Water Resources Research

RESEARCH ARTICLE
10.1029/2018WR024324

Special Section:
Dynamics in Intensively Managed Landscapes: Water, Sediment, Nutrient, Carbon, and Ecohydrology

Key Points:
- We present the development of a watershed sediment source and delivery model to evaluate conservation trade-offs
- The model is designed to provide reliable and robust estimates of sediment source reduction that is credible at the watershed scale with rapid run time to support decision analysis
- The model is used to bring consensus among stakeholders in identifying a priority strategy for investing public funds to reduce sediment loading and improve water quality

Supporting Information:
- Supporting Information S1

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Citation:
Cho, S. J., Wilcock, P. R., Belmont, P., Gran, K. B., & Hobbs, B. F. (2019). Simulation model for collaborative decision making on sediment source reduction in an intensively managed watershed. *Water Resources Research*, *55*, 1544–1564. https://doi.org/10.1029/2018WR024324

Received 26 OCT 2018
Accepted 29 JAN 2019
Accepted article online 5 FEB 2019
Published online 25 FEB 2019

Simulation Model for Collaborative Decision Making on Sediment Source Reduction in an Intensively Managed Watershed

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Abstract We developed a watershed sediment source and delivery model for use in evaluating conservation trade-offs in southern Minnesota, where sediment loading has been identified as a priority and there is substantial public investment in cleaner water. The model was developed in a stakeholder process and links user-specified management options to reductions in sediment loading at the outlet of a 2,880-km^2 intensively farmed watershed. The simulation model was formulated to allocate total sediment load among sources, which provides robustness to the model by constraining the relative magnitude of sediment loads and their reduction. A novel topographic filtering approach was used to develop spatially distributed maps of sediment delivery ratio, addressing the problem of storage between source and outlet. The dominant sediment source in the watershed is erosion of steep streamside bluffs in response to increases in river discharge. Rates of bluff erosion as a function of river discharge were determined from sediment loads measured at pairs of gages on individual streams. Using this analysis, upland water storage to reduce peak river flow was included as an option in the model. The model development process was designed to promote transparency and develop stakeholder trust through multiple meetings in which an underlying sediment budget was developed and refined. The model runs rapidly, providing real-time response to user choice and supporting Monte Carlo simulation of the influence of uncertainty on the calculated sediment load. The stakeholder group used the model to identify a priority strategy for investing public funds to improve water quality.

Plain Language Summary Water pollution from excess sediment poses serious threats to the livelihood of aquatic ecosystem as well as recreation. We present a watershed model, developed through a collaboration with local stakeholders, that evaluates different conservation scenarios to reduce sediment source and delivery. The model is used to bring consensus among stakeholders in identifying a priority strategy for investing public funds to improve water quality.

1. Introduction

Agricultural nonpoint source (NPS) pollution is a leading cause of impairment in U.S. rivers and streams (U.S. EPA, 2012a). Water quality management planning, required to allocate mitigation activities to effectively address NPS pollution, has been a subject of intensive modeling and research over the years (Belmont & Foufoula-Georgiou, 2017; Palmer et al., 2000; Shortle & Horan, 2001). Some of the major challenges in addressing NPS pollution include (1) reliable and robust quantification of locations, mechanisms, and rates of loading in order to assign appropriate management strategies (Belmont et al., 2011), (2) accurate and practicable information on best available, economically achievable pollution management options (U.S. EPA, 2012b), and (3) an accessible and reliable basis for evaluating the effectiveness and trade-offs among different management strategies at the watershed scale (Tomer et al., 2015).

Environmental modeling can address these challenges by bridging environmental observations with the social elements of conservation and investment constraints to support policy analysis and stakeholders' decision-making processes (Thomann, 1998; Tomer et al., 2015). In the case of intensively managed agricultural regions, stakeholders include the owners and managers of the farmland, who adopt conservation measures in response to regulation, incentives, and their own values and perceptions. Historical conflicts in environmental management can often be traced back to the lack of reliable, trusted, and mutually agreed-upon information on the causes of pollution and the consequences of environmental management (Thomann, 1998). Ongoing increases in model complexity can contribute to this conflict by introducing technical and timing barriers between model and stakeholder (Gaddis, 2010). A modeling approach to support environmental decision making needs to be transparent and accessible in order to support effective participation of decision makers (Haag & Kaupenjohann, 2001).

In this paper, we present a model that links water and sediment conservation actions to watershed sediment loads in a region dominated by row crop agriculture. The physical and social context of the water quality problem strongly informed the structure and key elements of the model. The model was developed in collaboration with local, state, industry, and environmental stakeholders from both private and public sectors. The model was intended to marshal the best available information on sediment sources and delivery in order to support understanding and provide forecasts of watershed response to management choices. Our goal was to provide a decision-support framework that was transparent, robust, and accessible in order to support evaluation of management options, leading to a consensus strategy for sediment load reduction that could be implemented at the watershed scale.

To do this, we built a modeling framework on a sediment budget in which the magnitude of the total sediment load and of individual sources were well constrained by multiple lines of independent evidence (Belmont et al., 2011; Gran et al., 2011). We use a novel topographic filtering model to link distributed sediment sources to the measured annual sediment load at the watershed outlet via spatially distributed values of sediment delivery ratio (SDR; Cho et al., 2018). The modeling framework incorporates conservation actions through their effect on either sediment production or sediment delivery. By structuring the model to adjust rates of sediment erosion and delivery already shown to produce the sediment load in an initial reference period, the model results are well constrained. We argue that this approach provides more robust, reliable forecasts than models based on approximations of physical processes (e.g., Johnson et al., 2012) that are hard to comprehensively verify and must be calibrated at scales much larger than those at which the mechanisms are represented in the model.

Because sediment supply from near-channel sources is a large part of the sediment budget, managing this source by reducing flood flows was a conservation action under consideration. We developed a relation between peak river discharge and near-channel sediment supply (NCSS) using sediment loads observed at paired stream gages within the incised river corridors. As with the application to soil erosion and delivery from uplands, the simulation model operates to reduce the observed total near-channel supply in proportion to estimated reductions in peak flows from water conservation actions. Strong constraints based on independent sediment information and a relatively simple, accessible, and quickly computed sediment allocation model act together to enhance stakeholder understanding and effective evaluation of management options.

2. Context for the Model

2.1. Watershed

The Upper Mississippi River combines with two coequal tributaries, the St. Croix River and the Minnesota River, in the southern portion of the Minneapolis-St. Paul metro area in Minnesota, USA. The Minnesota River, which contributes roughly one third of the combined flow of the system, produces 80–90% of the sediment load of the combined rivers, as documented by deposition in Lake Pepin, a naturally dammed riverine lake downstream of the confluences (Engstrom, 2009; Kelley & Nater, 2000). Within the Minnesota River basin, up to 50% of the sediment load comes from the 9,000-km^2 Greater Blue Earth River Basin (GBERB; Figure 1), which comprises only 20% of the basin area (Wilcock, 2009). The Le Sueur River is the largest contributor of sediment within the GBERB, delivering about one half of the total sediment load from less than one third of the overall drainage area. We develop the sediment simulation model for the 2,880-km^2

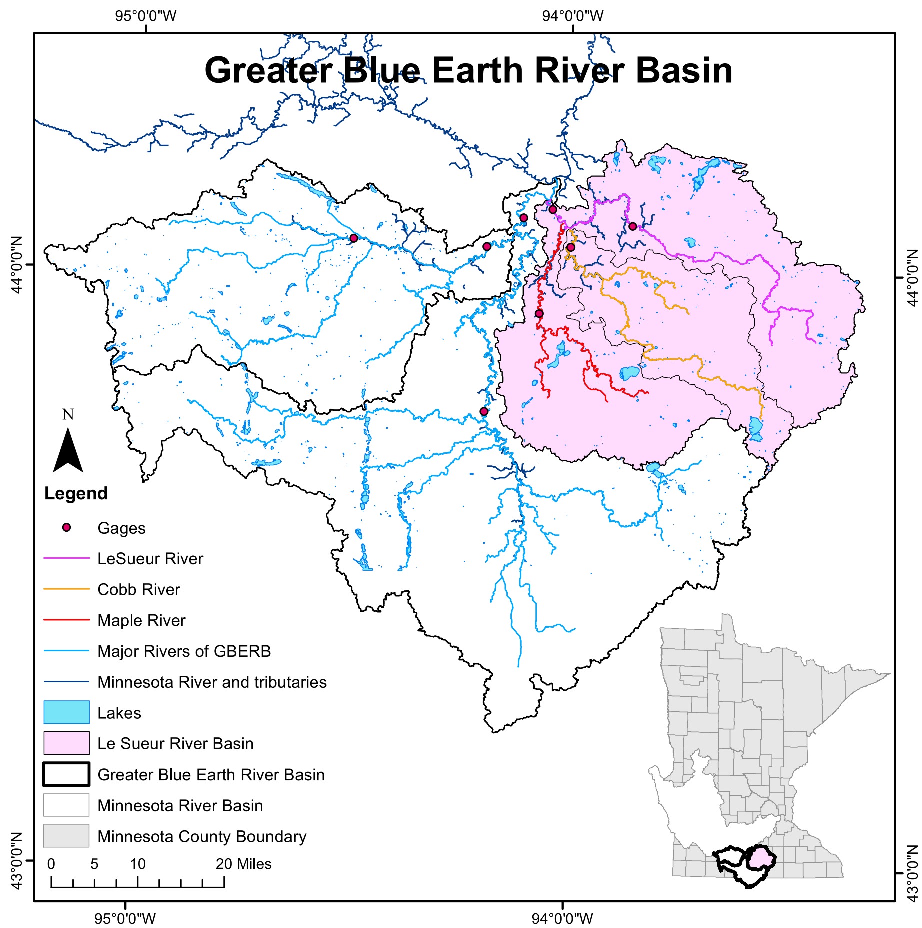

Figure 1. The Greater Blue Earth River Basin (GBERB) is a major contributor of sediment to the Minnesota River, delivering about one half of the total sediment load. Le Sueur River Basin, which consists of Maple River, Cobb River, and Le Sueur River watersheds, is the largest contributor within the GBERB.

