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Evaluation of Predicted Long-term Water Quality Trends to Changes in N Fertilizer Management Practices for a Cold Climate

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Abstract. Objectives of this study were to calibrate and validate a water quality model for monthly flow and NO_3-N losses, and evaluate a set of alternative nutrient management practices to reduce NO_3-N losses in an agricultural watershed. A dynamic watershed scale spatial modeling approach that uses ADAPT, a field scale model and GIS was calibrated to predict monthly flow and NO_3-N losses from a sub-watershed of Seven Mile Creek in south-central Minnesota. It is a 4029-ha watershed with over 85% of the total area under agriculture. Calibration and validation of the model were done using monitoring data from 2000-2002 and 2003-2004, respectively. For the calibration period, the model predicted mean monthly flow and NO_3-N losses of 0.38 m^3/s and 4.04 kg/ha, respectively, against measured flow and NO_3-N losses of 0.48 m^3/s and 3.77 kg/ha, respectively. For the validation period, the predicted mean monthly flow and NO_3-N losses were 0.29 m^3/s and 2.93 kg/ha, respectively, against measured flow and NO_3-N losses of 0.18 m^3/s and 1.37 kg/ha, respectively. Long-term simulations were made for a wide range of climatic conditions between 1955 and 2004 to evaluate the effects of fertilizer management practices on the NO_3-N losses. A 35% reduction in NO_3-N losses was observed when application rate and timing were changed from a fall application of 179.3 kg/ha to a spring application of 112 kg/ha.

Keywords. Water quality, ADAPT, nutrient management, nitrate-nitrogen, modeling

Introduction

It is a cliché that fertilizer application is essential for sustaining food and fiber production. Additives such as NO_3-N (nitrate-nitrogen) improve crop yield, nevertheless, can be harmful to the environment. In addition to raising local water quality concerns, excess NO_3-N loads from Midwest U.S. agriculture are suspected as a primary contributor to hypoxia in the Gulf of Mexico. Over-application of fertilizer exacerbates the problem and is a major cause for NO_3-N loads in the Mississippi River Basin.

Higher NO_3-N losses are associated with higher N application rates (Baker and Johnson, 1981), and with fall versus spring application (Baker and Melvin, 1994). Weed and Kanwar (1996) demonstrated that the amount of NO_3-N found in the tile drainage from a loamy soil in Iowa was highly influenced by crop rotation, but not by tillage practice. This is mainly due to application rates of N fertilizer that are greater for grain crops than for legume crops. Randall *et al.* (2003) concluded in a study on tile-drained Canisteo clay loam soil that NO_3–N losses from a corn (*Zea mays* L.) -soybean [*Glycine max* (L.) Merr.] rotation through subsurface drainage can be reduced by 13 to 18% by either switching from fal to spring N application or using nitrapyrin with late-fall applied anhydrous ammonia.

A modeling study by Nangia *et al.* (2005) predicted a 12% reduction in NO_3–N losses for a tile drained Minnesota field in a corn-soybean rotation under conservation tillage after the application rate was changed from 180 kg N/ha to 135 Kg N/ha. A further 8% reduction was predicted when application timing was changed from fall to spring. Davis *et al.* (2000) investigated long-term (1915-1996) NO_3-N losses in subsurface drainage for Minnesota climatic conditions at a plot scale, using the ADAPT (Agricultural Drainage and Pesticide Transport) model, using a wide range of drain spacings, depths, and nitrogen fertilizer application rates. The predicted results indicated that NO_3-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 Webster clay loam soil at Waseca, southern Minnesota, Randall *et al.* (2001) predicted NO_3–N losses that increased by 84% when application rate was increased by 50% (from 200 to 300 kg N/ha).

NO_3-N loading in the surface water is a function of transport volume (amount of water) and NO_3-N concentration in the transported water. The amount of drainage water leaving the landscape is largely a function of climate and soil properties. Drainage is further influenced by the temporal distribution of precipitation within a particular year (Randall and Mulla, 2001). Precipitation and cropping system have the greatest impacts on NO_3-N losses from agricultural landscapes to surface waters. In the upper Midwest, about two-thirds of the annual drainage and NO_3-N loading occur in April, May, and June when evapotranspiration (ET) is low compared to precipitation (Randall, 2002). Goolsby *et al.* (1997) noted that the concentration and flux of NO_3-N tends to be highest in the spring when stream flow is highest. Annual tile drainage in a Minnesota study conducted from 1986 to 1992 on a Webster clay loam with continuous corn ranged from 26 to 618 mm/yr with an average of 297 mm (Randall and Iragavarapu, 1995). Drainage was least in 1989 when growing season precipitation was 35% below normal and greatest in 1991 when growing season precipitation was 51% above normal. A 6-yr study conducted on a Normania clay loam at Lamberton, MN showed no tile drainage in 1988 and 1989 when annual precipitation was 69 and 76% of normal, respectively (Randall *et al.*, 1997). Drainage under continuous corn and corn–soybean rotation averaged 22 mm in 1990, 223 mm in 1991, 143 mm in 1992, and 469 mm in 1993. Annual precipitation in those four years was 95, 125, 117, and 160% of normal, respectively. Data from these three studies clearly indicate the strong relationship between precipitation and volume of subsurface tile drainage.

