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MODELING LONG-TERM NITROGEN LOSSES IN WALNUT CREEK WATERSHED, IOWA

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Abstract: *Adequate knowledge on the movement of nutrients under various agricultural practices is essential for developing remedial measures to reduce nonpoint source pollution. Mathematical models, after extensive calibration and validation, are useful for obtaining such knowledge and to identify site-specific best agricultural management practices. A spatial-process model that uses GIS and the ADAPT, a field scale daily time-step continuous water table management model, was calibrated and validated for flow and nitrate-N discharges from a 365 ha agricultural watershed in Walnut Creek, IA. This watershed was monitored for nitrate-N losses from 1992-1997. Spatial patterns in crops, topography, fertilizer applications and climate were used as input to drive the model. The first half of the monitored data was used for the calibration and the other half was used in validation of the model. For the calibration period, the observed and predicted flow and nitrate-N discharges were in excellent agreement with r^2 of 0.88 and 0.74, respectively. During the validation period, the observed and predicted flow and nitrate-N discharges were in good agreement with r^2 of 0.71 and 0.50, respectively. For all six years of data, the observed and predicted annual nitrate-N losses for the entire simulation were in excellent agreement with nitrate-N losses of 26 and 27 kg/ha, respectively. The calibrated model was used to investigate the long-term impacts of nitrate-N losses to changes in the rate of nitrogen fertilizer applications.*

Keywords: Watershed, Water Quality, ADAPT, GIS

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INTRODUCTION

High nitrate loadings from the Upper Mississippi River Basin are associated with tributaries from agricultural areas in the states of Iowa, Minnesota and Illinois, where a high percentage of agricultural land is in row crops which are drained with subsurface tile drainage systems. These loadings 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). For this reason, many long term water quality monitoring studies have been conducted throughout the Midwest U. S. with emphasis on N-application rates and timing, crop rotation, and climatic variability. Most of these studies have been conducted at plot and field scales to describe the effect of specific farming practices. However, there are only few such studies at a watershed scale as it requires all or most farmers within the watershed to follow prescribed farming practices. Further, it is difficult to evaluate more than one or two farming practices as it is economically not viable.

Mathematical models, after extensive calibration and validation, have proved to be efficient and effective tools for evaluating movement of nutrients under various agricultural management practices at plot, field and watershed levels. Several studies (Davis et al., 2000; Gowda et al.,1999a; Parsons et al., 1995) demonstrated the use of water quality simulation models to quantify the effects of potential changes in farming practices or their timing on water quality over a wide range of climatic conditions. The main objectives of this study were to: (1) calibrate and validate a spatial-process model that uses the ADAPT model, a field scale water table management model and GIS for flow and nitrate losses; and (2) use the calibrated spatial-process model to determine sensitivity of nitrate losses to changes in rate of fertilizer applications on a 365 ha agricultural watershed in Walnut Creek, IA.

MATERIALS AND METHODS

Study Area and Water Quality Data: The study watershed is one of five subwatersheds (known as subwatershed-220) located on the Des Moines Lobe in the western part of Walnut Creek watershed in central Iowa (Figure 1). Hereafter, the study watershed is referred to as the Walnut Creek subwatershed. Since 1991, the watershed has been intensively monitored for flow, sediment, nitrogen and pesticide losses as part of the Management Systems Evaluation Areas Program. Topography of the watershed is relatively flat, and soils are poorly drained. The Clarion-Nicollet-Canisteo soil association predominates with Webster, Harps and Okoboji soils occupying the closed depressions. About 90% of the land uses a corn and soybean crop rotation, and is tile drained.

