MODELING SEDIMENT AND PHOSPHORUS LOSSES IN AN AGRICULTURAL WATERSHED TO MEET TMDLs[1]

Brent J. Dalzell, Prasanna H. Gowda, and David J. Mulla[2]

ABSTRACT: This paper studies the effectiveness of alternative farm management strategies at improving water quality to meet Total Maximum Daily Loads (TMDLs) in agricultural watersheds. A spatial process model was calibrated using monthly flow, sediment, and phosphorus (P) losses (1994 to 1996) from Sand Creek watershed in south-central Minnesota. Statistical evaluation of predicted and observed data gave r^2 coefficients of 0.75, 0.69, and 0.49 for flow (average 4.1 m^3/s), sediment load (average 0.44 ton/ha), and phosphorus load (average 0.97 kg/ha), respectively. The calibrated model was used to evaluate the effects of conservation tillage, conversion of crop land to pasture, and changes in phosphorus fertilizer application rate on pollutant loads. TMDLs were developed for sediment and P losses based on existing water quality standards and guidelines. Observed annual sediment and P losses exceeded these TMDLs by 59 percent and 83 percent, respectively. A combination of increased conservation tillage, reduced application rates of phosphorus fertilizer, and conversion of crop land to pasture could reduce sediment and phosphorus loads by 23 percent and 20 percent of existing loads, respectively. These reductions are much less than needed to meet TMDLs, suggesting that control of sediment using buffer strips and control of point sources of phosphorus are needed for the remaining reductions.
(KEY TERMS: water quality; TMDL; nonpoint source pollution; best management practices (BMPs); agriculture tillage.)

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INTRODUCTION

The Minnesota River Basin contributes large amounts of sediment and phosphorus (P) from agricultural lands, often exceeding the U.S. Environmental Protection Agency's water quality standards, adversely affecting water quality at both local and regional levels. For example, sediment loading from the Minnesota River Basin is filling in Lake Pepin, a part of the Upper Mississippi River System (UMRS), at a rate that will lead to the disappearance of the lake in about 300 years (Engstrom and Almendinger, 2000). High sediment losses are attributed to erosion on intensive row cropped lands and stream bank erosion in the Minnesota River Basin. Roughly 26 percent of the total suspended sediment load and 33 percent of all the phosphorus entering the UMRS from the Minnesota River are contributed by the Lower Minnesota River watershed located near the mouth of the Minnesota River (Mulla and Mallawatantri, 1997). High P losses are primarily due to excessive soil P levels as a result of long term P fertilizer and manure applications and high soil erosion rates (Randall *et al.,* 1997a), although about one-fourth of the phosphorus loads are from wastewater treatment plant discharges.

The Minnesota River Basin has many of the most impaired rivers in the state of Minnesota. According to the Clean Water Act (CWA) of 1972, states are required to identify impaired water bodies and develop Total Maximum Daily Loads (TMDLs) for pollutants. By definition, a TMDL is the maximum allowable load of a pollutant that a water body or stream segment can receive from all sources without violating water quality standards. The process of developing and implementing TMDLs involves: (1) defining total allowable load, (2) allocating the load among many point and nonpoint sources, (3) identifying alternative management practices to comply with

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TMDLs, and (4) working with local stakeholder groups to select management practices to comply with TMDLs. The focus of this paper is primarily on the third step in the TMDL process. Typically, the third step involves evaluating the reductions in pollutant loads possible with various alternative management practices. These reductions are often estimated using expert knowledge combined with simple spreadsheet calculations, an approach that is often questioned by stakeholder groups. Alternatively, reductions in pollutant loads can be estimated using computer model simulations.

In the Minnesota River basin and many other basins, the Hydrological Simulation Program Fortran (HSPF) model is being used to estimate pollutant loads under various alternative management practices (Donigian *et al.,* 1996). This approach, however, is subject to large uncertainties in watersheds with spatially variable agricultural management practices because HSPF does not explicitly account for agricultural management practices such as tile drainage, conservation tillage, and rate and timing of fertilizer application. Rather, HSPF uses buildup and washoff coefficients to indirectly account for fertilizer application rate and timing effects, and indirectly accounts for tile drainage through adjustment of the partitioning between runoff and infiltration. While HSPF can be accurately calibrated to existing watershed scale water quality data, because it is not designed to explicitly account for agricultural management practices, its ability to accurately simulate the effects of changes in agricultural management practices on water quality is subject to large uncertainties.

Another important issue involved in attaining TMDLs is deciding how much of the reduction in pollutant loads should arise from point versus nonpoint sources. For example, Dilks and Sweet (1996) proposed two TMDL alternatives for phosphorus reduction in Saginaw Bay watershed. They are a maximum limit of 1 mg/l for wastewater treatment plants and a 55 percent reduction in nonpoint sources, and a maximum limit of 0.5 mg/l for wastewater treatment plants and a 40 percent reduction in nonpoint sources. Hession *et al.* (1995) used 10 µg/l chlorophyll *a* as the boundary between eutrophic and mesotrophic lakes and developed TMDL values for total phosphorus in an Oklahoma watershed. They did this by adjusting annual loads using a water quality model until chlorophyll *a* levels were reduced to 10 µg/l, giving a TMDL of 266 kg P/day. Nonpoint sources generated 75 percent of the total phosphorus loading to the watershed. To meet TMDL values through control of only point sources of phosphorus would require a 72 percent reduction in phosphorus from point source discharges. On the other hand, to meet the same goal through control of nonpoint sources, their model showed that a 22 percent reduction would be needed in the rate of phosphorus applied to land.