Le Sueur River Basin (LSRB), which has three main rivers: the Maple River, the Cobb River, and the mainstem Le Sueur River.

Both geologic and land use history play a strong role in determining sediment sources and their change over time. Retreat of the Laurentide Ice Sheet left relatively flat terrain, underlain by 50–60 m of fine-grained, interbedded Pleistocene till and glaciofluvial sand strata, mantled in places by glaciolacustrine deposits (Jennings, 2010). Meltwater along the southern margin of the retreating ice sheet formed glacial Lake Agassiz, which periodically drained to the south and east through glacial River Warren (Clayton & Moran, 1982; Fenton et al., 1983; Matsch, 1983; Teller & Clayton, 1983). The initial catastrophic drainage of the lake, dated to 13,400 calendar years before present, produced a broad, incised valley through which the smaller Minnesota River now flows. The maximum incision, as much as 70 m, occurred in the vicinity of the Blue Earth River confluence, triggering incision that has propagated 35–65 km upstream into major tributaries (Belmont, 2011; Bevis, 2015; Gran et al., 2013), leading to deep river valleys lined with tall, actively eroding bluffs. Bluffs are composed of fine-grained stacked tills with a mean silt and clay content of 65% (Belmont et al., 2011; Gran et al., 2009).

Sediment fingerprinting in the Le Sueur watershed and Lake Pepin shows that near-channel sources contributed most of the sediment to Lake Pepin before widespread European settlement of the Minnesota River valley (Belmont, 2011; Belmont et al., 2014). Development of row crop agriculture in the late nineteenth century and early twentieth century was synchronous with a tenfold increase in sediment delivery to Lake Pepin and a shift toward fields as the dominant source of sediment. Intensive agricultural land use persists to the present, with about 87% of the watershed in row crops, primarily corn and soybeans

(Minnesota Pollution Control Agency, 2007). Widespread farming is made possible by extensive artificial drainage (i.e., tiling and ditching) of the very flat landscape and modification to its natural stream courses (Spindler et al., 2012). Implementation of subsurface drainage has continued to evolve since the midtwentieth century, with older tile systems replaced by denser networks promoting quicker drainage and more reliable field access and improved crop production.

Based on stream gaging and the Lake Pepin record, sediment delivery from the watershed has remained high up until the present, even in the presence of advances in on-field soil conservation practice. Both agricultural fields and near-channel sediment sources are large (Belmont et al., 2011; Day et al., 2013a, 2013b; Gran et al., 2009; Kelly & Belmont, 2018; Sekely et al., 2002; Thoma et al., 2005), but the dominant source of fine sediment in recent decades has shifted back to near-channel sources, predominantly bluff erosion (Belmont, 2011), which correlates with the observed increase in river discharge (Novotny & Stefan, 2007). Increased river discharge has been attributed to a combination of changes in cropping, increased precipitation, and widespread adoption of enhanced drainage techniques (Foufoula-Georgiou et al., 2015; Schottler et al., 2013). Although agricultural fields continue to produce sediment, attention must now also focus on approaches that can reduce increased river flow and the associated delivery of sediment from erosion of near-channel sources.

2.2. Social Context

Social and economic context played a strong role in informing the objectives and operation of our simulation model of sediment sources and delivery and their response to management choices. Nearly all of the farmed land is in private ownership, so implementation of any management plan will require the collaboration of landowners responding to regulation, incentives, and their own perspective on the costs and benefits of soil conservation actions.

The watershed falls almost entirely within the state of Minnesota, where significant public investment has been directed toward improving water quality, which is an important, shared social value (The Minnesota State Legislative Coordinating Commission, 2016). A strategy identifying agreed-upon actions at the watershed scale may allow funds and programs to be directed efficiently to achieving the common goal of improved water quality. Consensus on a management strategy among farmers, industry groups, government regulators, and environmental organizations, if reached, can provide the basis for organized and effective action.

The Collaborative for Sediment Source Reduction (CSSR) was launched with the goal of developing a consensus strategy for reducing sediment loading and delivery from the GBERB. At the heart of the project is a collaborative of local, state, and industry stakeholders with whom we developed and applied the simulation model to forecast changes in sediment loading in response to different portfolios of conservation actions. A list of stakeholders and their representative organizations can be found in the supporting information. Combined with information on the cost and efficiency of management options, the model was used to evaluate different watershed strategies for reducing sediment loading. This paper describes the development and implementation of this model.

The model was developed in active collaboration with stakeholders over nine in-person meetings between 2012 and 2017. Early meetings focused on developing a shared understanding of sediment sources and on defining conservation practices that would be practicable and accepted. Later meetings were used to demonstrate components of the model in order to build familiarity and confidence in our ability to forecast watershed response to management actions. Throughout the process, choices regarding model complexity were made to balance improvements in prediction with accessibility to support transparency and stakeholder engagement. A flexible, step-by-step development approach served to accommodate the input and honor the effort of stakeholders. An important consideration in model development was to provide nearly instantaneous model output in order to support evaluation of trade-offs, deliberation, and negotiation (Falconi & Palmer, 2017).

Our goal was to support stakeholders with different interests in developing a shared understanding of how the watershed responds to different conservation strategies. To that end, we focused on watershed function without focusing on responsibility for the current watershed condition or for implementing and funding conservation actions. The stated goal of the collaboration was *To identify a consensus strategy for reducing* *sediment loading in the Greater Blue Earth watershed using a decision framework that incorporates the best available scientific information, accounts for uncertainty, and provides a model for decision making that is effective, cost-efficient, fair, and agreed upon by all stakeholders* (Wilcock et al., 2016).

2.3. Model Selection

The CSSR simulation model (termed "Management Option Simulation Model" or MOSM) connects management options (type, location, extent, cost, and efficiency) to reductions in sediment loading at the scale of a large river basin. The model was developed to support evaluation of different portfolios of management options in terms of their cost and the reduction in sediment loading from the watershed. We emphasized to the stakeholder group that we sought a model that was *reliable*, *robust*, *and rapid*. Reliable was defined as a model that provides solutions that are sufficiently well constrained to support decisions and credible at the watershed scale. Robust indicated that the model is unlikely to produce solutions outside the realm of plausibility and can operate reliably under a wide range of user input. A rapid model was defined as one producing results in seconds, thereby allowing immediate feedback for users, permitting multiple runs that can illustrate differences in sediment reduction with various portfolios and extents of management options, and providing a basis for determining uncertainty in the model results by using multiple model runs with plausible variation in the input or parameters. Reliability and robustness were supported by first developing a sediment mass balance for the watershed and structuring the model to allocate total sediment loading among possible sources.

Our modeling approach differs in important ways from other models commonly used to simulate watershed sediment loads. Many models represent the physical processes that drive water and sediment movement throughout the watershed. Some, like the Soil and Water Assessment Tool (SWAT; Arnold et al., 2011) and Hydrological Simulation Program—Fortran (HSPF; Bicknell et al., 1996), work at a "spatially lumped" scale. Others, such as Gridded Surface Subsurface Hydrologic Analysis (GSSHA; Downer & Ogden, 2006) and MIKE-Système Hydrologique Européen (MIKE-SHE; Refsgaard et al., 2010; Refsgaard & Storm, 1995), use smaller spatial units in an attempt to capture flow and transport at the scale at which the driving mechanisms can be realistically simulated. In either case, simulation of multiple hydrologic and transport processes requires a large number of boundary conditions and empirical parameters and generally requires extensive calibration to adjust parameter values to minimize the difference between model predictions and observations (e.g., Borah, 2004; Christiaens & Feyen, 2001; Downer & Ogden, 2003; Krysanova et al., 1998; Kumarasamy & Belmont, 2018; Smith et al., 2011). Uncertainty in model parameterization leads to problems of equifinality, wherein different models can provide similar answers (Beven, 2006; Beven & Freer, 2001) and identifiability, wherein it can be difficult to isolate particular physical process and to quantify the impacts of input parameters on the overall model predictions (Krysanova & Arnold, 2008). These problems, along with complexity of the models and length of time needed to set up and run them, can make it difficult to build credibility among decision makers and to facilitate active interaction between user and model in evaluating trade-offs among different management portfolios.

