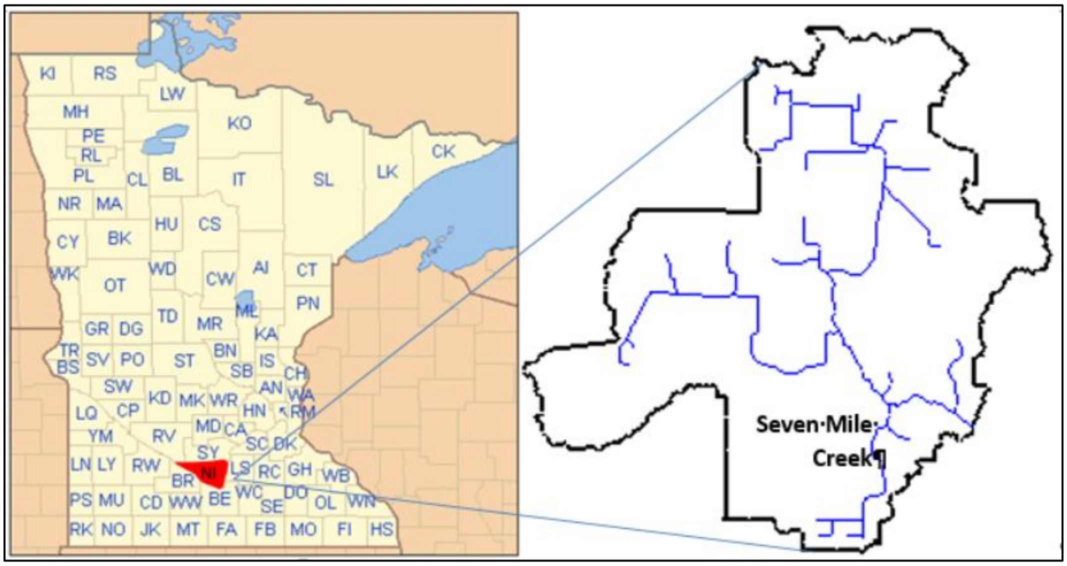
1.1 Background

The Minnesota River Basin is located primarily in southern Minnesota, and extends into parts of Iowa, South Dakota, and North Dakota (Figure 1). The basin drains approximately 38,850 km^2 of land to its main artery, the Minnesota River. From the origin in Big Stone Lake at the Minnesota/South Dakota border, the Minnesota River traverses 571 km to its confluence with the Mississippi River at Fort Snelling.

Figure 1. Minnesota River Basin.

The Seven Mile Creek Watershed lies in the Middle Minnesota River Basin in Nicollet County in Minnesota (Figure 2). The Seven Mile Creek drainage area includes 91 km^2. The watershed is predominately agricultural and characterized by uplands and ravines at the interface with the River Warren Escarpment in the downstream portion. The soils are primarily clay loam characterized as a Des Moines Lobe Till. The Middle Minnesota River contributes approximately 9% of the total suspended solids (TSS), 10% of the nitrogen (N), and 5% of the phosphorous (P) loads to the Minnesota River (Minnesota State University Mankato 2003). The watershed includes substantial hydrological modifications including extensive networks of subsurface drains.

Figure 2. Seven Mile Creek Watershed located in Nicollet County, Minnesota.



1.2 Objective

The Minnesota River Basin Integrated Study Team (IST) was tasked with assessing the condition of the Minnesota River Basin and recommending management options to improve the water quality in the basin. The IST was asked to identify and quantify strategies that specifically target the reduction of sediment transported through and out of the Minnesota River Watershed. State Study Partners have developed large-scale lumped parameter basin models using the SWAT[1] and the HSPF[2] lumped parameter hydrologic models for most of the Minnesota River Basin.

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[1] Soil and Water Assessment Tool

[2] Hydrologic Simulation Program-Fortran

These models are limited in their ability to assess the impact of best management practices (BMPs) at a field scale and project what the cumulative impacts are downstream. The objective of this modeling effort is to physically define the impacts of land management options at a fine scale.

1.3 Approach

A nested modeling approach was prescribed. The study team has defined three categories of models that vary their level of fidelity, input needs, and degree of complexity.

- Tier 1: Fundamentally simple. Provides a relative sense of cause/effects. Requires few input data.
- Tier 2: Provides a level of certainty to model economics. Needs more input data than Tier 1.
- Tier 3: Detailed, physically based processes. More input data required than Tier 2.

The Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model was chosen as a Tier 3 model for the Seven Mile Creek Watershed to help quantify the physical effects from BMPs within the Minnesota River Basin. GSSHA is a physically based, spatially distributed numerical model used to simulate important stream flow processes (Downer and Ogden 2004), evaluate flood inundation (Sharif et al. 2010), soil moisture (Downer and Ogden 2003), constituent fate and transport (Downer 2009), and snow accumulation (Follum and Downer 2013). The GSSHA model development focused on the interactions that define how a particular basin behaves with respect to changes in land use, climate, and BMPs. Nested Tier 3 hydrologic models include a field scale Tier 3 GSSHA Model of Red Top Farms; a HUC-12[1] model for the entire Seven Mile Creek Watershed; and a finer resolution model covering a sub-basin of the Seven Mile Creek Watershed. The models integrate the surface and groundwater interactions as well as the drain tile features of GSSHA.

A selected suite of alternative land-use scenarios was simulated with GSSHA to determine the watershed response to land-use changes at the small and medium scale and to test whether the type, size, and spatial

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[1] HUC = Hydrologic Unit Code

distribution of land uses will influence the effectiveness of land management strategies.

This report describes only the Tier 3 GSSHA modeling results. Results of the overall study effort are available from USACE[1].

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[1] USACE. In preparation. Minnesota River Basin Interagency Report.

2 Input and Observed Data

According to Section 8 of the Scope of Work (SOW), the US Army Corps of Engineers, Saint Paul District (USACE-MVP), was responsible for providing all required/requested data needed to accomplish the modeling needs. USACE-MVP was also charged with quality assurance. Unless otherwise noted, all data referenced in this report were provided by USACE-MVP, and the US Army Engineer Research and Development Center (ERDC) assumed the data were the best data available for conducting the study. ERDC assessed the quality and completeness of the provided data. Due to gaps in the needed data, ERDC conducted an extensive, if not exhaustive, effort to supplement the data provided by USACE-MVP and located and incorporated data and information related to defining drainage tile properties, sub-surface properties for simulating groundwater, and additional precipitation data, among others. The sources of these other data are noted in the report. All data provided/collected by ERDC underwent extensive quality control. Data were checked for completeness of record, recorded quality, internal consistency, and consistency with other data sets. Specific actions taken for each data type are discussed in individual sections below.

3 Spatial Data

3.1 Terrain

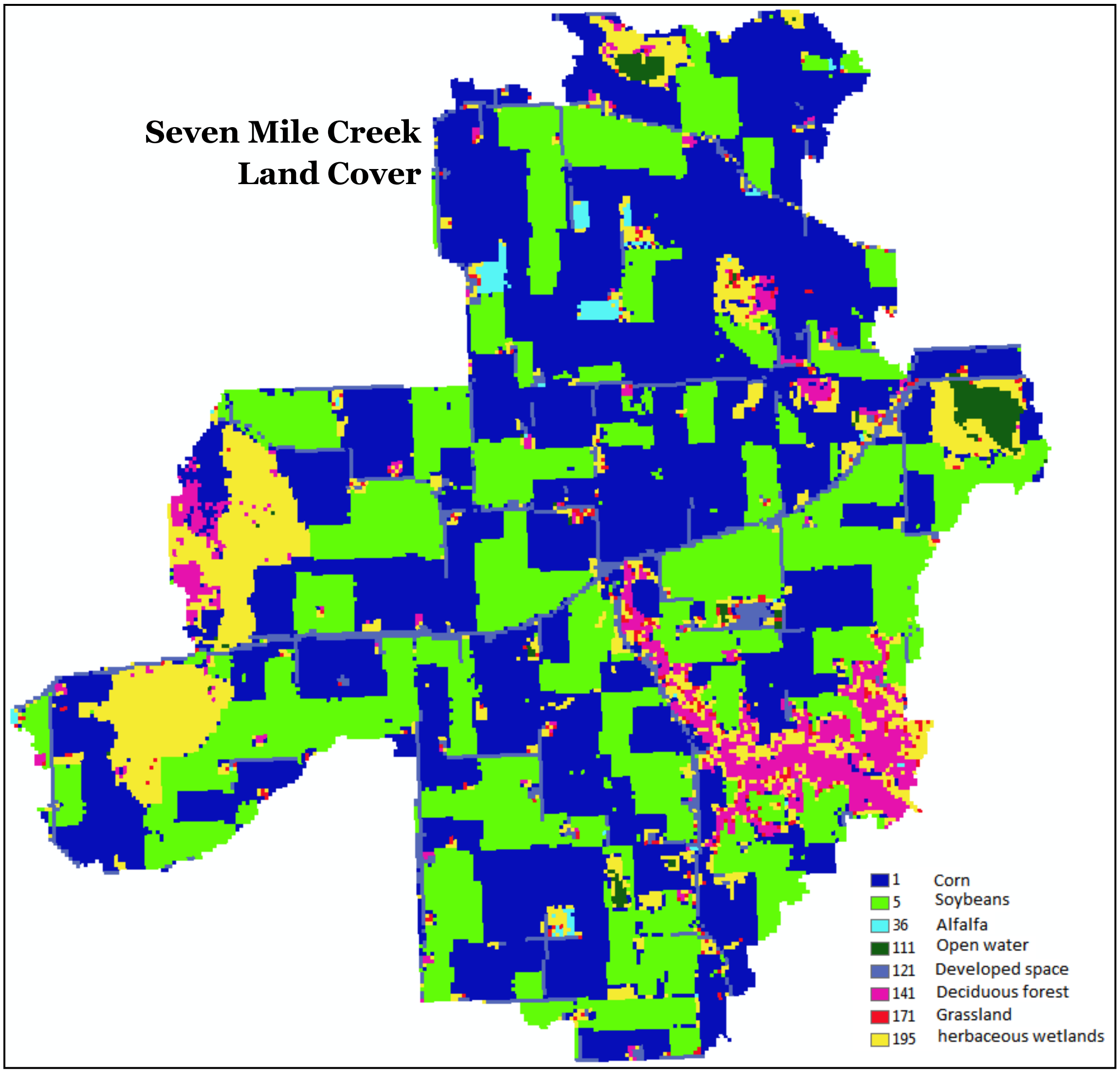
Ground elevation, slope, and aspect are derived from a digital elevation model (DEM) at 1/3 arc-second resolution (approximately 10 m) from the National Elevation Dataset (NED) provided by the US Geological Survey (USGS). NED data are referenced to the North American Datum of 1983. The DEM was resampled to match the 50 m grid size of the GSSHA model for the entire Seven Mile Creek Watershed and resampled to 25 m to match the resolution of the inset sub-watershed model.

3.2 Land cover

Land use data were obtained from the US Department of Agriculture (USDA) National Agricultural Statistics Service (http://nassgeodata.gmu.edu/CropScape/) (Han et al. 2012). The watershed is largely agricultural with 2-year rotations of corn and soy bean. Land uses were assumed static for the purposes of this study. Eight categories where used in the models. As shown in Figure 3, the distribution of these eight land uses in the Seven Mile Creek Watershed model is the following:

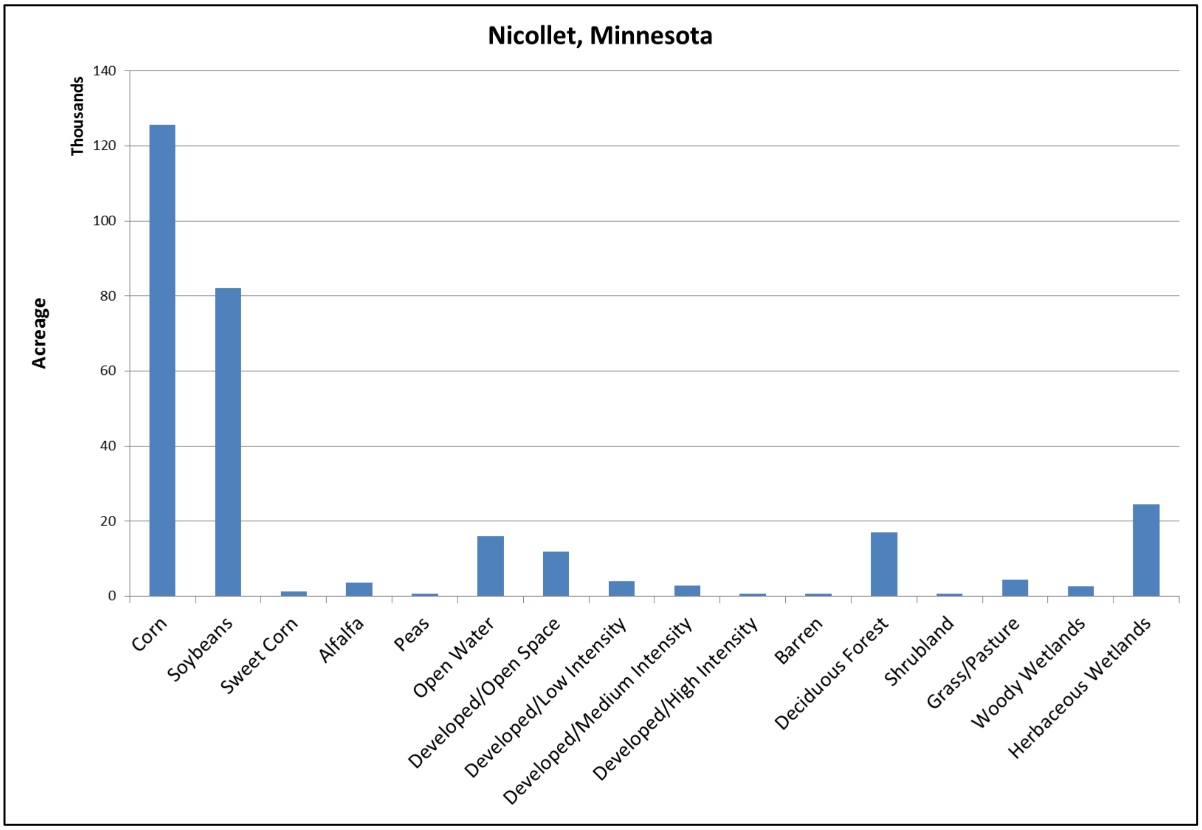
- Corn – 47%
- Soybeans – 32%
- Alfalfa – 0.5%
- Open Water – 0.9 %
- Developed Space – 5 %
- Deciduous Forest – 4%
- Grassland – 0.9%
- Herbaceous Wetland – 10%.

Figure 3. Land-use map obtained from USDA, National Agricultural statistics service, Cropland Data Layer (Han et al. 2012).



Eight unique land coverages were identified within the watershed with associated acreages provided in Figure 4.

Figure 4. Cropland data layer acreage for 2012 in Nicollet, Minnesota.



3.3 Soil characteristics

Three dominant soils were identified in the Seven Mile Creek Basin: clay loam (CL), loam (L) and mucky silt loam (MSL), as shown in Figure 5. Soil types were derived from USDA Natural Resources Conservation Service Soil Survey Geographic Database (SSURGO) (NCSS Staff 2014). The associated soil physical properties were obtained from the SSURGO site and are provided in Table 1. As shown in Figure 5, the predominant soils are tight poorly drained soils, clay and silt loams. Well-drained loam soils are found mostly along the stream channels.

Figure 5. Identification of soils within the Seven Mile Creek Watershed.

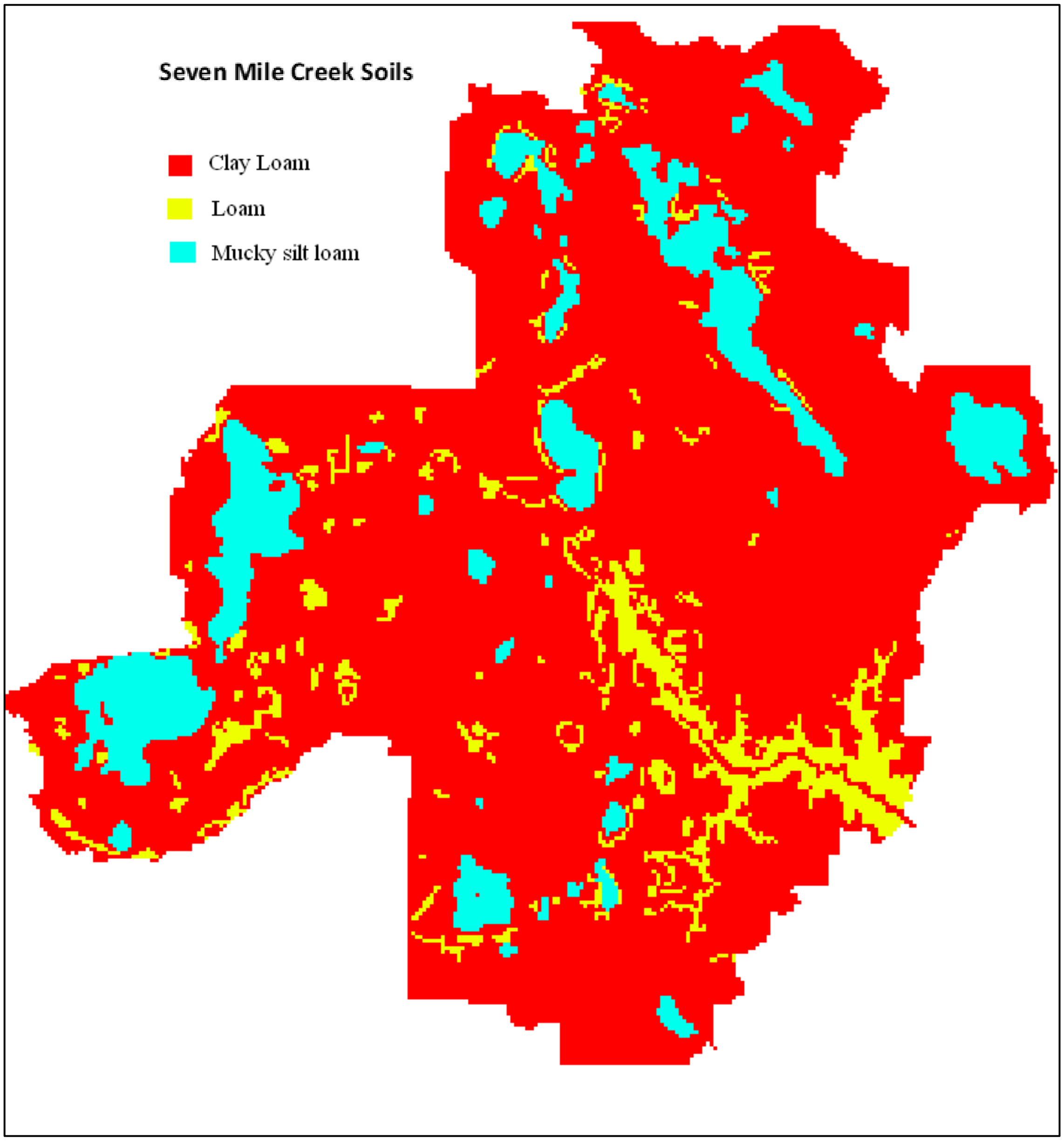
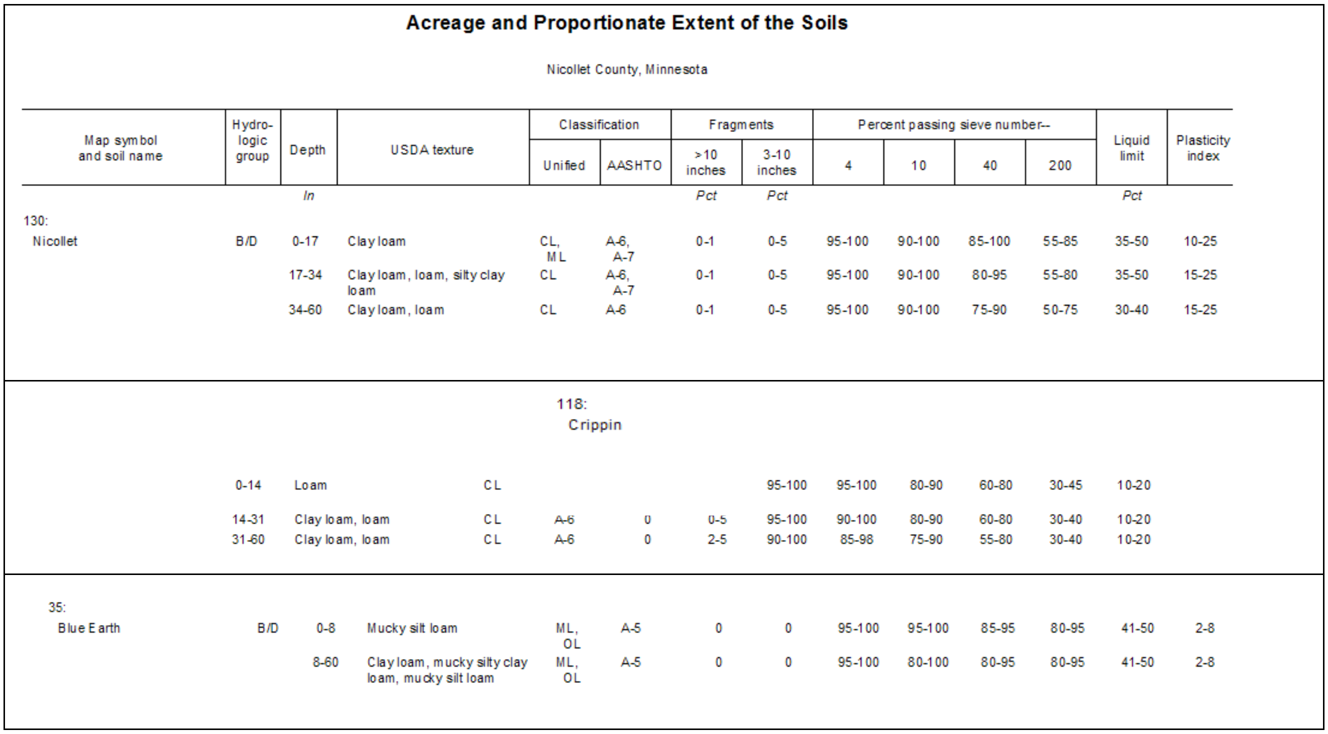


Table 1. Soil physical properties from SSURGO.



Acreage and Proportionate Extent of the Soils

Nicollet County, Minnesota

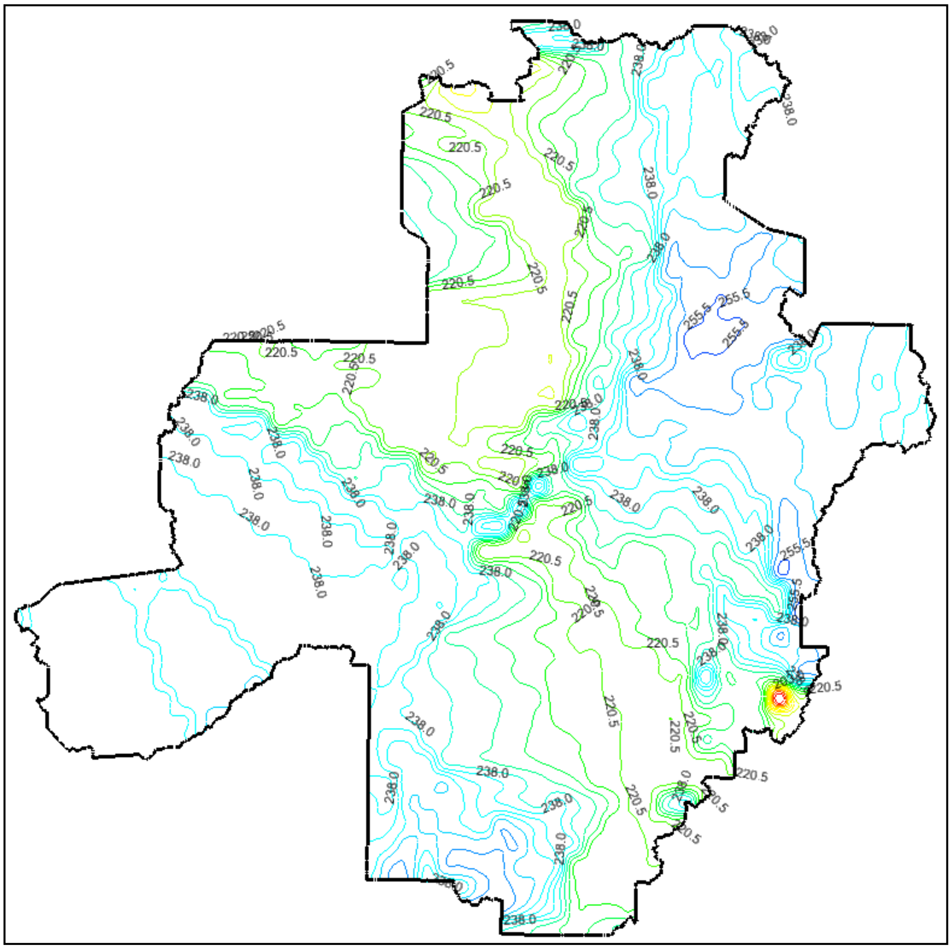
Map symbol and soil name	Hydro-logic group	Depth	USDA texture	Classification		Fragments		Percent passing sieve number--				Liquid limit	Plasticity index
				Unified	AASHTO	>10 inches	3-10 inches	4	10	40	200		
		In				Pct	Pct					Pct	
130: Nicollet	B/D	0-17	Clay loam	CL, ML	A-6, A-7	0-1	0-5	95-100	90-100	85-100	55-85	35-50	10-25
		17-34	Clay loam, loam, silty clay loam	CL	A-6, A-7	0-1	0-5	95-100	90-100	80-95	55-80	35-50	15-25
		34-60	Clay loam, loam	CL	A-6	0-1	0-5	95-100	90-100	75-90	50-75	30-40	15-25
118: Crippin													
		0-14	Loam	CL				95-100	95-100	80-90	60-80	30-45	10-20
		14-31	Clay loam, loam	CL	A-6	0	0-5	95-100	90-100	80-90	60-80	30-40	10-20
		31-60	Clay loam, loam	CL	A-6	0	2-5	90-100	85-98	75-90	55-80	30-40	10-20
35: Blue Earth	B/D	0-8	Mucky silt loam	ML, OL	A-5	0	0	95-100	95-100	85-95	80-95	41-50	2-8
		8-60	Clay loam, mucky silty clay loam, mucky silt loam	ML, OL	A-5	0	0	95-100	80-100	80-95	80-95	41-50	2-8

3.4 Geologic conditions

Bed rock elevations shown in Figure 6 were derived from well-boring logs from the Minnesota Well Index, Minnesota Department of Health (http://www.health.state.mn.us/divs/eh/cwi/). The boring logs were used to determine the depth to the impermeable layer (aquifer bottom) for simulating interactions with the ground water table.

