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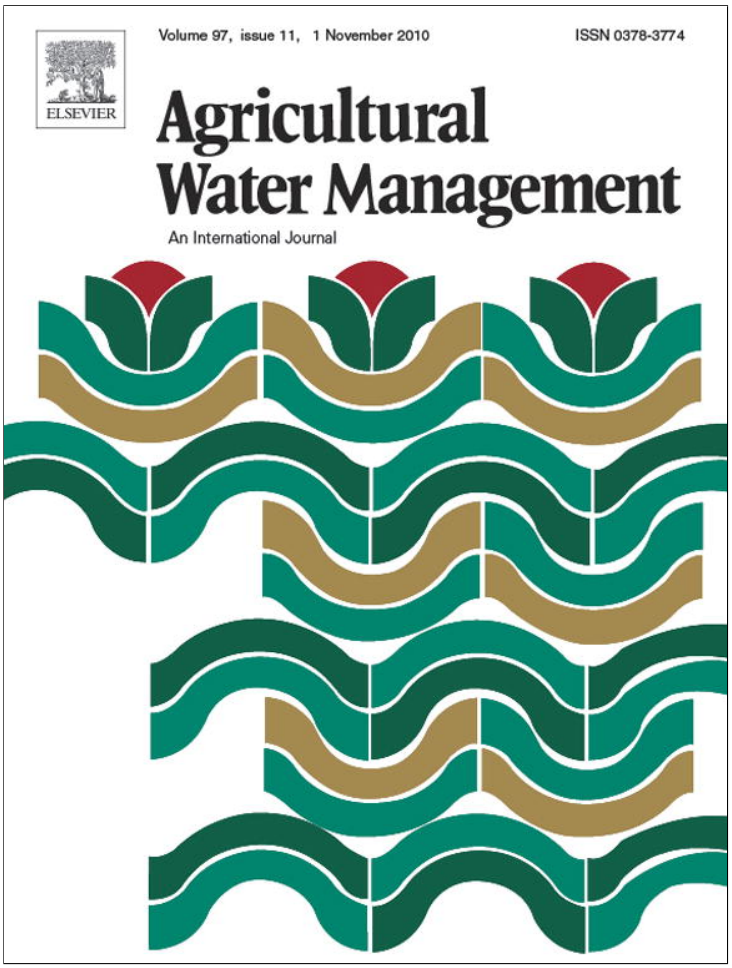

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Agricultural Water Management 97 (2010) 1855–1860

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Effects of changes in N-fertilizer management on water quality trends at the watershed scale

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ARTICLE INFO

Article history:
Received 10 March 2010
Accepted 30 June 2010
Available online 31 July 2010

Keywords:
Tile drainage
South-central Minnesota
Climate change
Nitrate-N loss

ABSTRACT

In this study, the ADAPT (Agricultural Drainage and Pesticide Transport) model was calibrated and validated for monthly flow and nitrate-N losses, for the 2000–2004 period, from two minor agricultural watersheds in Seven Mile Creek (SMC-1 and SMC-2) in south-central Minnesota. First, the model was calibrated and validated using the water quality data from the SMC-1 and again independently validated with the SMC-2 dataset. The predicted monthly flow and associated nitrate-N losses agreed reasonably with the measured trends for both calibration (r^2 = 0.81 and 0.70 for flow and nitrate-N losses, respectively) and validation (r^2 = 0.85 and 0.78 for flow and nitrate-N losses from SMC-1, and 0.89 and 0.78 for flow and nitrate-N losses from SMC-2, respectively) periods. The model performed less satisfactorily for the snowmelt periods than it did for the entire simulation period. Using the calibrated model, long-term simulations were performed using climatic data from 1955 to 2004 to evaluate the effects of climatic variability and N application rates and timing on nitrate-N losses. The predicted nitrate-N losses were sensitive to N application rates and timing. A decrease in the fall N application rate from 179.3 to 112 kg/ha decreased nitrate-N losses by 23%. By changing application timing from fall to spring at a rate of 112 N kg/ha, nitrate-N losses decreased by 12%. The predicted nitrate-N losses showed a linear response to precipitation with larger losses generally associated with wet years. A 25% increase in mean annual precipitation would offset reductions in nitrate-N loss achieved using better N fertilizer management strategies described above.

