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MODEL BASED NITRATE TMDLs FOR TWO AGRICULTURAL WATERSHEDS OF SOUTHEASTERN MINNESOTA[1]

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ABSTRACT: In this study, a set of nitrogen reduction strategies were modeled to evaluate the feasibility of improving water quality to meet total maximum daily loads (TMDLs) in two agricultural watersheds. For this purpose, a spatial-process model was calibrated and used to predict monthly nitrate losses (1994-96) from Sand and Bevens Creek watersheds located in south-central Minnesota. Statistical comparison of predicted and observed flow and nitrate losses gave r^2 coefficients of 0.75 and 0.70 for Sand Creek watershed and 0.72 and 0.67 for Bevens Creek watershed, respectively. Modeled alternative agricultural management scenarios included: six different N application rates over three application timings and three different percentages of crop land with subsurface drainage. Predicted annual nitrate losses were then compared with nitrate TMDLs assuming a 30% reduction in observed nitrate losses is required. Reductions of about 33 (8.6 to 5.8 kg/ha) and 35% (23 to 15 kg/ha) in existing annual nitrate losses are possible for Sand and Bevens Creek watersheds, respectively, by switching the timing of fertilizer application from fall to spring. Trends towards increases in tile-drained crop land imply that attaining nitrate TMDLs in future may require other alternative management practices in addition to fertilizer management such as partial conversion of crop land to pasture.

(KEY TERMS: nonpoint source pollution; tile drainage; ADAPT model; BMPs.)

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INTRODUCTION

Hypoxia in the Gulf of Mexico is a serious environmental issue which has been attributed primarily to nitrogen enriched waters entering the Gulf from the Mississippi River. The Upper Mississippi River Basin (UMRB) contributes one-third of the total nitrate loading to the Mississippi River (Alexander *et al.*, 1995), but comprises only about 15% of the total area of the Mississippi River Basin. High nitrate loadings leaving the UMRB are associated with tributaries from agricultural areas in the states of Minnesota, Iowa, Indiana, and Illinois where crop land is tile drained. Subsurface tile drainage systems in these regions enhance crop productivity by removing excess water from the rooting zone and facilitating timely planting operations. However, tile drain effluent carries large quantities of nitrate from agricultural land to lakes and rivers. The Minnesota River Basin located in southern Minnesota, with more than 30% of its crop land

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artificially drained, has been identified as one of several relatively high contributors of nitrogen (801-1500 kg/km^2/yr; Goolsby *et al.*, 1999) into the Upper Mississippi River.

High nitrate losses are also associated with excessive applications of N-fertilizer (Baker and Johnson, 1981; Kanwar *et al.*, 1988), especially fertilizer applied in the fall (Baker and Melvin, 1994). Fall applied fertilizer is subject to nitrification and leaching of nitrate, leading to nitrate losses in tile drainage prior to plant uptake. For example, a 6-year monitoring study on continuous corn plots at Waseca, Minnesota showed a 25% reduction in nitrate losses through tile drainage when the application rate was reduced from 202 kg-N/ha to 134 kg-N/ha (Buzicky *et al.*, 1983). In the same study, nitrate losses in tile drainage were reduced by 27% with spring applications of ammonium sulfate as compared with losses from fall applications. Unfortunately, farmers in the Minnesota River Basin and upper Midwest in general apply most of their fertilizer and manure during fall to take advantage of dry soil conditions and lower fertilizer costs (Randall and Schmitt, 1998). Further, a modeling study by Alexander *et al.* (2000) indicates that more than 90% of nitrogen loading entering the Mississippi River will be transported to the Gulf of Mexico with very little removal of nitrogen in transit. This implies that nitrogen reduction actions are necessary at the source, not only to meet the federal drinking water standard of 10 mg/l, but also to reduce the areal extent of hypoxia in the Gulf of Mexico.

According to the Clean Water Act (CWA), 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, and (3) identifying alternative management practices to comply with 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.

The Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (2001) set a coastal goal of reducing areal extent of hypoxia in the Gulf to 5,000 km^2 by 2015. They estimated that this would require a 30% reduction in nitrogen discharges from the Mississippi and Atchafalaya Rivers to the Gulf. Based on the introductory information provided above, the objectives of this study were to (1) evaluate the reductions in nitrogen losses possible with several alternative management practices in two agricultural watersheds located in south-central Minnesota; and (2) estimate how much of the reduction in nitrogen loadings 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 a Geographic Information System (GIS) and remote sensing databases, was calibrated to predict monthly flow and nitrogen loadings from study watersheds. This model explicitly accounts for the effects of all typical agricultural management practices on water quality including the impacts of changes in rate and timing of N-fertilizer, while accounting for increases in the percentage of crop land in subsurface tile drainage. Predicted nitrate losses from various management practices were then compared with nitrate TMDLs developed as per the Gulf of Mexico Hypoxia Task Force's recommendations.

METHODS AND MATERIALS

Study Area and Water Quality Data

Sand Creek and Bevens Creek watersheds are tributary watersheds of the Lower Minnesota River watershed (Figure 1) and are located in the Minnesota River Basin. Table 1 presents the general characteristics of Sand and Bevens Creek watersheds. The Sand Creek watershed covers approximately 650 km^2 of south-central Minnesota. The watershed is dominated by agricultural land use with approximately 63% of the area devoted to row crop agriculture, primarily corn and soybean. About 30% of the land in Sand Creek watershed has been improved with subsurface tile drainage systems, and conservation tillage is practiced on approximately 40% of crop land 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 northeastern portion of the watershed near the confluence with the Minnesota River. The average slope of Sand Creek watershed is 6.6%.

Bevens Creek watershed covers 340 km^2, mainly in Carver County, and is a significant source of

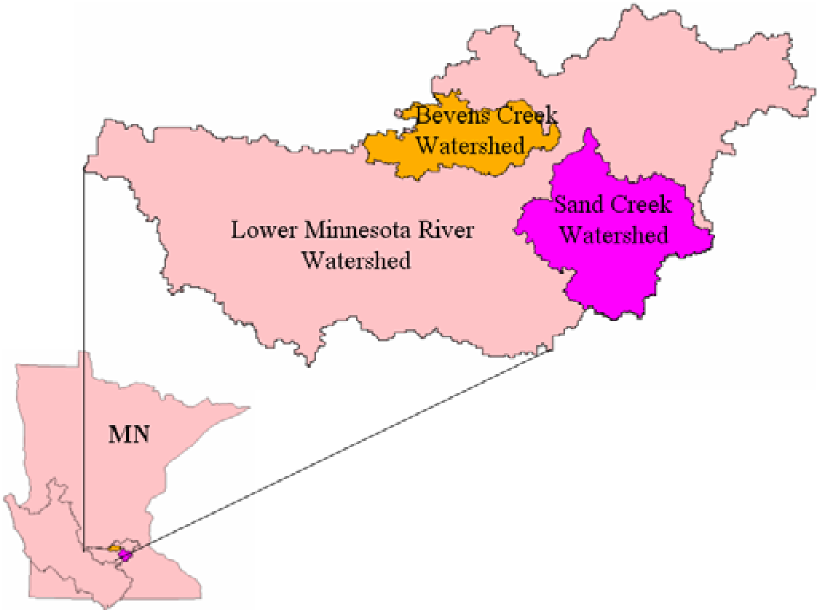

FIGURE 1. Location of Sand Creek and Bevens Creek Subwatersheds in the Lower Minnesota River Watershed, Southern Minnesota.

TABLE 1. Characteristics of Sand Creek and Bevens Creek Watersheds.

		Name of the Watershed	
Sl. No.	Characteristics	Sand Creek Watershed	Bevens Creek Watershed
1	Area (km^2)	651.9	340.5
2	Average slope (%)	6.6	5.4
3	% Crop land	63	84
4	% Crop land in tile drainage	30	58
5	% Crop land in conservation tillage	40	39

nitrate losses within the Lower Minnesota River Basin. Crop land accounts for about 85% of the land use in the watershed. About 39% of the crop land uses conservation tillage, primarily on land cropped to corn. Generally, flat topography and poorly drained soils are typical of this area, and 58% of the crop land has subsurface tile drainage system. Average annual precipitation in both Sand Creek and Bevens Creek watersheds is approximately 762 mm, most of which occurs during the growing season.

