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METHODS TO ESTIMATE EFFECTS OF DRAINAGE WATER MANAGEMENT ON ANNUAL NITROGEN LOSSES TO SURFACE WATERS

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ABSTRACT A method for estimating the effects of drainage water management (DWM) or controlled drainage (CD) on nitrogen (N) losses in drainage water was evaluated using a DRAINMOD simulation analysis. The method assumes that the effect of DWM on N losses is proportional to its effect on drainage volume. The analysis was conducted for a Portsmouth sandy loam (sl) in eastern North Carolina. DRAINMOD-NII simulations predicted that DWM would reduce 35-yr average N losses to surface waters by 37% for continuous corn and 34% for a corn-wheat-soybean rotation. The effectiveness of DWM on reducing annual N losses varied from 18 to 58% over the 35 year period. Results showed that the approximate method could be used to estimate the effect of DWM on annual N loads. The method estimated the annual effect of DWM on N losses within 3 kg/ha of that predicted by DRAINMOD-NII in 18 of 35 years. Over-estimated effects in some years were balanced by under-estimated effects in others, so that the method accurately predicted the effect of DWM in the long run. However, the accuracy of the approximate method is dependent on determining the average flow weighted N concentration of the drainage water. Overall, the approximate method appears to be a promising means of assessing impacts of DWM for purposes of nutrient trading.

Keywords: Drainage, Controlled Drainage, Drainage Water Management, DRAINMOD, Nitrogen, Water Quality, Environmental Impact.

INTRODUCTION Nitrogen losses from drained agricultural lands are a principal source of excess nitrogen (N) in streams and estuaries (Gilliam et al., 1999; Mitsch et al., 2001; Dinnes et al. 2002). Controlled Drainage (CD), or Drainage Water Management (DWM) can be used to significantly reduce N losses to surface waters (Gilliam et al., 1979; Skaggs and Gilliam, 1981; Evans et al., 1989, 1995; Lalonde et al., 1996; Tan et al., 1998; Fausey, 2005). It is practiced at the field level, close to the source and, as a pollution control practice, has the inherent advantage of preventing N from entering surface waters, as opposed to treating the waters to remove it. DWM also conserves water and, if properly managed, will increase yields for some soils, drainage systems and locations. In some areas this benefit, along with state and federal sponsored cost sharing to provide the required infrastructure, has been sufficient to promote its application, resulting in both crop yield and drainage water quality benefits. In other locations, because of the temporal distribution of rainfall, yield benefits may be marginal. In many areas, including NC, most subsurface drainage occurs during the winter months, when DWM has little effect on crop yield, but the greatest impact on improved water quality. Yield increases resulting from DWM will not always be sufficient incentive to promote the drainage water management necessary for the potential water quality benefits.

One approach to promote the use of DWM for reducing N loads to surface waters is an incentive program that would provide a return to the farmer/operator based on reduction of N loads. The program could be a nutrient trading arrangement or a state/federal funded program, or a combination of both. Properly applied and managed, DWM has the potential to reduce N losses to surface waters at a lower cost per kg N than alternative methods. A nutrient trading program could provide the incentive necessary to support an enthusiastic and imaginative application of DWM practices to substantially reduce N losses to surface waters. A fee to the farmer/operator would be paid for the reduction of N loads to surface waters on a per unit mass basis, not for simply applying the practice. To be successful, this program would require a method of documenting the application of the practice, and of determining the effects on N loss, on an annual basis. Documenting the application of the practice could be accomplished by methods ranging from farmer/operator records, with spot checks to insure accuracy, to the use of satellite based data acquisition systems capable of recording and transmitting weir settings on DWM structures.

