Precipitation Changes Impact Stream Discharge, Nitrate–Nitrogen Load More Than Agricultural Management Changes

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Nitrate–N losses to surface waters in the Upper Midwest of the Untied States have increased in recent decades, contributing to hypoxia in the Gulf of Mexico. This paper investigates whether increasing nitrate–N export from cropland in the Upper Midwest since the late 1960s results from changes in land use or climate. The Agricultural Drainage and Pesticide Transport (ADAPT) Model simulated current and historical agricultural systems under past and recent wet climate for Seven Mile Creek in Minnesota. Simulations were run with management and climate for three distinctly different periods—namely, 1965 to 1969, 1976 to 1980, and 1999 to 2003 (wettest period). Results showed discharge and nitrate–N losses responded more to changes in climate than management. The wetter period (1999–2003) caused a simulated 70% increase in discharge under 1960s-era management compared with that period's observed climate and a simulated 51% increase in discharge under 1970s-era management compared with the 1976 to 1980 climate. The recent, wetter climate also produced a 62% increase in nitrate–N losses for 1960s-era management compared with the actual climate and a 137% increase in nitrate–N losses for 1978 management conditions compared with actual 1970s climate. Had recent climate been in place and stable since 1965, agricultural changes would have decreased discharge by 6.4% through the late 1970s and then by another 21.1% under modern management but would have increased nitrate–N losses by 184% through the late 1970s and then decreased nitrate–N losses by 13.5% between 1978 and 2001. Management changes that were important drivers included increasing N-fertilizer rates, increases in corn acreage, and increases in crop yield. But the most important factor driving increased nitrate–N losses from agriculture since the 1970s was an increasingly wetter climate.

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J. Environ. Qual. 39:2063–2071 (2010)
doi:10.2134/jeq2010.0105
Published online 29 Sept. 2010.
Received 10 Mar. 2010.
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Global Circulation Model studies predict increased temperature and changes in precipitation around the world (Schneider et al., 1990; IPCC 1996a,b). Northern Hemisphere mid- and high-latitude regions have experienced increasing precipitation during autumn and winter (Folland et al., 2001) accompanied by increasingly heavy and extreme precipitation events (Karl and Knight, 1998), and an overall increase in temperatures. Groisman et al. (2001) showed that annual precipitation in the Upper Mississippi River Basin over the last 100 yr has increased 10 to 40%, with a 10% increase in heavy summer (April through July) precipitation events having greater than 102 mm of rain. Precipitation increases in Minnesota are generally greater than for the rest of the Upper Mississippi River Basin and range from 20 to 40%.

The export of nitrate–N by the Mississippi River to the Gulf of Mexico has tripled since the 1950s (Goolsby and Battaglin, 2000; Mulla, 2008), contributing to an increase in the extent of hypoxia in the Gulf of Mexico. The Upper Midwest contributes disproportionately, as it covers 18% of the Mississippi River Basin but accounts for 35% of the nitrate–N export to the Gulf of Mexico (Goolsby et al., 1999). This region is characterized by extensive row-crop agriculture, deep soils rich in organic matter, high rates of nitrogen applications from fertilizer, extensive networks of artificial subsurface drainage, and intense rainstorms from April through July. All of these factors combined explain the disproportionate nitrate–N loads originating in the Upper Mississippi River Basin.

Many researchers have predicted the effect of future climate changes on crop production using a combination of field studies and models (Thompson, 1986,1988; Hanratty and Stefan, 1998; Brumbelow and Georgakakos, 2001; Lobell and Asner, 2003). A few field studies have measured changes in drainage and nitrate–N losses as influenced by precipitation (Randall and Iragavarapu, 1995; Weed and Kanwar, 1996; Randall et al., 1997; Randall, 1998; Randall and Mulla, 2001). Donner et al. (2004) investigated the effects of changing climate, fertilizer application rates,

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Abbreviations: ADAPT Model, Agricultural Drainage and Pesticide Transport Model; DIN, dissolved inorganic nitrogen; GIS, geographic information system; LAI, leaf area indices.