Water table elevations were not readily available, so preliminary water table elevations were inferred. The water table was assumed to be near the surface for poorly drained soils. This inferred water table was drawn down during an initialization period in which the models were spun up in order for the water table and soil moisture to stabilize prior to the calibration and validation periods. The final state at the end of the initialization period provides more realistic starting conditions for simulations going forward.

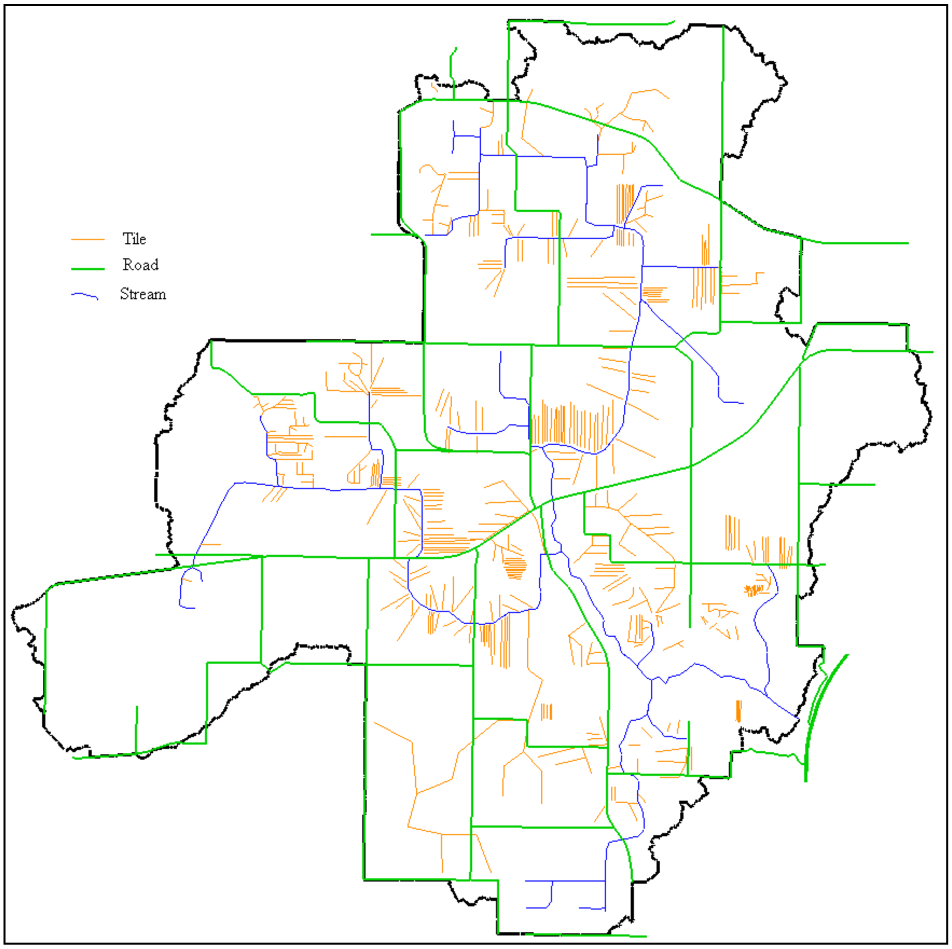
Figure 6. Bed rock elevations.



3.5 Drainage network

The drainage network at Seven Mile Creek consists of streams and ditches in addition to subsurface drains as depicted in Figure 7. USACE-MVP provided the shape files with locations of both public and private tile. No additional information on the tile drain system was provided or located. The figure also identifies ravines where significant erosion can be seen, which occur near the streams in proximity to the watershed outlet.

Figure 7. Drainage network consisting of streams, ditches, and subsurface drain tiles throughout Seven Mile Creek. Ravines with significant erosion are highlighted.



Stream and ditch cross sections were defined in the GSSHA models. Locations of surveyed cross sections are shown in Figure 8. Cross sections in the model are specifically defined according to information provided by Ann Banitt, USACE-MVP. A typical ditch cross section is shown in Figure 9.

Figure 8. Locations of surveyed channel cross sections.

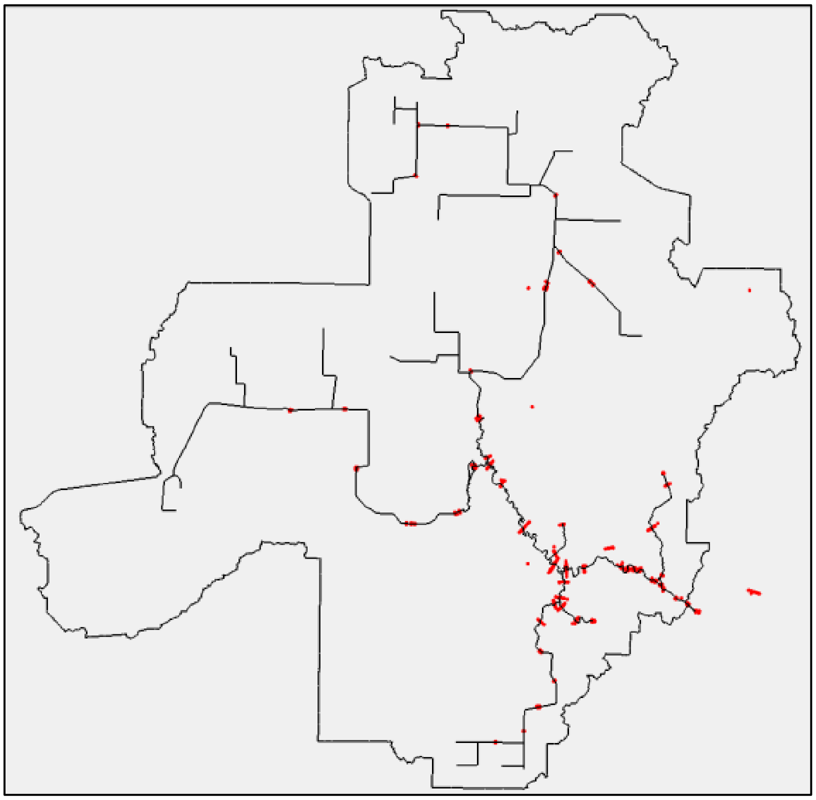
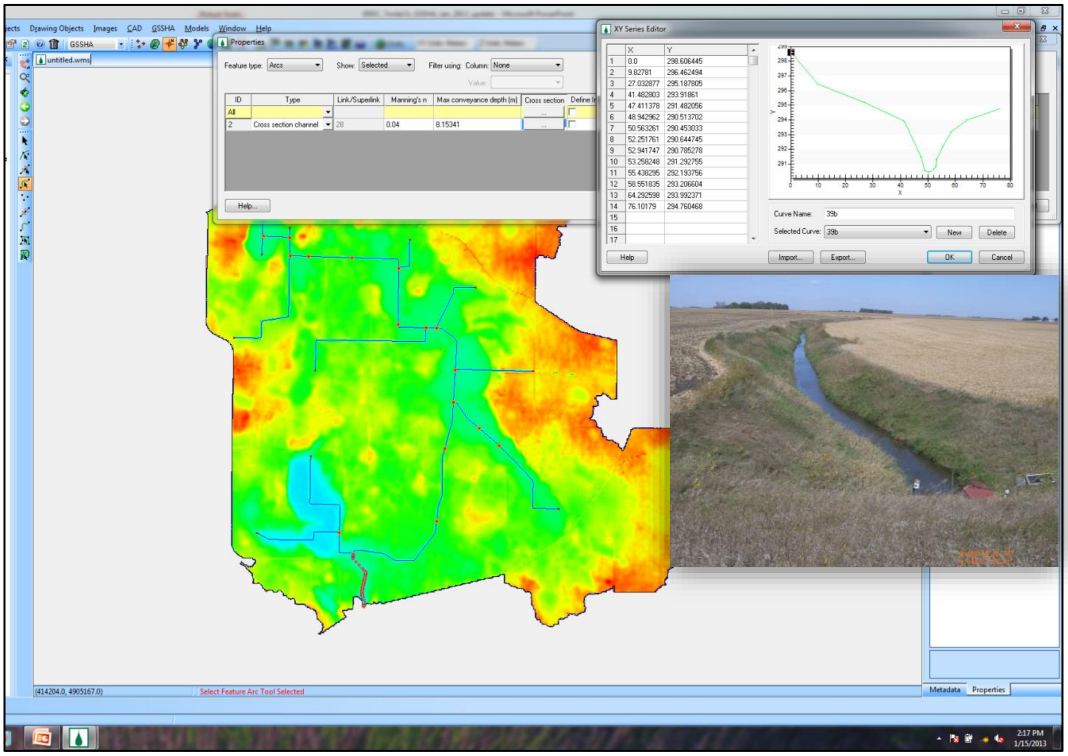


Figure 9. Streams and ditches defined in the model according to surveyed cross-sectional geometry.



Feature type: Arcs
Show: Selected
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All					...	☐
2	Cross section channel	28	0.04	8.15341	...	☐

	X	Y
1	0.0	298.606445
2	9.82781	296.462494
3	27.032877	295.187805
4	41.482803	293.91861
5	47.411378	291.482056
6	48.942962	290.513702
7	50.563261	290.453033
8	52.251761	290.644745
9	52.941747	290.785278
10	53.258248	291.292755
11	55.438295	292.193756
12	58.551835	293.206604
13	64.292598	293.992371
14	76.10179	294.760468
15		
16		
17		

Curve Name: 39b
Selected Curve: 39b

4 Forcing Data

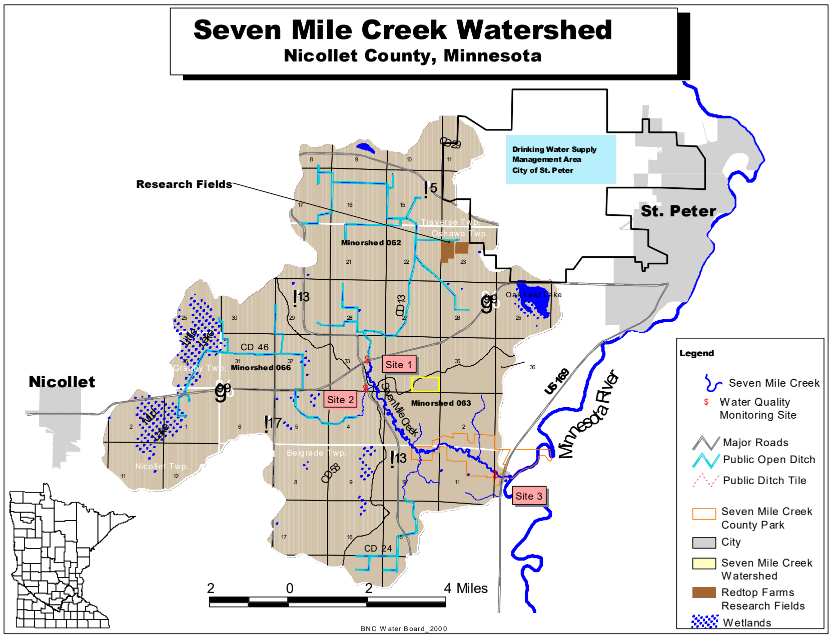
Long-term simulations in GSSHA require inputs for precipitation, air temperature, atmospheric pressure, relative humidity, wind speed, cloud cover, and solar radiation. Nearly continuous hourly hydro-meteorological (HMET) data were available from 2003 to 2008. The meteorological records were compiled to produce the necessary input files for the long-term simulation from the available data indicated in Table 2. HMET data were provided by USACE-MVP.

Table 2. Summary of the available HMET parameters required for the long term simulation.

HMET Parameters	Units
Precipitation	mm
Air Temperature	˚F
Barometric Pressure	in Hg
Wind Speed	knots
Relative Humidity	%
Total Sky Cover	10ths
Direct Radiation	W/m^2
Global Radiation	W/m^2

An assessment of the precipitation data provided by USACE-MVP, from state monitoring locations in the watershed, indicated that these were of only fair to poor quality, spotty, of coarse space and time resolution, and completely lacking any winter precipitation. ERDC conducted an extensive effort to fill in the gaps in the precipitation data set, and the final Seven Mile Creek precipitation gage file was compiled from multiple sources of data with varying time scales to cover a time period from February 2003 to August 2008. The primary source of data was from Red Top Farms, which had a single gage with a temporal resolution of 15 minutes and 1 hour, depending on the time period. Red Top Farms data were provided by Bill Vanryswick, Dept. of Agriculture. Precipitation data were also available from four monitoring gages located in the basin: SMC1, SMC2, SMC3 and SMC4 (Monitoring sites 1, 2, and 3 in Figure 10). Availability and quality of these data varied significantly. Coverage from these gages was spotty at best. When available, data were hourly. Notes on the quality of the data indicated that many were of poor quality. When these higher spatial resolution and lower temporal resolution data were available for periods when the Red Top Farms data were collected at 15 min, the hourly data were converted to 15 min data evenly distributing over the hour of collection. These data were then supplemented with radar data for the summer periods of 2006, 2007, and 2008 obtained from the Minnesota Department of Natural Resources. Radar rainfall was used to help define the spatial and temporal distribution of highly convective storms that typically are not captured by ground based stations. Those storm events that used radar products were derived from the National Oceanic and Atmospheric Administration NTP[1] 16-bit reflectivity products with storm total precipitation aerially adjusted using Minnesota's High Density observer gage network. When radar data were available, they replaced the available point gage data. The watershed was covered by 12 (2 km) × (2 km) radar pixels, as shown in Figure 11.

Figure 10. Location of USGS/MCES[2]/MPCA[3] precipitation, flow, and water quality gages.



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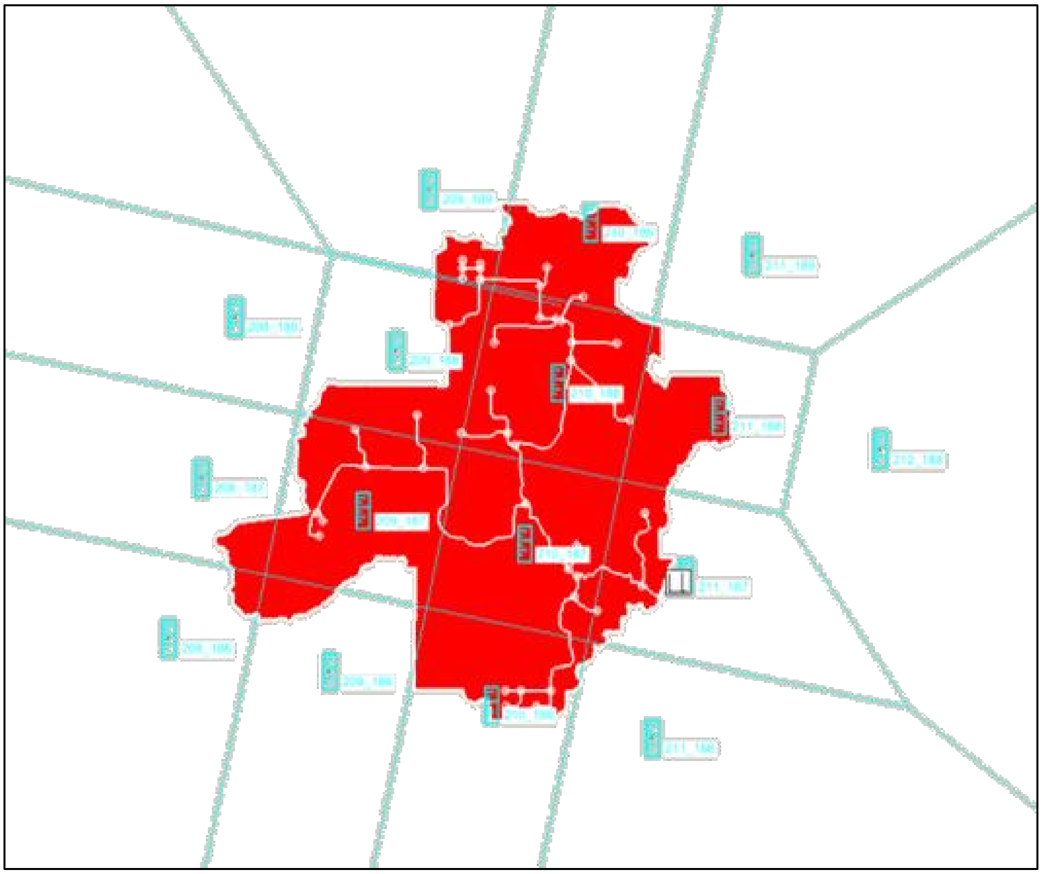
[1] Network Time Protocol

[2] Metropolitan Council of Environmental Services

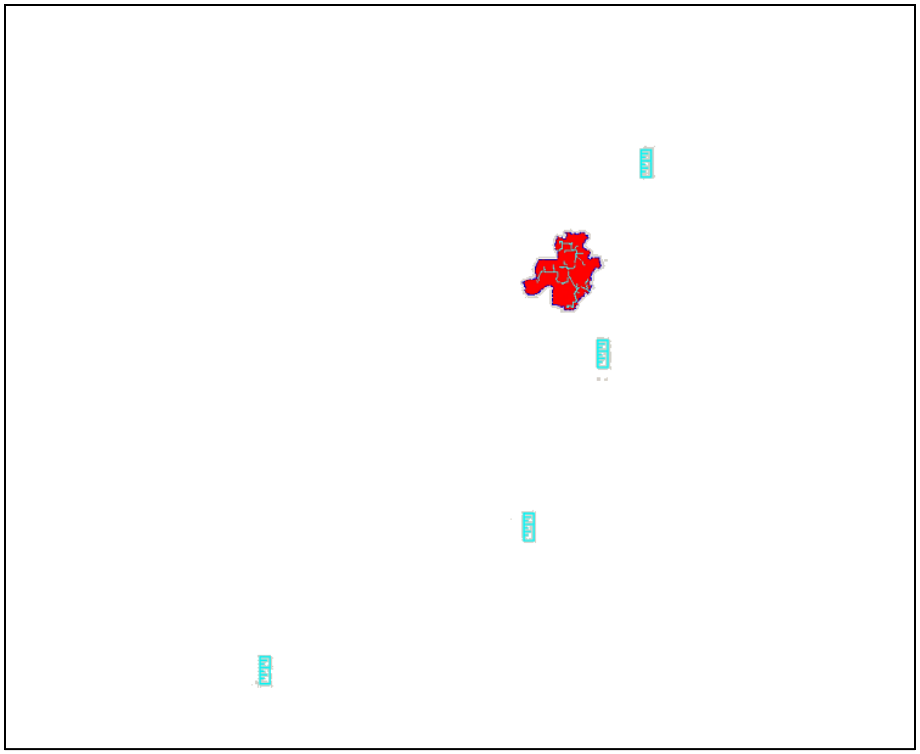
[3] Minnesota Pollution Control Agency

Figure 11. Radar rainfall pixels intersecting the Seven Mile Creek Watershed model.



None of the sources of precipitation described above had winter precipitation, approximately October through April, depending on the year. Because GSSHA is run in a continuous mode and snow accumulation, melt and runoff may be a significant portion of the water budget, estimates of winter precipitation were required. USACE MVP provided winter data from four sites: KMKT at Mankato Airport, Amboy, LeSueur, and Sherburn. These data were available on an hourly basis and used to fill any missing time periods but did not replace any of the previous data. None of these are within the Seven Mile Creek Basin. The relative locations of the gages are shown in Figure 12. As seen in Figure 12, the winter precipitation gages provide relatively poor coverage of the watershed, and therefore there is significant uncertainty in the amount and distribution of winter precipitation in the basin. As the winter precipitation provides the source of water for the spring thaw and runoff period, the lack of certainty in the winter precipitation data can cause increased uncertainty in spring runoff predictions.

Figure 12. Location of winter precipitation gages used in the Seven Mile Creek model.



Raw precipitation data were processed in Microsoft Excel utilizing a macro written at USACE-ERDC Coastal and Hydraulics Laboratory, which converts the data into a GSSHA rain gage file. After development, all data were checked by visually inspecting the file for correct format and errors as well as being checked by simulating the rainfall record in the GSSHA model. During simulations, the GSSHA model checks both the HMET and precipitation files for errors and reports on types and locations of errors. In addition to these checks on data formatting and processing, the rainfall record was also compared to observed stream records to try to eliminate phantom precipitation events, where large single values of rainfall were recorded but no corresponding stream flow was observed. The gages were also checked for internal consistency, to help eliminate gages that were not functioning properly for a given event. As the precipitation input file was extensive, and complicated by having numerous precipitation types and number and location of gage configurations, several iterations of model checking, followed by hand corrections, were required to produce a precipitation file best suited for the modeling effort.

In general, the precipitation gage data were judged of good quality for use at Red Top Farms, except for periods when radar rainfall data supplemented the gage data of rather poor quality for simulations in the larger basins. The Red Top Farms data were consistently recorded at higher temporal resolution and reported to be of good quality. The values at Red Top Farms are probably more applicable to the sub-basin watershed model, upstream of SMC1 in Figure 10, than for the Seven Mile Creek Basin model due to the spatial variability of precipitation likely in the larger basin. As described above, the other gage data, while providing some measure of spatial variability, were spotty and of rather poor quality, with spotty recording, poor temporal resolution, and much of the data being recorded as poor quality. No winter precipitation gages were available in the basin. The lack of measured precipitation in the basin during the winter months leads to a large uncertainty in the estimation of winter precipitation and subsequent snow melt, runoff, and hydrology response.

5 Observed Data

Flow data were provided by the Brown-Nicollet-Cottonwood (BNC) Water Quality Board at 15 min increments at four gage locations throughout the watershed at the monitoring sites shown in Figure 10. Data quality varied among the gages and throughout the period. The records from the gages had many periods of missing data. Much of the data were reported as being of poor quality or as estimated. Based on the amount of missing data and reported quality of data, it was felt that Gage 3, near the outlet, had the highest quality data; Gage 1, on the outlet of the northeast (NE) fork of Seven Mile Creek, had the second best data; Gage 2, on the northwest fork of Seven Mile Creek was considered of generally poorer quality compared to Gages 1 and 3; and Gage 4, on the southeast branch of Seven Mile Creek (not shown in the figure) had only spotty daily data, and was generally considered of poor quality. For these reasons, Gage 2 and 4 data were de-emphasized in calibration efforts and were not used for judging hydrologic response.

Grab samples of relevant water quality variables, TSS, N, and P, were available at all four of the gages referenced above. Grab samples corresponded to both low/base flow, as well as samples from events. In general, the samples do not allow a good definition of any particular storm event, and the peak discharge is rarely, if ever, captured. Available grab data from all four sites were utilized in model calibration and assessment despite the quality of the flow data associated with it.

