This document is made available electronically by the Minnesota Legislative Reference Library
as part of an ongoing digital archiving project. https://www.lrl.mn.gov

Best Management Practice Modeling Scenarios for the Minnesota River Basin Sediment Strategy

Blue Earth River (Minnesota Pollution Control Agency)

Prepared for

Minnesota Pollution Control Agency

Prepared by

TETRA TECH

One Park Drive, Suite 200 • PO Box 14409
Research Triangle Park, NC 27709

July 15, 2019

(This page left intentionally blank.)

Table of Contents

List of Tables

List of Figures

(This page left intentionally blank)

1.0 Introduction

As part of the technical assessment to support future revisions of the Minnesota River Basin (MRB) Sediment Strategy, Tetra Tech simulated sediment management practices with calibrated and linked Hydrologic Simulation Program – FORTRAN (HSPF; Bicknell et al., 2014) models. The modeling scenarios presented in this report assess the potential sediment reductions that could be achieved by implementing individual or combined Best Management Practices (BMPs). The BMPs evaluated target reductions in near channel sediment sources (e.g., ravine mitigation) and/or aim to prevent upland erosion (e.g., cover crops).

Several resources provide estimates of sediment load reductions for agricultural BMPs. For Minnesota practitioners and planners, the Agricultural Best Management Practices Handbook for Minnesota (Lenhart et al., 2017) and the Best Management Practice Database for the Scenario Application Manager (SAM; RESPEC, 2017) serve as important references. In the former reference, agricultural BMPs applicable to Minnesota are conceptually described, pollutant removal effectiveness from the literature is summarized, and costs of implementation are provided. The SAM manual provides guidance on BMP selection, cost estimates, and identification of suitable acres. In addition, default reduction efficiencies are provided for pollutants commonly of concern, including sediment. While these references provide useful information for selecting amongst BMPs and planning for construction or implementation, seasonal and interannual variability in BMP performance is neglected. These references often report large ranges in expected reductions for several BMP types; this is because BMP performance differs due to site characteristics and conditions, such as soil type, field topography, weather, and farmer-practitioner methods of implementation (e.g., use of strip-till versus mulch tillage, both of which are forms of conservation tillage). The collective impacts of widespread BMP implementation at the watershed-scale would also remain uncertain as the adoption of these BMPs by producers will likely occur over multiple years or decades.

We implemented a framework that builds on expected BMP performance from the literature and applies process-based, or mechanistic, models to evaluate potential sediment reduction, or flow reduction, strategies. The field-scale APEX model (Steglich et al., 2016) explicitly simulates crop growth and management operations (e.g., fertilization of summer cash crops). Results from APEX simulations were used to refine the expected performance of BMPs in HSPF models as a function of differences in soil type, topography, and weather. We evaluated sediment load reductions achieved at the watershed-scale with the HSPF models to support the MRB sediment strategy in three HUC8 watersheds. HSPF is suitable for studying the benefits of pairing complementary restoration activities, and in addition to individual BMP scenarios, three combination BMP scenarios were simulated.

Management scenarios were selected for this project in consultation with MPCA and the Sediment Reduction Strategy Technical Advisory Team (TAT). Under the current work order, Tetra Tech simulated BMPs for three HUC8 watersheds: Le Sueur River (HUC 07020011), Cottonwood River (07020008), and Middle Minnesota River (07020007). It is anticipated that MPCA staff will implement similar BMP scenario models for the remaining HUC8 watersheds in the MRB.

Based on consultation with the TAT, the following BMPs were selected for evaluation due to their potential acceptability to producers and ability to reduce sediment loads:

1. Fall cover crops
2. Riparian stream buffers
3. Increased conservation tillage
4. Treatment wetlands for surface and tile flow
5. Partial conversion of annual crops to perennial crops

6. Ravine mitigation

The following sections document the technical approach for simulating these BMPs in APEX (Section 2.1) and HSPF (Section 2.2). For each BMP represented in HSPF, we discuss (1) expected performance based on the literature, (2) suitability for application to specific areas, and (3) model assumptions for implementation. Sediment and flow reductions achieved at the watershed-scale are summarized and discussed for the three study watersheds in Section 3.0. Associated changes in nutrient loads are reported in the Appendix.

2.0 Best Management Practice Model Scenarios

2.1 APEX SIMULATIONS

The Agricultural Policy/Environmental eXtender (APEX) is a field, or small watershed, scale model generally suited to evaluate the impacts of land management strategies on water quantity and quality. APEX allows users to define detailed agricultural management practices and conservation practices, and simulate the impacts on hydrology, sediment yield and water quality. The spatial units in an APEX model (called subareas) are representative of unique combinations of land cover and soils and are equivalent to a land segment (Hydrologic Response Unit, HRU) in a HSPF model. The land segment module of a HSPF model may therefore be parameterized based on the subarea output of an APEX model. A schematic representation of the joint modeling approach using APEX and HSPF is shown below (Figure 2-1).

The APEX model was developed and is maintained by the Texas A & M AgriLife Research (https://epicapex.tamu.edu/). Runoff generation in the model is based on the empirical Soil Conservation Service (SCS) curve number method or the physically-robust Green and Ampt infiltration equations. The model generally operates at a daily time-step but can be used for simulations at sub-daily time-steps with the Green and Ampt method. The model simulates the full hydrologic cycle with options for explicit simulation of tile drains, a key hydrologic feature in much of the corn belt. APEX incorporates a plant growth model that is closely related to the plant growth model used in the Soil and Water Assessment Tool (SWAT; https://swat.tamu.edu/). There are six erosion/sediment yield equations (options) that can be applied to simulate sediment detachment and transport across the landscape. APEX also enables representation of important agricultural practices including tillage, planting and harvest, fertilizer and manure application, livestock grazing, *etc.* Conservation practices (such as cover crops, filter strips, *etc.*) can also be explicitly simulated using APEX.

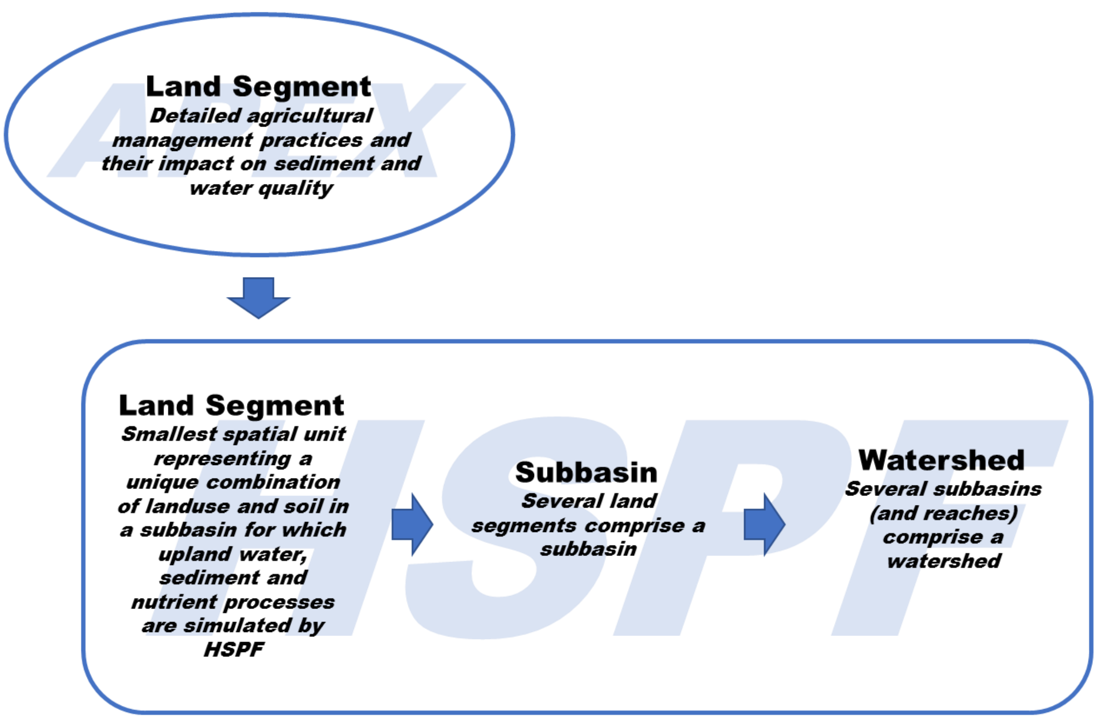


Figure 2-1. APEX-HSPF modeling framework

2.1.1 Baseline

APEX models were developed for every cropland HRU designated in the Minnesota River Basin HSPF models. This construct provides a consistent basis for extrapolation of the field-scale results to the watershed-scale models. APEX models were developed for all major soil types with areal coverages exceeding 1% of the total pervious area.

Key inputs for an APEX model consist of meteorological time-series data, topography, land use and associated management practices, and soil properties. Meteorological time-series data and topographical properties (e.g., elevation, slope, etc.) in the APEX models are consistent with cropland represented in the HSPF models.

Meteorological inputs consist of daily solar radiation, daily maximum and minimum air temperature, precipitation, relative humidity, and wind speed. Most of these data are already available from the meteorological forcing watershed data management (WDM) files developed for the Minnesota River Basin HSPF models. Relative humidity is not a time-series input for HSPF applications. However, relative humidity can be calculated using the following approximation of the Clausius-Clapeyron equation.

$$RH = 100 * \frac{EXP^{\left((17.625*TD)/(243.04+TD)\right)}}{EXP^{\left((17.625*T)/(243.04+T)\right)}}$$

where,

RH = relative humidity

TD = dew point temperature

T = air temperature

The primary objective of the APEX modeling is to evaluate conservation practices for nonpoint sediment load reduction from cultivated lands. Analysis of the USDA Cropland Data Layer (CDL) from 2008 to 2017 confirms that corn and soybeans are the major crops in the Minnesota River Basin watersheds. Approximately 54% and 42% of cultivated croplands are classified as corn and soybeans, respectively. Spring wheat, sweet corn, sugar beets, dry beans and peas are the other major crops that occupy the remaining 4% of cultivated cropland. Analysis of the county level field crop data published by the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) shows that only 3% of the corn harvested acres is dedicated to silage corn while the remainder is grain corn. Based on the above analyses, we have adopted a 2-year grain corn-soybean rotation as representative of the dominant agricultural practices in the Minnesota River Basin.

Soils properties in the APEX models are based on the State Soil Survey Geographic (SSURGO) database. APEX requires a wide range of soil physical and chemical properties that are readily retrievable from SSURGO. Subsurface tile drainage is a common management practice adopted for cultivated crops on poorly drained soils in the Midwest. Tile drains are explicitly simulated for APEX models with topographic slope < 3% and hydrologic soil group designated as A/D, B/D, C/D, or D.

Three general classes of cropland are simulated in the APEX model – conservation tillage with chemical fertilizer, conventional tillage with chemical fertilizer, and land receiving manure applications, which is consistent with the representation used in the Minnesota River Basin HSPF models. Typical management operations associated with a 2-year grain corn-soybean rotation under conventional tillage as simulated in the APEX models are shown in Table 2-1. Management practices associated with conservation tillage with chemical fertilizer and conventional tillage with manure application are shown in Table 2-2 and Table 2-3, respectively.

Table 2-1. APEX agricultural management practices for conventional tillage with chemical fertilizer application

Year	Fraction of Heat Units (Approximate Dates)	Operation
1	0.03 (April 27)	Tillage (field cultivator)
1	0.04 (May 1)	Fertilization (anhydrous ammonia @ 150 lbs-N/ac + P_2O_5 @ 61 lbs/ac)
1	0.04 (May 1)	Plant corn
1	1.2 (Oct 15)	Harvest and kill
1	0.01 (Oct 18)	Tillage (chisel plow)
2	0.05 (May 5)	Tillage (field cultivator)
2	0.06 (May 8)	Plant soybean
2	1.2 (Sep 30)	Harvest and kill
2	0.01 (Oct 3)	Tillage (chisel plow)

Table 2-2. APEX agricultural management practices for conservation tillage with chemical fertilizer application

Year	Fraction of Heat Units (Approximate Dates)	Operation
1	0.03 (April 27)	Tillage (field cultivator)
1	0.04 (May 1)	Fertilization (anhydrous ammonia @ 150 lbs-N/ac + P_2O_5 @ 61 lbs/ac)
1	0.04 (May 1)	Plant corn on ridges
1	1.2 (Oct 15)	Harvest and kill
2	0.05 (May 5)	Tillage (field cultivator)
2	0.06 (May 8)	Plant soybean on ridges
2	1.2 (Sep 30)	Harvest and kill

Table 2-3. APEX agricultural management practices for conventional tillage with manure application

Year	Fraction of Heat Units (Approximate Dates)	Operation
1	0.03 (April 27)	Tillage (field cultivator)
1	0.04 (May 1)	Fertilization (anhydrous ammonia @ 150 lbs-N/ac + P_2O_5 @ 61 lbs/ac)
1	0.04 (May 1)	Plant corn
1	1.2 (Oct 15)	Harvest and kill
1	0.01 (Oct 18)	Tillage (chisel plow)
2	0.05 (May 5)	Tillage (field cultivator)
2	0.06 (May 8)	Plant soybean
2	1.2 (Sep 30)	Harvest and kill
2	0.01 (Oct 3)	Tillage (chisel plow)
2	0.02 (Oct 6)	Manure application

The simulation time-period of the APEX models is consistent with the HSPF models, spanning 1995 to 2012. Runoff and sediment (sheet and rill erosion) generation in the APEX models are based on the NRCS Curve Number (CN) method and the small watershed Modified Universal Soil Loss Equation (MUSLE) or MUST, respectively. The choice of runoff and sediment generation methods are consistent with the nationwide APEX models developed by USDA NRCS (2017) to estimate the environmental benefits of adopting conservation practices on cropland and the Conservation Reserve Program (CRP).

Parameterization of the APEX models are generally based on the comparison of sediment and nutrient outputs against data collected at several experimental fields within the Minnesota River Basin watersheds - Discovery Farms, Red Top Farms, and Highway 90. APEX model parameters were further refined based on the unit area loads predicted by the HSPF models for cropland.

Table 2-4. Experimental fields in the Minnesota River Basin used for APEX model verification

Name	Area (acres)	Crop Rotation	Time-Period	Watershed
Blue Earth (BE1)	14.3 (surface runoff) 28.2 (subsurface tile)	Corn-soybean	2011 - 2017	Le Sueur
Renville (RE1)	81 (subsurface tile)	Soybean-sweet corn-peas	2011 - present	Middle MN
Red Top Farms	22.4 (subsurface tile)[1]	Corn-soybean	1998 - 2009	Middle MN
Highway 90	15.5 (N1 and N2, subsurface tile) 16.4 (S1 and S2, subsurface tile)[2]	Corn-soybean	2007 - 2010	Le Sueur

[1] Only East Field data were used for verification of APEX outputs. The corn-soybean-oats-alfalfa rotation on West Field varies considerably from the corn-soybean rotation simulated in the APEX models and therefore not used for model output verification.

[2] APEX outputs were verified against reported nutrient yields from S1 and N2 watersheds (aggressive fertilizer application rates) only since these conditions are more closely representative of faring practices as represented in the Minnesota River HSPF models.

Several parameters associated with the field-specific APEX models were calibrated to ensure a reasonable match between simulated and reported average annual sediment and nutrient yields and flow-weighted concentrations. Adjustments were generally limited to parameters in the APEX PARM file (PARM****.DAT) and relied primarily on recommendations in the APEX Model User's Manual Version 1501 (Steglich et al., 2018) and peer-reviewed publications (USDA NRCS, 2017; Wang et al., 2012; Bhandari et al., 2017; Ramirez-Avila et al., 2017; Yin et al., 2009). APEX models for the Discovery Farms, Red Top farm and Highway 90 site generally required the same set of parameters.

APEX-simulated average annual flow-weighted concentrations of sediment and nutrients are comparable to measured concentrations reported for the Discovery Farms (Table 2-5). It is important to note that there is very little overlap between the APEX model simulation time-period (1995-2012) and the period of data available for Discovery Farms (2011-present). A yearly comparison of APEX output against measured concentrations is, therefore, not feasible.

APEX models for the Red Top farm and Highway 90 site produced reasonable estimates of tile flow and associated nitrate-nitrogen and dissolved phosphorus (Figure 2-2. and Figure 2-3.). The average annual error in tile nitrate-nitrogen and dissolved phosphorus yields for Red Top farm were -2.4% and -27.6%, respectively. The error in average annual tile nitrate-nitrogen and dissolved phosphorus yields for the Highway 90 site were -0.1% and -32.6%, respectively. While the APEX models reasonably represent the average tile flow, it does not represent the inter-annual variability well. The models also generally tend to under-estimate dissolved phosphorus yield in tile flow. This is likely due to the simplified representation of tile drained systems within the APEX model.

Table 2-5. Comparison of APEX and measured flow weighted sediment and nutrient concentrations for Discovery Farms

Location	Constituent	Flow Pathway	Measured (mg/L)	Simulated (mg/L)	Error (%)
Discovery Farms	Sediment	Surface Runoff	463.7	418.6	-9.7
	Nitrate-Nitrogen		3.071	3.247	5.7
	Dissolved Phosphorus		0.326	0.344	5.7
	Total Nitrogen		7.335	5.973	-18.6
	Total Phosphorus		0.831	0.966	16.2
	Nitrate-Nitrogen	Subsurface Tile[3]	15.578	13.146	-15.6
	Dissolved Phosphorus		0.035	0.038	5.9

[3] Discovery Farms report sediment and organic nutrient transport in subsurface tile flow. APEX does not simulate sediment and sediment-bound or organic nutrient transport in tile flow.

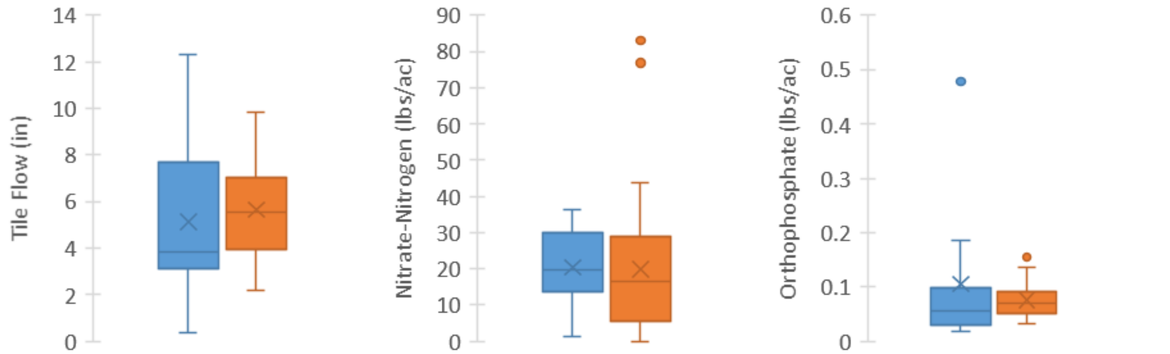


Figure 2-2. Simulated and observed range of annual tile flow and nutrient loads for Red Top farm.

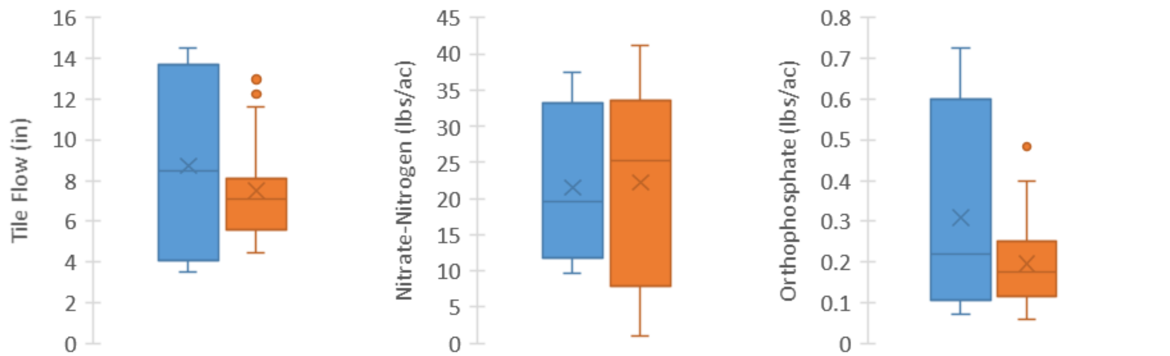


Figure 2-3. Simulated and observed range of annual tile flow and nutrient loads for Highway 90 site.

The parameters used for the Discovery Farm, Red Top farm and Highway 90 site APEX models were generally extendible to the models developed for cropland in the Cottonwood, Le Sueur, and Middle MN watersheds. However, some further parameter adjustments were required to match the baseline (i.e., pre-BMP) unit area cropland loads predicted by the HSPF models. This was done to maintain consistency between the APEX field-scale loads and HSPF cropland loads for representative existing or baseline conditions.

2.1.2 Fall Cover Crops

Cover crop performance has generally been poorer in Minnesota than is reported for more temperate locations due to the short growing season and cold weather that can limit fall/winter cover crop establishment and survival. Winter rye, however, is a viable cover crop because it can be seeded in September or early October in southern Minnesota since it germinates and grows in temperatures above 34º F and 38º F, respectively (http://www.alseed.com/UserFiles/Documents/Product%20Info%20Sheets-PDF/Basics%20Winter%20Rye-2010.pdf). Therefore, rye was selected as the representative fall cover crop.

APEX allows for multiple plants to be grown in the same land area at the same time. Therefore, this conservation practice scenario consisted of inter-seeding rye with annual crops (corn and soybean) in the early fall prior to the harvest. Consistent with recommendations of the University of Minnesota Extension (https://extension.umn.edu/cover-crops-minnesota/cover-crop-options), rye was inter-seeded with annuals. Rye was killed in spring prior to planting of the annual summer crop. A kill operation converts all standing biomass to residue in the APEX model. Fertilization and harvesting of rye were not simulated, consistent with other studies (Francesconi et al., 2015). Rye cover crop was simulated for conventional, conservation and manured tillage systems.

The key to cover crop effectiveness for erosion and nutrient loss reduction is survival during the winter months. Therefore, total biomass simulated for rye is a key indicator of the success of the cover crop. The range of average annual rye biomass simulated across fields with different characteristics (e.g., soil type) that apply conventional tillage in Cottonwood, Le Sueur and Middle MN are shown in Figure 2-4. The average simulated biomass is a little over 0.80 tons/ac. Similar magnitudes of biomass are simulated for conservation tillage and manured cropland. Since the cover crop is inter-seeded instead of planting after harvest, there is ample time for the cover crops to establish before the onset of winter. However, growth of cover crops is less vigorous due to weather some years. Cover crops are smaller in some harsher weather years compared to typical weather years, but cover crops never fully fail during the simulation.

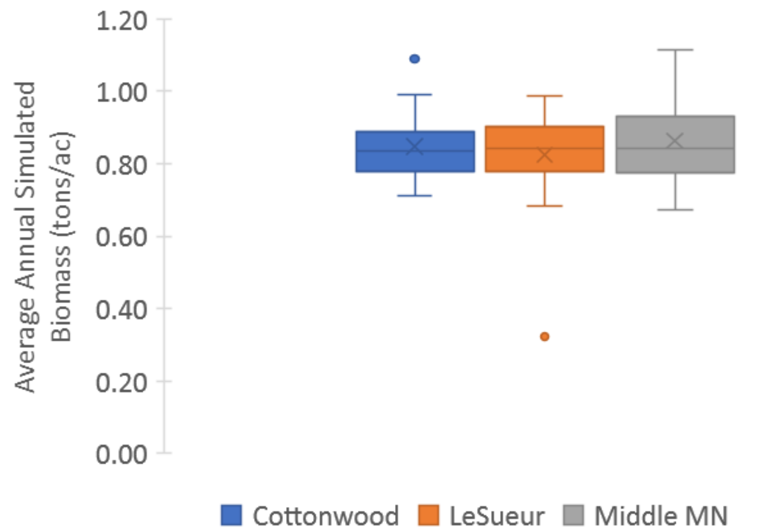


Figure 2-4. Range of simulated average annual rye biomass on conventional tillage cropland

The APEX models predicted large reductions in upland sediment load due to incorporation of fall cover crops (Table 2-6 and Figure 2-5.). The simulations suggest that cover crops produce a larger reduction in sediment load from cropland under conventional tillage compared to conservation tillage, which is expected because conservation tillage already provides cover during the cool season. Simulated reductions were comparable for well-drained (A/B) and poorly-drained (C/D) soils. Reductions are shown as positive in all APEX BMP results tables.

Table 2-6. Simulated change in average annual sediment loads for cover crops relative to baseline

Watershed	Simulated Reduction			
	Mean	Median	5th-Percentile	95th-Percentile
Cottonwood	66.1%	66.4%	45.3%	86.6%
Le Sueur	49.1%	49.1%	33.3%	66.0%
Middle MN	63.2%	62.8%	38.2%	90.9%

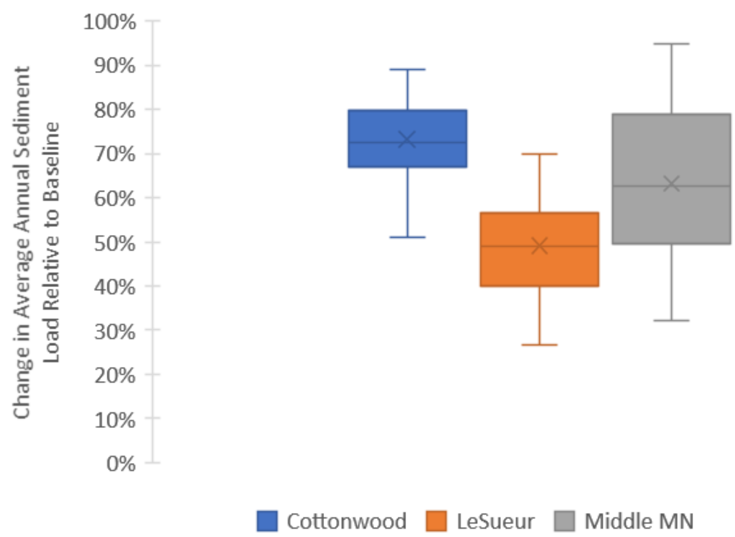


Figure 2-5. Range of simulated change in average annual sediment loads for cover crops relative to baseline.

2.1.3 Riparian Buffers

Riparian buffers are areas adjacent to water bodies and streams composed predominantly of trees that trap sediment, nutrients, and other pollutants. Riparian buffers not only filter local runoff but also treat upstream areas by filtering floodplain flow. Filter strips are vegetated areas that trap pollutants in surface runoff leaving a field. The filter strip routines are therefore appropriate for the field-scale APEX models developed for this study.

Waidler et al. (2011) summarizes two ways of simulating filter strips in APEX. One method is to simulate the filter strip as a separate subarea and route flow and pollutants through the filter strip subarea from an upstream subarea. This method requires information about the location and geometry of the filter strip. Because we are not simulating the specific geometry of individual fields, we use the second APEX method of filter strip simulation where the exact location of the filter strips is not known. The user specifies the fraction of the subarea that is controlled by vegetated buffers and the flow path length across the vegetated buffer. The second method (adopted for this study) is suitable for large subareas where the exact locations of the filter strips are not known. We further discuss the interpretation of the filter strip simulation in APEX in Section 2.2.2.3.

APEX does not use the vegetative filter strip (VFSMOD) routine of White and Arnold (2009), which is incorporated into the SWAT model. Instead, APEX treats the buffer as equivalent to floodplain flow with lowered velocity and increased surface roughness due to vegetation, which causes sediment and other pollutants to settle out.

The two parameters associated with filter strips in APEX are BCOF (fraction of subarea controlled by filter strips) and BWTH (filter strip width in meters). The values of BCOF and BWTH for this study for all APEX simulations are set at 1.0 and 15.24 meters (50 feet), respectively. The value of 50 feet for buffer width is representative of cropland edge-of-field nominal filter strip. Setting BCOF to 1 means that the results of the simulation are for the fraction of field area that is controlled by the filter strip, which inflates the apparent reduction. The APEX models suggest large reductions in sediment yield from cropland HRUs resulting from the adoption of filter strips (Table 2-7 and Figure 2-6.). Note that these reductions, which are quite large, are representative of field areas where sheet flow is maintained by runoff reaching the filter strip. If flow concentrates filter strip performance would be less efficient at reducing sediment loads.

Table 2-7. Simulated change in average annual sediment loads due to adoption of filter strips relative to baseline.

Watershed	Simulated Reduction			
	Mean	Median	5th-Percentile	95th-Percentile
Cottonwood	95.6%	95.7%	90.5%	99.3%
Le Sueur	91.1%	91.8%	83.8%	96.9%
Middle MN	95.1%	95.8%	87.5%	99.7%

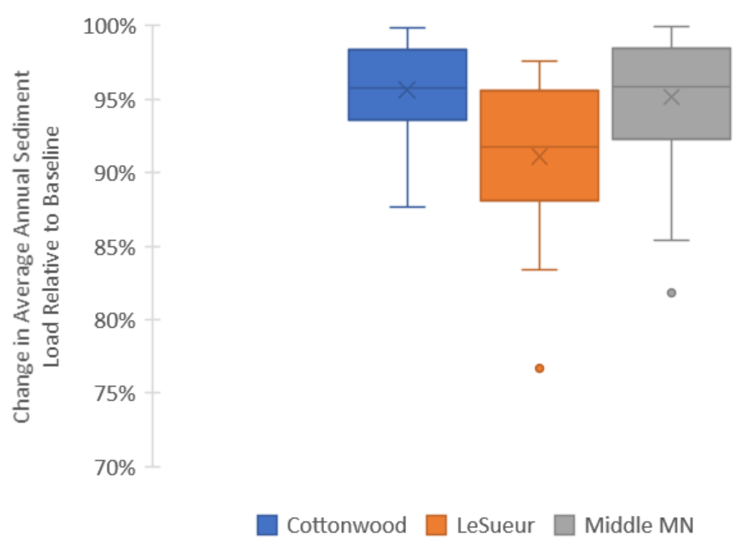


Figure 2-6. Range of simulated change in average annual sediment loads due to adoption of filter strips relative to baseline.