From 1994-96, Sand Creek and Bevens Creek watersheds were monitored by the Twin Cities Metropolitan Council for flow and nitrate loadings at their confluence with the Minnesota River. Monitoring data includes continuous flow and automatic stage-activated composite water samples for water quality analysis. Water samples were collected during storm events using a flow actuated Sigma Sampler (Hach Company, Loveland, Colorado, USA) with a Campbell CR10 data logger. In addition, periodic grab samples were also collected during base flow conditions. During 1994-96, a total of 86 and 88 water samples were collected and analyzed for nitrate losses in Sand Creek and Bevens Creek watersheds, respectively. Monthly nitrate losses were calculated using the U.S. Army Corps of Engineers FLUX model (Walker, 1996). The first-order regression model option in FLUX was used to estimate monthly loadings from daily concentration and flow data, using a stratification process involving high flow and low flow regimes to account for seasonal variation in nitrate concentrations.

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), a subsurface drainage model. The model has four components: hydrology, erosion, and nutrient and pesticide transport. The hydrology component consists of snowmelt, surface runoff, macro-pore flow, evapotranspiration, infiltration, subsurface drainage, sub-irrigation, and deep seepage. Additional enhancements to the model include potential evapotranspiration estimation using the method of Doorenbos and Pruitt (1977) as an alternative to the method of Ritchie (1972). Runoff is estimated using the SCS curve number method (Soil

Conservation Service, 1972) with daily curve number updates dependant on antecedent moisture conditions. The snowmelt component in ADAPT model is based on a theory proposed by Anderson and Crawford (1964). Snowmelt water depth is computed as the summation of snowmelt due to radiation, rainfall, conduction, convection, and condensation (Chung *et al.*, 1992).

The nitrogen cycle used in the ADAPT model includes routines for mineralization from crop residue, soil organic matter and animal waste; immobilization to crop residue, plant uptake, partitioning between soil and solution phases, nitrogen fixation by legumes, denitrification and fertilization. Nitrogen in the soil is divided into active and stable pools, and changes daily as a function of their relative size and carbon to nitrogen ratio of organic materials such as crop residue, roots and animal waste. Mineralization is modeled as a two step process, ammonification and nitrification, and is a function of temperature and soil water content. Denitrification is considered as a first order process with a rate constant depends on the total active soil carbon in each layer and occurs in soil layers that have water contents exceeding field capacity by 10% and increases with an increase in soil temperature. Plant uptake is calculated as a function of total dry matter. Nitrogen fixation by legumes takes place when the soil nitrogen level drops below a threshold value and then proceeds at a constant rate. Nitrogen from precipitation is user defined and assumed constant throughout the simulation period. Nitrogen input from fertilizer application is added to nitrate and ammonia pools at their respective formula rates. Nitrogen losses in runoff, sediment, and subsurface tile drainage are calculated using a partitioning coefficient. A partitioning coefficient of zero is used for nitrates while the coefficient assigned to ammonia is calculated as a function of clay content in the soil. More detailed information about ADAPT can be found in Chung *et al.* (1992), Desmond *et al.* (1995, 1996).

The ADAPT model was used here because of its ability to simulate subsurface tile drainage contributions to agricultural runoff. This capability is especially important in the Midwest where nearly 30% of crop land has been modified by 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 nitrate losses from tile drained plots in southern Minnesota from a long-term study (Davis *et al.*, 2000). To improve model performance, a frost depth algorithm developed by Benoit and Mostaghimi (1985) was incorporated in the model (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 crop land with conservation versus conventional tillage (Gowda *et al.*, 2001) which controls crop residue cover at planting. The overall classification accuracy of land cover and tillage maps developed are 92% and 77%, respectively. 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 Transformed HRUs (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 both Sand Creek and Bevens Creek watershed. GIS overlay analysis of land use, tillage, soil and slope layers for Sand Creek and Bevens Creek watersheds resulted in 81 and 63 THRUs, respectively.