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1. Introduction

Amendments of nitrogen fertilizer improve crop yield up to a point, but excess application can be harmful to the environment. In addition to raising local water quality concerns, excess nitrate-N losses from Midwestern U.S. agricultural regions have been linked to hypoxia in the Gulf of Mexico (Burkart and James, 1999; Rabalais et al., 2001; Jaynes et al., 2001; Randall et al., 2003). High nitrate-N losses are associated with cropland with subsurface tile drainage systems that receive fall applications of fertilizer N at rates in excess of plant uptake requirements (Baker and Johnson, 1981; Baker and Melvin, 1994).

Nitrate-N loads transported to surface water through subsurface tile drainage systems are a function of transport volume (amount of water) and nitrate-N concentration in the transported water. The amount of drainage water leaving the landscape is largely a function of climate, soil properties, and tile drainage depth, spacing and intensity. Drainage is further influenced by the temporal distribution of precipitation within a particular year.

Numerous field studies have shown that the corn (*Zea mays* L.)-soybean [*Glycine max* (L.) Merr.] rotation contributes significant losses of nitrate-N to subsurface tile drainage waters (Goldstein et al., 1998; Dinnes et al., 2002). In a four-year drainage study in Minnesota, flow weighted nitrate-N concentrations averaged 28 mg/L for continuous corn, 23 mg/L for a corn–soybean rotation, and <2 mg/L for alfalfa (*Medicago sativa* L.) and grass perennial crops (Randall et al., 1997). Precipitation and cropping system have the greatest impacts on nitrate-N losses from agricultural landscapes to surface waters (Randall and Mulla, 2001).

A wide range of Best Management Practices (BMPs) have been studied for their impact on nitrate-N losses (Mulla, 2008). Randall et al. (2003) studied nitrate-N losses from a tile-drained Canisteo clay loam soil in southern Minnesota, and showed that nitrate-N losses from a corn–soybean rotation can be reduced by from 13 to 18% by either applying N in the spring or using nitrapyrin (NP) with late-fall applied ammonia. Davis et al. (2000) simulated long-term (1915–1996) nitrate-N losses in subsurface tile drainage for Minnesota climatic conditions at the plot scale using the ADAPT

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doi:10.1016/j.agwat.2010.06.023

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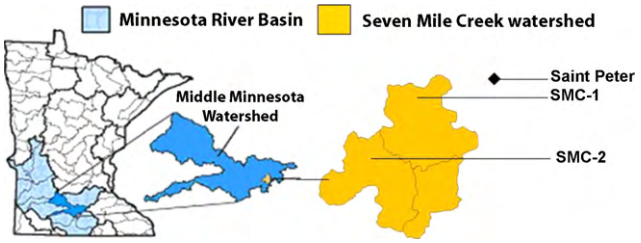

Fig. 1. Location of Seven Mile Creek watershed in the Minnesota River Basin.

(Agricultural Drainage and Pesticide Transport) model over a wide range of drain spacings, depths, and nitrogen fertilizer application rates. The predicted results indicated that nitrate-N losses were most sensitive to rate of fertilizer application, followed by depth of the tile drains, and tile spacing. In another modeling study involving continuous corn on a Webster clay loam soil at Waseca, southern Minnesota, Randall et al. (2000) predicted that NO_3-N losses increased by 84% when application rate was increased by 50% (from 200 to 300 kg N/ha).

There have been very few studies of nitrate-N losses at the watershed scale as affected by alternative fertilizer management practices (Mulla, 2008). Jaynes et al. (2004) obtained a 30% reduction in nitrate-N concentrations by reducing N fertilizer applications and switching from fall to spring N applications in a portion of the Walnut Creek watershed located in Iowa. Baksh et al. (2004) used the Root Zone Water Quality Model (RZWQM) for a single field in the same watershed, and showed that reducing the N fertilizer rate from 180 to 136 kg/ha (a 30% reduction) decreased nitrate-N losses in tile drainage from 54 to 45 kg/ha (a 17% reduction). Gowda et al. (2007) simulated nitrate-N losses in two Minnesota watersheds with contrasting extents of subsurface tile drainage. Tile drainage is installed in 30% of the agricultural land in Sand Creek, whereas Bevens Creek has 50% of the land in tile drainage. Reducing N fertilizer application rates from 180 to 140 kg/ha in Sand Creek caused a reduction in nitrate-N losses from 7.8 to 6.7 kg/ha (a 14% reduction). Reducing N fertilizer application rates from 169 to 130 kg/ha in Bevens Creek caused a reduction in nitrate-N losses from 21.3 to 19 kg/ha (an 11% reduction).