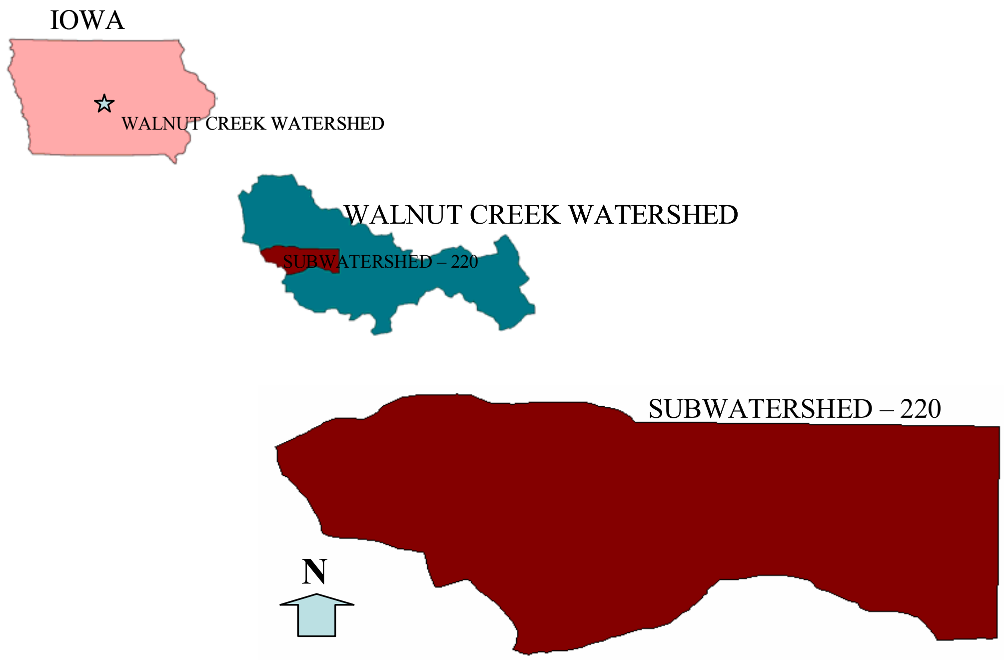


Figure 1. Location of the Walnut Creek subwatershed (subwatershed - 220) in central Iowa.

Discharges at the outlet were measured by a 1-stage measuring device which is connected to a Campbell Scientific Inc. (CSI) CR10 data logger. Flow measurements were made every 5-minutes. Water samples for water quality were collected automatically with ISCO peristaltic pump samplers. Sampling interval for water quality was based on the rate of change in water level, with more frequent water samples during storm events. In addition to automated collection, water quality samples were collected manually on a weekly basis and after major rainfall events by dipping sterilized glass bottles into stream flow.

ADAPT Model: The ADAPT model is a daily time step field scale water table management model which was developed as an extension of the GLEAMS model (Leonard et al., 1987). GLEAMS algorithms were augmented with algorithms for subsurface drainage, subsurface irrigation, and deep seepage and related water quality processes (Desmond et al., 1996). Other enhancements included adding the Doorenbos and Pruitt (1977) potential evapotranspiration method as an alternative to the Ritchie method (1972); modifying the runoff curve number based on daily soil water conditions; adding a Green-Ampt infiltration model; modeling snow-melt; and accounting for macropore flow. Recently, 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 and tested with Lower Minnesota River Basin flow data (Dalzell, 2000). The model gives estimates of pesticides and nutrients in tile drainage, in addition to the normal GLEAMS output. The model has four components: hydrology, erosion, nutrient and pesticide transport. The hydrologic component of the model consists of snow-melt, surface runoff, macropore flow, evapotranspiration, infiltration, subsurface drainage, subirrigation, and deep seepage. The weather data required for the ADAPT model are precipitation, temperature, wind speed, relative humidity, and solar radiation for the duration of simulation. However, the model has option of generating relative humidity and wind speed data if it is not available. Complete details of the model are presented by Chung et al.(1992), Ward et al. (1993), and Desmond et al. (1996). Gowda et al. (1999b) developed a spatial process model that uses the ADAPT model for predicting flow and nutrient discharges in the Rock Creek watershed of northern Ohio, and successfully used this model in many water quality studies in Minnesota (Davis et al., 2000; Dalzell, 2000) . Davis et al. (2000) calibrated and validated the ADAPT model for subsurface drainage conditions on a poorly drained Webster clay loam soil at Waseca, MN using measured data from an experimental plot with conventional tilled continuous corn from years 1983 through 1996.

Model Input: Climatic data such as daily values of precipitation and mean temperature used in the water quality simulation were the daily averages of data recorded at four weather stations within or near the study watershed to account for spatial variability. Other climatic data such as average relative humidity and wind speed was generated as part of the model simulation.

Figure 2 illustrates the SSURGO (Soil SURvey GeOgraphic) soil map of the Walnut Creek subwatershed. The soil properties such as depth of each horizon, particle size distribution, organic matter content, vertical hydraulic conductivity, soil water release curve for each of the SSURGO soil map units were derived from the Map Unit Use File (MUUF) soil database (Baumer et al., 1994). Since the political boundary between Boon and Stone counties passes through the watershed, and SSURGO is a county level soil map, soil properties were derived by soil map unit and by county. To avoid the duplication of soil map units used in the model simulation, soil properties between the map units were compared and soil map units were merged whenever there was no difference in values of model sensitive parameters. A topographic map developed by the National Soil Tilth Laboratory was used to derive average slope values for each of the soil map units.

