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Modeling Nitrate-Nitrogen Losses in Response to Tile Drain Depth and Spacing

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Abstract. The Agricultural Drainage and Pesticide Transport (ADAPT) model was used to evaluate the effects of tile drain spacing and depth on NO_3-N losses in southeastern Minnesota. The model was calibrated and validated using 4 years of monthly flow and nitrate loss data from two tile drained fields (11 and 9.3 ha) in Nicollet County. Half the monitoring data from the 11 ha field were used for calibration and half for validation of the model. The model was also validated using independent monitoring data from the 9.3 ha field. For the calibration period on the 11 ha field, the model predicted mean monthly tile drainage and NO_3-N losses of 141.5 m^3/day and 5.2 kg/ha, respectively, against measured tile drainage (126.2 m^3/day) and NO_3-N losses (4.5 kg/ha). For validation, the predicted mean monthly tile drainage and NO_3-N losses were 131.7 m^3/day and 4.4 kg/ha, respectively, against measured tile drainage and NO_3-N losses of 80.4 m^3/day and 3.0 kg/ha, respectively. Similar validation results were found with 9.3 ha field. Long-term simulations were made for a wide range of climatic conditions (1954-2003) to evaluate the effects of drain spacing and drain depth on tile drainage and NO_3-N losses. Simulations results indicate that increasing spacing and decreasing depth of tile drains reduces the tile drainage and NO_3-N losses, and can serve as a remedy to the excess NO_3-N losses.

Keywords. Water quality, ADAPT, tile drainage, drainage depth, nitrate-nitrogen, modeling

Introduction

Scientific investigations in the Gulf of Mexico have documented a large area with seasonally-depleted oxygen levels (< 2mg/l). Most aquatic species cannot survive at such low oxygen levels. NO_3-N flowing to the Mississippi River from agricultural lands is the major source of nutrients leading to hypoxia in the Gulf of Mexico (Goolsby et al., 1999). About half of the nitrogen applied to lands draining to the Gulf comes from commercial fertilizer and about 15 percent comes from animal manure. Other sources of nitrogen to the Gulf include urban runoff, industrial point sources and atmospheric deposition (USGS, 2000). While far away geographically, the Gulf hypoxia problem is intimately linked to the Midwest via the Mississippi River. The Upper Mississippi River Basin comprises only 15% of the Mississippi River drainage basin's area, but contributes more than 30% of the NO_3-N reaching the Gulf (Goolsby et al., 1997, Rabalais et al., 2000). Most of this nitrogen comes from agricultural areas in Minnesota, Iowa, and Illinois where a large percentage of crop lands are tile-drained (Davis et al., 2000).

Tile drainage systems enhances crop yields on poorly drained but highly productive soils and helps to reduce year to year variability in yields (Brown et al., 1998). Lal and Fausey (1998) reported that corn crop yields increased with decreasing distance from the tile drain in Central Ohio. Drainage improves aeration, increases the availability of nutrients, enhances crop productivity (Lal and Taylor, 1970, Cannell, 1979), and allows timely farm operations. It also reduces crop diseases, soil erosion, and surface runoff (Fausey et al., 1986). Consequently, it has become a routine practice over large areas of the Midwest. However, numerous studies have shown that the presence of tile drainage systems increase NO_3-N losses from fields through interception of NO_3-N in the soil profile (Skaggs et al. 1994; Baker, 1994, Logan et al., 1994, Soenksen, 1996), even when no additional fertilizer is applied (Randall and Iragavarapu, 1995, Baker and Johnson, 1997).

Tile drain configuration (spacing and depth) affects the quantity of tile discharge and thus quality. Hoover and Schwab (1976) found that a tile spacing of 9.1 m (30 feet) increased the tile flow discharge by 50% compared to a spacing of 15.2 m (50 feet). Schwab et al. (1961) compared 9.1 m and 18.2 m tiles spacing. Tile flow was considerably greater for 9.1 m spacing. A study by Cook et al. (2002) monitored tile effluents from drainage tiles installed at depths ranged from 0.61 m (2 ft) to 1.22 m (4 ft) in a 16 ha (40-acre) field in eastern Illinois under a corn-soybean rotation. They observed a direct correlation between decreased tile flow and decreased tile depth.