The magnitude of N losses in drainage water, and the effect of CD on those losses, depends on soil factors, drainage system design, crop species, rotation and yields, fertilization amounts and timing, weather variables and cultural practices. Further, the effectiveness of CD varies from year to year because of differences in weather. The best alternative for quantifying the effect of CD on N losses in drainage water spatially and temporally is the application of simulation models. The DRAINMOD-NII model (Youssef, 2003, Youssef et al., 2005) was developed to describe N dynamics in poorly drained soils. The model has been tested against field measurements and found to reliably predict N losses in drainage water for a range of soils and locations across the U.S. (North Carolina,Youssef et al., 2006; Iowa, Thorp et al., 2009; Illinois, David et al., 2009; and Minnesota, Luo et al., 2009). It has also been tested in Europe (Germany, Bechtold et al., 2007 and Sweden, Salazar et al., 2009). However, a large number of inputs and considerable modeling expertise are required for the application of this model. This paper evaluates a simpler DRAINMOD based approach for evaluating the effect of DWM on annual N loads.

Hypothesis Field studies on the effect of DWM on N losses in drainage water have generally shown that the practice increases evapotranspiration, surface runoff and seepage while reducing subsurface drainage. DWM or Controlled Drainage (CD) did not have a significant effect on the nitrate concentration in drainage water in the large majority of field studies conducted. There have been exceptions. Lalonde et al. (1995) found that DWM lowered nitrate concentrations in drainage water for a weir depth 75 cm deep, but not at a 50 cm depth, and Fausey (2005) found a significant but relatively small difference compared to conventional drainage. In other studies, drainage water N concentrations under DWM were not significantly different than those under conventional drainage. As a result, the effectiveness of DWM in reducing N losses in drainage water was nearly the same, on a percentage basis, as its effect in reducing drain flows. These findings support the following hypothesis.

The impact of DWM on nitrate loads in drainage water can be quantified on an annual basis by determining its effect on annual subsurface drainage volumes.

The validity of this hypothesis would greatly simplify the task of determining the effect of DWM on annual N losses to surface waters. Models such as DRAINMOD and DRAINMOD-NII can be used to predict the effect of DWM on both drainage volume and N load in drainage waters. Other models may also be used. However, it is at least an order of magnitude more difficult to determine the inputs and model nitrogen dynamics and losses in drainage water with DRAINMOD-NII than it is to simply predict the effect of DWM on drainage volumes. If the hypothesis is valid, it would be feasible to use a model such as DRAINMOD to predict the effect of DWM on drainage volumes at a scale necessary to support nitrogen trading or other incentive programs. Methods to quantify lateral and vertical seepage inputs to the model would have to be developed, but the approach would be feasible.

METHODS The hypothesis was tested by conducting a DRAINMOD simulation study for a field (Field 𝒟) (Figure 1) on the Tidewater Experiment Station near Plymouth North Carolina. Soil property and site parameter inputs are given in Table 1. To simplify the analysis, it was assumed that the fields surrounding field 𝒟 had the same crop and the same drainage management regime. Thus lateral seepage was assumed to be negligible.

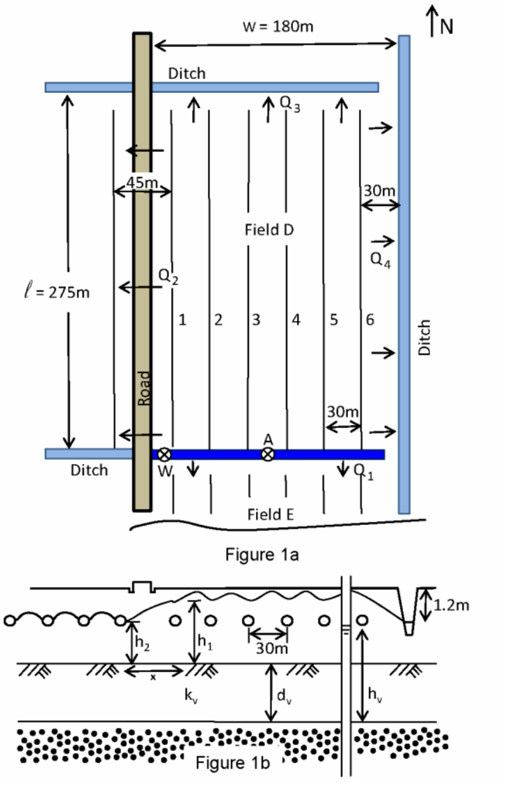

Figure 1. Schematic of field 𝒟 at the Tidewater Experiment Station near Plymouth, NC