Land use mapping within the watershed has been conducted since 1991. Aerial photos acquired by the USDA Farm Service Agency were used to extract land use information, digitized for field boundaries and verified by visual examination of selected fields. This information is stored in a GIS format. Land use maps for 1991 to 1997 for the Walnut Creek subwatershed (Figure 3; land use for 1991 is not shown) were clipped to derive Transformed Hydrologic Response Units (THRUs; Gowda et al., 1999a) and associated crop rotation sequences.

Site-specific information on planting and harvesting dates, tillage and nutrient management practices (timing, method of application, type of fertilizer or manure) have been collected for each field within the Walnut Creek watershed, since 1991, through a landowners-operators survey. Detailed information on the field data collection is presented in Hatfield et al. (1999). These data were linked to each field in the land use GIS layer as attributes. Land use attributes were linked to the tillage and nutrient management data associated with each field.

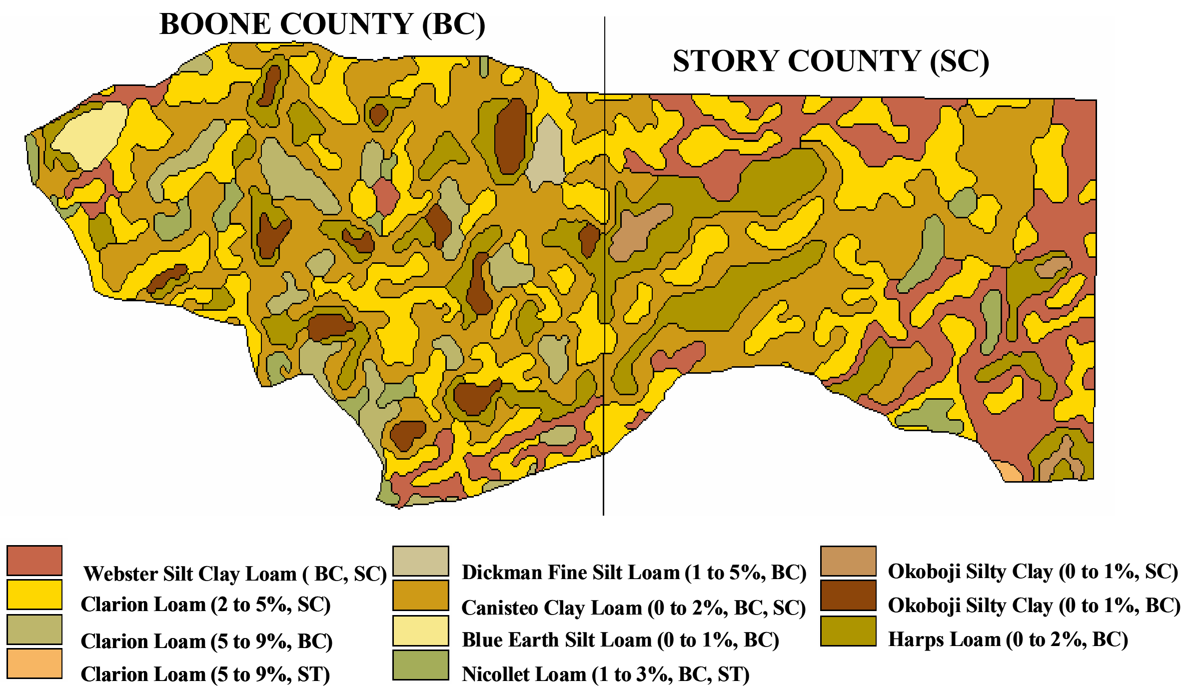


Figure 2. A SSURGO soil map of the Walnut Creek subwatershed.