2.1.4 Conservation Tillage

Conservation tillage is an umbrella term that incorporates a variety of residue-maintaining tillage practices including mulch till, strip till, ridge till, and no till; each practice has different erosion-prevention potential. The management practices for cropland under conservation tillage adopted in APEX are summarized in Table 2-2. In addition to changes in the tillage types, curve numbers for cropland under conversation tillage were reduced by three points relative to conventional tillage to represent anticipated changes in runoff, infiltration, and moisture retention due to increased soil cover. Wang et al. (2008), for field-scale APEX models in Iowa, applied a similar approach and reduced the curve number for conservation tillage by four points relative to conventional tillage. The range of reductions in average annual sediment yields predicted by the APEX models across fields applying conservation tillage relative to conventional tillage (Table 2-8 and Figure 2-5.) were generally comparable to the representation of conservation tillage in the existing HSPF models. The APEX models, however, show a larger range of predicted reductions due to a larger variability in soil properties simulated in APEX compared to HSPF.

Table 2-8. Simulated change in average annual sediment loads for conservation tillage relative to conventional tillage.

Watershed	Simulated Reduction			
	Mean	Median	5th-Percentile	95th-Percentile
Cottonwood	35.1%	35.0%	26.1%	45.5%
Le Sueur	26.3%	25.9%	21.4%	33.0%
Middle MN	35.0%	33.2%	24.2%	48.4%

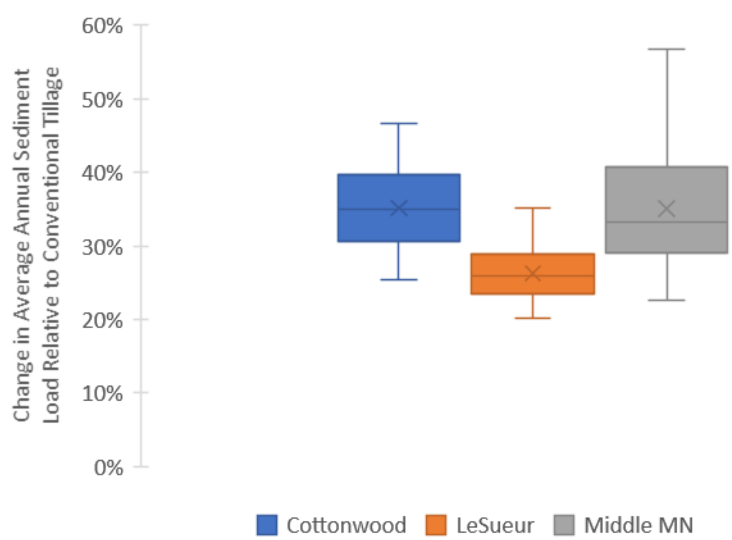


Figure 2-7. Range of simulated change in average annual sediment loads for conservation tillage relative to conventional tillage.

2.1.5 Perennials

This scenario consisted of converting cropland under corn-soybean rotation to perennial switchgrass. Switchgrass was planted using aerial seeding and harvested every year in late fall. Fertilization was not simulated, and switchgrass was re-seeded every six years. A key factor determining the effectiveness of perennials in reducing sediment and nutrient loads is survivability and biomass production. The range of average annual biomass simulated by APEX (Figure 2-8.) is comparable to unfertilized switchgrass trials conducted by the NRCS in Minnesota (Tober, 2007).

The APEX simulations predict large reductions in sediment yield (often exceeding 90%) on a unit area basis (Table 2-9). Note that these results are based on converting an acre of cropland to switchgrass. For a 20% adoption rate (i.e., converting 1/5 of an acre of active cropland to perennial switchgrass), the average reduction would be approximately 18%. Folle (2010) reports varying levels of expected sediment reduction (approximately 0 to 73%) from conversion of different proportions of cropland to switchgrass in the Le Sueur watershed using a SWAT model.

Table 2-9. Simulated change in average annual sediment loads for perennials relative to baseline.

Watershed	Simulated Reduction			
	Mean	Median	5th-Percentile	95th-Percentile
Cottonwood	96.6%	97.1%	92.6%	98.9%
Le Sueur	95.3%	95.4%	93.6%	97.1%
Middle MN	96.9%	97.1%	94.5%	98.9%

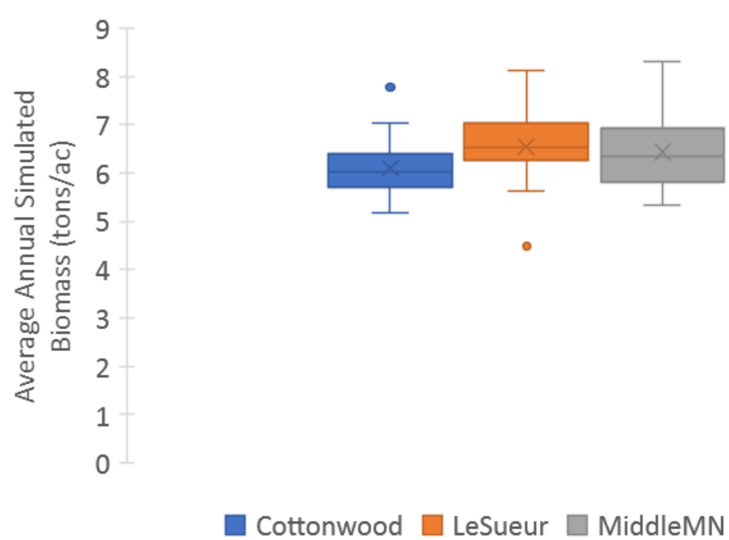


Figure 2-8. Range of APEX simulated average annual switchgrass total biomass.

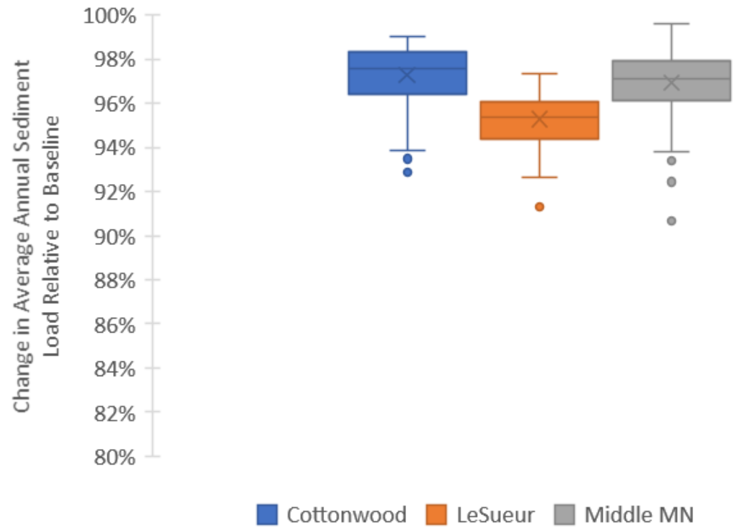


Figure 2-9. Range of simulated change in average annual sediment loads for perennials relative to baseline.

2.2 HSPF

Information from the APEX simulations was used to help refine BMP scenarios for the calibrated HSPF models of the Cottonwood River, Le Sueur River, and Middle Minnesota River watersheds, as discussed in the following subsections. The HSPF model scenarios examine and test the efficacy of different BMPs for controlling flow and sediment pollution at the watershed-scale (nutrient reductions are supplementary benefits presented in **Error! Reference source not found.**). In addition to the BMPs simulated in the field-scale APEX models (fall cover crops, riparian buffers, conservation tillage, and perennials), treatment wetlands and ravine mitigation practices are also assessed with the HSPF models. Expected performance, suitability, and the methodology to represent the practices in HSPF are discussed, and results are presented in Section 3.0.

2.2.1 Fall Cover Crops

2.2.1.1 Performance

Cover crops provide water quality benefits by (1) providing erosion cover, (2) taking up nutrients, and (3) increasing infiltration while reducing overland flow energy. Tank and Willows (2016) have demonstrated that rye grass cover crops after the cash crop can significantly reduce the export of dissolved phosphorus through tile drains. As with other BMPs, actual effectiveness is likely to vary considerably depending on local conditions. The review of BMP efficiencies conducted for the Chesapeake Bay Program (Simpson and Weammert, 2009) concluded that cover crop efficiencies for solids reductions varied from 0 to 20%, efficiencies for total phosphorus reduction varied from 0 to 15%, and efficiencies for nitrogen varied from 10 to 45%, depending on the geologic setting, type of cover crop, and method of planting.

Cover crops have been studied extensively in Minnesota, and performance has generally been poorer than in warmer locations due to the short growing season and weather that can limit cover crop establishment and survival. Pollutant removal efficiencies for cover crops were compiled for development of the MPCA's Scenario Application Manager (SAM) Tool (RESPEC, 2017). The recommended pollutant removal efficiencies from RESPEC (2017) consider multiple references, including the *Agricultural BMP Handbook for Minnesota* (Lenhart et al., 2017), *Nitrogen in Minnesota Surface Waters* (MPCA, 2013), documentation for the NBMP (Lazarus, 2014) and PBMP (Lazarus, 2015) tools, Smith (2014), and Zhu et al. (1989). Pollutant removal efficiencies are presented for nitrogen, phosphorus, and suspended sediment for three flow pathways: surface, interflow (often included tile drainage), and baseflow (groundwater) as shown in Table 2-10. *The Minnesota Nutrient Reduction Strategy* (MPCA, 2014) also presents pollutant removal efficiencies for cover crops (conditional on establishment success): 51% nitrogen reduction and 29% phosphorus reduction. While these summary removal efficiencies provide a reasonable general planning guide, the underlying studies show a wide range of performance with variability associated with soils, slopes, and weather. Long-term simulation modeling should help to understand, and represent, some of the sources of variability.

Table 2-10. Example default pollutant removal efficiencies for cover crops in MPCA's Scenario Application Manager (RESPEC, 2017)

BMP	Pollutant Removal Efficiency (Percent) [a]						
	TN			TP			TSS
	Surface	Interflow	Baseflow	Surface	Interflow	Baseflow	Surface
Corn and soybeans with cover crop	28	17–23	8–22	29	18–24	8–23	74
Short season crops with cover crop	43	27–36	12–34	29	18–24	8–23	74

a. Efficiency ranges are based on short, intermediate, and long-term impacts to account for lag time to achieve full effectiveness.

In addition to modifying water quality, cover crops also have hydrologic effects, such as increasing evapotranspiration from the soil and reducing the amount and velocity of runoff (Dabney et al., 2007). In a field study in central Iowa, a rye cover crop significantly increased the rise in soil water content at a 10-cm depth during rain events compared to plots without the cover crop. The study suggests that rye may affect soil water dynamics in the upper soil layers (Goeken, 2013).

Large variations in reported performance of cover crops may reflect year-to-year variability in weather, among other factors. This suggests the value of evaluating cover crop performance using agronomic models that incorporate multi-year weather timeseries.

Cover crop performance has been investigated extensively using the SWAT model. SWAT is well suited to represent cover crops as a second planting after harvest of a cash crop; however, SWAT does not allow for representation of interplanting of cover crops prior to cash crop harvest, although APEX does, as discussed in Section 2.1.2. Simulations by Folle et al. (2009) found that planting rye as a cover crop after soybean harvest reduced sediment loss by 32%. ET was also increased. In another SWAT model study for Little Cobb River, Schmidt et al. (2018) predicted an 18% reduction in sediment by using winter cover crops following grain corn, with small reductions in phosphorus and nitrogen load. Efficiency of the practice was limited by cold weather effects on establishment.

2.2.1.2 Suitability

Satellite-based estimates by the University of Minnesota confirmed by ground-truthing indicate that cover crops are used on less than 2.5% of cropland in Minnesota. Use on corn and soybeans is minimal (less than 2%), with most cover crops being applied to potatoes, small grains, and canning crops (Figure 2-10.).

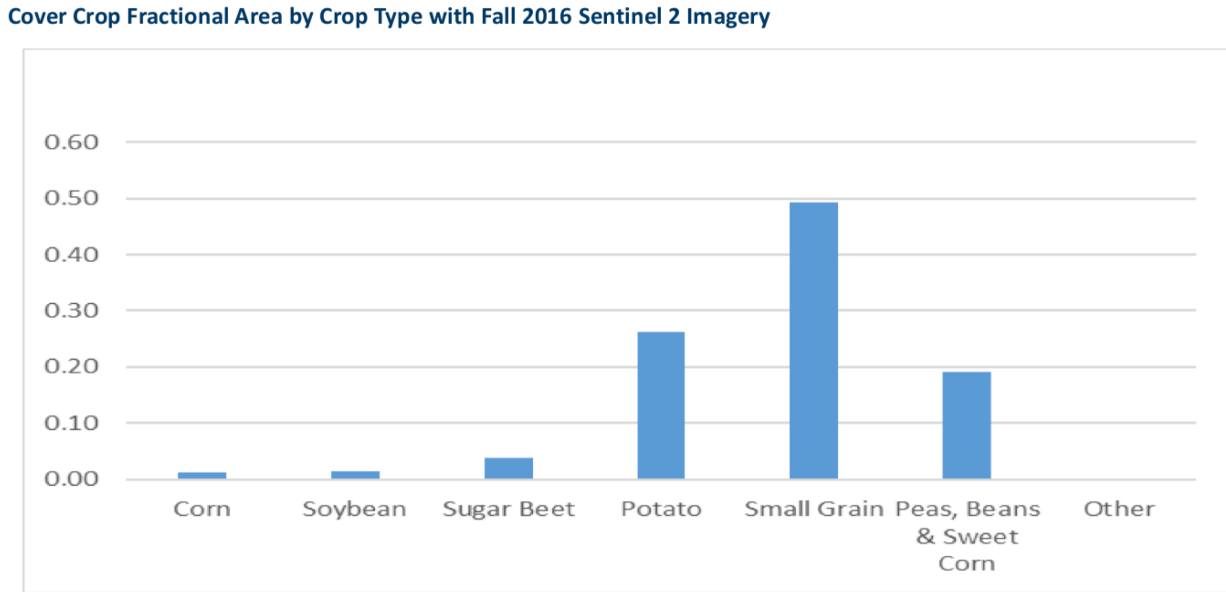


Figure 2-10. Use of cover crops by cash crop type (figure from presentation by M. Drewitz, D. Mulla, and B. Gelder at Tillage and Erosion Survey Project Advisory Committee Meeting, May 23, 2018, University of Minnesota, St. Paul, MN)

The existing HSPF models do not assume any use of cover crops. Thus, potential suitable acres for use of cover crops include all corn and soybean acres in the model (as based on the 2006 NLCD).

Given the very low levels of current adoption there is little to be gained from attempting to model HUC8-scale scenarios that incorporate existing rates. Model scenarios were developed that represent potential future conditions based on high levels of adoption of cover crops (25% and 75% of cropland).

2.2.1.3 Modeling Approach

For model implementation, cover crops are represented as inter-seeded rye in the early fall prior to the harvest of the summer crop (corn or soy). The presence of cover crops potentially affects several parameters in the HSPF model. Most significant is the increase in erosion cover, which reduces sediment detachment, from establishment of the cover crop until spring removal. Cover crops also take up water and nutrients from the soil and increase both interception and surface storage of water, reducing runoff. These effects are represented through parameter modifications in HSPF. HSPF is not, however, a plant growth model, so appropriate modifications to these parameters are not always evident. Therefore, we use the APEX model to evaluate the effects of cover crops and tune the HSPF parameters to reflect the relative change shown by APEX in total runoff volume, surface runoff, and export of sediment loads.

The APEX simulations (for each evaluated HRU) incorporate the following assumptions:

- An annual rye cover crop is inter-seeded with corn and soy cash crops in the early fall.
- Cover crop growth and biomass are simulated using the APEX plant growth model. If fall conditions are too cold the cover crop may fail, simulated directly by APEX based on the thermal tolerance ranges of annual rye.
- The cover crop is killed prior to planting the next cash crop, with all residue left in the field.
- Model runs are developed for cover crops in both conventional and conservation tillage.

The APEX model produces continuous daily output specific to the soil, slope, crop, and weather conditions of each individual HRU. The HSPF model, operating at a much broader spatial scale, incorporates an average representation of the performance of cover crops across similar HRUs. This translation is best done at a monthly time step. We adjusted the HSPF parameters for index to infiltration capacity (INFILT), interception storage capacity (MON-INTERCEP), upper soil zone moisture nominal soil water holding capacity (MON-UZSN), surface roughness (MON-MANNING), interflow (MON-INTERFLW), lower zone ET parameter (MON-LZETPARM), sediment transport capacity for sheet and rill erosion (KSER), and cover (MON-COVER) to approximate the relative monthly change in flow and sediment yield predicted by APEX.

2.2.2 Riparian Buffers

This scenario focuses first on riparian buffers as required under Minnesota's Buffer Law. A second version investigates expansion of the application of riparian buffers to all waterways. Minnesota's Buffer Law (MN Statute 103F.48, signed in 2015 and as subsequently amended) requires the following:

- For all public waters, the more restrictive of 1) a 50-ft average width, 30-ft minimum width, continuous buffer of perennially rooted vegetation, or 2) the state's shoreland management standards.
- For public drainage systems established under §103E, a 16.5-ft minimum width continuous buffer.

Figure 2-11. shows the waterbodies contained within the National Hydrography Dataset (NHD) high resolution flowline coverage to which the Buffer Law does and does not apply.

A polygon coverage of riparian buffers that were present prior to the buffer law was not available. Instead, the baseline models rely on the land use coverage in the 2006 NLCD, as analyzed by RESPEC for the 2014 model updates. This accounts for riparian buffers as pixels identified as forest, shrub, or grassland located along stream corridors. However, the NLCD is a 30-m resolution coverage, so the ability to resolve linear features such as buffers is limited. Buffers present prior to the buffer law provide habitat and remove land from production (and associated sediment and nutrient loading). We assume, however, that such existing buffers have not been optimized (e.g., by maintenance of sheet flow on the upland side) to provide treatment to adjacent cropland. The approach taken by RESPEC was similar to the Nutrient Reduction Strategy approach, but not identical. Namely, the Nutrient Reduction Strategy used the 2012 Cropland Data Layer to map the buffer land covers.

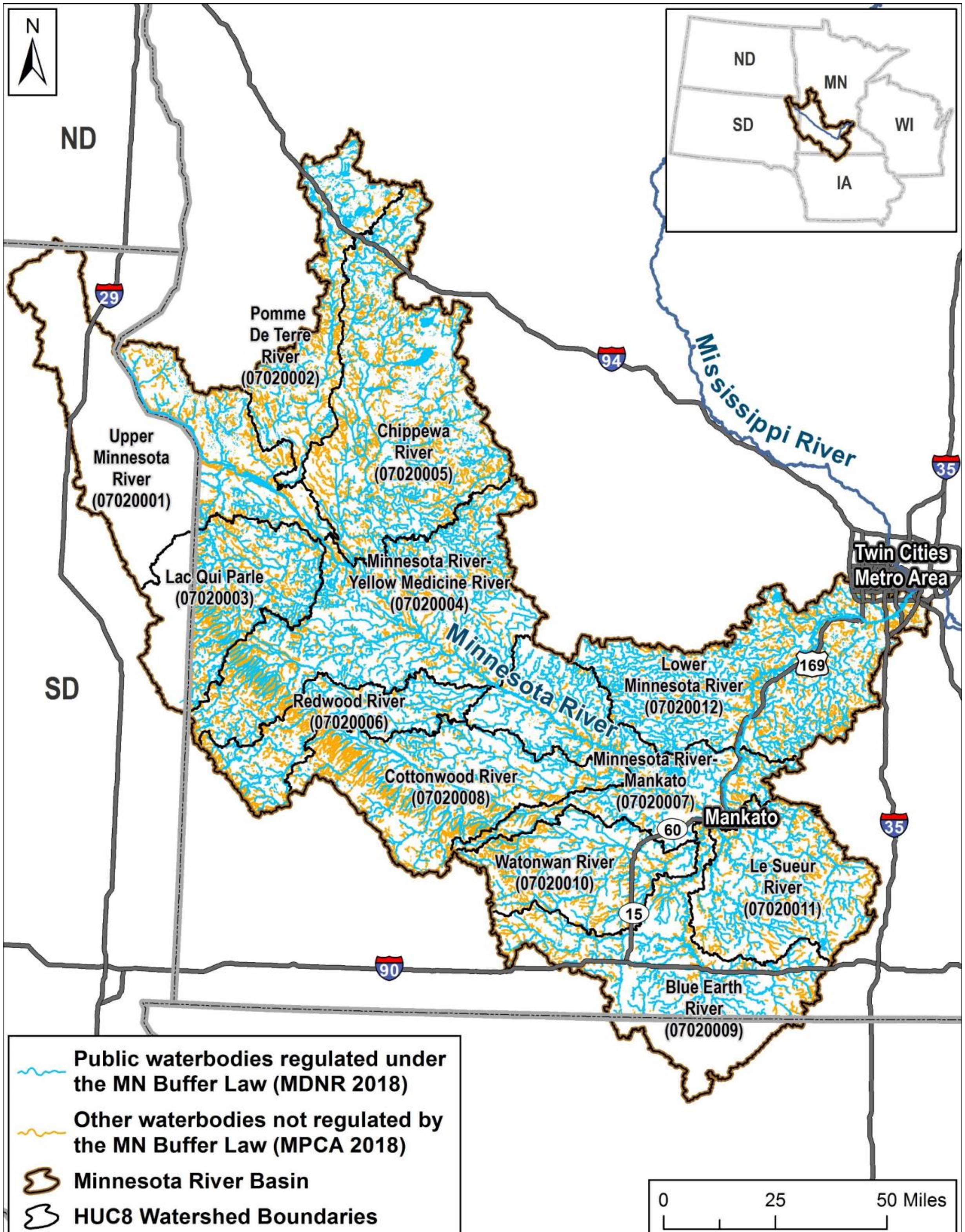


Figure 2-11. Applicability of Minnesota buffer law to National Hydrography Dataset (NHD) flowlines

2.2.2.1 Performance

Preserving natural vegetation along stream corridors and at field boundaries can effectively reduce water quality degradation associated with human disturbances. The root structure of the vegetation in a buffer enhances infiltration of runoff and subsequent trapping of nonpoint source pollutants. However, the buffers are only effective in this manner when the runoff enters the buffer as a slow moving, shallow “sheet”; concentrated flow in a ditch or gully will quickly pass through the buffer offering minimal opportunity for retention and uptake of pollutants.

Even more important than the filtering capacity of the buffers is the protection the buffers provide to streambanks. The rooting systems of the vegetation serve as reinforcements in streambank soils, which help to hold streambank material in place and minimize erosion. Due to the increase in runoff volume and peak rates of runoff associated with agricultural drainage and development, stream channels are subject to increasing erosional forces during stormflow events, leading to bank failure and channel widening. Preserving natural vegetation along stream channels reduces the potential for water quality and habitat degradation due to streambank erosion and provides filtration of pollutants in sheet flow runoff from adjacent areas.

Use of buffers is particularly important to mitigate loading in areas of highly erodible land. Buffers in such areas may achieve dual benefits by both filtering runoff from adjacent cropland and removing a portion of the highly erodible land along streams from tillage and production. If topography allows, buffers may also be used to treat effluent from tile drain outlets.

Removal efficiencies by filtration or plant uptake depend on contact time, which is in turn a function of buffer width. Effective removal of pollutants requires conditions of dispersed, relatively low velocity flow. The distance from the edge of the buffer that can be treated depends on soil and slope conditions, but flow originating far from the buffer will tend to form concentrated flow channels that short circuits treatment (Dosskey et al., 2002).

Because of the similarities between riparian buffers and filter strips, removal efficiencies for both are included. Pollutant removal efficiencies were compiled for development of the MPCA’s SAM Tool (RESPEC, 2017). The recommended pollutant removal efficiencies from RESPEC (2017) take into account multiple references, including the *Agricultural BMP Handbook for Minnesota* (Lenhart et al., 2017), *Nitrogen in Minnesota Surface Waters* (MPCA, 2013), the literature review in Section 2.1 of the Iowa Nutrient Reduction Strategy (Iowa Department of Agriculture and Land Stewardship, 2017), Mayer et al. (2007), O’Neill (2015), Smith (2014), and documentation for the NBMP (Lazarus, 2014) and PBMP (Lazarus, 2015) tools. Pollutant removal efficiencies are presented for nitrogen, phosphorus, and suspended sediment (Table 2-11). *The Minnesota Nutrient Reduction Strategy* (MPCA, 2014) also presents pollutant removal efficiencies for perennial buffers in riparian areas (replacing row crops): 95% nitrogen reduction and 58% phosphorus reduction. Application of fixed removal efficiencies is problematic as most reported rates are from small plot studies with relatively short travel distances, and often represent reductions in surface runoff, not *net* across both surface and subsurface flow pathways. To estimate effectiveness in a watershed context it is necessary to estimate what portion of flow from adjacent upland areas is maintained as non-concentrated flow. After accounting for areas farther from buffers and including flow that proceeds through private drainageways not subject to the buffer rule, effective removal efficiencies for riparian buffers at a watershed-scale are expected to be significantly lower than shown in Table 2-11.

Table 2-11. Default pollutant removal efficiencies for riparian buffers and filter strips in MPCA's Scenario Application Manager (RESPEC, 2017)

BMP	Pollutant Removal Efficiency (Percent)						
	TN			TP			TSS
	Surface	Interflow	Baseflow	Surface	Interflow	Baseflow	Surface
Riparian buffers, 16 ft wide (replacing row crops)	43	27–36	12–34	50	31–42	14–40	74
Riparian buffers, 50 ft wide (replacing row crops)	66	42–56	19–53	67	42–56	19–53	84
Riparian buffers, 100 ft wide (replacing row crops)	79	50–67	22–63	80	51–68	23–64	90
Filter strips, 50 ft wide (cropland field edge)	66	42–56	19–53	67	42–56	19–53	84
Riparian buffers, 50 ft wide (pasture)	44	33–44	14–39	45	34–45	14–39	50

Filter strip performance in Minnesota is well studied and is summarized by Lenhart et al. (2017). Sediment reductions depend on filter strip width. Lenhart et al.'s consensus summary of multiple sources reports an average removal efficiency of 86% (range 76 to 91%) for sediment. Lower rates of removal are reported for phosphorus (average removal of 65%, range 38 – 96%), largely because phosphorus is preferentially associated with fine sediment. The potential for nitrogen removal by filter strips appears to be relatively low due to the high solubility of inorganic nitrogen compounds, although particulate organic nitrogen will be trapped. Plants in filter strips can have some ability to extract nitrogen from shallow groundwater; however, the use of tile drainage will bypass filter strips.

2.2.2.2 Suitability

Riparian buffers can be used anywhere there is a relatively smooth transition from cultivated lands to a waterway; however, effective filtration by a buffer will only occur where non-concentrated flow can be maintained. Physical layout may preclude use of a buffers in some cases, such as where field topography does not allow maintenance of sheet flow. Nonetheless, riparian buffers could be used in a large fraction of the Minnesota River Basin, where slopes are generally mild.

A key determinant is the specification of where buffers apply and what width is required. We tested two riparian buffer scenarios: one with the buffers placed and sized as required by the Buffer Law (50 feet on public waters and 16.5 feet on ditches), and one with buffers extended to apply to all mapped streams and ditches, including private ditches.

The Buffer Law scenario is based on GIS analysis of the model land use cover (derived from 2001/2006 NLCD) that creates buffers of the required width on all regulated waterbodies, as defined by the state (https://www.dnr.state.mn.us/buffers/index.html). The baseline thus represents conditions prior to the passage of the Buffer Law. For the second scenario, we add to the first scenario 16.5 ft buffers on all additional lakes, ditches, and streams (including intermittent streams) shown on the MPCA statewide streams layer, which is based on the 24K National Hydrography Dataset coverage. For this scenario, we do not add additional buffers on small wetland areas that are shown on the National Wetland Inventory but not included under the Buffer Law, because many of these are fragments internal to fields or farmed.

Following the GIS analysis, cropland area that falls within the buffer widths was reassigned to grass. The remaining cropland area is divided into fractions that are within a specified control distance of the buffer and those that are not, as described in the next section.

2.2.2.3 Modeling Approach

Field-scale performance of riparian buffers was simulated in APEX using the filter strip routine with grassy vegetation consistent with the Buffer Law. APEX does not use the vegetative filter strip (VFSMOD) routine of White and Arnold (2009), which is incorporated into the SWAT model. Instead, APEX treats the buffer as equivalent to floodplain flow with lowered velocity and increased surface roughness due to vegetation, which causes sediment and other pollutants to settle out.

The best buffer pollutant removal performance is obtained when all flow is directed to the buffer as sheet flow and it is evenly distributed across the length of the buffer. In contrast, flow that becomes fully channelized can punch through the buffer with little or no pollutant removal. White and Arnold's approach recognizes that most real-world applications of buffers occur in situations where much of the field runoff is directed to a relatively small portion of the buffer. It thus divides the flow from the upland area into three categories: (1) general loading to the buffer without concentrated flow, (2) the fraction of (non-channelized) concentrated flow that is directed to the most heavily loaded 10 percent of the filter strip, and (3) fully channelized flow that is not subject to pollutant removal.

It is often stated that dispersed sheet flow cannot be maintained from areas more than 300 feet from a buffer edge, while a fraction of flow from areas closer to the buffer is also likely to be channelized[4]. White and Arnold also based their removal equations on field studies with a uniform length of 100 m (just over 300 feet) along the direction of flow. Runoff originating from more than 300 feet from the buffer edge is assumed to be fully concentrated with no pollutant or flow reduction by the buffer. We use the SWAT default assumption that 50% of the flow originating within 300 feet of the buffer is directed to the most heavily loaded 10 percent of the filter strip (Neitsch et al., 2014) and that none of the flow from within 300 feet directed to the most heavily loaded 10 percent of the filter strip is completely channelized, although it will receive less treatment than fully dispersed flow due to the larger drainage area to buffer area ratio. The flow directed to the most heavily loaded 10% of the buffer has a shorter contact time and less treatment, which could be expressed as a shorter effective path length through the buffer. For example, if flow from a distance of up to 300 ft passes through a 50-foot buffer, the ratio of upland flow length to buffer width (VFSratio) is 300/50 = 6. When the flow is split between 10% and 90% of the buffer length, each receiving half the total flow, the component VFSratios are 3.33 for the 90% portion with the lower fraction of flow and 30 for the 10% portion receiving the higher fraction of flow, with an average of 16.665. This could be thought of as an effective flow width in the buffer of 18.018 ft, which is 36% of the nominal buffer width of 50 feet – indicating that the effect of flow concentration is to reduce the contact time to 36% of the average that would be present if all flow (from within 300 feet) was maintained as unconcentrated sheet flow. Equivalently, we can specify that 36 percent of the contributing area (within 300 feet) is effectively treated by the buffer. This fraction is independent of the nominal buffer width. Taking the White and Arnold (2009) equations and simplifying the algebra, the fraction relating the effective to nominal control area will always be given by $2/[(1 - \text{dfcons})/0.9 + \text{dfcons}/0.1]$ where dfcons is the fraction of flow that goes through the most heavily loaded 10% of the buffer.