6 Hydrologic Processes

In terms of application of watershed models to the Minnesota River Basin in general, and the Seven Mile Creek Basin specifically, the GSSHA model is unique in that it is a fully distributed, physics-based model that explicitly simulates point processes at the grid level and then integrates point processes responses to produce the overall system response. Therefore, in GSSHA each physical process is explicitly simulated. GSSHA is also an option-driven model. Not all processes are needed to simulate all watersheds, and the user can specify which processes to simulate as well as the manner in which to simulate them. As described above, the Seven Mile Creek Watershed, while relatively small, is rather complex, hydrologically speaking. The streamflow is a combination of overland flow, groundwater baseflow, and tile drainage flow originating from winter snowfall, diffuse spring rainfall and snowmelt events, and intense summer thunderstorms. Below-zero winter temperatures means the ground freezes, inhibiting infiltration, increasing runoff, and reducing flow into tile drains. Overland and ravine sediment erosion are of concern as well as overland and in-stream nutrient loading. In an attempt to realistically simulate the hydrologic processes occurring in the Seven Mile Creek Watershed, as well as the hydrologic response of the basin, the following processes were simulated in the described fashion.

6.1 Precipitation

Precipitation was incorporated into the model using available rainfall gage data, as described above, and distributed over the models using Thiessen polygons. The distribution of Thiessen polygons varies with the gages being used during individual events. Snowfall accumulation and melt is simulated in the model using the Hybrid method, as described by Follum and Downer (2013).

6.2 Overland flow

Overland flow is simulated as two-dimensional (2D) lateral flow. The diffusive wave equation, which captures backwater effects, is solved using the ADE[1] method. Overland roughness values were assigned according to land cover within the range suggested by Senarath and Ogden (2000).

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[1] alternating direction explicit

Micro-depressions are represented as retention storage. Overland flow is routed through snowpack according to Darcy's law (Darcy 1856).

6.3 Frozen soil

Frozen soil is simulated with Continuous Frozen Ground Index (CFGI) model (Molnau and Bissell 1983), which simulates the soil as either frozen, or not frozen, based on an accounting of heat deficit, using the hourly air temperature in each grid cell. Frozen soils are considered impervious to infiltration. In addition, groundwater flux into tile drains ceases when the CFGI exceeds the threshold value in the cell and the ground is considered frozen. See http://www.gsshawiki.com/Frozen_Soil:Frozen_Soil for more detail.

6.4 Channel routing

A one-dimensional (1D) diffusive wave channel routing scheme is used to simulate stream flow. Channel cross sections were explicitly defined utilizing 49 surveyed cross sections.

6.5 Infiltration

The standard Green and Ampt (Green and Ampt 1911) model has proven effective for modeling infiltration into soils for single events in well-drained uniform soils, but several important common natural and man-made phenomena can invalidate the assumption of vertically uniform soils. Soil layering, non-uniform initial soil moisture, surface crusts, lenses, and high water tables violate the conditions necessary to apply the traditional Green and Ampt method. For these reasons, the three-layer Green and Ampt (multi-layer G&A) infiltration option in GSSHA (Downer 2002) was used to simulate infiltration in the Seven Mile Creek catchment. Soil layering was available from the SSURGO physical properties, Table 1. Three soil types were defined:

- Type 1: Clay Loam (layer 1), Loam (layer 2), Loam (layer 3)
- Type 2: Clay Loam (layer 1), Clay Loam (layer 2), Clay Loam (layer 3)
- Type 3: Silty Clay Loam (layer 1), Silty Clay Loam (layer 2), Silt Loam (layer 3).

For parameter assignment, soil types were combined with five dominant land-use types (corn/soy, alfalfa/grass, wetlands/water, developed, forest) to create 12 Land Use/Soil Type (LUST) categories to assign parameters.

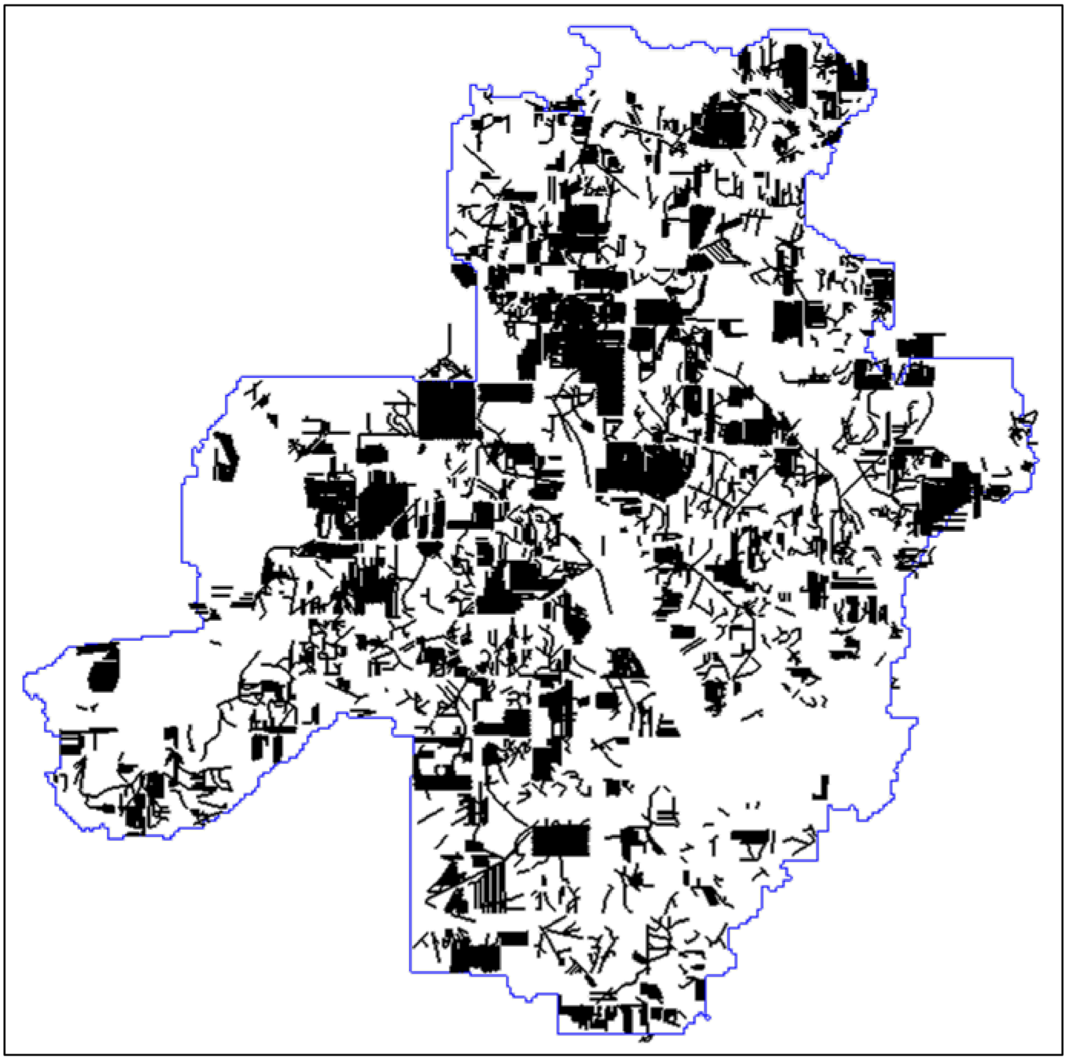
6.6 Groundwater

A lateral 2D simulation of saturated groundwater flow is included in the model. The watershed boundary for each model is used as a no-flow boundary condition. Groundwater recharge is provided by the multi-layer G&A model. Stream losses and gains are governed by a river flux boundary condition. The saturated water table provides the flux to tile drains. The tile drains provide a sink to the groundwater solution.

6.7 Tile drains

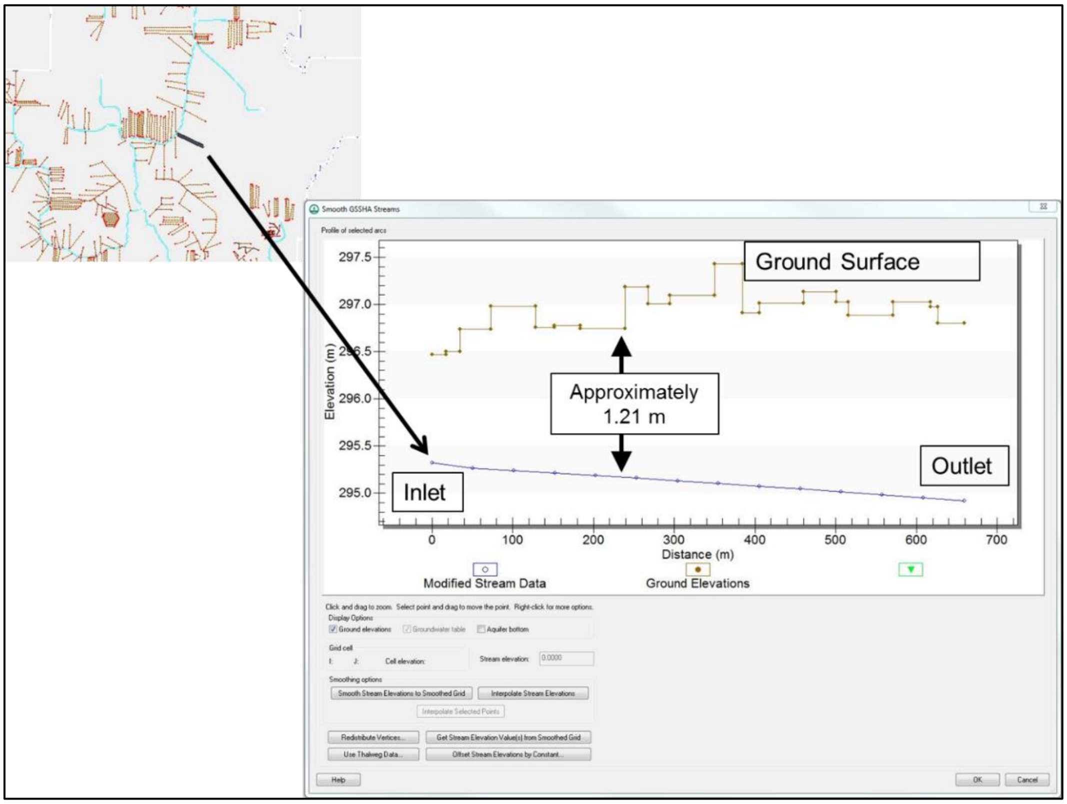
Tile drains were explicitly simulated in the models according to Downer and Pradhan (2014a). The tile drain networks were defined from USACE-MVP-provided shape files that described the public and private tile drain systems. The public tile drains are a matter of public record and are considered accurate. The private tile drains are considered an estimate of possible/probable tile locations obtained from a variety of sources. These tile locations are shown in Figure 13.

Figure 13. Reported location of private tiles in the Seven Mile Creek Watershed.



To the extent possible, this network was implemented in the GSSHA hydrologic models of the watershed. Information from the Red Top Farms tile network was used to populate the physical properties of the tiles in the GSSHA model. Drains in fields were assumed to be 15 cm. Mains were assumed to be 30 cm. All drains were placed approximately 1.2 m below the local land surface. Typical development of the tile model is shown in Figure 14.

Figure 14. Typical tile drain development.



Click and drag to zoom. Select point and drag to move the point. Right-click for more options.

Display Options

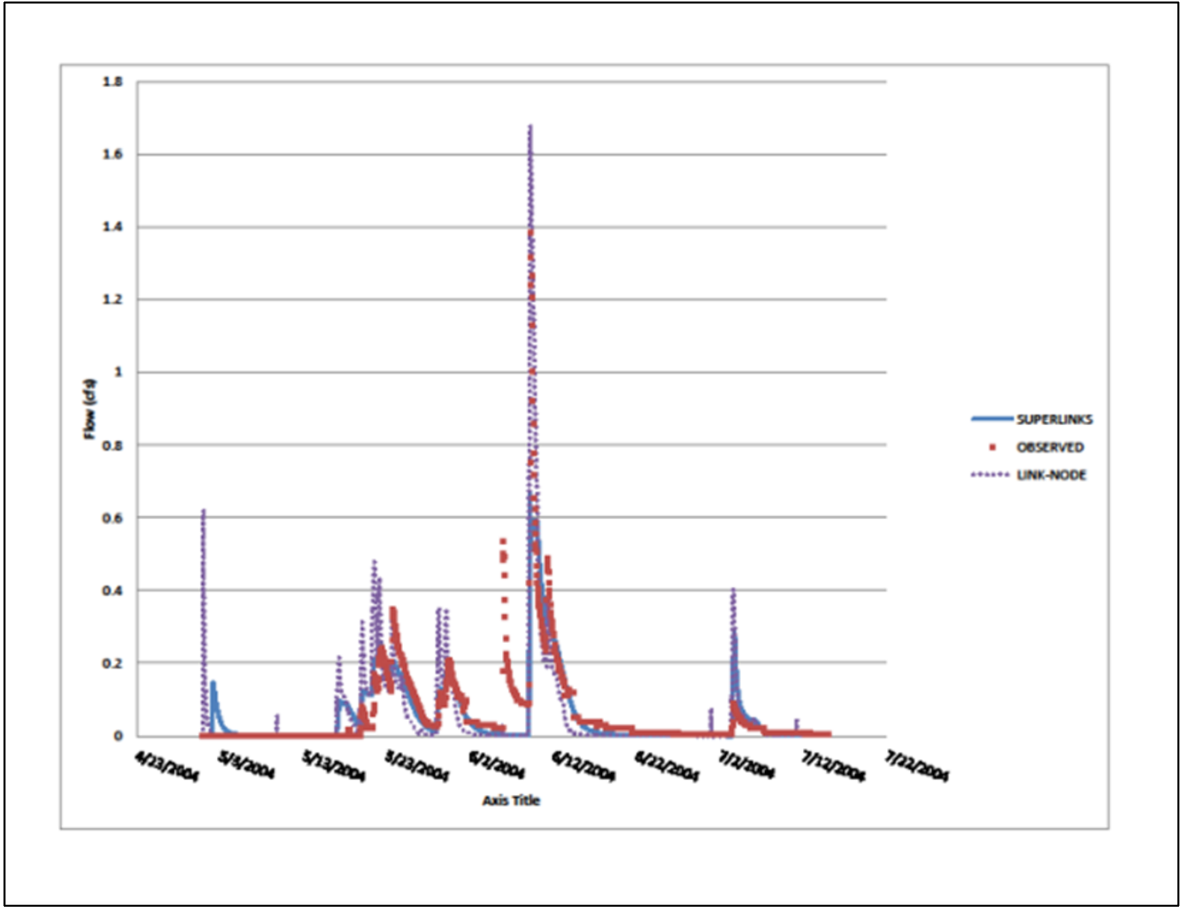
☑ Ground elevations ☑ Groundwater table ☐ Aquifer bottom

Stream elevation: 0.0000

Pipe roughness and hydraulic conductivity were assigned and then calibrated using observed tile flow data at Red Top Farms and observed stream flow in the basin. Excluding the Red Top Farms model, the tile drains in the models represent *effective* networks, meant to capture the effect of the tiles. The exact number, location, and properties of the actual tile network are impossible to know in such a complex network.

Initially, tiles were simulated using the SUPERLINKS dynamic routing model (Ogden et al. 2011). However, due to excessive simulation times, another method, a simple link/node model, was added to GSSHA and utilized for the long-term future scenario simulations. In the link/node routing model, once the water enters the tile drain, it is assumed to instantly be routed to the tile network outlet. Given the primary control on the tile flow is the movement in the sub-surface, both in the groundwater and into the tile drain, and that most segments of tile drain are short, and smooth, the assumption is reasonable for routing tile flow at the field scale. Comparison of flows at Red Top Farms and for the whole basin model indicated that the link/node routing model produced comparable results at drastically reduced simulation times (Figure 15).

Figure 15. Comparison of SUPERLINK and LINK/NODE tile routing models at Red Top Farms.



6.8 Evapotranspiration

Evapotranspiration (ET), a critical component of the seasonal water balance, is necessary for simulating soil wetting and drying. The Penman method (Penman 1948) was specified within GSSHA to calculate ET on an hourly basis, the same temporal resolution as the HMET inputs. The required model parameters were assigned according to the land-use map, Figure 3. Surface albedo values are based on recommended values from the GSSHA user manual (Downer and Ogden 2006). Canopy transmission coefficients were assigned according to light interception studies (Hutchison and Matt 1977) for deciduous forests. Canopy stomatal resistance was based on two published studies (Eliáš 1979; Verma and Baldocchi 1986). The Penman method is fairly sensitive to stomatal resistance (Lemeur and Zhang 1990), so considerable attention was given to stomatal resistance during initial calibration. HMET data described earlier are also used in ET calculations.

6.9 Soil erosion

Overland sediment erosion is routed using a 2D mass balance approach (Downer et al. 2014b). The simulation considers detachment of sediment due to rainfall impact (Gabet and Dunne 2003; Wicks and Bathurst 1996) as well as by surface runoff. In this study, the modified Kilinc and Richardson equations (1973) to determine sediment transport potential (Julien 1995) were used. Amounts of soils eroded by rainfall impact and/or overland flow shear below the transport capacity of the flow are routed with a 2D advection dispersion equation to the 1D channel network where the sediments are routing toward the watershed outlet. Eroded soils in excess of the transport capacity are settled using a trap efficiency equation. In GSSHA, any number, size, and density of particles can be simulated. In the Seven Mile Creek models soils were partitioned amongst sand, silt, and clay sizes, with a specific gravity of 2.65, that of quartz.

6.10 In-stream sediment transport

Once in the stream, sediment is routed as either wash load or bed load. Sediment sizes smaller than sand, silt, and clay are routed with a 1D advection dispersion equation. Sand, and larger size particles, are routed as bed load with Yang's Formula.

6.11 Nutrients

Nutrients, N and P, were simulated as first-order reactants in the model. For the purposes of this study, N is approximately analogous to nitrate+nitrite, and P is analogous to total phosphorous. N and P, in both the dissolved and sorbed phase, were simulated in the soils (1D vertical), the overland (2D lateral), and in the streams (1D). Groundwater concentrations were spatially variable but temporally static. These were assigned along with the other relevant variables, as described below.

7 Hydrologic Simulation

The Watershed Modeling System (WMS 9.1) was used for watershed delineation. Flow directions and accumulations were computed using the Topographic Parameterization Program method (Garbrecht and Martz 1993). This information, along with spatial data pertaining to terrain, soils, land cover, and temporal data related to HMET data, are fed to GSSHA.

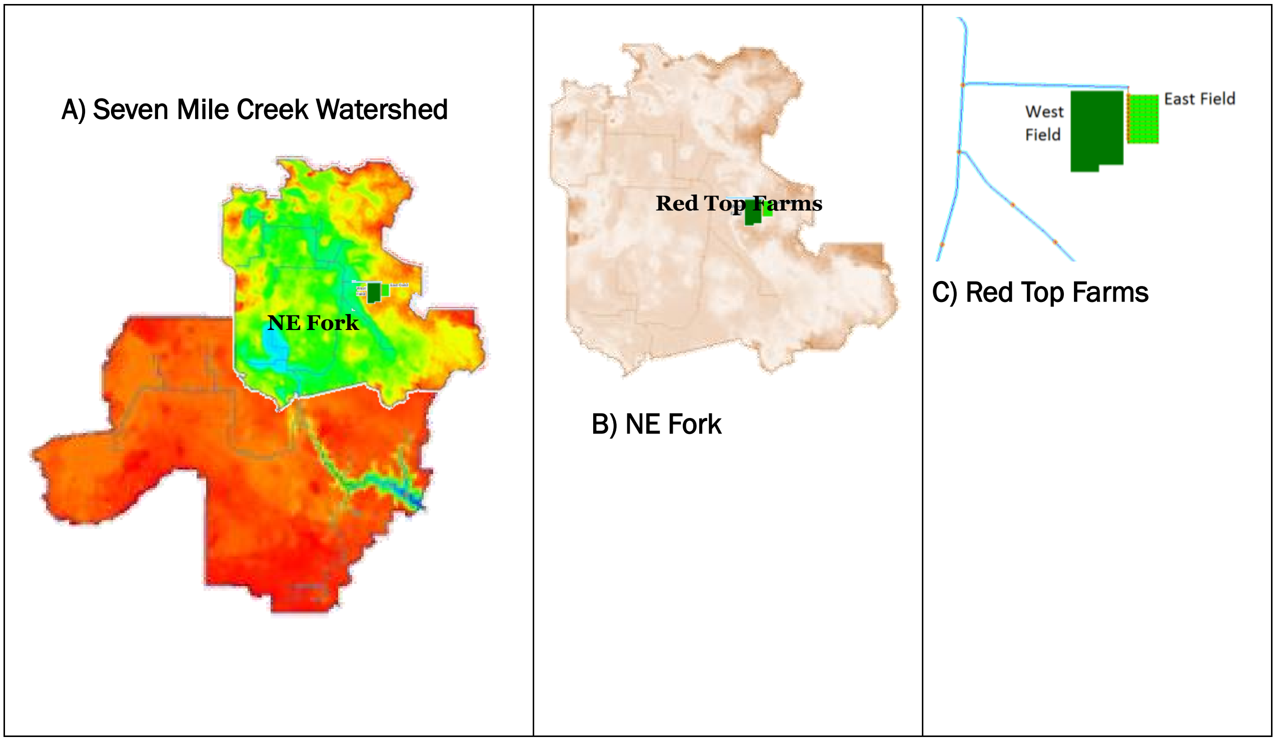
7.1 Modeling framework

A set of nested models was developed for analysis. The models include one of the entire Seven Mile Creek project, a model of the NE fork of Seven Mile Creek, and a model of the Red Top Farms experimental watershed. The Red Top Farm model is located within the NE Fork model, which lies within in the overall Seven Mile Creek extents. The nested framework is illustrated in Figure 16.

7.1.1 Seven Mile Creek model

The drainage area of the Seven Mile Creek is contained within one HUC12 boundary of 97.85 km^2. The Seven Mile Creek model was developed using a 50 m computational grid with 39,142 grid cells. The model has 91 stream links and 874 subsurface tile drainage nodes. The Seven Mile Creek Model is shown in Figure 16, A.

Figure 16. Nested modeling framework within the A) Seven Mile Creek Watershed identifying the B) NE Fork and C) Red Top Farms experimental watershed.



7.1.2 NE Fork Sub-basin model

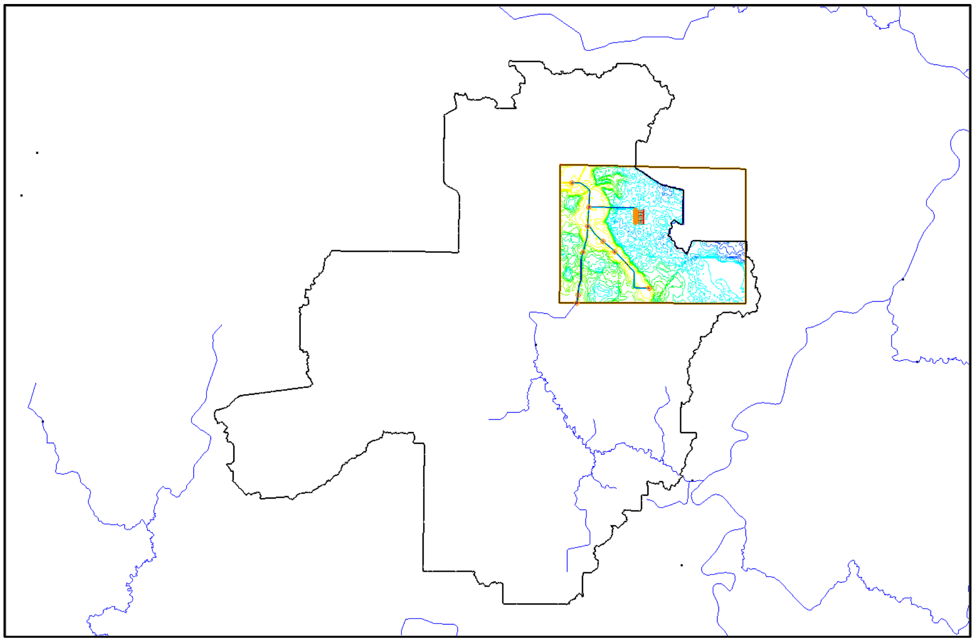
The NE Fork Sub-basin model is defined as the section of the basin upstream of the SMC1 gage, or monitoring Site 1 in Figure 10. The basin encompasses 39.04 km^{2}. This model is simulated at 25 m resolution, containing 62,467 grid cells. This model has 176 stream links and 312 sub-surface tile drainage nodes. The NE Fork sub model is shown in Figure 16, B.

7.1.3 Red Top Farms model

Red Top Farms is an experimental watershed located within the NE Fork section. The site includes two tiled agricultural fields with controlled/measured crops and application of fertilizers (Figure 16, C). Red Top Farms has a rich dataset associated with it including measured precipitation, tile flow, and water quality data collected between 1994 and 2010. The location is unique in that tile flow and water quality are measured in the field and relatable to soils, land use, and crop rotation.