The main objectives of this study were to: (1) calibrate and validate a spatial-process water quality model for monthly flow and associated nitrate-N losses at the scale of Minnesota's 7719 ha Seven Mile Creek watershed, and (2) use the calibrated model to evaluate long-term effects of different fertilizer application rates and timings on nitrate-N losses under a wide range of climatic conditions.

2. Materials and methods

2.1. Site description and water quality data

The calibration and validation of the ADAPT model were performed using farm field measurements made by the Minnesota Department of Agriculture (Nangia et al., 2008) and water quality measurements made by the Brown Nicollet Cottonwood Water Quality Board staff on two minor agricultural watersheds for the period 2000–2004. The study watersheds (SMC-1 and SMC-2) are located within the 7719-ha Seven Mile Creek (SMC) watershed in south-central Minnesota (Fig. 1). The model was calibrated and validated on the SMC-1 and independently validated again on the SMC-2.

SMC-1 and SMC-2 were monitored for flow on a daily basis and grab samples were collected for agrichemical analysis approximately 18 times a year during the growing season (April–September). Topography of the watersheds is relatively flat with an average slope of about 2.3%. Soils are rich in organic matter and are poorly drained. The Clarion (typic Hapludoll)–Webster (typic Endoaquoll)–Glencoe (cumulic Endoaqoll) association predominates, with Canisteo (typic Endoaquoll), Cordova (typic Arigaquoll) and Webster (typic Endoaquoll) soils also occupying a significant portion of the landscape, and 33 other minor soils comprising the rest. Agriculture is the predominant land-use in both watersheds (Table 1).

Table 1
Total area and land use in the watershed.

Sub-watershed	SMC-1	SMC-2
Total area	4029-ha (9957-ac)	3690-ha (9119-ac)
Land use	Percent area	
Cultivated land	85.7	85.2
Deciduous forest	6.3	2.6
Wetland	2.7	6.4
Grassland	2.7	4.0
Farmstead and rural residence	1.8	1.8
Water	0.6	<0.1
Other rural development	<0.1	<0.1
Grassland–shrub–tree (deciduous)	<0.1	<0.1
Exposed soil	<0.1	<0.1

According to a survey conducted by the Brown Nicollet Cottonwood Water Quality Board in which 60% of all the agricultural acres were covered, the corn–soybean rotation accounted for 93% of the agricultural land. Ninety-three percent of all corn acres received commercial N fertilizer with an average application rate of 158 N kg/ha (141 lb/ac). Eighty-one percent of all N applied to corn was applied in fall. Anhydrous ammonia supplied 72% of the commercial N applied to all inventoried acres. The remainder was in the form of DAP (7%), UAN (3%) and urea (18%). Liquid hog manure was injected on 356-ha of corn (10% of cultivated area) at a rate of 152 kg N/ha (136 lb N/ac). This was in addition to the fertilizer N applied on cornfields. Sixty-nine percent of the cultivated area had less than 30% crop residue cover (conventional tillage). The fields planted to a corn–soybean rotation were typically chisel plowed in the fall after harvest and spring cultivated before planting.

2.2. ADAPT model

The ADAPT model is a daily time step field scale water table management 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 drainage algorithms from DRAINMOD (Skaggs and Broadhead, 1982), a subsurface drainage model. The GLEAMS algorithms have been augmented with algorithms for subsurface drainage, subsurface irrigation, and deep seepage and related water quality processes (Desmond et al., 1996). Other enhancements include adding the Doorenbos and Pruitt (1977) potential evapotranspiration method as an alternative to the Ritchie method (1972); modifying runoff curve number [an empirical parameter used in hydrology for predicting streamflow from rainfall excess (USDA, 1986)] based on daily soil–water conditions; adding a Green-Ampt infiltration model; modeling snowmelt; 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 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 (Gowda, 1996; Davis et al., 2000). More detailed information about ADAPT

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Table 2
Values used for representing soil properties and subsurface drainage systems in the watershed.

Input variable	Value
Soil conservation service curve number (AMC II)	Ag-78, others-68
Evaporative constant (mm $d^{0.5}$)	4.0
Effective rooting depth (cm)	Soybean-64, corn-89
Surface sealing threshold[a] (cm)	15
Surface storage depth (cm)	2
Depth of impermeable layer (m)	6.4
Drain spacing (m)	24
Depth of drains (m)	1.2

[a] Surface sealing threshold: a rainfall higher than this value will increase the curve number and surface runoff.

can be found in Chung et al. (1992), Ward et al. (1993), Desmond et al. (1996), and Gowda (1996).