Changes in management practices change the pattern of movement of drain flow and associated nutrient losses within the agricultural system. Therefore, adequate knowledge of the movement of nutrients under various management practices is essential for developing remedial measures needed to reduce nonpoint source pollution. Although, long term monitoring of various combinations of soil types and agricultural drainage practices provide valuable data for understanding their impacts on water quality, it is expensive and time consuming to conduct field experiments.

Substantial advances have been made during the past decade in using simulation models in the prediction of agricultural chemicals in the environment. These models help to estimate the time required for natural processes to remove chemicals already in the soil and groundwater, to predict the movement and persistence of chemicals in soil, and to predict the fate of agricultural chemicals to assist farmers in designing effective crop, soil, and chemical management strategies (Wagenet and Hutson, 1986). Models can aid in evaluating alternative rates and timing of chemical application, the use of alternative chemicals with different properties, and optimum management practices for soil, water, and chemicals. They have proved to be effective and efficient tools for water resource management decision support.

As a result, a wide variety of surface and subsurface water quality simulation models have been developed and are being used to evaluate impact of agricultural management practices on water quality. The main objectives of this study are to:

1. calibrate and validate a spatial-process water quality model for monthly tile drainage and associated NO_3-N losses, and
2. use the calibrated model to evaluate the long term effects of different N application rates and timings on NO_3-N losses under a wide range of climatic conditions in the Seven Mile Creek watershed sub-basin located in south-central Minnesota.

Material and Methods

Site Description and Water Quality Data

The calibration and validation of the model were performed using water quality measurements made by the Brown Nicollet Cottonwood Water Quality Board staff for the period 2000-2004. The study watershed is one of three sub-watersheds located in the eastern part of the Seven Mile Creek watershed (Fig. 1) in south-central Minnesota. Hereafter, the study watershed is referred to as SMC-1.

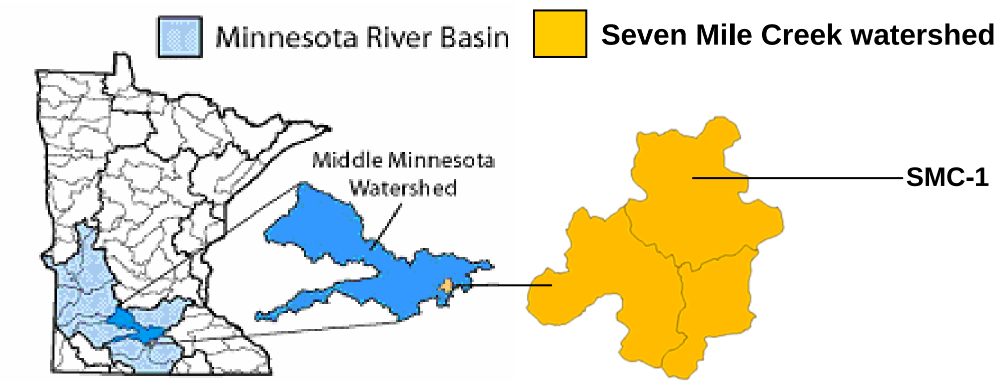

Figure1. Location of SMC-1 watershed in the Minnesota River Basin.

SMC-1 watershed is monitored for flow on a daily basis and grab samples are collected for agrichemical analysis approximately 18 times a year during the growing season (April-September). Topography of the watershed is relatively flat with an average slope of 2.3%. Soils are rich in organic matter and are poorly drained. The Clarion-Webster-Glencoe association predominates with Canisteo, Cordova and Webster soils occupying most of the landscape (50%), and 33 other soils comprising the rest. Agriculture is the predominant land-use in SMC-1 watershed (Table 1).