Table 1. Summary of DRAINMOD inputs for field D on the Tidewater Experiment Station, Plymouth NC

Soil Series	Portsmouth sl	
Depth to Restrictive Layer	215 cm	
Depth of layer (cm)	Hydraulic K (cm/hr)	V_d* (cm)
0-30 cm	15 cm/hr	0.83 cm
30-50	2	1.69
50-100	2	5.36
100-150	8	10.3
150-215	8	15.8
Saturated water content	0.365 cm^3/cm^3	
Wilting Point	0.17 cm^3/cm^3	
Drain Spacing	30 m	
Drain Depth	120 cm	
Drainage Coefficient	2.5 cm/d	
Drain Diameter	10 cm	
Effective Drain Radius	1.5 cm	
Depressional Storage	1 cm	

*** V_d is the drained or water free pore space (cm^3/cm^2) in the profile when the water table is at the bottom of the layer and the profile is drained to equilibrium**

The effect of vertical seepage on the water balance of field 𝒟 was considered by assuming that the restricting layer in Figure 1b is underlain by a confined aquifer with a constant hydraulic head, h_v. Based on soil borings and piezometer measurements in the watershed, the thickness of the restricting layer was taken as 2 m and the hydraulic head in the aquifer was assumed constant at 2.9 m referenced to a datum at the top of the aquifer. This hydraulic head is consistent with piezometeric readings during periods when drainage occurs, and equates approximately to the elevation of the bottom of the drainage canals in the watershed. The rate of vertical seepage is calculated in DRAINMOD by a simple application of Darcy's law and is dependent on the saturated vertical hydraulic conductivity of the restrictive layer, K_v. The K_v value was set to 0.02 cm/hr, based on measured response to DWM in the original field experiments. Simulations were conducted for two crop rotations, continuous corn (CC), and corn-wheat-soybean (CWS), both with conventional tillage. The CWS rotation results in three crops in two years. Corn, planted by April 15, is harvested in September, followed by winter wheat planted in late October or November and harvested in June of the following

Table 2. Summary of crop and fertilization inputs.

Crop	**Plant Date**	**Harvest Date**	**N Fertilizer Application**		**Potential Yield**
			DAP*	**Amt N (kg/ha)**	**Kg/ha**
I. Cont. Corn	April 15	Sept. 15	0	100	11,000
			45	100	
II.Cn-Wh-SB					
Corn	April 15	Sept 15	0	100	11,000
			45	100	
Wheat	Nov. 1	June 15	-3	25	5,500
			90	125	
Soybean	June 25	Nov.20		0	3,500

*** DAP: days after planting**

year. Soybean is then planted in June and harvested in November, followed by corn again the following April. Details regarding planting, harvesting, and N fertilization, are given in Table 2. Simulations were conducted for both conventional drainage and DWM which consisted of controlled drainage with weir depths given in Table 3.

In addition to inputs given in Tables 1 and 2, DRAINMOD-NII requires additional inputs for soil properties, crop biochemical composition data, transport parameters, inputs for the processes of urea hydrolysis, nitrification, denitrification, potential rates of decomposition and C/N ratios for litter and organic matter pools. The inputs given in detail by Youssef et al. (2005) for a Portsmouth soil at the Tidewater Experiment Station were used in these simulations, but are not repeated here.

Simulations were conducted for the 40-year period, 1968-2007. To allow time for initializing input variables and soil processes affecting the nitrogen balance, results of the first 5 years of the simulations were excluded from the analysis.

Table 3. Weir depths assumed for continuous corn and for the corn-wheat-soybean rotation for DWM treatment.