Based on the introductory information provided above, the objectives of this study were to (1) evaluate the reductions in sediment and phosphorus loads possible with several alternative farm management practices in Sand Creek watershed (located in the Minnesota River Basin); and (2) estimate how much of the reduction in pollutant loads could reasonably arise from controlling nonpoint source pollution. In this study, a dynamic watershed scale modeling approach (Gowda *et al.,* 1999) that uses the ADAPT (Agricultural Drainage and Pesticide Transport) field scale water table management model (Chung *et al.,* 1992), and Geographic Information System (GIS) and remote sensing databases, was calibrated to predict monthly flow, sediment, and P loadings from Sand Creek. This model explicitly accounts for the effects of all typical agricultural management practices on water quality, including the effects of various tillage implements on crop residue, the impacts of changes in fertilizer application rate and method, and the effects of crop rotation and tile drainage. The calibrated model was used to evaluate the improvement in water quality due to alternative agricultural management practices such as adoption of conservation tillage, conversion of crop land to grassland, and changes in P-fertilizer application rates. The effects of changing the percent crop land with subsurface drainage were also evaluated.

METHODS AND MATERIALS

Study Area and Water Quality Data

Sand Creek watershed is a tributary subwatershed of the Lower Minnesota River watershed (Figure 1), and is located in the Minnesota River Basin. It covers approximately 650 km^2 of south-central Minnesota and is one of the most significant sources of sediment and phosphorus within the Lower Minnesota River watershed. Sand Creek watershed is dominated by agricultural land use with approximately 63 percent of the area devoted to row crop agriculture, primarily corn and soybean (Table 1). About 30 percent of the land in Sand Creek watershed has been improved with subsurface tile drainage systems, and conservation tillage is practiced on approximately 40 percent of cropland in the watershed. The topography of Sand Creek watershed is gently rolling in the upland portions of the watershed, with steeper slopes located in the northwestern portion of the watershed near the

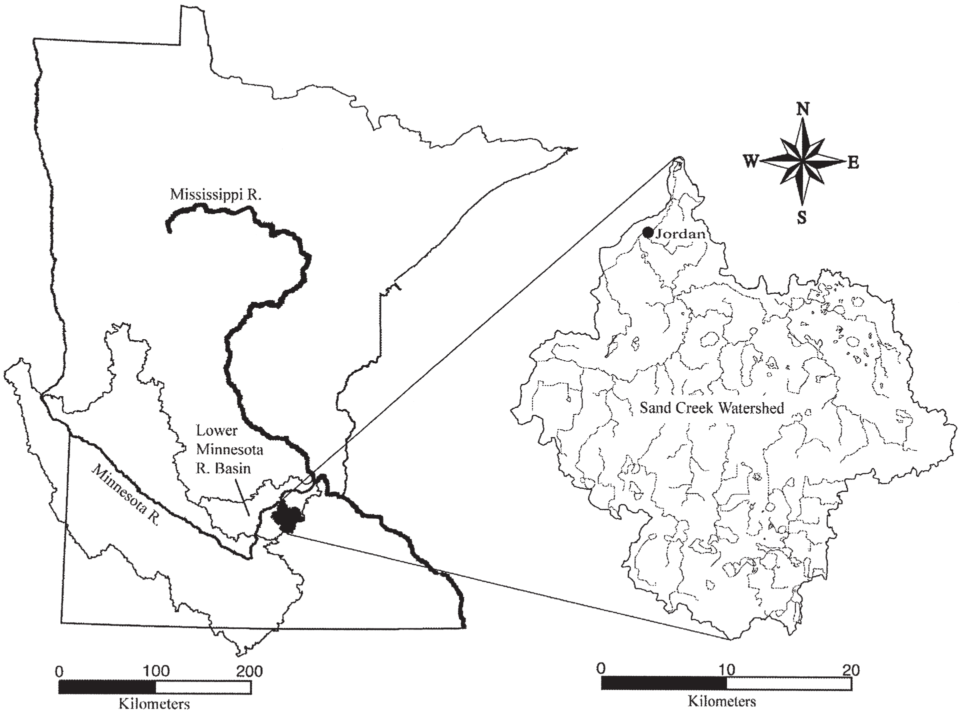

Figure 1. Location of Sand Creek Watershed in the Lower Minnesota River Watershed, Southern Minnesota.

confluence with the Minnesota River. The average slope of Sand Creek watershed is 6.6 percent.

TABLE 1. General Characteristics of Sand Creek Watershed.