and crop rotation on nitrate–N export by the Mississippi River. Donner and Kucharik (2003) used models to investigate the role of climate variability, land cover, and N-fertilizer application on crop yield, N cycling, and nitrate–N export in the Upper Mississippi Basin from 1974–1994. The model indicated a 30% increase in N-fertilizer application across the basin would have caused only a 4% increase in mean maize yield but a 53% increase in mean dissolved inorganic nitrogen (DIN) leaching, whereas a 30% decrease in N-fertilizer application would have caused a 10% decrease in maize yield but a 37% decrease in DIN leaching. McIsaac and Libra (2003) found that the annual nitrate–N flux by the Mississippi River from 1960–1999 was related to annual streamflow and the net anthropogenic input of N to the river basin over the previous 2 to 9 yr. Hatfield et al. (2009) studied nitrate–N export to the Raccoon River Basin in relation to agricultural practices. The historical database of nitrate–N concentrations sampled at the Des Moines Water Works were combined with observations on N-fertilizer use, animal production, crop yields, land-use changes, and precipitation patterns to evaluate these interrelationships. They found that comprehensive changes in agricultural management practices are needed to improve water quality, rather than only changing fertilizer rate or timing. Lucey and Goolsby (1993) studied the excess nitrate–N concentration at public water supply intakes on the Des Moines and Raccoon rivers in Iowa. They found that substantial quantities of nitrate–N were being leached from the soil and transported by subsurface flow during the early 1990s. Schilling et al. (2008) used the SWAT Model to evaluate potential impacts from future land use and land cover change on the annual and seasonal water balance of the Raccoon River Watershed in West Central Iowa. Zhao et al. (2000) used DRAINMOD–N Model to evaluate the long-term, field-scale effect of N application rate and drain spacing on corn (*Zea mays* L.) yield and nitrate–N losses from a moderately well-drained Normania clay loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) soil under continuous corn in southwest Minnesota. However, no studies have attempted to separate the impacts of changing agricultural management practices from increasing precipitation on nitrate–N losses in the Midwest Cornbelt states. This study investigates the effect of changing agricultural management practices and an increasingly wetter climate over the past 40 yr on stream discharge and nitrate–N loadings to surface waters for an agricultural watershed in South Central Minnesota. The uniqueness of this study is in evaluating the impacts of a wide range of management practices relative to climate change. Also, the selected watershed has experienced larger increases in the extent of tile drainage than watersheds in Iowa, which were more extensively tiled at earlier time periods.

Materials and Methods

We used the Agricultural Drainage and Pesticide Transport (ADAPT) (Chung et al., 1992) Model for this study. It was selected because it explicitly accounts for all management changes that took place in the watershed, including changes in density of tile drainage. The model has been calibrated and used extensively in the Upper Midwest for studying the effects of agriculture on drainage water quality (Davis et al., 2000; Dalzell et al., 2004; Nangia, 2005, Gowda et al., 2007; Nangia et al., 2008, 2010a,b). The model was calibrated and validated for monthly discharge and associated nitrate–N losses in two subbasins [SMC–1 (4029 ha) and SMC–2 (3690-ha)] of the Seven Mile Creek Watershed (Fig. 1) in south-central Minnesota from 2000 to 2004. The SMC–1 and SMC–2 watersheds are monitored for flow on a daily basis. Grab samples were collected for agrichemical analysis approximately 18 times a year during the growing season (April through September). Topography of the watersheds is relatively flat, with an average slope of 2.3%. Soils in Seven Mile Creek are primarily clay loam Mollisols formed in glacial till under prairie grass. Soils (Clarion–Webster–Glencoe Association) are rich in organic matter and extensively drained with subsurface tiles. Agriculture is the predominant land use in both watersheds with 88% and 85% of the area under cultivation in SMC–1 and SMC–2, respectively. Soil properties required by ADAPT include soil-water release curve data, drained volume, and upward flux vs. depth, infiltration parameters, and saturated vertical and horizontal hydraulic conductivities. These data were derived from NRCS, Map Unit Use File 2.14 database (Baumer et al., 1987). Table 1 presents soil properties used in the model simulations. These parameters were held constant for all simulations, unless otherwise stated.

The ADAPT Model was calibrated for two space and time datasets, making it robust and reliable in making hypothetical runs. It was calibrated using 2000–2002 data for SMC–1 watershed and validated twice, first with 2003–2004 data for SMC–1 and then with 2000–2004 data for the SMC–2 watershed. Statistical measures such as mean and root mean squared error (RMSE), coefficient of determination (r^2), and slope and intercept of the least square regression line between measured and predicted values were used to evaluate the match between measured and predicted flow and nitrate–N discharges for the calibration period. In addition, an index of agreement (d): was used to evaluate the match between measured and predicted flow and nitrate–N discharges for the calibration period. The d value is a measure of the degree to which the predicted variation precisely estimates the observation variation, and d is equal to one for perfect agreement. Validation of the model involved predicting flow and nitrate–N losses without changing the values of input parameters obtained by calibration. Using this calibrated model, we wanted to determine the relative impact of changes in agricultural management practices vs. the impact of increasing precipitation on river discharge and nitrate–N losses over the past 40 yr.

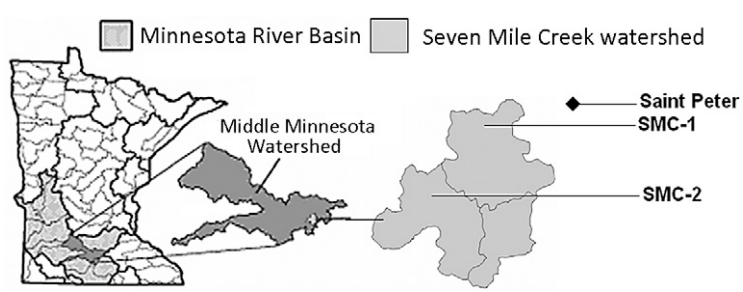

Fig. 1. Location of watershed-scale study site in the Minnesota River Basin.