2.3. Model input

For simplicity of model setup, land under grassland and grassland–shrub–tree (deciduous) categories was represented as a single land use (grassland). Farmstead and rural residences, other rural development, and exposed soil categories were also lumped together. Wetland and water categories were ignored in this study as they were small in area and located on the periphery of the watershed.

Precipitation data used for calibration and validation were measured on site using a tipping bucket rain gauge during the 2000–2003. Precipitation data for the remaining periods and other climatic data such as daily values of average air temperature, solar radiation, wind speed, and average relative humidity were taken from Saint Peter weather station located 8 km east the watershed. Soil properties required by ADAPT include soil–water release curve data, drained volume and upward flux versus depth, infiltration parameters, and saturated vertical and horizontal hydraulic conductivities. These data were derived from the Natural Resources Conservation Service (NRCS), Map Unit Use File (MUUF) 2.14 database (Baumer et al., 1987). Table 2 presents soil properties used in the model simulations. These parameters were held constant for all simulations, unless otherwise stated.

Our modeling methodology requires the study area to be divided into Hydrologic Response Units [HRUs; Gowda (1996)]. In the Hydrological Response Unit (HRU) formation process, spatial data layers of slope, land use, manure spread areas adjacent to feedlots, areas within 30 m of streams and ditches having higher sediment delivery ratios (the ratio of sediment yield of a drainage basin to the total amount of sediment moved by sheet erosion and channel erosion), and soil type were overlaid using a GIS software. The result was a GIS layer consisting of 126 HRUs containing unique combinations of soil type, land use, management and proximity to surface waters.

2.4. Model calibration

The ADAPT model was first calibrated for monthly flow and nitrate-N losses at the SMC-1 outlet for the 2000–2002 period (Fig. 1). Sediment delivery ratios were set at 0.01 for forests and grasses, 0.05 for cropland, residential areas and rural developments, and 0.08 for agricultural fields within 30 m of streams or ditches. Improvements in the nitrate-N loss predictions were made by adjusting initial total nitrogen and nitrate-N 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-N discharges for the calibration period. The index of agreement d is a measure of the degree to which the predicted variation precisely estimates the observed variation. The value of d is unity when there is a perfect agreement between predicted and observed values. Validation of the model involved predicting flow and nitrate-N losses without changing the values of input parameters obtained by calibration. For validation, the calibrated model was applied to the SMC-1 for the 2003–2004. A second independent validation of the model was carried out by applying the calibrated SMC-1 model to the SMC-2 sub-basin from 2000 to 2004 (Fig. 1).

2.5. Nitrogen fertilizer application rate and timing

Long-term simulations (1955–2004) were performed with the ADAPT model to investigate the effects of variation in the rate and timing of fertilizer application on nitrate-N losses under different climatic conditions. Input parameters used in the simulations for evaluating various practices were the same as those used in the model calibration. Combinations of four N application rates [112 (100), 134.5 (120), 157 (140), and 179.3 (160) kg/ha (lb/ac)] and three application timings (fall, spring and split—50% in fall and 50% in spring) were used for this purpose. In this analysis, the tile drain spacing was held constant at 24 m and tile drain depth was held constant at 1.2 m.

2.6. Manure management

Ten percent of the study area (356-ha) received nitrogen through manure application in addition to the inorganic fertilizer application. The rate of manure application was 154 kg/ha and was mostly in form of dairy liquid slurry. Simulations were conducted to predict improvements in water quality due to reduction in rate of manure application on the existing manure spread areas. Three application rates—132, 88, and 44 kg/ha were compared with an existing baseline application rate of 154 kg/ha.

3. Results and discussion

3.1. Model calibration

Table 3 shows good agreement between predicted and observed flow and nitrate-N losses during the calibration and validation periods. During calibration, attempts were made to minimize the RMSE and obtain r^2 and d values closest to value of unity. Overall, the model under predicted the mean monthly flow (0.38 m^3/s) by 26%. This is partly due to errors in predicting flow in May and June months of 2000 (Fig. 2) when most of the precipitation occurred at the end of May and beginning of June, and errors in predicting timing and magnitude of snowmelt during April 2001. In April 2001, 156 mm (51% above normal) of precipitation occurred on frozen soil causing intense runoff (~5 m^3/s). Ditch culverts and tile drain outlets were filled with ice at the onset of this process, causing water to pond in fields. Only after the ice melted did the ponded water leave the fields, causing sudden and intense flooding in the streams and ditches. The ADAPT model may miss the onset of soil freeze/thaw during periods when temperatures are close to 0 °C and does not account for ice blockages in culverts and at drain outlets. This caused errors in predicting the magnitude and timing of runoff and tile drainage in the month of April 2001.