Characteristics	Sand Creek Watershed
Area (km^2)	651.9
Average Slope (percent)	6.6
Percent Crop Land	63
Percent Crop Land in Tile Drainage	30
Percent Crop Land in Conservation Tillage	40

From 1994 to 1996, Sand Creek watershed was monitored by the Twin Cities Metropolitan Council for flow, sediment, and P loadings at its confluence with the Minnesota River near the City of Jordan, Minnesota. Water quality data collected before this time period were of poor quality, and so were not utilized in this study. Water samples were collected during storms using a flow actuated Sigma sampler with a Campbell CR10 data logger. In addition, samples were collected by technicians during normal flow conditions. Monthly total suspended solids and P losses were calculated with the U.S. Army Corps of Engineers' FLUX model. The first-order regression model option in FLUX was used to estimate monthly sediment loading from daily concentration and flow data, using a stratification process involving high flow and low flow regimes selected by the model.

ADAPT Model

The ADAPT model is a daily time step field scale water table management simulation model that was developed by integrating GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) (Leonard *et al.,* 1987), a root zone water quality model, with subsurface drainage algorithms from DRAINMOD (Skaggs, 1982), and a subsurface drainage model. More detailed information about ADAPT can be found in Chung *et al.* (1992), Ward *et al.* (1993), and Desmond *et al.* (1996). Additional enhancements to the model include potential evapotranspiration estimation with the Doorenbos and Pruitt method (1977) as an alternative to the Ritchie method (1972). Runoff was estimated using the Soil Conservation Service (SCS) curve number method

(SCS, 1985) with daily curve number updates dependent on antecedent moisture conditions. Soil erosion was estimated using the Universal Soil Loss Equation (Foster *et al.,* 1980)

$$A = R\ K\ LS\ C\ P \quad (1)$$

where A is predicted annual erosion rate, R is the rainfall/runoff erosivity (available from county lookup tables), K is soil erodibility (available from tables of soil series data described below), LS is the slope length and steepness factor (estimated from elevation), C is the cover management factor (estimated from crop residue cover at planting using methods below), and P is the supporting practices factor (assumed equal to one in this study). Edge of field sediment losses were estimated by multiplying predicted erosion rates by a sediment delivery ratio (the ratio of sediment transported beyond the edge of field to the predicted rate of erosion). The phosphorus cycle used in the ADAPT model includes routines for mineralization, immobilization, fertilization, animal waste application, and crop uptake. Phosphorus losses are simulated at a daily time step based on rates of sediment loss and soil concentrations of phosphorus, as well as rates of runoff and concentrations of soluble phosphorus (Knisel *et al.,* 1993). The concentration of phosphorus in the surface layer available for runoff and percolation is calculated as

$$C = CPLAB \times EXP\left[\frac{-(F - ABST)}{CPKD\left(\frac{1-POR}{2.65}\right) + POR}\right] \quad (2)$$

where C is the concentration of phosphorus in the surface layer of soil available for surface runoff and percolation into the layer below (µg/g), CPLAB is the concentration of labile phosphorus (µg/g), based on the dry weight of the soil, CPKD is the partitioning coefficient based on percent clay in the soil, F is the total storm infiltration or rainfall minus runoff (cm), POR is the porosity, and ABST is the initial abstraction from rainfall (cm), as estimated by

$$ABST = 0.2 \times (SAT - SW) \quad (3)$$

where, SAT and SW are volumetric water content for the day and at saturation, respectively.

The concentration of P in water (CPLABW, mg/l) is calculated as

$$CPLABW = \frac{C \times CPKD \times \beta}{1 + CPKD \times \beta} \quad (4)$$

where β is the extraction coefficient for phosphorus to surface runoff.

The labile phosphorus in runoff (ROLP, kg/ha) and phosphorus associated with sediment (SEDLP, kg/ha) are calculated as

$$ROLP = 0.1 \times CPLABW \times Q \quad (5)$$

$$SEDLP = 0.1 \times ER \times SY \times CPKD \times CPLABW \quad (6)$$

where Q is the surface runoff, SY is the sediment yield (kg/ha), and ER is the sediment enrichment ratio. The ER is defined as the ratio of specific surface area of sediment to the specific surface area of the residual soil (Leonard *et al.,* 1987).

The ADAPT model was used here because of its ability to simulate the water quality effects of all typical agricultural management practices (tillage, crop rotation, and fertilizer management), including subsurface drainage contributions to agricultural runoff. The ability to accurately simulate tile drainage effects is especially important in the Midwest, where nearly 30 percent of all cropland has been improved using subsurface tile drainage systems (Zucker and Brown, 1998), which can have a significant impact on the quantity and quality of runoff and drainage from agricultural watersheds. Recently, the ADAPT model was calibrated and validated for conditions in southern Minnesota using long term monitoring data collected from an experimental plot with continuous corn (Davis *et al.,* 2000). Also, a frost depth algorithm developed by Benoit and Mostaghimi (1985) was incorporated to enhance the model's capability to predict flow during spring and fall months (Dalzell, 2000).

Model Input

Model inputs include information about land cover, crop residue cover at planting, slope, and soil. Land cover was developed using the Landsat Thematic Mapper (TM) image acquired on July 29, 1995. The Landsat TM image acquired on May 31, 1997, was used to differentiate cropland with conservation versus conventional tillage (Gowda *et al.,* 2001), which controls crop residue cover at planting. Soil map units in the watershed were identified with the STATSGO (STATe Soil GeOgraphic) (Baumer *et al.,* 1994) soils database, and soil characteristics for each map unit were extracted from the MUUF (Map Unit Use File) database, a PC based soils database. Slope information for the watershed was determined by overlaying STATSGO map unit boundaries on a 30 m resolution digital elevation model, and extracting the average slope for each map unit.