Other input data include planting and harvesting dates, rate of fertilizer application and climatic data such as daily precipitation, temperature, relative humidity, solar radiation, and wind velocity. Six crop rotation sequences were developed for row crops simulated by the model. The average N fertilizer application rates for corn in Sand Creek and Bevens Creek watersheds during 1994-96 were 140 and 130 kg/ha, respectively (Bruening, 1998). Fertilizer N applications were applied by farmers with equal frequency in fall and spring. Climatic data such as daily values of precipitation and mean air temperature used in the water quality simulation were the averages of data recorded at 11 and 6 weather stations within or near (within 5 km from the watershed boundary) Sand Creek and Bevens Creek watersheds to account for spatial variability. Mean daily precipitation values were substituted with median precipitation values for days in which standard deviation of precipitation data was greater than 10 mm. For the simulation period, the annual precipitation varied from 725-760 mm for Sand Creek watershed and 720-850 mm for Bevens Creek watershed and was representative of normal conditions.

Model Calibration

The model was calibrated for monthly flow and nitrate losses at the watershed outlet using 3 years of monitoring data from 1994 to 1996. Due to wintertime freezing conditions in Minnesota, observed data are not available for all months of the year; rather, complete monitoring data are available from the months of April to October in 1994 and 1996 and from April to November in 1995. As a result, measures of model performance are a comparison only of the months in which observed data are available. While the ADAPT model is capable of predicting runoff resulting from snow melt, evaluation of model performance during these events prior to April was not possible for this study. During the model calibration, default soil characteristics derived from the MUUF database were used for most soils. Adjustments were made to initial depth to water table, and total nitrogen and nitrate-nitrogen concentrations in each soil horizon to improve the match between observed and predicted flow and nitrogen losses. Table 2 presents the calibrated parameter values used in the water quality simulation for both Sand Creek and Bevens Creek watersheds.

Statistical measures such as mean and Root Mean Square Error (RMSE), coefficient of determination (r^2) and slope and intercept of the least square regression line between measured and predicted values, and index of agreement (d; Willmott, 1981), were used to evaluate the match between measured and predicted flow and nitrate losses. The index of agreement reflects the degree to which the predicted variation accurately estimates the observed variation and is calculated as:

$$d = 1 - \frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}(|P'_i| + |O'_i|)^2}$$

$$\text{where} \quad P'_i = P_i - O \text{ and } O'_i = O_i - O \qquad (1)$$

where N, is the number of cases, P_i is the predicted value, and O_i, is the corresponding observed value. For perfect model performance, the RMSE should be zero, and the index of agreement should be one. Efforts were made to minimize the RMSE to zero and index of agreement close to one.

TABLE 2. Calibrated Parameter Values Used in the Water Quality Simulation.

Input Variable	**Value**
SCS curve number (AMC II)	Crops = 78, others = 68
Evaporation constant (mm $d^{0.5}$)	4.0
Effective rooting depth (mm)	1,150
Surface sealing threshold (mm)	44
Surface storage depth (mm)	25
Depth to impermeable layer (m)	4.57
Drain spacing (m)	27
Depth of drains (m)	1.2
Initial depth to water table (m)	1.8
Total nitrogen (%)	0.17
Nitrate-nitrogen concentration (ppm)	2
Potentially mineralizable nitrogen (kg/ha)	100

Alternative Agricultural Management Practices

Using the calibrated model, several simulations were made to evaluate impacts of changes in the nutrient and drainage management practices on water quality. Input parameters used in these simulations were the same as those used in the model calibration unless otherwise mentioned. Existing N fertilizer application rates and timing were used in the baseline simulations for nitrate losses. Alternative management practices include: six different N application rates (by changing the existing rate by −20, −10, 0, +10, +20, and +30% over three different timings: fall, spring, and 50% in fall and 50% in spring). These combinations were used to evaluate the sensitivity of nutrient losses to fertilizer rate and timing of application. To account for trends in the installation of new subsurface tile drainage systems in the watershed, the abovementioned simulations were repeated for two other drainage scenarios by increasing the existing percentage of crop land with tile drainage systems by +10 and +20%.

TMDLs

Monthly TMDLs were calculated by assuming that observed monthly nitrate losses at the outlet of the watershed should be reduced by 30%. This goal for a 30% reduction in nitrate losses is based on recommendations of Gulf of Mexico Watershed Nutrient Task Force (2001) to reduce the areal extent of hypoxic zones in the Gulf. Thus, the nitrate TMDLs were equal to 70% of the observed monthly losses. To comply with these TMDLs, reduction of nitrogen losses through various alternative nutrient management practices was evaluated using the ADAPT model.