A reduction in NO_3-N loading by 20% has been recommended to reduce hypoxia in the Gulf of Mexico (Mitsch et al., 1999). Identification of suitable agricultural management strategies to reduce NO_3-N loadings from agricultural systems will be a valuable exercise as the knowledge gained from such studies are transferable to other agricultural areas in the Midwest. The main objectives of this study are to: (i) calibrate and validate the ADAPT model for tile drainage and associated NO_3-N losses on a commercial farm with corn *(Zea mays L.)* - soybean *[Glycine max (L.) Merr.]* rotation and conventional tillage, and (ii) evaluate the long term effects of different drain spacing and depths on rates of subsurface drainage and NO_3-N losses. The ADAPT model was selected for its ability to simulate major hydrologic processes such as tile drainage and spring snow-melt runoff that are typical of Upper Midwest U.S. Further, the ADAPT model was calibrated and validated for various hydrologic conditions in this region (Davis et al., 2000).

Material and Methods

ADAPT Model: The ADAPT model is a daily time step field-scale model and includes enhancements over GLEAMS, such as addition of the Doorenbos and Pruitt (1977) potential evapotranspiration method as an alternative to the Ritchie method (1972), modification of runoff curve number based on daily soil water conditions, addition of a Green-Ampt infiltration model, snowmelt modeling, and accounting for macropore flow. 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 includes daily values of rainfall, ambient temperature, wind speed, relative humidity, and solar radiation for the duration.

Site Description and Water Quality Data: The calibration and validation of the model for flow and NO_3-N losses were performed using water quality measurements made on two fields in a commercial farm located 8 km west of St. Peter, Minnesota (Fig. 1).

Figure 1. Location of two commercial fields in southeastern Minnesota.

The site is set up such that a 21 ha (52 acre) field is split roughly in half [west field = 11 ha (28 acres, 213 m x 540 m) and east field = 9.3 ha (23 acres, 174 m x 540 m)] (Fig. 1). The site is dominated by poorly drained clay loam soils that developed under tall prairie grasses in the glacial till. Soils at study area included Cordova (Typic Argiaquolls), Cordova-Rolfe (Typic Argialbolls), Canisteo (Typic Haplaquolls), LeSueur (Aquic Argiudolls), Harps (Typic calciaquolls) and Okoboji (Cumulic haplaquolls). The average annual precipitation in the region is about 737 mm. The growing season typically lasts from mid/late May until early/mid October.

The site is drained with 152 mm (6 inches) diameter cement tile drains placed at about 30 m (100 feet) spacing and 1.1 m (3.7 feet) depth with an average slope of 0.3%. Information on agronomic practices and tillage operations is available dating back to 1994. The fields were planted to a corn-soybean rotation with chisel plowing in the fall after harvest and spring cultivation before planting. Soybean was planted in 1994, 1996, 1998, 2000 and 2003, and corn was planted in 1995, 1997, 1999, 2001 and 2002. For corn, anhydrous ammonia was injected in the fall and di-ammonium phosphate (DAP) and urea were broadcast in spring. No fertilizer was applied to soybean. A variable rate application was carried out at the site for another study from 1997 to 1999. For this purpose, the field was divided into multiple strips. For corn, strips received N fertilizer at rates of 101 (90), 146 (130) and 179 (160) kg N ha^{-1} (lb N ac^{-1}). Details of planting and harvesting dates, fertilizer application rates and tillage operations implemented during 1994-2003 are presented in Nangia et al (2005).

Model Inputs: Model simulations were made using climatic data from 1994-2003. Precipitation was measured on site using a tipping bucket rain gauge during 1999-2003. Precipitation data for the remaining years and other climatic data such as daily values of average air temperature, solar radiation, wind speed, and average relative humidity were taken from the St. Peter weather station located about 8 km from the site. Water quality monitoring was conducted from 1998-2003. Samples were taken during storm events and grab samples were collected during base flow conditions. Tile drain flows were measured at 1-minute frequency using an ISCO area-velocity meter and outputs were 15-minute average discharges. Soil input for ADAPT include soil-water release curve data, drained volume and upward flux versus depth, infiltration parameters, and saturated vertical and horizontal hydraulic conductivity. These parameters were held constant for all simulations. These data were derived from the Natural Resources Conservation Service , Map Unit Use File (MUUF) database.

Our modeling methodology requires the study area to be divided into Hydrologic Response Units (HRUs). In the HRU formation process, spatial data layers of variable N application rates for 1997 and 1999 and soil types were overlaid with Arc View 3.0 GIS software to capture the variability in N fertilizer application rate against soil type. The result was a GIS layer consisting of 11 HRUs containing unique combinations of soil type and N fertilizer application rates. Since nutrient management data were available for the site from 1994-2003, simulations were conducted starting from 1994. Although water quality data were available from 1998 onwards, model simulations were made to start from 1994 to reduce initialization errors.