	Continuous Corn (CC)	**Corn-Wheat-Soybean Rotation (CWS)**	
Dates	**Weir Depth (cm)**	**Weir Depth (cm)**	**Weir Depth (cm)**
		Yr.1, Corn-Wheat	**Yr.2, Wheat-Soybean**
Jan. 1-Mar. 14	**30**	**30**	**60**
Mar. 15-May 14	**125**	**125**	**60**
May 15-June 1	**60**	**60**	**125**
June 1-July 31	**60**	**60**	**60**
Aug. 1- Oct. 14	**120**	**125**	**60**
Oct. 15-Oct. 31	**30**	**125**	**60**
Nov1-Nov. 30	**30**	**125**	**125**
Dec. 1-Dec. 31	**30**	**30**	**30**

RESULTS Average annual predicted quantities for the 35 year period, 1973-2007, are given in Table 4 for the hydrologic variables and Table 5 for the nitrogen variables. Results in Table 4 indicate that CD increased predicted ET and surface runoff by an average of about 3 cm per year on both rotations. It increased predicted vertical seepage by 15 to 20 cm and decreased subsurface drainage by over 42% for CC and 38% for the CWS rotations. CD was somewhat more effective for continuous corn than for the three-crop-in-two-years rotation because the weir depth during the fallow winter months was closer to the surface (30 cm) for CC than when winter wheat was grown (60 cm) in CWS.

Results in Table 5 for components of the nitrogen balance show that predicted long-term average annual losses of N in subsurface drainage water for the CWS rotation was over 30% less than for CC for both conventional drainage and CD. On average, less fertilizer was applied and the N uptake was greater for the CWS than for the CC rotation. N-rich and readily decomposable soybean residues increased mineralization in CWS compared to CC. Predicted denitrification was also less for CWS than for CC because, in part, the weir depths during the winter months were deeper for years when wheat was grown. Also the NO_3-N concentrations in the shallow groundwater were higher for CC, compared to CWS, because the soil remains fallow for longer periods and greater amounts of N fertilizer are applied. The higher NO_3-N concentrations promoted greater denitrification for CC than for CWS. However, decreased N fertilizer application and increased plant uptake for CWS caused N losses in drainage water to be less than predicted for CC. The use of rotations that include crops that are less heavily fertilized is a well known method of reducing N loss from drained agricultural lands, as demonstrated by these predictions.

Table 4. Summary of effect of CD on hydrologic components for two crop rotations. Values are average annual predicted depths (cm) for the 35-year period 1973-2007 for a Portsmouth s.l. soil near Plymouth, NC.

Crop/Treatment	Rain	ET	Runoff	Vertical Seepage	Subsurface Drainage
Continuous Corn					
Drainage	130	61.1	3.4	6.4	59.7
Controlled Drainage	130	64.7	6.5	26	34.4
Change Due to CD	0	3.6	3.1	19.6	-25.3 (-42%)
Corn-Wheat-Soybean					
Drainage	130	66.2	3.4	8.9	51.4
Controlled Drainage	130	69.3	6.0	24	31.9
Change Due to CD	0	3.1	2.6	15.1	-19.5 (-38%)

Results summarized in Table 5 indicate that CD had a minimal effect on long-term annual average N released by mineralization and removed from the soil solution by immobilization. However, the water conservation provided by CD resulted in an increase in plant uptake (in both rotations), and the higher water table and increased vertical seepage through reduced zones resulted in more N lost by denitrification. CD was predicted to reduce the average annual loss of N to surface waters via subsurface drainage by 37% for CC and 34% for the CWS rotation. This predicted response to CD is somewhat less than the 40 to 50% reduction measured in the 1970s on this same field by Gilliam et al. (1979). However, at the time of the field measurements, the fields surrounding Field D were not managed in CD as assumed here. Thus lateral seepage losses would have made CD more effective in reducing N losses in drainage water than predicted in the simulations presented herein. This factor could have accounted for the difference between the 34% reduction predicted here and the 40 to 50% reduction reported by Gilliam et al. (1979).