[4] The 300-foot limit is found in many BMP design manuals without citation. This statement comes from older versions of the NRCS Conservation Practice Standard 393 for filter strips, but has been removed from newer versions. The Conservation Practice Standard in turn appears to have copied the statement from the TR-55 manual.

In sum, the APEX model runs are undertaken with an assumption that 100% of the upland drainage area is treated by the riparian buffer. However, for application in HSPF the following adjustments are then made:

- Area within the applicable buffer width (50 or 16.5 feet) are transferred from cropland to a grass land use category.
- Area of cropland within 36% x 300 ft = 108 feet of the buffer have loads reduced in accordance with the results of the APEX model application.
- Cropland areas more than 108 feet from a buffer receives no load reduction.

One approach to implementation in the HSPF model is to specify cropland HRUs that are within the effective buffer treatment distance as a new set of HRUs. That would, however, greatly complicate the model setup as the cropland HRUs are separated by weather station, hydrologic soil group, and the presence of conservation tillage and manure application. The latter two factors do not have explicit spatial definition, but rather are based on county-level statistics. Therefore, a more parsimonious approach to the simulation is to adjust the MASS-LINK block factors that assign upland loads to receiving stream segments to reflect the average percentage of cropland that is treated by buffers under a given scenario. These factors are discounted by adjusting for the buffer removal rate for a given constituent (as estimated by the APEX modeling) and the fraction of cropland that is treated. If the buffer removal rate for the constituent is α and the fraction of cropland that is effectively treated by buffers is β, then the adjusted throughput to the stream is given by multiplying by $[\alpha * \beta + (1 - \alpha)]$.

The APEX simulation does not provide direct information on the benefits associated with stream bank stabilization by buffer vegetation. Those benefits are, however, incorporated into HSPF, where the shear stress-based simulation of channel erosion for both silt and clay incorporates a parameter that specifies the maximum possible erodibility (in lb./ft^2-d). We have modified this parameter based on a literature review of the relative change in bank erosion rates with buffers established.

2.2.3 Conservation Tillage

Conservation tillage involves a variety of practices, including no-till and mulch tillage. The most important distinction for the uses of the model is between practices that achieve high residue cover and those that do not. Transect Tillage Surveys were conducted by NRCS every two years between 1998 and 2007 for Minnesota counties with at least 30% of their land area in agriculture. In 2007, after cessation of NRCS funding, the Minnesota Board of Water and Soil Resources performed their own detailed tillage transect surveys (Fisher and Moore, 2008), which is the most recent survey currently available from the Tillage Transect Survey Data Center. The surveys identify no-till, ridge-till, and mulch-till practices as conservation tillage with greater than 30% residue. These results can be used to calculate the conservation tillage fraction of cropland for each surveyed county for the period when data were collected. Counties have conducted more recent tillage transects, however there is not a central repository for these data.

2.2.3.1 Performance

In a literature review of global studies, Montgomery (2007) found that the median soil loss rate for conventional agriculture was 1.537 mm/yr, while the rate for conservation agriculture was only 0.082 mm/yr. Shiptalo et al. (2013) studied sediment loss from small (< 1 ha) test plots in Ohio, and found that soil loss was least from no-till (807 kg/ha/yr), intermediate from chisel plowed (1073 kg/ha/yr), and greatest from disked watersheds (1177 kg/ha/yr).

USEPA (2003) reports the findings of several studies regarding the impacts of tillage practices on pollutant loading. The reductions achieved by conservation tillage reported in these studies are summarized below:

- 50% reduction in soil loss rate for practices leaving 20 to 30% residual cover
- 75% reduction in soil loss rate for reduced tillage practices
- 90% reduction in soil loss rate for practices leaving 70% residual cover
- 68 to 76% reduction in total phosphorus
- 55% reduction in total nitrogen load for reduced tillage practices (This level of reduction does not seem to be the case in Minnesota. A 55% reduction appears reasonable for surface runoff of N, but in the Minnesota River basin much of the N is transported to streams by subsurface pathways, including tile drains, and not strongly affected by reduced tillage.)

In general, the results reported in USEPA (2003) appear overly optimistic relative to carefully managed plot studies. Such studies often report reductions in surface runoff, and not the net reduction from changes in surface and subsurface flows and concentrations. The Chesapeake Bay Program recently undertook a thorough review of BMP effectiveness (Simpson and Weammert, 2009) that resulted in a downward revision of conservation tillage effectiveness, with revised efficiencies stated at 30% removal of solids, 22% removal of total phosphorus, and 8% removal of total nitrogen.

MDA's Agricultural BMP Handbook (Lenhart et al., 2017) concludes that conservation tillage can reduce soil loss up to 90% relative to conventional tillage. They site a study near Morris, MN on a 12% slope that observed a 96% reduction between moldboard plow and ridge till, accompanied by a 34% reduction in phosphorus load (Moncrief et al., 1996; Ginting et al., 1998). Note that these results compare conservation tillage to aggressive moldboard plowing. Relative reduction is likely to be less for conservation tillage relative to modern conventional tillage practices that reduce soil disturbance but may not leave surface residue. Present-day conventional tillage in the Minnesota River watershed is represented in the APEX modeling as chisel plow, not moldboard plow.

Although no-till systems are more effective in reducing sediment loading from crop fields, they tend to concentrate phosphorus in the upper two inches of the soil profile due to surface application of fertilizer and decomposition of plant material (IAH, 2002; UME, 1996). This pool of phosphorus readily mixes with precipitation and can lead to increased concentrations of dissolved phosphorus in surface runoff. Chisel plowing may be required once every several years to reduce stratification of phosphorus in the soil profile.

In contrast to phosphorus, conservation tillage does not lead to reliable reductions in inorganic nitrogen load, especially on tile drained fields. Indeed, McIsaac et al. (1993) found that no till produced the highest flow-weighted mean concentration of nitrogen in runoff of all tillage types examined. This is apparently associated with greater infiltration under no till practices that can enhance nitrogen leaching from the soil.

Results vary based on local meteorological, soil, and agricultural conditions. It is thus advisable to combine local studies and process-based representation of BMP performance to accurately reflect actual efficiencies achievable under local soil and slope conditions in southern Minnesota.

Pollutant removal efficiencies were compiled for development of the MPCA's SAM Tool (RESPEC, 2017). The recommended pollutant removal efficiencies from RESPEC (2017) take into account multiple references, including the *Agricultural BMP Handbook for Minnesota* (Lenhart et al., 2017), *Nitrogen in Minnesota Surface Waters* (MPCA, 2013), the literature review in Section 2.1 of the Iowa Nutrient Reduction Strategy (Iowa Department of Agriculture and Land Stewardship, 2017), Mayer et al. (2007), O'Neill (2015), Smith (2014), and documentation for the NBMP (Lazarus et al., 2014) and PBMP

(Lazarus et al., 2015) tools. Pollutant removal efficiencies are presented for nitrogen, phosphorus, and suspended sediment (Table 2-12). Reduced tillage is not expected to have a large effect on solids loading from land with slope less than 2% in the Minnesota River Basin due to naturally low rates of surface runoff. RESPEC (2017) notes "Additional review of sediment reductions is needed, and defaults of 50% and 80% are suggested at this time based on the sediment-bound phosphorus reduction research." As with the studies cited above, the proposed TSS removal efficiencies may be higher than would be achieved relative to existing tillage practices.

The *Minnesota Nutrient Reduction Strategy* (MPCA, 2014) also presents pollutant removal efficiencies for conservation tillage: 63% phosphorus reduction. The *Minnesota Nutrient Reduction Strategy* does not include a removal for nitrogen or sediment.

Table 2-12. Default pollutant removal efficiencies for conservation/reduced tillage in MPCA's Scenario Application Manager (RESPEC, 2017)

BMP	Pollutant Removal Efficiency (Percent)				
	TN			TP	TSS
	Surface	Interflow	Baseflow	Surface	Surface
Conservation tillage to increase residue to over 30% on lands sloping more than 2%	33%	0%	0%	33%	50%
No till on lands sloping more than 4%	79%	0%	0%	68%	80%

2.2.3.2 Suitability

Conservation tillage can be applied to most cropland where the cash crops generate sufficient amounts of residue, including corn – soybean rotations. When corn is grown for silage, most of the above-ground biomass is harvested, so conservation tillage may not be applicable. Canning and early season crops may also not generate sufficient residue by themselves. However, both early season crops and corn silage could be followed by a cover crop to help increase residue levels. In the Minnesota River Basin, the clear majority of cropland (88 to 98 percent of crop area by HUC8) is in corn – soybean rotation, and the models do not separately simulate the small amounts of other crop types. Therefore, for the model scenario, all cropland currently in conventional tillage is assumed to be suitable for conservation tillage excluding manured land due to the conflicting need to incorporate manure, which reduces residue cover. Thus, manured lands were not considered suitable for conservation tillage.

The existing HSPF models as redeveloped by RESPEC (Burke, 2012) estimate the fraction of cropland that is in conservation tillage based on an average of the 2004 and 2007 Tillage Transect Surveys (http://mrbdc.mnsu.edu/minnesota-tillage-transect-survey-data-center; Fisher and Moore, 2008). RESPEC took the raw transect survey data and averaged the results by model weather zone, rather than working from the county-level summaries. This is still a road-based and relatively sparse sample of fields, so the results are subject to a fair amount of uncertainty. The Hawk-Yellow Medicine and Chippewa model conservation tillage fractions are based on weighted county-level estimates.

The current HSPF model varies the conservation tillage fraction by weather zone, resulting in a patchwork estimate of distribution of conventional and conservation tillage within each HUC8 (see Figure 2-12.). Averages across HUC8 watersheds are shown in Table 2-13.

Table 2-13. Average conservation tillage rates (percent of cropland) in existing HSPF models of the Minnesota River Basin, based on average of 2004 and 2007 Tillage Transect Surveys

HUC8	Watershed	Conservation Tillage
07020004	Hawk – Yellow Medicine	37.1%
07020005	Chippewa	47.7%
07020006	Redwood	70.3%
07020007	Middle Minnesota	35.9%
07020008	Cottonwood	60.5%
07020009	Blue Earth	36.5%
07020010	Watonwan	40.3%
07020011	Le Sueur	32.5%
07020012	Lower Minnesota	33.9%

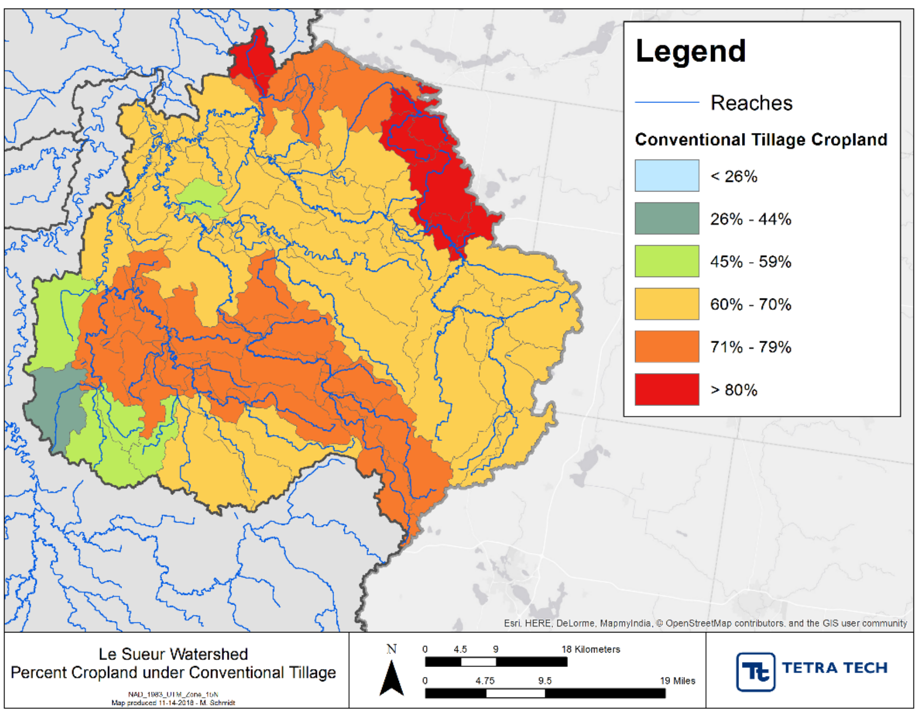


Figure 2-12. Le Sueur River HSPF model distribution of conventional tillage

2.2.3.3 Modeling Approach

Conservation tillage is already included in the calibrated HSPF models. We did not change the model parameters for simulation of conservation tillage given that the model calibration incorporates those parameter values; however, we do compare the efficacy of conservation tillage on sediment reduction as simulated by HSPF to the results of APEX runs and other values in the literature.

Model scenarios test adjusting the existing amounts of conservation tillage that are represented in the HSPF. In addition to the baseline, we investigated impacts of a higher level of implementation.

The high conservation tillage scenario was intended to increase conservation tillage to a high level of adoption on all suitable acres. MPCA first suggested this scenario assume 70% adoption of conservation tillage on cropland with slope above 2%. However, because the amount of cropland with slopes above 2% is small in these watersheds this does not have the intended effect of substantially increasing adoption rates. Therefore, the final scenario was modified to assume 80% adoption on cropland with slopes greater than 2% and 60% adoption on cropland with lower slopes (Table 2-14). For Cottonwood, the net increase relative to the model baseline is still quite small due to the high initial adoption rate from the 2004-2007 tillage transects. Estimates of 2017 conservation tillage implementation from the University of Minnesota are also provided in Table 2-14.

Table 2-14. Conservation tillage percentages for various scenario assumptions

Watershed	Existing Model (2004/7 transects)	2017 Satellite-based Estimates from the University of Minnesota	70% Adoption on Slopes >2%	80% Adoption on Slopes >2%	80% on Slopes > 2%; 60% on Low Slopes
Cottonwood	60.5%	45.1%	45.8%	46.3%	68.4%
Le Sueur	32.5%	45.7%	48.8%	50.7%	70.3%
Middle MN	35.9%	22.1%	26.1%	29.4%	66.6%

2.2.4 Treatment Wetlands

Treatment wetlands can help address excess sediment yield directly by trapping sediment – although effective trapping may introduce the need for periodic sediment removal to ensure long-term sustainability. A key factor in many streams with excess sediment loads is the erosion and degradation of streambanks. Streambank erosion normally occurs because of one of three factors: change in stream flow, water flowing over or through the streambank, and the discharge of concentrated runoff. The stream flow regime is affected by artificial drainage, cropping system and crop biomass changes, and climate change, and artificial drainage has been implicated as a major factor in creating more erosive streams (Schottler et al., 2013). Retention of water in treatment wetlands has the potential to significantly reduce tile drain flow peaks and reduce the total flow volume reaching flowing creeks by a large amount, thus decreasing the flow energy available for channel degradation.

An approach to achieve many of the benefits of natural wetlands while avoiding landowner participation problems is to create constructed treatment wetlands to treat tile drain effluent in riparian areas or ditch borders outside of high quality farmland, as described in the Natural Resources Conservation Service (NRCS) CP 656 Practice Standard (FWP Constructed Wetland; USDA, 2016 – formerly referred to as CP 39). Significant support for this practice has emerged as a strategy to help achieve the reductions in nitrogen loading called for to address hypoxia in the northern Gulf of Mexico (Iovanna et al., 2008).

2.2.4.1 Performance

Nitrogen removal is one of the primary incentives for use of treatment wetlands. Results from wetland systems in Iowa indicate nitrate removal rates of 40 to 90% from subsurface drainage systems (Iowa Dept. of Agriculture, 2009), although others have reported somewhat lower rates (e.g., Tanner and Sukias, 2011). For an edge-of-field tile drain treatment wetland in southwestern Minnesota, Lenhart et al.

(2016) report 68% nitrate removal over a three-year period, mostly due to denitrification in wetland subsoils. In general, the nitrate removal efficiency of constructed wetlands to treat agricultural drainage is well studied (e.g., Crumpton et al., 2006) as to both temporary sequestration of N in biomass and permanent removal via denitrification and off-gassing. The Agricultural BMP Handbook (Lenhart et al., 2017) cites five treatment wetland studies from the Midwest with nitrate removal rates ranging from 40 to 93%. Rozema et al. (2016) summarize agricultural treatment wetland performance from 21 studies in Eastern Canada and the Northeastern US. The mean nitrate reduction from 18 studies of wetlands treating surface flow was 42%.

Treatment wetlands can also provide benefits other than nitrogen removal. USDA (2010) states "The purpose of this practice is to develop a constructed wetland to treat effluent from row crop agricultural drainage systems. The constructed wetland system is designed to reduce nutrient and sediment loading and provide other water quality benefits while providing wildlife habitat." Mean load reductions cited by Rozema et al. for the 18 studies of constructed wetlands treating surface flow were 77% for TSS, 76% for BOD_5, and 63% for TP. For restored tile wetlands, the BMP Database for SAM (RESPEC, 2017) recommends using reduction factors of 52% for TN, 43% for TP, and 75% for sediment. O'Neill (2015) summarizes agricultural BMP performance for phosphorus removal from studies conducted in the Midwest and found that the median load reduction for "wetland creation" for dissolved P was 45% (n = 16).

Constructed wetlands, depending on design, may potentially provide additional functions as well, such as sequestering carbon, reducing greenhouse gas emissions, or improving groundwater recharge. In addition, such wetlands may provide recreational and educational opportunities. The possibility also exists that adjacent upland buffer areas may provide harvestable biomass for energy production and/or native seed production areas. On the other hand, constructed wetlands could potentially increase rates of mercury methylation and greenhouse gas emissions.

2.2.4.2 Suitability

Treatment wetlands are suitable at specific sites that have appropriate hydrology, climate, terrain, and soil characteristics. There must be adequate precipitation (with the appropriate timing and intensity), water must accumulate in landscape depressions, and soil must be conducive to wetland vegetation (e.g., hydric) or the locale for the wetland needs to have a water table at or close to the soil surface under natural conditions. In addition, consideration must be given to farmer willingness to make changes in their land use management practices to improve water quality.

Prior to settlement, the Minnesota River Basin had extensive areas of natural wetlands, although 90 percent or more of these have been lost due to agricultural drainage improvements (Mitsch and Gosselink, 2000). This indicates that potential sites for treatment wetlands will be widespread throughout much of the watershed (Kalcic et al., 2018).

In addition to controlling flows and settling sediment, a motivation for treatment wetlands is likely to be nitrate removal from tile line flow, and wetlands are therefore expected to be sited where tile lines can be daylighted. Model simulation assumes that land suitable for treatment wetlands is present in every catchment, although specific potential sites are not explicitly identified (e.g., through an overlay of flow accumulation and hydric soils). There will not be wetland sites available for every field with tile drainage, but producer acceptance of wetland creation is also likely to be relatively low, in which case site suitability is not likely to be a bounding constraint.

2.2.4.3 Modeling Approach

Conceptually, treatment wetlands are similar to the Iowa design in that they are represented as located high up in the drainage network and primarily fed by daylighted tile drains, although also capturing some surface runoff. The HSPF models assume that most corn/soy cropland in the studied watersheds (Cottonwood, Le Sueur, and Middle Minnesota) will be tile drained. The model does not have a separate representation of tile drained land or varying tile density. HSPF also does not contain an explicit representation of tile drains, but simulates this through an enhanced interflow component. For the purposes of the model, this scenario connects treatment wetlands to a random 20% of the active cropland area. In practice, the focus would and should be on tile-drained land, especially fields with pattern tile that has a defined outlet point that can be daylighted. We can only approximate this in the model, so the performance for nitrate removal may be under-estimated.

The treatment wetland scenario assumes that such wetlands are placed in each model subbasin and that the wetlands treat runoff and interflow (approximated flow from tiles) from 20% of the cropland. (Achieving this level of treatment is ambitious and perhaps not feasible, but will help to bound the estimate of relative benefits that could be obtained from this approach.) While real applications would likely involve multiple small wetlands in each subbasin, these are represented in the model as a single aggregate wetland per model subbasin to reduce complexity of the HSPF model application.

We need to simulate the effects of wetlands on both sediment delivery and alteration of the runoff hydrograph, which may influence channel stability. Therefore, it is necessary to employ a hydrologically explicit representation. In HSPF, this can be accomplished most efficiently by routing 20% of the cropland HRUs to a unit-area wetland reach representation. The output of this unit-area reach representation is then be multiplied by the contributing acreage and routed to the stream. Our initial estimate was that the ratio of land treated to wetland area should be around 20:1. In other words, treatment wetlands to address 20% of the cropland runoff should occupy about 0.95% of the *total* cropland area. The ratio was adjusted during testing to provide the appropriate wetland surface area needed to accomplish design objectives, as discussed below. This land area was converted from cropland to a unit-area reach in the HSPF model implementation of the scenario.

The sizing or hydraulic representation of the wetland reaches is based on the CP 656 requirements to design the wetland (1) to "handle the peak flow and runoff volume from the 25-year frequency, 24-hour duration storm without overtopping the embankment, and (2) "so that water levels will return to design operating levels within 72 hours after a 10-year frequency, 24-hour duration storm event." Note that these storm events are significantly larger than the effective discharge for sediment transport discussed in the Objective 2 memos, which lay between the median flow and the 1.5-year 24-hour storm events. (Note that the sediment transport effective discharge range includes the 90th percentile flow, which is used as the flow target discussed in the companion memorandum, *Sediment Strategy Flow Targets*.) We assume that the wetlands will be constructed with a sediment forebay that is cleaned out periodically to prevent aggradation and loss of storage volume.

The design operating levels are not explicitly stated in the conservation practice, although the design should achieve a hydraulic retention time "that will achieve the intended water quality results." Given the CP 656 definition for the practice, "*An artificial wetland ecosystem with hydrophytic vegetation for biological treatment of water*", a configuration was specified to maintain appropriate aquatic vegetation and to promote water quality treatment. An operating average water depth of about 1 foot is consistent with most recommendations for these purposes.

Exact sizing of the wetlands was confirmed through model experiments relative to the CP 656 design criteria. We sized the BMP to account for upland contribution of surface runoff, interflow (as representative of tile flow), and a fractional contribution of groundwater based on HSPF simulation output. Groundwater contribution to treatment wetlands is likely, since they should be located where there is sufficient inflow to maintain wetland vegetation. In addition, the models were configured to represent direct input of precipitation to the pond surface, as well as evaporation from the pond surface. The BMP configuration and outlet assumptions were sized to achieve multiple objectives: control of the 10-year storm for water quality treatment, safe passage of the 25-year event, and sufficient groundwater input to prevent complete evaporative drying of the wetland on a frequent basis. The following steps were used to carry out the design process:

- An outlet orifice was placed at a stage of 1 foot to maintain a permanent pool consistent with the operating water depth assumption. The orifice was sized to discharge inflow volumes from storm events up to the 10-year 24-hour event over a 72-hour time period.
- A spillway weir was placed at a stage of 4 feet for passage of inflow volumes in excess of the 10-year 24-hour storm. The weir was sized to safely pass larger flooding events (e.g., the 25-year storm).
- Synthetic 24-hour storm hyetographs were developed using the SCS Type II distribution from TR-55, paired with 10-year and 25-year 24-hour storm depths from Atlas 14 at Mankato, MN (4.38 and 5.33 inches, respectively). Test models were created and initialized with average warm season antecedent conditions (using the PWAT-STATE1 table) preceding input of the design storm hyetographs.
- Hourly output from the test model runs was used to construct an inflow hydrograph to the wetland. Storm event outflow from cropland varies mostly according to HSG class, so the inflow hydrograph was constructed to represent the relative contribution from AB versus CD soils in the model (e.g., 58.3% AB and 41.7% CD for the Le Sueur model).
- Optimization was used to find the minimum wetland size needed to store the inflow and direct rainfall from the 10-year 24-hour storm (without exceeding the spillway stage) while discharging the volume over a 72-hour period. An additional orifice was added as needed at an intermediate stage (e.g., around 3 feet) to facilitate the optimization, under the constraint that the intermediate orifice allowed for gradual release of the storage volume over 72 hours. An FTABLE (HSPF table representing the stage, storage, surface area, and discharge relationship) was constructed to represent combined orifice and weir outflows at various stages according to the results of the optimization.
- Groundwater inflow to (interception by) the wetlands was set to 10% of the total groundwater output from the upland treated area; the remaining 90% of the groundwater was routed directly to the receiving reach effectively bypassing the wetland. Treatment wetlands will likely be placed in areas with hydric soils and some groundwater interception is needed to prevent the wetlands from drying up during summer.
- The scenario UCI file was constructed to represent all the elements discussed previously. Pollutant load reductions were applied to outflow from the 72-hour detention orifices, while outflow from the weir was untreated. The assumed reductions for the treated outflow were as follows:
    - Sediment: 75%
    - Nitrate: 42%
    - Phosphate: 45%
    - BOD and labile organic species: 76%

Examination of model output over the course of the 1995 – 2012 simulation period confirmed that long term inflows, outflows, and evaporation from the wetlands were reasonable, that long-term average wetland stages were reasonable, and that complete drying of the wetlands due to evaporation during extended dry periods occurred infrequently.

The sediment reduction for treated outflow from the wetlands was assumed to be 75%. However, a fraction of outflow was assumed to be untreated from the spillway. While the percentage of outflow from the spillway was very low, the fraction of total sediment mass discharged from the spillway was quite high in some cases. As an example, one of the wetlands in the Cottonwood model discharges 96% of long-term outflow from the treatment outlet, and the remaining 4% from the untreated spillway. However, 38% of the total simulated sediment input load to the wetland is discharged from the untreated spillway. This occurs because of very high sediment transport associated with the largest runoff events, resulting in high sediment outflow concentrations and loads discharged from the untreated spillway. The net performance for this example is 46% removal rather than the expected 75% removal.

The effect of the treatment wetlands on reach flows associated with highest sediment transport is also not immediately intuitive. As an example, outflow (from both the orifice and spillway) is plotted against recurrence interval in Figure 2-13 for the Cottonwood wetland discussed in the previous paragraph (assuming an upland contributing area of 100 acres). Wetland outflow is significantly lower than inflow for recurrence intervals greater than 2 years, which is expected given the goal of controlling the 10-year event. However, when zooming in to lower recurrence intervals (Figure 2-14), wetland outflow exceeds inflow for much of the range below about a 1.2-year recurrence interval. The reason is that the wetland design objectives in CP 656 do not address volume control for smaller, more frequent events. The outflow orifice for the 10-year event must be sufficiently large enough to discharge the target volume over 72 hours. The volume from smaller events is discharged relatively quickly, and over an extended duration compared to untreated runoff. If treatment wetlands are to be effective for reducing basin-scale flows in the Minnesota River system to address near-channel sediment erosion, the wetland design criteria should be adapted to incorporate extended detention for more frequent storm events.