Objective One: For the 11-ha field, half the monitoring data was used for calibration (1999-2001) and half the data for validation (2002-2003) of the ADAPT model monthly flow and NO_3-N losses (Fig. 2). The model was validated again for independent monitoring data for the 9.3-ha field. The model was calibrated by varying hydrologically sensitive parameters such as saturated vertical hydraulic conductivity, rooting depth, leaf area index, drainage coefficient, and soil moisture retention curves to achieve the closest agreement between predicted and observed tile drainage and NO_3-N losses. Due to winter-time freezing conditions in Minnesota, observed data were not available for all months of the year. As a result, measures of model performance are a comparison of the months in which observed data were available. Although the ADAPT model is capable of predicting runoff and tile drainage resulting from snowmelt, evaluation of model performance for these events was not possible.

Model Evaluation Criteria: Five statistical procedures: (1) the observed and predicted means, (2) the coefficient of determination (r^2), (3) the slope and intercept of a least square regression between the predicted and observed values, (4) root mean square error (RMSE), and (5) an index of agreement were used to assess the level of agreement between the predicted and observed data for calibration years. 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.

Objective Two: Long term simulations were made using 50-year climatic record to investigate the effects of tile drain depth or spacing on the probability of experiencing large NO_3-N losses. Predicted annual nitrate losses were used in the exceedance probability analysis. Daily rainfall and temperature data were used for the entire period of simulation. Input parameters used in the long-term simulations were the same as those used in the model validation. Simulations were made with three drain spacings (27, 40, 100 m) at three different drain depths (0.9, 1.2 and 1.5 m) to evaluate their effect on the magnitude of subsurface drainage and associated NO_3-N losses. The predicted tile drainage and NO_3-N losses were ranked in decreasing order and the exceedance probabilities were calculated.

Results and Discussion

Model Calibration and Validation:

Table 1 shows excellent agreement between model predictions and measured flow and NO_3-N losses for the calibration and validation periods. In the calibration phase, attempts were made to minimize the RMSE and obtain r^2 and d values closest to a value of unity.

Table 1. Model performance statistics for predicted monthly flow and NO_3-N discharge during calibration and validation years.

Statistics		Calibration on 11-ha field		Validation on 11-ha field		Validation on 9.3-ha field	
		Flow (m^3/day)	NO_3-N (kg/ha)	Flow (m^3/day)	NO_3-N (kg/ha)	Flow (m^3/day)	NO_3-N (kg/ha)
Mean	Observed	126.2	4.5	80.4	3.0	137.5	3.4
	Predicted	141.5	5.2	131.7	4.4	136.0	4.5
RMSE		60.7	2.9	71.8	2.5	69.3	2.1
R^2		0.87	0.85	0.92	0.91	0.94	0.90
Slope		0.72	0.71	1.08	0.68	0.70	0.80
Intercept		50.6	2.0	45	2.5	39.8	1.8
d		0.92	0.91	0.91	0.91	0.95	0.93

Comparison of measured and calibrated values for monthly tile drainage (Fig. 2a) shows that the model overpredicted drainage in wet months. This is primarily due to the difficultly in predicting tile drain flow during spring snowmelt runoff. Statistical evaluation of the monthly predicted and observed flow gave an r^2 value of 0.87, with a slope and intercept of 0.72 and 50.6 m^3/day, respectively. The index of agreement was about 0.92 and the RMSE was 48% of the observed mean monthly flow (Table 1). We can conclude from these results that the model performs reasonably well in predicting tile drainage during the non-snowmelt period.