Spatial data development for watershed application of the ADAPT model consists of a two-part process, namely (1) Hydrologic Response Unit (HRU) development, and (2) aggregation of HRUs into Transformed Hydrologic Response Units (THRUs). In the HRU formation process, spatial data layers of land cover, soils, slope (averaged by STATSGO map unit), and tillage were overlain with ARC/INFO GIS software. The result is a GIS layer consisting of many polygons that each contains hydrologic characteristics that are unique from those around it. The number of HRUs that result from this initial definition can be quite large. Sand Creek, for example, has over 54,000 HRUs associated with it. However, there are many HRUs in a watershed that have the same hydrologic characteristics as other HRUs, but are different from each other by location only. These similar HRUs are then aggregated together to form THRUs – the functional modeling unit. It should be noted that THRUs do not retain the positional information initially present in the HRUs. This data arrangement is based on the assumption that the time of concentration in the study watershed is less than 24 hours, the time step resolution of the model. This assumption is valid for Sand Creek watershed. GIS overlay analysis of land use, tillage, soil, and slope layers for the Sand Creek watershed resulted in 81 THRUs.

Other input data included county wide average planting and harvesting dates, rate of fertilizer application, and soil phosphorus concentrations, as well as climatic data such as precipitation, temperature, relative humidity, solar radiation, and wind velocity. Six crop rotation sequences were developed for row crops as input to the model. The average P fertilizer application rate for corn in Sand Creek watershed during 1994 to 1996 was 18 kg/ha (Bruening, 1998). Fertilizer P applications were applied by farmers with equal frequency in fall and spring. Soil bioavailable phosphorus concentrations in Sand Creek average 35 µg/g (Fang *et al.,* 2002), while soil total P concentrations average 600 µg/g. Climatic data such as daily values of precipitation and mean temperature used in the water quality simulation were the averages of data recorded at 11 weather stations within or near the study watershed to account for spatial variability. Mean daily precipitation values were substituted with median precipitation values for days in which standard deviation of precipitation data across weather stations was greater than 10 mm.

Model Calibration

The model was calibrated for monthly flow, sediment, and P loadings at the watershed outlet using monitoring data from 1994 to 1996. A sediment delivery ratio of 0.15 was used in the calibration of upland sediment losses with the model. Based on stream bank surveys conducted by the local Soil and Water Conservation District, 20 percent of the sediment was assumed to be due to stream bank erosion (Skone, 1990). Based on point source monitoring data and feedlot inventories, it was assumed that point sources such as waste water treatment plant and feedlots in the Sand Creek watershed contributed a P loading of about 20 tons per year (Johansson, 2000). These point sources account for about 27 percent of the total P losses between April and October in the Sand Creek watershed.

Statistical measures such as mean and Root Mean Square Error (RMSE), coefficient of determination (r^2) and slope and intercept of the least squares regression line between measured and predicted values, and index of agreement (d) were used to evaluate the match between measured and predicted flow, sediment, and P losses. For perfect model performance, the RMSE should be zero, and the index of agreement should be one. In practice, model performance is never perfect, and RMSE values under 75 percent or an index of agreement over 0.75 indicate satisfactory model performance.

Due to wintertime freezing conditions in Minnesota, observed data were not available for all months of the year. Rather, complete monitoring data were available from the months of April to October in 1994 and 1996 and from April to November 1995. As a result, measures of model performance are a comparison only of the months in which both predicted and observed data were available. While the ADAPT model is capable of predicting runoff and tile drainage resulting from snowmelt, evaluation of model performance during these events prior to April was not possible for this study.

Alternative Farming Practices

Using the calibrated model, several simulations were made to evaluate impacts of changes in nutrient, drainage, tillage, and land use management practices on water quality. Input parameters used in these simulations were the same as those used in the model calibration unless otherwise mentioned. The effect of various levels of adoption of conservation tillage practices on water quality in Sand Creek watershed was evaluated by changing the amount of land cover under conservation tillage. Conservation tillage as referred to here involves any combination of tillage practices that leaves at least 30 percent of the soil surface covered by crop residue at planting. Baseline simulations assumed that all crop land in the watershed was in conventional tillage to gauge progress towards controlling sediment loads since the advent of conservation tillage. Levels of adoption of conservation tillage used in the simulations include 40 (existing level of adoption), 50, 75, and 100 percent of the crop land in the watershed. Model simulations were also made by changing land cover from conventional to conservation tillage, accompanied by a 10 percent conversion of cropland to pasture.

Existing fertilizer application rate was used in the baseline simulations for P losses. Alternative management practices include five different P application rates (by changing the existing rate by -20, -10, +10, +20, and +30 percent over three different timings – fall, spring, and 50 percent in fall and 50 percent in spring). These rates were used to evaluate the sensitivity of P losses to fertilizer rate. As rates of fertilizer application are changed, the model adjusts soil P concentration to account for plant uptake of P. Soil bioavailable P concentrations typically decrease slowly, and experimental data show that soil bioavailable P in soils near Sand Creek decreases from 1 to 2 µg/g/yr in response to reductions in P fertilizer application, due to plant uptake of soil P (Randall *et al.,* 1997b). To account for trends in the installation of new subsurface tile drainage systems in the watershed, the above mentioned simulations were repeated for two other drainage scenarios by increasing the existing percentage of cropland with tile drainage by +10 and +20 percent.