Crop rotations and agricultural management practices in the study area differ from those in the past. Kuehner (2004) used Farm Service Agency and NRCS records to document historical changes in the percentage of cropland planted to corn, soybean [*Glycine max* (L.) Merr.], small grains, alfalfa (*Medicago sativa* L.), and grass or forest. Kuehner (2004) used historic aerial photos along with a geographic information system (GIS) to assess these changes. The photos were rectified using a bilinear or 1.5-order polynomial transformation method with a minimum of 5 to 10 ground control points to maintain a root mean squared error ≤ 0.7. The results of this study were used to estimate crop rotation and the percent coverage of different crops in three representative time periods, namely 1967, 1978, and 2001 (Table 2). Relatively short growing season crops, such as soybeans, were not grown very extensively during the 1960s. Alfalfa transpired more water than the corn and soybean crops. Alfalfa and soybean crops provided nitrogen fixation, thus replenishing the soil naturally and allowing reduced reliance on inorganic fertilizers. For the corn–small grain rotation, wheat was considered the small grain crop grown in the study area. Kuehner (2004) suggests that small grain crops grown in the past were a mix of wheat, oats, and barley.

Fertilizer application rates and timings have changed in the past 40 yr (Goolsby and Battaglin, 2000). Nitrogen fertilizer sold in the Mississippi River Basin was used to estimate the percent change in application rate over the past 40 yr (Table 3). These estimates were derived from Golsby and Battaglin (2000).

Crop yields have increased dramatically during the past 40 yr. Lower yields in the past 40 yr were simulated by reducing leaf area indices (LAI) of crops in proportion with measured reductions in crop yield going back in time (i.e., hindcasting) (Table 4). By adjusting LAI, crop water uptake was reduced, leading to decreased evapotranspiration.

Table 1. Values used for representing soil properties and subsurface drainage systems in the watershed.

Input variable	Value
Soil Conservation Service curve no. (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† (cm)	15
Surface storage depth (cm)	2
Depth of impermeable layer (m)	6.4
Drain spacing (m)	24
Depth of drains (m)	1.2

† Surface sealing threshold: a rainfall greater than this value will increase the curve number and surface runoff.

Table 2. Changes in crop rotations from 1967–2001.

Crop rotation	Period		
	1967	1978	2001
	Area (% of cropland)		
Alfalfa–corn–small grains	39	18	6
Corn–soybean	44	66	94
Corn–small grain	4	10	–
Corn–corn	13	6	–
Small grain–small grain	–	–	–

The anhydrous ammonia form of N fertilizer has decreased in popularity relative to urea over the last 40 yr (Randall, personal communication, 2005; Table 5), but it is still the dominant form (Randall and Iragavarapu, 2005). Anhydrous ammonia was assumed to be injected in the fall and urea was assumed to be broadcast in the spring.

Kuehner (2004) used historical aerial photographs and GIS for estimating land use percentages during the simulation periods. Table 6 illustrates the changes in percentages of land use in five categories. There are three large lakes in the SMC–1 and SMC–2 subbasins. They have remained unchanged since 1967. Wetland area has been reduced significantly and was mostly replaced with agricultural cropland. There have been minor reductions in forest and pasture land use.

U.S. National Weather Service measurements of daily precipitation and average air temperature at St. Peter, MN (8 km east of the Seven Mile Creek watershed, Fig. 1), were used as model input. The reason for choosing St. Peter precipitation records was that the station was nearest to the watershed and gave the best calibration and validation statistics. Two climatic scenarios were simulated for the three time periods (1967, 1978, and 2003), corresponding with three different land management combinations. The first scenario was to simulate discharge and water quality using 5 yr of actual climatic data observed at these three times. The second scenario was to simulate discharge and water quality for the three different land management combinations, using the same 5-yr record

Table 3. Changes in rate of N–fertilizer application from 1967 to 2001.

Crop	Period		
	1967	1978	2001
	N-fertilizer application rate (kg ha^{-1})		
Small grain (wheat)	28.6	68.6	80
Corn	56	135	157

Table 4. Changes in crop yield as a percentage of 2001 yields.

Period	Yield (% of 2001 yields)
1967	64
1978	71
2001	100

Table 5. Changes in use of urea and anhydrous ammonia from 1967 to 2001.

N fertilizer	Period		
	1967	1978	2001
	%		
Anhydrous ammonia	99	90	81
Urea	1	10	19

Table 6. Comparison of changes in land use from 1967–2001.

Land use	Area		
	1967	1978	2001
	%		
Forest	6.4	6.3	6.3
Pasture	4.3	2.9	3.5
Wetlands	3.8	0.5	0.0
Lakes	5.5	5.5	5.5
Agriculture	80.0	84.8	84.7

of actual climatic data from 1999 to 2003. The first scenario simulates actual discharge and water quality for the three management combination time periods and is used to identify temporal trends in discharge and water quality, resulting from a combination of changes in both climate and management effects. The second scenario gives discharge and water quality for the three management combinations using identical, recent climatic records and is used to infer the temporal trends in discharge and water quality, resulting from only changes in management. The particular time periods were selected because of data availability and representation of major shifts in farm management practices.

Average precipitation during 1999 to 2003 was highest among the three periods with 650 mm during 1976 to 1980, 760 mm during 1965 to 1969, and 950 mm during 1999 to 2003 (Fig. 2).

The effect of various crop rotations on water quality for the study area was simulated for each time period. Weighted averages of the crop nitrate–N losses based on their planted area were used to estimate the total nitrate–N losses from the study area resulting from diverse cropping patterns. An average of the nitrate–N losses from cropland plus forest and grassland area was computed to estimate the total nitrate–N losses. These losses were compared with the baseline scenario (2003) for current land use data.