An alternative approach to evaluating pollutant management options in agricultural watersheds uses watershed digital elevation models (DEMs) and reduced-complexity hydrologic models. Two examples are Prioritize, Target, Measure Application (PTMApp; Houston Engineering Inc., 2016) and Agricultural Conservation Planning Framework (ACPF; Tomer et al., 2015). These models are used to target sites for different management types based on watershed drainage area and feature a user interface that allows selection of specific practices to evaluate their effectiveness and cost in reducing sediment and nutrient loading. These models have some similarity to the approach we adopt here in that they rely on watershed topography and implement a reduced-complexity approach that can facilitate stakeholder interaction. Our approach differs in that we more fully implement the distance, elevation, and storage areas between source and outlet in our representation of watershed topography and that we use the watershed topography to link observed sediment loads and distributed sediment sources to develop a high-resolution spatial distribution of SDR (i.e., 30-m resolution for a 2,880-km^2 watershed requires calculation over 3.2 million cells), and we provide a basis for evaluating uncertainty through the development of a distribution of SDR values for each sediment source.

In developing the watershed model, we did not exclude simulation of physical processes where they can be adequately represented. In particular, we used physically based model formulations to characterize water flow through the watershed. We used a calibrated SWAT model to define a 25-year baseline daily record of water yield and flow for 30 subbasin. The effect of water storage actions on river flow was estimated using conventional level pool routing whose impact was propagated through the channel network using the standard Muskingum-Cunge method. In contrast, we found that two key sediment processes, near-channel supply and sediment storage between source and watershed outlet, could not be adequately represented using a physically based approach and we sought alternative approaches that could provide a reliable and quickly calculated representation of these key processes.

The dominant sediment source in the watershed is bluff erosion by undercutting along the main river channels passing through the incised zone. Bluff sediment supply can be specified as a point source in some watershed models but cannot be reliably predicted as a flow-driven mechanism. Specifically, no existing model has the ability to predict the changes in bluff sediment supply with changes in river flow at the watershed scale (Foufoula-Georgiou et al., 2015; Kelly & Belmont, 2018). To address this modeling gap, we developed an independent relation between river discharge and NCSS based on observation of total suspended solids at pairs of gages within the incised zone on the same river.

The other key sediment process that is not well captured in existing watershed models is the deposition and storage of sediment in transport. Only a fraction of soil eroded from fields is delivered to the stream. Only a fraction of field or bluff sediment delivered to the streams actually makes it all the way to the watershed outlet. To address this sediment delivery problem (De Vente et al., 2007; Walling, 1983), we developed an approach that uses high-resolution topography to link sediment sources to the sediment loads measured at stream gages (Cho et al., 2018).

Importantly, a sediment delivery approach allows us to define the model structure in terms of an allocation of total sediment load among sources, which is key for providing estimates of sediment delivery that are reliable, robust, and rapid. That is, the model acts to distribute the results of the physical processes (sediment loading to rivers) across the watershed, rather than cumulate the spatially distributed sediment erosion and flux from the driving factors. Our starting point is a watershed sediment budget, which is based on estimates of the rates and locations of sediment sources using multiple, independent information sources that provide reliable and independent checks on estimated sediment loading rates (Belmont, 2011; Gran et al., 2011; Smith et al., 2011). The sediment delivery model does not use a single, optimal distribution of SDR but a range of sediment delivery determined by site topography and model parameters drawn from a conditioned parameter range using the generalized likelihood uncertainty estimate methodology (Beven, 2001; Beven & Binley, 2014). Because the simulation model calculates quickly, the effect of uncertainty in sediment delivery is readily evaluated in Monte Carlo simulations.

The simulation model requires specification of the type and location of different management options for reducing sediment loading. A full representation of possible conservation actions and best management practices could be overwhelming. We used the sediment delivery concept to organize the management options implemented in the model. For instance, actions can be taken to (1) reduce the rate of soil erosion on fields, (2) reduce the delivery of eroded sediment to the channel network, and (3) reduce the rate of NCSS, all of which is assumed to enter the channel network. Actions to reduce near-channel supply can involve direct stabilization of banks and bluffs. Alternatively, because the rate of NCSS depends on river discharge, actions can be taken to store water higher in the watershed, which will reduce river discharge and near-channel sediment input in the incised portion of the watershed. We found that the stakeholder group was comfortable working with a single option for each category of management action. The model user can specify the efficiency and cost of the management options in order to simulate different kinds of management actions (e.g., a simple water storage pond is cheaper to install and operate than a wetland restoration).

To use the model, the user selects the extent to which different management options are implemented, as well as location. Location is grouped into three zones (upland, incised, and transitional areas in between) for three subwatersheds (Le Sueur, Cobb, and Maple; see Figure 2). Even with only seven management options and nine zones, there is a wide range of choices when considering multiple management options as well as the location and extent to which those options are implemented.

Throughout the project, our target was a model that is well constrained to produce “reasonable” answers. It is designed to provide reliable estimates of the reduction in sediment loading relative to the period (2006–2010) over which the sediment budget was developed. Because the model projects forward from a

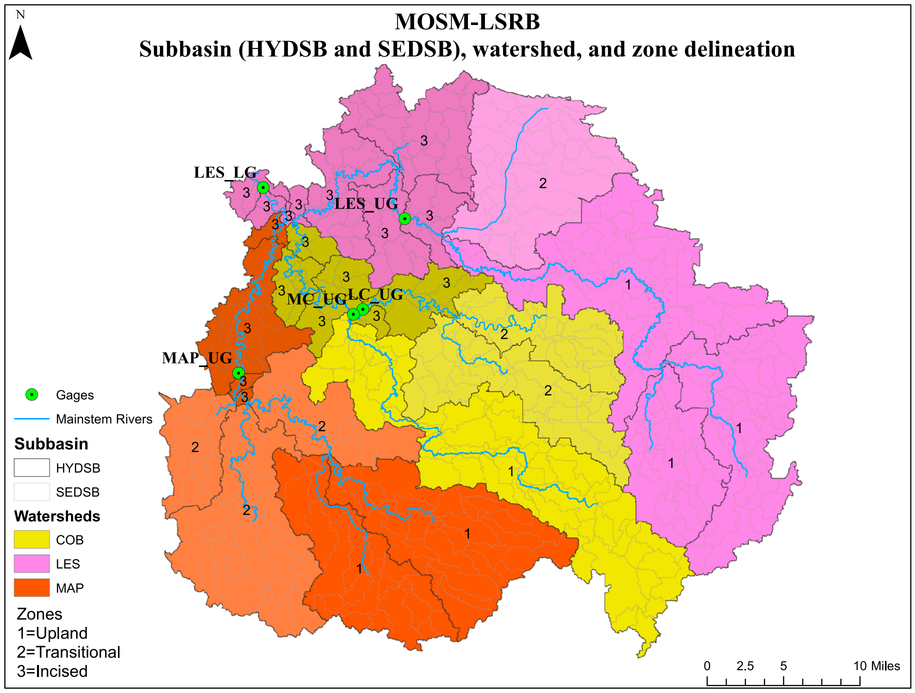

Figure 2. The Le Sueur River Basin (LSRB) consists of three subwatersheds (Le Sueur, Cobb, and Maple), in which three geomorphic zones (1 = upland, 2 = transitional, and 3 = incised) are defined. MOSM simulates sediment loading at five gage locations, three above the incised zone (Maple near Sterling Center [MAP_UG], Main Cobb [MC_UG], Little Cobb [LC_UG], and Le Sueur at St. Clair [LES_UG]) and one at the watershed outlet (Le Sueur below the confluence with the Maple and Cobb Rivers [LES_LG]). MOSM = Management Option Simulation Model; HYDSB = hydrologic subbasin; SEDSB = sediment subbasin.

reference period with a known sediment budget, the reliability of the forecasts necessarily diminish over time sufficient to significantly change the landscape. Consistent with the management challenge, we argue that the time frame for reasonable model forecasts is measured in decades and not centuries, over which sediment deposited between source and outlet may become remobilized. Significant features of the model are the ability to characterize SDR as a function of location and topography and its ability to predict the reduction in sediment loading from the largest sediment source, bluffs, as a function of water storage and river flow.

The CSSR simulation models for the Le Sueur River Basin and the Greater Blue Earth River Basin along with a user manual and a computational module handbook can be downloaded at the University of Minnesota Digital Conservancy (Cho et al., 2017). In this paper, we use the CSSR simulation model for the LSRB to demonstrate the model structure and outputs.

3. MOSM

3.1. Spatial Scale and Input Data

Three spatial scales are defined for the simulation model. Management actions are specified at the coarsest model scale, termed zones, which are delineated by three subwatersheds (LeSueur, Cobb, and Maple Rivers) and three broad geomorphic regions of the LSRB (Figure 2). Zone 1 is furthest from the watershed outlet and is characterized by flat upland topography (typically less than 10 m of relief per square kilometer). Zone 2 is a transitional area, and Zone 3 encompasses the incised portion of the watershed, characterized by bluffs along the mainstem rivers and steep first- and second-order tributaries linking the relatively small amount of flat upland area to the incised river channels. Model zones are the only scale at which the user interacts with the model and are used to allocate the type, extent, and location of management actions for water storage and for reducing sediment production and delivery.

The second spatial scale for the model, hydrologic subbasins (HYDSBs), is used for routing water through the channel network and estimating the effect of distributed water storage on attenuating peak river discharges in the incised zone. The watershed is divided into 30 HYDSBs. The change in sediment loading from near-channel sources, particularly bluffs, is estimated using a regionalized relation between river discharge and sediment loading (section 3.4). In addition to attenuating peak river discharge, water storage structures can also directly trap sediment, which is incorporated in the sediment delivery and loading module.