TMDLs

Monthly TMDLs were calculated for sediment and P losses for the duration of calibration by multiplying observed monthly flow with actual pollutant concentrations. The water quality standard of 25 Nephelometric Turbidity Units (NTUs) was used for calculating sediment TMDLs (MPCA, 2002). To calculate a TMDL for sediment load, it was assumed that 1 NTU is equal to 4.4 mg/l (MPCA, 2002).

Although Minnesota has no water quality standards for phosphorus in rivers, the Minnesota Pollution Control Agency has adopted a phosphorus concentration guideline of 90 µg/l to protect lakes in southern Minnesota from eutrophication (MPCA, 2002). Since flowing rivers can tolerate concentrations of phosphorus that are somewhat greater than this guideline without experiencing severe eutrophication, a scenario was examined in which the TMDL for riverine phosphorus was based on a critical phosphorus concentration of 100 µg/l. Phosphorus TMDLs based on this critical concentration were then compared with existing pollutant loads at the outlet of the Sand Creek watershed to determine the amount of load reductions needed. To comply with these TMDLs, reductions in pollutant loadings through various alternative farming practices were evaluated using the ADAPT model.

RESULTS AND DISCUSSION

Model Calibration

Figure 2 compares the predicted and observed monthly flow values during the calibration period. Trend and magnitude of the predicted monthly flow values were similar to those of observed data, except for the month of April 1994 and 1996. The model overpredicted flow for April 1994 by 58 percent, and underpredicted for April 1996 by 44 percent. Overall, the predicted mean monthly flow for the calibration period (4.11 m^3/sec) closely matched the observed flow value (4.37 m^3/sec). Flow was underpredicted only by 6 percent. Poor performance of the model in predicting flow for April 1994 and 1996 may be partly due to errors in the prediction of timing and magnitude of snowmelt events in those months. The model predicted 75 percent of the variability in flow with an RMSE equivalent to 38 percent of the observed mean monthly flow, and the model gave an index of agreement of 0.92. All of these statistical measures indicate that the model is very satisfactory at predicting flow in Sand Creek.

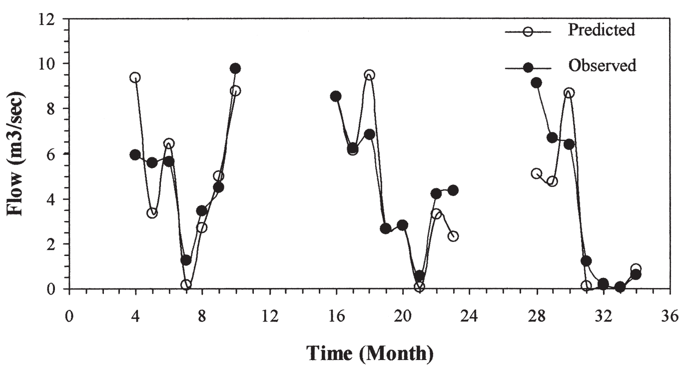

Figure 2. Comparison Between Predicted and Observed Monthly Flow Values for Sand Creek Watershed From1994 to1996.

The model predicted 69 percent of the variability in sediment losses observed at the outlet of the Sand Creek watershed. The trend in predicted monthly sediment losses (Figure 3) was similar to that of the observed data. The model underpredicted mean monthly sediment losses (2,849 tons) by only 10 percent. The worst sediment predictions occurred during

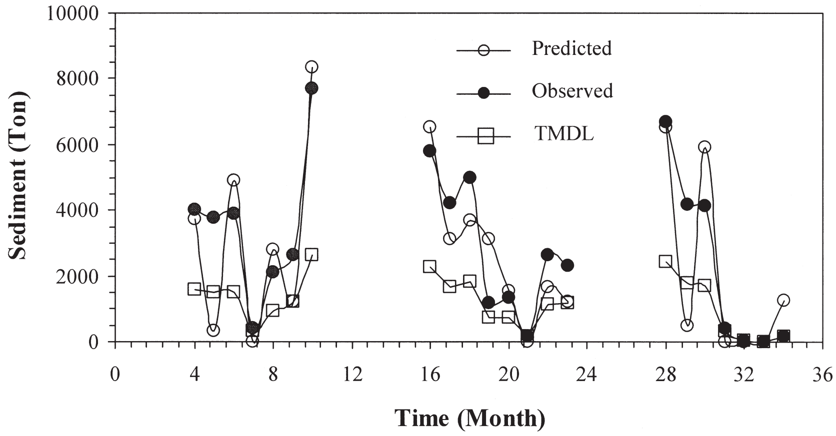

Figure 3. Comparison of Sediment TMDLs With Predicted and Observed Monthly Sediment Losses for Sand Creek Watershed From 1994 to1996.