Table 1. Total area and land use in the watershed

Total area	4029-ha (9957-ac)
Land use	**Percent area**
Cultivated land	85.7
Deciduous forest	6.3
Wetland	2.7
Grassland	2.7
Farmstead and rural residence	1.8
Water	0.6
Other rural development	<0.1
Grassland-shrub-tree (deciduous)	<0.1
Exposed soil	<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 entire agricultural land. The other crops planted were sweet corn (3%), alfalfa (3%) and other (1%). Ninety-three percent of all field corn acres received commercial N fertilizer. Average fertilizer N rate across all field corn acres surveyed was 158 kg/ha (141 lb/ac). Eighty-one percent of all N applied to field 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%) or urea (18%). Liquid hog manure was injected on 880 acres of corn (10% of cultivated area) at a rate of 152 kg N/ha (136 lb N/ac). Sixty-nine percent of the cultivated area had less than 30% residue cover (conventional tillage). The fields planted to a corn-soybean rotation were chisel plowed in the fall after harvest and spring cultivated before planting.

ADAPT Model

The Agricultural Drainage and Pesticide Transport model (ADAPT) was developed by Alexander (1988) and improved by both Ward *et al.* (1988) and Schalk (1990) by incorporating the water balance algorithms of DRAINMOD, and the sediment, nutrient, and pesticide transport algorithms of GLEAMS (Leonard *et al.*, 1987). Soil freeze/thaw processes were recently added to the model (Dalzell, 2000). It has been calibrated for various hydrologic conditions in the Midwest (Desmond *et al.*, 1995; Gowda, 1996; Davis *et al*, 2000). The model has four components: hydrology, erosion, and nutrient and pesticide transport. The hydrology component consists of snowmelt, surface runoff, macropore flow, evapotranspiration, infiltration, subsurface drainage, subirrigation, and deep seepage. The weather input data required for ADAPT model simulation include daily values of rainfall, ambient temperature, wind speed, relative humidity, and solar radiation for the duration.

The snowmelt component in ADAPT is based on theory proposed by Anderson and Crawford (1964) and Viessman *et al.* (1989). Snowmelt water depth is computed as the summation of snowmelt due to radiation, rainfall, conduction, convection, and condensation (Chung *et al.*, 1992). A heat flow based model is used in ADAPT to predict the rate and depth of soil frost development and disappearance, based on procedures described in Benoit and Mostaghimi (1985). The model uses constant values for thermal conductivity, and heat capacity, and is driven by daily inputs of air temperature and snow depth. Further details of the ADAPT model are presented by Chung *et al.* (1992), Ward *et al.* (1993), and Desmond *et al.* (1996, 1998).

Model Inputs

For simplicity of model setup, 86% of the watershed area was considered as cultivated land with fields planted to a corn-soybean rotation. Land under grassland and grassland-shrub-tree (deciduous) categories were considered as the same land use. Farmstead and rural residence, other rural development, and exposed soil categories were also lumped together. Since they are small and on the periphery of the watershed, land use under wetland and water categories were ignored for this study. Eighty-one percent of all N applied was to field corn as a fall application and the rest was spring applied. N fertilizer was applied to corn in fall at a rate of 158 kg/ha (141 lb/ac) as anhydrous ammonia or in spring using broadcast urea. Liquid hog manure was injected on a 356-ha (880-ac) area at a rate of 152 kg N/ha. This was in addition to the fertilizer N applied throughout the corn fields.

Model simulations were made using climatic data from 2000-2004. Precipitation was measured on site using a tipping bucket rain gauge during the 2000-2003 growing season. 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 a weather station located inside 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.

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 (cm)	15
Surface storage depth (cm)	2
Depth of impermeable layer (m)	6.4
Drain spacing (m)	24
Depth of drains (m)	1.2

Our modeling methodology requires the study area to be divided into Hydrologic Response Units [HRUs; Gowda (1996)]. In the HRU formation process, spatial data layers of landscape slope, land use classification, manure spread areas adjacent to feedlots, areas within 100 feet of streams and ditches having higher delivery ratios, and soil type were overlaid using Arc View 3.0 GIS software. The result was a GIS layer consisting of 126 HRUs containing unique combinations of soil type and land use.

Model Calibration

The ADAPT model was calibrated using measured data during the growing season at the outlet of the SMC-1 watershed for 2000-2002. Model calibration and validation consisted of predicting and comparing monthly flow and NO_3-N losses with measured data during the monitoring period. Sediment delivery ratios of 0.01 for forests and grasses, 0.05 for croplands, residential areas and rural developments, and 0.08 for agricultural fields within 100 feet of streams or ditches were used in the model simulation. Improvements in the nitrogen 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 NO_3-N discharges for the calibration period. Validation of the model involved predicting flow and NO_3-N losses without changing the values of input parameters obtained by calibration. For validation, the calibrated model was applied to the watershed for 2003-2004 datasets.