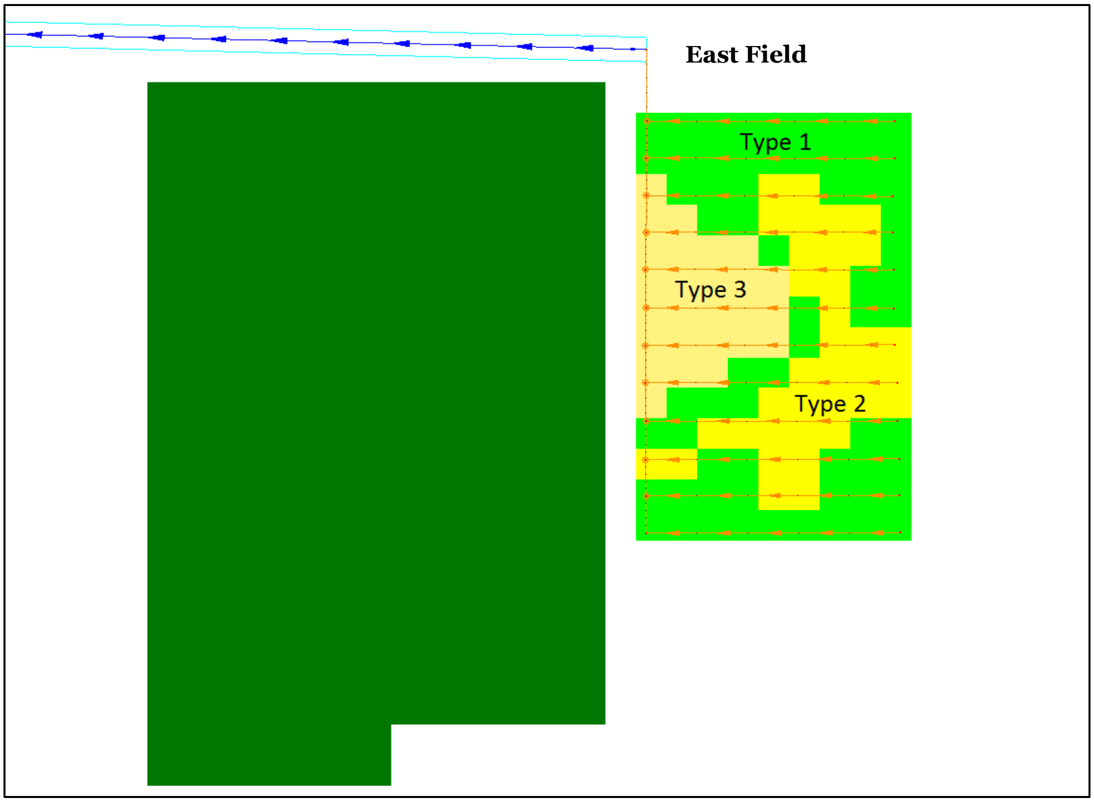
The Red Top Farms GSSHA model was developed with the intent to facilitate hydrologic process understanding and to support GSSHA model parameterization throughout the entire Seven Mile Creek Watershed system. Although the Red Top Farms area is small, the model had to be large enough to develop groundwater boundary conditions. The Red Top Farms model domain, depicted in Figure 17, encompasses 12.58 km^2 with 20,133 grid cells at 25 m resolution. The model includes the ditch network within the model domain with nine channel links.

Figure 17. Location of Red Top Farms model domain in relation to the Seven Mile Creek study area.



The Red Top Farms GSSHA model was developed in a manner such that state observations of response from the approximate 12.59 km^2 acre Red Top Farms East Field named “RM” could be compared with their model simulated counterparts. The Red Top Farms GSSHA model of the East Field, including the tile drains reflected in the model, is shown in Figure 18.

Figure 18. Tile drain network and soil type distribution in the East Field of the Red Top Farm model.



Similar to the larger models, the East Field was simulated with the following three soil types:

- Type 1: Clay Loam (layer 1), Loam (layer 2), Loam (layer 3)
- Type 2: Clay Loam (layer 1), Clay Loam (layer 2), Clay Loam (layer 3)
- Type 3: Silty Clay Loam (layer 1), Silty Clay Loam (layer 2), Silt Loam (layer 3).

7.2 Initialization

Assumptions about the water table and initial soil moisture conditions based strictly on the soil descriptions result in improbable discontinuities at boundaries between soil types. To equilibrate the model, the simulation was initialized over a period from late September 2003 to the first of May 2004. At the end of each initialization period, the final state is fed back into the model as new initial conditions. Initialization had to be repeated several times during model calibration when parameter sets where updated. This process was repeated until the base flow in the channels was reasonable and the water table was stable and smooth. This process provides the initial groundwater table and soil moisture conditions at the start of the calibration period. The calibration and validation periods include an additional simulation start-up period before the calibration/validation results are used.

7.3 Calibration/validation

Calibration/validation periods were selected with the intent of having a dry period with little or no tile flow for calibrating surface runoff processes as well as a period during wet conditions characterized by a high water table for calibrating tile flow. Periods with the most complete precipitation, discharge, sediment, and nutrient records were identified as 2004, 2006, 2007, and 2008. The wet period was chosen as May 1 to July 15, 2004, and the dry period was chosen to be June 15-June 30, 2006, since these timeframes had adequate observed data for calibration/validation and best met the desired hydrologic conditions.

The Secant Levenberg-Marquardt (SLM) method (Levenberg 1944; Marquardt 1963) for model independent parameter estimation and the Shuffled Complex Evolution (SCE) general purpose global optimization method (Duan et al. 1992, 1993)as described by Skahill et al. (2012a, 2012b) were used to calibrate the GSSHA models to observed data. The basics of SLM are provided in Skahill et al. (2009). The BNC Water Quality Board provided observed flow at 15 min increments at four gage locations throughout the watershed along with less frequent sediment and nutrient concentrations. Sediment loads were calibrated using the ERDC implementation of the SCE method (Skahill et al. 2012a,b). Flow was calibrated using the ERDC implementation (Skahill et al. 2012a,b) of the SLM method. The SLM method employs a nonlinear least squares minimization local search algorithm. To better accommodate scaling issues resulting from mismatches of units among the various parameters, and in an attempt to decrease the degree of nonlinearity of the parameter estimation problem, the logs of the adjustable model parameters were estimated instead of their native values; past experience has demonstrated that greater efficiency and stability of the parameter estimation process can often be achieved through this means (Doherty and Skahill 2006).

Initially, model calibration was hampered by long simulation times. While these issues were eventually resolved, as described above, the calibration strategy was based on this limitation at the time. To facilitate a quicker hydrologic calibration, calibration of different model components was separated with the basic strategy to use the Red Top Farm model to determine parameters relevant to tile drainage during a wet period and to use the Seven Mile Creek model to determine surface and groundwater parameters during a dry period, when little or no tile flow was expected to be a factor. Once all the model parameters were determined for the Seven Mile Creek model in this manner, they would be validated for the same wet period used to determine the tile drain parameters in the Red Top Farm model. Parameters determined in this fashion were then applied to the NE Fork Sub-basin model with adjustment of parameters as needed.

7.3.1 Red Top Farms tile parameter calibration

Simulation of Red Top Farms was beyond the SOW, and this model was developed with the purposes of testing/demonstrating the ability of the GSSHA model to explicitly simulate tile drainage flow and to develop an appropriate tile drain parameter set that can be used in the Seven Mile Creek and NE Fork models. Flow from the tile drainage network provided in Figure 18 was used as the basis for comparison with observed data. No surface flow is measured or included. Observed measurements of flow at the outlet of the East Field were compared with simulated values from the model every 30 min for the period May 1, 2004 – July 15, 2004, excluding the period May 5, 2004, 1200, through May 8, 2004, 1200, resulting in a total of 3456 model-observation compares to constitute the objective function. In attempts to stabilize the variance of the residuals, the objective function in fact consisted of the sum of weighted squared differences between 3456 modeled and transformed flow values, with all weights assigned a value of 1. The Box-Cox transformation with $\lambda = 0.3$ (Box and Jenkins 1976; Misirli et al. 2003) was employed to transform the observed and modeled flows.

To support calibration of the Red Top Farms GSSHA model, five parameters were specified as adjustable, viz.,

1. Groundwater Hydraulic Conductivity – the GSSHA model input parameter named GW_UNIF_HYCOND, which specifies and assigns a uniform value throughout the entire model domain for the groundwater hydraulic conductivity.
2. Tile Roughness – the roughness value uniformly assigned to all of the tile represented in the GSSHA model developed to simulate the East Field of Red Top Farms.

3. Tile Conductance – the conductance value uniformly assigned to all of the tile represented in the GSSHA model developed to simulate the East Field of the Red Top Farms.
4. Canopy Stomatal Resistance – the GSSHA model input parameter named CANOPY_RESIST, only for those grid cells representing the East Field of the Red Top Farms, and which parameterizes evapotranspiration calculations within the GSSHA model to support continuous simulation.
5. Soil Hydraulic Conductivity – a multiplier value that is uniformly applied to base values specified for the soil hydraulic conductivity for all three layers of soil for the three distinct soil types characterized within the East Field of the Red Top Farms. The base hydraulic conductivity values were obtained from GSSHA model parameter guidance provided with the GSSHA documentation: http://www.gsshawiki.com/Infiltration:Parameter_Estimates.

The SLM local search was configured for efficiency in the Red Top Farms model. In particular, no full update of the model sensitivity matrix was employed; and column cyclic updating was deactivated for the duration of the optimization. The Red Top Farms model calibration period spanned the period from May 1 to July 15, 2004. Calibration of tile roughness, hydraulic conductivity, and ET parameters resulted in an 84% reduction in the sum of the squared residuals. The final estimated model parameter set is listed in Table 3 below along with an estimate of uncertainty. Note that the reported 95% confidence limits provide only an indication of parameter uncertainty. They rely on a linearity assumption that may not extend as far in parameter space as the confidence limits themselves.

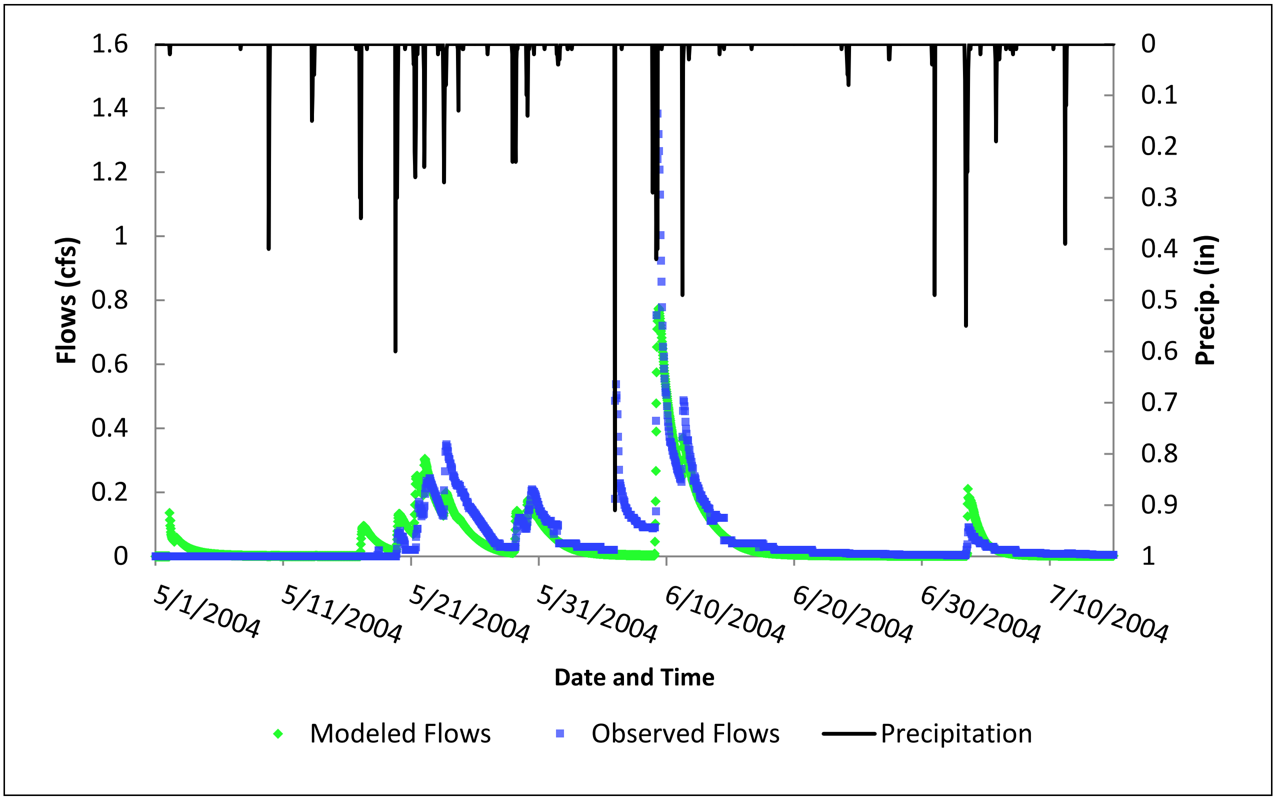
Table 3. Red Top Farms parameterization.

Parameter			Initial Value	Final Value	Sensitivity	95% Confidence Limits	
						Lower	Upper
Manning Roughness	Tile		0.0091	0.0031	0.00182	0.0029	0.0031
Hydraulic Conductivity (cm/hr)	Tile		3.918	1,718	0.00288	1685	1752
	Groundwater		1.0043	0.0051	0.00220	0.0049	0.0052
	MUSYM_L107A_RM	upper	0.099	98.03	0.00164	94.52	101.7
		intermediate	0.651	646.0	0.00164	623.8	671.0
		lower	0.651	646.0	0.00164	623.8	671.0
	MUSYM_112_RM	upper	0.099	98.03	0.00164	94.52	101.7
		intermediate	0.099	98.03	0.00164	94.52	101.7
		lower	0.099	98.03	0.00164	94.52	101.7
	MUSYM_134_RM	upper	0.099	98.03	0.00164	94.52	101.7
		intermediate	0.099	98.03	0.00164	94.52	101.7
		lower	0.336	333.3	0.00164	321.4	345.7
Evapo-transpiration	Stomatal Resistance (s/m)		100.67	56.86	0.00184	54.82	58.98

Note that of the values shown in Table 3, only tile properties, Manning roughness and hydraulic conductivity are used in subsequent modeling efforts. The observations at Red Top Farms included no surface flow. Additionally, the Red Top Farms model was configured solely to simulate the tile drains, with no intention of using the other values. During calibration, the values were allowed to float to better match the tile flow. Without a constraint of matching surface flow, the soil hydraulic conductivity parameters were allowed to become high. They are not and are not intended to be representative of conditions in the watershed. Calibration of surface features is best done to surface water flow, not tile flow.

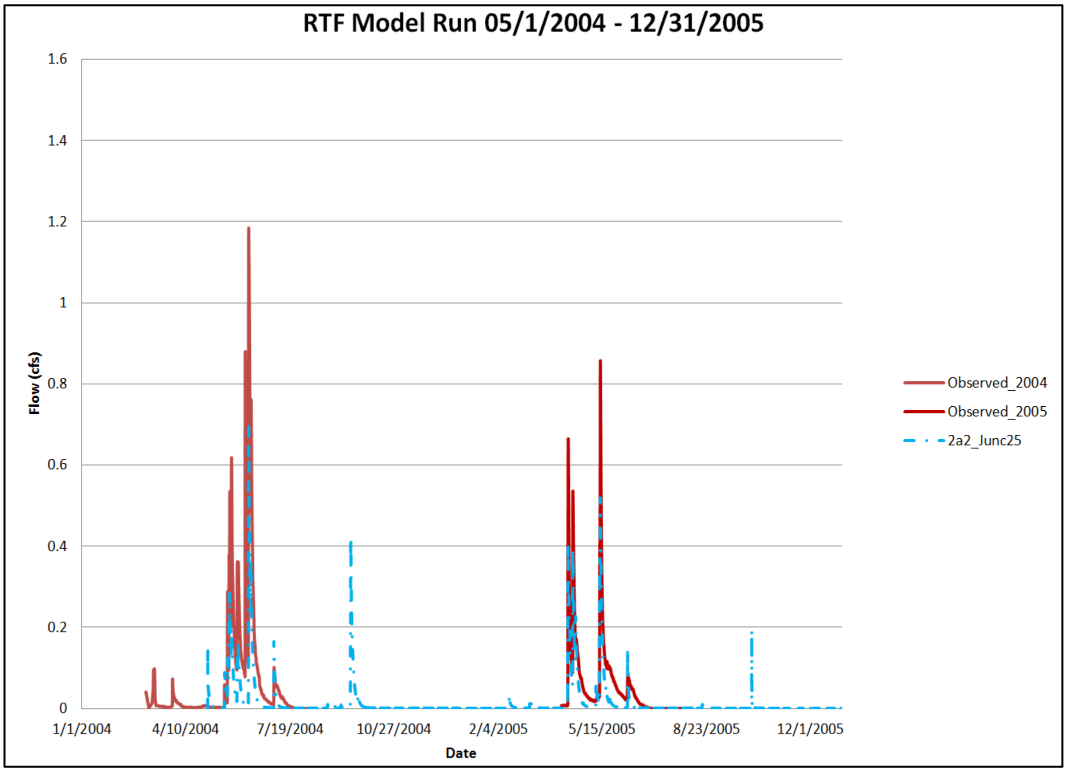
The information encapsulated in Figure 19 summarizes model-to-measurement misfit at the final estimated parameter set. The related computed Nash and Sutcliffe efficiency (NSE) score of 0.86 indicates a Red Top Farms East Field GSSHA calibrated model of predictive value.

Figure 19. Observed versus measured tile flow for the East Field of the Red Top Farms model.



This parameters set was further tested by extending the simulation period through the next wet season, 2005. The results of this experiment are shown in Figure 20. As shown in the figure, even after simulating a dry season, and a snow accumulation and melt season, the model, with the calibrated parameter set, demonstrates sufficient skill in simulating the measured tile flow from the East Field of the Red Top Farms model. This demonstrates that the GSSHA model can be used to simulate tile drain flow for a well-defined tile drainage system.

Figure 20. Extended Red Top Farms East Field tile flow results.

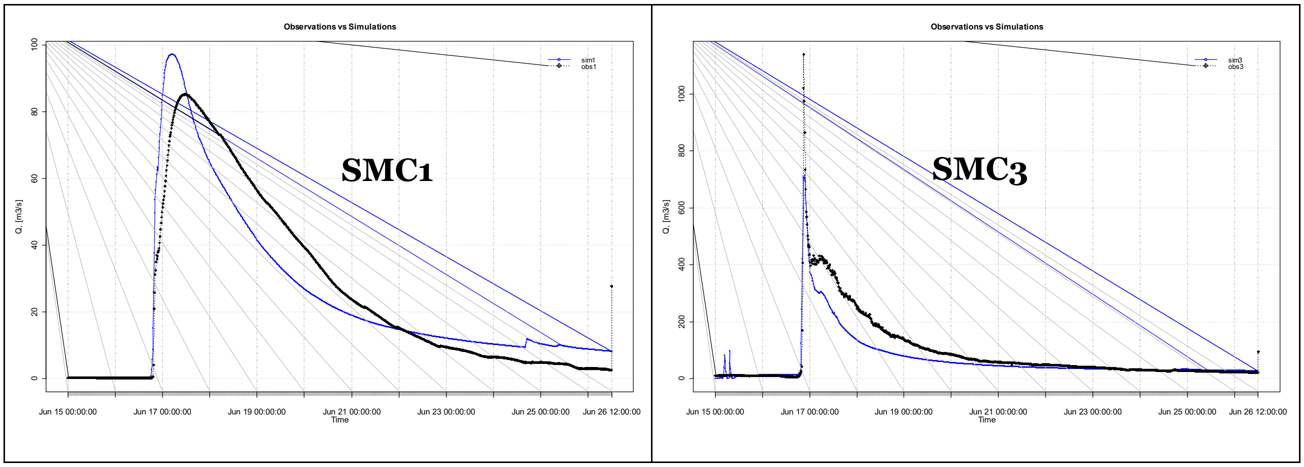


7.3.2 Seven Mile Creek model calibration

The field scale Red Top Farms model was used to inform parameters related to generation of tile flow in larger model domains. The larger Seven Mile Creek model was initially calibrated to a single event in June of 2006 in which tile flow was assumed to be minimal as the preceding period is relatively dry and the flow gage at Red Top Farms indicates no tile flow during this period. Radar rainfall estimates were available to drive the model during this period. Calibration over this period focused on capturing the surface runoff generating characteristics. Fifteen-minute observed flows at the two gaged locations within the watershed were used to assess the goodness-of-fit (Table 4). Manning roughness, soil hydraulic conductivity, overland flow retention depths, and groundwater parameters were adjusted during calibration. An 85% reduction in the sum of the squared weighted residuals resulted.

A comparison of observed and simulated discharge for the single June 2006 event is presented in Figure 21 below. The gage labeled “SMC1” corresponds to the outlet at the NE Fork Sub-basin model while the one labeled “SMC3” is at the Seven Mile Creek Watershed outlet. Figure 10 identifies locations of the monitoring sites. As seen in Figure 21, the model does a fairly good job of capturing the hydrograph shape, with the ascending limb, peak flow, and recession well represented. The NSE is 0.72 for SMC1 and 0.89 for SMC3, indicating very good reproduction of measured flow for this period. Storm total volumes are also well presented. Given the accuracy in reproduction of the flow for this period, this model should be usable for determining the sediment erosion parameter values.

Figure 21. Comparison of simulated discharge (blue lines) from the 50 m resolution Seven Mile Creek GSSHA model with observed flow (black lines) for four gages for the June 2006 event.



The same 2004 period considered initially for the calibration of the Red Top Farms model (May 1 - July 15) was revisited to verify the results and perform final calibration of the overall model during *wet* conditions for fine tuning the combined contributions from surface runoff, subsurface flow, and tile flow. Point gage data from Red Top Farms were used to drive the models for this period. The cost function was marginally reduced by adjusting groundwater parameters in this phase. Comparison of simulated and observed values is shown in Figure 22. Summary statistics are shown in Table 4. As seen in the figure, the model does a good job of representing the overall model response at Gage 3 and to a lesser extent at Gage 1, where the larger flows are well represented, but some of the smaller flows are not. The statistics attest to this visual impression. NSE for Gage 3 is 0.65, not as strongly positive as the dry period but still good. NSE for Gage 1 is 0.45, still strongly positive but not as high as Gage 3 or for the previous period. Total flow at Gage 1 is underestimated by 40%.

There are several potential/likely reasons for the differences between measured and simulated flow for this dry and wet calibration/validation periods. The calibrated model was driven by radar rainfall, is temporally removed away from the effects of snow accumulation and melt, and has little suspected tile flow as conditions are relatively dry, and data from the Red Top Farms site indicate no tile flow occurs during this period. As noted previously, confidence in the winter precipitation is not high due to the lack of winter precipitation gages in the actual basin. The winter precipitation sets the stage for spring melt and runoff. Errors in winter precipitation will result in additional errors in spring melt runoff. In addition, these errors will be exacerbated by errors in tile flow, which are derived from the groundwater, which is derived from the winter precipitation and spring melt. Additionally, as noted previously, the exact existing tile drainage system is not represented in the model, only the best understanding of what the tile drainage system may be. Errors in volume for the validation are probably a combination of errors in winter precipitation, use of a different type of precipitation data to drive the model (point versus radar), and tile drain flow. Still, the model is thought be to of sufficient quality to make predictive assessment of the land-use alternatives.

Figure 22. Comparison of simulated discharge versus observed measurements at the four Seven Mile Creek gage locations from 2004.

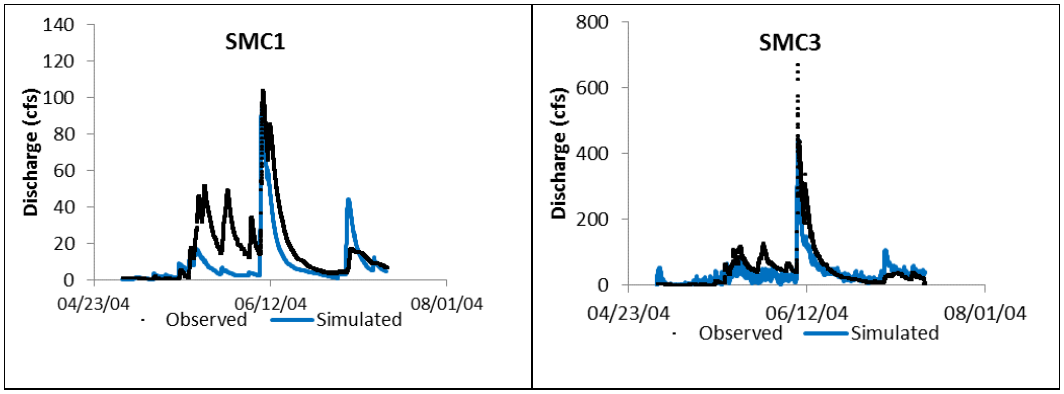


Table 4. Goodness-of-fit parameters for the overall Seven Mile Creek model.