April 1994 and 1996, where the model also underpredicted monthly flow values. The model gave an RMSE equivalent to 49 percent of the observed mean monthly sediment losses, partly as a result of underprediction of sediment losses for May 1994 and 1996. Predicted sediment losses had an index of agreement of 0.91, which indicates very satisfactory model performance.

Trends in the predicted P losses were in agreement with measured losses for the duration of simulation (Figure 4), with the model explaining 49 percent of the variability in measured data. The model underpredicted the mean monthly P losses (6.92 tons) by 29 percent. This was mainly due to model's inability to capture variability in observed P losses during snowmelt runoff in 1996. The RMSE was equivalent to 58 percent of the observed mean monthly P for the calibration period. The index of agreement was about 0.79, indicating satisfactory model performance.

TMDLs

TMDLs varied with flow as they were calculated using the observed monthly flow. Figure 3 compares sediment TMDLs with the predicted and observed monthly sediment losses for Sand Creek watershed during 1994 to 1996. Sediment TMDLs were exceeded in most months. To comply with sediment TMDLs, a 59 percent reduction in sediment losses (from observed losses) is required. Figure 4 compares TMDLs for phosphorus with the predicted and observed monthly P losses. Observed monthly P losses exceeded TMDLs in most months, and an 85 percent reduction in P losses (from observed losses) is required to comply with TMDLs for phosphorus.

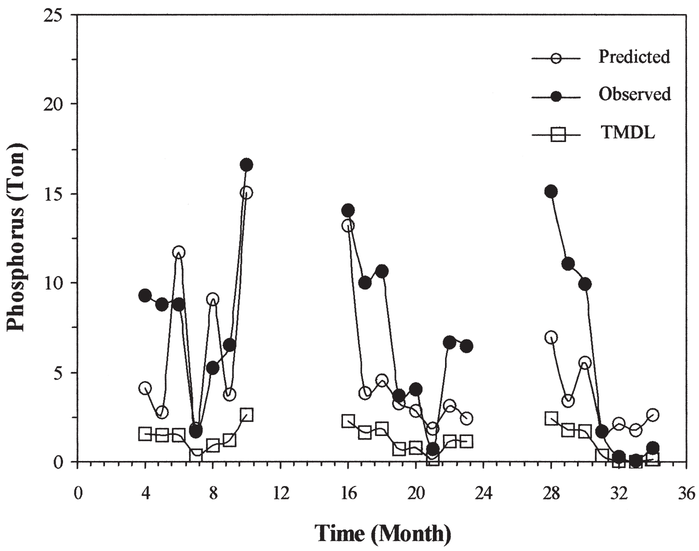

Figure 4. Comparison of P TMDLs With Predicted and Observed Monthly P Losses for Sand Creek Watershed From 1994 to1996.

Alternative Agricultural Management Practices

Model simulations were made to evaluate the effects of alternative nutrient management practices. Predicted annual sediment and phosphorus losses at the mouth of the watershed were about 0.44 ton/ha and 0.97 kg/ha, respectively, under present management conditions. Sediment and phosphorus losses (Table 2) from row cropland are much higher than watershed scale losses due to deposition at the bottom of hillslopes. Row crops are the major source of upland sediment and phosphorus losses, with small to negligible losses for pasture and forest land.

TABLE 2. Predicted Annual Edge-of-Field Sediment and Phosphorus Losses for Sand Creek Watershed.

Land Use Type	Sediment Loss (ton/ha)	Phosphorus Loss (kg/ha)	Area (ha)
Row crop	3.0	5.33	40,293
Pasture	0.0	0.01	19,083
Forest	0.0	0.02	2,779

Drainage and Nutrient Management Practices

Annual sediment losses were decreased by 21 percent (from 0.44 to 0.35 ton/ha) when crop land in tile drainage increased from 30 to 50 percent. This reduction is related to a decrease in surface runoff from tile drained land. Figure 5 illustrates changes in predicted annual P losses in response to six different P fertilizer application rates at three different timings. The magnitude of the changes is quite small. These small changes are primarily due to the large magnitude of point source P losses in the watershed. About 39 percent of the annual total P loadings are from point sources, before alternative management practices were evaluated. The most effective alternative phosphorus management scenario involved a 20 percent reduction in fertilizer application rate, with all of the fertilizer applied in spring, and with 50 percent of the cropland having tile drainage. This scenario gave annual P losses of about 0.90 kg/ha. In comparison, P losses were 1.03 kg/ha for the worst case scenario involving a 30 percent increase in fertilizer application rate, with all of the fertilizer applied in fall, and 30 percent of the cropland in tile drainage. P losses were reduced by 13 percent between the most and least effective fertilizer management scenarios. The combination of applying 20 percent less fertilizer in spring gives a 10.8 percent reduction in P losses