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 N fertilizer application on NO_3-N losses. Input parameters used in the simulations for evaluating various practices were the same as those used in the model calibration. 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. The use of multiple application rates and timings was to demonstrate the sensitivity of nitrogen losses to variation in precipitation as the application rate and timing changed.

Results and Discussion

Objective One

Drainage Simulations during Snowmelt Periods

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 drainage (Sands *et al.*, 2003). Little, if any, subsurface drainage occurs during the winter season, while considerable drainage may occur during late March through June. Average daily temperatures from December to March in 2000-2004 were below or close to 0^oC at the weather station. During this period, for days in which the average daily temperature was a few degrees below 0^oC, the daily maximum temperature was usually above 0^oC. 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.

Model Calibration

Table 3 shows good agreement between model predictions and observed drainage and NO_3-N losses in tile drainage during the calibration and validation periods. In the calibration, attempts were made to minimize the RMSE and obtain r^2 and d values closest to a value of unity. Overall, the model under predicted the flow (0.38m^3/s) by 26%. This is partly due to errors in predicting flow in May-June, 2000 [Fig. 2(a)] when most of the precipitation occurred at the end of May and beginning of June, and in predicting timing and magnitude of snowmelt for April, 2001. During April, 2001 15.6 cm (51% above normal) of precipitation occurred on frozen soil causing intense runoff (~5 m^3/s for 25 continuous days). 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. Since the model is not very good at predicting soil freeze/thaw during periods when temperatures are close to 0^{o}C, nor can it predict ice blockages in culverts and outlets, this caused errors in predicting the magnitude and timing of runoff and tile drainage in the month of April, 2001.

Table 3. Model performance statistics for predicted monthly flow and NO_3-N losses during calibration and validation years

Statistics		Calibration Period		Validation Period	
		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
	Predicted	0.38	4.04	0.29	2.93
RMSE		0.37	3.98	0.17	2.14
R^2		0.81	0.70	0.85	0.78
Slope		0.71	0.81	1.01	1.15
Intercept		0.05	0.99	0.11	1.36
d		0.88	0.88	0.93	0.81

Figure 2(b) illustrates the relationship between predicted and observed monthly NO_3-N losses for the calibration period. The predicted mean monthly NO_3-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 NO_3-N losses gave an r^2 of 0.7, with a slope and intercept of 0.81 and 0.99, respectively. Errors in the prediction of NO_3-N losses are primarily due to errors in predicting drainage flows and partitioning of flow between subsurface drainage and surface runoff during snowmelt period.

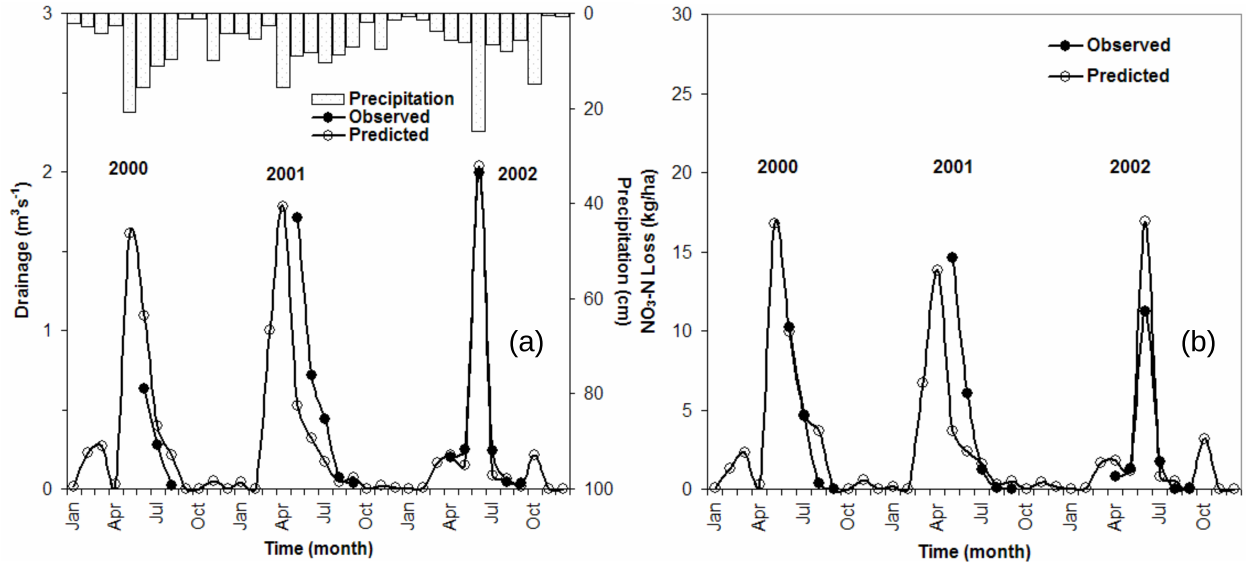

Figure 2. Comparison between predicted and observed monthly (a) drainage and (b) NO_3-N losses during calibration period