	SMC1		SMC3	
	Calibration	Validation	Calibration	Validation
Pearson's correlation coefficient (r)	0.976	0.75	0.944	0.86
Coefficient of determination (R2)	0.953	0.563	0.891	0.74
Index of agreement (d)	0.953	0.819	0.95	0.853
Nash-Sutcliffe efficiency (NSE)	0.725	0.447	0.849	0.655
Mean absolute error (MAE)			10.011	28.471
Mean square error (MSE)	3.284	10.414	916.187	1485.337
Root mean square error (RMSE)	95.553	211.853	30.269	38.54
Percent bias (PBIAS)	9.775	14.555	-20.5	-1.3
Volumetric efficiency (VE)	33.8	-39.7	0.728	0.391
Ratio of RMSE (rsr)	0.602	0.378	0.388	0.588

Initial and final parameter values are listed below in Table 5 along with confidence bounds. Again, note that the reported 95% confidence limits provide only an indication of parameter uncertainty.

Table 5. Calibrated parameter values.

Parameter			**Initial Value**	**Final Value**	**Sensitivity**	**95% Confidence Limits**	
						Lower	**Upper**
Manning Roughness	Stream Roughness		0.050	0.167	0.018	0.137	0.204
	Ditch Roughness		0.050	0.500	0.037	0.433	0.577
	Row Crop Overland		0.025	0.271	0.0306	0.224	0.329
	Forest Overland		0.025	0.644	0.0321	0.468	0.886
	Wetland Overland		0.025	0.563	0.0250	0.190	1.663
	Tile		0.011	0.011	-	-	-
Hydraulic Conductivity (cm/hr)	Streambed		1.000	4.941	0.9710	-	-
	Ditch bed		0.000	0.000	0.00091	0.000	-
	Groundwater		20.00	12.62	1.1021	-	-
	Tile		2000	2010	0.866	-	-
		upper	0.040	0.008	0.0318	0.005	0.011

	Clay loam	intermediate	0.573	0.109	0.0318	0.078	0.153
		lower	0.760	0.145	0.0318	0.103	0.202
	loam	upper	0.606	0.115	0.0318	0.082	0.161
		intermediate	0.760	0.145	0.0318	0.103	0.202
		lower	0.760	0.145	0.0318	0.103	0.202
	Mucky silt loam	upper	0.048	0.009	0.0318	0.007	0.013
		intermediate	0.360	0.068	0.0318	0.049	0.096
		lower	0.360	0.068	0.0318	0.049	0.096
Retention Depth (mm)	Row Crop		1.00	0.890	0.0179	0.321	2.465
	Deciduous Forest		5.00	3.647	0.0181	0.686	19.40
	Herbaceous Wetland		50.0	16.753	0.0161	8.567	32.76
Groundwater Properties	Sat/Unsat		0.750	0.955	0.099827	0.888	1.027
	Porosity		0.600	0.400	0.0664	0.371	0.431

7.3.3 NE Fork Sub-watershed model calibration

The parameter values developed for the Seven Mile Creek model were transposed to the NE Fork Sub-watershed model and tested during the calibration/validation periods. The model was compared to 15 min flow data from SMC1. Analysis of these simulation periods indicated that no adjustment of parameter values obtained from the Seven Mile Creek model was required. Results of this testing are shown in Figure 23 and Figure 24 for the dry and wet seasons, respectively. Goodness-of-fit statistics for the two periods are provided in Table 6. As seen in Figure 23 and Table 6, the calibration model has a very good fit to the observed data, with an extremely high NSE value of 0.95. As seen in Figure 24 and in Table 6, the validation is of lesser, although acceptable, accuracy, with an NSE of 0.433, still strongly positive. Volumes are underestimated for the validation period. The overall result is very similar to the results at this gage for the larger Seven Mile Creek model. The reasons for the underprediction of flows at Gage 1 for this model are the same as described above.

Figure 23. Comparison of simulated and observed discharge at the NE Fork model for the June 2006 event (calibration period).

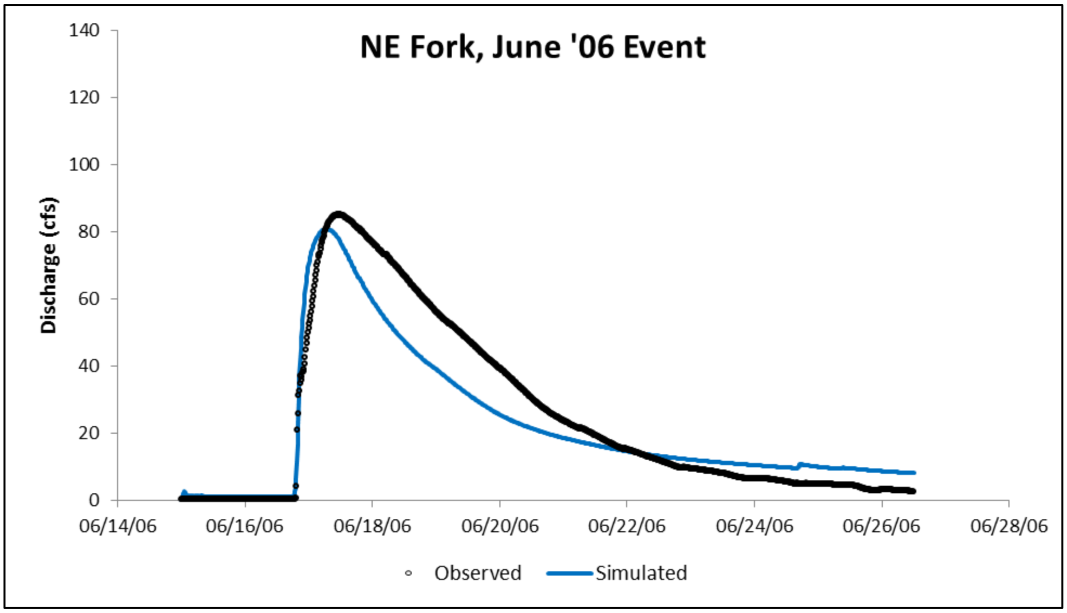


Figure 24. Comparison of simulated and observed discharge at the NE Fork model for the summer 2004 period (validation period).

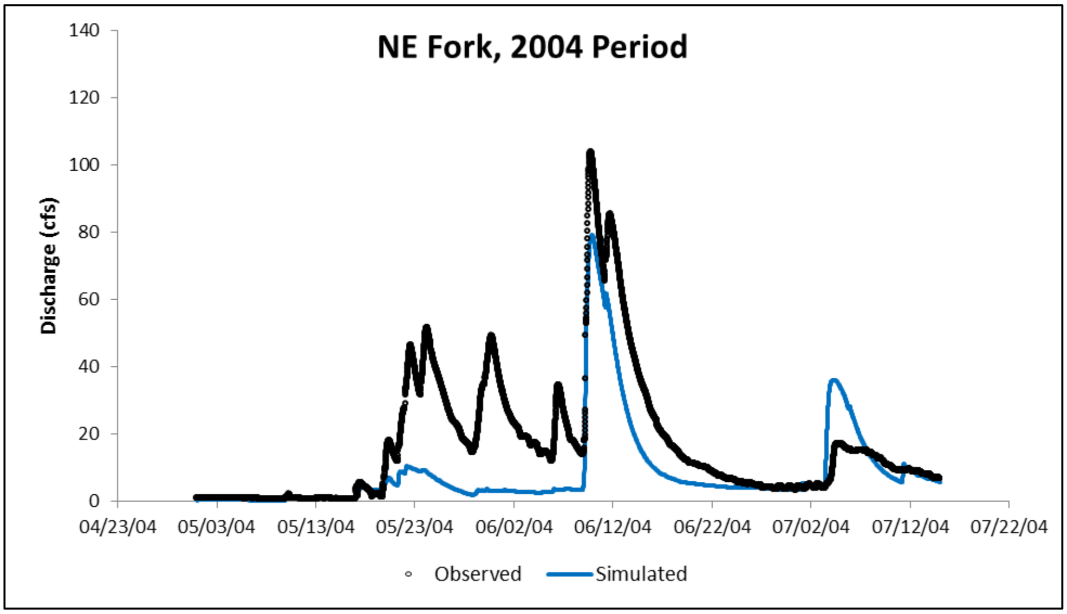


Table 6. Goodness-of-fit characteristics of NE Fork Models.

	25m NE Fork	
	Calibration	Validation
Pearson's correlation coefficient (r)	0.994	0.775
Coefficient of determination (R^2)	0.989	0.601
Index of Agreement (d)	0.981	0.806
NSE	0.905	0.433
Prediction efficiency (P_e)	0.932	0.669
MAE	2.569	9.848
MSE	33.056	217.588
RMSE	5.749	14.751
PBIAS	31	-46
VE	0.689	0.412
rsr	0.308	0.753

7.3.4 Sediment calibration

As noted above, observed sediment data were sparse. There were 11 sediment observations available from the four Seven Mile Creek gage locations over the same June 2006 period considered for the flow calibration. As a result, sediment loads were inferred based on the relationship between discharge and TSS. That relationship is illustrated in Figure 25. A similar approach was used by Barr Engineering (2009) to estimate sediment loads at a single gage. From this established relationship, sediment loads associated with the June 2006 calibration event were derived.

Figure 25. Relationship between discharge and TSS at Seven Mile Creek used to estimate the volume of sediment associated with the calibration event.

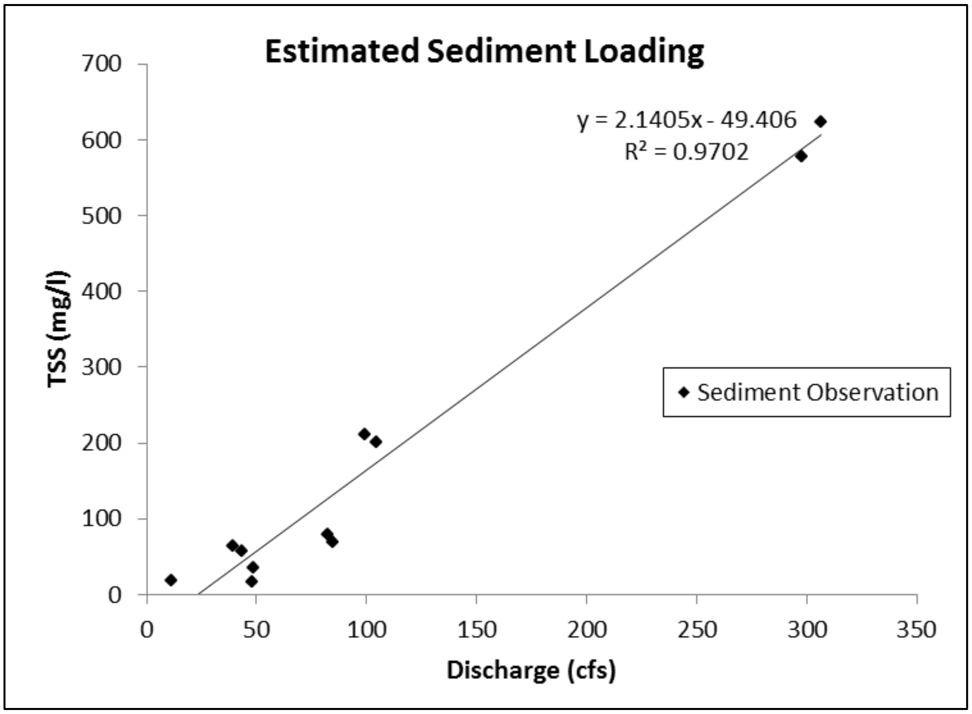
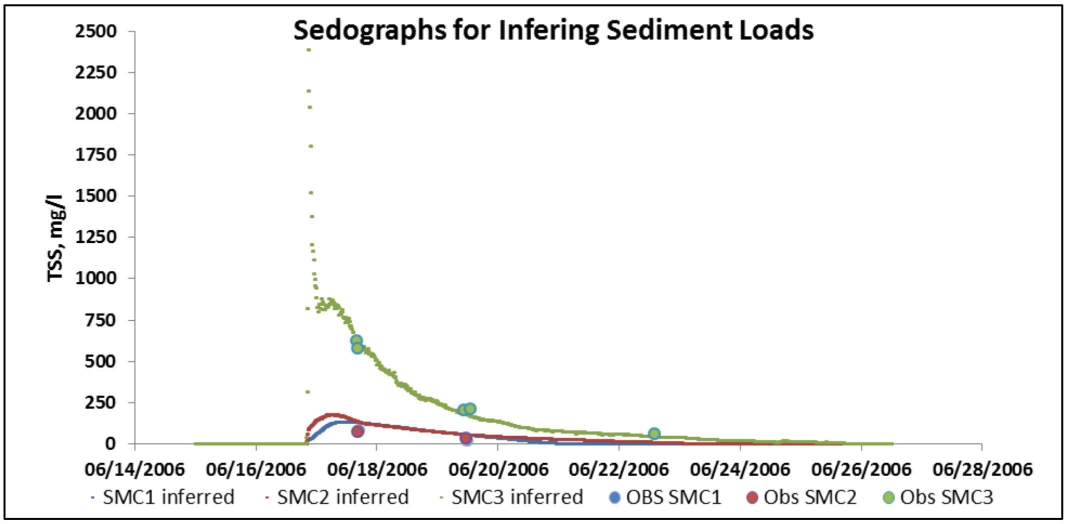


Figure 26 shows the inferred sediment loadings at three gage locations within the Seven Mile Creek Watershed. There was insufficient flow data at the fourth gage (SMC4) to infer sediment loads at that location. The empirical relationship may not hold for flows in excess of 8.5 $m^3 s^{-1}$.

Figure 26. Sedographs derived from an empirical relationship between discharge and suspended sediment used to estimate the sediment volume from the June 2006 calibration event.



Calibration was done using the SCE general purpose global optimization method (Duan et al. 1992, 1993) as described by Skahill et al. (2012a, 2012b). The soil erodibility factor/soil cropping factor/conservation factor parameter was used to adjust the sediment transport capacity to match the total volume of sediment from the model to the inferred volume derived from the observations.

For the NE Fork Sub-basin model, five erodibility values were calibrated to the total inferred sediment discharge at SMC1, 17.31 m^3. The final simulated value of sediment discharge was within 1% of this value. The final erodibility values are as listed in Table 7. Due to the distribution of land uses and soil types in the watershed, erodibility was calibrated for only selected LUST categories. In Table 7, values with an asterisk were adjusted during calibration. Values without an asterisk were assigned based on literature values and not adjusted.

Table 7. Final erodibility values for the NE Fork model (CL – clay loam; L – loam; MSL – mucky silt loam).

Land Use	Soil Type	Erodibility *K*
Corn/Soy	CL/L	0.000351*
Alfalfa	CL	0.00028
Wetlands	CL/L/MSL	0.00268*
Developed	CL/L/MSL	0.00808*
Forest	CL/L/MSL	0.000706*
Corn/Soy	MSL	0.0000318*
Alfalfa	L	0.00038
Alfalfa	MSL	0.00048

*calibrated values

For the Seven Mile Creek Watershed model, estimated total sediment values from SMC 1, 2, and 3 were used. During the automated calibration process, 80% of the weight was put on the value at SMC3, with 10% each on the values at SMC2 and SMC1. Estimated values of total sediment discharge at these three gages were 17.31, 24.25, and 1735.22 m^3, for SMC 1, 2, and 3, respectively. The final simulated values were within 10% of the estimated values. Final calibrated erodibility values for the LUST categories are shown in Table 8.

Table 8. Final calibrated erodibility values for the Seven Mile Creek model with LUST categories (CL – clay loam; L – loam; MSL – mucky silt loam).

Land Use	Soil Type	Erodibility
Corn/Soy	CL	0.0002
Corn/Soy	L	0.00219
Corn/Soy	MSL	0.000003
Alfalfa	CL/L/MSL	0.000012
Wetlands	CL	0.000161
Wetlands	L	0.00161
Wetlands	MSL	0.000478
Developed	CL/L/MSL	0.0015
Forest	CL/MSL	0.000947
Forest	L	0.0084

Calibrated erodibility tended to be related more to soil type than to land use. In general, the loam soils were more erodible than the CL/MSL soil types. This is not predicted by standard guidance for selecting erodibility, with increasing erodibility for finer soil textures. In this case, the opposite seems to be true. Testing of soil erodibility in the field indicated a similar pattern, with the loam soils being more erodible that the silts[1]. Possible explanations are that the finer soils are more cohesive and that the location of ravines and gullies (Figure 7) is largely located in the loam soil type (Figure 5). Exposed soils in ravines/gullies may be much more erodible than soils with some type of land cover. Another possible explanation is that the limited observed sediment data skewed the results. For the Seven Mile Creek model, the estimated contribution from SMC1 and SMC2 was only approximately 2% of the total load at SMC3. In calibration, this has the effect of forcing the model to produce most of the sediment in the lower portion of the watershed, where the loam soils are located.

7.3.5 Nutrients

A combination of land use, manure spreading, and feed lot location index maps were used to assign parameter values for nutrients. Permitted

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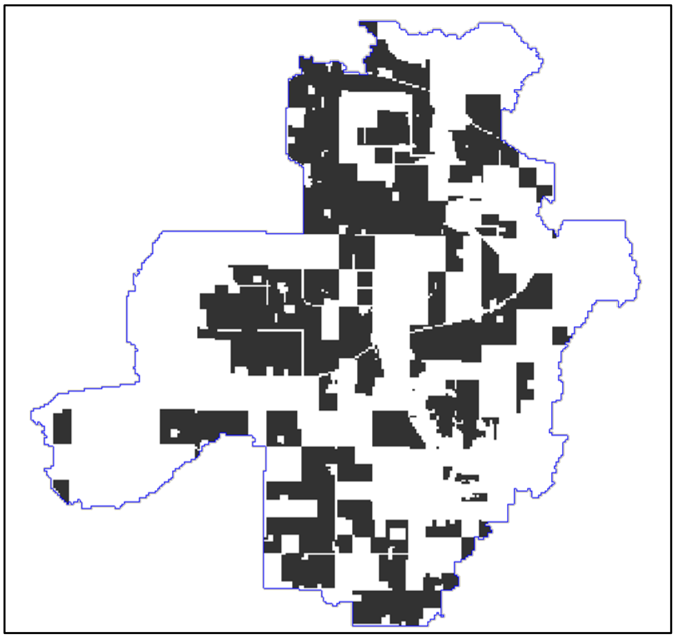
[1] Chis Lenhart. Personal communication, University of Minnesota. 2015.

manure spreading fields cover approximately 40% of the watershed. The location of tracts of land where manure spreading was permitted as of 2008 (but not necessarily utilized) is shown in Figure 27. Manure spreading locations and amount vary over time. Manure spreading is thought to increase P in the soils, with a corresponding reduction in the partition coefficient[1]. From prior experience, feed lots are a potential hotspot for high soil concentrations of both N and P. Data to populate the nutrient parameters were particularly scarce. No soil concentration or partition coefficient data were available. Initial soil concentration values were assigned based on measured values from a previous study in a similar setting in Wisconsin (Johnson et al. 2009; Pradhan et al. 2014). These values may not be representative of the actual values at Seven Mile Creek. The soil P concentration was increased, amount depending on land use, for areas with manure spreading. Groundwater concentrations were assigned based on average observed tile drain values at Red Top Farms and low stream flow values at SMC1 and SMC3. These values were relatively consistent over time, indicating that the assumption in GSSHA of constant groundwater concentrations is probably reasonable at Seven Mile Creek.

Figure 27. Location of permitted manure spreading fields, shown in black.



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[1] Chuck Reagan. Personal communication. Minnesota Pollution Control Agency. 2015.

The calibration period for nutrients is the period June 15-30, 2006. Only a few observed data points were available, with none corresponded to high flows. Soil uptake and partition coefficients were adjusted to better fit the available points. The model and parameter set do not necessarily represent *the* conditions at Seven Mile Creek but more represent a plausible set of conditions for the watershed based on extremely limited data. Final water/soil partition coefficients were 0.001 and 300.00 for N and P, respectively. Spatially distributed parameter values are shown in Table 9. In the NE Fork Sub-basin model, K_N is 10^{-3} d^{-1} and $Uptake_P$ is 10^{-4}.

Final calibration model results are shown in Figure 28 for the NE Fork Sub-basin model, and Figure 29 and Figure 30 for the Seven Mile Creek model. As is seen in the figures, the observed data are sparse. Results for N look better than results for P, which are probably over estimated. At SMC1 in the Seven Mile Creek Watershed model, the concentrations tend to drift higher as the streams start to go dry. This is an artifact of the numerical computations. As there is very little flow at this point in the simulation, there is very little effect on mass calculations.

Table 9. Nutrient parameter values, K – soil/water partition coefficient.

Land Use	Manure Spreading	Soil N mg kg^{-1}	Soil P mg kg^{-1}	GW N mg L^{-1}	GW P mg L^{-1}	Soil K_N	Soil K_P	$Uptake_N$ d^{-1}	$Uptake_P$ d^{-1}
Corn	No	2200	629	13	0.07	10^{-2}	17	10^{-5}	10^{-7}
Soy	no	2200	629	13	0.07	10^{-2}	17	10^{-5}	10^{-7}
Alfalfa	no	2750	761	13	0.07	10^{-2}	26	10^{-5}	10^{-7}
Open water	no	0	0	13	0.07	10^{-2}	30	10^{-5}	10^{-7}
Developed	no	1000	500	13	0.07	10^{-2}	30	10^{-5}	10^{-7}
Forest	no	4500	710	13	0.07	10^{-2}	20	10^{-5}	10^{-7}
Grassland	no	3200	611	13	0.07	10^{-2}	37	10^{-5}	10^{-7}
Wetland	no	3200	611	13	0.07	10^{-2}	30	10^{-5}	10^{-7}
Feedlot		16000	3215	13	0.07	10^{-2}	10	10^{-5}	10^{-7}
Corn	yes	2200	1530	13	0.07	10^{-2}	13	10^{-5}	10^{-7}
Soy	yes	2200	1530	13	0.07	10^{-2}	13	10^{-5}	10^{-7}
Alfalfa	yes	2750	1662	13	0.07	10^{-2}	18	10^{-5}	10^{-7}
Open water	yes	0	901	13	0.07	10^{-2}	20	10^{-5}	10^{-7}
Developed	yes	1000	1401	13	0.07	10^{-2}	20	10^{-5}	10^{-7}
Forest	yes	4500	1611	13	0.07	10^{-2}	15	10^{-5}	10^{-7}
Grassland	yes	3200	901	13	0.07	10^{-2}	23	10^{-5}	10^{-7}
Wetland	yes	3200	901	13	0.07	10^{-2}	20	10^{-5}	10^{-7}

Figure 28. Nutrient concentrations at the outlet of the NE Fork for June 2006 event.

NE Fork Model – Nutrient Concentations

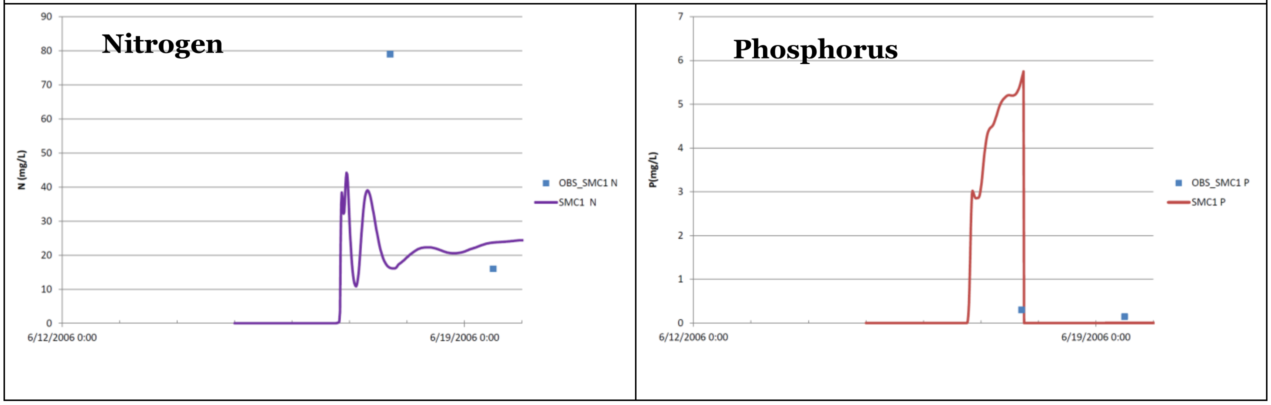


Figure 29. Simulated N concentrations at the outlet of Seven Mile Creek for the June 2006 event.