In cold climates where soil freeze/thaw occurs, fall soil moisture recharge and climatic conditions during the transition from winter to spring (snowmelt period) determine the timing and magnitude of spring tile drainage (Sands et al., 2003). Little, if any, subsurface drainage occurs during the winter season, while considerable subsurface drainage may occur during late March through June.

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Table 3
Model performance statistics for predicted monthly flow and nitrate-N losses during calibration and validation years.

Statistics		Calibration on SMC-1 sub-basin		Validation on SMC-1 sub-basin		Validation on SMC-2 sub-basin	
		Flow (m^3/s)	NO_3-N (kg/ha)	Flow (m^3/s)	NO_3-N (kg/ha)	Flow (m^3/s)	NO_3-N (kg/ha)
Mean	Observed	0.48	3.77	0.18	1.37	0.18	1.37
	Predicted	0.38	4.04	0.29	2.93	0.28	2.93
RMSE		0.37	3.98	0.17	2.14	0.15	2.14
r^2 (unit less)		0.81	0.70	0.85	0.78	0.89	0.78
Slope		0.71	0.81	1.01	1.15	1.09	1.15
Intercept		0.05	0.99	0.11	1.36	0.09	1.36
d (unit less)		0.88	0.88	0.93	0.81	0.95	0.99

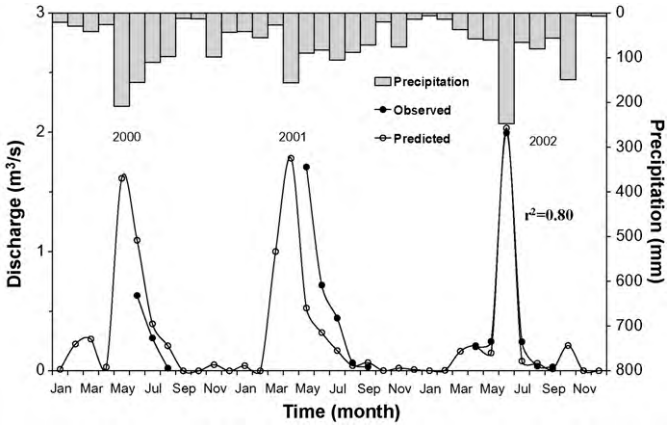

Fig. 2. Comparison between predicted and observed monthly discharge for SMC-1 during the calibration period.

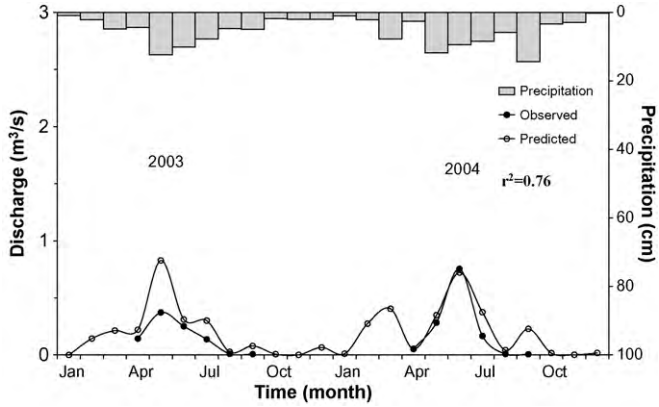

Fig. 4. Comparison between predicted and observed monthly discharge during validation on the SMC-1 sub-basin.

Average daily temperatures from December to March in 2000–2004 were below or close to 0 °C at the weather station. During this period, for days on which the average daily temperature was a few degrees below 0 °C, the daily maximum temperature was usually above 0 °C. Typically during this period, snow that melts during the daytime refreezes when the temperature drops in the evening, producing little surface runoff and infiltration. But since ADAPT input data includes a single average daily air temperature value for snow freeze/thaw calculation, the soil freeze/thaw condition is not precisely computed for such periods. This creates inaccuracies in partitioning of drainage between subsurface flow and surface runoff during snowmelt in early spring.