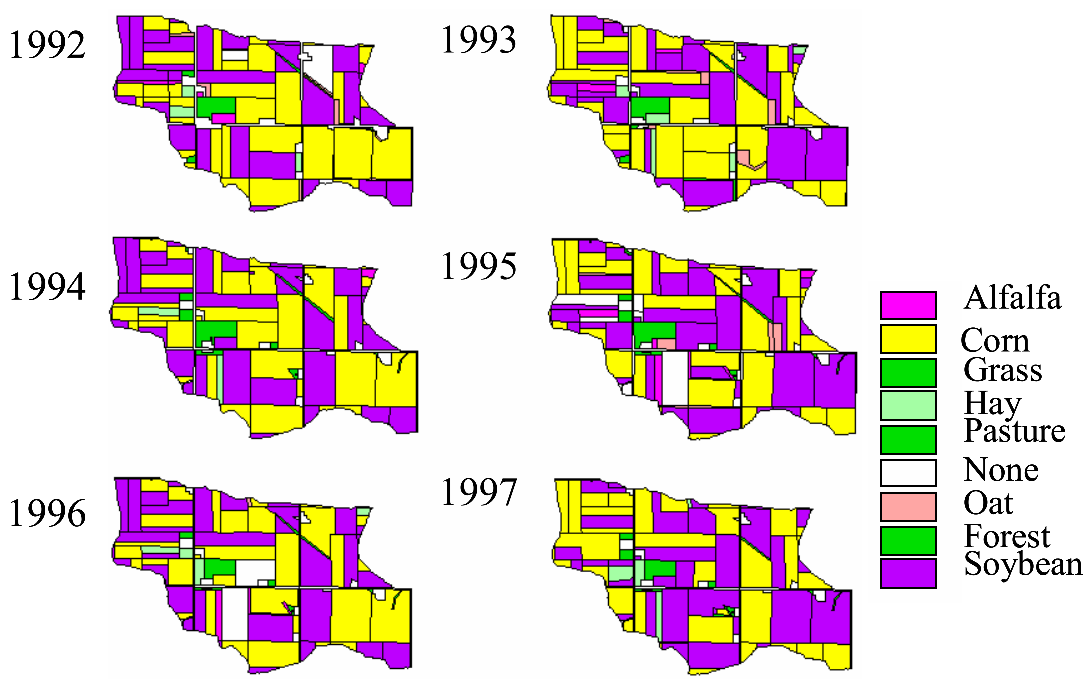


Figure 3. Land use distribution in the Walnut Creek subwatershed from 1992 to 1997.

The spatial process model used in this study requires a set of modeling units known as THRUs for the study watershed. It involves identifying unique hydrologic response units as a first step, by overlaying available hydrologically sensitive spatial data layers in the area of interest. In this study, unique HRUs were identified by overlaying soil, slope, land use layers using Arcview 3.0 GIS software (ESRI Inc., 2000). The unique HRUs with similar watershed characteristics were grouped to form THRUs. To dissolve THRUs that were created as a result of errors in digitizing the field and crop boundaries in each year, THRUs whose area is less than 0.04 ha were merged with THRUs with characteristics closely similar to the one in question.

Model Calibration and Validation: The spatial process model was calibrated and validated using the water quality data measured in the study watershed from August 1991 to December 1997. The first half (August 1991 to December 1994) of the measured water quality data were used for calibration, and the other half was used to validate the model using monthly flow and nitrate discharges. The calibration of the model for flow was done by adjusting initial depth of water table, soil water release curve, soil porosity, leaf area index, and depth and hydraulic conductivity of the impeding layer. Improvements in the nitrate loss predictions were made by adjusting initial total nitrogen and nitrate levels in the soil horizons. 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), were used to evaluate the match between measured and predicted flow and nitrate discharges for the calibration period, and to determine their predictability during the validation period.

N-Fertilizer Application Rate and Timing: Several simulations were made for the period of 1991-1997 to determine the effect of variation in rainfall and rate of N fertilizer application on nitrate losses. Input parameters used in the simulations for evaluating various practices were the same as those used in the model validation, unless otherwise mentioned. Six N application rates (by changing the existing rate by -10, -20, 0, +10, +20, and +30%) were used for this purpose. The use of multiple application rates was to demonstrate the sensitivity of nitrate losses to variation in precipitation as the application rate changed.

RESULTS AND DISCUSSIONS

GIS overlay analysis resulted in 290 THRUs with 65 crop sequences. Although the corn-soybean or soybean-corn rotation was followed on about 90% of the crop land, the high number of crop sequences was the result of changes in the crop rotation sequence adopted in different years in different fields, or the result of more than one soil type within a crop or field boundary. Corn received anhydrous ammonia (140 kg/ha N) in fall and urea (30 kg/ha N) in spring (Table 1).

Table 1. N fertilizer rates and timing of application for corn, soybean and oat crops in the Walnut

Creek subwatershed from 1991 to 1997.

Land Use	Baseline Application Rate (N kg/ha)	
	Fall (Anhydrous Ammonia)	Spring (Urea)
Corn	140	30
Soybean	-	2
Oat	-	20

Model Calibration: Table 2 shows excellent agreement between model predictions and measured flow and nitrate losses for the calibration period and good agreement for the validation period. In the calibration phase, attempts were made to minimize the RMSE and obtain r^2 and d values closest to a value of unity. Comparison of measured and calibrated values of monthly flow shows (Figure 4) that the magnitude and trend in the predicted monthly flows closely followed the measured data in most of the months. The predicted mean monthly flow is 2244.9 m^3/day against a measured value of 2174.2 m^3/day. However, the model over predicted flow by 29% for July 1993. This may be partly due to model's inability to capture the effects of consecutive heavy rainfalls that caused floods throughout the Midwest in 1993. Also, the model slightly under predicted flow during spring snow-melt events (March and April) in 1992, and over predicted flow during the 1994 cropping season. Statistical evaluation of the measured and observed flow gave an r^2 value of 0.88, with a slope and intercept of 0.85 and 439.7 m^3/day, respectively. The index of agreement was about 0.96 and the RMSE was 66% of the observed mean monthly flow.