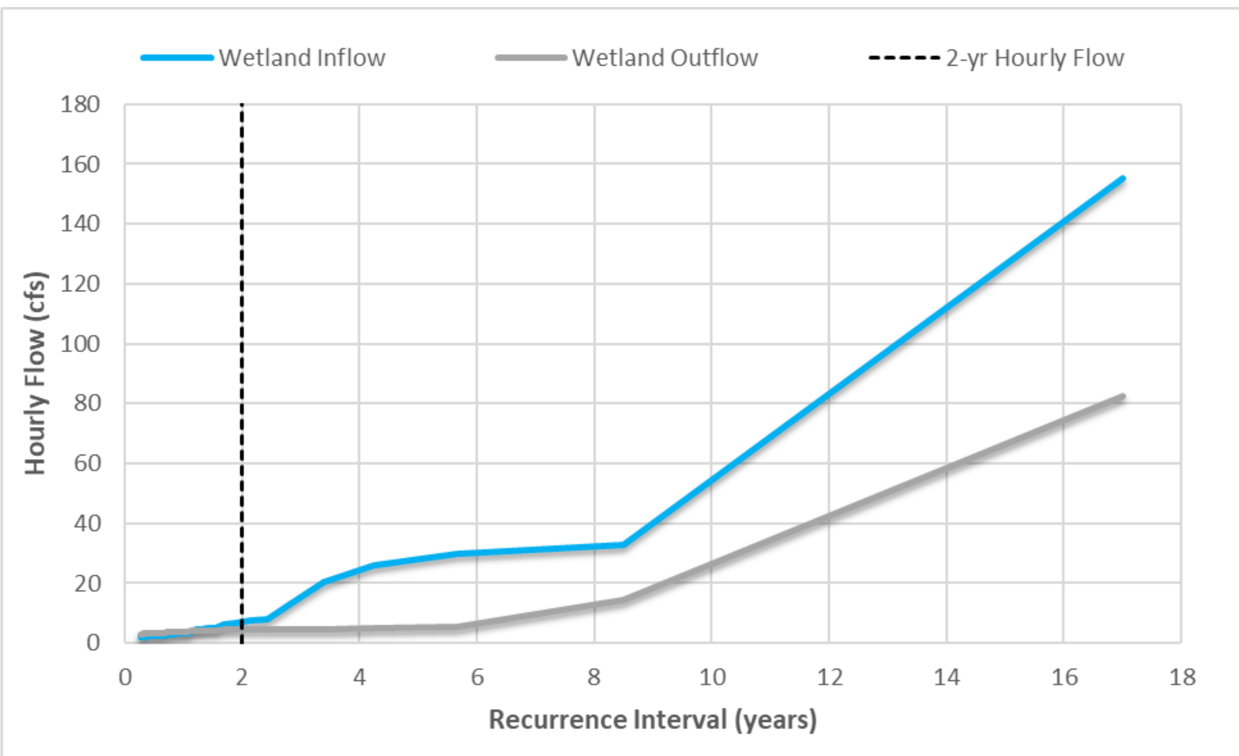


Figure 2-13. Example flow analysis for Cottonwood treatment wetland, focusing on larger recurrence intervals

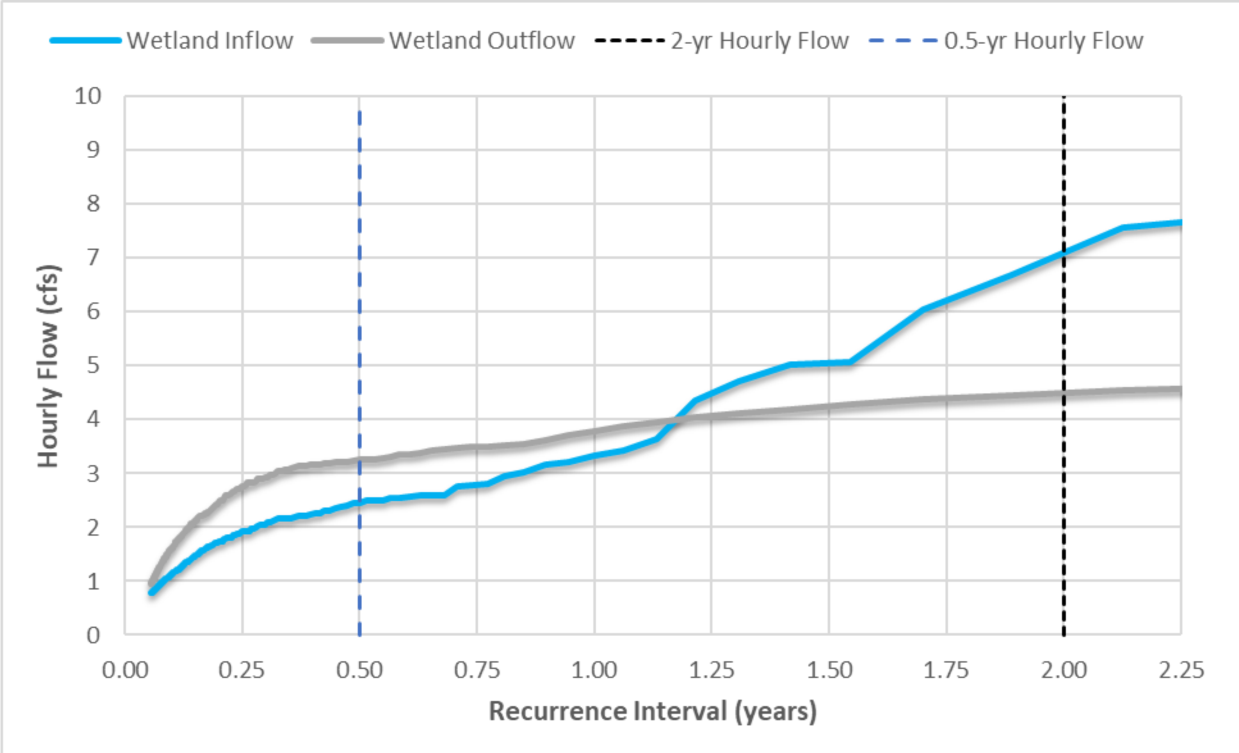


Figure 2-14. Example flow analysis for Cottonwood treatment wetland, focusing on smaller recurrence intervals

2.2.5 Perennials

This scenario evaluates the potential water quality benefits associated with converting some cropland in the watershed currently used to cultivate summer cash crops to perennial crops. Switchgrass is a perennial crop that can be grown in Minnesota and harvested for bioenergy; therefore, switchgrass was selected as the representative perennial crop for this scenario. For this scenario 20% of cropland is used for growing switchgrass. Perennial crops can be used as prairie strips in fields or mixed into longer, multi-year rotations with summer cash crops, but those options are not evaluated in this study.

2.2.5.1 Performance

Unlike annual summer crops, perennial crops maintain erosion cover throughout the year. Established perennial crops begin rapid growth and evapotranspiration earlier compared to annual crops planted as seed in the spring. The USACE (2016) draft whitepaper on Minnesota River Alternative Landscape Analysis describes perennial "grassland/reserve" (i.e., native grassland without frequent fire disturbance) as follows:

Vegetation: The Grassland/Reserve class is composed almost entirely of dense grass cover, typically of few species. Grasses may be native, such as switchgrass and big bluestem, or may be non-native, such as Kentucky bluegrass and reed canary grass. This class has few forbs since they do not compete well against grasses without disturbance. Thick grasses cover the soil with substantial biomass, a high number of stems per area, and both standing and flattened dead grass.

Soils and Hydrology: The soil characteristics of this class vary, but would tend to have higher organic matter as biomass builds up. The amount of organic matter would depend on land use preceding the *grassland reserve, the length of time the land has been fallow, and the original characteristics of the soil. The hydrologic regime is the same as for native prairies.*

Disturbance: There is little disturbance in this land cover class. The absence of grazing, mowing, and fire promotes thick grass biomass. There tends to be more standing and dead biomass than in native prairie or pasture/hay land covers.

Lenhart (2017) lumps perennial crops in with other types of conservation cover and notes the benefits of reduced soil erosion and lower surface runoff, along with reduced nutrient loads. Exact results depend on the type of perennial cover and whether it is periodically harvested and replanted.

In many instances, perennial crops will be sited to also serve as riparian buffers or filter strips, providing additional treatment for adjacent cropland. For this scenario, we do not assign a buffer function, but rather analyze only the change in source loads associated with conversion to perennial crops. Combination of both perennial cover and riparian buffer functioning can be inferred by combining the results of the perennial cover scenario with those of the riparian buffer scenario.

2.2.5.2 Suitability

Perennial grass crops are theoretically suitable for most croplands in the Minnesota River Basin, much of which was originally in prairie or savanna land cover. The main obstacle to implementation of perennials is producer objections to removing profitable farm land. Some mitigation is provided by allowing periodic harvest of biomass for cellulosic fuel production, as is included in this scenario.

This scenario assumes that 20% of cropland is converted to switchgrass as a perennial cover. While we choose a single perennial for modeling purposes, we would expect in practice that a wide variety of perennial crops may be used either in a single field and/or collectively across the landscape.

2.2.5.3 Model Assumptions

The specific management assumptions for perennials are that the switchgrass is on a six-year rotation, with annual biomass harvest in the fall and reseeding every sixth year during which there is a short period of exposed soil; no application of fertilizer is represented. These management assumptions are used in APEX simulations to estimate the performance of switchgrass for HSPF. Perennials were targeted on cropland with poorly draining soils and extended to better drained soils as necessary to achieve the 20% conversion target.

Distinctions among grassland types have generally not been fully addressed in most MPCA-funded HSPF models. The current MPCA modeling guidance (AQUA TERRA, 2012) suggests relying primarily on NLCD land cover and says “The ‘Barren’, ‘Shrub/Scrub’, and ‘Grassland’ categories can be combined since they represent small portions of the study area.” While it is true that these usually are small portions of the study area, the pollutant load generating characteristics of these land uses can be quite different. Very little land in the existing models is categorized as grassland, therefore, cropland was shifted to grassland and the grassland HRUs were parameterized to represent perennial switchgrass. Parameterization started with the existing grassland parameter set, which was modified to approximate results obtained from APEX simulations of switchgrass production. The APEX predicted performance of switchgrass varied across the study watersheds, as did loading rates from existing cropland in HSPF, so different parameter adjustments were applied accordingly in HSPF. The key parameters adjusted to represent changes in evapotranspiration, surface runoff, and sediment erosion were INTERCEP, LZETPARM, MANNINGS, UZSN, COVER, and KSER, and monthly varying parameters were established to be representative of continuous cover. Conversion to perennials will mostly be on poorer soils so it was not considered necessary to subset by HSG or slope. Nutrient accumulation rates, sediment potency factors, and subsurface concentrations were also refined based on APEX simulations, although nutrient load reductions are not the primary focus of this study.

2.2.6 Ravine Mitigation

Ravines are a substantial source of sediment load, especially in the Greater Blue Earth River Basin. Interventions that limit ravine incision can result in a substantial reduction in this load. The Management Options Simulation Model (MOSM) is a spreadsheet-based tool that provides a reduced complexity representation of the results from the Greater Blue Earth River (GBER) sediment budget (Wilcock et al., 2016; Collaborative for Sediment Source Reduction, 2017), which includes the Blue Earth, Watonwan, and Le Sueur HUC 8 watersheds.

2.2.6.1 Performance

The load estimated to be generated by ravines in MOSM arises from a combination of ravine tip migration, incision of the bed, and hillslope erosion, as well as any sediment coming into the ravine from the upstream fields. The load coming out of each ravine was based on several years of ravine monitoring in five ravines in the lower Le Sueur, calculation of TSS loads on ravines and the mainstem channel, and comparing calculated loads with incised ravine areas. Through this, the MOSM team developed a relationship that linked incised ravine area to annual TSS load. Ravines are typically dendritic with multiple tips, and the number of tips can be used to partition the load estimated from a single ravine with a certain incised ravine area into the number of tips. A strategy for slowing or stopping the extension of ravine tips into farmland is to use berms and ponds to capture field runoff (Tran, 2015). This could possibly be combined with grade control structures within ravines to slow channel incision. MOSM allows the user to specify a stabilization effectiveness by ravine tip.

Loads from uncontrolled ravines in MOSM are estimated based on a sediment loading rate per unit area of the ravine of 0.002 Mg/m^2-yr (Gran et al., 2011). The MOSM documentation states “Typically, 20% of sediment outputs from ravines are sourced from upstream of ravines.” Therefore, the maximum that can be gained from ravine tip stabilization is about an 80% reduction, although evidence on exactly what can be reliably achieved is unclear.

2.2.6.2 Suitability

Control of sediment loads through tip stabilization or other strategies is potentially applicable to ravines throughout the Minnesota River Basin. However, currently we have detailed spatial information on ravines only for the Le Sueur watershed.

2.2.6.3 Modeling Approach

In the existing HSPF model of the Le Sueur River, ravines were simulated as a separate land use based on information from the University of Minnesota’s Ravines, Banks, and Bluffs Project and the GIS layers of bluff and ravine locations assembled for the Integrated Sediment Budget for the Le Sueur River basin (Gran et al., 2011; Figure 2-15). (Bluffs are also represented as a separate land use, but bluff loads are not changed in this scenario.) Ravine mitigation in the Le Sueur model can be implemented in HSPF by reducing the sediment load transmitted to the receiving waters by 80%, consistent with the maximum suggested in the MOSM analysis. (The Le Sueur model also simulates some gully erosion within cropland HRUs. This is addressed using the method for the other watersheds described in the next paragraph.)

For HUC8 watersheds other than the Le Sueur, ravines are not simulated as a separate land use (HRUs for ravines are listed under the PERLND block but no ravine land area is included in the SCHEMATIC); however, gully formation on crop land is represented using simplified HSPF routines for simulating scour of the soil matrix by overland flow. The ravine components are not directly calibrated to measurements of ravine extension, but were adjusted during the sediment calibration to help maintain the overall sediment mass balance while also preserving the ratio of sediment recently derived from the surface to total sediment load inferred from radiometric data.

For watersheds other than the Le Sueur, we assume that the 80% rate of reduction estimated for Le Sueur ravines can be achieved in the gully erosion output (SCRSD) produced by the cropland HRUs. This was implemented in the MASS-LINK connections.

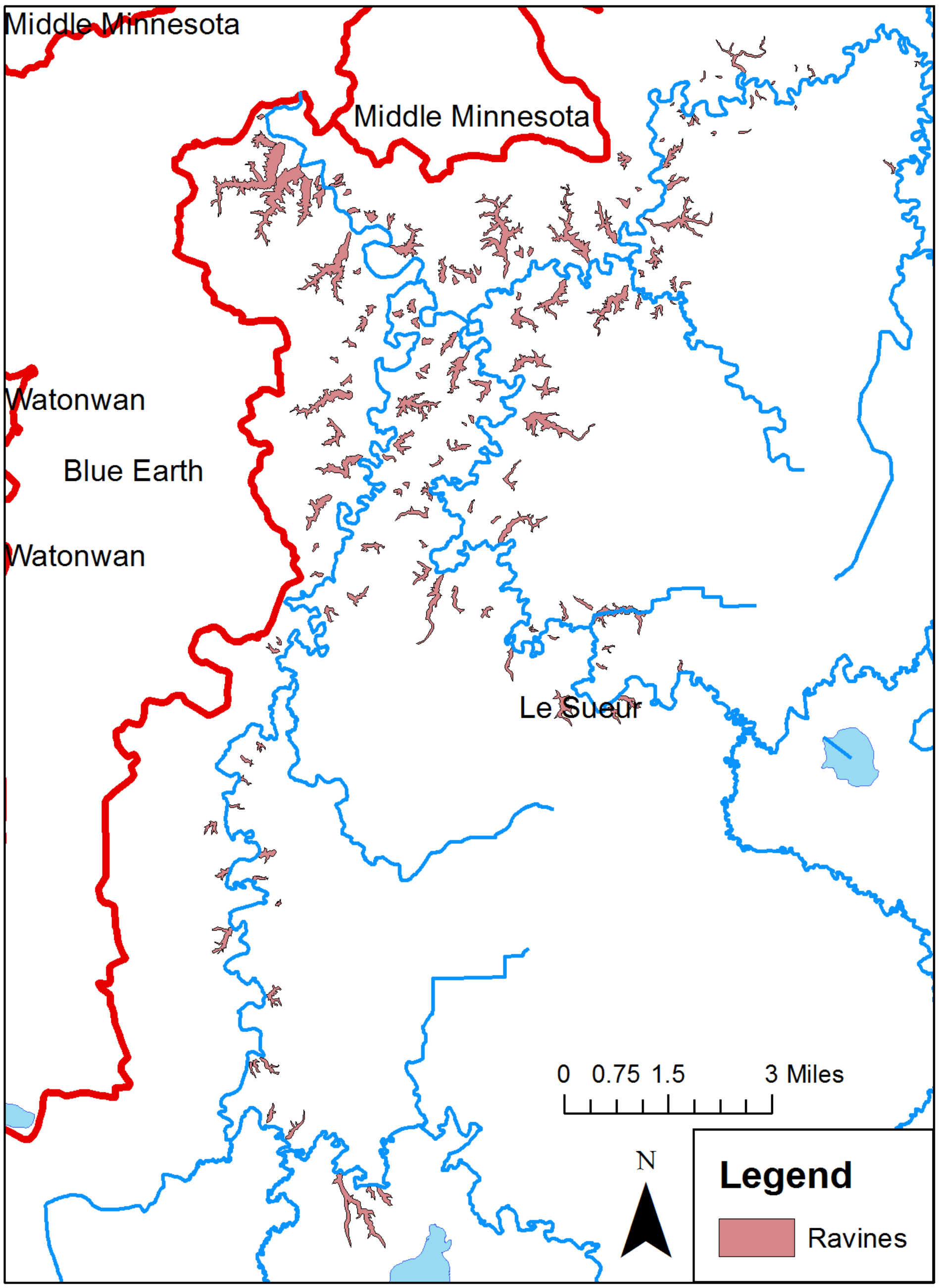


Figure 2-15. Mapped ravines in the western Le Sueur River Watershed

Coverage from work described in Gran et al. (2011).

2.2.7 Combination Scenarios

Three scenarios that represent BMPs implemented in combination were selected with input from MPCA and the sediment strategy Technical Advisory Team. Results from the individual BMP modeling scenarios, and anticipated acceptability and feasibility of the practices, were considered during the selection of the combination scenarios. These three scenarios assess the potential comprehensive impacts of implementing agricultural BMPs in combination across the study watersheds. The three combination BMP modeling scenarios, which were simulated for the Cottonwood, Le Sueur, and Middle Minnesota watersheds, include the following:

1. Cover crops (high adoption, 75% of cropland) + perennials + treatment wetlands
2. Cover crops (high adoption, 75% of cropland) + buffers (all) + ravine mitigation
3. Cover crops (low adoption, 25% of cropland) + conservation tillage + treatment wetlands

Some BMP combinations, such as cover crops and perennials, must be implemented on different cropland, whereas other practice pairings, such as cover crops and treatment wetlands, can treat the same cropland. For the first combination scenario, which includes better performing practices, 20% of cropland was converted to perennial switchgrass (as was done for this individual BMP scenario). Then cover crops were adopted on 75% of the remaining cropland. Lastly, 20% of active cropland (i.e., cropland not converted to perennials) was treated by wetlands. A similar approach was applied for the second combination scenario; cropland was converted to riparian buffers then 75% of the remaining cropland implemented cover crops. Ravine mitigation was then incorporated. For the final combination scenario, higher rates of implementation of conservation tillage were combined with a lower adoption of cover crops (25%) and 20% of cropland was routed to treatment wetlands.

It is important to note that additional BMPs either treat cropland that has already been treated by another BMP (e.g., a buffer receives flow from a field using cover crops) or treat cropland that exhibits lower baseline erosion (e.g., flat fields). Therefore, combining multiple BMPs will often be less effective compared to when the practice is implemented in isolation.

Results for the combination scenarios are presented with the results from the individual BMP scenarios in Section 3.0.

(This page left intentionally blank.)

3.0 Results

The BMP modeling scenarios were evaluated for changes in flow, both annual average flow and the 95th percentile flow (equaled or exceeded 5% of the time), and sediment load. We choose the 95th percentile flow because high flow events are likely to not only erode and transport sediment from the landscape, but also exhibit sheer power that can scour channel beds and banks. Percent reductions are evaluated at the downstream pour point or mouth of each HUC8 and are relative to the baseline models (Figure 3-1. to Figure 3-3.). These results represent the reductions achieved for the period of 1996-2012. Note that reductions presented for the Middle MN watershed include the BMPs being implemented in Cottonwood and Le Sueur as well as locally in the Middle MN watershed, but not in the other upstream HUC8s that were not included in this phase of the study.

The implementation level and BMP performance comprehensively impact the reduction at the watershed outlet. For example, the maximum reduction in the total upland load that could be expected for a BMP that reduces field sediment load by 50% implemented across 20% of the watershed would be 10% (50% x 20% = 10%). However, the actual reduction at the watershed outlet would be lower because near channel sources also contribute sediment to the stream. If 40% of the total sediment load is from upland erosion in this hypothetical example, then the maximum reduction at the outlet would be about 4% (10% x 40% = 4%). For this reason, the basin-scale load reductions may appear to be significantly less than the field-scale reductions often presented in the literature. Implementation levels are summarized in Table 3-1. Furthermore, BMPs that detain water and promote infiltration can reduce surface runoff and sediment pollution but increase leaching and pollution from interflow and groundwater. All results presented in this report indicate the *net* reduction across all flow pathways (surface runoff, interflow, and groundwater) and in-channel processes (e.g., deposition and scour of sediment in the reach network). Therefore, BMPs that alter pollutant pathways are comprehensively assessed in terms of water quality impacts at the watershed-scale. This applies to all results presented in this section.

Table 3-1. Implementation level summary for BMP modeling scenarios

BMP	Modeled Implementation Level
Cover Crops (25% adoption)	Cover crops adopted on 25% of cultivated cropland.
Cover crops (75% adoption)	Cover crops adopted on 75% of cultivated cropland.
Riparian Buffers (Buffer Law)	Buffers represented on public waterways and drainage systems.
Riparian Buffers (All)	Buffers represented on all waterways.
Conservation Tillage (High Adoption)	Adoption of conservation tillage on 80% of cropland with slopes ≥ 2% and on 60% of cropland with slopes < 2% (Table 2-14).
Treatment Wetlands	Treatment wetlands receive flow from 20% of cultivated cropland.
Perennials	Perennials replace 20% of cultivated cropland.
Ravine Mitigation	Prevents gully erosion on cropland and ravines.

The BMPs studied in this report are designed to primarily target reductions in sediment loading (excluding treatment wetlands), and flow reductions are ancillary benefits that in some cases reduce near-channel sediment sources. In regards to the individual BMP scenarios, perennials, which intercept precipitation and enhance evapotranspiration and infiltration, reduce average annual flow volumes by about 5% in Cottonwood and Le Sueur (Figure 3-1.). Perennials are also effective at reducing the 95th percentile flow by about 7% in both headwater study watersheds (Figure 3-2.). A large portion of the drainage area contributing flow to the Middle MN is not represented as implementing perennials for purposes of this study (e.g., the Watonwan watershed), thus, the reductions are significantly lower at this assessment location for all practices. Cover crops also facilitate moisture retention on fields by enhancing interception of precipitation, increasing winter and early spring evapotranspiration, and by improving soil composition as cover crop residue is maintained on fields. These attributes are predicted to provide annual average flow reductions slightly above 3% when cover crops are adopted on 75% of cropland, and by about 1% when cover crops are adopted on 25% of cropland.

Treatment wetlands are designed to capture and slowly release water allowing particulate matter time to settle out of the water column. As discussed in Section 2.2.4, recommendations specify that treatment wetlands be sized for the 24-hour duration, 10-year return storm, with a 72-hour release that returns the wetland depth to the permanent pool depth. Such outlet structure sizing results in the rapid release (< 72 hours) of lower precipitation depth storms that occur more frequently. Thus, the reductions in annual average flow for treatment wetlands implemented based on the current design criteria, are shown to provide minimal reductions in the 95th percentile flow at watershed outlets (Figure 3-1. and Figure 3-2.). Treatment wetlands established based on multiple objectives (e.g., multiple outlets to handle different storm sizes) are likely to perform better as discussed in Section 2.2.4. Flow reductions for other BMPs, including riparian buffers, conservation tillage, and ravine mitigation, are smaller.

Instead of leaving fields exposed in the non-growing season, cover crops provide vegetative cover and roots that stabilize soils and prevent erosion. Cut cover crop residue maintained on fields prior to spring planting also provides erosion protection. Of all the BMP scenarios, adding cover crops on 75% of cropland provides the largest benefit in terms of sediment load reductions (Figure 3-3.). Reductions at the outlet of Cottonwood and Le Sueur are about 14% and 13%. Converting cropland used to cultivate annual crops to perennial switchgrass provides nearly the same magnitude of benefits, at 14% and 11%, respectively. Riparian buffers reduce sediment loads at watershed outlets by about 6% in Cottonwood and 5% in Le Sueur.

The largest reductions in annual flow, 95th percentile flow, and sediment load are achieved with the BMP combination scenario that pairs cover crops (adopted on 75% of cropland), perennials, and treatment wetlands. In the Cottonwood River watershed, this scenario reduces the sediment load by about 25%. Combining covers crops (adopted on 75% of cropland), buffers (all waterways), and ravine mitigation provides reductions in sediment load of about 19%, 23%, and 7% in Cottonwood, Le Sueur, and Middle Minnesota, respectively (Figure 3-3.).