Predicted annual N losses in drainage water for conventional and controlled drainage are plotted in Figure 2 for continuous corn. While the average predicted annual N loads were 41.7 and 26.2 kg/ha for conventional drainage and CD respectively, there was great variability from year-to-year. For example, the predicted N loss for conventional drainage varied from a low of 12.3 kg/ha/yr in 1997 to a high of 87.3 kg/ha/yr in 1989. The effectiveness of CD in reducing N loads also varied significantly from year-to-year. The greatest reduction in N losses due to CD was 30.6 kg/ha predicted for 2003 and the smallest was 5.7 kg/ha predicted for 1985. On a percentage basis, CD was most effective in 2007 when it reduced the N load by 58% and least effective in 1985 (18% reduction).

Table 5. Summary of effect of CD on components of the nitrogen balance for continuous corn and corn-wheat-soybean rotations. Values given are average annual predicted nitrogen inputs or losses in kg/ha/yr for the 35-year period 1973-2007 for a Portsmouth s.l. soil near Plymouth, NC

Drainage Treatment	N Fertilizer Applied	Rainfall Deposition	Net Mineral-ization	Plant Uptake	Denitri-fication	Runoff	Subsurf. Drainage
Drainage	**200**	**8.0**	**57.3**	**169**	**51.1**	**0.1**	**41.7**
CD	**200**	**8.0**	**58.4**	**176**	**60.8**	**0.1**	**26.2**
Change	**0**	**0**	**+1.1**	**+7**	**+8.7**	**0**	**-15.5 (37%)**
Drainage	**174**	**8.0**	**90.7**	**202**	**41.7**	**0.1**	**27.6**
CD	**174**	**8.0**	**90.8**	**206**	**46.3**	**0.2**	**18.3**
Change	**0**	**0**	**-.1**	**+4**	**+5.3**	**+.1**	**-9.3 (34%)**

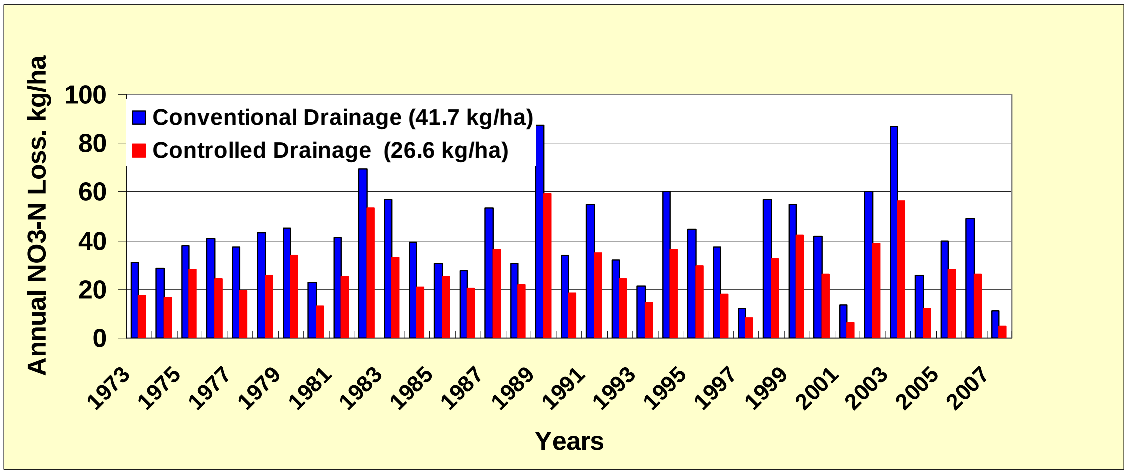

Figure 2. Predicted annual NO_3-N losses for continuous corn under conventional drainage and controlled drainage on a Portsmouth sl soil at Plymouth, NC.