RESULTS AND DISCUSSIONS

Sand Creek Watershed

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 in 1994 and 1996. The model over predicted flow for April 1994 by 58%, and under predicted for April 1996 by 44%. Overall, the predicted mean monthly flow for the calibration period (4.11 m^3/sec), closely matched the observed value (4.37 m^3/s) and flow was under predicted only by 6%. Poor performance of the model in predicting flow for April of 1994 and 1996 may be partly due to errors in the prediction of timing and magnitude of snow-melt events in those months. The model predicted 75% of the variability in flow with an RMSE equivalent to 38% of the observed mean monthly flow, and the model gave an index of agreement of 0.92.

Predicted mean monthly nitrate losses (44 tons) for the calibration period were in close agreement with the observed data (42.9 tons). Figure 3 compares the predicted monthly nitrate losses against measured data. The predicted trends in nitrate losses were similar to those of observed data, and the model predicted 70% of the variability in observed nitrate losses. The RMSE was equivalent to 53% of the observed mean monthly nitrate losses, and the index of agreement was about 0.88.

Alternative Agricultural Management Practices and TMDLs. Model simulations were made to evaluate the effects of alternative nutrient management practices. Predicted annual nitrate losses from the watershed was about 6.7 kg/ha, respectively, under present management conditions. These conditions include 30% of the crop land with subsurface tile drainage system, half of the fertilizer applied in fall, and N-fertilizer rates of 140 and 16 kg/ha on corn and soybean crops, respectively. Figure 4 illustrates the predicted annual nitrate losses in response to six different N fertilizer application rates over three different timings and three different levels of tile drainage. The results of using alternative management practices for nitrogen were very complex. In general, nitrate losses were sensitive to rate, timing of N fertilizer applications, and the extent of tile drainage. Nitrate losses increased with increases in the N fertilizer rate. For example, the predicted annual nitrate losses decreased from 7.8 to 6 kg/ha when fertilizer application rates were reduced from +30 to −20% of the baseline rate. This is a 23% reduction in nitrate losses with a 50% reduction in N application rate. At a constant N fertilizer rate, switching

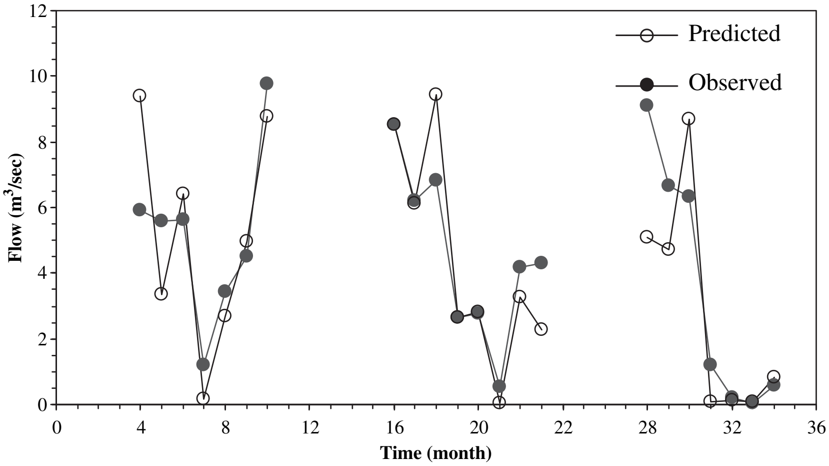

FIGURE 2. Comparison Between Predicted and Observed Monthly Flow Values for Sand Creek Watershed From 1994 to1996.