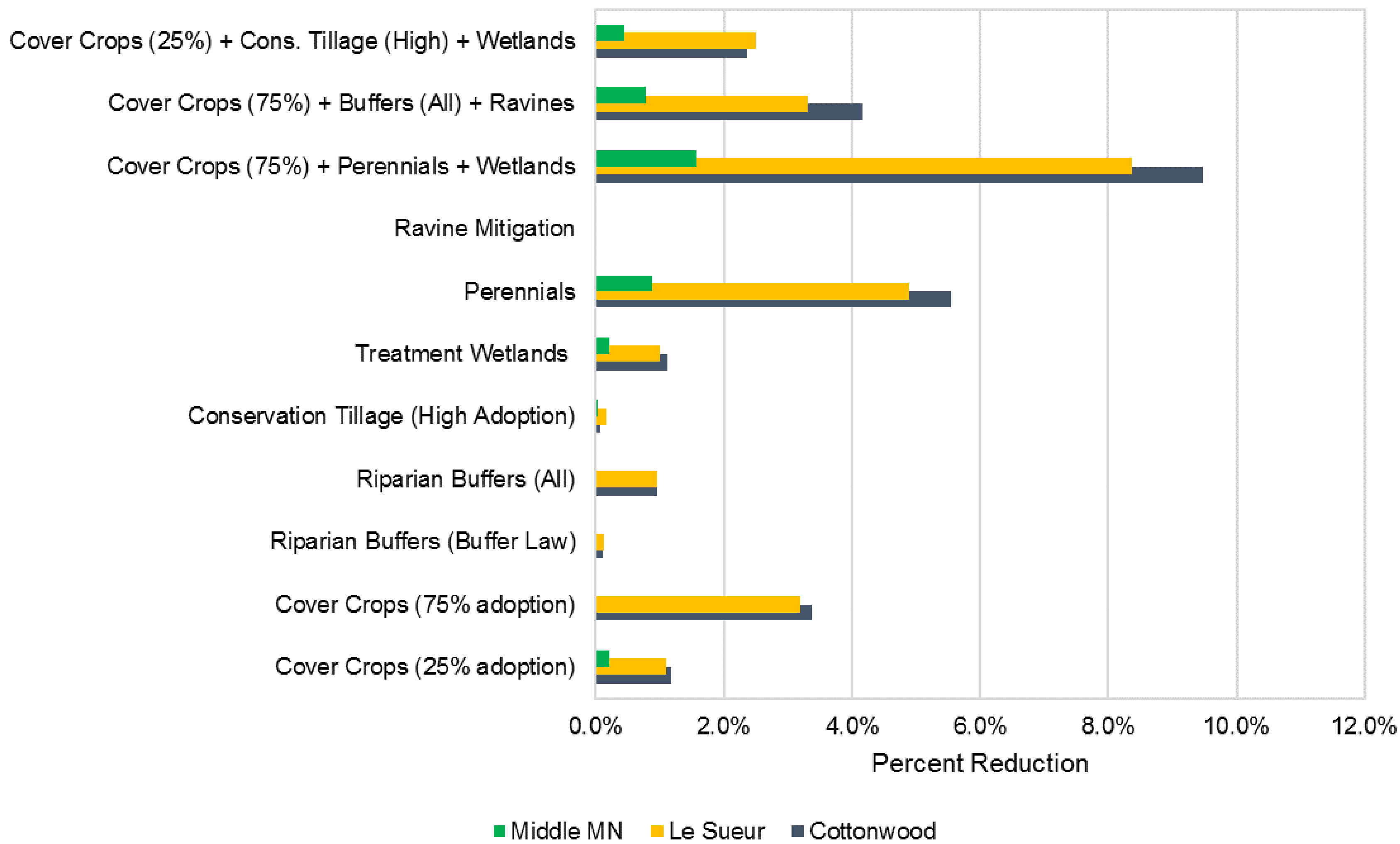


Figure 3-1. Percent reduction in annual average flow volume

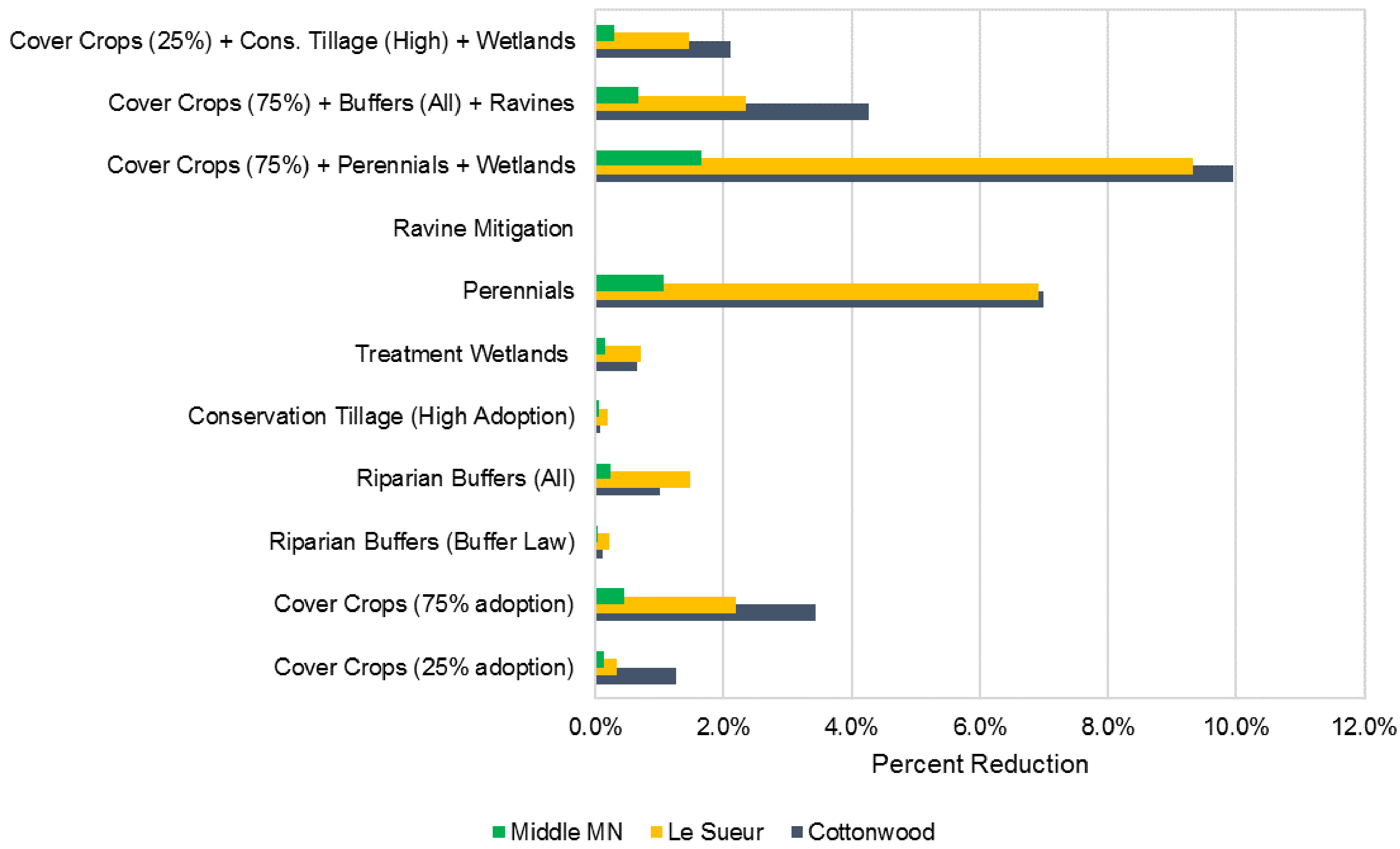


Figure 3-2. Percent reduction in 95th percentile flow

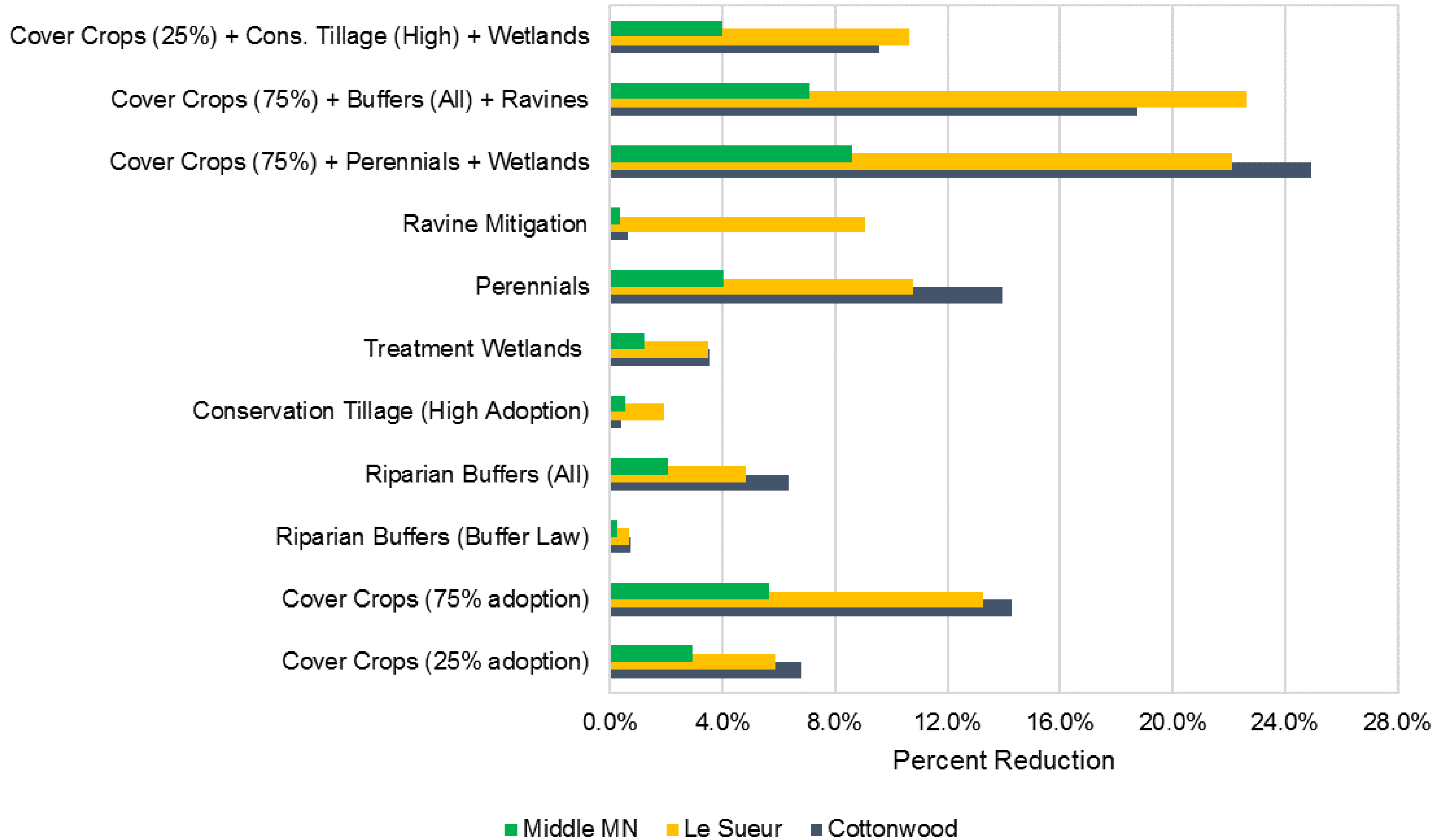


Figure 3-3. Percent reduction in annual sediment load

BMPs perform differently under varied weather conditions, such as during years with infrequent, but intense, rainstorms versus years with frequent, lower intensity, rainstorms, or exceptionally dry years. Thus, the reductions in flow and sediment load achieved with the BMPs vary across the simulation period. To show inter-annual differences in BMP performance, percent reductions are summarized for wet, normal, and dry years, categorized by annual flow volume, in Table 3-2 to Table 3-7. Annual reductions are also presented in Table 3-8 to Table 3-19. The tables are color-coded, with the three wettest years (based on flows at the downstream pour point of the HUC8) shown in red, the three middle (normal) years in tan, and the three driest years in green. These results are for the whole HUC8 watershed (i.e., include cropland not treated by the BMP and other land uses). Reduction in flow volume or sediment load is indicated by a positive percentage. As previously mentioned, the Middle MN River watershed is downstream of Cottonwood and Le Sueur, therefore, the results reflect BMP implementation in all three watersheds. For most BMPs, percent reductions are larger for the normal and drier years when less overflow and bypassing occur; however, the mass reduced is larger for the wetter years that produce more load.

Table 3-2. Summary of annual flow reductions at the HUC8 outlets for individual BMP scenarios (wet, normal, and dry years)

Year	Baseline Flow (cfs)	Pollutant Removal Efficiency (Percent)							
		Cover Crops (25% adoption)	Cover Crops (75% adoption)	Riparian Buffers (Buffer Law)	Riparian Buffers (All)	Conservation Tillage (High Adoption)	Treatment Wetlands	Perennials	Ravine Mitigation
Cottonwood River Watershed									
Wet	945	1.00%	2.83%	0.07%	0.51%	0.02%	0.72%	3.60%	0.00%
Normal	483	1.91%	5.34%	0.16%	0.91%	0.19%	1.38%	5.99%	0.00%
Dry	307	1.81%	5.07%	0.22%	1.61%	0.24%	2.08%	7.45%	0.00%
Le Sueur River Watershed									
Wet	1,044	0.85%	2.46%	0.11%	0.78%	0.10%	0.76%	4.11%	0.00%
Normal	647	1.01%	2.97%	0.17%	1.23%	0.17%	1.05%	6.19%	0.00%
Dry	400	1.37%	3.95%	0.22%	1.55%	0.32%	1.70%	7.99%	0.00%
Middle Minnesota River Watershed									
Wet	10,207	0.16%	0.46%	0.02%	0.14%	0.01%	0.13%	0.60%	0.00%
Normal	5,410	0.22%	0.60%	0.03%	0.25%	0.03%	0.26%	0.98%	0.00%
Dry	2,947	0.29%	0.83%	0.06%	0.45%	0.08%	0.41%	1.77%	0.00%

Table 3-3. Summary of annual flow reductions at the HUC8 outlets for combination BMP scenarios (wet, normal, and dry years)

Year	Baseline Flow (cfs)	Pollutant Removal Efficiency (Percent)		
		Cover Crops (75% adoption) + Perennials + Treatment Wetlands	Covers Crops (75% adoption) + Buffers (all) + Ravine Mitigation	Cover Crops (25% adoption) + Conservation Tillage + Treatment Wetlands
Cottonwood River Watershed				
Wet	945	6.61%	3.16%	1.68%
Normal	483	11.51%	5.87%	3.27%
Dry	307	13.64%	6.36%	3.98%
Le Sueur River Watershed				
Wet	1,044	6.78%	2.56%	1.79%
Normal	647	9.54%	3.13%	2.43%
Dry	400	12.76%	4.14%	3.85%
Middle Minnesota Watershed				
Wet	10,207	1.10%	0.57%	0.30%
Normal	5,410	1.71%	0.82%	0.49%
Dry	2,947	2.88%	1.26%	0.79%

Table 3-4. Summary of 95th percentile flow reductions at the HUC8 outlets for individual BMP scenarios (wet, normal, and dry years)

Year	Baseline Flow (cfs)	Pollutant Removal Efficiency (Percent)							
		Cover Crops (25% adoption)	Cover Crops (75% adoption)	Riparian Buffers (Buffer Law)	Riparian Buffers (All)	Conservation Tillage (High Adoption)	Treatment Wetlands	Perennials	Ravine Mitigation
Cottonwood River Watershed									
Wet	4,765	1.63%	4.08%	0.01%	0.10%	-0.01%	0.53%	3.95%	0.00%
Normal	1,619	1.52%	4.60%	0.21%	1.68%	0.27%	0.88%	8.76%	0.00%
Dry	1,126	1.47%	4.62%	0.19%	1.55%	0.30%	1.39%	7.46%	0.00%
Le Sueur River Watershed									
Wet	4,963	0.85%	3.14%	0.22%	1.49%	0.00%	1.17%	6.99%	0.00%
Normal	2,548	-0.05%	1.19%	0.23%	1.50%	0.40%	0.24%	7.52%	0.00%
Dry	1,672	0.27%	1.64%	0.27%	1.96%	0.48%	1.21%	10.06%	0.00%
Middle Minnesota River Watershed									
Wet	47,059	0.24%	0.66%	0.02%	0.14%	0.04%	0.14%	1.08%	0.00%
Normal	20,344	-0.48%	-0.36%	0.04%	0.28%	-0.01%	0.07%	0.89%	0.00%
Dry	13,285	0.47%	0.90%	0.07%	0.55%	0.09%	0.44%	2.26%	0.00%

Table 3-5. Summary of 95th percentile flow reductions at the HUC8 outlets for combination BMP scenarios (wet, normal, and dry years)

Year	Baseline Flow (cfs)	Pollutant Removal Efficiency (Percent)		
		Cover Crops (75% adoption) + Perennials + Treatment Wetlands	Covers Crops (75% adoption) + Buffers (all) + Ravine Mitigation	Cover Crops (25% adoption) + Conservation Tillage + Treatment Wetlands
Cottonwood River Watershed				
Wet	4,765	4.98%	4.13%	2.05%
Normal	1,619	13.79%	5.21%	2.83%
Dry	1,126	13.59%	6.02%	3.51%
Le Sueur River Watershed				
Wet	4,963	8.43%	3.27%	2.19%
Normal	2,548	9.86%	1.40%	0.38%
Dry	1,672	14.79%	1.84%	2.17%
Middle Minnesota Watershed				
Wet	47,059	1.56%	0.78%	0.39%
Normal	20,344	1.10%	-0.08%	-0.36%
Dry	13,285	3.12%	1.45%	0.80%

Table 3-6. Summary of sediment reductions at the HUC8 outlets for individual BMP scenarios (wet, normal, and dry years)

Year	Baseline Load (1000 tons/yr)	Pollutant Removal Efficiency (Percent)							
		Cover Crops (25% adoption)	Cover Crops (75% adoption)	Riparian Buffers (Buffer Law)	Riparian Buffers (All)	Conservation Tillage (High Adoption)	Treatment Wetlands	Perennials	Ravine Mitigation
Cottonwood River Watershed									
Wet	358.5	6.14%	12.66%	0.64%	5.49%	0.31%	2.91%	9.58%	0.34%
Normal	94.0	7.68%	15.37%	0.61%	5.27%	0.72%	3.06%	15.62%	0.15%
Dry	48.9	7.20%	16.24%	0.82%	6.88%	0.71%	5.21%	20.01%	0.15%
Le Sueur River Watershed									
Wet	470.5	5.37%	12.69%	0.66%	4.80%	1.88%	3.42%	9.76%	6.85%
Normal	194.0	5.99%	13.54%	0.79%	5.63%	2.10%	3.79%	13.74%	1.95%
Dry	103.6	8.70%	17.16%	0.93%	6.50%	2.24%	4.61%	17.96%	2.75%
Middle Minnesota River Watershed									
Wet	2,039	2.09%	3.80%	0.21%	1.73%	0.32%	0.87%	2.68%	0.11%
Normal	884	3.48%	7.05%	0.28%	2.26%	0.53%	1.50%	4.72%	0.70%
Dry	480	2.94%	5.84%	0.30%	2.41%	0.54%	1.65%	6.45%	0.18%

Table 3-7. Summary of sediment reductions at the HUC8 outlets for combination BMP scenarios (wet, normal, and dry years)

Year	Baseline Load (1000 tons/yr)	Pollutant Removal Efficiency (Percent)		
		Cover Crops (75% adoption) + Perennials + Treatment Wetlands	Covers Crops (75% adoption) + Buffers (all) + Ravine Mitigation	Cover Crops (25% adoption) + Conservation Tillage + Treatment Wetlands
Cottonwood River Watershed				
Wet	358.5	18.92%	16.46%	8.28%
Normal	94.0	26.47%	18.96%	10.20%
Dry	48.9	34.08%	21.33%	12.02%
Le Sueur River Watershed				
Wet	470.5	20.76%	19.48%	10.20%
Normal	194.0	25.24%	16.67%	10.78%
Dry	103.6	32.65%	20.20%	14.63%
Middle Minnesota Watershed				
Wet	2,039	5.55%	5.05%	2.75%
Normal	884	10.54%	8.46%	4.75%
Dry	480	11.02%	7.50%	4.36%

Table 3-8. Annual flow reductions for BMP scenarios in the Cottonwood River watershed

Year	Baseline Mean Flow (cfs)	Flow Reduction (Percent)										
		Cover Crops (25% adoption)	Cover Crops (75% adoption)	Riparian Buffers (Buffer Law)	Riparian Buffers (All)	Cons. Tillage (High Adoption)	Treatment Wetlands	Perennials	Ravine Mitigation	Cover Crops (75%) + Perennials + Wetlands	Cover Crops (75%) + Buffers (all) + Ravines	Cover Crops (25%) + Cons. Tillage + Wetlands
1996	576	0.84%	2.43%	0.11%	1.11%	0.01%	0.62%	5.50%	0.00%	8.23%	3.47%	1.53%
1997	856	0.85%	2.54%	0.10%	0.84%	0.05%	0.88%	4.30%	0.00%	7.29%	3.26%	1.78%
1998	439	1.33%	3.78%	0.25%	1.76%	0.22%	1.32%	7.92%	0.00%	12.20%	5.28%	2.72%
1999	388	0.66%	2.06%	0.10%	1.49%	0.03%	1.14%	7.97%	0.00%	11.32%	3.62%	2.11%
2000	282	2.00%	5.60%	0.32%	2.28%	0.36%	2.36%	9.76%	0.00%	16.63%	7.48%	4.46%
2001	891	1.22%	3.21%	0.13%	0.43%	0.09%	0.93%	3.35%	0.00%	6.62%	3.31%	1.96%
2002	396	1.17%	3.74%	-0.07%	0.94%	-0.01%	1.47%	5.23%	0.00%	10.47%	4.87%	3.19%
2003	287	1.33%	3.86%	0.18%	1.70%	0.17%	1.82%	8.57%	0.00%	13.76%	5.40%	3.37%
2004	570	1.11%	2.89%	0.18%	1.39%	0.03%	1.36%	7.69%	0.00%	11.35%	4.11%	2.42%
2005	491	2.01%	5.74%	0.22%	0.90%	0.30%	1.21%	6.04%	0.00%	11.56%	6.11%	3.13%
2006	594	0.66%	2.08%	0.04%	0.98%	-0.05%	0.83%	5.74%	0.00%	8.63%	3.15%	1.70%
2007	519	2.38%	6.48%	0.01%	0.06%	0.05%	1.62%	4.02%	0.00%	10.77%	6.21%	3.98%
2008	363	0.92%	2.52%	0.15%	1.34%	0.07%	1.36%	6.40%	0.00%	10.04%	3.75%	2.38%
2009	350	2.11%	5.76%	0.16%	0.86%	0.18%	2.06%	4.03%	0.00%	10.54%	6.21%	4.13%
2010	973	1.48%	4.36%	0.03%	0.28%	-0.02%	0.68%	3.23%	0.00%	7.48%	4.42%	2.14%
2011	970	0.31%	0.93%	0.07%	0.81%	0.00%	0.56%	4.22%	0.00%	5.74%	1.75%	0.95%
2012	422	1.22%	3.38%	0.17%	1.51%	0.16%	1.61%	10.54%	0.00%	15.05%	4.74%	2.97%
Mean	551	1.19%	3.38%	0.11%	0.95%	0.07%	1.12%	5.55%	0.00%	9.48%	4.17%	2.37%

Table 3-9. 95th percentile flow reductions for BMP scenarios in the Cottonwood River watershed

Year	Baseline Flow (cfs)	Flow Reduction (Percent)										
		Cover Crops (25% adoption)	Cover Crops (75% adoption)	Riparian Buffers (Buffer Law)	Riparian Buffers (All)	Cons. Tillage (High Adoption)	Treatment Wetlands	Perennials	Ravine Mitigation	Cover Crops (75%) + Perennials + Wetlands	Cover Crops (75%) + Buffers (all) + Ravines	Cover Crops (25%) + Cons. Tillage + Wetlands
1996	1,839	0.84%	3.81%	0.16%	1.06%	-0.09%	1.10%	10.56%	0.00%	16.58%	5.76%	1.69%
1997	3,499	1.72%	5.34%	0.02%	0.16%	-0.04%	0.54%	4.48%	0.00%	6.59%	5.09%	2.22%
1998	1,636	0.21%	1.13%	0.10%	0.85%	0.34%	1.06%	3.94%	0.00%	6.43%	1.81%	1.98%
1999	1,256	-0.06%	0.46%	0.11%	1.30%	0.32%	0.76%	7.71%	0.00%	9.93%	1.85%	1.12%
2000	1,317	1.04%	4.55%	0.33%	2.76%	0.43%	1.07%	11.24%	0.00%	16.88%	6.77%	3.63%
2001	5,029	1.96%	4.12%	-0.02%	-0.18%	0.09%	0.51%	4.11%	0.00%	3.88%	3.98%	2.43%
2002	1,206	0.20%	2.42%	0.35%	3.01%	-0.02%	1.04%	10.93%	0.00%	15.40%	5.21%	2.60%
2003	1,158	0.67%	2.21%	0.20%	1.76%	0.30%	1.64%	8.83%	0.00%	12.63%	3.87%	2.58%
2004	2,895	1.76%	2.21%	0.16%	1.39%	-0.02%	0.57%	9.90%	0.00%	10.52%	3.87%	1.95%
2005	1,566	0.93%	3.65%	0.26%	2.02%	0.27%	0.96%	12.89%	0.00%	17.86%	4.97%	2.61%
2006	2,359	-0.80%	-0.77%	0.25%	2.03%	0.07%	-0.79%	9.84%	0.00%	10.49%	1.31%	0.07%
2007	1,656	3.42%	9.03%	0.28%	2.17%	0.21%	0.61%	9.44%	0.00%	17.08%	8.84%	3.90%
2008	1,451	1.06%	2.25%	0.26%	1.86%	-0.01%	1.24%	10.91%	0.00%	13.12%	4.25%	2.42%
2009	904	2.71%	7.09%	0.05%	0.12%	0.17%	1.45%	2.31%	0.00%	11.25%	7.43%	4.32%
2010	4,644	1.94%	5.70%	0.01%	0.03%	-0.07%	0.26%	2.54%	0.00%	4.96%	5.43%	2.13%
2011	4,622	1.00%	2.41%	0.05%	0.44%	-0.05%	0.81%	5.21%	0.00%	6.09%	2.98%	1.59%
2012	2,690	0.76%	1.32%	0.23%	1.92%	0.22%	0.66%	9.63%	0.00%	19.34%	2.76%	1.53%
Mean	2,337	1.26%	3.43%	0.12%	1.00%	0.08%	0.65%	6.99%	0.00%	9.95%	4.26%	2.11%

Table 3-10. Annual sediment reductions for BMP scenarios in the Cottonwood River watershed

Year	Baseline Load (1000 tons/yr)	Pollutant Removal Efficiency (Percent)										
		Cover Crops (25% adoption)	Cover Crops (75% adoption)	Riparian Buffers (Buffer Law)	Riparian Buffers (All)	Cons. Tillage (High Adoption)	Treatment Wetlands	Perennials	Ravine Mitigation	Cover Crops (75%) + Perennials + Wetlands	Cover Crops (75%) + Buffers (all) + Ravines	Cover Crops (25%) + Cons. Tillage + Wetlands
1996	140.4	5.42%	11.76%	0.82%	6.89%	0.46%	3.34%	15.01%	0.30%	24.27%	17.02%	8.23%
1997	294.9	3.16%	7.22%	0.60%	5.14%	0.28%	1.96%	8.28%	0.15%	14.16%	11.47%	4.90%
1998	77.7	6.80%	11.94%	0.72%	6.11%	1.43%	2.42%	16.66%	0.12%	23.98%	16.59%	8.87%
1999	68.8	4.55%	8.66%	0.84%	6.96%	0.58%	3.00%	19.71%	0.07%	26.90%	14.50%	7.34%
2000	59.9	9.26%	19.09%	1.10%	9.13%	1.63%	6.13%	26.94%	0.32%	42.14%	25.82%	14.76%
2001	361.8	8.07%	15.55%	0.68%	5.86%	0.30%	3.53%	9.97%	0.47%	21.42%	19.25%	10.34%
2002	61.7	8.73%	15.46%	0.84%	7.33%	1.64%	5.14%	19.76%	0.59%	32.76%	20.93%	12.99%
2003	55.9	5.35%	11.87%	0.85%	7.27%	0.08%	3.76%	22.69%	0.13%	31.49%	17.61%	8.70%
2004	278.3	10.60%	24.12%	1.06%	9.11%	-0.24%	5.38%	20.72%	3.00%	39.91%	29.78%	14.47%
2005	94.5	7.31%	16.23%	0.60%	5.15%	-0.17%	2.74%	16.05%	0.12%	27.83%	19.70%	9.60%
2006	173.5	7.77%	15.03%	0.79%	6.68%	-0.04%	3.62%	14.27%	0.66%	26.02%	19.68%	10.30%
2007	109.8	8.93%	17.94%	0.52%	4.55%	0.90%	4.02%	14.15%	0.21%	27.61%	20.58%	12.13%
2008	62.2	2.96%	5.78%	0.77%	6.57%	0.36%	2.55%	16.63%	0.02%	22.01%	11.65%	5.34%
2009	30.9	6.98%	17.77%	0.50%	4.23%	0.41%	5.75%	10.40%	0.00%	28.61%	20.55%	12.60%
2010	340.0	6.60%	14.75%	0.56%	4.85%	0.36%	2.87%	9.45%	0.39%	20.12%	17.82%	8.84%
2011	373.7	3.75%	7.67%	0.68%	5.75%	0.28%	2.32%	9.33%	0.17%	15.23%	12.32%	5.67%
2012	194.8	10.46%	22.58%	1.01%	8.48%	1.12%	6.16%	22.97%	1.06%	40.15%	27.85%	15.32%
Mean	163.5	6.80%	14.29%	0.74%	6.34%	0.40%	3.53%	13.95%	0.62%	24.92%	18.75%	9.57%

Table 3-11. Annual flow reductions for BMP scenarios in the Le Sueur River watershed

Year	Baseline Mean Flow (cfs)	Flow Reduction (Percent)										
		Cover Crops (25% adoption)	Cover Crops (75% adoption)	Riparian Buffers (Buffer Law)	Riparian Buffers (All)	Cons. Tillage (High Adoption)	Treatment Wetlands	Perennials	Ravine Mitigation	Cover Crops (75%) + Perennials + Wetlands	Cover Crops (75%) + Buffers (all) + Ravines	Cover Crops (25%) + Cons. Tillage + Wetlands
1996	619	0.64%	2.01%	0.12%	0.88%	0.10%	0.78%	4.35%	0.00%	6.68%	2.12%	1.77%
1997	637	0.98%	2.95%	0.17%	1.24%	0.15%	0.96%	6.29%	0.00%	9.51%	3.08%	2.23%
1998	664	1.09%	3.19%	0.19%	1.34%	0.18%	0.97%	6.79%	0.00%	10.28%	3.41%	2.48%
1999	870	0.80%	2.24%	0.13%	0.91%	0.21%	0.76%	4.69%	0.00%	7.20%	2.36%	1.99%
2000	639	0.95%	2.76%	0.15%	1.11%	0.17%	1.21%	5.49%	0.00%	8.83%	2.90%	2.59%
2001	970	0.85%	2.45%	0.12%	0.81%	0.11%	0.86%	4.47%	0.00%	7.20%	2.54%	1.88%
2002	491	2.09%	5.95%	0.14%	0.99%	0.28%	1.41%	5.06%	0.00%	11.20%	6.09%	4.29%
2003	362	1.04%	3.02%	0.27%	1.94%	0.27%	1.57%	10.20%	0.00%	14.09%	3.28%	3.19%
2004	820	1.48%	4.11%	0.08%	0.61%	0.13%	1.11%	3.20%	0.00%	7.48%	4.16%	2.92%
2005	721	1.31%	3.72%	0.12%	0.86%	0.21%	0.92%	4.29%	0.00%	8.06%	3.80%	2.68%
2006	619	0.86%	2.56%	0.17%	1.18%	0.25%	1.11%	6.04%	0.00%	9.04%	2.60%	2.37%
2007	839	1.74%	5.01%	0.05%	0.31%	0.08%	0.82%	1.53%	0.00%	6.36%	5.14%	2.90%
2008	550	0.50%	1.53%	0.21%	1.47%	0.21%	1.14%	7.59%	0.00%	9.88%	1.72%	2.07%
2009	465	1.92%	5.57%	0.13%	0.93%	0.26%	1.45%	4.70%	0.00%	10.48%	5.60%	3.98%
2010	1,269	1.25%	3.62%	0.07%	0.48%	0.08%	0.67%	2.52%	0.00%	6.02%	3.68%	2.07%
2011	893	0.44%	1.30%	0.15%	1.05%	0.13%	0.74%	5.35%	0.00%	7.11%	1.46%	1.43%
2012	375	1.16%	3.26%	0.25%	1.78%	0.43%	2.07%	9.06%	0.00%	13.72%	3.53%	4.39%
Mean	694	1.10%	3.19%	0.13%	0.95%	0.17%	1.00%	4.89%	0.00%	8.37%	3.30%	2.49%

Table 3-12. 95th percentile flow reductions for BMP scenarios in the Le Sueur River watershed

Year	Baseline Flow (cfs)	Flow Reduction (Percent)										
		Cover Crops (25% adoption)	Cover Crops (75% adoption)	Riparian Buffers (Buffer Law)	Riparian Buffers (All)	Cons. Tillage (High Adoption)	Treatment Wetlands	Perennials	Ravine Mitigation	Cover Crops (75%) + Perennials + Wetlands	Cover Crops (75%) + Buffers (all) + Ravines	Cover Crops (25%) + Cons. Tillage + Wetlands
1996	2,809	0.10%	0.55%	0.15%	1.13%	0.03%	-0.15%	6.56%	0.00%	6.86%	0.70%	0.23%
1997	2,290	0.07%	1.09%	0.31%	2.17%	-0.04%	0.34%	9.91%	0.00%	11.65%	1.40%	0.44%
1998	2,106	-0.47%	-0.56%	0.15%	0.94%	0.38%	0.68%	8.42%	0.00%	8.79%	-0.41%	1.04%
1999	4,047	-1.03%	-1.38%	0.07%	0.48%	0.36%	0.33%	3.04%	0.00%	3.13%	-1.28%	0.33%
2000	3,247	0.24%	3.03%	0.22%	1.40%	0.87%	-0.30%	4.24%	0.00%	9.14%	3.20%	-0.34%
2001	4,989	0.85%	2.02%	0.12%	0.91%	0.27%	0.26%	5.50%	0.00%	6.20%	2.15%	2.29%
2002	1,627	2.50%	6.63%	0.04%	1.42%	0.45%	1.49%	10.61%	0.00%	16.72%	6.82%	5.01%
2003	1,540	0.00%	2.46%	0.28%	2.00%	0.65%	0.81%	12.01%	0.00%	16.81%	2.82%	2.20%
2004	3,145	0.15%	2.32%	0.30%	2.19%	0.04%	0.50%	10.67%	0.00%	12.18%	2.63%	0.95%
2005	3,160	-1.93%	0.19%	0.22%	1.57%	0.46%	0.20%	4.24%	0.00%	6.81%	0.25%	-0.31%
2006	2,808	1.66%	2.73%	0.25%	1.77%	0.28%	0.69%	9.38%	0.00%	12.05%	2.93%	2.47%
2007	3,682	0.65%	4.65%	0.09%	0.64%	0.03%	0.52%	1.22%	0.00%	5.17%	4.43%	1.41%
2008	2,421	0.07%	1.24%	0.28%	2.00%	-0.09%	0.81%	8.21%	0.00%	11.79%	1.50%	1.46%
2009	1,765	0.70%	2.66%	0.19%	1.36%	0.16%	1.01%	9.09%	0.00%	14.55%	2.83%	2.26%
2010	5,588	1.62%	7.08%	0.29%	2.05%	-0.26%	1.95%	7.60%	0.00%	11.82%	7.16%	3.24%
2011	4,313	0.09%	0.31%	0.25%	1.52%	-0.01%	1.30%	7.85%	0.00%	7.27%	0.50%	1.03%
2012	1,713	0.11%	-0.21%	0.34%	2.52%	0.63%	1.81%	9.08%	0.00%	13.02%	-0.12%	2.06%
Mean	3,015	0.33%	2.20%	0.21%	1.47%	0.20%	0.71%	6.90%	0.00%	9.32%	2.34%	1.46%

Table 3-13. Annual sediment reductions for BMP scenarios in the Le Sueur River watershed