Seven Mile Creek Model – Nitrogen Concentrations

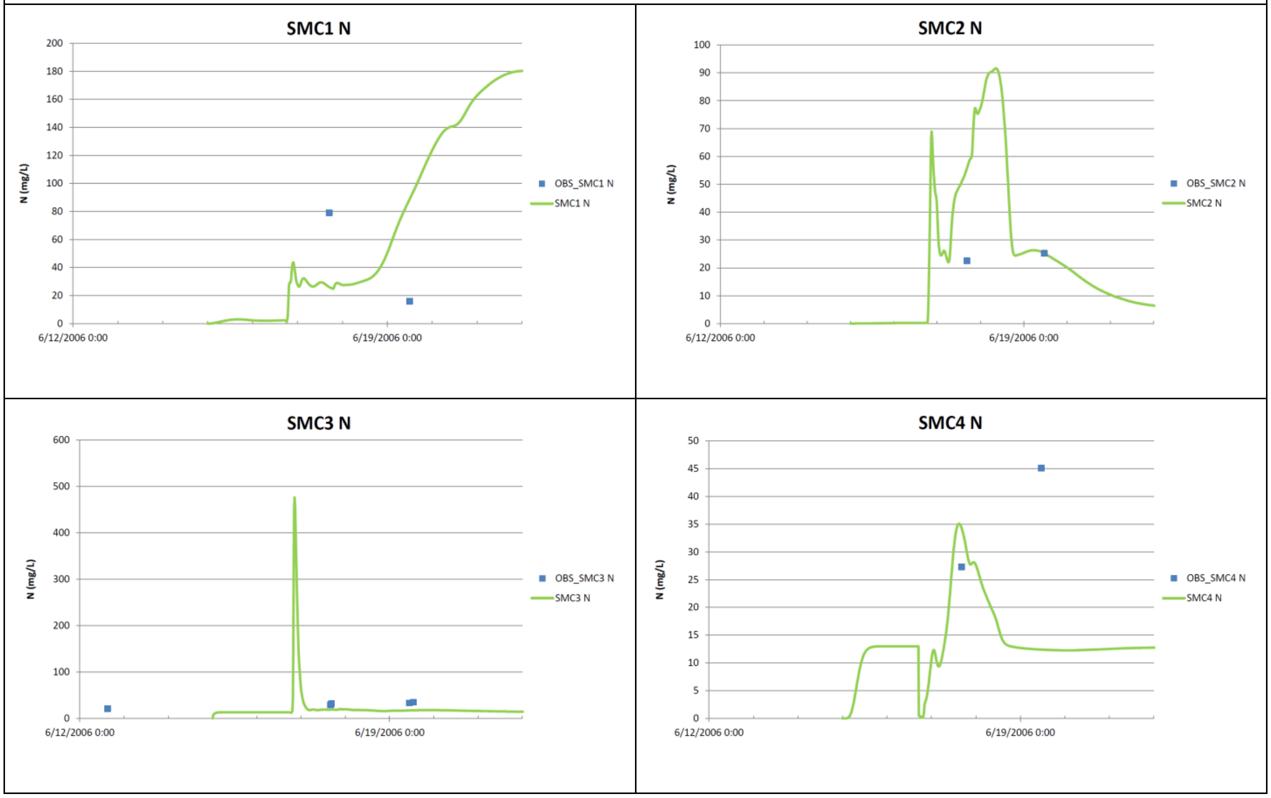
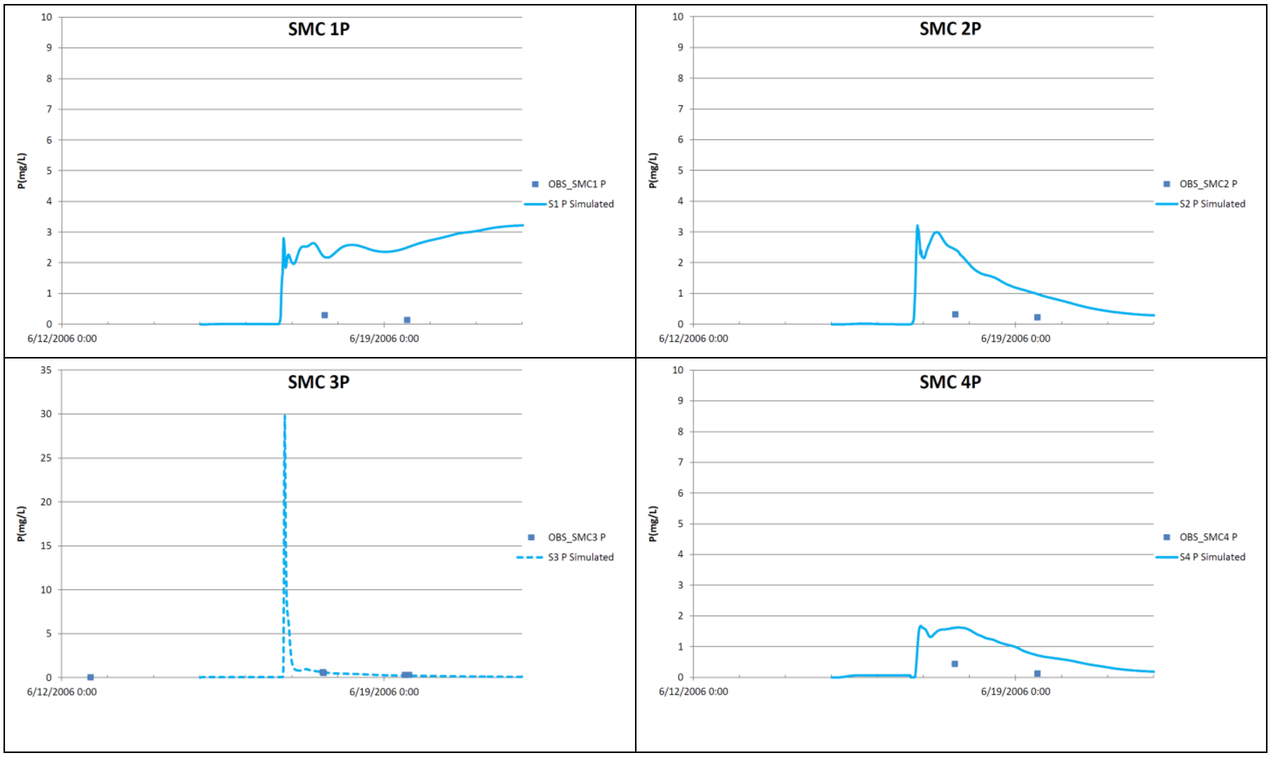


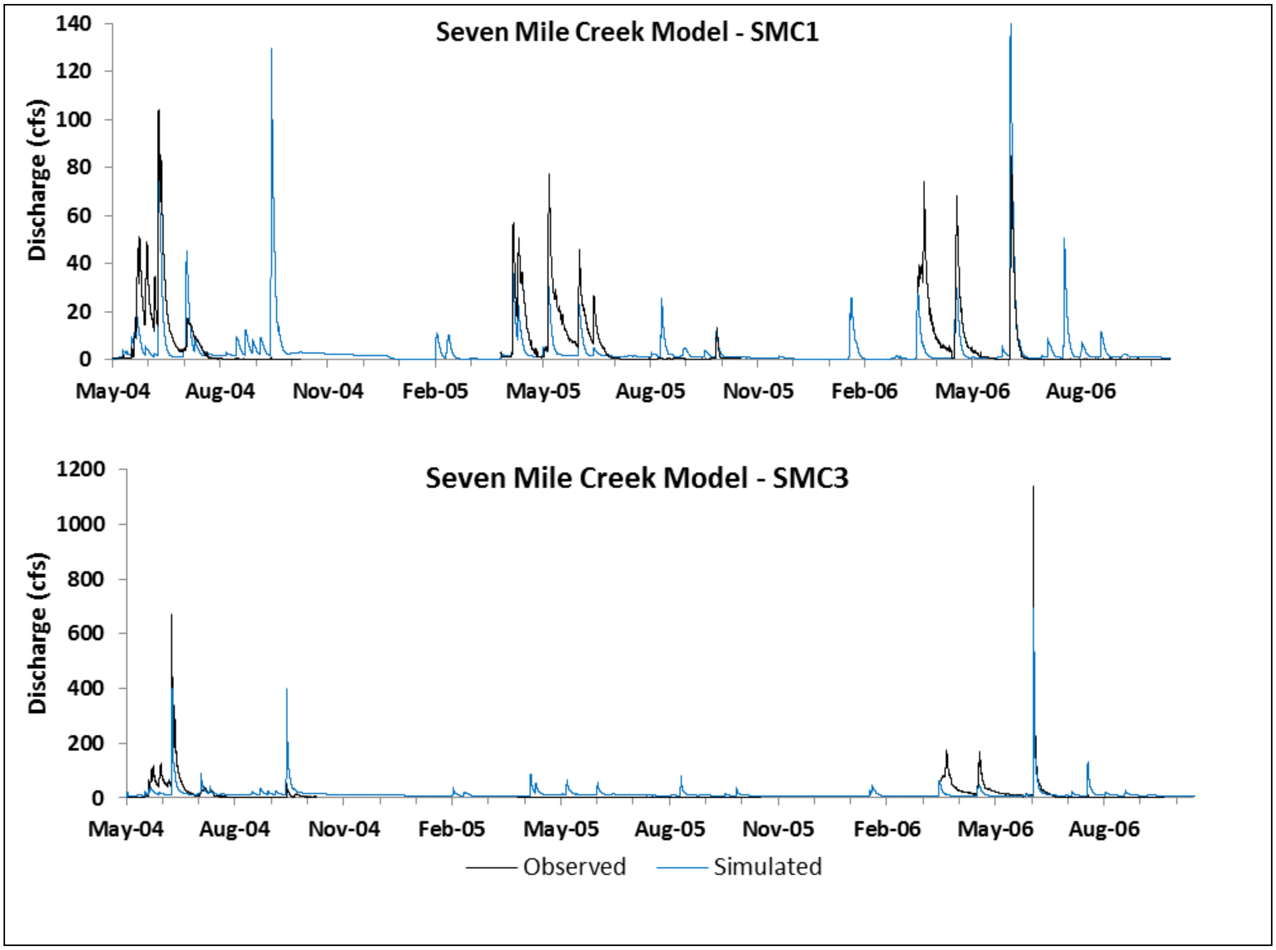
Figure 30. Simulated P concentrations at the outlet of Seven Mile Creek for the June 2006 event.



7.4 Long-term simulations

The calibrated/verified Seven Mile Creek Watershed model and NE Fork Sub-basin model were used to simulate flow over the better part of a 3-year period (2004-2006). The models simulated frozen ground and snow accumulation throughout the winter periods to characterize existing conditions in the basin. The results of these simulations are shown in Figure 31.

Figure 31. Long-term simulation results for the Seven Mile Creek Watershed compared with observed discharges at SMC1 and SMC3.



As is seen in the figure, the models compare well for the calibration and validation periods in 2004 and 2006. Comparisons at other times vary. Note that the quality of the observed precipitation and flow data varies considerably during the simulation; 2005 is considered a poor-quality data year. Also note that the model parameter set was developed using hourly distributed radar rainfall. These data were only available for select summer events as described above. At other times, the rainfall is 15 min point data a Red Top Farms, or combined with observed values from SMC1, SMC2, and SMC3. During summer periods especially, this coverage may not accurately reflect the rainfall distribution in the watershed. As noted, the point data are also variable in quality, with 2005 being a poor coverage year. Model results will be superior if radar data are used for the period of interest. Still, the precipitation record used in this period can be considered *typical* if not an accurate reproduction of actual events, and the simulated flow and sediment results are accurate for the precipitation record provided, as demonstrated during the calibration/validation period. These model results of this period of record are useful for comparison of hydrology and sediment from different future land-use scenarios.

The long-term simulations took several days to complete. Runtimes for the Seven Mile Creek Watershed model at 50 m resolution took between 91 to 131 hours to finish with multiple runs going simultaneously on an Intel® Xeon® CPU X5650 at 2.67 GHz with 24.0 GB random access memory (RAM). The higher resolution NE Fork Sub-basin Models took considerably longer with runtimes from 7 to 19 days on an Intel Xeon CPU E5-2630 at 2.30 GHz with 16.0 GB RAM.

7.5 Alternate land-use scenarios

The physically based, spatially distributed nature of the GSSHA model makes it ideal for evaluating targeted landscape modifications. The calibrated Seven Mile Creek Watershed model was used to simulate hydrology as well as nutrient and sediment displacement throughout the watershed, for the present-day land use to identify relative differences among four different future scenarios. The various scenarios were defined by the IST using the LANDFIRE program to generate the hypothetical scenarios. The modeling sub-team made the decisions about how the scenarios are configured and how they should be represented in the model. The four future scenarios are the following:

1. Pre-development (PreDev) – scenario involving native vegetation believed to be representative the condition of the land prior to human settlement in the area.
2. Agricultural (AG) – scenario in which commodity prices dictate agricultural intensification in order to maximize the production on the land.
3. Water Quality (WQ) – scenario in which the land is managed in order to protect the water resources within the watershed.
4. Biodiversity (BD) – scenario in which the land is managed to maximize wildlife habit.

7.6 Simulation specifics

7.6.1 Tile drains

Tile drains are closely associated with the agricultural areas in the watershed. In the base model simulations, the existing tile drain system is included in all the simulations. The same tile drain network is used for all future land-use scenarios. The tile drain network is not modified for changes in land use. This has the implied assumptions that restoration efforts will remove the tile drains (possibly) and that additional agricultural areas will not include tile drains (unlikely but possibly negligible considering the minimum amount of farmable area not currently in production). For the Pre-Dev, BD, and WQ land-use scenarios, the tile drain system is turned off; no tile flow is calculated for these scenarios. For the BD and WQ cases simulating the scenarios with tile flow on had the effect of cycling the increased infiltrated water into and out of the tile drains as the infiltrated water was collected in the tiles and then resurfaced, only to be infiltrated again and collected in other tiles. This result is non-intuitive, and the tiles were subsequently eliminated from these scenarios.

7.6.2 Parameter values

To a great degree, the calibrated/verified parameter sets were not modified to simulate the future scenarios. One exception exists in that the parameter value of the soil vertical hydraulic conductivity and overland roughness for the *grass* land use. In the base model, the land-use grass largely represents alfalfa and hay fields, agricultural land uses where the soil matrix is largely destroyed through tillage/compaction and the vertical soil hydraulic conductivity is low, representative of an agricultural land use. For future land uses with significant ecologic restoration, water quality and biodiversity, and for the pre-development scenario, the term *grass* is assumed to correspond to some type of native prairie grass. In the restoration case, it is reasonable to assume that over time the soil matrix will be partially re-established, at least in the top layer. For this reason, the soil vertical hydraulic conductivity for the top layer of soil for grass in these future scenarios is increased. In the PreDev scenario, it is fair to assume that the entire soil column, A, B, and C, horizons will be more representative of natural conditions in the watershed. Correspondingly, in the PreDev case, the soil vertical hydraulic conductivity of grass is increased in all three layers. Currently, there is no native prairie in the watershed, and thus no such land use in the model. In this watershed, the only land use with a presumed intact soil matrix is forest. Typically, a forest is expected to have a higher soil vertical hydraulic conductivity than a grassland, due to the decomposition of leaf litter and additional bioturbation. For that reason, the soil vertical hydraulic conductivity values for prairie grass were raised closer to that of the forest values in the corresponding soil types. Values of soil vertical hydraulic conductivity, K cm hr^{-1}, for forest and grass in the relevant soil types used in the scenarios are shown in Table 10.

Table 10. Soil vertical hydraulic conductivity values, K, cm hr^{-1} used in the scenarios.

Scenario	Base	All	WQ/BD	Pre-Dev	Base	ALL	WQ/BD	Pre-Dev
Land Use	Grass	Forest	Grass	Grass	Grass	Forest	Grass	Grass
Soil	Clay loam	Clay loam	Clay loam	Clay loam	Loam	Loam	Loam	Loam
Layer 1 K	0.0077	0.1500	0.1100	0.1100	0.1152	0.6060	0.3500	0.3500
Layer 2 K	0.1090	0.5730	0.1090	0.5730	0.1445	0.7600	0.1445	0.7600
Layer 3 K	0.1446	0.7600	0.1446	0.7600	0.1445	0.7600	0.1445	0.7600

Similarly, the overland roughness values developed for alfalfa were thought to not be representative of the conditions in a native prairie environment. Whereas alfalfa fields may look lush from the top, at the ground level there is little actual foliage. Overland roughness values are similar to other crops. A native prairie is very dense, with much higher values of overland roughness expected. In terms of roughness, the prairie is thought to most closely resemble the herbaceous wetlands in the present-day model. As shown in Table 5, the overland roughness in the herbaceous wetland is 0.562. For comparison, the value for alfalfa is 0.24 and forest is 0.643. For the restoration scenarios, the land-use grass is given an overland roughness value of 0.562.

7.6.3 Nutrients

For nutrients, land use alone was used to populate the parameter values, and the appropriate values from Table 9 were applied. Because the application of manure is unknown in the future, spreading was assumed to occur in fields described as corn and not to occur in fields described as soy. This is a somewhat arbitrary way of trying to account for the general distribution of manure spreading in the different scenarios. The possible location of feedlots is unknown. Feedlots were not considered in the scenarios. Also, the prescribed values for groundwater concentration do not vary amongst the scenarios. The nutrient concentration values prescribed represent the as-is (Base) condition and may be representative of the AG scenario, but likely are high for the WQ and BD scenarios and possibly quite high for the PreDev scenario. Additionally, soil nutrient concentrations were not changed for the scenarios. It is possible that these values are not representative of the future scenario values.

7.7 Results

7.7.1 Discharge

Simulations were run for each alternate land-use scenario over the same period of record (May 1, 2004, to January 7, 2007) that was considered in the long-term simulation of present conditions described above. Hydrographs for each scenario are provided in Figure 32, Figure 33, and Figure 34 for each year of the simulation for the Seven Mile Creek Watershed model. As seen in the figures, the hydrographs from the Base and AG models tend to be spikey with high peaks, fast recessions and little base flow. This is a result of agricultural drainage and loss of the soil matrix. As more natural areas are included, the BD and WQ scenarios, hydrograph peaks decrease, recessions extend, and base flow increases. For the PreDev case, the hydrographs are markedly different with low peaks, with extended recessions and significant base flow. In the PreDev case, surface flows from large events like those that occur in late 2004 are greatly reduced (Figure 32). The BD and WQ cause a similar, though reduced, effect. This water is being infiltrated and converted to groundwater. While there is some groundwater discharge during and immediately after the event (Figure 32), much of the water is stored in the ground. During subsequent springs (Figures 33 and 34), some of this water may be discharged, as groundwater discharge to the stream and or seeps, resulting in the increased discharge seen in the early melt season. A similar but lesser effect is seen for the BD and WQ scenarios (Figures 33 and 34). The discharge shown in Figures 33 and 34 during the early spring, February/March, is not precipitation runoff; it is a combination of snow melt and groundwater discharge. In addition to the snow melt and groundwater discharge to the stream, the model indicates seep water bound up in the snow pack. As the snow pack begins to melt, the seep water is released along with the snow melt. Precipitation is still falling as snow, but the daytime temperatures are getting high enough to melt the snow, releasing snow melt and any water bound up in the snow pack. A high water table in the restoration alternatives adds substantial groundwater discharge to this flow. The Base and AG scenarios actually result in lower early spring runoff, as the groundwater table has been effectively lowered prior to the beginning of winter precipitation.

Results from the NE Fork Sub-basin model simulations are shown in Figure 35, Figure 36, and Figure 37 for the 3 years, respectively. The NE Fork Sub-basin model shows similar result except that there is very little runoff from the PreDev model. In this case, the varying result is a function of varying contributions from the different sources of flow into the stream. In the NE Fork Sub-basin model, base flow in the stream is negligible, both from the observed data and from the model calibration and validation results. All flow into the stream at SMC1 is a combination of overland flow and tile discharge. For the PreDev model, there are no tiles, so all of the additional groundwater recharge is adding to the water table, but that water is not being discharged in the ditches above SMC1. Instead, it is discharged into the stream between SMC1 and SMC3, resulting in the increased base flow shown in the Seven Mile Creek Watershed model in Figure 32 through Figure 34. The exception to this is the early spring flows, February/March, where the restoration scenarios result in higher flows. The reasoning is the same as discussed above. In this case, the seep water bound up in the snow pack is the source of increased flow in the restoration alternatives, PreDev, BD, WQ, over the Base and Ag scenarios. Once the snow melts and the water table drops, approximately April 1 for 2005 and 2006, the pattern changes.

Figure 32. Simulated discharge from each of the alternative land-use scenarios.

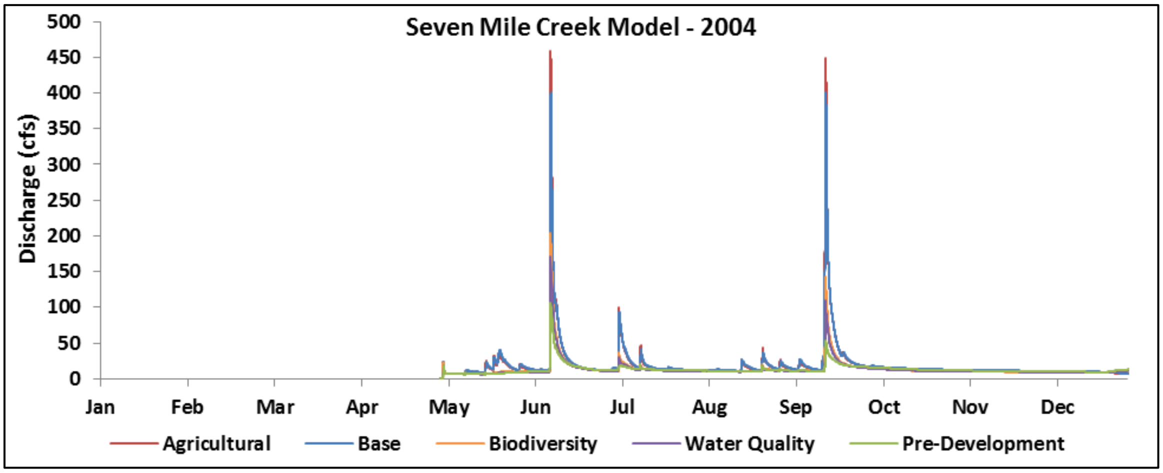


Figure 33. Simulated discharge from each of the alternative land-use scenarios.

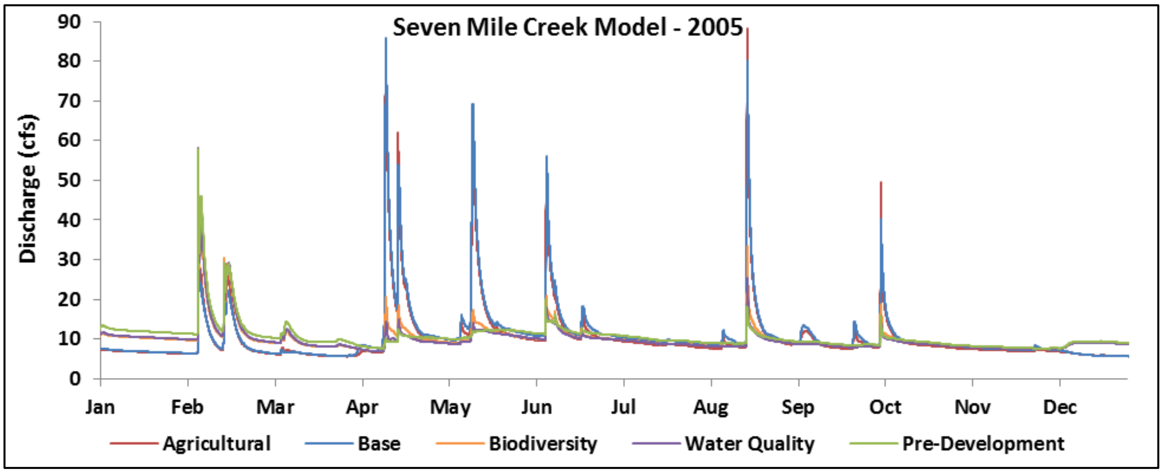


Figure 34. Simulated discharge from each of the alternative land-use scenarios.

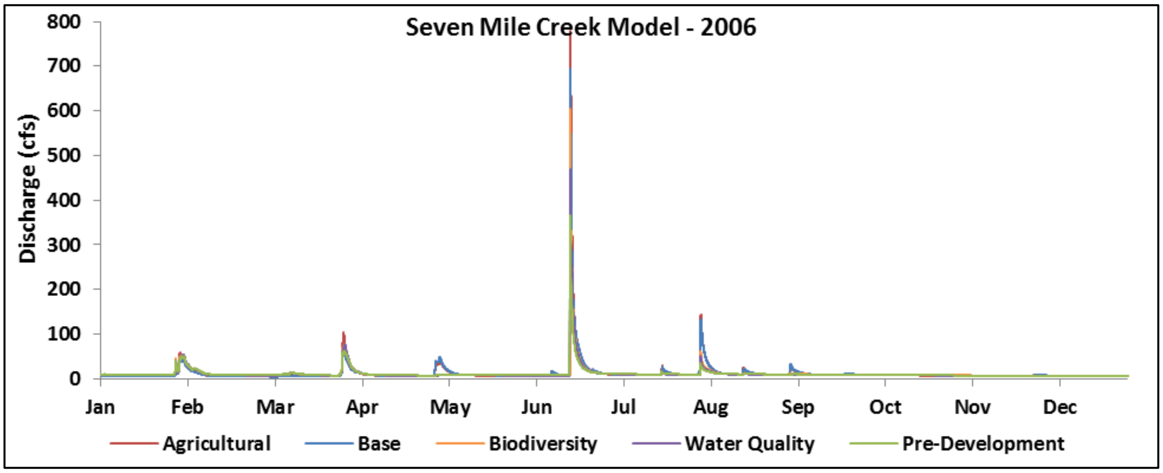


Figure 35. Simulated discharge from each alternative land-use scenarios in NE Fork.