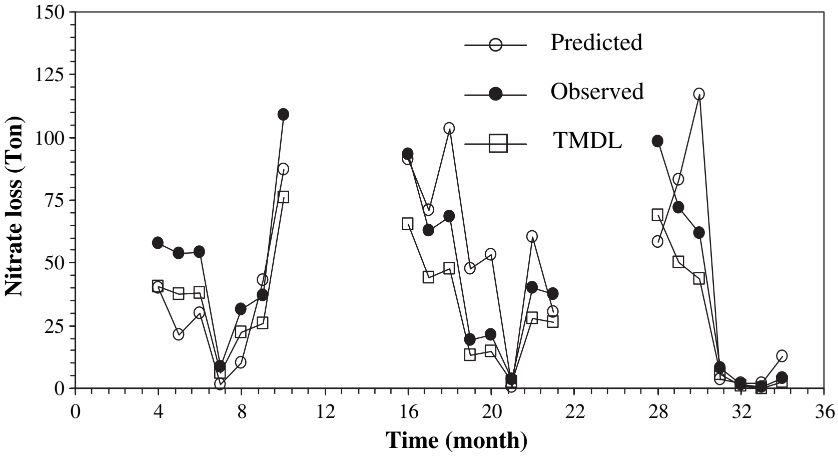

FIGURE 3. Comparison of Nitrate TMDLs With Predicted and Observed Monthly Nitrate Losses for Sand Creek Watershed From 1994 to 1996.

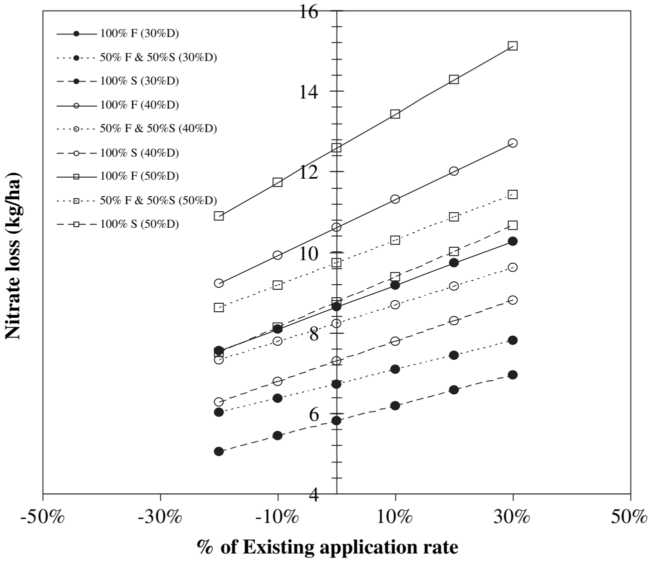

FIGURE 4. Predicted Annual Nitrate Losses for Various Changes in Nutrient and Drainage Practices for Sand Creek Watershed (D – Tile Drainage, F – Fall, S – Spring).

from fall to spring applications produced substantial reductions in nitrate losses. With the baseline application rates, the predicted nitrate losses for Sand Creek watershed were reduced from 8.6 to 5.8 kg/ha when the timing was changed from fall to spring. This is a 33% reduction in nitrate losses.

As expected, predicted nitrate losses increased as the percentage of crop land with subsurface tile drainage increased (Figure 4). With the baseline application rate and timing, the predicted annual nitrate losses were increased by 31% when crop land with subsurface tile drainage was increased from 30% to 50%. These increases in nitrate losses were due to a change in the partitioning of flow between surface and tile drainage, i.e., decreases in surface runoff and increases in tile drainage. It is well known that drainage is the major carrier of nitrate from crop lands to river systems in the Upper Midwest (Zucker and Brown, 1998). Of the simulated scenarios, the greatest reduction in nitrate losses was associated with a scenario involving a 20% reduction in fertilizer application rate, with 100% of the fertilizer applied in spring, and with 30% of the crop land in subsurface tile drainage. This scenario gave predicted annual nitrate losses of about 5.1 kg/ha, a 24% reduction from baseline conditions. The worst scenario for nitrate losses was one involving a 30% increase in fertilizer application rate, with 100% of the fertilizer applied in fall, and with 50% of the crop land in tile drainage. This scenario gave predicted annual nitrate losses of about 15.1 kg/ha, nearly triple the losses observed with the best scenario.

Figure 3 compares nitrate TMDLs with the predicted and observed monthly nitrate losses for Sand Creek watershed. The TMDLs varied with observed nitrate losses as they were equal to 70% of observed monthly nitrate losses. Nitrate TMDLs were violated in most months as expected. The nitrate TMDLs can be attained by changing the application of fertilizer from fall to spring. Other ways of attaining nitrate TMDLs exist through a reduction in the fertilizer rate coupled with conversion of a portion of row crop land to pasture in the watershed.