Model Validation

Figure 3(a) illustrates the relationship between predicted and measured monthly drainage for the validation period. 2003-2004 received significantly less precipitation compared to the calibration period (2000-2002). In contrast to the calibration period, the model over-predicted total drainage. The comparison of predicted and measured monthly drainage gave an r^2 value of 0.85, with a slope and intercept of 1.01 and 0.11 m^3/s. The index of agreement 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.

Figure 3(b) illustrates the relationship between predicted and measured monthly NO_3-N losses for the validation period. The model over-predicted NO_3-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. ADAPT over-predicted subsurface drainage and under-predicted surface runoff. This caused more NO_3-N losses compared to the observed.

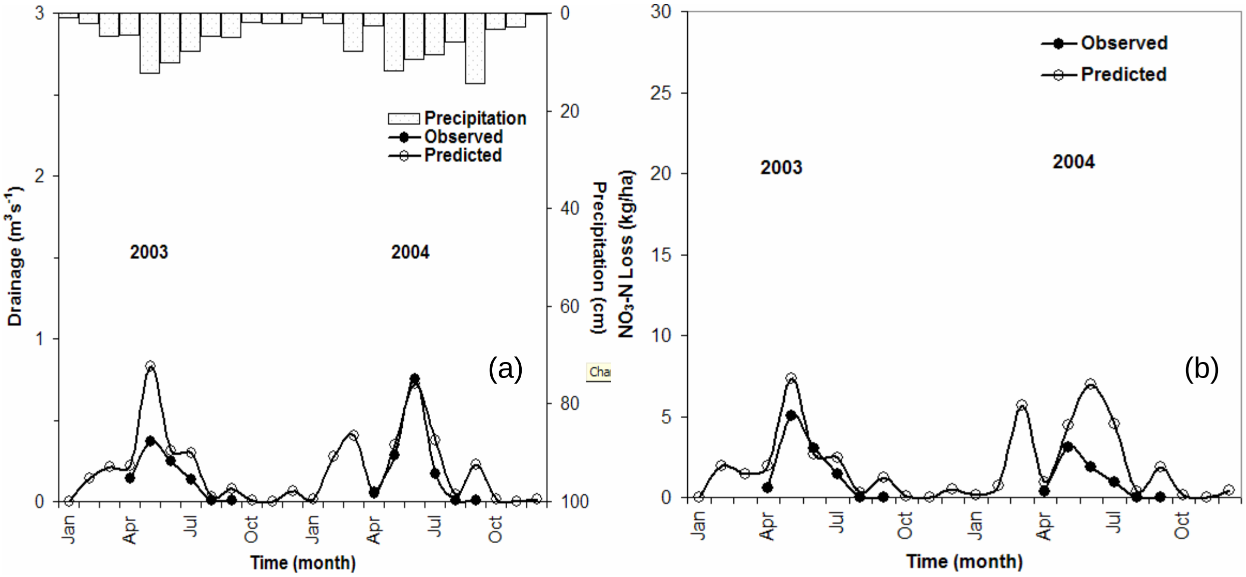

Figure 3. Comparison between predicted and observed monthly (a) drainage and (b) NO_3-N losses during validation period

Objective Two

Nitrogen Application Rate and Timing

Figure 4 illustrates the long-term NO_3-N losses for four different application rates and three different timings. In this analysis, the tile drain spacing was held constant at 24 m and tile drain depth was held constant at 1.2 m. The curves indicate that NO_3-N losses increase as N application rate increased. For example, the NO_3-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 NO_3-N losses indicated that NO_3-N losses can be reduced by 17% when reducing N application rates from 157 to 112 kg/ha.