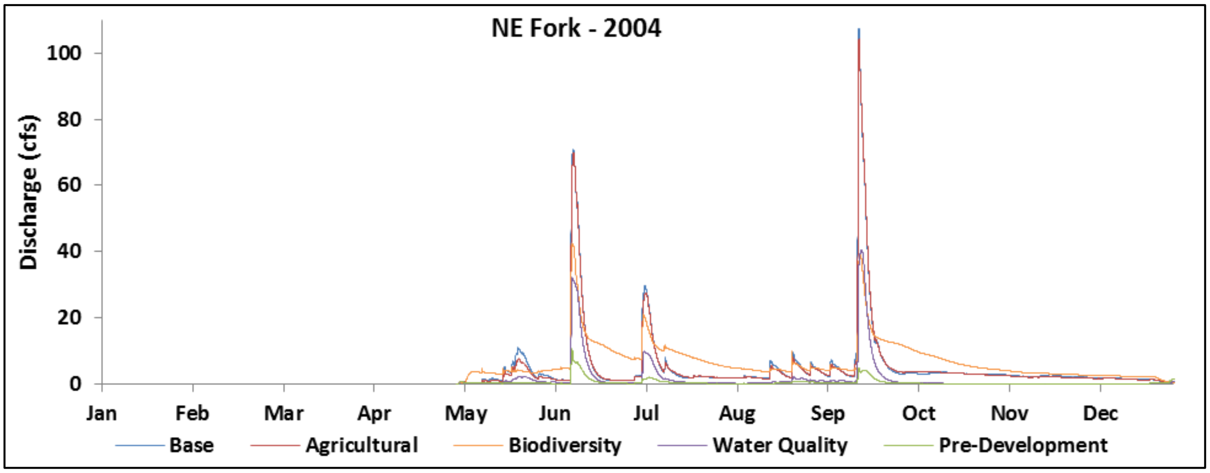


Figure 36. Simulated discharge from each alternative land-use scenarios in NE Fork.

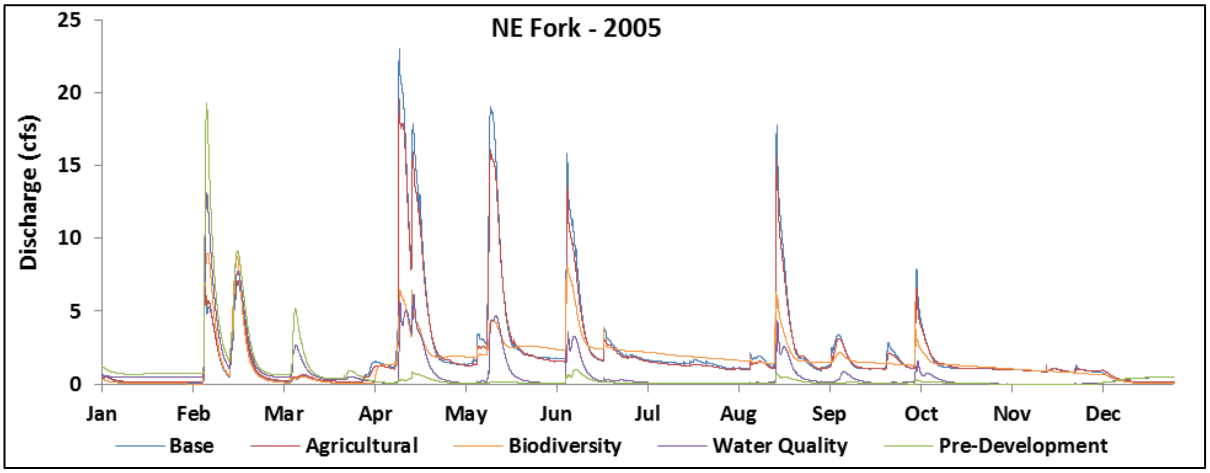
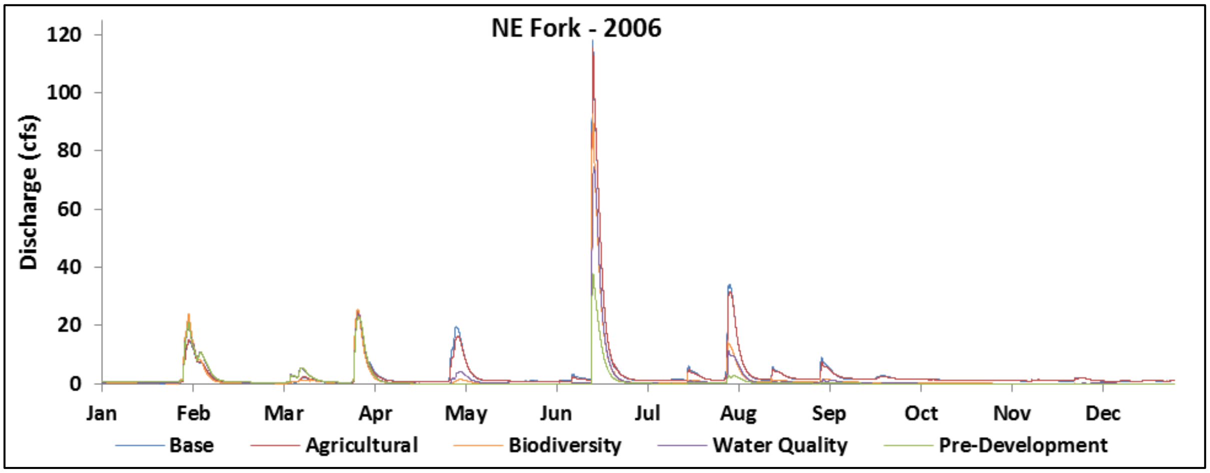


Figure 37. Simulated discharge from each alternative land-use scenarios in NE Fork.



7.7.2 Water balance

Water balances from the alternate scenarios are compared with the Base scenario to identify the relative hydrologic response associated with the different scenarios; results for the Seven Mile Creek Watershed model are summarized in Table 11 and Figure 38. For the Base scenario, runoff is approximately 20% of total precipitation; evaporation is approximately 82% of total precipitation, with approximately 12% of precipitation going to groundwater recharge. For the PreDev and restoration scenarios, BD and WQ, discharge is slightly reduced, on the order of 10%. Total infiltration increases to almost 100% for the PreDev scenario. ET is reduced, and baseflow increases to approximately 22% of the total precipitation. In general, results from the AG case are very similar to the Base case, with slightly less infiltration, slightly reduced flow (due to reduction in baseflow), and increased ET, when compared to the Base case. As noted previously, the AG and Base models are very similar.

Results for the NE Fork Sub-basin model are summarized in Table 12. In general, the results are consistent with the Seven Mile Creek Watershed model results, shown in Table 11, with the PreDev, BD, and WQ scenarios resulting in increased infiltration and groundwater recharge, and reduced ET, while the AG scenario has the opposite effect. The results are more significant for the NE Fork model. Because of the lack of baseflow in the NE Fork model, restoration cases convert in this watershed result in substantial reductions in streamflow due to the increased infiltration.

At the Seven Mile Creek Watershed outlet, a significant source of water is the baseflow, the groundwater recharging the stream. Contributions to Seven Mile Creek stream flow at SMC3 are 52% groundwater, 33% surface water, and 15% tile flow. In the Seven Mile Creek model, the baseflow is 81% of total discharge in the PreDev scenario, with only 19% surface flow. The BD and WQ scenarios also increase base flow, to approximately 75% of total discharge. The AG scenario results in only 36% baseflow, with tile flow 18% and surface flow 46%, making up the difference.

In the NE Fork Sub-basin model, baseflow is not a source of streamflow, but seepage can be, depending on the scenario. For the Base case, stream flow contributions at SMC1 are 43% surface water and 57% tile flow. For the PreDev scenario, the flow is 100% surface water flow. For the AG case, tile flow is increased to 80% of the total discharge at SMC1. Surface water flows to the stream consist of a combination of direct precipitation runoff, seepage, and tiles discharging on the overland. The actual contribution of streamflow from any source is complicated by runoff, run-on, re-infiltration, and re-emergence from the groundwater. As seepage can be high in the early spring under the restoration scenarios, it may contribute significantly to streamflow during these periods. With the Base and AG models, seepage is negated by the tile drains.

Figure 38. Water balance as a percentage of total precipitation within the Seven Mile Creek Watershed for present conditions (Base) compared with the results from the four alternate land-use scenarios. (Note: Totals were not available for the AG scenario.)

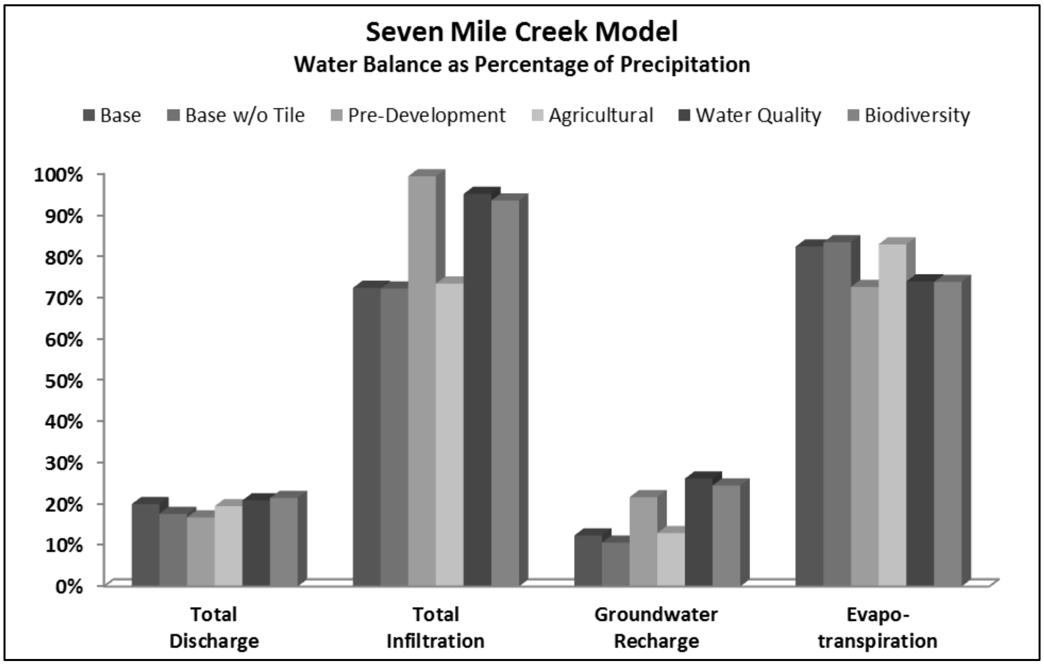


Table 11. Summary of the water balance in 10^6 m^3 for the various long-term Seven Mile Creek simulations.

Scenario	Total Precipitation	Total Discharge	Total Infiltration	Groundwater Recharge	ET
Base	161	32	117	20	133
Base-no tile	161	28	117	17	135
PreDev	161	27	160	35	117
AG	161	31	119	21	134
WQ	161	26	147	29	126
BD	161	27	144	29	126

Table 12. Summary of the water balance in 10^6 m^3 for the NE Fork simulations.

Scenario	Total Precipitation	Total Discharge	Total Infiltration	Groundwater Recharge	Evapo-transpiration
Base	65	9.5	45	7.5	53
Base-no tile	65	5.0	45	2.8	56
PreDev	65	1.7	66	11.0	49
AG	65	9.8	49	9.8	55
WQ	65	3.1	52	8.3	50
BD	65	2.2	60	9.4	51

These results are instructive and indicate the value of the modeling approach for better understanding the system dynamics. The results help explain how the basin functions and the effects of certain practices on the watershed. The discharge and water balance indicate that for the entire Seven Mile Creek Basin, base flow is a significant part of the water budget, but not so upstream of SMC1. In terms of process, they are quite different basins, and the results from one are not translatable to the other. The contribution of tile flow is more significant in the sub-basin than in the overall basin. Without the tile contribution, the streams would likely be dry much of the time, flowing only briefly after rainfall events large enough to produce overland flow, and during the spring snow melt season. It is unlikely that this result could be discerned without separating the processes of surface water flow, base flow, and tile flow. Surface water runoff is important at both levels. Agricultural practices decrease infiltration and increase surface flow.

7.7.3 Sediment

Table 13 provides the annual sediment yields associated with each of the scenarios. Yearly sediment yield varied considerably over the 3 years, with 2006 delivering 72% of the total yield for the Seven Mile Creek Basin and 48% for the NE Fork model, for the Base case, with much of this sediment being delivered during the June 2006 calibration event, a particularly large event during the observed period of record. This is typical of sediment delivery, where much of the total sediment load is produced in a few large events. The *average* annual sediment loading rate at SMC3 is 247 kg hectare^{-1} yr^{-1}. The average annual sediment loading rate at SMC1 is 13.6 kg hectare^{-1} yr^{-1}, indicating that most of the sediment load originates between SMC1 and SMC3, consistent with the observed sediment measurements and the model calibration.

An advantage of physically based, spatially distributed approach is that it can be used to identify sediment sources and sinks throughout the watershed. Figure 39 shows the locations of sediment erosion and deposition throughout the Seven Mile Creek Watershed. As can be seen in Figure 39, the ravines near the watershed outlet, as well as the locations where tiles discharge on the overland flow plane, are erosion hotspots, shown in red in the figure. Figure 39 clearly shows erosion occurring in the measured ravines, as noted in Figure 7. Figure 40 shows an expanded view of the erosion patterns around tile discharge locations. The concentrated flow from the tile drains is a major source of erosion in the model. Other notable features in Figure 40 are the lack of erosion that occurs in the wetland areas (Figure 3).

Figure 39. Output from the GSSHA model showing locations of net sediment erosion/deposition (meter) throughout the Seven Mile Creek Watershed for the present conditions (Base scenario).

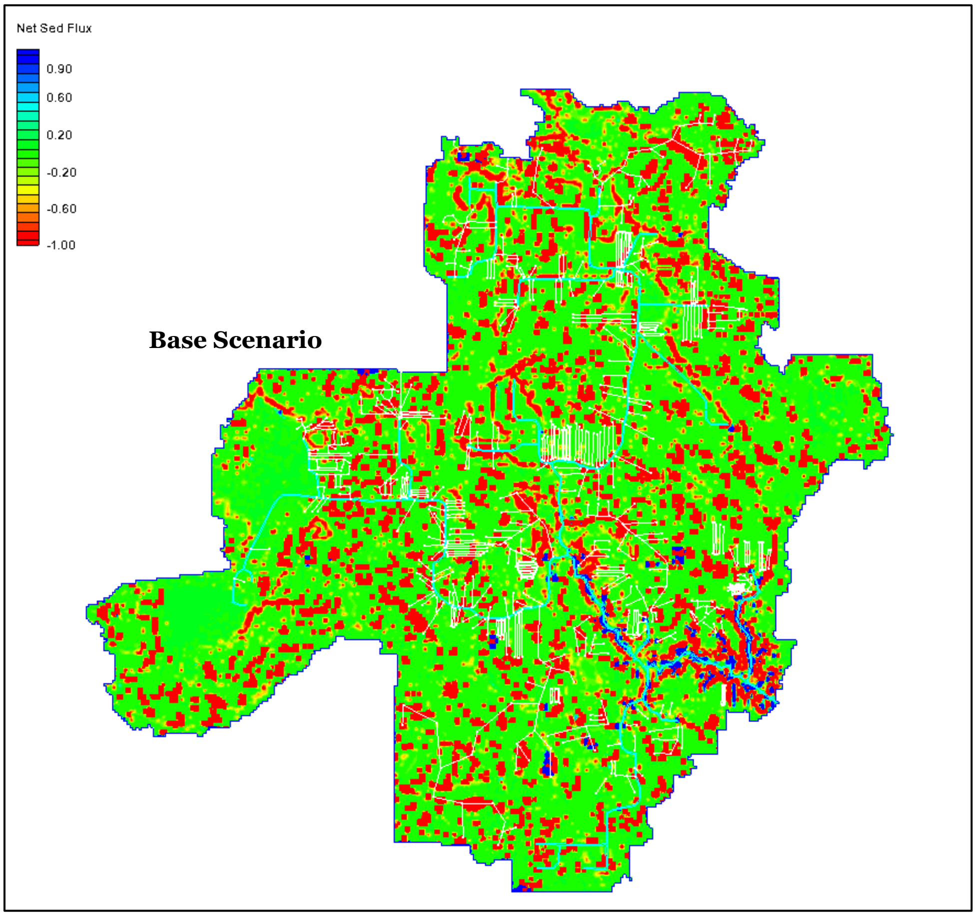
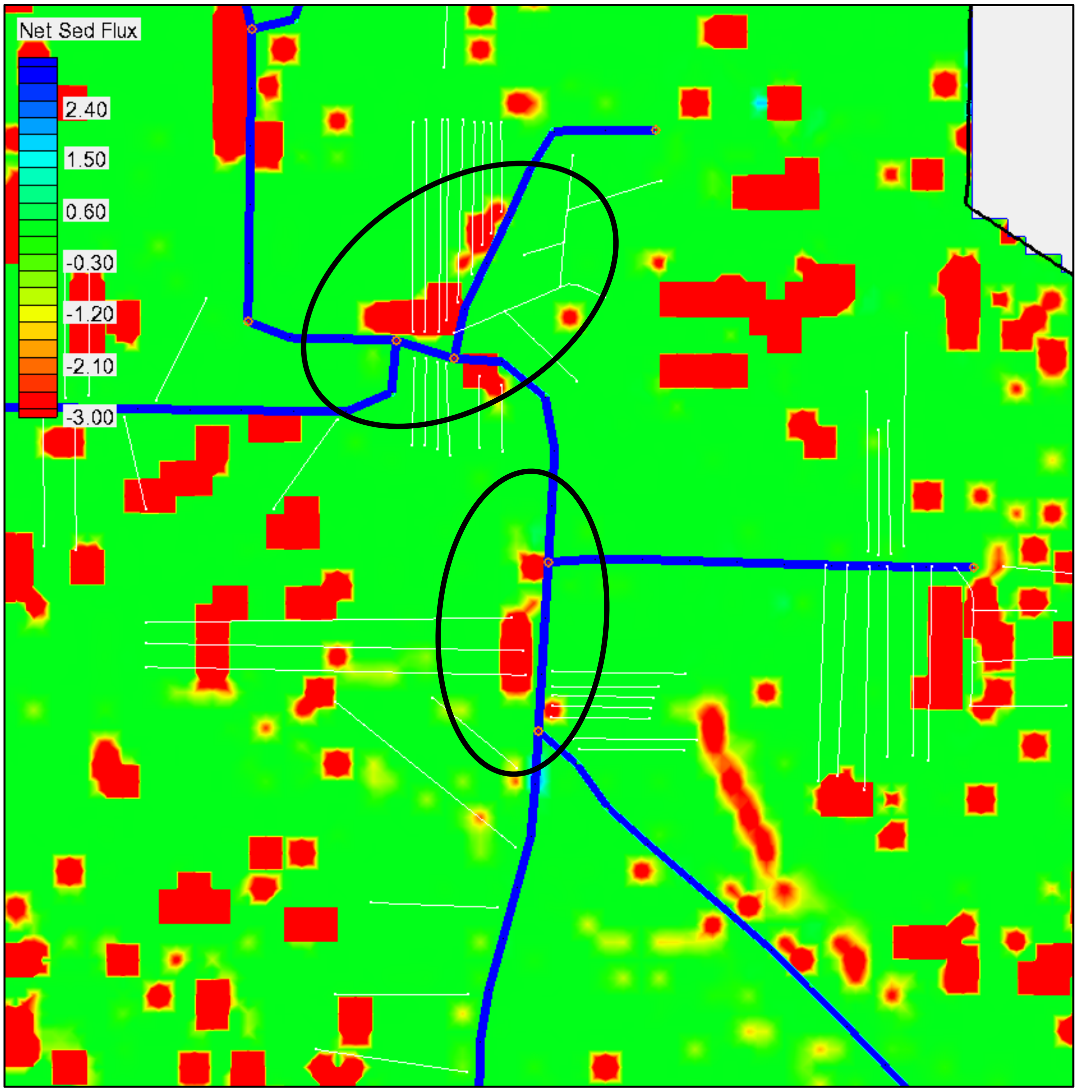


Figure 40. Erosion can be observed from the simulations locally concentrated around tile outlets at select locations.



To further assess the effects of the tile drains on erosion, the Base scenario was run without tile drains to quantify their contribution to sediment loads. The results are consistent with the source of flow in the models. For the Seven Mile Creek model, the effect was negligible; for the NE Fork Subwatershed, the sediment loading rate was reduced by a third (Table 13).

Table 13. Simulated annual sediment loading rate (TSS) within the Seven Mile Creek Watershed and NE Fork Sub-basin Models for present conditions (Base) compared with the results from the four alternate land-use scenarios.

TSS Loading Rate (Kg hectare^{-1} yr^{-1})		
Scenario	Seven Mile Creek	NE Fork Sub-watershed
Base	247	13.6
Base w/o Tile	247	9.0
AG	332	13.3
PreDev	166	4.1
BD	289	10.0
WQ	224	17.6

As described in the Scenario Development Section 7.5, the four scenarios were simulated with using the calibrated erodibility parameter values for each of the LUST categories in the models (Table 7 and Table 8). Tile drains were simulated in the Base and Ag scenarios but not in the restoration scenarios, PreDev, BD, and WQ. Results, in terms of sediment loading rate kilogram hectare^{-1} yr^{-1} are shown in Table 13. For the Seven Mile Creek Watershed model, in comparison to the Base, the AG scenario produced significant increases in sediment loads in the Seven Mile Creek Watershed but not in the NE Fork Watershed. The increase in loading rate is 34%. In the NE Fork model, there is no significant difference between the Base and AG scenarios. For the PreDev case, there is a decrease in loading rate by approximately a third for the Seven Mile Creek Watershed model and a two-thirds decrease for the NE Fork Sub-watershed model. In the PreDev, surface runoff is reduced, and tile flow is eliminated. This has the effect of reducing erosion in both models with more effect seen at the SMC1 gage, where tile flow is a greater percentage of the total flow. The WQ scenario results in slightly reduced sediment load at the Seven Mile Creek model and an increase in sediment load in the NE Fork model. The BD scenario had an opposite effect. Both of these alternatives result in increased infiltration and reduced runoff, so it would be expected that both would reduce sediment load at both scales. The problem likely lies in the sediment erosion parameters for the “forest/loam” LUST.

Two potential issues are the erosion values for grass and forest loam. The calibrated erosion value for grass corresponds to alfalfa fields and is probably significantly higher than grass in the restoration scenarios that represent some form of native prairie vegetation. Table 14 shows the distribution of land uses in the scenarios. As indicated in the table, the amount of grass is much higher in the restoration and PreDev scenarios. Due to the high percentage of grass in these scenarios, the use of the erodibility values derived for alfalfa may result in a significant overestimation of erosion in these scenarios. The suitability of these assumptions should be reassessed. The other potential issue is the erosion value for the forest/loam LUST category. As the forest/loam LUST group occurs mainly in conjunction with the ravines, the sediment erosion parameter derived from the calibration may be higher than it would be without the ravines. This may result in an overestimation of sediment erosion from other forest/loam areas in the restoration scenarios. As shown in Table 14, in the present-day (Base) conditions, forest is only 4% of the land use, much of that occurring along the streams in the loamy soils, which also happens to be areas of the highest erosion.

Table 14. Distribution of land uses in the model scenarios (%).

Scenario	Corn/Soy	Developed	Alfalfa/Grass	Wetlands/Water	Forest
Base	79	5	1	11	4
AG	76	5	6	7	5
PreDev	0	0.2	80	7	13
BD	47	5	28	8	11
WQ	36	5	41	8	11

7.7.4 Nutrients

Due to lack of confidence in the parameter values and excessive simulation times nutrient simulations were conducted for the June 2006 calibration period only. Results from the simulations are summarized in Table 15. As shown in the table, the model did not show much differentiation between the different land-use scenarios, with only slight, though intuitively in the correct direction, differences noted. More difference was noted in the NE Fork Sub-basin model of P than for the other cases. As the parameters were not consistent across the two models the, mass balances for the two models, especially for N, are not necessarily comparable . There are many assumptions built into these model results that may be overriding the effects of the land-use changes. These assumptions should be reassessed.

Table 15. Simulated nutrient loads within the Seven Mile Creek model and NE Fork for present conditions (Base) compared with the results from the four alternate land-use scenarios.