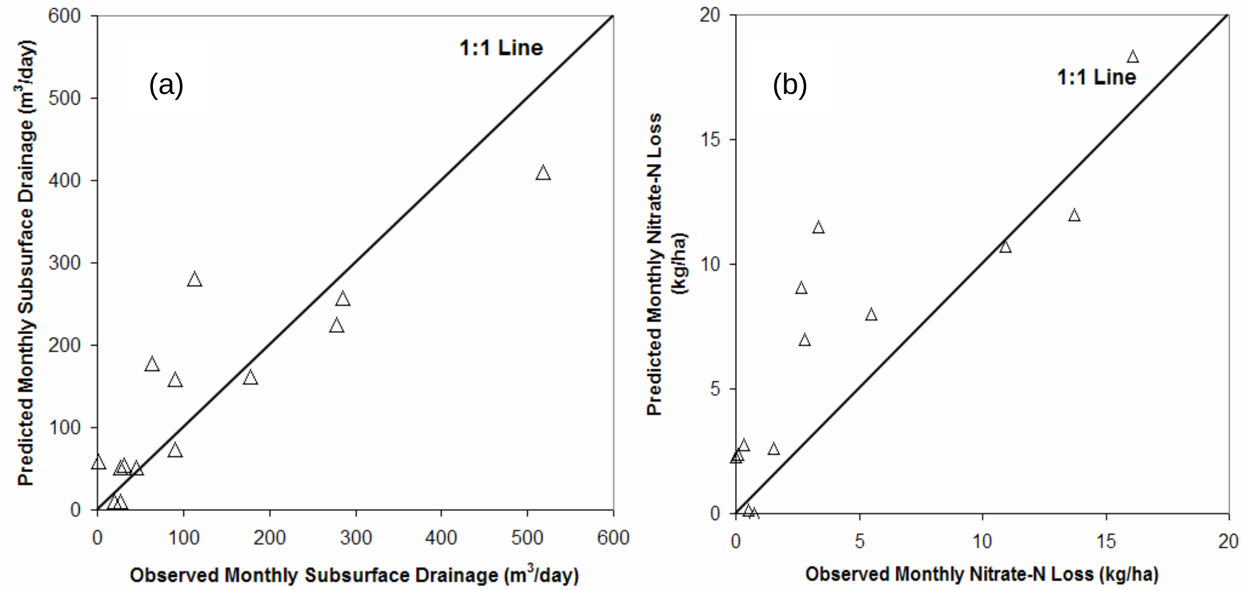

Figure 2. Comparison between predicted and observed (a) monthly subsurface drainage values and (b) monthly NO_3-N values for the calibration period

Model Validation

Validation on the 11-ha field: Comparison of measured and predicted values of monthly flow for validation years on the 11-ha field shows (Fig. 3a) that the magnitude and trend in the predicted monthly flows closely followed that of measured data in most months. There was fair agreement between predicted mean monthly flow of 131.7 m^3/day and measured flow of 80.4 m^3/day (Table 1). The model over predicted flow by 64%. This may be partly due to errors in the prediction of timing and magnitude of snowmelt events in winter months. A comparison of predicted and measured monthly flow values gave an r^2 value of 0.92 with a slope and intercept of 1.08 and 44.98 m^3/day, respectively. The index of agreement was about 0.91.

NO_3-N losses during validation followed the drainage trend for the site. Both overpredicted during snowmelt periods. There was fair agreement between predicted mean monthly NO_3-N losses of 4.4 kg/ha and measured losses of 3 kg/ha (Table 1). The model overpredicted NO_3-N losses by 32%. This may be partly due to errors in the prediction of timing and magnitude of snowmelt events in winter months (Fig. 3b). A comparison of predicted and measured monthly flow values gave an r^2 value of 0.91 with a slope and intercept of 0.68 and 2.5 kg/ha, respectively. The index of agreement was about 0.91.

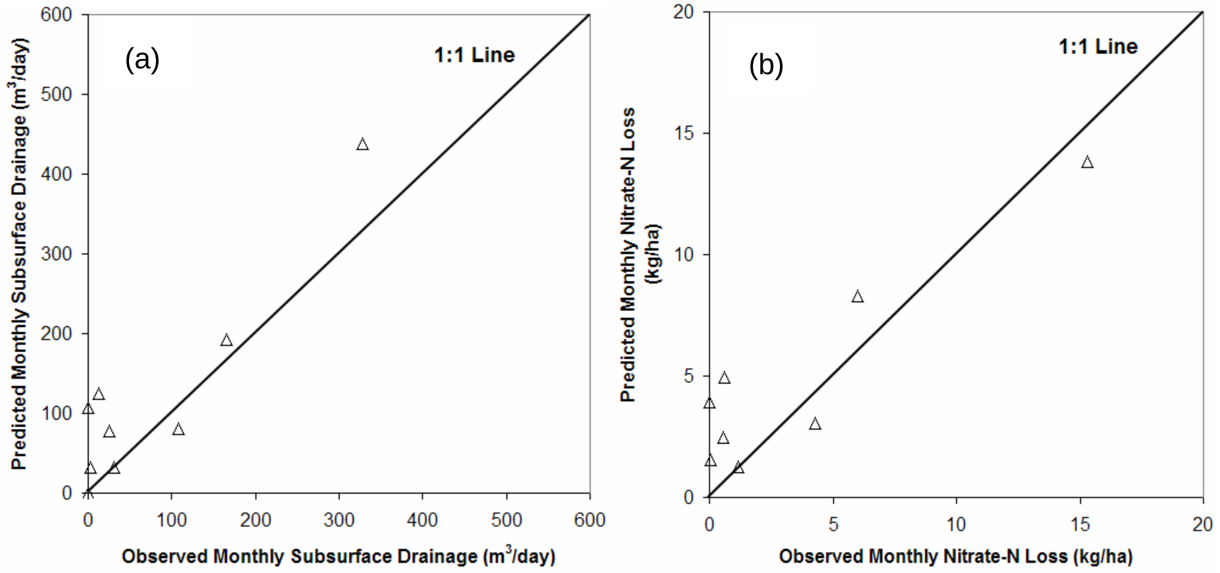

Figure 3. Comparison between predicted and observed (a) monthly subsurface drainage values and (b) monthly NO_3-N values for the validation on 11-ha field.