Sediment erosion, delivery, and loading are modeled at the finest spatial scale of the model with 529 sediment subbasins (SEDSBs). Changes in field and near-channel sediment production and delivery are calculated at this scale. Storage and sediment delivery through the channel network are estimated based on the mean distance and change in elevation, calculated using a 30-m DEM, between each SEDSB and the watershed outlet ("LES_LG" in Figure 2; section 3.2).

Higher-resolution information was used in developing the supporting model database. Field erosion was calculated at the resolution of Natural Resources Conservation Services field soil map units and sediment delivery was evaluated in Topofilter at a 30-m resolution. Soil erosion functionality in the SWAT model was used to define mean annual soil erosion rates per unit area from 46,387 spatial subunits. Spatially distributed topography at 3-m resolution was used to map candidate on-field management locations, and field-scale cropping/practice information was used to allocate management actions (specified by the user at the zone level) into HYDSB and SEDSB according to rules that approximate the most favorable local siting (section 3.5).

Input data for MOSM consist of mean annual erosion rates from field and near-channel sources, high-resolution topography, water yield, hydraulic dimensions of major tributary channels, and observed mean annual sediment loading at gage locations. An integrated sediment budget for the LSRB tabulates sediment sources, including field, ravines, streambanks, and bluffs from an analysis of gaging, sediment fingerprinting, and a suite of geomorphometric techniques (Gran et al., 2011), and provides mean annual sediment supply rates to MOSM and its ancillary models. The ancillary models used to generate additional MOSM inputs included Topofilter, which defines SDR at each SEDSB (section 3.2), the NCSS model, which estimates bluff erosion rates as a function of river discharge (section 3.3), and a calibrated SWAT model, which provides a baseline 25-year daily flow record at each HYDSB (Kumarasamy & Belmont, 2018; section 3.4).

The primary MOSM outputs are annual sediment loading at the mouth of the watershed and annual management cost. This information provides the basis for evaluating the benefit and cost of different combinations of management action (section 4).

3.2. SDR Structure of the Model

MOSM uses the sediment delivery conceptual model to link sediment sources to delivery at the watershed outlet. SDR for each of the 529 SEDSBs is developed from the Topographic Filtering simulation model (Topofilter; Cho et al., 2018), which links field and near-channel sediment production rates to annual sediment loading measured at multiple gages throughout the watershed using sediment transfer functions to account for the effects of the watershed topography on sediment delivery and storage.

Topofilter evaluates spatially distributed sediment delivery using two simple sediment transfer functions on field and in stream, where the model formulation and parameter values are informed by widely available data on high-resolution topography, soil loss, and water quality. First, SDR on field ($SDRf$) for 30-m raster cell i in SEDSB j ($SDRf_{ij}$) is calculated based on the distance (L_{fij}) and elevation change ($\Delta E_{f_{ij}}$) between a field raster cell and the nearest stream raster cell:

$$SDRf_{ij} = \exp\left(a_1 \left(\frac{\Delta E_f}{L_f}\right)_{ij}^{b_1} L_{f\,ij}\right) \tag{1}$$

where a_1 and b_1 are fitting parameters that are applied uniformly across all SEDSBs in each subwatershed, such that the spatial variation in $SDRf_{ij}$ is a function only of the topography between each field cell and its adjacent stream cell.

Second, in-stream SDR (*SDRs*) in each SEDSB j ($SDRs_j$) is defined as a function of stream flow length (L_{sj}), elevation change (ΔE_{sj}), and floodplain area (A_j^{CFP}) from the centroid of each SEDSB j to the subwatershed outlets demarcated by the gage locations in Figure 2:

$$SDRs_j = \exp\left(a_2 \left(\frac{\Delta E_s}{L_s}\right)_j^{b2} A_j^{\mathrm{CFP}}\right) \tag{2}$$

where a_2 and b_2 are fitting parameters applied uniformly across all SEDSBs in each subwatershed such that the spatial variation in $SDRs_j$ is a function only of the topography and available storage area between each SEDSB to the subwatershed outlet.

Many combinations of parameter values in equations (1) and (2) may result in a satisfactory fit between the calculated and observed sediment loading, an example of the problem of *equifinality* (Beven, 2001). Topofilter uses the generalized likelihood uncertainty estimate method to define a conditioned parameter space for a_1, b_1, a_2, and b_2 (Beven & Binley, 1992). Monte Carlo simulations of 10,000 model trials are used to eliminate those parts of each parameter range that do not provide acceptable estimates of sediment load. The conditioned parameter space is used to calculate the composite overall SDR values (SDR_j) for each SEDSB j as the product of on-field SDR ($SDRf_{ij}$), which is averaged over all raster cells in each SEDSB, and in-stream SDR ($SDRs_j$). Topofilter outputs include a set of SDR estimates at each SEDSB and the watershed sediment loading estimates calculated as the product of soil production and SDR. Figure 3 shows the spatial distribution of simulated SDR values of one particular solution set that gives a sediment loading prediction equal to the observed value.

MOSM is set up to perform Monte Carlo trials drawing from the distribution of SDR values in order to evaluate the impact of variability in sediment delivery predictions on management decisions. Both the mean and year-to-year variability in sediment loading values from the reference period 2006–2010 were used to inform the Topofilter parameter conditioning. We included year-to-year variability to provide a basis for evaluating annual variability in sediment delivery. For example, over 1000 Monte Carlo simulations, MOSM selects a range of SDR values that result in a population of sediment loading estimates that has the mean and standard deviation of the observed sediment loading during 2006–2010. Additional detail on the Topofilter application in MOSM, including model formulation, parameter selection, and model predictions, can be found in Wilcock et al. (2016) and Cho et al. (2017).

Sediment delivery is also used to organize the various management options represented in the model. Management options act to either (1) reduce the annual sediment production from fields or near-channel sources (see section 3.3) or (2) reduce the delivery of field-derived sediment to the channel network as described below.

Different conservation actions can be taken to reduce the delivery of eroded field sediment to the stream. Reduction in sediment delivery is accomplished by reducing *SDRf* in ((1)) by an efficiency defined for the conservation action, which may be implemented either on the field or along the riparian zone. Actions to reduce sediment production and delivery on field decrease the overall field sediment input to stream. Sediment supply from near-channel sources, bluffs and ravines, may be reduced by stabilization measures, which are defined by efficiencies for specific actions. Near-channel sediment production is assumed to be fully delivered to the river channel, but the model provides the ability for users to adjust sediment delivery if field evidence suggests that sediment delivery from these features is less than 100%. Both field and near-channel sediment delivered to the channel network is subject to an SDR defined for river transport (SDRs; Figure 4).

Net erosion from stream channel migration, widening, and incision is intrinsically included in our observations of NCSS (section 3.3). Because bluffs and ravines contribute far more sediment to the channel network than the net contributions from stream bank erosion (Gran et al., 2011), a management option explicitly for streambank modification was not a priority among stakeholders and was not included in the simulation model.

3.2.1. Sediment Source Magnitude Estimates

Annual soil erosion on agricultural fields can be reduced via different tillage and cropping practices (Folle et al., 2009; Maalim et al., 2013). Conventional tillage prepares soil for agricultural production using