The baseline scenario represented most recent management and consisted of a fertilizer-N application rate of 154 kg/ha, 94% of cropland under a corn–soybean rotation, and 6% of cropland under an alfalfa–corn–small grain rotation. The baseline scenario also included subsurface tile spacings and depths of 27 m and 1.2 m, respectively. The LAI (Table 4) and N-fertilizer application rates (Table 5) were reduced for earlier years to account for lower values in the past. The tile drainage network in earlier years was also adjusted according to spacings common in the past. For the 1967 simulation, a spacing of 40 m was considered; for the 1978 and 2001 simulations, a spacing of 27 m was considered. These spacing values were based on information published in Wilson (2000), which was based on data from Lamberton, southwest Minnesota.

Results

Model Calibration

Table 7 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

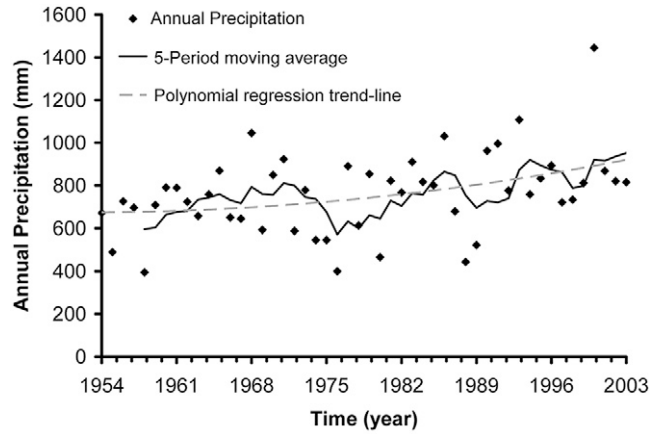

Fig. 2. Annual precipitation during 1954 to 2003 recorded at St. Peter weather station.

the RMSE and obtain r^2 and d values closest to value of unity. Overall, the model underpredicted the mean monthly flow (0.38m^3/s) by 26%. This is partly due to errors in predicting flow in May and June of 2000 (Fig. 3a) when most of the precipitation occurred at the end of May and beginning of June, and to 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, whereas considerable subsurface drainage may occur during late March through June. Average daily temperatures from December through 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 less than 0°C, the daily maximum temperature was usually more than 0°C. Typically during this

Table 7. Model performance statistics for predicted monthly flows and nitrate losses in Seven Mile Creek, MN, during calibration and validation years (2000–2004).

Statistics		Calibration on SMC–1		Validation on SMC–1		Validation on SMC–2	
		Flow	NO_3–N	Flow	NO_3–N	Flow	NO_3–N
		m^3 s^{-1}	kg ha^{-1}	m^3 s^{-1}	kg ha^{-1}	m^3 s^{-1}	kg ha^{-1}
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
Root mean squared error		0.37	3.98	0.17	2.14	0.15	2.14
r^2 (dimensionless)		0.80	0.70	0.76	0.74	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
Index of agreement (d)		0.88	0.88	0.93	0.81	0.95	0.99