Validation on the 9.3-ha field: A second validation of the model was carried out on the 9.3-ha field from1999-2003 (Figs. 4a and 4b). Validation results were better for this site compared to the 11-ha field (Table 1). Mean flows were very close to each other (observed: 137.5 and predicted: 136 m^3/day), and RMS errors were also smaller for both tile drain flow and NO_3-N losses (69.3 kg/ha and 2.1 kg/ha). Correlation coefficients of 0.90 and 0.94 were observed for drain flow and NO_3-N losses with slopes and intercepts of 0.70 and 39.8, and 0.80 and 1.8, respectively.

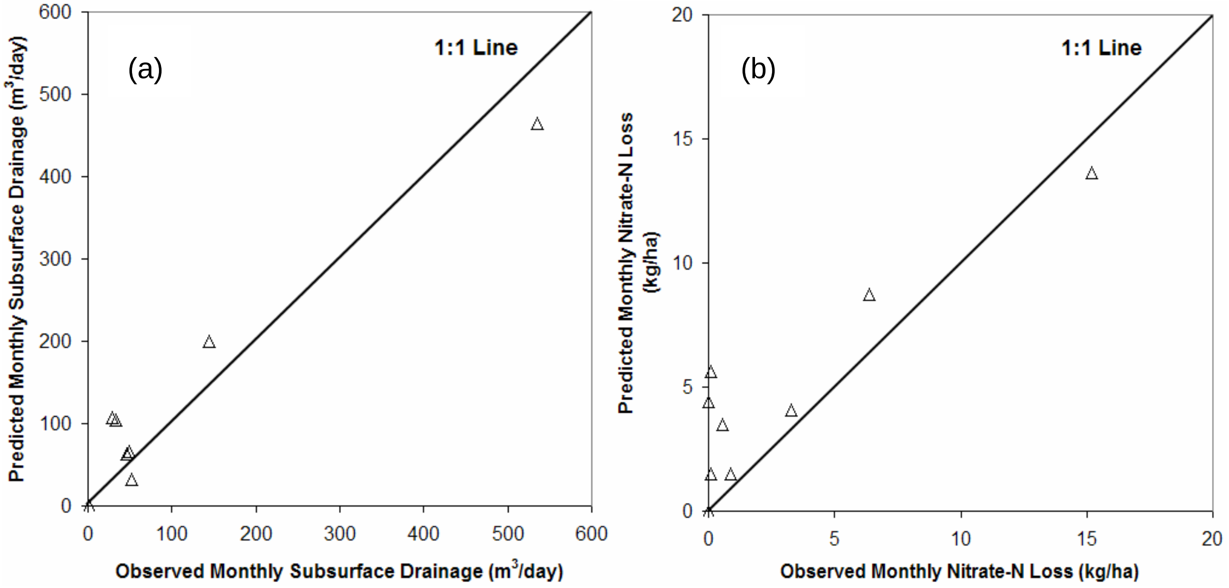

Figure 4. Comparison between predicted and observed (a) monthly subsurface drainage values and (b) monthly NO_3-N values for validation on the 9.3-ha field.

Water and Nitrogen Budgets

Tables 2 and 3 compare predicted and observed average annual water and nitrogen budgets, respectively for 1999-2003 for the 11-ha field. The predicted annual tile drainage was about 23.2% of the total precipitation, which is comparable to the measured value of 25.3%. The predicted annual evapotranspiration was 68.8% of the total precipitation, and is comparable with the measured values (64.1% in 1992 and 72.0% in 1994) on a fine-textured tile-drained soil located in central Iowa (Moorman et al., 1999). Measured evapotranspiration values were not available for our study site. This comparison indicates that the model is partitioning water reasonably well.

Table 2. Model predicted and field estimated components of water balance: annual averages for all years from 1999-2003.