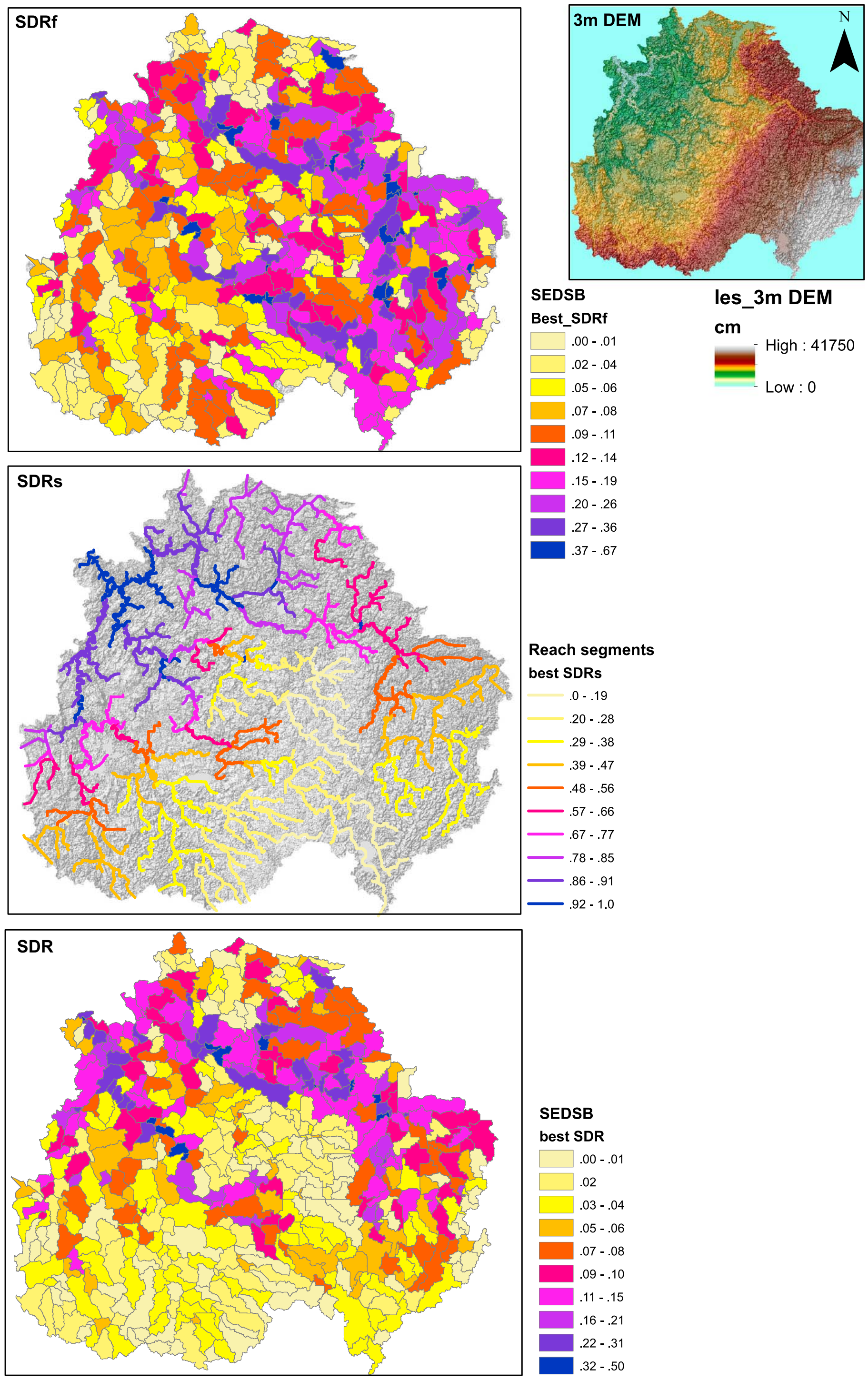

Figure 3. Topofilter simulation of sediment delivery ratio (SDR) on field (*SDRf*), in stream (*SDRs*), and the overall *SDR*, calculated with a parameter set for which sediment loading estimates at gage locations (Figure 2) equal the mean observed loads from 2006 to 2010. The insert on the upper right shows a 3-m DEM to illustrate the influence of watershed topography on the Topofilter calculation of SDR. DEM = digital elevation model; SEDSB = sediment subbasin.

moldboard plow and disk, and local, field-scale erosion rates from this practice can average 1–2 orders of magnitude greater than under native vegetation and long-term geological erosion (Montgomery, 2007; Phillips et al., 1980). The Cropland Data Layer from the U.S. Department of Agriculture National Agricultural Statistics Service indicates that corn-soybean rotation accounted for about 80% of cropland in

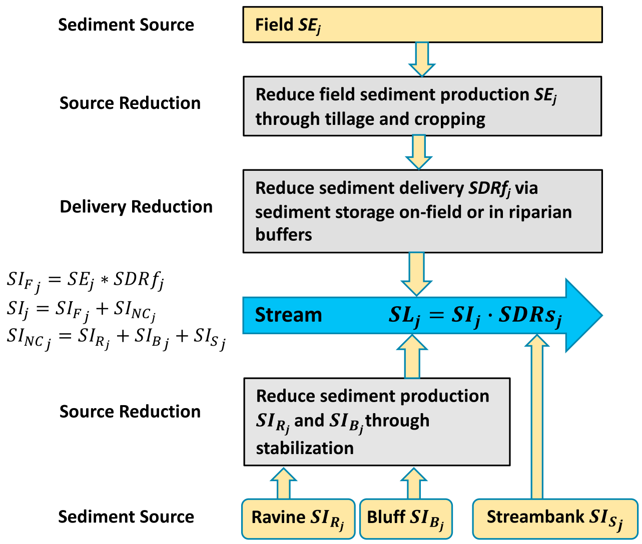

Figure 4. Sediment loading schematic for Management Option Simulation Model. Sediment inputs (SI_j) from sediment subbasin j include field erosion delivered to the channel network ($SI_{Fj} = SE_j*SDRf_j$) and input from near-channel sources SI_{NCj} consisting of ravines (SI_{Rj}), bluffs (SI_{Bj}), and streambanks (SI_{sj}). Management actions can reduce the magnitude of all sources as well as the delivery of eroded soil to the channel network $SDRf_j$. The fraction of SI_j delivered to the watershed outlet (SL_j), is determined by the stream SDR (SDR_{sj}). SDR = sediment delivery ratio.

the LSRB, with continuous corn accounting for most of the remaining 20% during the reference period for our model, 2006–2010 (U.S. Department of Agriculture, 2014).

MOSM includes three tillage/cropping options. For example, the default inputs in the model consist of (1) corn-soybean rotation with conventional tillage (T1), (2) continuous corn production with conventional tillage (T2), and (3) corn-soybean rotation with winter rye cover crop (T3). The cropland area A_a of each SEDSB is composed entirely of the three types (i.e., $A_a = A_{a1} + A_{a2} + A_{a3}$). These tillage/cropping options and their distribution can be specified by the user with appropriate erosion factors (T_1, T_2, and T_3). Values of the erosion factor are derived from the Universal Soil Loss Equation's (USLE) C factor, which includes the effect of crop canopy, surface cover, and surface roughness (Renard, 1991). The effect of different tillage/cropping options on soil erosion rate (SE; Mg/year) in each SEDSB is expressed as an area-weighted average for each practice:

$$SE = \left[T_1\frac{A_{a1}}{A_a} + T_2\frac{A_{a2}}{A_a} + T_3\frac{A_{a3}}{A_a}\right]SE_d \tag{3}$$

where SE_d is the soil erosion rate in the absence of any conservation actions. SE_d was determined using the USLE functionality of the SWAT model in order to take advantage of the detailed Natural Resources Conservation Services soil maps and the USLE parameters embedded in SWAT (Gassman, 2007). Reductions in SE_d from changes in tillage and cropping are achieved by changing the extents of A_{a1}, A_{a2}, and $A_{a3.}$ For the full formulation of soil erosion under different land management scenarios, refer to the MOSM computational module handbook (Cho et al., 2017).

Ravine and bluff stabilization acts to reduce sediment production at the site and decrease the overall near-channel sediment input to stream (SI_{NC}). Mean annual soil erosion rates from near-channel sources (ravines, streambanks, and bluffs) were obtained from an integrated sediment budget for the watershed (Gran et al., 2011). The sediment budget estimates of soil erosion rates were constrained by mass balance and tested against independent lines of evidence including sediment fingerprinting, gage data analysis, and a suite of geomorphic change detection techniques (Belmont et al., 2011; Gran et al., 2011). NCSS in the incised zone did not show strong spatial variation, so $SI_{NC}$was distributed evenly along the stream channel network within each sediment budget cell.

3.3. Water Routing Module

The dominant source of sediment in the study watershed has shifted over recent decades from field soil erosion to erosion of near-channel sources, primarily the steep bluffs along the incised lower portions of the watershed (Belmont et al., 2011, 2014). This increase is associated with an increase in river flows throughout the region (Foufoula-Georgiou et al., 2015; Kelly & Belmont, 2018; Novotny & Stefan, 2007; Schottler et al., 2013). One strategy for reducing sediment loading is to increase water storage in upper parts of the watershed and thereby reduce high flows through the incised lower parts of the watershed. Such water conservation actions would act to replace a portion of the upland water storage lost to widespread agricultural drainage.

In order to evaluate the effectiveness of such actions, it was necessary to develop a relation between river discharge and NCSS. We made use of sediment sampling on a stream gaging network in the most incised tributaries of the Minnesota River. Eight streams have had total suspended solids (TSS) sampling sufficient to estimate annual loads at two stream gages bracketing large parts of the incised zone (Figure 5). Nearly all of the TSS during higher flows is composed of sediment, such that subtracting the calculated load at the upstream gage from that at the downstream gage provides a measure of the sediment added between the gages. The sampling record was sufficient that the comparison could be based directly on quasi-

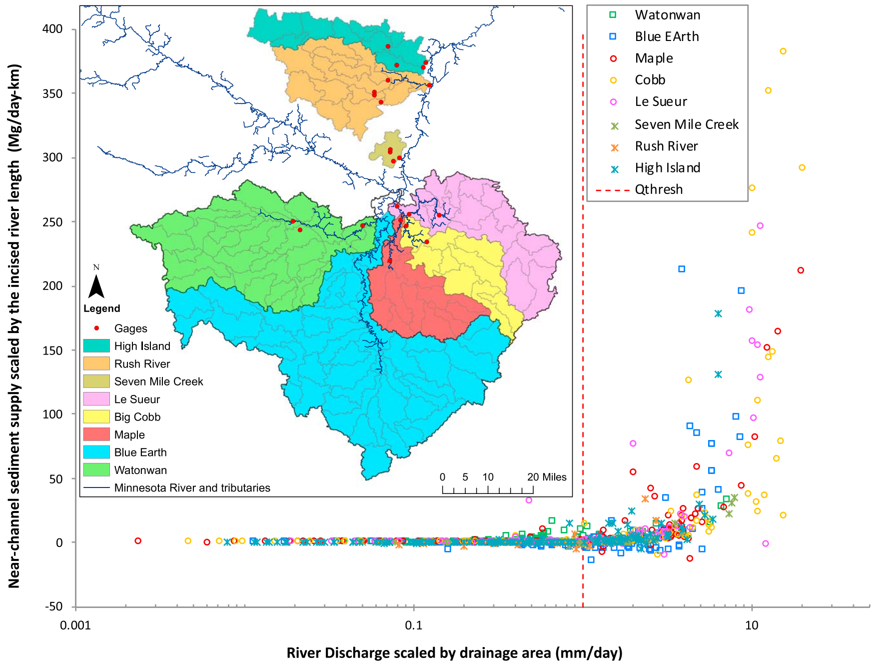

Figure 5. Near-channel sediment supply from analysis of quasi-synchronous total suspended solids (TSS) samples from paired gages on stream reaches on deeply incised tributaries of the Minnesota River. Incremental loads are calculated by subtracting values at upstream gage from downsteam, adjusted for estimated input from minor tributaries, and scaled by kilometer of river length. River discharge is scaled by drainage area. A threshold discharge of approximately 1 mm/day is evident for this region. Inset map shows eight watersheds with paired gages.