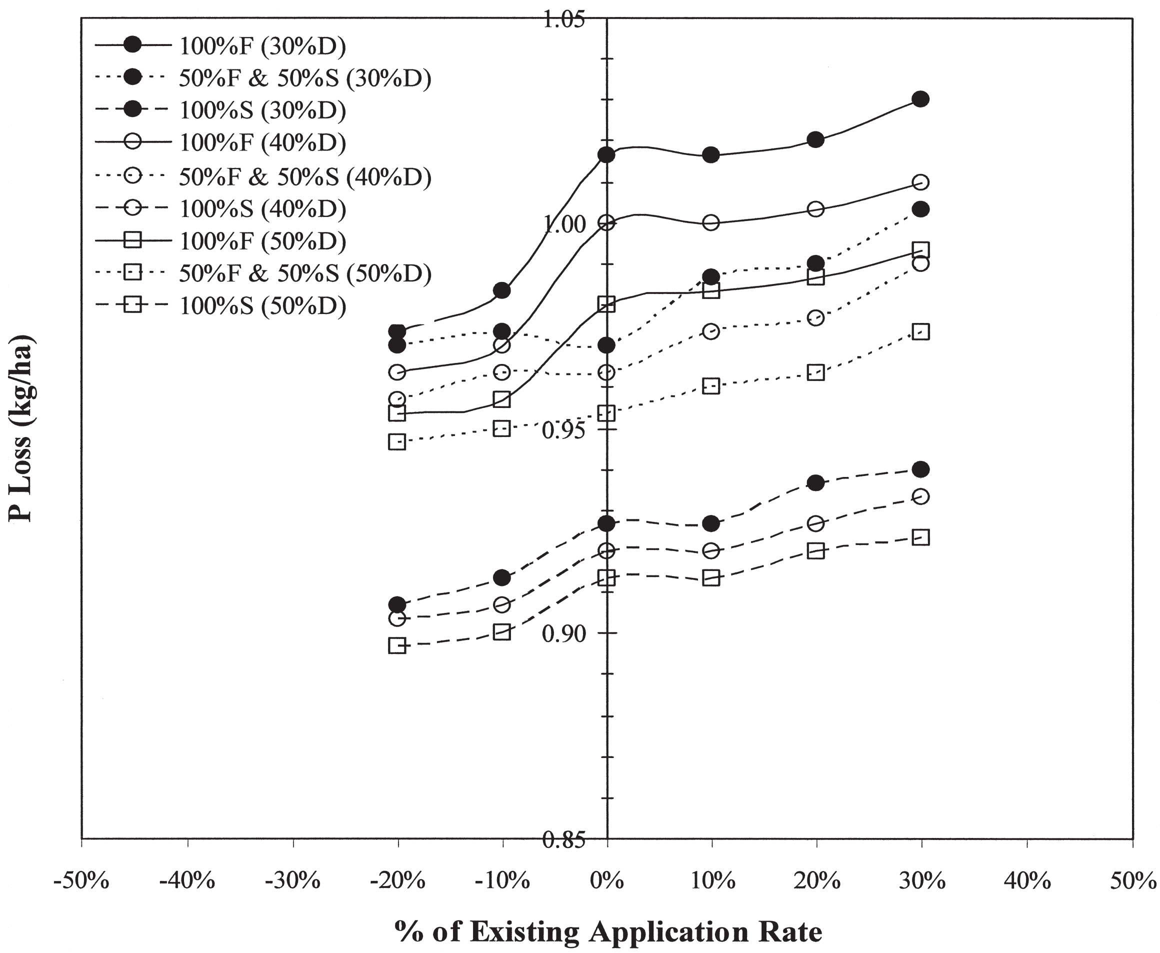

Figure 5. Predicted Annual P Losses in Sand Creek Watershed for Changes in Fertilizer Application Rates (x-axis), Timing of Fertilizer Application (F - Fall, S - Spring), and Extent of Crop Land With Tile Drainage (D).

compared with fall fertilizer applications at typical existing rates. The amount of cropland in tile drainage had little impact on P losses in steeper landscapes of Sand Creek watershed, due to good soil internal drainage, because in these soils drainage has little impact on the partitioning between runoff and infiltration.

Tillage Practices

Changes in the adoption of conservation tillage in Sand Creek watershed were simulated with the calibrated model. A linear relationship was observed between percent of cropland with conservation tillage and reductions in sediment and P losses at the mouth of the watershed (Figure 6). Adoption of conservation tillage on 40 percent of the cropland results in a 20 percent reduction in sediment losses compared to a baseline scenario in which all cropland uses conventional tillage. Adoption of conservation tillage on 75 percent of the cropland gives a 33 percent reduction in sediment losses, as compared with the baseline scenario. A 40 percent reduction in sediment losses is possible if conservation tillage is used on all cropland. Compared to losses under the existing 40 percent adoption rate of conservation tillage, sediment losses would have been increased by about 25 percent if all cropland in the watershed had been in conventional tillage. On the other hand, if all the cropland was in conservation tillage, sediment losses would be reduced by 24 percent when compared with current rates of sediment loss.