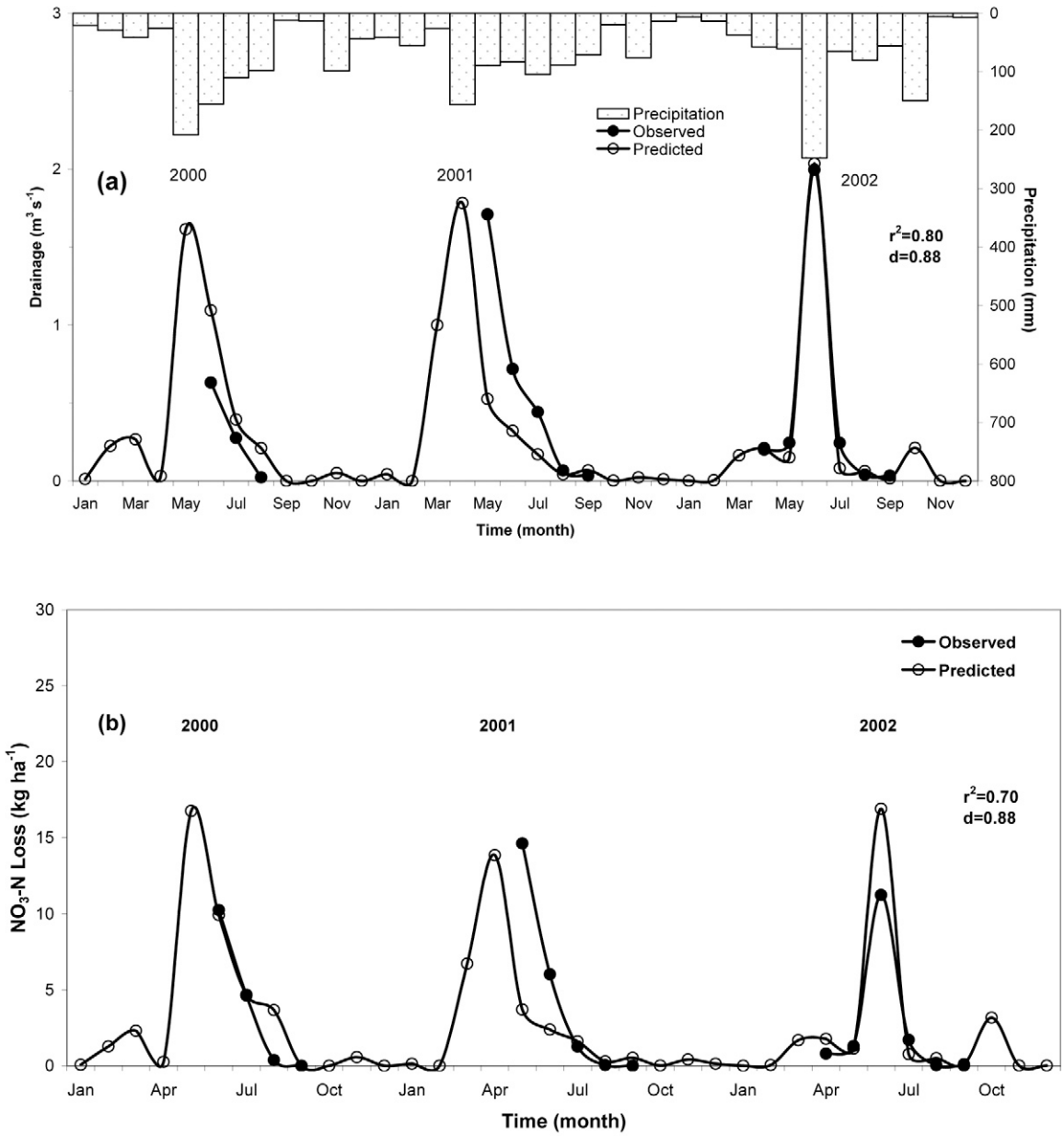

Fig. 3. Comparison between predicted and observed (a) monthly discharge and (b) nitrate–N losses on SMC–1 watershed during the calibration period.

period, snow that melt during the daytime refreezes when the temperature drops in the evening, producing little surface runoff and infiltration. But since ADAPT input data include 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.

Figure 3b 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 (Fig. 3a). The predicted losses were 7% more than the observed. Statistical evaluation of the observed and predicted nitrate–N losses gave an r^2 value of 0.70, 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.

Model Validation

Figure 4a illustrates the relationship between predicted and measured monthly subsurface tile drainage in the validation period for the SMC–1. During 2003 to 2004, the SMC–1 received significantly less precipitation compared with the calibration period (2000–2002). In contrast to the calibration period, the model overpredicted 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.