A second strategy for reducing NO_3-N losses in drainage is to change the timing of application. Farmers prefer to apply fertilizers in the fall before planting, when they have ample amount of time, to avoid dealing with uncertain weather conditions in spring. But fall application causes increased leaching losses of fertilizer due to nitrification of ammonia. Figure 4 illustrates the long-term NO_3-N losses for three different application timings. Fall application is most convenient for the farmer but produces the greatest losses. Spring and split applications produce smaller losses and are beneficial for crop production as well. A split application is most favorable for plant growth, as the fall portion of application provides nutrients at germination and a spring side-dressing helps plant to emerge and grow to maturity. But it is tedious and expensive to apply fertilizer twice, and is not very popular in the farming community. A spring application is practical and reduces NO_3-N losses as well. Spring application is beneficial for plant growth and produces the smallest NO_3-N losses.

For an application rate of 157 kg/ha (140 lb/ac) a 14.3% reduction in NO_3-N losses was achieved by changing application timing from fall to spring. Similar reductions in NO_3-N losses were found with other application rates. Averaged across twenty-five rotation cycles, the smallest NO_3–N losses were found with spring N application, followed by split N application timing.

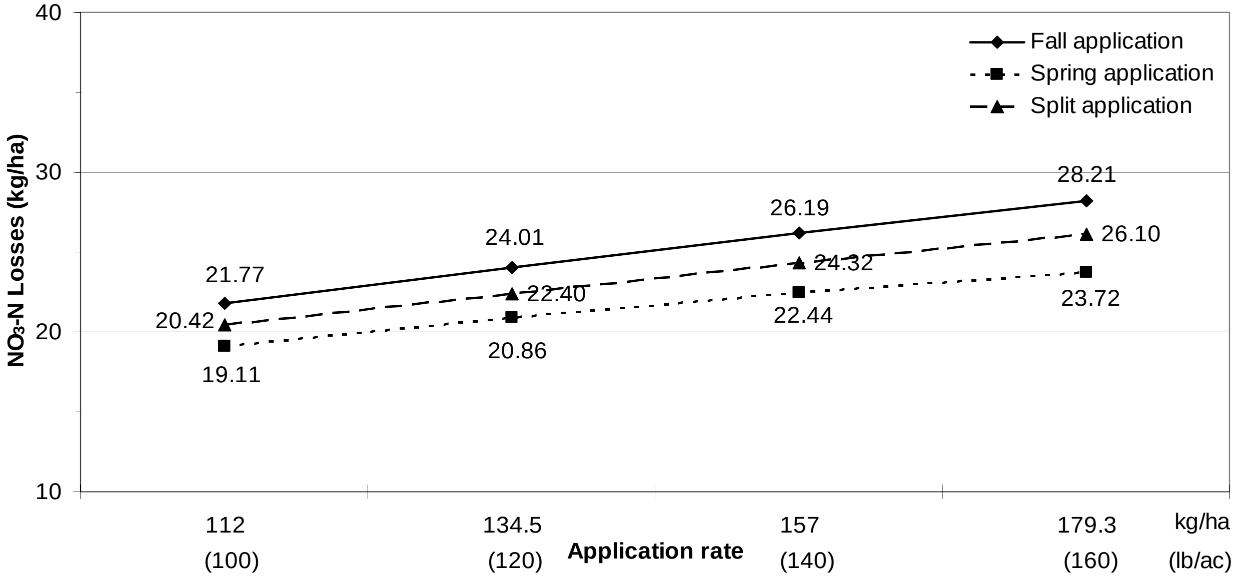

Figure 4. Comparison of predicted annual NO_3-N losses for changes in the N application rate and timing

Climatic Variability

Figure 5 shows the regression lines for the relationship between N application rates and NO_3-N losses at a fixed drain spacing of 24 m and a fixed depth of 1.2 m. These relationships were obtained by running the model for 50 years and plotting predicted drainage losses of NO_3-N versus N application rates. As expected, the predicted NO_3-N losses in wet years were much greater than in dry years for a given rate of applied N, and the magnitude of NO_3-N losses increased as the NO_3-N application rate increased. In dry years, NO_3-N losses through tile drainage were quite low for all N application rates, because of a lack of precipitation to drive NO_3-N leaching. During years with normal precipitation (73.7 cm), NO_3-N losses were reduced from about 31.7 kg/ha to about 24.3 kg/ha when N fertilizer application rates were reduced from 179.3 to 112 kg/ha.