Fig. 3 illustrates the relationship between predicted and observed monthly nitrate-N losses for the calibration period. The predicted mean monthly nitrate-N losses were in close agreement with the measured data, as in the case of flow. The predicted losses were 7% higher than the observed. Statistical evaluation of the observed and predicted nitrate-N losses gave an r^2 value of 0.7, with a slope and intercept of 0.81 and 0.99, respectively. Errors in the prediction of nitrate-N losses are primarily due to partitioning of flow between subsurface drainage and surface runoff during the snowmelt period.

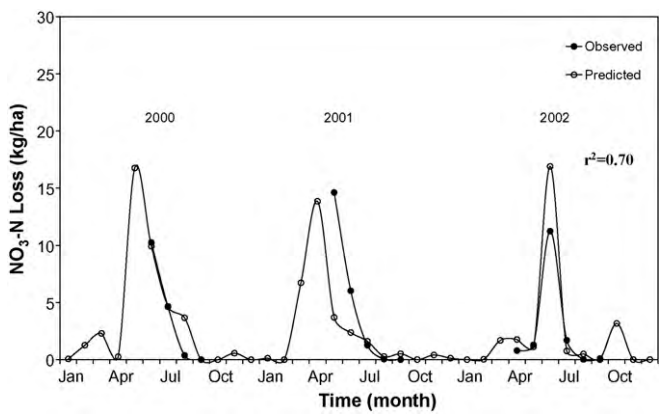

Fig. 3. Comparison between predicted and observed monthly nitrate-N losses in SMC-1 during the calibration period.

3.2. Model validation

Fig. 4 illustrates the relationship between predicted and measured monthly subsurface tile drainage in the validation period for the SMC-1. During 2003–2004, the SMC-1 received significantly less precipitation compared to the calibration period (2000–2002). In contrast to the calibration period, the model over-predicted total subsurface tile drainage. The comparison of predicted and measured monthly subsurface tile drainage gave an r^2 value of 0.85, with a slope and intercept of 1.01 and 0.11 m^3/s, respectively. The index of agreement (*d*) was about 0.93. Differences in the statistical results between calibration and validation periods are partly due to very large rainfall events that occurred in the wettest years of 2000 and 2001.

Fig. 5 illustrates the relationship between predicted and measured monthly nitrate-N losses for the validation period. The model over predicted nitrate-N losses. This over prediction was primarily due to errors in partitioning the drainage flow between subsurface drainage and surface runoff during the snowmelt period. The ADAPT over predicted subsurface drainage and under predicted surface runoff. The subsurface drainage is a major carrier of nitrate and consequently caused more nitrate-N losses compared to the observed.

A second validation of the ADAPT model was carried out on the SMC-2 sub-basin. Figs. 6 and 7 compare the monthly subsurface drainage associated nitrate-N losses from the SMC-2 sub-basin with the observed data. The calibrated model was compared with five years of observed data from SMC-2. For monthly flow, the r^2

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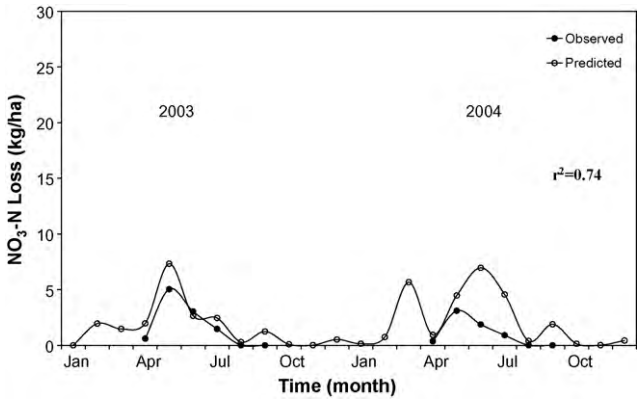

Fig. 5. Comparison between predicted and observed monthly nitrate-N losses during validation on SMC-1 sub-basin.