synchronous (within two hours) samples, rather than using a fitted rating curve at each gage. The topography of the incised zone is such that only a few small tributaries enter the streams between gages, and that nearly all of the incremental sediment load can be assigned to the erosion of near-channel bluffs and ravines.

When the incremental sediment loading is scaled by the length of river channel between the gages and river discharge is scaled by drainage area, observations from all eight incised streams demonstrate a remarkable collapse to a common trend. There is a threshold of active NCSS in the vicinity of a specific discharge of 1 mm/day, or approximately 20% exceedance on the daily flow record, which is similar to the flows observed to initiate slope failures based on repeat photography of the bluffs (Kelly & Belmont, 2018). A power function with exponent 2.1 fits the data for specific discharge larger than 1 mm/day, and when this function is integrated over the observed river discharge, the result produced annual sediment loads in close agreement with the near-channel component of the watershed sediment budget, which was determined based on direct observation of bluff retreat, sediment fingerprinting, and the total sediment load leaving the watershed (Gran et al., 2011). The power function based on the observations in Figure 5 was used to estimate NCSS in MOSM, such that reduction in river discharge from upland water storage produces smaller NCSS. Further detail on the paired-gage analysis can be found in Wilcock et al. (2016) and Cho et al. (2017).

The linkage between NCSS and water discharge introduces the need to include water storage, water routing, and the resulting near-channel sediment loading in our model. The water routing module simulates the timing and magnitude of larger river discharges and their response to water conservation actions higher in the watershed. The water routing module of MOSM is used to estimate the effect of distributed water storage on daily water yield. The base condition for watershed hydrology is water yield for each of the 30 HYDSB on a daily time step from 1 January 1985 to 31 December 2009. This information was developed from a 30-subbasin SWAT model calibrated to peak flows recorded at the gage locations shown in Figure 2 (Kumarasamy & Belmont, 2018). The number, size, and location of water storage structures within each HYDSB are specified by the model user. Level pool routing with a standard spillway discharge relation is used to calculate the outflow hydrograph from each water storage structure (Chow et al., 1988). Drainage area for water storage locations is estimated using the site topography and flow accumulation values (Mitchell, 2015; Mitchell et al., 2018). Cumulative daily water storage in each HYDSB is determined based on the number and size of storage sites. This storage is then used to change daily water yield from each HYDSB and routed through the channel network to determine discharge changes in the incised zone.

Channel routing downstream of each HYDSB is calculated using a standard Muskingum-Cunge routing model. The parameters of this lumped hydrologic routing method were calculated based on measured channel geometry (Belmont, 2011; Call et al., 2017) and kinematic wave celerity (Chow et al., 1988). Water is routed from each HYDSB through successive stream reaches until arriving at the watershed outlet. MOSM-simulated river discharge was checked against the observed and SWAT-simulated discharges. Root-mean-square deviation between the observed daily river discharge and both simulation outputs were comparable. Water storage functions implemented in SWAT produced similar peak flow attenuation to MOSM (Mitchell, 2015; Mitchell et al., 2018). The water routing model implemented in MOSM runs very quickly and allows the sediment reduction from different water storage scenarios to be immediately evaluated, a key requirement of our decision-support approach.

3.4. Management Options

MOSM is designed to predict changes in sediment loading as a function of type, extent, and location of management options, all of which depend on user inputs. Management options are organized according to their role in sediment source reduction, by reducing either erosion or delivery. Field erosion can be reduced through crop management choices, and delivery of field-eroded sediment to the channel network can be reduced through practices such as grassed waterways, terracing, or riparian buffers. Sediment production from ravines and bluffs can be reduced through direct stabilization efforts. Bluff erosion can also be reduced through upland water storage lowering flood flows in the incised zone, so a water storage option is included in the management options. Examples of each type of management option are given in Table 1.

Stakeholders played a key role in defining the types of management practices most likely to be feasible and accepted. One priority was to keep the number and possible location of management actions to a number that would not overwhelm model users. We found that the stakeholders were willing to work with a single option within each of the seven management categories in Table 1, provided that they were free to specify the cost, efficiency, and extent of each option.

Stakeholders were provided with example values for the efficiency and cost of management action (Table 2) from expert interviews and general published guidance (Daberkow et al., 2008; Lewandowski et al., 2015a, 2015b; Miller et al., 2012; Schnitkey et al., 2016; Tonn, 2017). Detail on the sample values in Table 2 can be found in Wilcock et al. (2016). Importantly, stakeholders were also free to select their own values of cost and efficiency and often did.

An important constraint is the extent of suitable land available for the different management actions. Model user specifies the extent of each type of management action (Table 1) but cannot specify an extent larger than the land available within each of the nine model zones. The extent of available management sites was determined based on local topography, aerial photographs, soil survey, and land use/land cover databases. The extent of land suitable for changes in cropping and tillage was set equal to the area of cultivated crop lands reported in the 2011 National Land Cover Database (Multi-Resolution Land Characteristic Consortium, 2018). The distribution of the three cropping/tillage options reported in the years 2006–2010 (U.S. Department of Agriculture, 2014) was used to define a reference case, and reductions in soil erosion were defined in terms of changes relative to that case. Agricultural field management option sites were identified as locations where runoff may concentrate and scour before entering the stream. Using stream power index (SPI), calculated with a 3-m DEM as the product of local drainage area times slope, we found that an index value of $7 \leq \mathrm{SPI} \leq 11$ provided a realistic delineation of suitable sites. Riparian buffer sites were identified along ditches and natural streams using local ditch maps (Minnesota Pollution Control Agency, 2012a) and National Hydrography Database (U.S. Geological Survey, 2017). Water conservation sites were identified from natural topographic depressions with a 3-m DEM with sufficiently high steady state wetness index, topographic index (TI) defined as area divided by slope (Quinn et al., 1995). We found that an index value of $TI \geq 11.5$ delineated potential water storage sites adequately. In-channel water storage sites were identified from local ditch maps (Minnesota Pollution Control Agency, 2012a). Ravine tips

Table 1
Example Management Options Grouped According to Role in Reduction of Sediment Sources Delivery

Management types	Description	Location of implementation	Example management practices
Cropping and tillage	Reduce soil erosion rates by reducing disturbance and stabilizing with organic matter or permanent vegetative cover.	Field	Conservation tillage, reduced tillage, and cover crops
Agricultural Field	Reduce delivery of eroded soil by conveying or diverting concentrated runoff through terracing, contouring, or vegetated swales.	Field	Grassed waterways and terracing
Water Conservation	Water storage structures placed high in the watershed intercept runoff and attenuate flood flows downstream. Also trap sediment.	Field	Water retention ponds and wetland restoration
In-channel water storage	Water storage in upland ditches or channels to attenuate flood flows downstream.	Channel	Outflow controls, two-stage channels
Riparian buffers	Riparian vegetation (grass, forbs, sedges, etc.) acts to rap upland sediment.	Field near channel	Vegetated buffer strips
Ravine management	Prevent head cutting, incision, and expansion by stabilizing grade and reducing flow.	Ravines	Grade control and inflow management
Bluff management	Structural measures to arrest streambank erosion and stabilize bluff toe to prevent bluff retreat.	Bluffs	Bank protection and toe stabilization

Note. Each category of management type includes a range of specific management practices.

and bluffs were identified from discrete mapping of sediment sources as part of the sediment budget (Bevis, 2015). Details on the determination of management action extents can be found in Wilcock et al. (2016) and Cho et al. (2017).