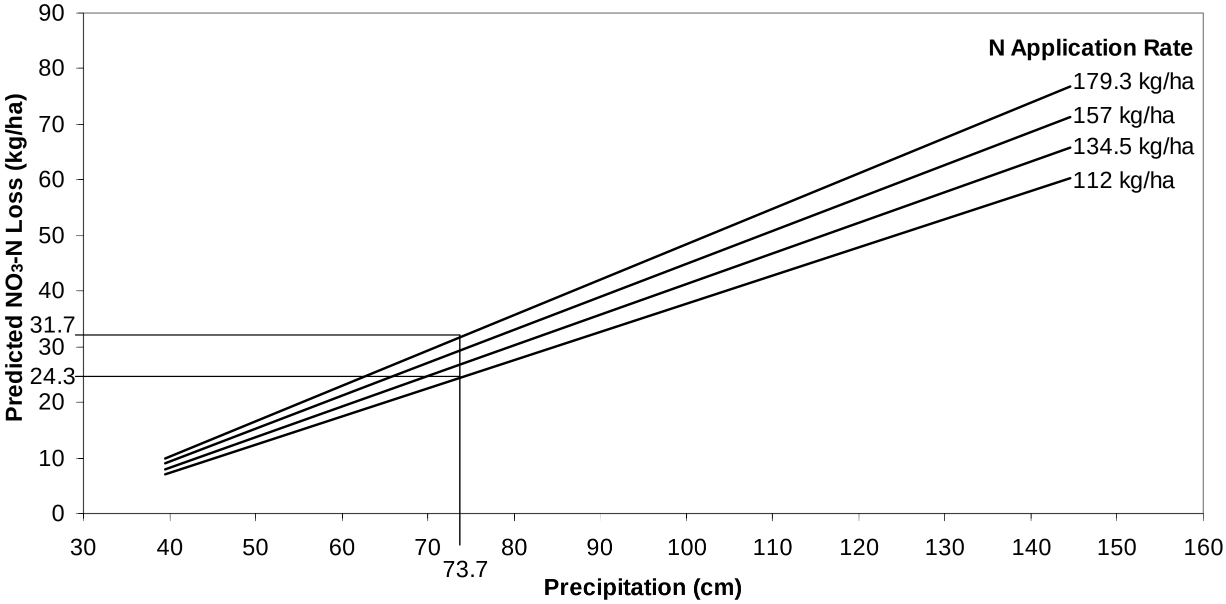

Figure 5. Regression lines showing relationship between predicted NO_3-N loss and annual precipitation for a range of N application rates. Number adjacent to each line is the N application rate.

Conclusions

The ADAPT model was calibrated and validated for tile drainage and NO_3-N losses in south-central Minnesota for the period from 2000-2004. The water quality data used in the calibration and validation of the model were collected from the SMC-1 watershed under various land-uses, and N fertilizer application types and timings. The predicted drainage flows and associated NO_3-N losses agreed reasonably with the measured trends for both calibration and validation periods. The model performed less satisfactorily for the snowmelt periods than it did for the entire period. These results suggest that challenges and opportunities exist for improving drainage model performance in the transitional months between winter and spring, where a significant portion of the annual drainage volume occurs.

Using the calibrated model, analyses were performed on the N application rates and timing. The predicted NO_3-N losses were sensitive to N application rates. A decrease in the fall N application rate from 179.3 to 112 kg/ha decreased NO_3-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, losses decreased by a further 12%.

Long-term simulations were performed using climatic data from 1955-2004 to evaluate the effects of climatic variability and N application rates on the NO_3-N losses. The predicted NO_3-N losses suggest that larger losses are generally associated with wet years.

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References

Alexander, C. 1988. ADAPT-A model to simulate pesticide movement into drain tiles. MS thesis. Columbus, Ohio: Ohio State University, Department of Agricultural Engineering.

Anderson, E. A., and N. H. Crawford. 1964. The synthesis of continuous snowmelt runoff hydrographs on a digital computer. Technical Report No. 36. Palo Alto, Cal.: Stanford University, Department of Civil Engineering.

Baker, J. L. and H. P. Johnson. 1981. NO_3-nitrogen in tile drainage as affected by fertilization. *J. Environ. Qual*. 10:519-522

Baker, J. L. and S. W. Melvin. 1994. Chemical management, status, and findings. P. 27-60. *In* Agricultural drainage well research and demonstration project. Annual report and project summary. Iowa Dep. Of Agriculture and Iowa State Univ., Ames

Baumer, O. W., R. D. Wenberg, and J. W. Rice. 1987. The use of soil water retention curves in DRAINMOD. Technical paper. Licoln, Neb.: USDA-SCS Midwest National Technical Center.

Benoit, G. R. and S. Mostaghimi. 1985. Modeling frost depth under three tillage systems. *Trans. ASAE* 28(5):1499-1505.

Chung, S. O., A. D. Ward, and C. W. Schalk. 1992. Evaluation of the hydrologic component of the ADAPT water table management assessment model. *Trans. ASAE* 35(2):571-579

Dalzell, B. J. 2000. Modeling and evaluation of nonpoint pollution in the Lower Minnesota River Basin. M.S. Thesis, Water Resources Program, University of Minnesota, St. Paul, MN. 281 p.