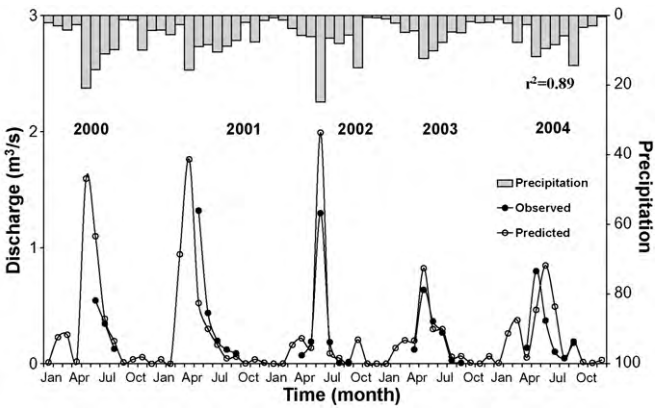

Fig. 6. Comparison between predicted and observed monthly discharge during validation on the SMC-2 sub-basin.

improved from 0.85 to 0.89 compared to SMC-1. This could be result from offset of the poor match in 2001 by better matches in the remaining four years. Similar to results in SMC-1, inability to simulate ice blockage and snowmelt in SMC-2 caused large errors in the spring of 2001.

The r^2 for monthly nitrate-N losses was the same as in the calibration period. The predicted mean monthly nitrate-N losses were 2.93 kg/ha, with an RMSE of 2.14 kg/ha and an index of agreement (d) of 0.99 for validation on the SMC-2, compared to 1.37 kg/ha, 3.98 kg/ha and 0.88 for the calibration period, respectively. Moreover, for 2002 there was a better match between observed and

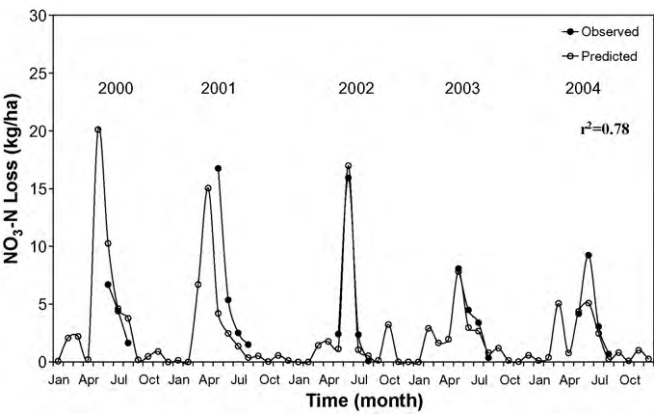

Fig. 7. Comparison between predicted and observed monthly nitrate-N losses during validation on the SMC-2 sub-basin.

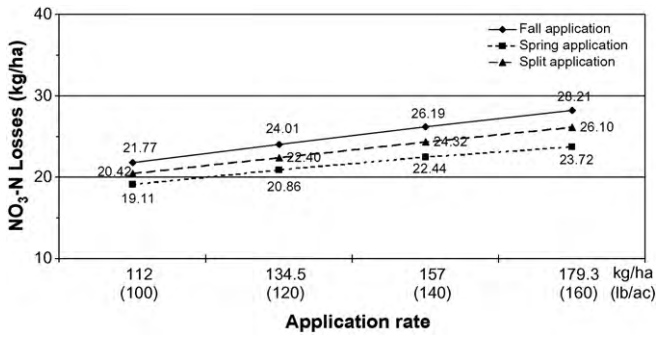

Fig. 8. Comparison of predicted annual nitrate-N losses for changes in the N application rate and timing in SMC-1.

predicted nitrate-N losses compared to observed and predicted monthly flow. This is probably because the model over predicted surface runoff, but correctly predicted subsurface drainage flows.

3.3. Nitrogen application rate and timing

Fig. 8 illustrates the long-term (1955–2004) simulated nitrate-N losses for four different application rates and three different timings. The curves indicate that nitrate-N losses increase as N application rate increased. For example, the nitrate-N losses associated with fall N application rates of 112, 134.5, 157, and 179.3 kg/ha were 21.8, 24, 26.2, and 28.2 kg/ha, respectively. Comparison of predicted annual nitrate-N losses indicated that losses can be reduced by 17%, by reducing N application rates from 157 to 112 kg/ha, a 28% decrease.

Fig. 8 illustrates the long-term annual nitrate-N losses for three different application timings. For an application rate of 154 kg/ha, a 14.3% reduction in nitrate-N losses was achieved by changing N application timing from fall to spring. Similar reductions in nitrate-N losses were found with other application rates. Among twenty-five N-fertilizer management scenarios, the smallest nitrate-N losses were found with spring N application followed by split N application timing.