Implementation of selected management actions in the model requires allocation of the user-selected extent of management actions across the 30 HYDSB for water management and across the 529 SEDSB for sediment management. MOSM prioritizes all candidate sites according to user-selected criteria based on soil type, upstream drainage area, site extent, or location in the watershed. In model operation, the user-specified extent of management action for each of the nine zones is allocated using *greedy adding heuristics*

Table 2
Example Cost and Efficiency Values for Management Options in MOSM

Example management option information			
Installation	Maintenance	Life span (year)	Efficiency
Corn-soybean rotation with conventional tillage			
$39–41/acre ($41/acre)	$86–90/acre ($90/acre)	1	USLE C factor
Continuous corn with conventional tillage			
$39–41/acre ($39/acre)	$86–90/acre ($86/acre)	1	USLE C factor
Winter rye cover crop			
$20–60/acre ($21/acre)	$20–110/acre ($21/acre)	1	USLE C factor
Agricultural field management option			
$1,900–$4,500/acre ($3,200/acre)	$64/acre ($64/acre)	10	Reduce sediment delivery from field (75%)
Riparian buffer management option			
$500–$2,000/acre ($1,000/acre)	$45/acre ($45/acre)	10	Reduce sediment delivery from field (65%)
Water conservation management option			
$300–$17,000/acre ($3,000/acre)	$250–574/acre ($574/acre)	25	Reduce peak river discharge in incised zone Reduce sediment delivery from field (90%)
In-channel water storage management option			
$15,000–$20,000/structure ($250/foot)	$1.4/foot ($1.4/foot)	10	Reduce peak river discharge in incised zone
Ravine stabilization management option			
$1,000–$21,000 ($6,000/tip)	$35/tip ($35/tip)	10	Reduce ravine sediment loading (25%)
Bluff stabilization management option			
$11–1,000/foot ($500/foot)	$0.7/foot ($0.7/foot)	5	Reduce bluff sediment loading by (75%)

Note. The costs of installation and maintenance shown in parentheses are used to illustrate model outputs in Figures 7 and 8. MOSM = Management Option Simulation Model; USLE = Universal Soil Loss Equation.

(Cohon, 2004). Using this approach, candidate sites are sorted by priority and incorporated in the model starting from the highest priority site until the cumulative total extent reaches the user-specified extent. Once the candidate sites are selected, the extent of each management action is accumulated for each HYDSB and SEDSB.

3.5. Cost of Management Actions

MOSM calculates the annualized cost (C_{ann}) of implementing management practices with different life spans. The annualized cost is defined as the uniform end-of-year payment over the lifetime that would have the same present worth as the actual time series of cash expenditures. These expenditures include installation and maintenance costs over the life span of each management practice, as well as opportunity costs (foregone net revenues from crops if productivity is lowered or land is taken out of production, as measured by the land value) with default interest rate (i) of 5%:

$$C_{\mathrm{ann}} = \left[\left(\frac{P_{\mathrm{inst}} + P_{\mathrm{land}}}{1+i}\right)\left(\frac{(1+i)^n \cdot i}{(1+i)^n - 1}\right) + P_{\mathrm{mntn}}\right]{}^*A \tag{4}$$

where P_{inst}, P_{land}, and P_{mntn} are installation, land acquisition, and annual maintenance costs per extent for each management action (A) with life span (n). Management actions on agricultural fields that take land out of agricultural production when implemented include land acquisition cost (P_{land}) in the annual cost calculation. The default cost of agricultural and marginal land is assumed to be $8,297/acre based on the farmland values in 2016, determined based on the crop productivity index rating and the web soil survey data in the Blue Earth County ("Blue Earth County, MN Farmland Prices and Values | AcreValue," 2016). In practice, management options such as water and sediment basins and buffer strips may be sited on lower cost land due to either soil quality or location (Boserup, 2017). Installation and maintenance costs, life span of each management action, the cost of agricultural land, marginal land, and the interest rate may be specified by the model user.

3.6. Model Operation

The simulation model consists of three primary modules: (1) management option allocation (section 3.4), (2) hydrologic routing (section 3.3), and (3) sediment delivery and loading (section 3.2). User interaction with the model consists of specifying the extent, cost, and efficiency of seven types of management actions across three zones of each of the three subwatersheds in the LSRB (Figure 6). The model first allocates the specified management actions across the 30 HYDSB and 529 SEDSB. It then evaluates the effects of water storage on peak river flow and the resulting changes in NCSS (Figure 5). The effects of sediment production and delivery management options are subsequently calculated to estimate the reduction in sediment loading from the watershed (Figure 4). The model accounts for interaction among different management options. For example, sediment delivery is adjusted when the contributing areas for agricultural field management and water storage overlap. Also, peak flow attenuation accomplished by water storage reduces bluff sediment production rate; thus, the benefit of direct stabilization of bluffs is reduced in proportion to any reduction in NCSS through flow reduction. All computational modules are written in *Visual Basic for Application* within *Microsoft Excel*, which was chosen based on stakeholders' familiarity with the software. Complete module codes and a user's guide are available at Cho et al. (2017).

4. Results and Discussion

The primary MOSM outputs are annual sediment loading at the mouth of the watershed and annual cost of management choices. Model output was developed in collaboration with the stakeholder group in order to provide the most useful information for decision support. The relative cost efficiency of different management options depends on both installation and maintenance costs and the specified sediment reduction efficiency. Rather than prescribing a single, "best" estimate for these parameters, the simulation model is set up so that these inputs can be easily changed, with nearly immediate output, in order to support a broad discussion of different management portfolios.

A useful starting point for decision making is a plot of unit cost for sediment reduction ($per metric ton of sediment reduction) as a function of the extent of individual management actions implemented in isolation (Figure 7). By illustrating the relative cost and sediment reduction associated with each management option,

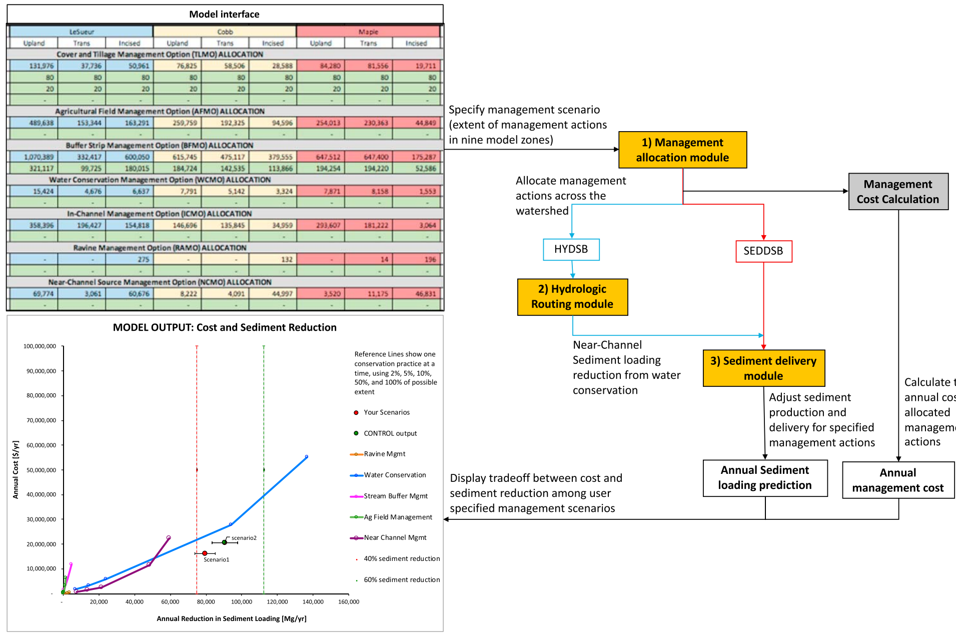

Figure 6. Schematic overview of Management Option Simulation Model structure, consisting of management option allocation, water routing, and sediment delivery and loading modules.

the plot provides a starting point for discussing the cost basis (e.g., how should land or lost production costs be considered for actions that take land out of agricultural production?) as well as the ancillary benefits and costs not included in the model, such as ecological or recreational benefits or the increase in production costs.

On-field sediment trapping (e.g., grassed waterways; Table 1) was found to play little role in reducing sediment loading at the mouth of the basin, primarily because much of the reduced delivery occurs high in the watershed and that reduction is then discounted by sediment storage along the channel network, represented by typically small stream SDRs in the uplands (Figure 3). This does not indicate that actions like grassed waterways do not produce worthwhile, even cost-efficient local benefits, but rather indicates that they are unlikely to provide a watershed-scale solution for reducing sediment loading. Similarly, in-channel water storage was found to produce little reduction in sediment loading at the watershed scale because too little of that storage is available. Riparian buffer strips, which have received political support for enforcement of existing regulation (Minnesota State Government, 2017), provide somewhat more reduction in sediment loading, although much less than other alternatives. They were also found to be expensive, based largely on the cost of displaced agricultural production. These findings help to inform ongoing discussions of the basis and any compensation for increased compliance with the buffer law in Minnesota.

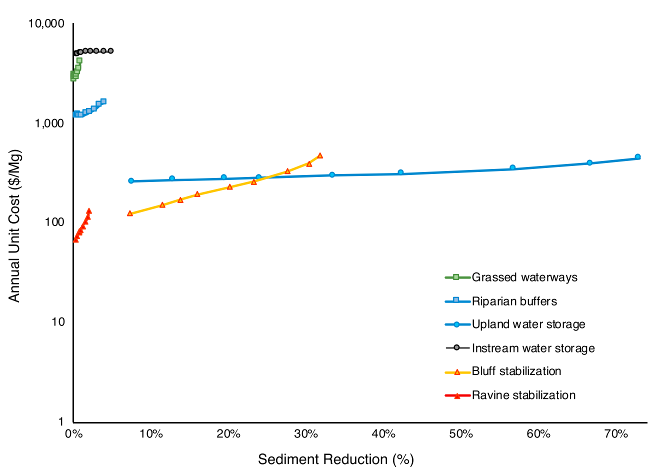

Figure 7. Annual unit cost and sediment reduction of individual management options implemented at 5%, 10%, 15%, 20%, 30%, 40%, 60%, 80%, and 100% of available extent. Sediment reduction expressed as a percentage of the average annual load of 190,000 Mg.