During the calibration period, predicted monthly nitrate losses were in close agreement with the measured data (Figure 5), however, the predicted mean monthly nitrate loss was about 37% higher than the measured value. Over prediction of nitrate losses was mainly due to over prediction of flow (29%) for the month of July 1993 which increased nitrate losses by 51%. Predicted nitrate loss for this month alone accounted for about 9% of the measured total nitrate losses for the calibration period. The remaining portion of prediction error was attributed to errors in flow predictions during spring snow-melt events (March and April) of 1992. Statistical evaluation of the measured and observed nitrate losses gave an r^2 value of 0.71 with an slope and intercept of 0.62 and 104.7 kg, respectively. The index of agreement was about 0.89 and the RMSE was about 23% higher than the measured value. Overall, the model seems to predict nitrate losses reasonably well when the predicted monthly flows were in agreement with the measured data.

Model Validation: The predicted mean monthly flow of 2067.4 m^3/day was in close agreement with the measured flow of 2036.8 m^3/day (Figure 6), with a RMSE equal to 52% of the observed mean flow. A comparison of predicted and measured monthly flow values gave an r^2 value of 0.75 with a slope and intercept of 0.89 and 425.3 m^3/day, respectively. The index of agreement was about 0.93.

Table 2. Model performance statistics for predicted monthly flow and nitrate discharges in Walnut

Creek subwatershed during the calibration and validation years.

Statistic		Calibration period (August 1991 to 1994)		Validation period (January 1995 to December 1997)	
		Flow	Nitrate	Flow	Nitrate
Mean	Observed	2174.2 m^3/day	666.0 kg	2036.8 m^3/day	854.0 kg
	Predicted	2244.9 m^3/day	912.0 kg	2067.4 m^3/day	647.0 kg
RMSE[1]		1426 m^3/day	819 kg	1058 m^3/day	1245 kg
R^2		0.88	0.71	0.75	0.50
Slope		0.85	0.62	0.89	0.97
Intercept		439.7 m^3/day	104.7 kg	425.3 m^3/day	225.0 kg
d[1]		0.96	0.89	0.93	0.80

[1] RMSE - Root Mean Square Error, d - index of agreement.