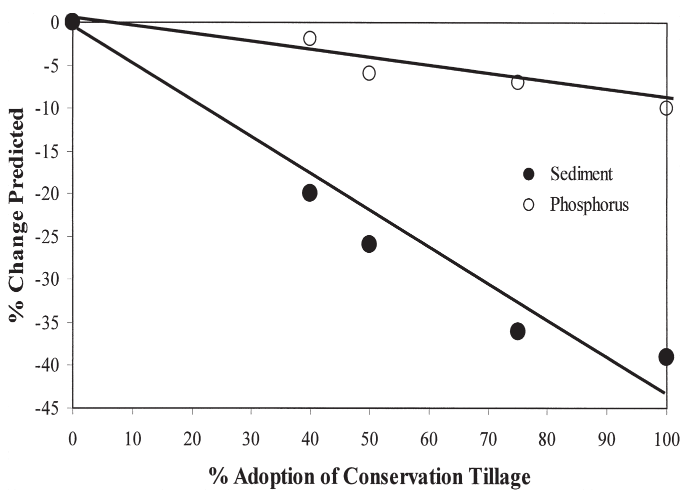

Figure 6. Predicted Percentage Change in Average Annual Sediment and Phosphorus Losses in Response to Changes in Adoption of Conservation Tillage in Sand Creek Watershed From 1994 to1996.

The modeling shows that further reductions in sediment losses are possible through a conversion of cropland to pasture, which is typically alfalfa in a three-year rotation or permanent grass. For example, the same level of reduction in annual sediment losses associated with adoption of conservation tillage on 75 percent of the cropland can also be achieved by adopting conservation tillage on 50 percent of the cropland and converting 10 percent of the cropland to pasture. Similarly, the same level of reduction in sediment losses by adopting conservation tillage on all cropland can be achieved with 75 percent of the cropland in conservation tillage coupled with 10 percent of the cropland in pasture. Roughly the same level of reduction in annual sediment losses achieved by adopting conservation tillage on 25 percent of cropland can be achieved by converting 10 percent of the cropland to pasture. This may be a viable option in southern Minnesota, where dairy farmers have historically been numerous.

P losses were somewhat less sensitive to changes in the adoption rate of conservation tillage, due to the large magnitude of phosphorus from point sources in the watershed. Adoption of conservation tillage on 40, 50, 75, and 100 percent of the cropland reduced P losses by 2, 6, 7, and 10 percent, respectively, compared to P losses in a scenario in which all cropland was in conventional tillage. Compared to current P losses with a 40 percent adoption rate of conservation tillage, a 4.8 percent reduction in annual P losses can be achieved by adopting conservation tillage on 75 percent of the cropland. Alternatively, the adoption of conservation tillage on 75 percent of cropland combined with conversion of 10 percent of cropland to pasture would give a 9.6 percent reduction in P losses. The combination of conservation tillage on 75 percent of cropland, conversion of 10 percent of cropland to pasture and improved fertilizer management strategies would give a total reduction in P losses of about 20 percent.

TMDLs

An increase in the adoption of conservation tillage from the existing 40 percent to a simulated 75 percent of cropland would reduce sediment losses by 16 percent. If this practice were coupled with conversion of 10 percent of cropland to pasture, it would reduce sediment losses by another 7 percent. Although significant reductions in sediment losses occurred with increases in the adoption of conservation tillage, they were not sufficient to reduce sediment loads to the level required by sediment TMDLs. Thus, control of streambank erosion, which contributes 20 percent of the total sediment losses, or installation of riparian buffer strips would also be needed to meet sediment TMDLs. Adoption of conservation tillage on 75 percent of the cropland coupled with conversion of 10 percent of the cropland to pasture and a 20 percent reduction in spring applied P fertilizer rate would reduce P losses by only 23 percent. Although these reductions in P losses were significant, they were not enough to attain TMDLs. Further reductions in P losses could be obtained by controlling emissions from point sources such as feedlots and wastewater treatment plants.

CONCLUSIONS

A spatial process model was calibrated and used for predicting sediment and P losses in Sand Creek watershed. Model predictions were in good agreement with measured flow, sediment, and P losses, with r^2 values of 0.75, 0.69, and 0.49, respectively. The calibrated model was used to estimate sediment and P losses under alternative nutrient, tillage, and drainage management scenarios involving different rates and timing of P fertilizer applications, various levels of adoption of conservation tillage, and conversion of cropland to pasture. Adoption of conservation tillage in Sand Creek was effective at reducing predicted sediment losses. However, adoption of conservation tillage on 100 percent of the cropland reduced sediment losses only by 24 percent, compared to a TMDL which requires a reduction of 59 percent. In view of this, a combination of increases in the adoption of conservation tillage, conversion of a portion of the cropland to pasture, installation of riparian buffer strips, and stabilization of stream banks seems to be needed to attain sediment reduction goals in the Sand Creek watershed.

Phosphorus losses were sensitive to the rate and timing of fertilizer application, adoption levels of conservation tillage, and conversion of row crops to pasture. Adoption of conservation tillage on 75 percent of the cropland gave a reduction in P losses of 4.8 percent, while switching fertilizer application timing from fall to spring gave a 9 percent reduction, and reducing fertilizer rate by 20 percent gave a 5 percent reduction. The combination of switching fertilizer application timing from fall to spring, reducing application rate, reducing soil losses through adoption of conservation tillage on 75 percent of cropland, and converting 10 percent of the cropland to pasture gave a total reduction in phosphorus losses of about 23.4 percent. Adoption of TMDLs for phosphorus requires an 85 percent reduction in P loads. It will be impossible to attain this reduction through increases in the adoption of best management practices on agricultural lands alone. It will also be very important to reduce point source loads of phosphorus in the watershed to attain phosphorus TMDLs.

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