Ravine management emerged as the most cost-efficient management option, although the total number of ravines and their associated sediment production is sufficient to reduce sediment loading by no more than 5% (Figure 7). This suggests that ravines may be a useful component of a larger management portfolio but cannot be the entire solution.

The two management options that provide the largest reductions in watershed sediment loading are those that address the largest sediment source, bluffs. Because bluffs are also located closer to the watershed outlet than on-field options, these management options—water storage

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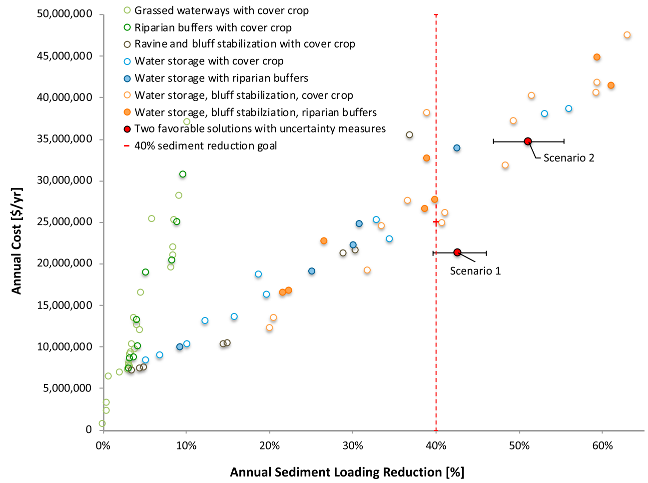

Figure 8. Trade-off curve for various management scenarios. The red dotted line indicates the Total Maximum Daily Load goal 40% sediment loading reduction level. Two example management scenarios (1 and 2) are compared with various scenarios.

and bluff stabilization—provide relatively strong efficiency. Direct stabilization of bluffs is more cost effective than upland water storage actions at smaller reductions in sediment load. The cost for sediment reduction by bluff stabilization may actually increase more rapidly than indicated in Figure 7 if unit costs were structured to increase with extent, arguing that the more accessible and less expensive projects are likely to be undertaken first. The stakeholder group recommended that bluffs that threaten infrastructure and produce exceptionally large amounts of sediment are worth targeting, but that bluff stabilization is not the most effective solution for long-term reduction in sediment loading across the watershed (Consensus statement, supporting information).

Water conservation actions result in large sediment reductions because the NCSS is hydrologically driven and has a strong cumuative effect as peak river flows are reduced throughout the channel network. Direct sediment storage in water conservation structure accounts for a negligible fraction of the reduced sediment load. The cumulative load reduction from direct bluff stabilization is limited to about 32% of the total watershed sediment loading, whereas water storage can produce much larger cumulative sediment reduction at greater cost efficiency (Figure 7). Longer storage of water in upland locations and reductions in peak river flows have additional benefits not included in the model, such as increased wildlife habitat and nutrient load reduction. These findings were important in leading the stakeholder group to recommend priority investment in upland water storage as a critical component of a strategy to reduce sediment in the Minnesota River (Consensus statement, supporting information).

The Total Maximum Daily Load established for the LSRB specifies reduction of total suspended solids by 40% (Minnesota Pollution Control Agency, 2012b). Based on an average sediment load of 190,000 Mg measured from 2006 to 2010, the target annual sediment load reduction is 74,000 Mg/year. A reduction of this magnitude requires a portfolio of management actions that includes reducing bluff sediment loading using one or both of water conservation and bluff stabilization. Figure 8 compares a range of management portfolios. We highlight two scenarios with substantial water conservation and bluff stabilization in combination. Scenario 1 includes 12,000 acres of water storage (about 20% of available candidate sites) and 24,000 m of bluff stabilization (about 30% of available candidate sites) and provides an annual sediment load reduction of 79,000 Mg (43% reduction) at an annual cost of $21 million. Scenario 2 increases acreage in water conservation to about 25% of available sites and river length in bluff stabilization to about 40% of available sites and incorporates cover crops to 30% of total agricultural land. This scenario produces an annual reduction in sediment loading of 95,000 Mg (51% reduction) at an annual cost of $35 million.

The model can be run in stochastic mode to produce a range of sediment reduction estimates based on the uncertainty in the SDR. Error bars on the two scenarios are based on the 10th and 90th sediment reduction percentiles from 1000 Monte Carlo trials using different parameters in equations (1) and (2) drawn from the conditioned parameter space in the Topofilter analysis. These show that the first scenario may not meet the 40% reduction goal, a useful factor in evaluating the preference for one scenario over the other.

The unit curves (Figures 7) and trade-off curves (Figure 8) provided the basis for stakeholder discussion of the relative merits of different portfolios of management actions. The discussion included the basis for assigning cost for different management practices, the ancillary costs and benefits of different practices, and the local versus watershed-scale implications of different choices. The discussions explicitly did not include responsibility for the current water quality, the mechanism for paying for different management choices, or the relative merits of regulation and incentives for encouraging adoption of management practices. Rather, the goal of the exercise was to provide a clear message from diverse stakeholders on a broader strategy to meet the mandated Total Maximum Daily Load goals. To this end, the group reached consensus that local stabilization of bluffs and ravines are a useful component of a broader strategy, especially in accessible locations with large sediment supply and possible infrastructure impacts, but that water conservation—water storage on upland fields in order to reduce river discharge and NCSS—was critical to the broader strategy of reducing sediment loading and required priority investment by state and federal agencies.

5. Conclusion

Soil and water conservation in intensely managed agricultural regions occurs within a complex social context. Nearly all of the farmed land is in private ownership, so widespread implementation of conservation practice will require the collaboration of landowners responding to regulation, incentives, and their own perspective on the costs and benefits of soil conservation actions. Implementation of watershed-scale conservation programs is most likely to be successful if a broadly supported strategy can be found. Here, we describe a sediment source and delivery model developed to evaluate conservation trade-offs in southern Minnesota, where sediment loading has been identified as a priority and there is broad public support and investment in cleaner water. The model was developed as part of a stakeholder process intended to engender understanding and consensus by supporting evaluation of different portfolios of management options in terms of cost and the reduction in sediment loading from a 2,880-km^2 intensively farmed watershed.

Large parts of the stakeholder process were given over to development of a sediment budget for the watershed, supporting shared understanding of the problem, and to identification of conservation practices that would be practicable and accepted by the farming community. The magnitude and location of different sediment sources were identified using multiple, independent sources of information, subject to the strong constraint of mass balance relative to the total sediment load leaving the watershed. The simulation model was formulated to allocate the total sediment load among sources, resulting in a robust model that constrained the relative magnitude of sediment loads and their reduction. The sediment delivery concept was used to define the structure of the model and to define a reduced list of management options based on their role in reducing either sediment production or delivery.

The model uses a novel topographic filtering approach to provide spatially distributed estimates of SDR. This approach addresses one of the main challenges in watershed sediment models—estimating interim storage between source and outlet. A second challenge for watershed sediment models is estimating near-channel sediment sources that are poorly represented in physically based models. The dominant sediment source in the watershed is erosion of steep streamside bluffs in the lower, incised portions of the river network. This erosion has accelerated and become the dominant sediment source in recent decades in response to increases in river discharge. Reduction in peak river flow through water storage higher in the watershed is an important method for reducing sediment loading. Rates of bluff erosion and their variation with river discharge were determined from sediment loads measured at pairs of gages on individual streams crossing through the incised, rapidly eroding parts of the watershed.

We sought to support transparency and develop stakeholder trust through multiple meetings in which the underlying sediment budget was developed and refined. The simulation model supported trade-off evaluation among a tractable number of accepted conservation practices with clearly defined effect on sediment production or delivery. We aimed to provide reliable and robust estimates of reduction in sediment loading by defining the effect of management actions in terms of a sediment delivery conceptual model that was constrained within uncertainty by the total sediment load. SDR values throughout the watershed were precalculated and the model runs rapidly, providing real-time response to user choice and supporting Monte Carlo simulation of the influence of uncertainty on the calculated sediment load. The stakeholder group used the model to identify a priority strategy for investing public funds to reduce sediment loading and improve water quality.

Acknowledgments
This work was funded by the Minnesota Agricultural Water Resources Center, a 319 Grant from the U.S. Environmental Protection agency via the Minnesota Pollution Control Agency, and by Minnesota Clean Water Land and Legacy Amendment funds provided through the Minnesota Pollution Control Agency and the Minnesota Department of Agriculture. This work was supported by the US Department of Agriculture NRCS (69-3A75-14-269) and Utah Agricultural Experiment Station, approved as paper 9179. This work would not have been possible without the participation of the stakeholders who invested many days over many years, teaching us about local conditions and agricultural practice and maintaining their commitment to cleaner water and collaboration through development and application of the simulation model. Management Option Simulation Model (MOSM) and supporting documents can be found in the University of Minnesota Digital Conservancy (http://hdl.handle.net/11299/191082).

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