Dalzell, B. J., P. H. Gowda and D. J. Mulla. 2004. Modeling sediment and phosphorus losses in an agricultural watershed to meet TMDLs. *Journal of the American Water Resources Association (JAWRA)* 40(2):000-000

Davis, D. M., P. H. Gowda, D. J. Mulla, and G. W. Randall. 2000. Modeling nitrate nitrogen leaching in response to nitrogen fertilizer rate and tile drain depth or spacing for southern Minnesota, USA. *J. Environ. Qual*. 29, pp. 1568–1581

Desmond, E. D., A. D. Ward, N. R. Fausey, and T. J. Logan. 1995. Nutrient component evaluation of the ADAPT water management model. Proceedings of the International Symposium on Water Quality Modeling, April, Orlando, FL, pp. 21-30. ASAE, St. Joseph, MI.

Desmond, E. D., A. D. Ward, N. R. Fausey, and S. R. Workman. 1996. Comparison of daily water table depth prediction by four simulation models. Transactions of ASAE, 39(1):111-118.

Desmond, E. D., A. D. Ward, N. R. Fausey, and T. J. Logan. 1998. Subsurface drainage flow partitioning in a layered and saturated soil profile. Paper No. 98-2231, ASAE Annual International Meeting, July 12-16, Orlando, FL. ASAE, St. Joseph, MI.

Gowda, P.H. 1996. An Integrated Spatial-Process Model to Predict Agricultural Nonpoint Source Pollution. Unpublished Ph.D. diss. The Ohio State Univ., Department of Agricultural Engineering, Columbus, OH.

Goolsby, D. A., W. A. Battaglin, and R. P. Hopper. 1997. Sources and Transport of Nitrogen in the Mississippi River Basin. *In* Proc. of the Conf. From the Corn Belt to the Gulf—Agriculture & Hypoxia in the Mississippi River Watershed, St. Louis, MO. 14–15 July 1997. Am. Farm Bureau, Park Ridge, IL

Leonard, R. A., W. G. Knisel, and D. A. Still. 1987. GLEAMS: Groundwater loading effects of agricultural management systems. *Trans. ASAE* 30(5): 1403-1418.

Nangia, V., P. Gowda, D. Mulla and G. Sands. 2005. Field scale application of a water quality modeling approach for alternate agronomic practices, paper # 701P0105. *In: Proc. P. W. Gassman (ed.), 3rd ASAE water quality and TMDL conference*, Atlanta, GA.

Randall, G.W. and T.K. Iragavarapu. 1995. Impact of long-term tillage systems for continuous corn on nitrate leaching to tile drainage. *J. Environ. Qual*. 24:360–366.

Randall, G.W., D.R. Huggins, M.P. Russelle, D.J. Fuchs, W.W. Nelson, and J.L. Anderson. 1997. Nitrate losses through subsurface tile drainage in CRP, alfalfa, and row crop systems. J. Environ. Qual. 26:1240–1247.

Randall, G. W. and D. J. Mulla. 2001. Nitrate Nitrogen in Surface Waters as Influenced by Climatic Conditions and Agricultural Practices. J. Environ. Qual. 30:337–344

Randall, G. W., J. Vetsch, and J. Huffman. 2003. Nitrate losses in subsurface drainage from a corn-soybean rotation as affected by time of nitrogen application and use of nitrapyrin*. J. Environ. Qual.* 32, pp. 1764–1772.

Schalk, C. W. 1990. Modifying the hydrology component of the ADAPT model. MS thesis. Columbus, Ohio: Ohio State University, Department of Agricultural Engineering.

Viessman, W., Jr., G. L. Lewis, and J. W. Knapp. 1989. *Introduction to Hydrology*. 3rd ed. New York, N.Y.: Harper and Row.

Ward, A. C., C. A. Alexander, N. R. Fausey, and J. D. Dorsey. 1988. The ADAPT agricultural drainage and pesticide transport model. In *Proc. Modeling Agricultural, Forest, and Rangeland Hydrology*, 129-141. St. Joseph, Mich.: ASAE

Ward, A. D., E. Desmond, N. R. Fausey, T. J. Logan, and W. G. Logan. 1993. Development studies with the ADAPT water table management model. 15th International Congress on Irrigation and Drainage. Hague, Netherlands.

Weed, D. A. J. and R. S. Kanwar. 1996. Nitrate and water present in and flowing from root-zone soil. *J. Environ. Qual*. 25:709-719