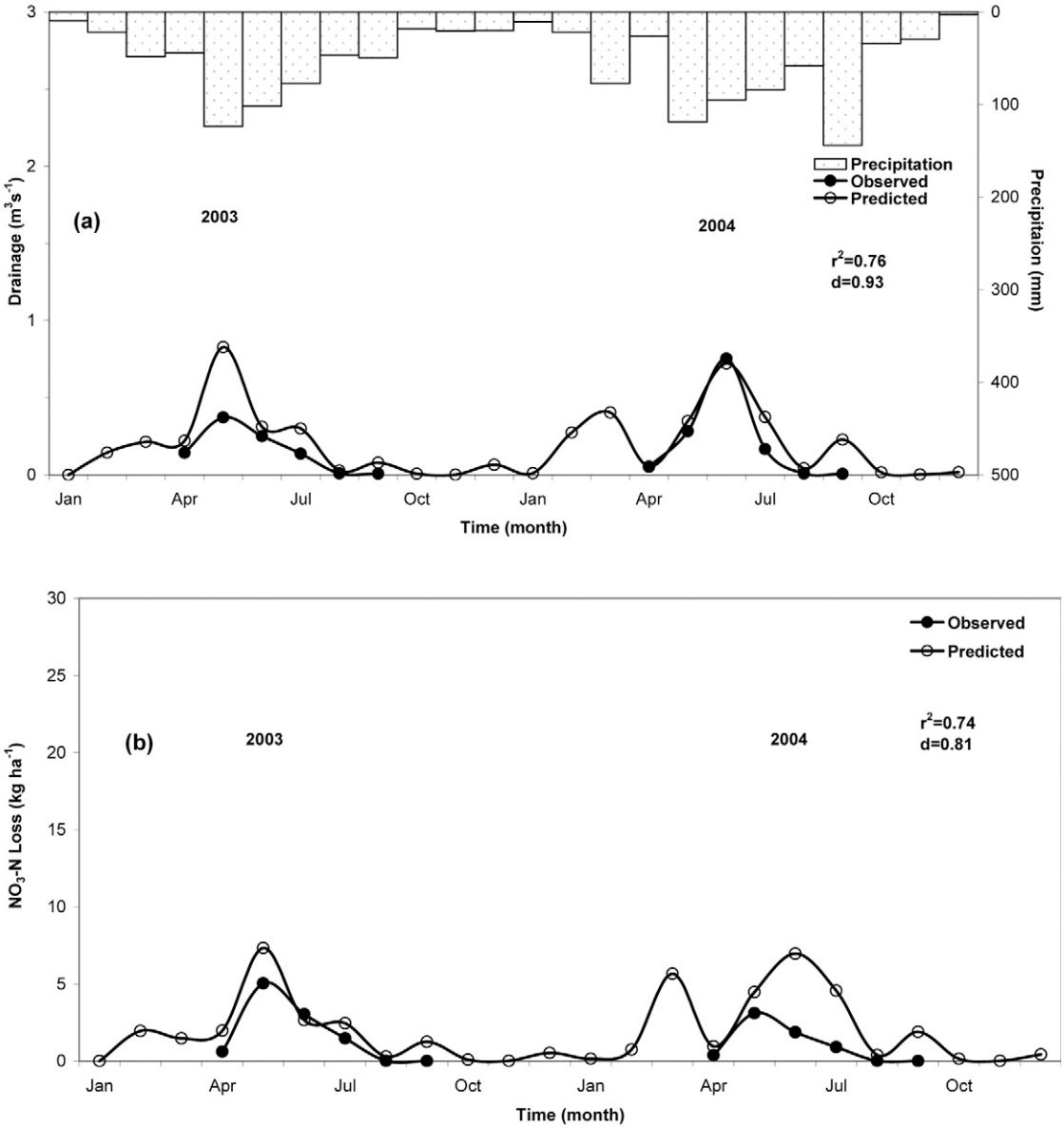

Fig. 4. Comparison between predicted and observed (a) monthly discharge and (b) nitrate–N losses during validation on the SMC–1 watershed.

Figure 4b illustrates the relationship between predicted and measured monthly nitrate–N losses for the validation period. The model overpredicted 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 Model overpredicted subsurface drainage and underpredicted surface runoff. Subsurface drainage is a major carrier of nitrate and consequently caused more nitrate–N losses compared with the observed.

A second validation of the ADAPT Model was performed on the SMC–2 subbasin. Figures 5a and 5b compare the monthly subsurface drainage and associated nitrate–N losses from the SMC–2 subbasin with the observed data. The calibrated model was compared with 5 yr of observed data from SMC–2. For monthly flow, the r^2 improved from 0.85 to 0.89, compared with SMC–1. This could result from offset of the poor match in 2001 by better matches in the remaining 4 yr. Similar to results in SMC–1, the 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 with 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 predicted nitrate–N losses compared with observed and predicted monthly flow. This is probably because the model overpredicted surface runoff but correctly predicted subsurface drainage flows. Results from the second validation were possibly better than those during calibration because more samples were used for computing agreement statistics during validation than calibration. Details of model calibration can be found in Nangia et al. (2010b).

Figure 6 shows discharge as a function of management in three different time periods (1967, 1978, and 2001) for actual climatic conditions vs. climatic conditions from 1999–2003 (recent climate scenario). Under actual climatic conditions, discharge increased by 6.9% (from 151.3 mm to 161.7 mm)