Bevens Creek Watershed

Model Calibration. Trends in the predicted monthly flow values showed reasonable agreement with the observed data (Figure 5). However, the model under predicted the mean monthly observed

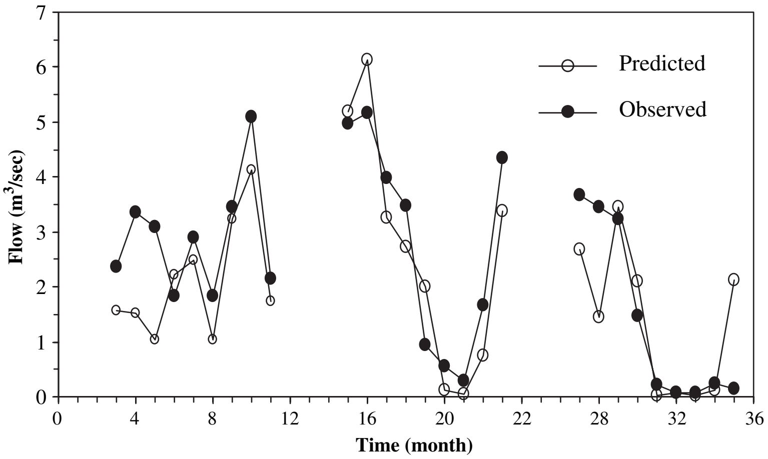

FIGURE 5. Comparison Between Predicted and Observed Monthly Flow Values for Bevens Creek Watershed From 1994 to 1996.

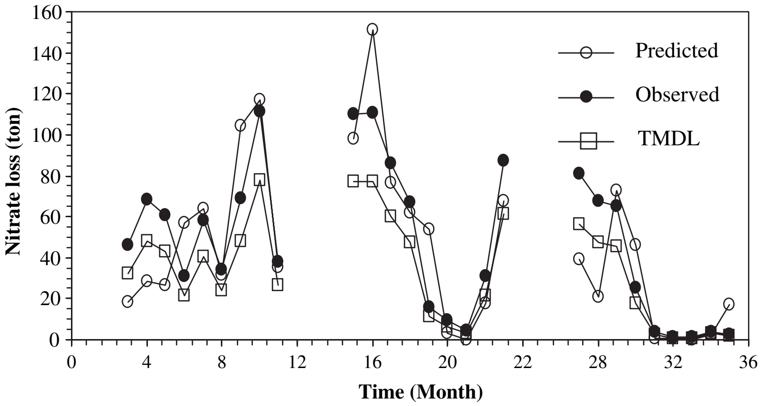

FIGURE 6. Comparison of Nitrate TMDLs With Predicted and Observed Monthly Nitrate Losses for Bevens Creek Watershed From 1994 to 1996.

flow (2.37 m^3/s) by 11% as a result of under prediction of flow from snowmelt events in 1994 and 1996. The ADAPT model predicted these events earlier than they actually occurred. Overall, the model predicted 72% of the variability in observed flow, with an RMSE equivalent to 40% of the mean monthly observed flow and an index of agreement of 0.91.

Figure 6 compares predicted trends and magnitudes in nitrate losses against observed data. Predicted monthly nitrate losses were strongly correlated to trends in the predicted flow. The model explained about 67% of the variability in observed data. Under prediction of nitrate losses in March and April of 1994 and 1996 and in November 1996 was mainly due to errors in the prediction of flow for those months. The predicted mean monthly nitrate loss of 41 tons was 15% less than the observed losses. The RMSE was equivalent to 48% of the observed mean monthly nitrate losses with an index of agreement of about 0.90.

Alternative Agricultural Management Practices and TMDLs. Alternative management practice scenarios included changes in the rate of N-fertilizer application and timing and changes in the amount of crop land with tile drainage. Predicted annual nitrate losses from the watershed were about 19 kg/ha under present management conditions. These conditions include 50% of the crop land with subsurface tile drainage system, half of the fertilizer applied in fall, and a N-fertilizer rate of 130 and 16 kg/ha for corn and soybean crops, respectively. Although the existing N-fertilizer rate for corn in Bevens Creek watershed is 10 kg/ha less than that in Sand Creek watershed, predicted annual nitrate losses for Bevens Creek watershed were roughly 2.8 times higher than that for Sand Creek watershed. Higher losses of nitrate in the Bevens Creek watershed were attributed to its greater percentage of crop land with subsurface tile drainage systems than in Sand Creek watershed.