3.4. Manure management

Simulations were conducted to predict nitrate-N loss reductions if manure application rates were reduced from the existing 154 kg/ha to 132, 88, and 44 kg/ha. Fig. 9 compares losses from each of these three application rates with the baseline existing application rate of 154 kg/ha. Reducing application rates from 154 kg/ha to 132, 88, or 44 kg/ha reduces nitrate-N losses by 0.42, 1.06, or 1.92%, respectively. The area receiving manure was only 10% (356 ha) of the entire watershed area, whereas the predicted losses reported

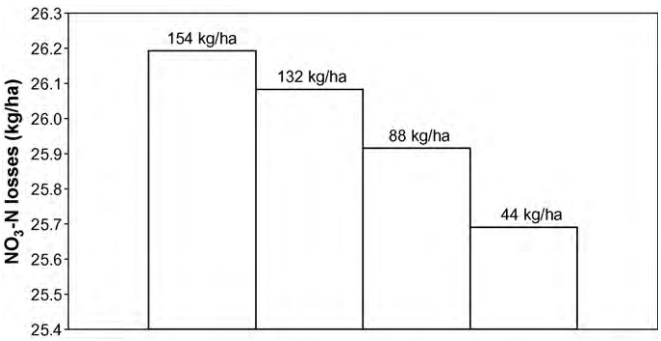

Fig. 9. Changes in NO_3-N losses from the watershed due to changes in manure application rates.

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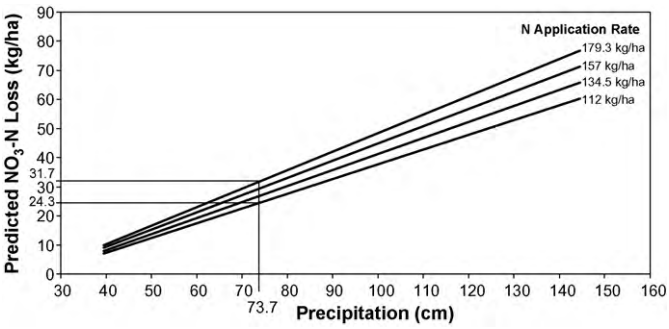

Fig. 10. Regression lines showing the relationship between predicted nitrate-N losses in SMC-1 and annual precipitation for a range of N application rates. Number adjacent to each line is the N application rate.

are from the entire watershed. Reducing manure application rates on a small portion of the watershed generated only small improvements (<2%) in overall water quality of the study area.

3.5. Climatic variability

Fig. 10 shows the regression lines for the relationship between N application rates and nitrate-N losses in SMC-1 at a fixed tile drain spacing and depth of 24 and 1.2 m, respectively. As expected, the predicted nitrate-N losses in wet years were much greater than in dry years for a given rate of applied N, and the magnitude of nitrate-N losses increased as the nitrate-N application rate increased. In dry years, nitrate-N losses through subsurface tile drainage were quite low for all N application rates, because of a lack of precipitation to drive nitrate-N leaching. During years with normal precipitation (737 mm), nitrate-N losses were reduced from about 31.7 kg/ha to about 24.3 kg/ha (23.3% reduction) when N fertilizer application rates were reduced from 179.3 to 112 kg/ha. These reductions in nitrate-N losses could be nearly offset if annual precipitation were to increase by 25% (Fig. 10), suggesting that an increasingly wetter climate in the Upper Midwest would make it difficult to meet both production and environmental goals using N fertilizer management strategies alone.

4. Conclusions

The ADAPT model was calibrated and validated for flow and nitrate-N losses in south-central Minnesota for the period from 2000 to 2004. The predicted flow and associated nitrate-N losses agreed reasonably with the measured trends for both calibration (r^2 = 0.81 and 0.70 for flow and nitrate-N losses, respectively) and validation (r^2 = 0.85 and 0.78 for flow and nitrate-N losses from SMC-1, and 0.89 and 0.78 for flow and nitrate-N losses from SMC-2, respectively) periods. The model performed less satisfactorily for the snowmelt periods than it did for the entire period.

The predicted annual nitrate-N losses were sensitive to N application rates. A decrease in the fall N application rate from 179.3 to 112 kg/ha decreased nitrate-N losses by 23%. Spring application produced the smallest losses for all application rates. By changing application timing from fall to spring at a rate of 112 kg/ha, nitrate losses decreased by a further 12%. The predicted long-term nitrate-N losses show a linear response to precipitation, and larger losses are generally associated with wet years.

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