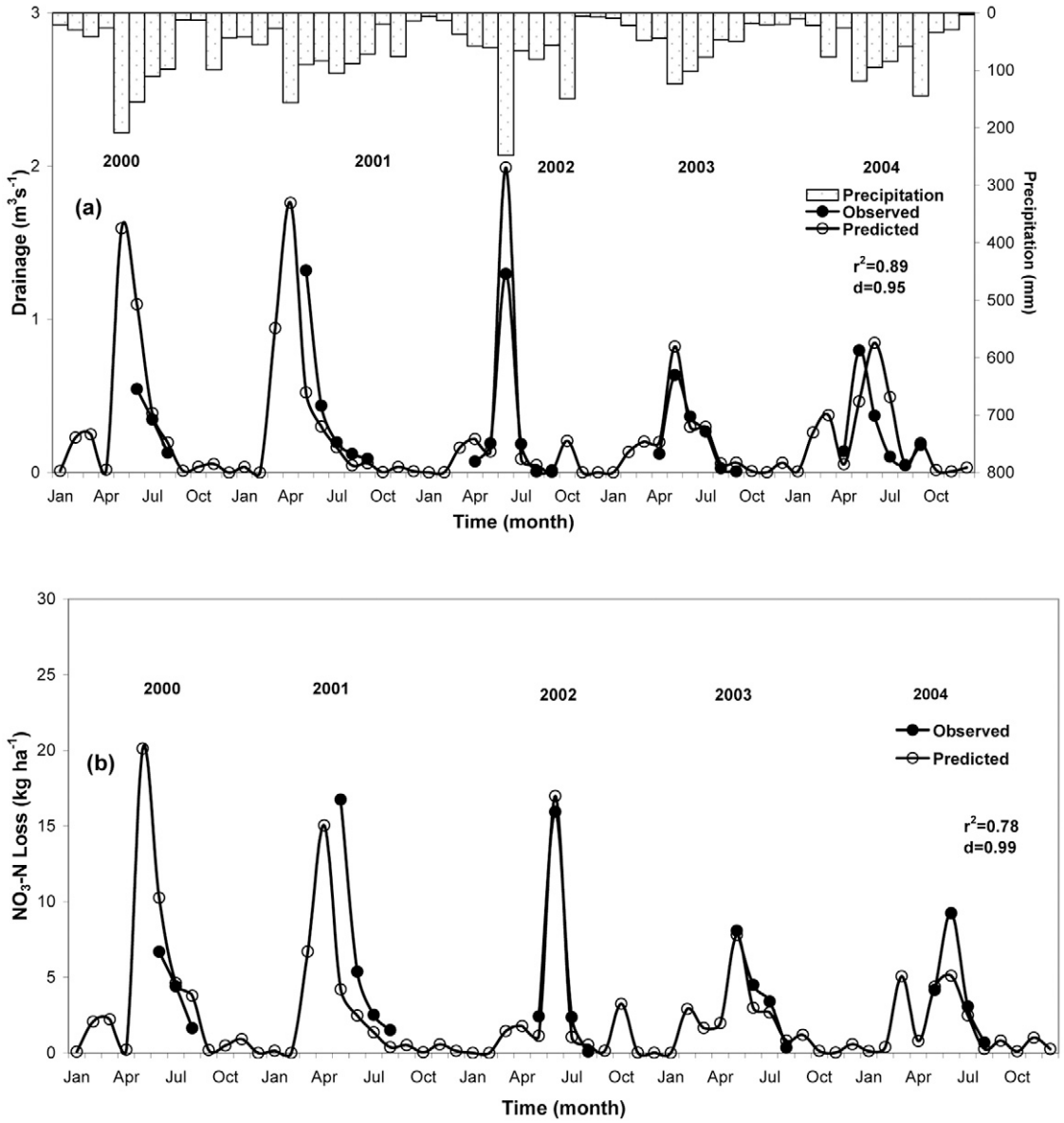

Fig. 5. Comparison between predicted and observed (a) monthly discharge and (b) nitrate–N losses during validation on the SMC–2 watershed.

from 1967 to 1978, and by 25.1% (from 161.7 mm to 191.2 mm) from 1967 to 2001. Increased discharge from 1978 to 2001 is due to several factors, including an increasingly wetter climate, increased intensity of tile drainage, and reductions in the area of perennial crops (Table 2).

Figure 6 also shows discharge as a function of management in three different time periods (1967, 1978, and 2001) for identical recent climatic conditions (1999–2003). In this scenario, discharges decreased by 4.7% (from 256.9 mm to 244.7 mm) from 1967 to 1978, and by 27.6% (from 244.7 mm to 191.8 mm) from 1967 to 2001. Decreased discharge from 1967 to 2001 is primarily due to large increases in crop yield and evapotranspiration (Table 4), with corresponding reductions in runoff and tile drainage. Effects of crop yield on discharge offset effects of increasing tile drainage intensity and loss of perennial cropland.

Figure 6 can also be used to infer the direct effects of an increasingly wetter climate for any specific management combination scenario. For example, if the management combination typical of 1967 had experienced the wetter recent climatic conditions of 1999 to 2003, discharge would have increased by 70% in comparison with actual discharge levels (151.2 mm vs. 256.9 mm). Similarly, for management conditions prevailing in 1978, discharge would have increased by 51.4% (161.7 mm vs. 244.7 mm) with the wetter recent climatic patterns of 1999 to 2003 in comparison with actual climatic effects typical of 1976–1980.

Figure 7 shows nitrate–N losses as a function of management in 1967, 1978, and 2003 for actual climatic conditions vs. recent wetter climatic conditions (1999–2003). Using actual climatic records, nitrate–N loads increased by 95% (from 50 to 97 Mg) between 1967 and 1978, and by 299% (from 50 to 199 Mg) between 1967 and 2001. These large increases are due to the effects of both an increasingly wetter climate (greater discharge shown in Fig. 6) and changes in agricultural management, including increasing rates of N fertilizer and increases in corn acreage. However, in terms of annual

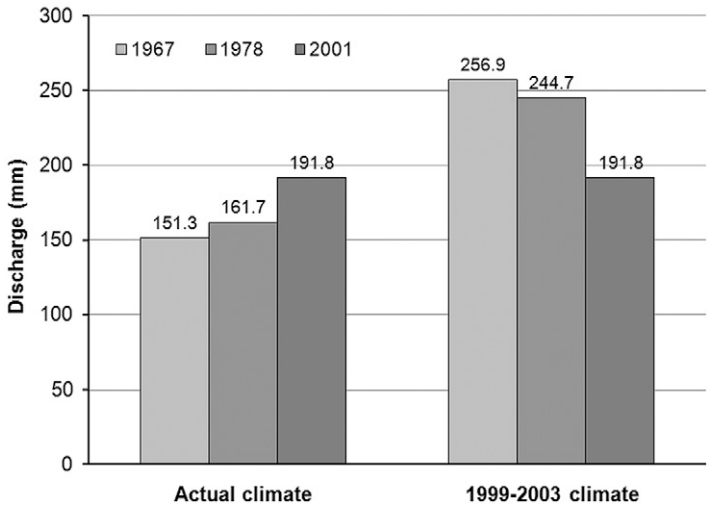

Fig. 6. Changes in discharges from the SMC–1 and SMC–2 subwatersheds of the Seven Mile Creek watershed with actual and recent (1999–2003) climatic patterns during the three time periods.

nitrate–N losses (Fig. 8), the values were 14.9, 13.9, and 27.7 kg N/ha for 1967, 1978, and 2001, respectively.