Year	Baseline Load (1000 tons/yr)	Pollutant Removal Efficiency (Percent)										
		Cover Crops (25% adoption)	Cover Crops (75% adoption)	Riparian Buffers (Buffer Law)	Riparian Buffers (All)	Cons. Tillage (High Adoption)	Treatment Wetlands	Perennials	Ravine Mitigation	Cover Crops (75%) + Perennials + Wetlands	Cover Crops (75%) + Buffers (all) + Ravines	Cover Crops (25%) + Cons. Tillage + Wetlands
1996	201.5	3.37%	9.50%	0.58%	4.23%	1.94%	3.01%	9.89%	22.79%	18.56%	32.49%	7.84%
1997	149.2	4.65%	11.64%	0.75%	5.33%	1.92%	2.93%	12.64%	1.60%	22.37%	14.54%	8.42%
1998	167.8	5.85%	12.77%	0.81%	5.79%	2.00%	3.55%	15.33%	1.45%	26.09%	15.78%	10.40%
1999	316.1	7.39%	15.03%	0.72%	5.23%	2.37%	3.95%	11.49%	2.01%	23.78%	18.04%	12.47%
2000	264.9	7.48%	16.19%	0.80%	5.75%	2.37%	4.88%	13.25%	2.79%	27.28%	19.68%	13.54%
2001	404.3	5.40%	13.79%	0.70%	5.05%	1.48%	3.75%	10.33%	2.11%	22.19%	16.77%	10.22%
2002	99.1	7.57%	16.65%	0.71%	5.08%	1.34%	3.11%	12.41%	0.64%	26.22%	19.40%	11.25%
2003	79.3	8.39%	14.39%	0.98%	6.88%	2.12%	3.75%	21.35%	0.64%	32.81%	17.26%	12.38%
2004	418.1	6.07%	14.74%	0.53%	3.91%	1.75%	3.54%	8.35%	22.88%	20.69%	37.65%	10.90%
2005	236.2	6.50%	14.49%	0.71%	5.08%	2.30%	3.81%	11.18%	3.73%	23.47%	18.73%	11.80%
2006	158.5	4.16%	8.34%	0.75%	5.34%	1.53%	2.82%	13.60%	0.71%	20.81%	11.30%	7.89%
2007	355.0	4.07%	8.91%	0.40%	2.91%	0.52%	1.91%	4.07%	19.26%	11.48%	29.49%	6.25%
2008	151.2	5.11%	10.35%	0.81%	5.81%	1.64%	3.37%	15.75%	0.59%	24.29%	13.30%	9.10%
2009	101.8	7.26%	17.75%	0.81%	5.71%	2.27%	4.43%	13.86%	3.05%	29.73%	20.57%	13.59%
2010	700.7	6.13%	14.15%	0.60%	4.38%	2.67%	3.48%	8.36%	17.49%	20.86%	28.69%	11.89%
2011	306.5	4.58%	10.12%	0.69%	4.98%	1.48%	3.03%	10.60%	0.95%	19.23%	12.98%	8.49%
2012	129.6	10.44%	19.33%	0.99%	6.92%	2.34%	5.66%	18.68%	4.57%	35.43%	22.75%	17.91%
Mean	249.4	5.90%	13.25%	0.67%	4.85%	1.91%	3.51%	10.79%	9.05%	22.11%	22.62%	10.65%

Table 3-14. Annual flow reductions for BMP scenarios in the Middle Minnesota River watershed

Year	Baseline Mean Flow (cfs)	Flow Reduction (Percent)										
		Cover Crops (25% adoption)	Cover Crops (75% adoption)	Riparian Buffers (Buffer Law)	Riparian Buffers (All)	Cons. Tillage (High Adoption)	Treatment Wetlands	Perennials	Ravine Mitigation	Cover Crops (75%) + Perennials + Wetlands	Cover Crops (75%) + Buffers (all) + Ravines	Cover Crops (25%) + Cons. Tillage + Wetlands
1996	6,101	0.16%	0.47%	0.03%	0.25%	0.02%	0.14%	0.92%	0.00%	1.47%	0.73%	0.34%
1997	8,561	0.17%	0.50%	0.03%	0.20%	0.00%	0.17%	0.73%	0.00%	1.31%	0.69%	0.34%
1998	4,885	0.21%	0.62%	0.04%	0.34%	0.04%	0.23%	1.25%	0.00%	1.95%	0.91%	0.45%
1999	5,296	0.13%	0.38%	0.04%	0.29%	0.04%	0.18%	1.04%	0.00%	1.60%	0.72%	0.41%
2000	2,922	0.34%	0.99%	0.06%	0.45%	0.08%	0.42%	1.51%	0.00%	2.73%	1.38%	0.80%
2001	8,982	0.18%	0.51%	0.02%	0.12%	0.01%	0.16%	0.60%	0.00%	1.13%	0.57%	0.31%
2002	3,693	0.28%	0.81%	0.04%	0.36%	0.07%	0.38%	1.16%	0.00%	2.28%	1.21%	0.80%
2003	2,637	0.28%	0.82%	0.05%	0.41%	0.05%	0.38%	1.48%	0.00%	2.56%	1.21%	0.73%
2004	5,346	0.26%	0.68%	0.05%	0.36%	0.02%	0.31%	1.43%	0.00%	2.22%	0.97%	0.54%
2005	5,796	0.28%	0.81%	0.02%	0.18%	0.07%	0.18%	0.76%	0.00%	1.49%	0.86%	0.42%
2006	5,523	0.16%	0.44%	0.03%	0.25%	0.01%	0.20%	1.06%	0.00%	1.71%	0.76%	0.44%
2007	5,791	0.38%	1.01%	0.01%	0.07%	0.04%	0.27%	0.42%	0.00%	1.52%	1.07%	0.71%
2008	4,278	0.13%	0.38%	0.03%	0.25%	0.04%	0.24%	0.88%	0.00%	1.43%	0.59%	0.39%
2009	5,363	0.24%	0.69%	0.02%	0.14%	0.06%	0.26%	0.46%	0.00%	1.20%	0.73%	0.49%
2010	11,042	0.23%	0.65%	0.01%	0.11%	0.00%	0.12%	0.52%	0.00%	1.16%	0.72%	0.34%
2011	10,597	0.07%	0.22%	0.02%	0.18%	0.01%	0.11%	0.70%	0.00%	1.03%	0.43%	0.24%
2012	3,284	0.25%	0.67%	0.06%	0.48%	0.10%	0.43%	2.33%	0.00%	3.36%	1.17%	0.82%
Mean	5,888	0.21%	0.58%	0.03%	0.23%	0.03%	0.21%	0.89%	0.00%	1.57%	0.79%	0.44%

Table 3-15. 95th percentile flow reductions for BMP scenarios in the Middle Minnesota River watershed

Year	Baseline Flow (cfs)	Flow Reduction (Percent)										
		Cover Crops (25% adoption)	Cover Crops (75% adoption)	Riparian Buffers (Buffer Law)	Riparian Buffers (All)	Cons. Tillage (High Adoption)	Treatment Wetlands	Perennials	Ravine Mitigation	Cover Crops (75%) + Perennials + Wetlands	Cover Crops (75%) + Buffers (all) + Ravines	Cover Crops (25%) + Cons. Tillage + Wetlands
1996	17,230	0.07%	0.71%	0.01%	0.09%	0.07%	0.05%	0.45%	0.00%	3.33%	1.03%	0.19%
1997	41,752	0.12%	0.16%	0.01%	0.05%	0.01%	0.16%	0.19%	0.00%	0.28%	0.17%	0.18%
1998	15,736	-0.01%	0.17%	0.02%	0.18%	0.07%	0.28%	0.79%	0.00%	1.24%	0.34%	0.35%
1999	17,445	-0.03%	0.05%	0.02%	0.15%	0.11%	0.14%	0.78%	0.00%	1.00%	0.20%	0.24%
2000	12,768	0.17%	0.68%	0.06%	0.45%	0.02%	0.01%	1.52%	0.00%	2.04%	1.10%	0.23%
2001	51,967	0.31%	0.76%	0.01%	0.06%	0.06%	0.05%	0.81%	0.00%	1.27%	0.83%	0.37%
2002	9,055	1.31%	1.93%	0.15%	1.23%	0.06%	-0.20%	3.18%	0.00%	3.68%	2.56%	1.27%
2003	10,216	0.19%	0.66%	0.09%	0.72%	-0.06%	0.39%	2.19%	0.00%	2.84%	1.34%	0.53%
2004	22,727	-1.75%	-1.79%	0.09%	0.67%	-0.14%	0.28%	1.32%	0.00%	1.52%	-1.05%	-1.44%
2005	17,945	0.19%	0.57%	0.03%	0.26%	0.06%	0.06%	0.61%	0.00%	1.66%	0.82%	0.31%
2006	21,487	0.29%	0.58%	0.02%	0.13%	0.08%	-0.17%	1.23%	0.00%	1.44%	0.68%	0.18%
2007	16,982	0.29%	1.18%	0.02%	0.15%	0.09%	0.24%	1.12%	0.00%	2.25%	1.28%	0.53%
2008	15,170	0.06%	0.18%	0.03%	0.24%	0.12%	0.20%	1.19%	0.00%	1.64%	0.41%	0.39%
2009	16,818	0.04%	0.12%	0.00%	0.03%	0.04%	0.10%	0.12%	0.00%	0.32%	0.14%	0.17%
2010	43,976	0.25%	0.91%	0.04%	0.28%	0.03%	0.25%	1.96%	0.00%	2.79%	1.13%	0.53%
2011	45,233	0.15%	0.32%	0.01%	0.08%	0.03%	0.11%	0.48%	0.00%	0.60%	0.37%	0.27%
2012	16,871	1.06%	1.34%	0.06%	0.47%	0.30%	0.93%	3.06%	0.00%	4.47%	1.92%	1.63%
Mean	23,140	0.13%	0.46%	0.03%	0.23%	0.05%	0.16%	1.07%	0.00%	1.65%	0.67%	0.30%

Table 3-16. Annual sediment reductions for BMP scenarios in the Middle Minnesota River watershed

Year	Baseline Load (1000 tons/yr)	Pollutant Removal Efficiency (Percent)										
		Cover Crops (25% adoption)	Cover Crops (75% adoption)	Riparian Buffers (Buffer Law)	Riparian Buffers (All)	Cons. Tillage (High Adoption)	Treatment Wetlands	Perennials	Ravine Mitigation	Cover Crops (75%) + Perennials + Wetlands	Cover Crops (75%) + Buffers (all) + Ravines	Cover Crops (25%) + Cons. Tillage + Wetlands
1996	794	4.01%	9.34%	0.42%	3.27%	1.30%	1.96%	6.64%	0.82%	14.55%	11.52%	6.15%
1997	1,445	2.96%	5.36%	0.31%	2.46%	0.50%	1.17%	3.01%	0.22%	7.58%	7.14%	3.83%
1998	556	4.68%	8.99%	0.33%	2.55%	1.14%	1.52%	5.72%	0.95%	12.77%	10.46%	6.25%
1999	800	1.72%	2.52%	0.15%	1.18%	0.38%	0.59%	2.82%	0.03%	4.79%	3.40%	2.17%
2000	516	2.19%	3.95%	0.20%	1.60%	0.51%	1.11%	4.23%	0.06%	7.45%	5.08%	3.14%
2001	2,040	2.30%	4.05%	0.22%	1.77%	0.35%	0.92%	2.66%	0.12%	5.61%	5.29%	2.98%
2002	405	5.76%	11.49%	0.40%	3.18%	1.40%	2.74%	6.70%	0.65%	16.60%	13.29%	8.16%
2003	270	1.51%	3.15%	0.23%	1.89%	0.11%	0.92%	5.46%	0.03%	7.83%	4.65%	2.33%
2004	1,495	5.98%	12.76%	0.46%	3.65%	1.07%	2.50%	8.00%	1.88%	18.42%	14.82%	8.19%
2005	723	2.10%	3.73%	0.14%	1.15%	0.28%	0.65%	3.24%	0.03%	5.84%	4.48%	2.60%
2006	698	3.56%	6.28%	0.29%	2.35%	0.33%	1.42%	4.79%	0.20%	9.87%	7.84%	4.53%
2007	813	2.31%	4.55%	0.13%	1.09%	0.32%	0.89%	2.70%	0.18%	6.20%	5.16%	3.08%
2008	445	1.00%	1.65%	0.17%	1.41%	0.25%	0.58%	3.31%	0.01%	4.68%	2.86%	1.55%
2009	460	0.89%	2.12%	0.10%	0.79%	0.19%	0.59%	1.36%	0.01%	3.34%	2.71%	1.54%
2010	2,416	2.49%	4.53%	0.17%	1.33%	0.37%	0.88%	2.34%	0.14%	5.81%	5.33%	3.10%
2011	1,661	1.48%	2.82%	0.26%	2.07%	0.25%	0.81%	3.03%	0.06%	5.22%	4.53%	2.17%
2012	656	5.13%	10.40%	0.46%	3.74%	0.99%	2.92%	9.64%	0.44%	17.79%	12.78%	7.59%
Mean	953	2.93%	5.68%	0.26%	2.08%	0.54%	1.25%	4.06%	0.37%	8.60%	7.07%	3.99%

3.1.1 University of Minnesota Conservation Tillage Estimates

The University of Minnesota Tillage and Erosion Survey Project is currently working to develop a tool that will estimate spring residue cover based on satellite-derived data. Based on results presented at the Advisory Committee Meeting of May 23, 2018, predictions based on satellite imagery show promise, but yield relatively low correlation coefficients (R^2 = 0.37 for Sentinel 2 training data and 0.48 for Landsat 8 imagery). Preliminary data on a minor watershed scale from 2017 imagery are shown for example in Figure 3-4. In the future, these methods could be used to further refine estimates of conservation tillage adoption rates. The estimates of conservation tillage derived from this project for 2017 imagery are substantially lower than the estimates from the 2004 and 2007 Tillage Transect Surveys for the Cottonwood and Le Sueur watersheds. Whether this is due to different methodology or to actual reductions in conservation tillage is uncertain.

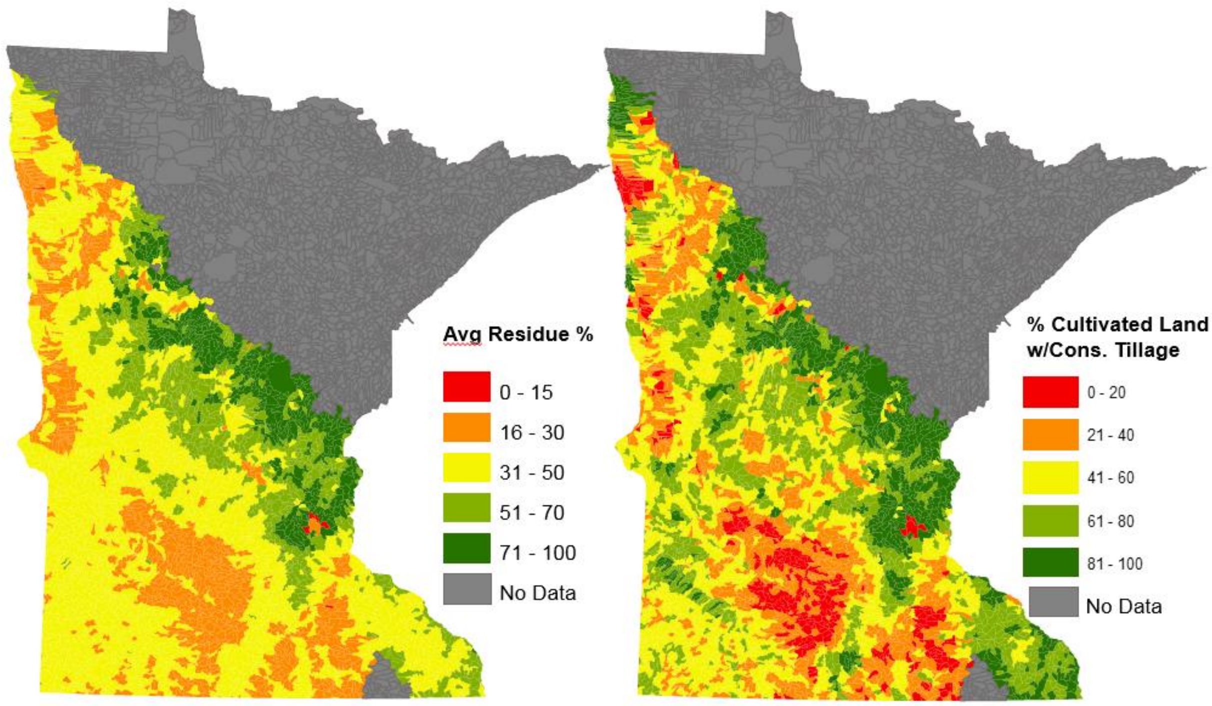


Figure 3-4. 2017 analysis -- average residue % and portion of cultivated land in conservation tillage minor watershed (Source: University of Minnesota)

In addition to the main high conservation tillage implementation scenario, a second baseline model scenario was completed to reflect satellite-based analyses conducted by the University of Minnesota. The intention of this scenario was to update conservation tillage rates from 2004/6 to 2017 conditions. This scenario is conditional on the provision of spatial coverages showing best estimates of cultivated land in conservation tillage, similar to the right panel of Figure 3-4. As shown in Table 2-14, this reduces conservation tillage from baseline modeled conditions in Cottonwood and Le Sueur, and thus results in an increase in TSS loads relative to the original baseline model. To ensure a consistent comparison of the high conservation tillage with the other BMP scenarios, the baseline model that represents conservation tillage according to the Tillage Transect Surveys (2004/6) was applied as the reference for evaluating reductions (all other tables and figures in Section 3.0). A complementary analysis was completed that evaluated benefits of high adoption assuming the University of Minnesota tillage estimates as the baseline condition.

Adoption of conservation tillage in the baseline model is already quite high, thus, reductions in sediment loads are relatively small for the conservation tillage BMP scenario. Another scenario (not included in most of the summary tables and figures in this section) applied satellite-based estimates of conservation tillage developed by the University of Minnesota that represented 2017 conditions. The representation of conservation tillage in the baseline models is based on 2004-2006 Tillage Transect surveys. Lower levels of implementation are indicated by the University of Minnesota estimates in some regions, therefore, the sediment load for this scenario is higher (negative reduction) compared to the baseline model. Whether this represents an actual reduction in the use of conservation tillage, or simply reflects the difference between two different and uncertain methods, is not known. If the University of Minnesota conservation tillage implementation levels are assumed as the baseline, then the reductions achieved with the high adoption scenario are shown in Table 3-17 and Table 3-19. These results represent annual flow volume and sediment load reductions at the HUC outlet.

Table 3-17. Reductions for high conservation tillage scenario with University of Minnesota 2017 estimates as the baseline implementation level for the Cottonwood River Watershed

Year	Percent Reduction	
	Annual Flow Volume	Annual Sediment Load
1996	0.14%	0.67%
1997	0.15%	0.80%
1998	0.44%	2.04%
1999	0.51%	1.50%
2000	0.63%	2.64%
2001	0.08%	1.71%
2002	0.52%	3.10%
2003	0.46%	1.17%
2004	0.22%	3.38%
2005	0.57%	1.98%
2006	0.17%	2.02%
2007	0.22%	1.66%
2008	0.33%	0.94%
2009	0.50%	1.85%
2010	0.04%	0.94%
2011	0.11%	0.79%
2012	0.63%	2.82%
Mean	0.27%	1.65%

Table 3-18. Reductions for high conservation tillage scenario with University of Minnesota 2017 estimates as the baseline implementation level for the Le Sueur River watershed

Year	Percent Reduction	
	Annual Flow Volume	Annual Sediment Load
1996	0.04%	0.08%
1997	0.03%	0.06%
1998	0.03%	0.17%
1999	0.04%	0.27%
2000	0.05%	0.36%
2001	0.02%	0.31%
2002	0.09%	0.24%
2003	0.06%	0.33%
2004	0.04%	0.37%
2005	0.04%	0.21%
2006	0.04%	0.11%
2007	0.03%	0.30%
2008	0.04%	0.18%
2009	0.08%	0.38%
2010	0.02%	0.29%
2011	0.02%	0.21%
2012	0.12%	0.66%
Mean	0.04%	0.27%

Table 3-19. Reductions for high conservation tillage scenario with University of Minnesota estimates as the baseline implementation level for the Middle Minnesota River watershed

Year	Percent Reduction	
	Annual Flow Volume	Annual Sediment Load
1996	0.03%	1.65%
1997	0.01%	0.78%
1998	0.08%	1.70%
1999	0.07%	0.56%
2000	0.13%	0.69%
2001	0.02%	0.75%
2002	0.12%	2.01%
2003	0.09%	0.37%
2004	0.04%	2.51%
2005	0.12%	0.63%
2006	0.02%	0.97%
2007	0.06%	0.52%
2008	0.06%	0.37%
2009	0.10%	0.28%
2010	0.00%	0.60%
2011	0.02%	0.42%
2012	0.18%	1.76%
Mean	0.05%	0.96%

3.1.2 Reductions in Sediment Sources

Percent reductions in upland, near-channel, and ravine loads are presented for Cottonwood and Le Sueur in Figure 3-5. and Figure 3-6.. Such an analysis will be more useful for the Middle MN River watershed following BMP scenarios being extended into the other contributing watersheds, thus, it was not included as part of this project. Cover crops adopted on 75% of cropland in the Le Sueur River watershed reduce the watershed-wide upland sediment load by about 36%, however, cover crops also increase near-channel sediment load due to increased baseflow, although only slightly (about 1%). Cover crops are predicted to be more effective in the Cottonwood River watershed (about a 58% reduction in sediment load is achieved with a 75% implementation level). Perennials reduce upland sediment loads by 19.8% and 36.7% in Le Sueur and Cottonwood and reduce near-channel sediment by 5.1% and 7.2%. Ravine mitigation reduces the loads from ravine processes by about 27.5% in Le Sueur.

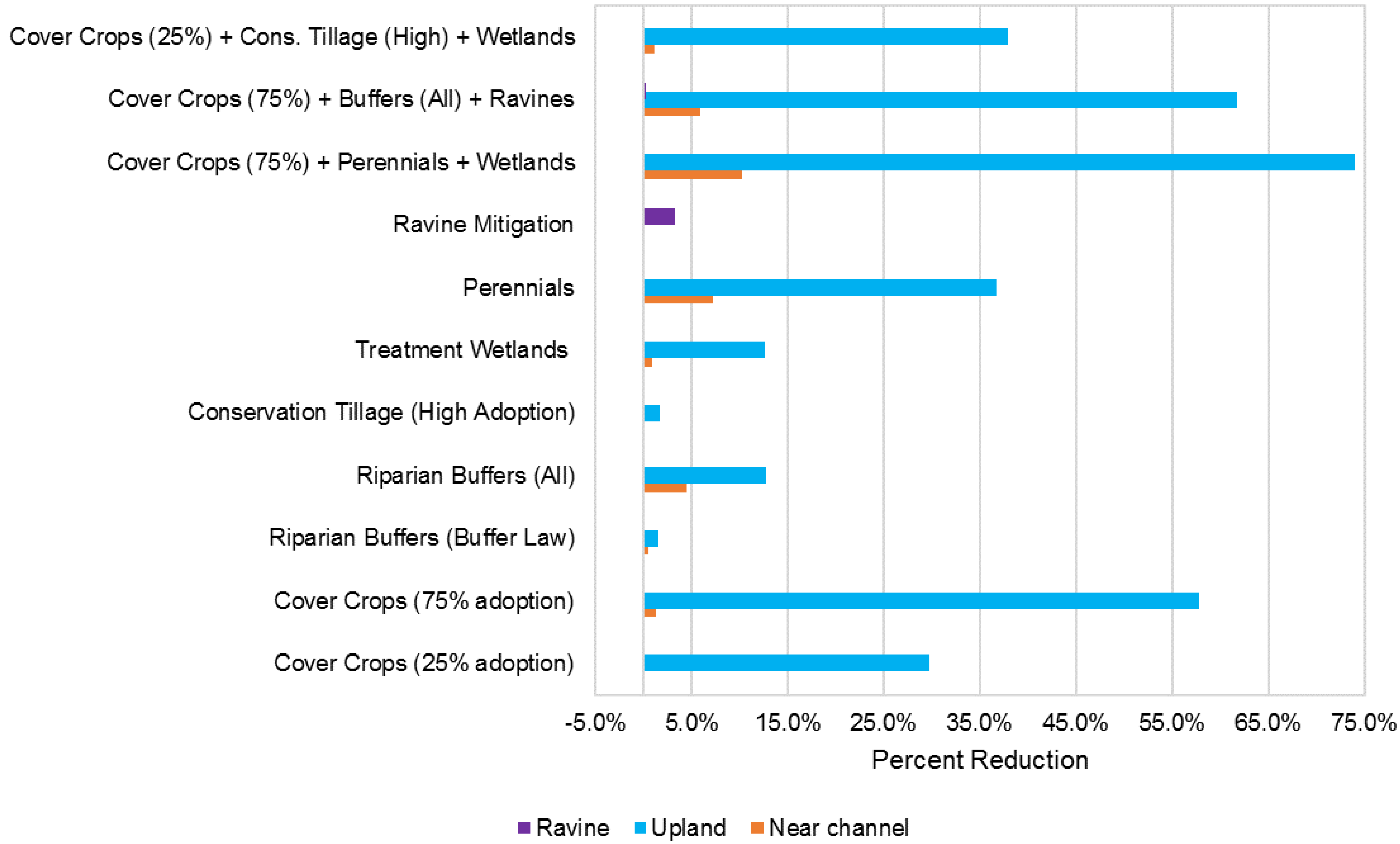


Figure 3-5. Percent reduction in upland, near-channel, and ravine loads for BMP scenarios in the Cottonwood River watershed

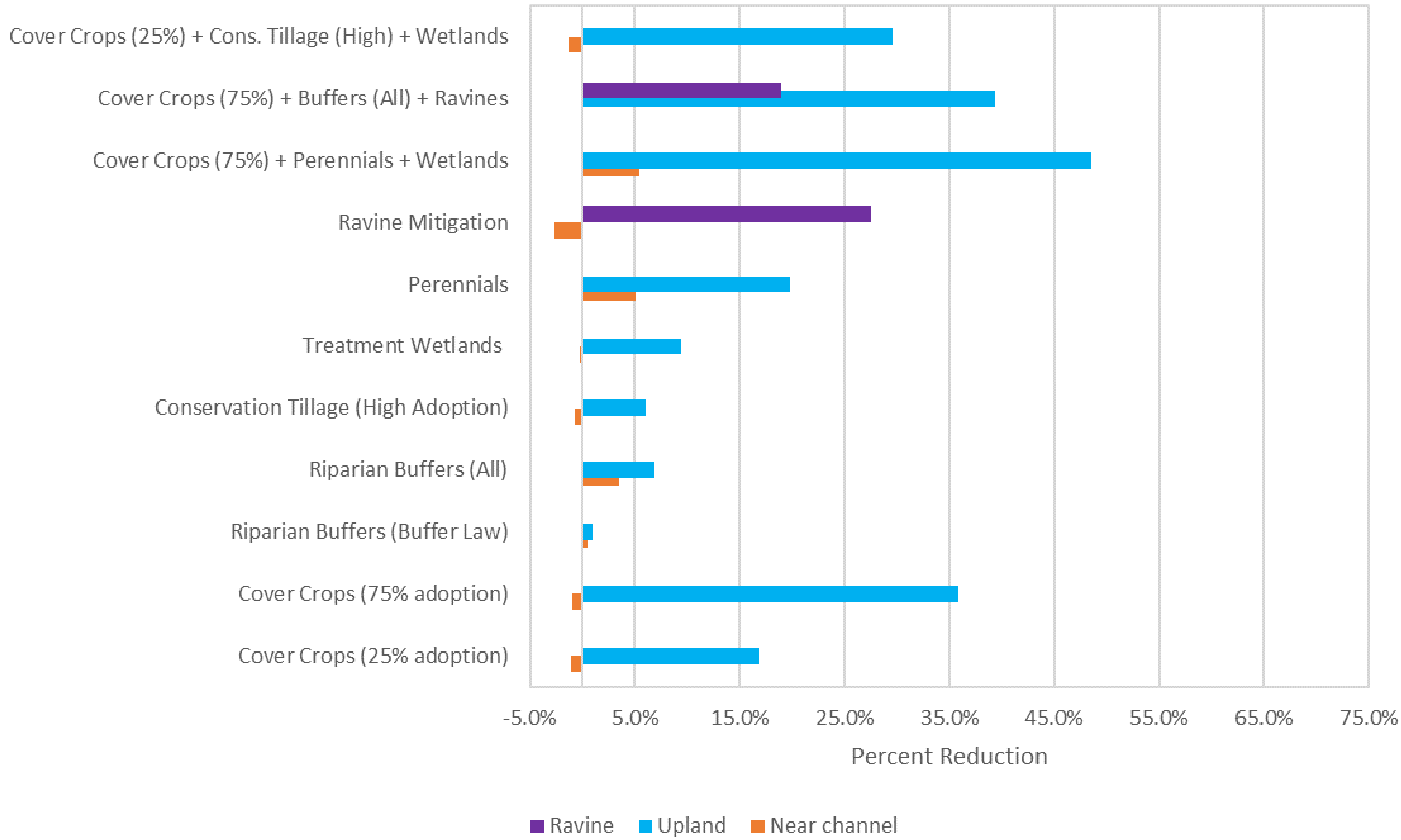


Figure 3-6. Percent Reduction in upland, near-channel, and ravine loads for BMP scenarios in the Le Sueur River watershed

3.1.3 Comparison of Sediment Removal Results to Other Models

The scenarios reported in this study use the APEX and HSPF models to simulate effectiveness of BMPs in reducing sediment load. This section compares the scenario results to BMP sediment reduction efficiencies reported in two other projects.

3.1.3.1 Scenario Application Manager

MPCA's Scenario Application Manager (SAM) (RESPEC, 2017) summarizes efficiencies for several BMPs addressed in this report (see Section 2.2 for additional information on SAM removal efficiencies). The HSPF-SAM interface applies static removal efficiencies (i.e., reduction factors) in the MASS-LINK block of a HSPF model thereby reducing the simulated load delivered to the reaches. The removal efficiencies in SAM represent the assumed efficiency of a BMP in reducing loads generated at the HRU level, which is directly comparable to the field-scale APEX models implemented in this study. The APEX models do not apply static reduction efficiencies, but rather predict the effectiveness of BMPs in reducing sediment load at the HRU scale.

The performance of most BMPs is expected to vary under different physical and climatic settings. For example, the effectiveness of cover crops in reducing pollutant yields is contingent upon the success of the cover crop which indirectly depends on several factors including climate, nutrient availability for growth, and soil properties. The effectiveness of BMPs is therefore expected to vary both temporally and spatially; however, the default pollutant removal efficiencies in SAM are often a single value or range based on a summary of field-scale studies from Minnesota and elsewhere in the Midwest. The APEX models provide a range of sediment removal efficiencies (Table 3-20) specific to local conditions (weather, soils, slope, crop management practices, etc.) in the Minnesota River Basin watersheds.

SAM's sediment removal efficiencies for fall cover crops and perennials are consistent with the range simulated by APEX. Riparian buffers appear on average to perform better in APEX than the default efficiency proposed for SAM; however, the APEX simulations only address runoff from field areas close to the buffer from which sheet flow can be maintained, and actual area treated in the HSPF model is a fraction of the total field area.