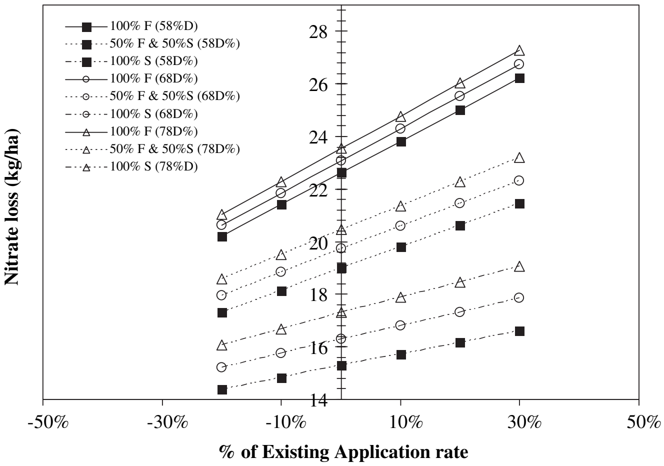

FIGURE 7. Predicted Annual Nitrate Losses for Various Changes in Nutrient and Drainage Practices for Bevens Creek Watershed (D – Tile Drainage, F – Fall, S – Spring).

Figure 7 illustrates variations in predicted annual nitrate losses in response to changes in drainage and nutrient management practices. In general, predicted nitrate losses increased as the rate of fertilizer application increased above the baseline application rate, and vice-versa. For example, predicted nitrate losses were reduced by 19% from 21 to 17 kg/ha when N application rates were reduced from +30% to −20% of the baseline rate. With N application rate kept constant at the baseline level, predicted nitrate losses were greater for fall application (23 kg/ha) than for spring application (15 kg/ha). This is a 35% reduction in nitrate losses when switching from fall to spring fertilizer application. Finally, nitrate losses increased when the amount of crop land in subsurface tile drainage increased. Of the simulated scenarios, the best scenario to reduce nitrate losses was one involving a 20% reduction in N application rates, with 100% of the fertilizer applied during the spring, and with 58% of the crop land in subsurface tile drainage. This scenario gave predicted nitrate losses of about 14 kg/ha. The worst scenario for nitrate losses was one involving a 30% increase in nitrogen application rates, with 100% of the fertilizer applied during the fall, and with 78% of the crop land in subsurface tile drainage. This scenario gave predicted nitrate losses of about 26 kg/ha, nearly double the losses observed with the best scenario.

Figure 6 compares nitrate TMDLs with the predicted and observed monthly nitrate losses for Bevens Creek watershed. As in Sand Creek watershed, at present, the nitrate TMDLs can be attained by changing the application of fertilizer from fall to spring. However, with increases in subsurface tile drainage on crop land, the model predicts that nitrate losses will increase. To offset these increases, other ways of attaining nitrate TMDLs such as reductions in fertilizer rate or conversion of a portion of row crop land to pasture may be required.

CONCLUSIONS

A spatial-process model was calibrated and used to predict flow and nitrate losses (1994-1996) in Sand Creek and Bevens Creek watersheds. Model predictions and measured flow and nitrate losses were in good agreement for both watersheds. For Sand Creek watershed, the r^2 values for flow and nitrate losses were 0.75 and 0.70, respectively. The model gave similar statistical results for Bevens Creek watershed. The calibrated model was used to investigate nitrate losses under alternative nutrient management scenarios involving different rates and timing of N-fertilizer applications while accounting for growth in the percentage of crop land in subsurface tile drainage. Predicted nitrate losses were sensitive to timing, rate of fertilizer application, and subsurface tile drainage as expected. At present, in Sand Creek watershed, a 33% reduction in nitrate losses can be achieved to comply with TMDLs (that require a 30% reduction) by switching the timing of fertilizer application from fall to spring. Similar reductions in nitrate losses can be achieved for Bevens Creek watershed as well. The nitrate TMDL for Bevens Creek watershed was much higher than that for Sand Creek watershed due to a greater area of crop land in subsurface tile drainage system in Bevens Creek watershed. Further reductions in nitrate losses are possible by reducing N application rates, while maintaining a constant level of crop land in tile drainage.

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