	Model predictions		Field observations	
	Depth (cm)	Percent of precipitation	Depth (cm)	Percent of precipitation
Precipitation	76.6	100.0	76.6	
Evapotranspiration	52.7	68.8		
Tile drainage	17.8	23.2	19.4	25.3
Runoff	4.1	5.4		
Deep seepage	3.3	4.3		

The crop uptake was 149.5% of the applied because results presented here are for a corn-soybean rotation with no N fertilizer application in soybean cropping years. The predicted annual average NO_3-N loss through tile drains (29.8 kg/ha) was about 46% of the applied N and about 1.4% higher than the measured NO_3-N losses (28.9 kg/ha). The predicted NO_3-N loss by denitrification was about 10.3% of the total N applied, which is comparable to estimated values (10-25%) reported by Meisinger and Randall (1991).

Table 3. Model predicted and field estimated components of the nitrogen budget: annual averages for all years from 1999-2003.

	Model predictions		Field observations	
	Nitrogen (kg/ha)	Percent of applied N	Nitrogen (kg/ha)	Percent of applied N
Inputs: Fertilization	64.8		64.8	
Mineralization	64.4			
Rainfall	26.8			
Nitrogen fixed	54.9			
Total input	210.9			
Loss: Crop grain uptake	96.9	149.5		
Drainage	29.8	46.0	28.9	44.6
Denitrification	6.7	10.3		
Sediment	14.1	21.8		
Runoff	2.3	3.5		
Deep seepage	7.6	11.7		
Ammonia volatilized	0.0	0.0		
Total losses	157.4			

Drain Spacing

Figs. 5a and 5b illustrate the long-term exceedance probability curves for tile drainage and NO_3-N losses at tile drain spacings of 27, 40 and 100 m, respectively. For these analyses, tile drain depth and N fertilizer application rate were held constant at 1.2 m and 123 kg/ha (110 lb/ac), respectively. As expected, the exceedance probability curves for tile drainage show that both median and maximum annual tile-drain flows increased as tile-drain spacing decreased. The median (2-yr return interval) predicted tile-drain flow for spacings of 27, 40 and 100 m were about 18.1, 15.8, and 12 cm, respectively. Median tile-drain flow was decreased by 33% when tile-drain spacing was increased from 27 to 100 m.

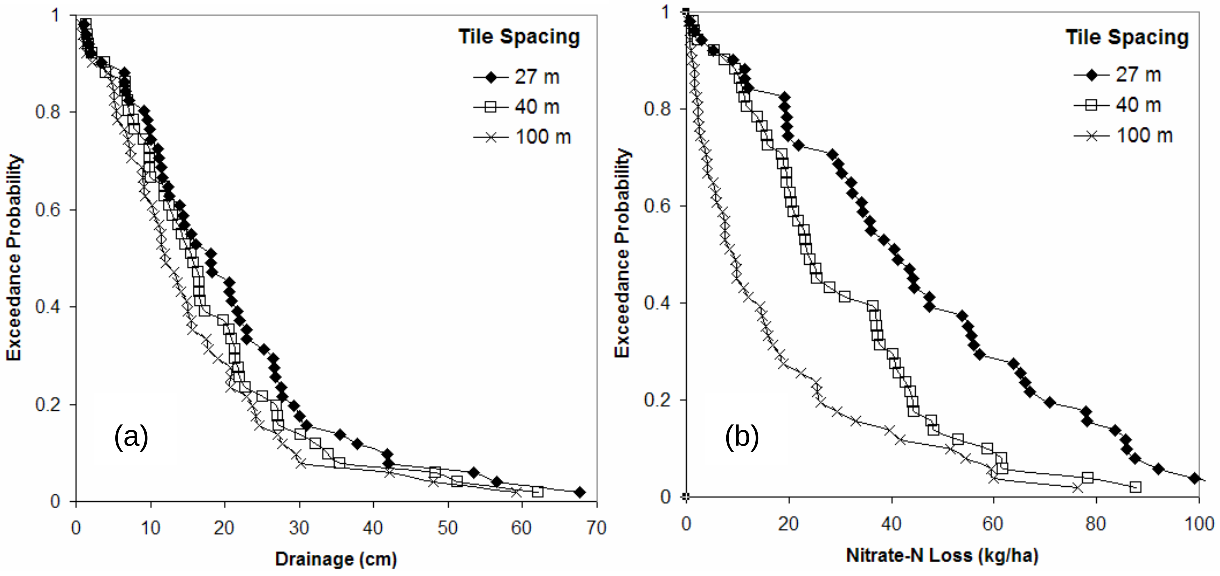

Figure 5.Exceedance probability curves of predicted (a) subsurface drainage flow and (b) NO_3-N loss at three tile-drain spacing. Drain depth is held constant at 1.2 m.