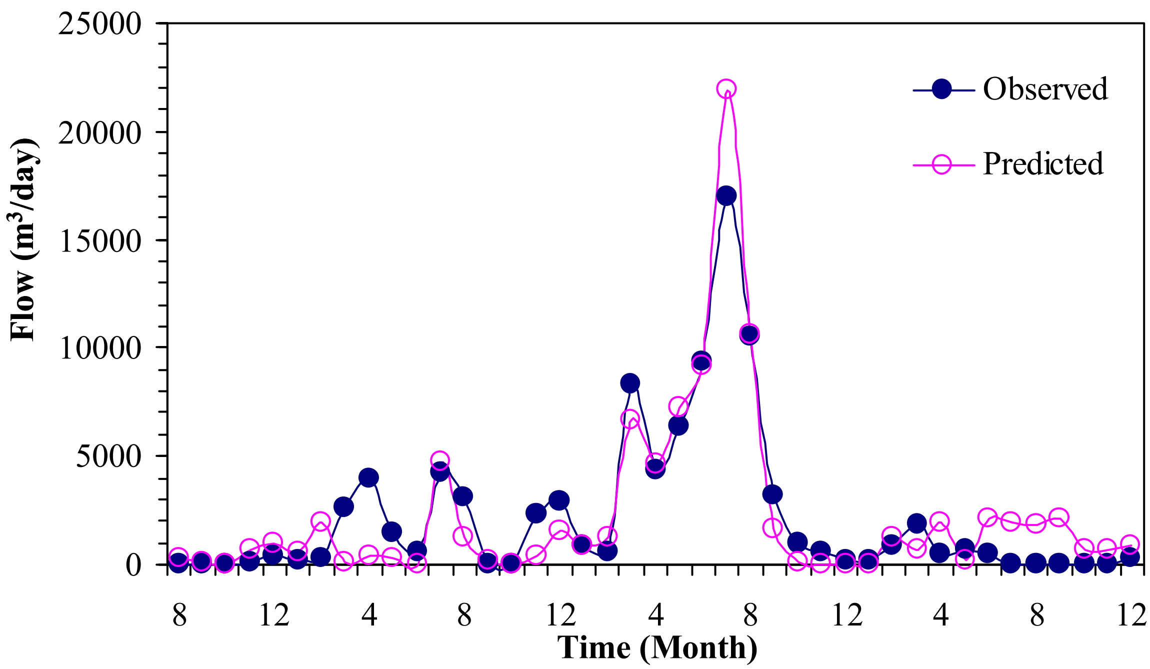
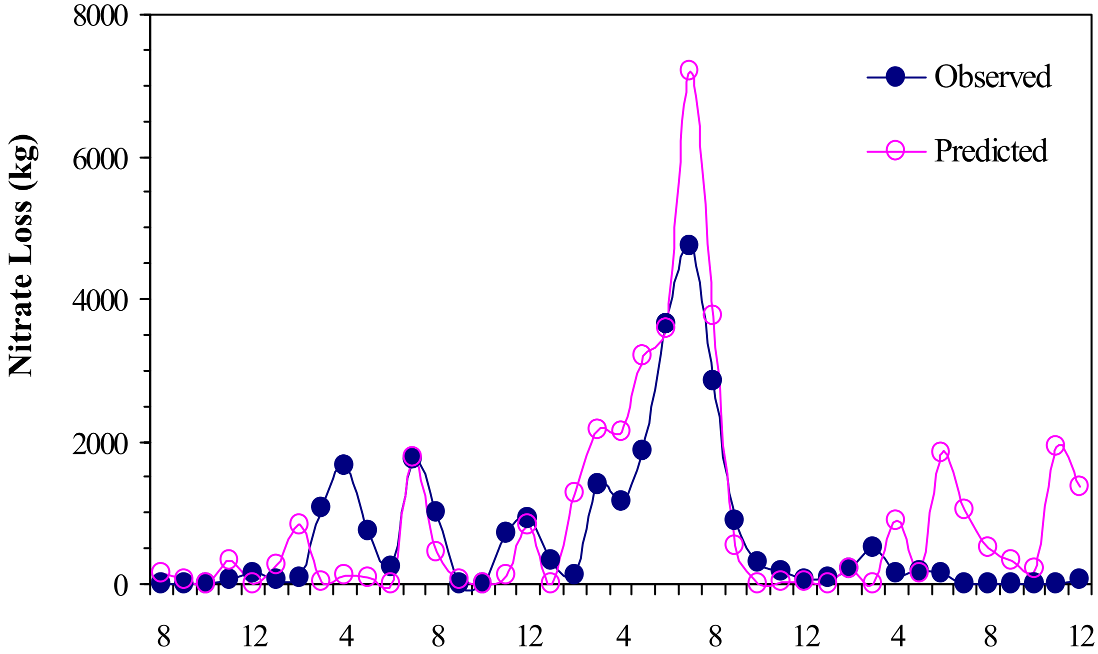


Figure 4. Comparison between predicted and observed monthly flow values for the Walnut Creek

subwatershed during the calibration period.



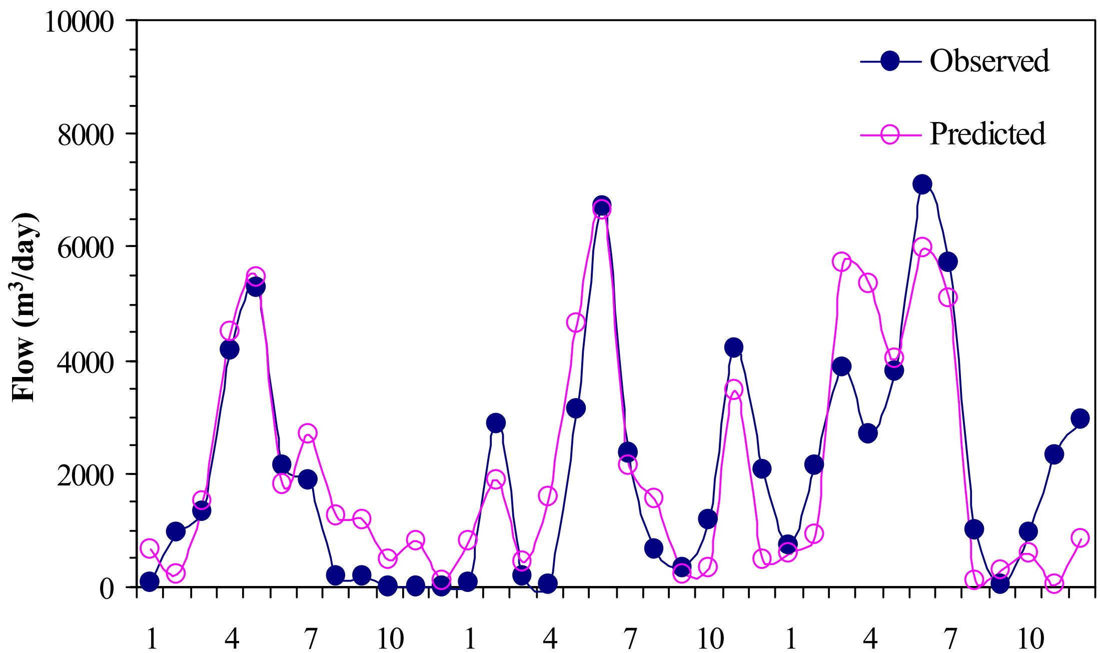


Figure 5. Comparison between observed and predicted nitrate losses for the Walnut Creek subwatershed during the calibration period.