Using the recent and wetter climatic patterns of 1999 to 2003, nitrate–N losses increased by 184% (from 81 to 230 Mg) between 1967 and 1978, and by 146% (from 81 to 199 Mg) between 1967 and 2001 (Fig. 7). The large increases between 1967 and 1978 are due primarily to large increases in the rate of N-fertilizer applications (Table 3) and the increasing area devoted to corn production (Table 2). Between 1978 and 2001, nitrate–N losses were predicted to decrease by 13.5% using climatic records typical of 1999 to 2003. These decreases are attributable primarily to reduced discharge (Fig. 6) due to increasing crop yields (Table 4) and increases in crop evapotranspiration. However, in terms of annual nitrate–N losses (Fig. 8), the values were 24.2, 32.9, and 27.7 kg N/ha for 1967, 1978, and 2001, respectively.

The effects of climate on nitrate–N loss can be identified by comparing nitrate–N losses under actual climatic conditions with losses under 1999 to 2003 climatic conditions for 1967, 1978, or 2003. For 1967 management, nitrate–N losses increased by 62% (from 50 to 81 Mg) when 1965 to 1969 climatic patterns were compared with 1999 to 2003 climatic conditions (Fig. 7). For 1978 management, nitrate–N losses increased by 137% (from 97 to 230 Mg) for 1999 to 2003 climatic patterns in comparison with losses for 1976 to 1980 climatic patterns (Fig. 7). Thus, an increasingly wetter climate has a significant effect on nitrate–N losses.

According to United Nations Environment Programme, riverine nutrient flows to coastal regions affected by hypoxia have increased since the industrial revolution by 15-fold in North Sea watersheds, 11-fold in northeast U.S. watersheds, 10 fold in the Yellow River Basin, and sixfold in the Mississippi River Basin (UNEP, 2006). Most of these increases have been attributed to increased use of inorganic fertilizer. Our study shows that an increasingly wetter climate from 1967 to 2001 can explain a large part of the increased discharge and nutrient export from Upper Midwest watersheds. Increased nutrient export can also be explained by increases in the use of N fertilizer between 1967 and 1978.

Conclusions

The climate of the Northern Hemisphere has become wetter with more frequent instances of heavy rainfall events. The ADAPT Model was calibrated using monthly discharge and nitrate–N loss data for an agricultural watershed in South Central Minnesota. The calibrated model was used to isolate effects of precipitation trends on streamflow and nitrate–N losses. Streamflow and nitrate–N losses from the watershed have increased in response to an increasingly wetter climate over the past 40 yr. If the climate remained constant, discharges from the watershed would have been reduced due to significant improvements in crop yield. Under constant climatic conditions, nitrate–N losses would have increased between 1967 and 1978 and decreased between 1978 and 2001. This study points to the importance of climate change as well as changing agricultural practices on nitrate–N loadings to the Gulf of Mexico from the Mississippi River.

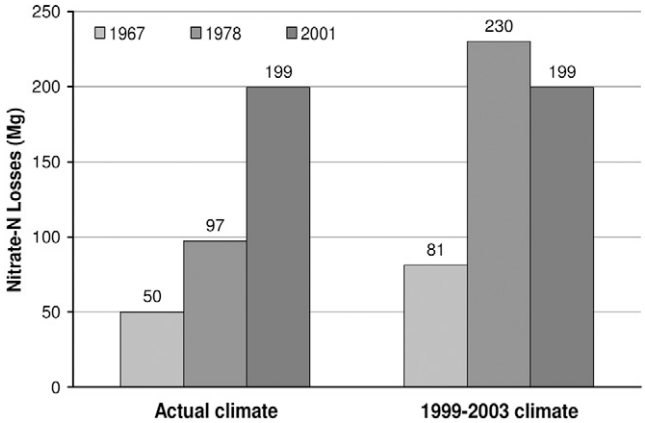

Fig. 7. Changes in nitrate losses (Tg) from the SMC–1 and SMC–2 subwatersheds of the Seven Mile Creek watershed with actual and recent (1999–2003) climatic patterns during the three time periods.

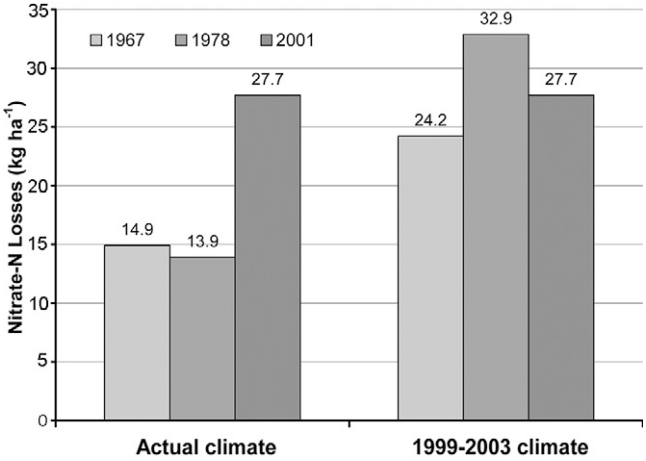

Fig. 8. Changes in nitrate losses (kg/ha/yr) from the SMC–1 and SMC–2 subwatersheds of the Seven Mile Creek watershed with actual and recent (1999–2003) climatic patterns during the three time periods.

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