Exceedance probability curves for NO_3-N loss show that both median and maximum annual tile-drain flow increased as tile-drain spacings decreased. The median predicted NO_3-N losses for spacings of 27, 40 and 100 m were about 43.1, 24.1, and 9.5 kg/ha, respectively. The magnitude of median NO_3-N losses was reduced by 78% when the drain spacing was increased from 27 to 100 m. Comparison of drain flow and NO_3-N losses suggested that NO_3-N concentrations in tile drainage increased as tile-drain spacing increased. This is because at larger tile-drain spacing the model predicts increased soil moisture, more frequent anaerobic conditions in the root zone, and decreased crop yields. Thus, increased denitrification does not remove all of the excess soil N resulting from reduced crop uptake as tile spacing increases.

Presence of water table in the root zone during growing season may adversely affect crop health and thus crop yield. Since the ADAPT model is not very accurate at predicting crop yield, the number of days when the water table was less than 30 cm from the surface was counted for different tile drain spacings and depths (Fig. 6). As tile spacing increase or tile depth decreases, the number of days with a shallow water table increases. So there is a tradeoff between reducing drainage flow and NO_3-N losses, and providing healthy conditions for crop to grow.

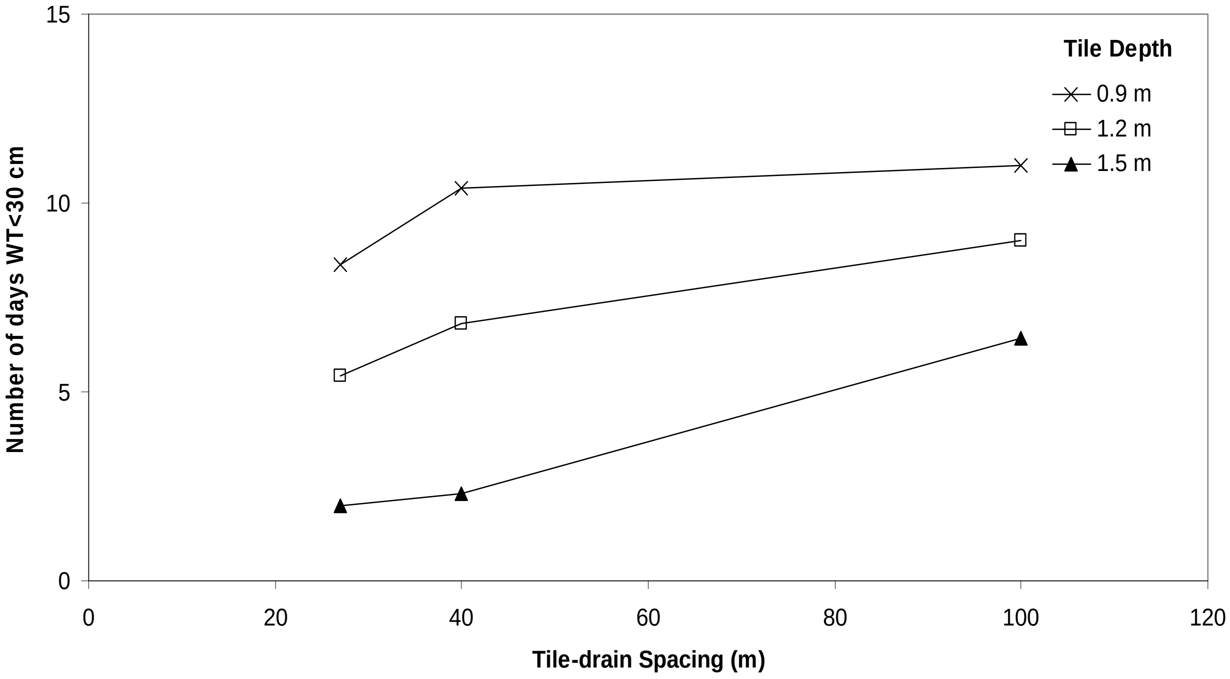

Figure 6: Number of days when water table is less than 30 cm from the surface.

Drain Depth

Figs. 7a and 7b illustrate the long-term exceedance probability curves for tile-drain flows and NO_3-N losses, respectively, at drain depths of 0.9, 1.2 and 1.5 m. For these analyses, drain spacing was held constant at 27 m and N application rate was held constant at 123 kg/ha. The median and maximum tile-drain flows and NO_3-N losses increased as drain depth was increased. The predicted median tile-drain flows for 0.9, 1.2 and 1.5 m depths were 14.4, 18.1 and 19.4 cm, respectively. Similar trends were observed in NO_3-N losses. The predicted median NO_3-N losses associated with tile-drain depths of 0.9, 1.2 and 1.5 m were about 17.5, 41.3 and 43.1 kg/ha, respectively.