Figure 6. Comparison between observed and predicted flow for the Walnut Creek subwatershed during the validation period.

Figure 7 compares predicted and measured monthly nitrate losses for the validation period. Although the trends in both measured and predicted nitrate losses were similar, the magnitudes of predicted nitrate losses were generally lower than the measured values. During the validation period, the model under predicted nitrate losses by 24%, with a predicted monthly mean of 647 kg against a measured value of 854 kg. The under prediction of nitrate losses may be partly due to over prediction of nitrate losses during the calibration period and consequent reduction in nitrogen concentration in soils as a result of very large rainfall events that occurred during 1993. Statistical comparison of measured and predicted nitrate losses gave an r^2 value of 0.50 with a slope and intercept of 0.97 and 225 kg, respectively. The index of agreement was about 0.80 and the RMSE was about 46% higher than mean monthly observed nitrate losses.

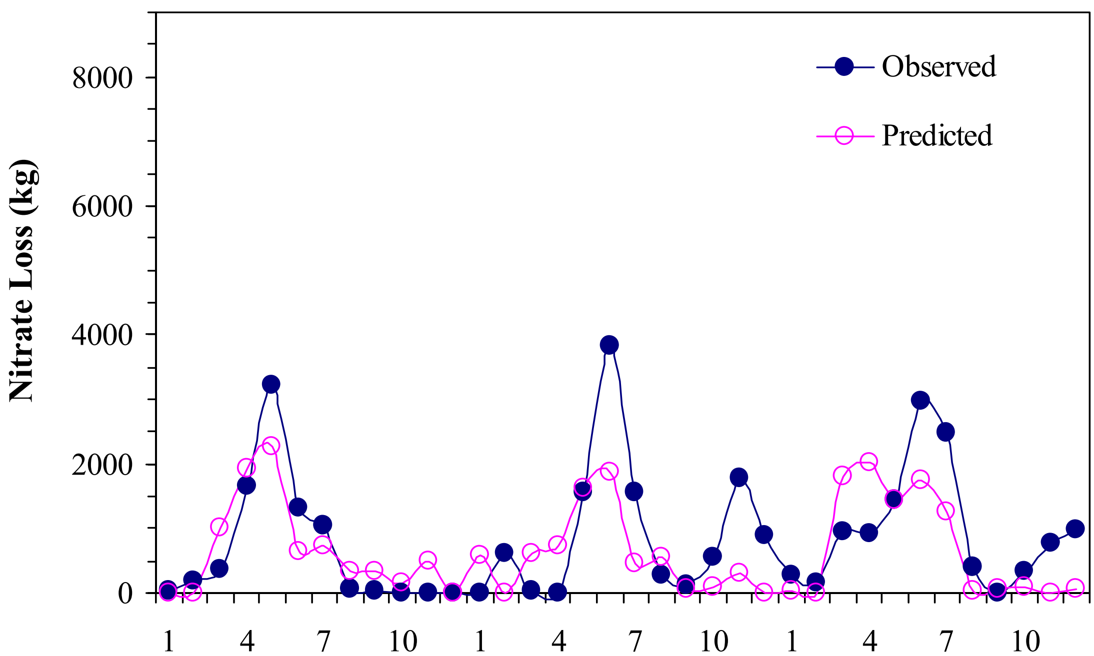


Figure 7. Comparison between observed and predicted nitrate losses for the Walnut Creek subwatershed during the validation period.