The average simulated sediment reduction for the conservation tillage scenarios using APEX is lower than the efficiencies used in SAM. It is our understanding that the estimates in SAM for conservation tillage are based on going from traditional deep tillage practices (such as moldboard plow) to medium or shallow tillage practices. However, based on the tillage transect surveys it is apparent that deep tillage practices are not widely adopted in the Minnesota River Basin watersheds. Representative baseline conditions in the APEX models therefore consisted of using medium tillage practices (such as chisel plow and field cultivator). Conservation tillage scenarios in APEX consisted of simulating shallow tillage practices such as ridge till. The expected reduction in sediment load from switching to a shallow till from a medium till is therefore lower than that expected from going from a deep till to a shallow till.

Table 3-20. Comparison of APEX simulated sediment removal efficiencies to SAM (RESPEC, 2017)

BMP	APEX (average and range)	SAM [a]
Fall Cover Crops	60.5% (26.6% to 94.7%)	74% (into corn/soybean or after early harvest crops)
Riparian Buffers and Filter Strips	94.3% (76.7% to 99.9%)	50% - 90% - Riparian buffers 84% - Filter strips
Conservation Tillage	32.8% (20.1% to 56.8%)	50% - Greater than 30% residue cover on lands sloping more than 2% 80% - No till on lands sloping more than 4%
Perennials	96.4% (88.5% to 99.6%)	96%

a. Note that the Appendix in RESPEC, 2017, does not match the summary tables contained within the text of the document. Values presented in this table are from Appendix A of RESPEC, 2017.

3.1.3.2 Management Option Simulation Model

The Management Option Simulation Model (MOSM) simulates water and sediment loading from a watershed and evaluates the impact of management practices on sediment load reduction. MOSM (CSSR, 2017a) is the result of a collaborative effort of Johns Hopkins University, University of Minnesota and Utah State University. MOSM is a spreadsheet tool that compiles annual sediment budgets for the Greater Blue Earth River Basin (GBERB) based on prior studies, empirical methods and GIS analyses. The effectiveness of BMPs in reducing sediment loads in MOSM are in most cases user-defined, and the results generated at the watershed-scale by MOSM are largely dependent on these user-defined removal efficiencies.

Wilcock et al. (2016) evaluated MOSM for sediment source characterization and implications of conservation practices on sediment load in the GBERB, including the Le Sueur River. The MOSM spreadsheet tool reports annual sediment reductions for several reference scenarios. The reference scenarios predict reductions in annual sediment load for different levels (ranging from 2 to 100%) of adoption of conservation practices. The conservation practices considered within MOSM are as follows.

- TLMO - Tillage management - conventional, conservation and reduced tillage
- AFMO - Agricultural field management consisting of grassed waterways and terraces.
- WCMO - Wetland restoration, sediment basins, and water and sediment conservation basins
- BFMO - Buffer strip management consisting of filter strips, field borders, contour buffer strips and alternative tile inlets
- RAMO - Ravine tip stabilization
- ICMO - In-channel WCMOs

Wilcock et al. (2016) report predicted reductions in the GBERB for several conservation practice scenarios using MOSM.

- Reductions for TLMO+AFMO scenarios range from 219 to 15,610 Mg/yr (< 1% to 3.6% of the present sediment load of 439,071 Mg/yr).
- Reductions for TLMO+BFMO scenarios range from 4,015 to 14,509 Mg/yr (< 1% to 3.3% reduction).
- Reductions for TLMO+RAMO scenarios range from 6,092 to 59,042 Mg/yr (1.4% to 13.4%).

- Reductions for TLMO+WCMO scenarios range from 7,705 to 139,415 Mg/yr (1.8% to 31.8%).
- Reductions for TLMO+WCMO+NCMO scenarios range from 34,113 to 118,486 Mg/yr (7.8% to 27.0%).

The details associated with the level of adoption for each conservation practice scenario can be found in Table 7.2 and Table 7.3 of Wilcock et al. (2016).

The underlying runoff hydrology in MOSM is provided by a SWAT model, which appears to provide a fair to good fit to observed flow in the Le Sueur basin (see Kumarasamy and Belmont, 2017). SWAT model output of USLE soil loss is also used as the starting point for field erosion. Transport from field to stream requires application of a sediment delivery ratio (SDR) to the USLE estimates. Rather than assigning a drainage-area based SDR, MOSM uses a spatially distributed GIS-based estimator of sediment delivery known as TopoFilter (see below). Loading from ravines and bluffs is taken from the GBERB studies. Routing is via the level pool method. The model routing algorithm is linked to a near-channel sediment supply (NCSS) model, which establishes the relationship between peak river discharge and sediment loading from near-channel sources in the incised zone. The NCSS is expressed as an exponential regression relationship on peak discharge relative to a basin-specific threshold (CSSR, 2017b).

The TopoFilter component was developed by Cho (2017). The general concept is summarized in a poster presentation as follows: "Topographic filter simulation model (Topo-Filter) adapts GLUE methodology to identify multiple plausible SDR (i.e., 10,000 MC realizations) for each grid in a watershed. The model is conditioned against observed SL [sediment loads] at multiple gage locations." The SDR is summarized at the level of sediment subbasins from analysis on a 10 meter DEM. The SDR for an individual grid cell in theory takes the following form (Cho, 2017), applicable, with different parameters, to both on-field transport and in-stream transport:

$$SDR = exp\left[a\left({}^{\Delta E}/_{L}\right)^{b} L\right]$$

where ΔE is change in elevation (m) and L is the flow length (m). Fitting the model at the mouth of the Le Sueur and defining streams as NHD bluelines. In Chapter 4, Cho (2017) incorporated the complete set of sediment sources for the Le Sueur and refit stream SDRs as a function of A_f, defined as the sum of the the floodplain area within the subbasin and all downstream subbasins to the outlet:

$$SDR = exp\left[a\left({}^{\Delta E}/_{L}\right)^{b} A_f\right]$$

The calibration matched calculated loads at the mouth of each of the five major subbasins within the Le Sueur HUC8. (The resulting parameters are thus conditional on the SWAT-calculated USLE sediment loss estimates.) Separate sets of feasible parameters a and b were fit for each major subbasin, and MOSM uses a Monte Carlo simulation approach to pick realizations from the feasible set. The resulting field SDRs range from 0.07 to 0.18, while the in-stream SDRs range from 0.24 to 0.90, depending on distance from the mouth.

Although specific removal efficiencies are not prescribed for most BMPs in MOSM, guidance on several of the BMPs is provided in the accompanying manuals and literature. CSSR (2017b, p. 12) implies that adding a cover crop to a corn-soybean rotation should result in sediment removal of 73%, consistent with SAM. Cho (2017) applies a 75% effectiveness for ravine mitigation, while Cho (2019) applies a 65% sediment removal efficiency to stream buffers.

HSPF, like MOSM, evaluates impacts of BMP implementation at the watershed-scale. However, HSPF simulates BMPs over a range of physical and climatic conditions, thus, represents temporal and spatial variability in BMP effectiveness. For this reason, the HSPF methodology is more robust than using user-defined efficiencies implemented within MOSM. In addition, HSPF represents changes in flow and pollutant transport throughout the stream network due to BMP implementation (e.g., reduced channel scour), which cannot be assessed with MOSM. Nevertheless, MOSM is a useful tool for initial scoping of watershed-wide conservation practice implementation plans if adequate local field studies can be used to determine expected removal efficiencies.

(This page left intentionally blank.)

4.0 Conclusions and Future Needs

Tetra Tech implemented a HSPF modeling framework to evaluate the watershed-scale impacts of agricultural BMPs in the watersheds of the Minnesota River Basin to support planning for the Sediment Strategy. Estimates of expected average rates of pollutant removals are provided for BMPs in the literature. However, field characteristics (e.g., soil type, slope, crop type) and naturally varying conditions (precipitation and temperature) can significantly alter the performance of agricultural BMPs. These differences are represented in the HSPF models, which provide representative results for the Cottonwood, Le Sueur, and Middle MN watersheds. In addition, the HSPF models serve as a tool for assessing the collective impacts of widespread BMP implementation at the watershed-scale. Benefits achieved, including reducing annual flow volume, the 95th percentile flow (which represents events capable of significant upland erosion, gulling, and instream scour of channel beds and banks), and sediment load are presented in Section 3.0. In addition, ancillary changes in nutrients are provided in the Appendix to support comprehensive planning efforts in the basin.

This work included BMP scenarios representing adoption of fall cover crops at levels of 25% and 75% of cropland, riparian buffers (MN buffer law and buffers on all waterways), higher adoption of conservation tillage, treatment wetlands, partial conversion of cropland to perennials, and ravine mitigation. These practices were first studied in isolation, and the HSPF parameterization was developed based on information from field-scale APEX models. Cover crops (high adoption on 75% of cropland) and perennials were predicted to provide the highest reductions in average annual flow and the 95th percentile flow. The highest reductions in sediment were also achieved with these two practices. Three scenarios representing BMPs implemented in combination were also completed, which provided the best benefits. Pairing fall cover crops (75%) with perennials and treatment wetlands achieved reductions in sediment load at the outlets of Cottonwood and Le Sueur greater than 22%.

It is important to note that the BMPs studied here have the potential to perform differently in practice, and modeling assumptions applied generally represent conservative benefits likely to be achieved at the watershed-scale. For example, conservation tillage as calibrated in the original, baseline model was expanded on additional cropland. This calibration was based on instream monitoring records and upland loading rates presented in the literature and reflects conservation tillage implemented during the simulation period (1995-2012). Other, more progressive forms of conservation tillage that disturb soils minimally and provide more residue cover may improve moisture retention and soil composition, thus, enhancing water quality benefits beyond what is predicted in the modeling scenarios. A potential future modeling scenario that could valuable for the Sediment Strategy could examine the benefits achieved with more progressive forms of conservation tillage or no-till.

Future work should also include assessing and establishing design criteria for treatment wetlands that are aligned with objectives of the Sediment Strategy. Benefits of treatment wetlands are likely to be improved if designed with new, multi-objective criteria in mind (i.e., require multiple outlet structures designed for storms of different sizes to ensure adequate detention time).

Perennials other than switchgrass, such as shrubs or trees, may also be more effective at reducing flow volumes, peak flows, and limiting upland sediment export, and future efforts should evaluate different perennial options. Additional studies regarding the effectiveness of ravine mitigation strategies and cover crop performance in the basin would be useful to guide adoption incentives, or requirements. These aspects of BMP implementation, design, and effectiveness should be further studied through field and modeling applications.

Future modeling work for the Sediment Strategy should extend the individual and combination BMP scenarios, at least those that are the most promising, into the other watersheds of the Minnesota River Basin (e.g., Blue Earth and Watonwan). Performance and water quality benefits achieved can be evaluated at the outlets of these watersheds, and reassessed at key downstream locations, such as the outlet of the Middle MN River watershed.

Lastly, BMP performance is subjective to weather conditions, and changes in climate such as prolonged droughts, more intense storms, and warmer temperatures can potentially improve (e.g., fall cover crops) or worsen BMP performance, which is important to consider in the context of long-term watershed management and planning. Future modeling scenarios could assess the performance of BMPs in the basin under potential future climate scenarios.

5.0 References

Acharya, B.S., H. Blanco-Canqui, R.B. Mitchell, R. Cruse, and D. Laird. 2019. Dedicated Bioenergy Crops and Water Erosion. *Journal of Environmental Quality*, 48(2), pp. 485-492.

AQUA TERRA Consultants. 2012. Modeling Guidance for BASINS/HSPF Applications under the MPCA One Water Program. Prepared for Minnesota Pollution Control Agency by AQUA TERRA Consultants, Mountain View, CA.

Bhandari, A.B., N.O. Nelson, D.W. Sweeney, C. Baffaut, J.A. Lory, A. Senaviratne, G.M. Pierzynski, K.A. Janssen and P.L. Barnes. 2017. Calibration of the APEX model to simulate management practice effects on runoff, sediment, and phosphorus loss. *Journal of Environmental Quality*, 46(6), pp.1332-1340.

Cho, S.J. 2017. Development of Data-Driven, Reduced-Complexity Watershed Simulation Models to Address Agricultural Non-Point Source Sediment Pollution in Southern Minnesota. A dissertation submitted to Johns Hopkins University in conformity with the requirements for the degree of Doctor of Philosophy in Environmental Engineering and Management. Baltimore, MD.

Cho, S. J., Wilcock, P. R., Belmont, P., Gran, K. B., and Hobbs, B. F. 2019. Simulation model for collaborative decision making on sediment source reduction in an intensively managed watershed. *Water Resources Research*, 55. DOI:10.1029/2018WR024324

CSSR (Collaborative for Sediment Source Reduction). 2017a. Management Option Simulation Model User Manual. [authors: S.J. Cho, P. Wilcock, K. Gran, P. Belmont, Patrick; and B. Hobbs]. https://conservancy.umn.edu/handle/11299/191082.

CSSR (Collaborative for Sediment Source Reduction). 2017b. Management Option Simulation Model Computational Module Handbook.

Dabney, S.M., J.A. Delgado, and D.W. Reeves. 2001. Using winter cover crops to improve soil and water quality. *Communications in Soil Science and Plant Analysis* 32:7-8, 1221-1250. DOI: 10.1081/CSS-100104110

Fisher, S.J., and R. Moore. 2008. 2007 Tillage Transect Survey, Final Report. Water Resources Center, Minnesota State University, Mankato.

Folle, S., B. Dalzell, and D. Mulla. 2009. Evaluation of Best Management Practices (BMPs) in Impaired Watersheds Using the SWAT Model. Prepared by Department of Soil, Water and Climate, University of Minnesota for the Minnesota Department of Agriculture.

Folle, S.M., 2010. SWAT Modeling of Sediment, Nutrients and Pesticides in the Le-Sueur River Watershed, South-Central Minnesota.

Goeken, R. 2013. Effects of perennial and cover crops on hydrology in Iowa. Graduate Theses and Dissertations. #13322.

Gran, K., P. Belmont, S. Day, C. Jennings, J.W. Lauer, E. Viparelli, P. Wilcock, and G. Parker. 2011. An Integrated Sediment Budget for the Le Sueur River Basin. Report wq-iw7-29o. Minnesota Pollution Control Agency, St. Paul, MN.

IAH. 2002. Illinois Agronomy Handbook, 23rd Edition. University of Illinois Extension, College of Agricultural, Consumer, and Environmental Sciences.

Iowa Department of Agriculture and Land Stewardship. 2017. Iowa Nutrient Reduction Strategy: A Science and Technology-based Framework to Assess and Reduce Nutrients to Iowa Waters and the

Gulf of Mexico. Prepared by Iowa Department of Agriculture and Land Stewardship, Iowa Department of Natural Resources, and Iowa State University College of Agriculture and Life Sciences.

Kalcic, M., W. Crumpton, X. Liu, J. D'Ambrosio, A. Ward, and J. Witter. 2018. Assessment of beyond-the-field nutrient management practices for agricultural crop systems with subsurface drainage. *Journal of Soil and Water Conservation*, 73: 62-74.

Kumarasamy, K. and P. Belmont. 2017. Multiple domain evaluation of watershed hydrology models. *Hydrol. Earth Syst. Sci. Discuss*., doi:10.5194/hess-2017-121, 2017.

Lazarus, W., J. Tang, G. Kramer, D. Mulla, and D. Wall. 2014. Watershed Nitrogen Reduction Planning Tool (NBMP.xlsm) for Comparing the Economics of Practices to Reduce Watershed Nitrogen Loads. Department of Applied Economics, University of Minnesota, Minneapolis, MN.

Lazarus, W., J. Tang, G. Kramer, D. Mulla, and D. Wall. 2015. Watershed Phosphorus Reduction Planning Tool (PBMP.xlsm) for Comparing the Economics of Agricultural Practices to Reduce Watershed Phosphorus Loads. Department of Applied Economics, University of Minnesota, Minneapolis, MN.

Lenhart, C., B. Gordon, J. Peterson, W. Eshenaur, L. Gifford, B. Wilson, J. Stamper, L. Krider, and N. Utt. 2017. *Agricultural BMP Handbook for Minnesota, 2nd Edition*. St. Paul, MN: Minnesota Department of Agriculture.

Mayer, P.M., S.K. Reynolds, Jr., M.D. McCutchen, and T.J. Canfield. 2007. Meta-analysis of nitrogen removal in riparian buffers. *Journal of Environmental Quality*, 36: 1172–1180.

McIsaac, G., J.K. Mitchell, and M.C. Hirschi. 1993. Nitrogen and phosphorus concentrations in runoff from corn and soybean tillage systems. In *Proceedings of the Conference on Agricultural Research to Protect Water Quality*, pp. 230–232. Soil and Water Conservation Society, Ankeny, IA.

MDA (Minnesota Department of Agriculture). 2016. Cover Crops. Minnesota Department of Agriculture. www.mda.state.mn.us/protecting/conservation/practices/covercrops.aspx.

Mitsch, W., and J. Gosselink. 2000. *Wetlands*. John Wiley & Sons, New York.

Montgomery, D. R. 2007. Soil erosion and agricultural sustainability. *Proc. Natl. Acad. Sci*. 104: 13268–13272.

MPCA (Minnesota Pollution Control Agency). 2014. The Minnesota Nutrient Reduction Strategy. MPCA, St. Paul, MN. Document number wq-s1-80. https://www.pca.state.mn.us/sites/default/files/wq-s1-80.pdf.

Neitsch, S.L., J.G. Arnold, J.R. Kiniry, and J.R. Williams. 2011. Soil and Water Assessment Tool, Theoretical Documentation, Version 2009. TR-406. Texas Water Resources Institute, College Station, TX.

O'Neill, A.M. 2015. Increasing the Environmental Services of Working Agricultural Lands through Best Management Practices. Ph.D. Thesis, University of Minnesota, Minneapolis, MN.

Ramirez-Avila, J.J., D.E. Radcliffe, D. Osmond, C. Bolster, A. Sharpley, S.L. Ortega-Achury, A. Forsberg, and J.L. Oldham. 2017. Evaluation of the APEX model to simulate runoff quality from agricultural fields in the southern region of the United States. *Journal of Environmental Quality*, 46(6), pp.1357-1364.

RESPEC. 2017. Documentation of the Best Management Practice Database Available in the Scenario Application Manager. Draft Topical Report RSI-2742. Prepared by Seth Kenner and Jared Oswald for the Minnesota Pollution Control Agency.

Rozema, E.R., A.C. VanderZaag, J.D. Wood, A. Drizo, Y. Zheng, A. Madani and R.J. Gordon. 2016. Constructed Wetlands for Agricultural Wastewater Treatment in Northeastern North America: A Review. *Water*, 8(5: Article number 173): 1-14. doi : 10.3390/w8050173.

Schmidt, M.L., S. Sarkar, J.B. Butcher, T. Johnson, and S. Julius. (submitted 2018). Agricultural best management practice sensitivity to changing air temperature and precipitation. In review, *Transactions of the ASABE* .

Shiptalo M.J., L.B. Owens, J.V. Bonta, and W.M. Edwards. 2013. Effect of no-till and extended rotation on nutrient losses in surface runoff. *Soil Science Society of America Journal*, doi: 10.2136/sssaj2013.01.0045.

Simpson, T., and S. Weammert. 2009. Developing Nitrogen, Phosphorus and Sediment Reduction Efficiencies for Tributary Strategy Practices, BMP Assessment: Final Report. Mid-Atlantic Water Program, University of Maryland.

Smith, L.A. 2014. BMP Nutrient and Sediment Reductions and Implementation Strategies for the Prioritization, Targeting, and Measuring Water Quality Improvement Application. Master of Science Thesis, University of Minnesota, Minneapolis, MN.

Steglich, E.M., Osorio, S., Doro, L., Jeong, J., and J.R. Williams. 2018. Agricultural Policy/Environmental Extender Model User's Manual Version 1501. 2018. Natural Resources Conservation Service and Blackland Research and Extension Center, Temple, TX 76502.

Steglich, E.M., J. Jeong, and J.R. Williams. 2016. Agricultural Policy/Environmental eXtender Model User's Manual Version 1501. http://epicapex.tamu.edu/apex/.

Tober, D.A. 2007. Switchgrass biomass trials in North Dakota, South Dakota, and Minnesota. https://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/ndpmcpu7093.pdf.

Tank, J. L., and E. Willows. 2016. Cover Crops and Phosphorus Loss. www.indianawatershedinitiative.com/uploads/8/0/9/5/80953414/tank_lab_phosphorus_one_pager_28oct16.pdf.

Tran, A.M.-T. 2015. Analyses of Potential Ravine and Bluff Stabilization Sites within the Blue Earth and Le Sueur River Basins (Master of Science Thesis). Minnesota State University Mankato, Mankato, MN.

UME (University of Minnesota Extension). 1996. Tillage Best Management Practices for Corn-Soybean Rotations in the Minnesota River Basin. University of Minnesota Extension, FO-06676.

USACE (U.S. Army Corps of Engineers). 2016. Whitepaper: Minnesota River Alternative Landscape Analysis. March 2016.

USDA NRCS (U.S. Department of Agriculture, Natural Resources Conservation Service). 2017. Effects of Conservation Practices on Water Erosion and Loss of Sediment at the Edge of the Field: A National Assessment Based on the 2003-06 CEAP Survey and APEX Modeling Databases. 74 pp.

USEPA (U.S. Environmental Protection Agency). 2000. BASINS Technical Note 6, Estimating Hydrology and Hydraulic Parameters for HSPF. EPA-823-R00-012. Office of Water, U.S. Environmental Protection Agency, Washington, DC.

USEPA (U.S. Environmental Protection Agency). 2003. National Management Measures to Control Nonpoint Source Pollution from Agriculture. EPA 841-B-03-004, July 2003.

USEPA (U.S. Environmental Protection Agency). 2006. BASINS Technical Note 8, Sediment Parameter and Calibration Guidance for HSPF. Office of Water, U.S. Environmental Protection Agency, Washington, DC.

Waidler, D., M. White., E. Steglich, S. Wang, J. Williams, C.A. Jones, and R. Srinivasan. 2011. Conservation Practice Modeling Guide for SWAT and. APEX. Texas Water Resources Institute Technical Report No. 399. Texas A&M University System, College Station, TX.

Wang, X., P.W. Gassman, J.R. Williams, S. Potter and A.R. Kemanian. 2008. Modeling the impacts of soil management practices on runoff, sediment yield, maize productivity, and soil organic carbon using APEX. *Soil and Tillage Research*, 101(1-2), pp.78-88.

Wang, X., J.R. Williams, P.W. Gassman, C. Baffaut, R.C. Izaurralde, J. Jeong, and J.R. Kiniry. 2012. EPIC and APEX: Model use, calibration, and validation. *Transactions of the ASABE*, 55(4), pp.1447-1462.

White, M.J. and J.G. Arnold. 2009. Development of a simplistic vegetative filter strip model for sediment and nutrient retention at the field scale. *Hydrological Processes*, 23: 1602-1616.

Wilcock, P., S.J. Cho, K. Gran, B. Hobbs, P. Belmont, M. Bevis, B. Heitkamp, J. Marr, S. Mielke, N. Mitchell, and K. Kumarasamy. 2016. Final Report: Collaborative for Sediment Source Reduction, Greater Blue Earth River Basin. Report to Minnesota Pollution Agency, Minnesota Dept. of Agriculture, and Minnesota Agricultural Water Resources Center.

Yin, L., X. Wang, J. Pan and P.W. Gassman. 2009. Evaluation of APEX for daily runoff and sediment yield from three plots in the Middle Huaihe River Watershed, China. *Transactions of the ASABE*, 52(6), pp.1833-1845.

Zhu, J.C., C.J. Gantzer, S.H. Anderson, E.E. Alberts, and R.R. Beuselinck. 1989. Runoff, Soil, and Dissolved Nutrient Losses from No-Tillage Soybean and Winter Cover Crops. *Soil Science Society of America Journal*, 53: 1210–1214.

Appendix A. Nutrient Reductions

In addition to reducing flow and sediment loads, some of the BMPs evaluated for this report can provide substantial co-benefits in reducing nutrient loads. Reductions in total nitrogen (TN) and total phosphorus (TP) are presented in the following tables and figures for the three study watersheds, which include Cottonwood, Le Sueur, and Middle MN. Results are shown for the individual BMP scenarios as well as for the three combination BMP scenarios. Reductions are evaluated at the downstream pour point, or mouth, of the watershed and are relative to the baseline conditions. Annual results are provided to show inter-annual variability in performance due to differences in weather conditions. The tables are color-coded, with the three wettest years (based on flows at the downstream pour point of the HUC8) shown in red, the three middle years in tan, and the three driest years in green. All reductions presented in this section for the Middle MN River watershed include the same BMP(s) being practiced in the Cottonwood and Le Sueur watersheds. Nutrient reductions are also presented for the field-scale APEX models in Figure 5-1. to Figure 5-4..

Table 5-1. Annual TN load reductions for BMP scenarios in the Cottonwood River Watershed

Year	Baseline Load (tons/yr)	Pollutant Removal Efficiency (Percent)										
		Cover Crops (25% adoption)	Cover crops (75% adoption)	Riparian Buffers (Buffer Law)	Riparian Buffers (All)	Cons. Tillage (High Adoption)	Treatment Wetlands	Perennials	Ravine Mitigation	Cover Crops (75%) + Perennials + Wetlands	Cover Crops (75%) + Buffers (all) + Ravines	Cover Crops (25%) + Cons. Tillage + Wetlands
1996	5,196	3.37%	10.04%	1.62%	13.11%	-0.50%	4.32%	18.24%	0.00%	30.09%	21.70%	7.17%
1997	7,831	4.28%	12.98%	1.61%	13.14%	-0.39%	4.78%	19.55%	0.00%	33.88%	24.20%	8.48%
1998	3,748	5.26%	15.36%	1.62%	13.25%	-0.65%	4.42%	19.86%	0.00%	35.45%	26.38%	8.85%
1999	3,491	4.20%	12.48%	1.65%	13.36%	-0.32%	3.36%	18.80%	0.00%	31.90%	24.02%	7.14%
2000	2,763	5.46%	14.14%	1.67%	13.48%	-0.18%	6.19%	20.18%	0.00%	36.47%	25.57%	10.80%
2001	11,043	3.84%	11.64%	1.59%	13.08%	-0.66%	6.05%	18.39%	0.00%	32.91%	23.05%	9.02%
2002	3,332	4.62%	12.89%	1.60%	13.14%	0.05%	3.19%	17.66%	0.00%	31.11%	24.13%	7.65%
2003	2,717	4.76%	13.68%	1.65%	13.62%	0.16%	3.89%	18.78%	-0.01%	33.45%	25.28%	8.66%
2004	5,976	3.24%	8.28%	1.58%	13.11%	-0.43%	5.65%	18.04%	0.00%	29.97%	20.26%	8.18%
2005	4,404	5.69%	16.52%	1.59%	12.89%	-0.08%	3.74%	18.88%	0.00%	34.83%	27.02%	9.13%
2006	6,106	4.09%	11.55%	1.58%	12.86%	-0.42%	4.31%	18.90%	0.00%	31.84%	22.77%	7.86%
2007	4,574	6.37%	17.33%	1.52%	12.35%	-0.56%	4.18%	19.34%	0.00%	35.89%	27.16%	9.53%
2008	3,473	4.44%	12.52%	1.61%	13.15%	-0.40%	3.44%	18.46%	0.00%	31.47%	23.86%	7.32%
2009	2,386	5.91%	16.70%	1.55%	12.62%	0.03%	2.08%	18.18%	0.00%	32.75%	26.87%	7.91%
2010	7,871	4.88%	13.77%	1.53%	12.48%	-0.21%	4.17%	17.74%	0.00%	32.12%	24.26%	8.55%
2011	10,334	3.06%	9.38%	1.62%	13.21%	-0.43%	5.37%	18.35%	0.00%	30.92%	21.24%	7.94%
2012	5,883	3.79%	10.48%	1.63%	13.37%	-0.14%	6.78%	19.03%	0.00%	33.80%	22.43%	10.06%
Mean	5,360	4.3%	12.3%	1.6%	13.0%	-0.4%	4.8%	18.7%	0.0%	32.6%	23.6%	8.5%

Table 5-2. Annual TP load reductions for BMP scenarios in the Cottonwood River Watershed

Year	Baseline Load (tons/yr)	Pollutant Removal Efficiency (Percent)										
		Cover Crops (25% adoption)	Cover crops (75% adoption)	Riparian Buffers (Buffer Law)	Riparian Buffers (All)	Cons. Tillage (High Adoption)	Treatment Wetlands	Perennials	Ravine Mitigation	Cover Crops (75%) + Perennials + Wetlands	Cover Crops (75%) + Buffers (all) + Ravines	Cover Crops (25%) + Cons. Tillage + Wetlands
1996	170.1	2.39%	6.66%	1.21%	11.75%	0.14%	4.36%	17.04%	0.01%	25.19%	17.55%	6.57%
1997	225.8	1.40%	5.90%	1.09%	10.74%	0.17%	3.90%	13.45%	0.00%	20.77%	15.90%	5.23%
1998	84.6	3.87%	9.54%	1.13%	11.11%	0.71%	4.27%	17.90%	0.02%	27.29%	19.41%	8.09%
1999	79.0	1.98%	5.95%	1.17%	11.41%	0.35%	3.68%	18.25%	-0.03%	25.14%	16.53%	5.75%
2000	60.0	3.91%	11.17%	1.33%	12.51%	1.09%	6.89%	21.54%	-0.01%	34.36%	22.35%	10.67%
2001	239.1	4.63%	10.72%	0.88%	9.29%	0.17%	6.80%	13.28%	0.01%	25.96%	18.71%	10.79%
2002	67.4	4.58%	10.54%	1.22%	11.80%	1.25%	4.30%	17.14%	0.04%	27.48%	20.86%	8.83%
2003	50.1	3.16%	8.39%	1.18%	11.66%	0.02%	4.54%	19.71%	-0.03%	28.79%	18.96%	7.45%
2004	173.3	6.35%	15.46%	1.22%	11.10%	-0.38%	6.18%	19.19%	0.01%	34.32%	24.73%	11.42%
2005	88.9	4.55%	12.28%	1.05%	10.47%	-0.04%	4.58%	16.91%	0.01%	28.91%	21.28%	8.91%
2006	147.6	4.43%	10.28%	1.15%	11.06%	-0.01%	4.47%	17.11%	0.00%	27.37%	20.05%	8.39%
2007	106.6	5.58%	13.72%	0.95%	9.83%	0.47%	5.04%	16.21%	-0.01%	29.08%	21.89%	10.23%
2008	62.2	2.46%	6.38%	1.06%	10.68%	0.18%	4.38%	17.61%	0.02%	25.25%	16.25%	6.66%
2009	60.7	4.54%	12.71%	1.08%	11.06%	0.13%	3.44%	17.05%	-0.01%	28.54%	22.04%	7.90%
2010	291.8	3.31%	9.36%	1.05%	10.56%	0.19%	4.35%	14.36%	0.00%	24.26%	18.75%	7.38%
2011	306.5	1.74%	4.75%	1.08%	10.69%	0.17%	4.66%	14.18%	0.00%	21.21%	14.83%	6.23%
2012	129.7	5.79%	13.49%	0.96%	9.56%	1.33%	8.33%	19.57%	0.01%	34.70%	21.54%	13.91%
Mean	137.8	3.6%	9.4%	1.1%	10.7%	0.3%	5.0%	16.1%	0.0%	26.4%	18.9%	8.3%