Scenario	7 Mile Creek N (kg)	7 Mile Creek P (kg)	NE Fork N (kg)	NE Fork P (kg)
Base	628	33	0.38	7.43
PreDev	612	32	0.36	6.97
AG	628	33	0.38	7.43
WQ	614	33	0.36	7.01
BD	612	33	0.36	7.01

8 Discussion of Results

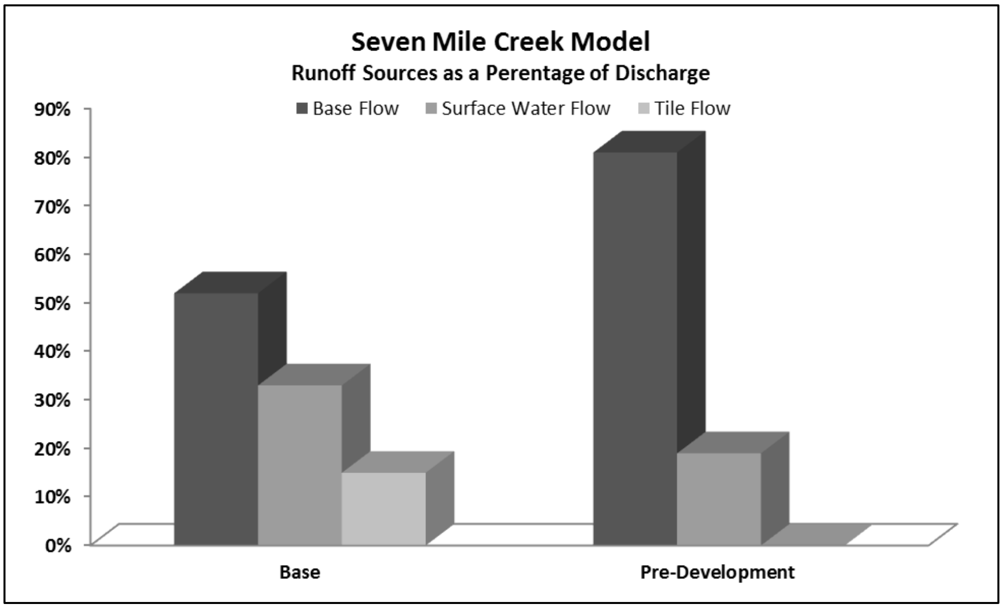
The GSSHA model was employed at Seven Mile Creek in an effort to better understand the existing system and to assess the effects of possible restoration scenarios that may be applicable in the watershed.

8.1 Flow regimes

Discharge from the watershed is a mixture of surface water (33%), tile flow (15%), and groundwater (52%), so that at the watershed outlet, groundwater is the primary overall source of flow with surface flow and tile being less significant sources of water at the outlet (Figure 41). Still, surface water and tile flow account for approximately half of the discharge. In the upper watershed, the flow regime is quite different, with surface water being 43% of the total discharge, tile being 57% of discharge, and groundwater being negligible. Currently, the predominance of overland flow sources results in high discharge during events, causing erosion of ravines and high sediment loads.

Prior to development, flow at the outlet was primarily base flow, 81%. Flow in the sub-basin was surface water. Peak flows at both sites were much lower with extended flow over the year. There is little resemblance between the historic and present-day flow conditions.

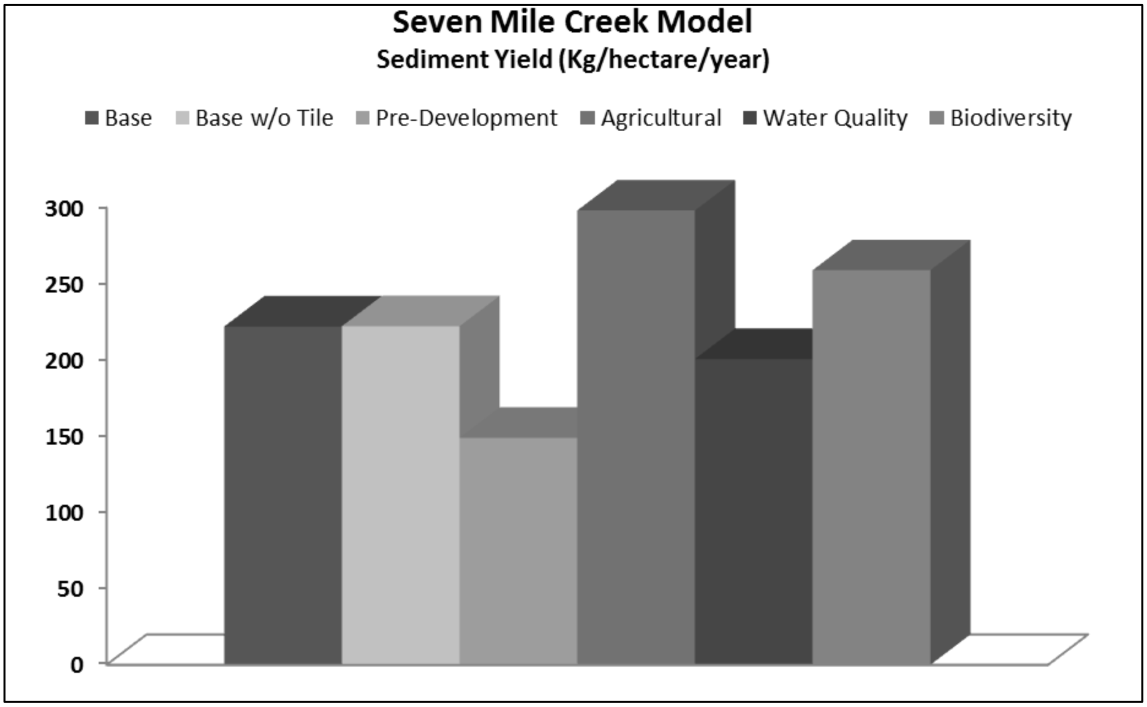
Figure 41. A comparison between present-day conditions (Base) with the native regime (pre-development) of the respective surface and groundwater components of flow.



8.2 Sediment

The observed data and the model results indicate that at the watershed scale the primary source of sediments is from ravines and gullies near the stream channels and is the source of more than 90% of the sediment load at the watershed outlet. These gullies/ravines are the result of increased overland surface runoff due to a combination of increased surface runoff from fields and from tiles discharging above the nick points. Scenario modeling indicates that much of the sediment load can be eliminated by converting the row crops back to native prairie (Figure 42). Other ways to reduce the surface discharge should be investigated, such as repairing/eliminating ravines/gullies.

Figure 42. Annual sediment yields associated with the various land uses.



8.3 Effect of row cropping

The effects of row cropping on the flow and sediment are dramatic. Row crops increase the surface runoff and increase erosion. At the watershed scale, the source of increased erosion is related to gullies and ravines. At the field scale, the increased erosion is due to increased overland discharge. Row crops reduce infiltration, reduce groundwater recharge, and increase ET. These findings were consistent across scales.

8.4 Tile drains

Tile drains are designed to quickly lower the water table below the root depths after rainfall events. The modeling indicates they do this well at Seven Mile Creek.

8.4.1 Water budget

Tile drains result in significantly more discharge, more infiltration, with less surface flow, evaporation, and lower groundwater recharge. The effect is larger at the small scale than the watershed scale. The most dramatic effect is seen on groundwater recharge.

8.4.2 Flow regime

Tile increases overall flow, this effect being larger at the smaller scale. Tile has the effect of increasing flow on the receding limb of the hydrograph (Figure 43 and Figure 44). Tiles appear to result in reduced early season snow runoff by lowering the groundwater table and reducing both groundwater discharge to the stream, as well as seepage, which may be tied up in the snowpack and released as it melts. This effect may be exaggerated in the model. The process of snow melt runoff is poorly understood and one of the greatest remaining challenges in hydrology. Still, the tile drains, in combination with row crops, result in higher late spring and summer flows and lower early spring flows. At the large scale, the effects of tile are less pronounced (Figure 43); at the small scale the effects are more pronounced (Figure 44) where the tile drains are shown to substantially increase the peak flows and extend the recession limb of the hydrograph.

Figure 43. Comparison of outflow at Seven Mile Creek between simulated flow with and without tile drains.

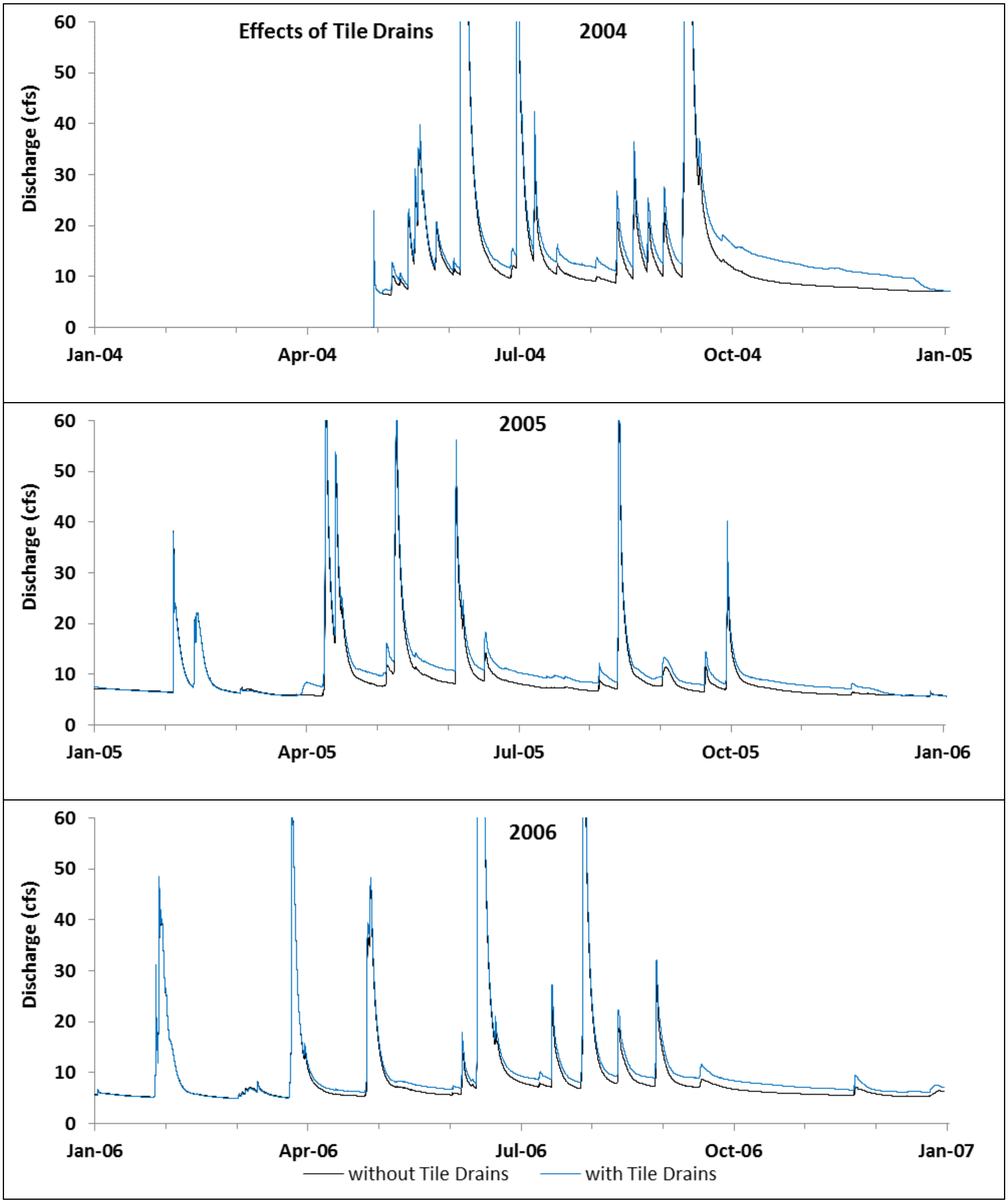
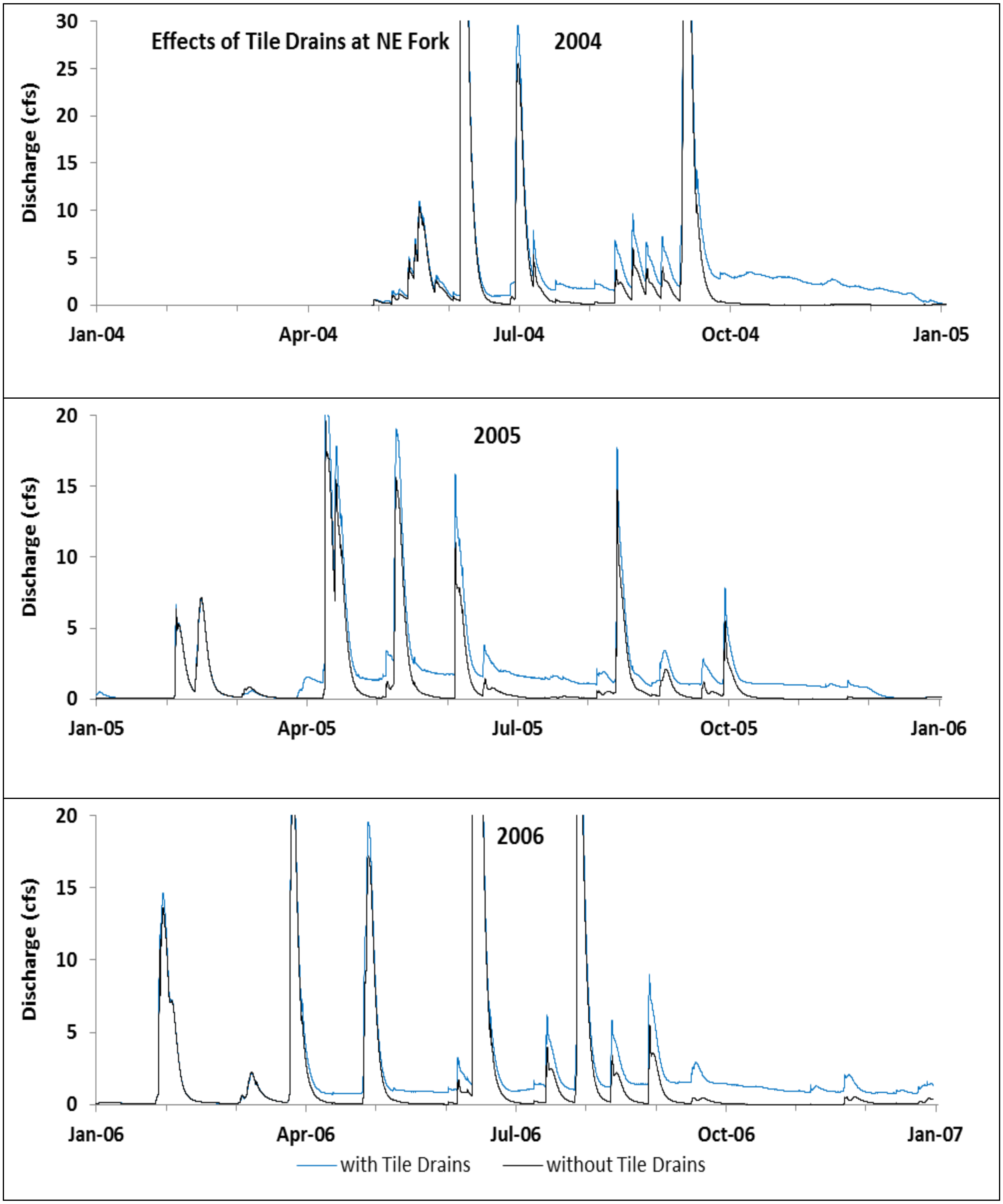


Figure 44. Comparison of outflow at the NE Fork between simulated flow with and without tile drains.



8.4.3 Sediment

Tiles are shown to significantly affect erosion in the fields. In the sub-basin model, removing the tiles reduced sediment load by 33%. At the watershed scale, removing the tiles had no effect on total sediment load. This is due to two reasons. First, most of the sediment load is generated during large events when tile flow is only a small part of total flow. Second, without tile, surface runoff from the fields is increased. In either case, the overland discharge still concentrates in low spots, ravines, which causes the bulk of erosion in Seven Mile Creek. Reducing tile flow will reduce erosion in the fields, but it will not stop the already developed ravines from continuing to erode and may in fact exacerbate the problem by shifting more of the runoff to overland flow.

8.4.4 Nutrients

While the nutrient modeling results were inconclusive, some inferences can be drawn from the hydrologic and sediment results. Since tile increased overall discharge from the fields it likely increases both N and P loads during events. Since increasing tile flow results in increased erosion from fields, it likely results in increased P load to the stream. In addition, tile results in a more continuous addition of high N groundwater to the streams. All indications are that tile increases both N and P load. Lack of verifiable modeling results precludes more quantitative statements.

9 Future Efforts

While this modeling effort produced useful models for simulating and understanding conditions in the Seven Mile Creek Watershed and assessing possible future conditions in the watershed, the effort also identified numerous areas where the modeling could possibly be improved with additional effort. Some key issues were identified.

9.1 Precipitation data

As discussed in detail in the data section (Section 4), the precipitation data were problematic. The lack of consistent data across the simulation period, as well as the lack of winter precipitation/snow estimates within the watershed, is thought to degrade the modeling results. The inclusion of radar data for selected events appeared to improve the modeling effort. Using radar data for simulation of all events of interest may increase the confidence in the subsequent results. It might also be possible to use the Red Top Farms rain gage to calibrate the radar data, or to use the measurement at Red Top Farms at 15 min and the spatial distribution of rainfall and build a combined data set. Likewise, finding a better source of winter precipitation data or snow cover, SNODAS[1] has been suggested, would likely improve the results.

9.2 Hydrologic calibration/validation

Utilizing any improved precipitation input could potentially improve the calibration and some adjustment to the parameter set may occur. Additionally, utilizing the link/node tile drain model would allow for longer calibration periods. Longer calibrations, with more events, and different size events can improve the robustness of the model parameter set.

9.3 Nutrients

Two big issues hamper the nutrient simulations: a lack of (1) measured or good estimates of soil N and P concentrations and (2) observed N and P concentrations in the streams. Measurements of, or better estimates of, N and P for the different land uses would solve the first issue. Extending the simulation period may help to solve the second. Given the difficulty with obtaining input data for the N and P simulations, an alternative approach

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[1] Snow Data Assimilation System

to assessment might be to use the flow, sediment, and available N and P observations to develop relations between these parameters and then utilizing the flow and sediment results from the model to estimate N and P based on these relationships.

9.4 Future scenarios

Two issues are thought to primarily affect the future scenario simulations: (1) the tile drainage network in the future scenarios and (2) the adjustment of parameters to address the addition of a new land type use type in the model, native prairie.

In the current set of models, the tile drainage system is either *on* or *off*. Ideally, the tile system would be modified to match the different future scenarios, with tile removed from areas taken out of production and added to areas put into production.

As the native prairie is not present in the watershed, suitable parameter values must be determined or estimated for this land use in the future scenario modeling. In this effort, the soil hydraulic conductivity and overland roughness were adjusting using surrogates for the prairie that were in the watershed: forest for soil hydraulic conductivity and herbaceous wetland for overland roughness. While this is reasonable, it is not necessarily accurate. The Minnesota Department of Natural Resources is currently investigating soil parameter values for native prairie. The results of their investigation may improve the parameter values of soil hydraulic conductivity in these models. Similar efforts may provide better estimates of overland roughness, overland retention depth, and particularly the soil erosion coefficients used in the models. A related issue is the value of the soil erosion coefficient used for the forest/loam LUST category, which may not be representative of the combination of land use and soil type in areas not affected by ravines and gullies. These two values of erodibility should probably be reassessed in light of the results of the *BD* and *WQ* scenarios, which were inconclusive.

The final issue that should be assessed in relation to the future scenarios is modification of the ditch system. In the restoration scenarios, and especially the PreDev scenario, it may be appropriate to remove the ditch system or parts of it from the network. Removing the ditch will likely result in dramatic differences in both water and sediment delivery. The ditches are an efficient means of removing water and sediments from the watershed.

10 Summary

Seven Mile Creek is a smaller tributary into the larger Minnesota River Basin that is thought to be representative of the conditions encountered throughout the basin, with the predominant land use being agriculture, with significant alteration of hydrology due to land-use change and drainage features and increased sediment and nutrient yield. Nested GSSHA hydrologic models were built of the Seven Mile Creek Watershed, the NE Fork Sub-basin of the watershed, and small experimental watershed, Red Top Farms, to try to understand dominant hydrologic processes in the watershed and estimate the effect of modern agricultural practices on hydrology, sediment, and nutrient yield, as well as assess the potential impacts of alternative land-use scenarios. Observed data were obtained for the period 2003 through 2010. The quality of the observed data varies significantly. Two periods, spring 2004 and summer 2006, were chosen as some of the best observed data periods that represent wet and dry hydrologic conditions in the basin. The suite of models was calibrated/verified to these periods and then used to simulate the period 2004-2006 to determine water, sediment, and nutrient yields for present-day conditions, as well as for alternative land-use scenarios, including restoration alternatives, and increased agriculture alternatives. A predevelopment case was also simulated to try to estimate the historic system response. The Red Top Farm model showed significant skill in reproducing measured tile flow from an instrumented field. This is the first known instance of actually reproducing measured tile flow in a hydrologic model. The larger models showed skill in reproducing both wet and dry season flows, as well as estimated sediment yield. Due to a lack of input data/observed data, the ability to adequately simulate nutrients is suspect.

Observed data and the long-term simulations indicated that the bulk of the sediment load is derived in the lower portion of the watershed. Erodibility parameter values indicated that the loamy soils, in the lower portions of the watershed, were more erodible. The tile drains were shown to exacerbate the erosion problems by concentrating flow. This is a very significant factor at the sub-watershed scale.

When utilized to simulate the alternate land uses, the models indicate that the historic conditions were significantly different from the present-day hydrologic conditions with the present-day condition yielding higher hydrograph peaks and lower base flow, as well as significantly more sediment than historically occurred at the basin outlet. In the sub-watershed above SMC1, the model indicated that in this section of the stream historical flows were small and intermittent in this region. It is likely that the historic stream, if any existed, was quite small. The drainage system simulated in the PreDev scenario is certainly not representative of the historic conditions, and the actual historic channel probably produced even lower flows and sediment delivery. Partial restoration alternatives resulted in more natural hydrologic patterns, with lower peak flows and higher baseflow, but the results for sediment were mixed. Some of the assumptions built into these simulations should be reassessed. Simulation of the AG alternative scenario indicated that removing the last vestiges of natural area in the watershed will have a significant impact on hydrology, water balance, and sediment yield and that it is important to preserve some natural areas to maintain present-day water quality.

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Acronyms and Abbreviations

1D	one-dimensional
2D	two-dimensional
AG	agricultural
BD	biodiversity
BMP	best management practice
BNC	Brown-Nicollet-Cottonwood
CFGI	Continuous Frozen Ground Index
CHL	Coastal and Hydraulics Laboratory
CL	clay loam
d	index of agreement
DEM	digital elevation model
ERDC	US Army Engineer Research and Development Center
ET	evapotranspiration
GSSHA	Gridded Surface Subsurface Hydrologic Analysis
HMET	hydro-meteorological
IST	integrated study team
L	loam
LUST	Land Use/Soil Type
MAE	mean absolute error
MSE	mean square error
MSL	mucky silt loam
MVP	Saint Paul District
N	nitrogen
NED	National Elevation Dataset
NSE	Nash and Sutcliffe efficiency
P	phosphorus
PBIAS	percent bias

PreDev	pre-development
R2	coefficient of determination
RAM	random access memory
RMSE	root mean square error
rsr	ratio of RMSE
SCE	shuffled complex evolution
SLM	Secant Levenberg-Marquardt
SOW	Scope of Work
SSURGO	Soil Survey Geographic Database
TSS	total suspended solids
USACE	US Army Corps of Engineers
USDA	US Department of Agriculture
USGS	US Geological Survey
VE	volumetric efficiency
WMS	Watershed Modeling System
WQ	water quality

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14. ABSTRACT

The Minnesota River Basin (MRB) Integrated Study Team (IST) was tasked with assessing the condition of the MRB and recommending management options to reduce suspended sediments and improve the water quality in the basin. The Gridded Surface Subsurface Hydrologic Analysis (GSSHA) was chosen by the IST as the fine scale model for the Seven Mile Creek Watershed to help quantify the physical effects from best management practices within the MRB. The predominately agricultural Seven Mile Creek Watershed produces high total suspended solids and nutrients loads, contributing roughly 10% of the total load to the Minnesota River. GSSHA models were developed for a small experimental field research site called Red Top Farms, a Hydrologic Unit Code (HUC)-12 model for the entire Seven Mile Creek Watershed, a sub-basin of the Seven Mile Creek Watershed. After calibration, the resulting models were able to simulate measured tile drain flows, stream flow, suspended sediments, and to a lesser extent, nutrients. A selected suite of alternative land-use scenarios was simulated with the models to determine the watershed response to land-use changes at the small and medium scale and to test whether the type, size, and spatial distribution of land uses will influence the effectiveness of land management options.

15. SUBJECT TERMS
Computer simulation, Environmental management, Hydrologic models, Minnesota River Watershed (S.D. and Minn.), Watershed management, Watersheds

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