N-Fertilizer Application Rate: Annual nitrate losses in the Walnut Creek subwatershed were about 24 kg/ha under prevailing management conditions. These conditions include a fall application of 140 kg N/ha as anhydrous ammonia and a spring application of 30 kg N/ha as urea for corn fields (Table 1). Nitrate losses were sensitive to application rates (Figure 8). Reductions in nitrate losses were proportional to reductions in N fertilizer application rates. For example, annual nitrate losses were reduced from 26 to 23 kg/ha when fall applied N was reduced from +30 to -20% of the baseline rate (140 kg/ha). In other words, an 11% reduction in nitrate losses resulted from a 50% reduction in fall applied fertilizer nitrogen in the watershed. Reductions in nitrate losses can be larger at a field scale where only corn is grown. On a continuous corn field with Clarion Loam soil, an 8% reduction in nitrate losses (against a 4% reduction at the watershed level) resulted from a 20% reduction in fall applied fertilizer nitrogen. This shows that nitrate loss reduction goals at a watershed level will always be smaller than nitrate loss reductions observed at a field scale. Of the simulated scenarios, the greatest reduction in nitrate losses was associated with a 20% reduction in applied fertilizer application rate. The greatest increases in nitrate loss were associated with fertilizer applied at a rate 30% greater than the existing application rate.

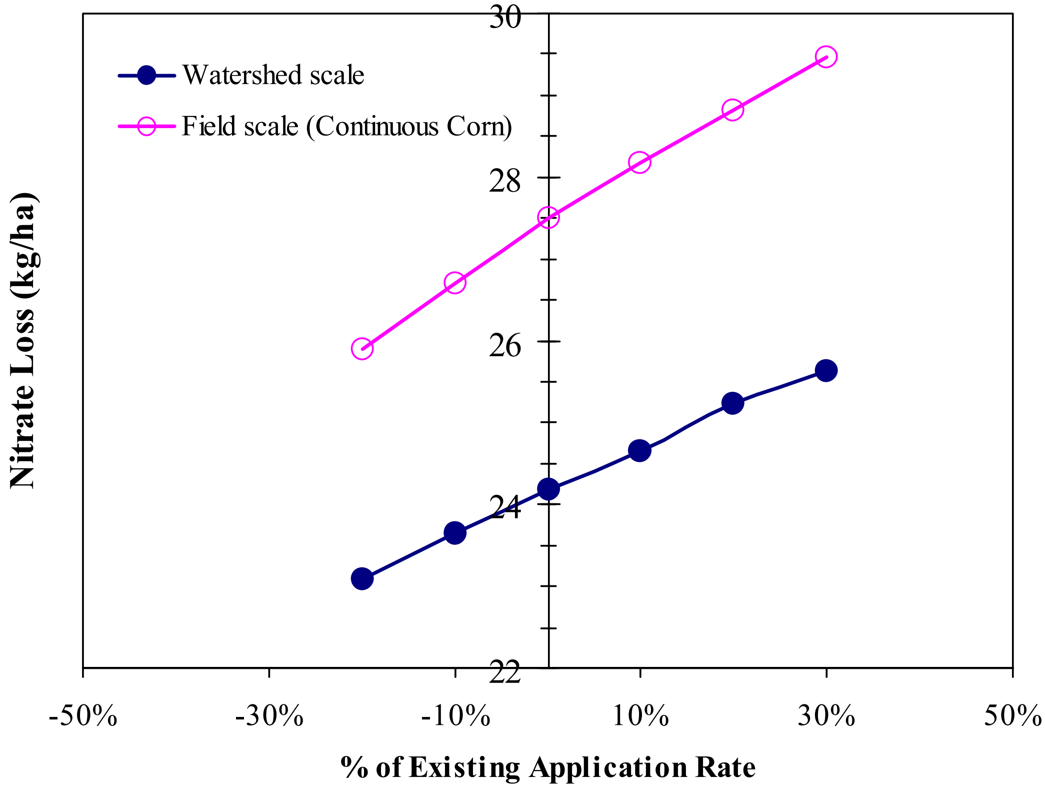


Figure 8. Comparison of predicted annual nitrate-N losses for change in the baseline nitrogen fertilizer application rate for a field with continuous corn and for Walnut Creek subwatershed.

CONCLUSIONS

A spatial-process model that uses GIS and the ADAPT, a field scale daily time-step continuous water table management model, was calibrated and validated for flow and nitrate discharges from a 365 ha agricultural watershed in Walnut Creek, IA. For the calibration period, the observed and predicted flow and nitrate discharges were in excellent agreement, with r^2 values of 0.88 and 0.74, respectively. During the validation period, the observed and predicted flow and nitrate discharges were in good agreement, with r^2 values of 0.71 and 0.50, respectively. Differences in the statistical results between calibration and validation periods may be partly due to very large events in the wettest year of 1993. For all six years of data, the observed and predicted annual nitrate losses were in excellent agreement with nitrate losses of 26 and 24 kg/ha, respectively. The calibrated model was used to investigate nitrate loss responses to alternative nutrient management scenarios such as rate of nitrogen fertilizer applications. Nitrate losses are sensitive to amount of fertilizer applied and goals, but to reduce nitrate losses at a watershed level requires setting higher nitrate loss reduction goals at the field scale.

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