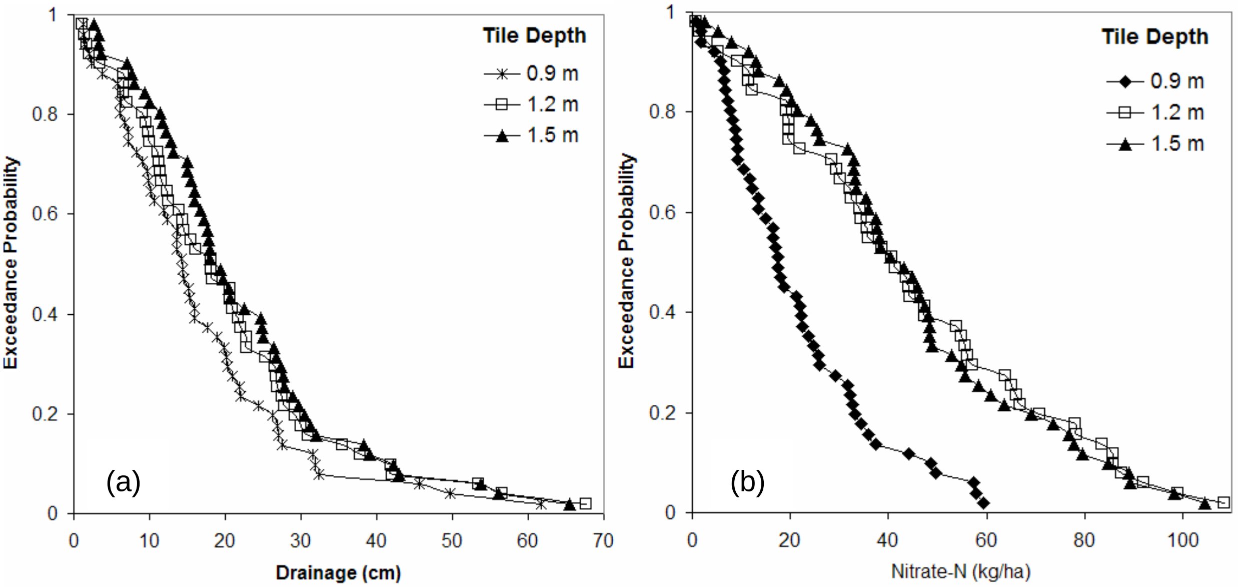

Figure 7: Exceedance probability curves of predicted (a) subsurface drainage and (b) NO_3-N losses at different tile-drain depths. Drain spacing is held constant at 27 m.

A range of combinations of drain spacing and depths can achieve same levels of drainage and NO_3-N losses. But each combination has its advantages and constraints. Closer spacing of tile-drains increases drainage and NO_3-N losses, and increases costs. Wider spacing of tile-drains increases stress on the crop due to longer periods of high moisture conditions in the soil. Table 4 summarizes the NO_3-N losses that are possible and their respective exceedance probabilities over a range of drain spacing and depth combinations. These results can be used to develop tile drain depth and spacing strategies for achieving desired production or environmental targets in the region around the study site.

Table 4. NO_3-N losses and their respective exceedance probabilities across a range of drain spacings and drain depths.

Drain spacing (m); 0.9 m depth (constant)	Exceedance probability		
	0.10	Median	0.90
		Nitrate-N loss (kg/ha)	
27	48.6	17.5	5.7
40	46.7	9.7	1.7
100	27.0	5.8	1.0
Drain depth (m); 27 m spacing (constant)	Exceedance probability		
	0.10	Median	0.90
		Nitrate-N loss (kg/ha)	
0.9	48.6	17.5	5.7
1.2	85.8	41.3	9.1
1.5	84.9	43.1	13.0

Conclusions

The ADAPT model was calibrated and validated for tile drainage and associated NO_3-N losses on a commercial farm with corn-soybean rotation and conventional tillage for the period 1999-2003. The predicted tile drain flows and NO_3-N losses agreed reasonably with the measured trends for both calibration and validation periods. Validation results on the 9.3-ha field gave improved statistics than validation results on the west field. Comparison of water and nitrogen budgets against measured data and the literature showed that the model is partitioning the water well.

A sensitivity analysis was performed on the tile drain spacing and depth using the calibrated model. The predicted tile drain flows and NO_3-N losses increase with decrease in drain spacing, and vice versa, albeit at different extent. An increase in tile drain spacing by 240% (from 27 to 100 m) reduced tile drain flows and NO_3-N losses by 33 and 71%, respectively.

Increased tile drain spacing or decreased tile drain depth could be a remedy for excess NO_3-N loads in the Gulf of Mexico.

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