Table 5-3. Annual TN load reductions for BMP scenarios in the Le Sueur River Watershed

Year	Baseline Load (tons/yr)	Pollutant Removal Efficiency (Percent)										
		Cover Crops (25% adoption)	Cover crops (75% adoption)	Riparian Buffers (Buffer Law)	Riparian Buffers (All)	Cons. Tillage (High Adoption)	Treatment Wetlands	Perennials	Ravine Mitigation	Cover Crops (75%) + Perennials + Wetlands	Cover Crops (75%) + Buffers (all) + Ravines	Cover Crops (25%) + Cons. Tillage + Wetlands
1996	6,199	4.21%	12.45%	1.29%	9.41%	-0.10%	8.46%	22.41%	0.01%	38.90%	18.31%	11.50%
1997	6,154	4.06%	12.51%	1.32%	9.66%	-0.25%	8.59%	23.50%	0.01%	40.31%	18.45%	11.09%
1998	7,574	3.42%	11.58%	1.32%	9.71%	0.04%	8.65%	20.85%	0.01%	37.33%	17.70%	11.42%
1999	10,810	0.05%	4.52%	1.34%	9.72%	0.28%	9.03%	19.50%	0.02%	32.03%	11.19%	9.47%
2000	7,530	-0.68%	1.16%	1.36%	9.74%	0.37%	9.24%	18.72%	0.03%	29.20%	8.11%	9.19%
2001	11,941	0.26%	3.03%	1.32%	9.58%	-0.02%	8.97%	19.67%	0.02%	30.53%	9.74%	8.99%
2002	4,623	5.59%	17.45%	1.33%	9.71%	-0.15%	8.53%	23.75%	0.03%	43.94%	23.10%	12.83%
2003	4,013	0.92%	7.10%	1.34%	9.93%	-0.25%	9.13%	23.81%	-0.02%	37.87%	13.61%	9.38%
2004	8,976	3.51%	12.02%	1.32%	9.73%	0.15%	9.14%	19.97%	0.01%	37.58%	18.14%	12.56%
2005	7,715	3.20%	11.91%	1.35%	9.68%	0.16%	8.63%	20.23%	0.01%	37.26%	17.97%	11.87%
2006	6,893	2.25%	9.06%	1.34%	9.63%	0.01%	8.88%	21.33%	0.00%	36.44%	15.29%	10.61%
2007	8,549	7.32%	22.22%	1.29%	9.33%	-0.28%	8.44%	21.21%	0.02%	44.48%	27.37%	14.41%
2008	6,217	0.73%	5.41%	1.35%	9.80%	0.01%	9.09%	21.49%	0.00%	34.53%	11.99%	9.68%
2009	3,842	6.11%	18.77%	1.27%	9.24%	-0.31%	7.85%	23.49%	0.05%	43.60%	24.11%	12.56%
2010	13,905	4.15%	15.49%	1.32%	9.52%	0.07%	8.62%	19.14%	0.03%	38.68%	21.23%	12.69%
2011	10,537	1.99%	8.11%	1.33%	9.70%	-0.18%	8.84%	21.16%	0.01%	35.54%	14.47%	10.18%
2012	4,028	-1.84%	1.55%	1.38%	9.88%	0.00%	10.02%	20.98%	0.07%	32.02%	8.52%	8.29%
Mean	7,618	2.6%	10.1%	1.3%	9.6%	0.0%	8.8%	20.8%	0.0%	36.6%	16.3%	11.0%

Table 5-4. Annual TP load reductions for BMP scenarios in the Le Sueur River Watershed

Year	Baseline Load (tons/yr)	Pollutant Removal Efficiency (Percent)										
		Cover Crops (25% adoption)	Cover crops (75% adoption)	Riparian Buffers (Buffer Law)	Riparian Buffers (All)	Cons. Tillage (High Adoption)	Treatment Wetlands	Perennials	Ravine Mitigation	Cover Crops (75%) + Perennials + Wetlands	Cover Crops (75%) + Buffers (all) + Ravines	Cover Crops (25%) + Cons. Tillage + Wetlands
1996	192.2	-0.74%	1.51%	0.97%	7.57%	0.85%	6.96%	10.58%	0.07%	17.83%	6.44%	7.83%
1997	185.3	-7.30%	-3.76%	1.12%	8.60%	0.63%	7.52%	13.25%	0.08%	17.81%	1.93%	3.34%
1998	187.5	-2.31%	1.32%	1.12%	8.56%	0.92%	7.29%	11.64%	0.08%	18.96%	6.76%	6.74%
1999	261.3	-4.78%	-1.79%	1.08%	8.14%	1.13%	8.43%	8.46%	0.13%	15.07%	3.79%	6.70%
2000	218.4	-4.49%	-2.43%	1.24%	8.56%	1.17%	8.44%	11.01%	0.14%	17.90%	3.36%	6.98%
2001	332.4	-0.29%	0.14%	0.98%	7.43%	0.69%	7.33%	7.78%	0.11%	14.61%	5.27%	8.82%
2002	109.3	2.84%	9.52%	1.00%	8.14%	0.55%	6.87%	10.19%	0.05%	22.92%	14.12%	10.99%
2003	103.3	-1.46%	0.13%	0.77%	7.06%	0.20%	6.41%	13.86%	-0.10%	19.89%	4.46%	6.87%
2004	319.3	-6.74%	-3.61%	0.95%	6.99%	0.84%	7.03%	8.21%	0.05%	12.07%	1.28%	3.19%
2005	180.3	1.95%	7.94%	0.98%	7.42%	1.08%	6.80%	6.80%	0.05%	18.88%	12.46%	10.71%
2006	168.8	1.12%	3.28%	0.91%	7.04%	0.64%	6.46%	9.52%	0.00%	17.65%	7.70%	9.21%
2007	281.5	2.87%	13.11%	0.96%	7.36%	0.15%	6.41%	5.88%	0.08%	20.35%	17.33%	9.91%
2008	161.4	-1.97%	-0.77%	0.95%	7.27%	0.61%	6.88%	11.10%	0.02%	16.72%	3.95%	7.18%
2009	124.3	1.82%	5.32%	0.76%	6.08%	0.76%	4.59%	7.37%	0.23%	15.10%	9.00%	8.26%
2010	507.0	-0.06%	3.92%	1.00%	7.43%	1.17%	6.93%	7.54%	0.12%	16.65%	8.77%	9.06%
2011	330.0	-4.81%	-2.97%	1.02%	7.95%	0.53%	7.41%	10.01%	0.04%	15.05%	2.48%	5.22%
2012	96.3	0.11%	1.50%	1.23%	8.85%	1.30%	9.03%	14.51%	0.37%	23.43%	7.01%	12.20%
Mean	221.1	-1.8%	1.6%	1.0%	7.6%	0.8%	7.1%	9.2%	0.1%	17.0%	6.6%	7.6%

Table 5-5. Annual TN load reductions for BMP scenarios in the Middle Minnesota River Watershed

Year	Baseline Load (tons/yr)	Pollutant Removal Efficiency (Percent)										
		Cover Crops (25% adoption)	Cover crops (75% adoption)	Riparian Buffers (Buffer Law)	Riparian Buffers (All)	Cons. Tillage (High Adoption)	Treatment Wetlands	Perennials	Ravine Mitigation	Cover Crops (75%) + Perennials + Wetlands	Cover Crops (75%) + Buffers (all) + Ravines	Cover Crops (25%) + Cons. Tillage + Wetlands
1996	39,886	0.84%	2.54%	0.47%	3.66%	0.29%	1.78%	5.93%	0.00%	9.60%	5.88%	2.85%
1997	60,000	-1.07%	1.00%	-1.69%	0.87%	0.00%	-0.74%	2.72%	0.00%	8.33%	3.53%	0.29%
1998	34,541	1.09%	3.20%	0.36%	2.85%	0.16%	1.32%	4.62%	0.00%	8.31%	5.64%	2.50%
1999	44,545	0.78%	2.23%	0.29%	2.26%	0.15%	0.93%	3.61%	0.00%	6.21%	4.20%	1.77%
2000	27,850	1.04%	2.65%	0.33%	2.63%	0.18%	1.47%	4.02%	0.00%	7.40%	4.94%	2.51%
2001	85,000	2.21%	3.90%	1.75%	4.16%	0.00%	2.90%	5.82%	0.00%	11.76%	6.32%	3.65%
2002	24,785	1.01%	2.88%	0.46%	3.69%	0.39%	1.61%	5.43%	0.00%	9.28%	6.18%	2.87%
2003	18,931	1.25%	3.53%	0.40%	3.20%	0.17%	1.16%	4.78%	0.00%	8.66%	6.26%	2.50%
2004	55,000	2.49%	3.48%	2.38%	5.19%	0.00%	3.85%	6.85%	0.00%	9.83%	6.50%	4.49%
2005	44,622	1.04%	2.99%	0.30%	2.41%	0.20%	1.00%	3.97%	0.00%	7.23%	5.03%	2.15%
2006	42,204	1.06%	2.95%	0.38%	3.00%	0.11%	1.30%	4.78%	0.00%	8.28%	5.57%	2.38%
2007	39,137	1.48%	3.99%	0.33%	2.58%	0.13%	1.08%	4.69%	0.00%	8.54%	6.05%	2.57%
2008	31,310	0.90%	2.58%	0.32%	2.58%	0.11%	0.98%	4.06%	0.00%	6.99%	4.82%	1.93%
2009	28,471	1.08%	3.01%	0.26%	2.03%	0.21%	0.53%	3.55%	0.00%	6.24%	4.65%	1.78%
2010	80,000	3.19%	4.93%	2.54%	4.49%	0.00%	3.27%	5.91%	0.00%	6.25%	6.80%	4.23%
2011	75,000	4.04%	5.79%	3.54%	6.18%	0.00%	4.63%	7.87%	0.00%	13.33%	8.46%	5.50%
2012	31,759	1.13%	3.17%	0.58%	4.60%	0.30%	2.85%	7.14%	0.00%	12.32%	7.37%	4.08%
Mean	44,885	1.6%	3.4%	1.0%	3.5%	0.1%	2.0%	5.3%	0.0%	9.0%	5.9%	3.1%

Table 5-6. Annual TP load reductions for BMP scenarios in the Middle Minnesota River Watershed

Year	Baseline Load (tons/year)	Pollutant Removal Efficiency (Percent)										
		Cover Crops (25% adoption)	Cover crops (75% adoption)	Riparian Buffers (Buffer Law)	Riparian Buffers (All)	Cons. Tillage (High Adoption)	Treatment Wetlands	Perennials	Ravine Mitigation	Cover Crops (75%) + Perennials + Wetlands	Cover Crops (75%) + Buffers (all) + Ravines	Cover Crops (25%) + Cons. Tillage + Wetlands
1996	1,559	0.41%	1.51%	0.41%	3.35%	0.12%	1.89%	4.42%	0.00%	7.45%	4.70%	2.36%
1997	2,394	-0.11%	0.70%	0.30%	2.57%	-0.01%	1.25%	2.84%	0.00%	4.45%	3.18%	1.02%
1998	1,119	0.24%	1.24%	0.30%	2.48%	0.13%	1.25%	3.28%	0.00%	5.23%	3.58%	1.50%
1999	1,342	-0.06%	0.52%	0.27%	2.21%	0.00%	1.08%	2.93%	0.00%	4.12%	2.67%	0.96%
2000	820	-0.08%	0.63%	0.31%	2.54%	0.00%	1.59%	3.54%	0.00%	5.25%	3.11%	1.33%
2001	2,606	0.60%	1.60%	0.23%	1.96%	0.04%	1.35%	2.24%	0.00%	4.67%	3.37%	1.88%
2002	844	0.23%	1.08%	0.36%	2.92%	0.10%	1.72%	3.85%	0.01%	6.15%	3.87%	1.93%
2003	587	0.10%	0.91%	0.26%	2.30%	-0.11%	0.98%	3.20%	-0.01%	4.53%	3.11%	0.97%
2004	1,715	0.49%	2.00%	0.40%	3.15%	0.06%	2.28%	4.58%	0.01%	8.28%	4.95%	2.71%
2005	1,319	0.40%	1.45%	0.22%	1.84%	0.06%	0.91%	2.35%	0.00%	4.17%	3.12%	1.36%
2006	1,288	0.59%	1.71%	0.30%	2.60%	-0.04%	1.33%	3.55%	0.00%	5.82%	4.11%	1.80%
2007	1,382	0.90%	2.40%	0.22%	1.91%	0.07%	0.92%	2.27%	0.00%	4.91%	4.03%	1.81%
2008	898	0.25%	0.97%	0.22%	1.94%	0.02%	0.94%	2.43%	0.00%	3.80%	2.81%	1.14%
2009	1,233	0.46%	1.30%	0.16%	1.34%	0.06%	0.40%	1.59%	0.00%	2.81%	2.48%	0.89%
2010	3,541	0.40%	1.43%	0.21%	1.86%	0.03%	0.96%	2.28%	0.01%	4.18%	3.12%	1.29%
2011	2,937	0.30%	1.05%	0.26%	2.29%	0.03%	1.16%	2.77%	0.02%	4.49%	3.22%	1.41%
2012	844	0.99%	2.80%	0.47%	3.85%	0.26%	3.23%	6.14%	0.00%	11.01%	6.34%	4.21%
Mean	1,555	0.4%	1.4%	0.3%	2.3%	0.0%	1.3%	3.0%	0.0%	5.2%	3.6%	1.6%

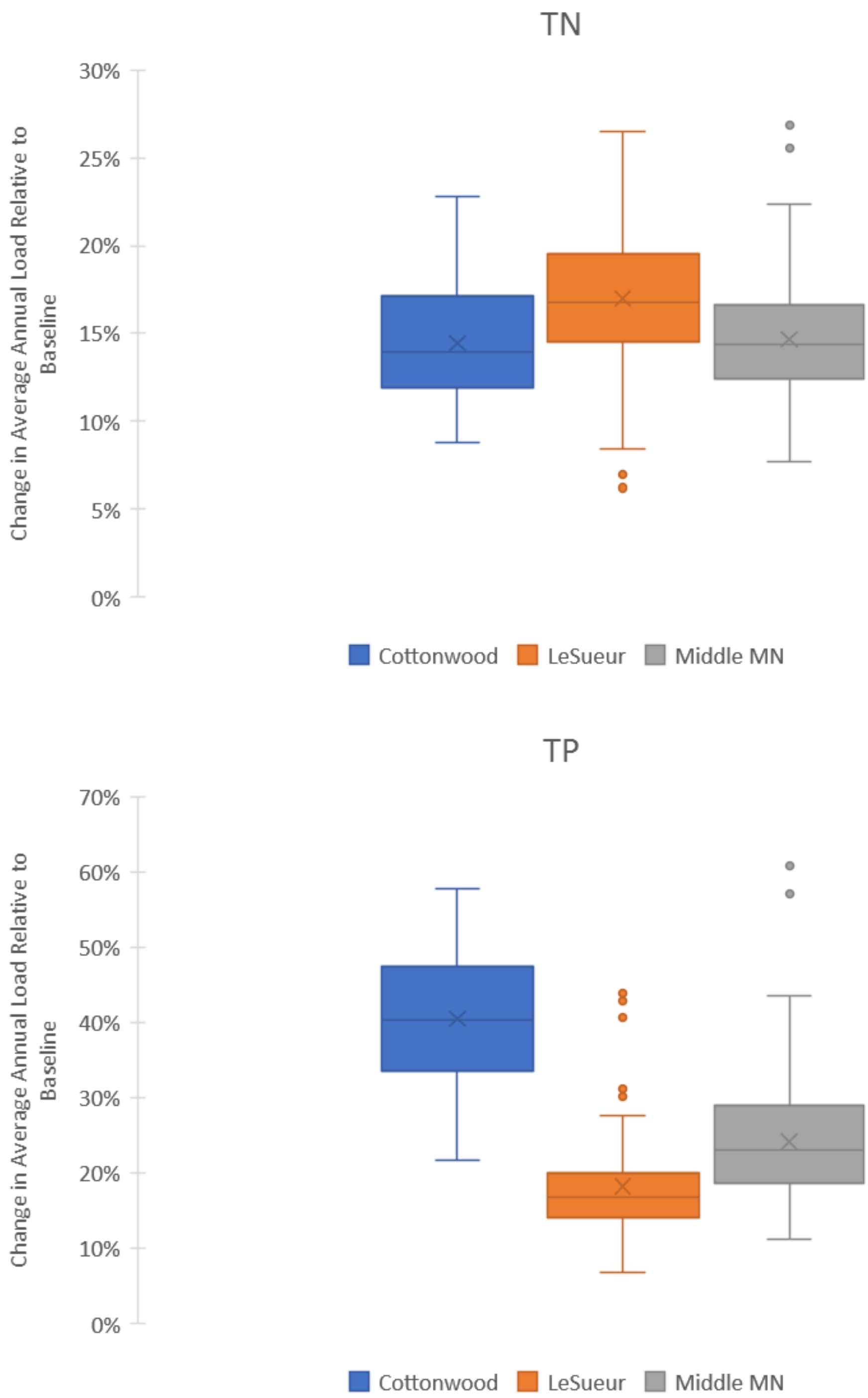


Figure 5-1. Range of simulated change in average annual TN and TP loads for cover crops relative to baseline for field-scale APEX models.

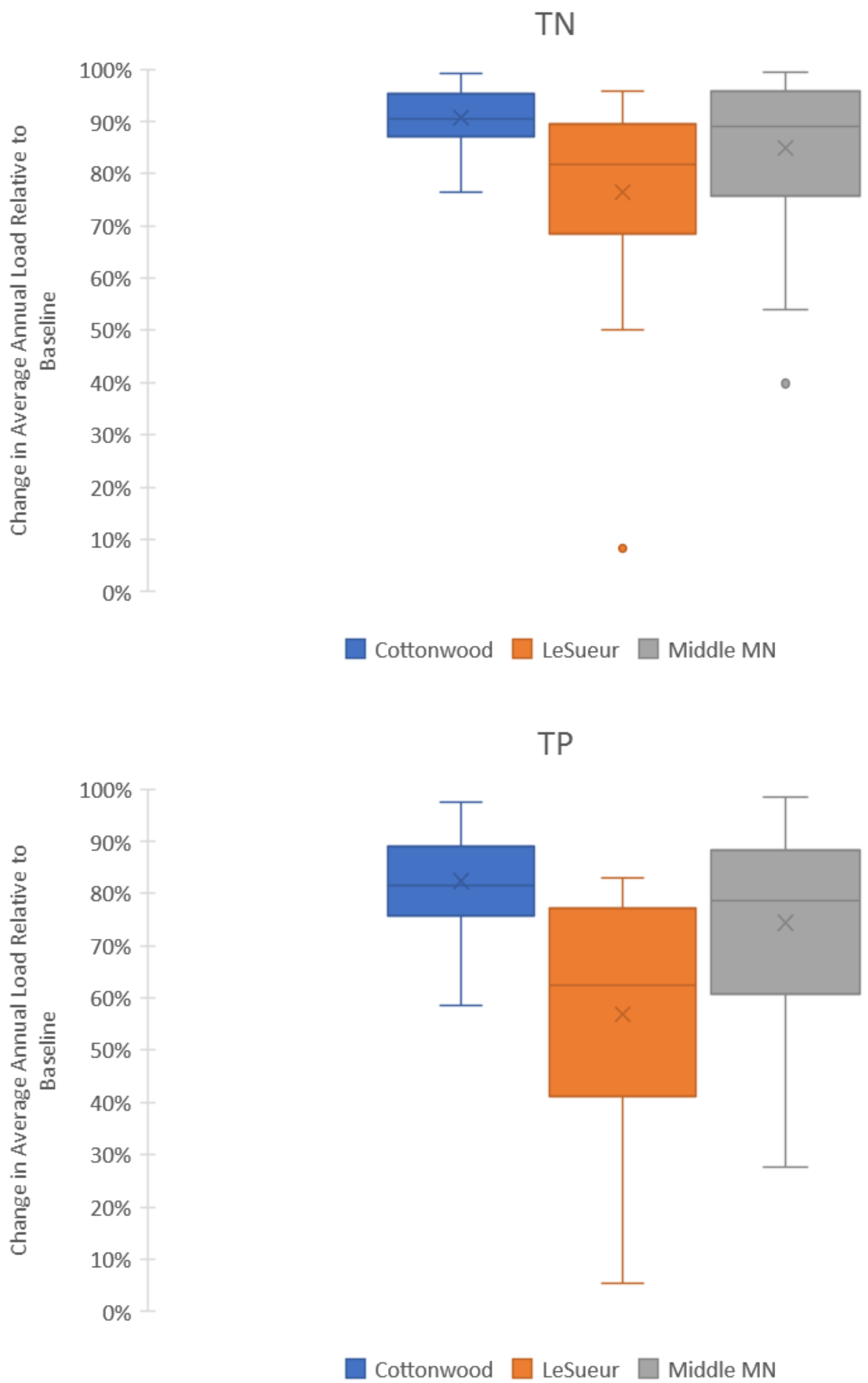
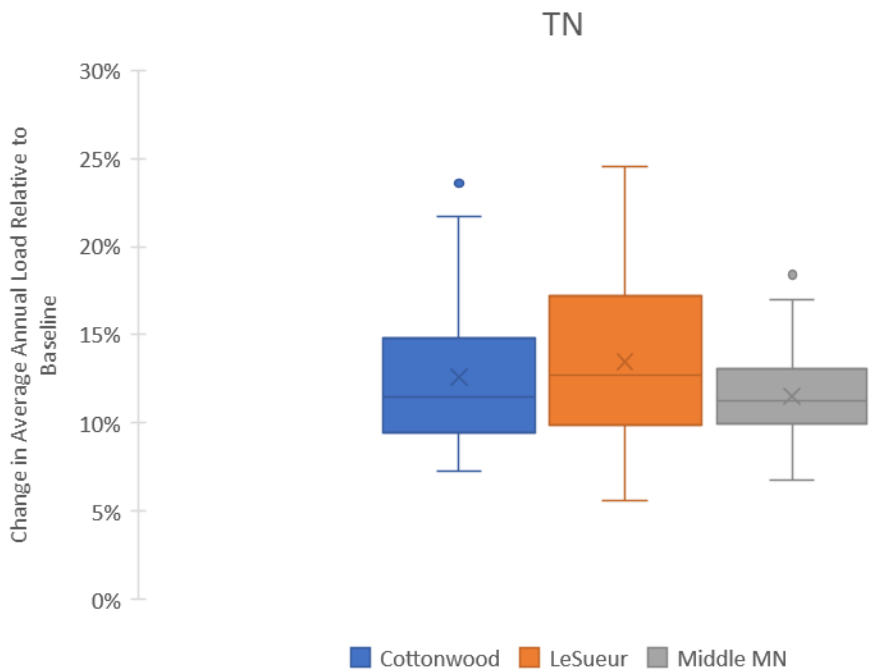


Figure 5-2. Range of simulated change in average annual TN and TP loads due to adoption of filter strips relative to baseline for field-scale APEX models.



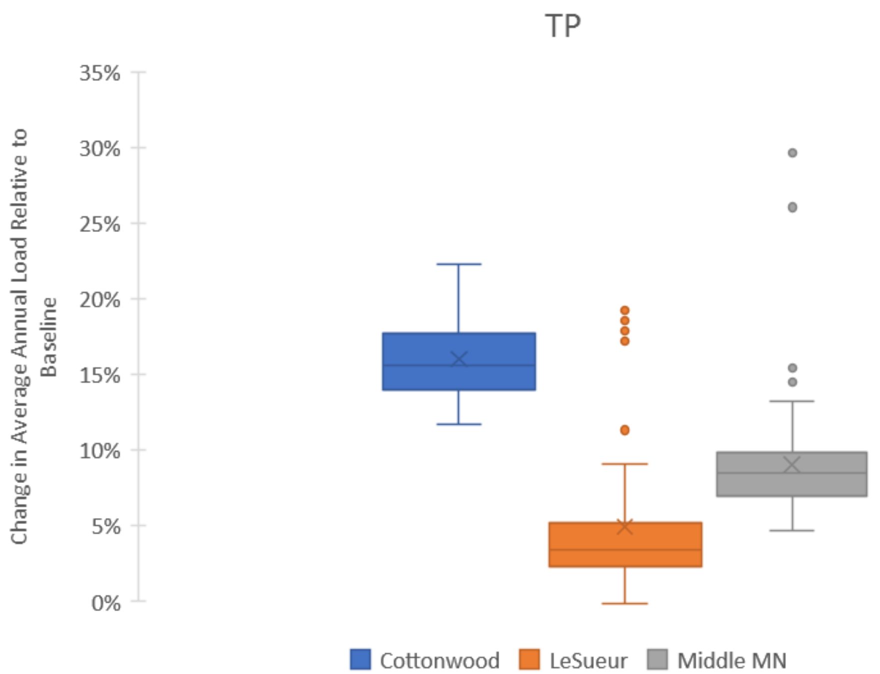
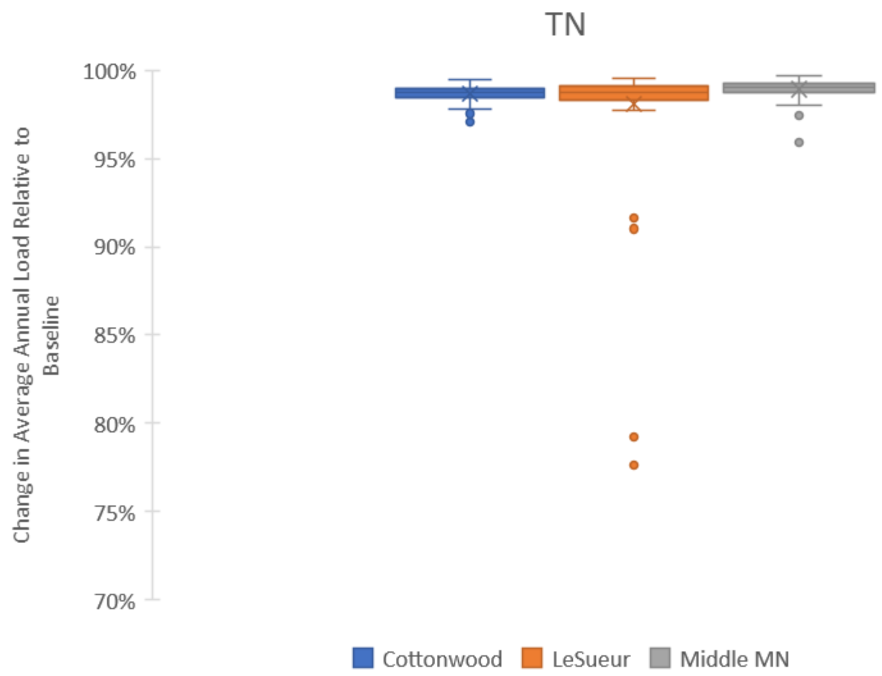


Figure 5-3. Range of simulated change in average annual TN and TP loads for conservation tillage relative to conventional tillage for field-scale APEX models.



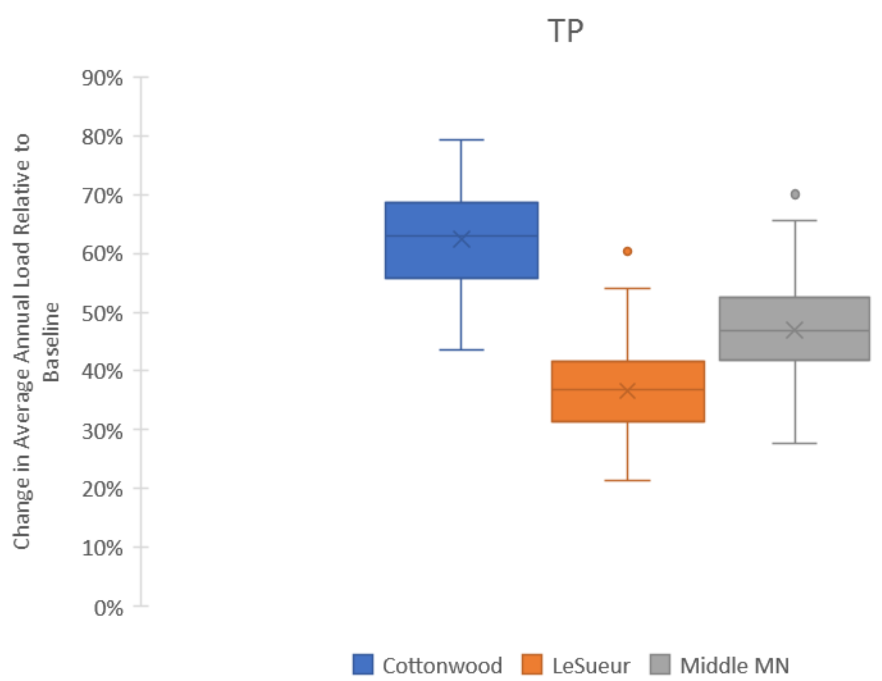


Figure 5-4. Range of simulated change in average annual TN and TP loads for switchgrass relative to baseline for field-scale APEX models.