Estimating Effect of DWM on N Loss, Testing the Hypothesis The hypothesis was tested by estimating the effect of DWM on N losses based on its predicted effect on drainage volumes. Predicted N losses via surface runoff were negligible for the simulations conducted in this study (<0.1 kg/ha/yr), so the annual N load in drainage water can be calculated as,

$$M = C\ V/10, \tag{1}$$

where M is the annual nitrogen load in subsurface drainage water (kg/ha), V is subsurface drainage volume (cm, expressed as a depth, or volume per unit surface area) and C is the average flow weighted nitrogen concentration (mg/L) for the year. Nitrogen in subsurface drainage water is mostly NO_3-N, but does include NO_2-N, NH_4-N and organic N. It is recognized that the forms of N and their concentrations vary with time, in response to changes in water table depth, weather events, fertilization, crop uptake, and numerous other factors. The concept of flow weighted average concentration is used here to facilitate development of a simple method of estimating the effect of DWM on N loss from drained fields. Most field studies have concluded that DWM does not result in a big change in N concentrations in the drainage water. While this is not true for all cases, it will be assumed in the approximate method presented here for estimating the annual effects of DWM on N loads. Then the reduction in N load due to DWM can be estimated as,

$$M_D - M_{DWM} = C\ (V_D - V_{DWM})/10, \tag{2}$$

where M_D and M_{DWM} are annual N loads for conventional drainage (D) and drainage water management (DWM), respectively, and V_D and V_{DWM} are the annual drainage volumes for the respective practices. Estimates of C values for field $\mathcal{D}$ for the two crop rotations were calculated from Eq. 2 above using 35-year average predicted values for annual N loads (M) and flow volumes (V). The values were C = 6.0 mg/L for continuous corn and 4.6 mg/L for the corn-wheat –soybean rotation. Once the C value has been determined, the impact of CD on annual N losses in drainage water can be estimated from drainage volumes using Eq. 2.

Table 6. Results of the effect of DWM on N losses in drainage water from field D, as predicted (modeled) by DRAINMOD-NII (column 6) and by the approximate method (column 7) for a six year period. Average results for the 35 year period are also given.

Year	Modeled Drainage V (cm)		Modeled N Loss in Drainage Water,M (kg/ha)		Modeled Effect, DWM kg/ha	Estimated Effect, DWM kg/ha	Difference Estimated-Modeled kg/ha
	D	DWM	D	DWM			
1980	52.4	29.5	22.9	13.1	9.8	13.7	4.0
1981	39.5	23.1	41.2	25.2	15.9	9.8	-6.1
1982	63.7	35.8	69.4	53.6	15.8	16.7	0.9
1983	84.9	48.7	56.7	32.9	23.9	21.7	-2.2
1984	67.3	49.2	39.3	20.8	18.5	10.9	-7.6
1985	48.5	21.4	30.8	25.1	5.7	16.3	10.6
Average	59.4	34.6	43.4	28.5	14.9	14.8	-0.1
Avg. 35 Yr	59.7	34.4	41.7	26.6	15.1	15.2	0.1

Results of the method are shown for the 6-year period, 1980-1985 in Table 6. Results in columns 2-6 were predicted (modeled) by DRAINMOD-NII for field 𝒟 for each year, as discussed above. The modeled effect of DWM (Column 6) is the difference in N loss predicted for D and DWM (column 4-column 5). The estimated effect of DWM (M_D-M_{DWM}) is given in column 7 and was calculated by Eq. 2 using predicted values for V_D and V_{DWM} in columns 2 and 3, respectively. That is, this is the estimated effect of DWM obtained by using DRAINMOD to predict the difference in drainage volumes only (no simulations of the nitrogen dynamics). Results given in Table 6 indicate that the approximate method gave results in good agreement with the results of DRAINMOD-NII for 3 of the six years, but either overestimated or underestimated the effect in the other three years. Overall, the average"error" for the estimated effect was only 0.1 kg/ha over the six year period. Results for all 35 years are plotted in Figure 3 and summarized in Table 6. On average overpredictions of the effect of DWM by the approximate method in some years (as compared to predictions of DRAINMOD-NII) were balanced by underpredictions in other years. The average difference in the predicted effect of DWM by the two methods was only 0.1 kg/ha over the 35 years. Differences in annual N losses

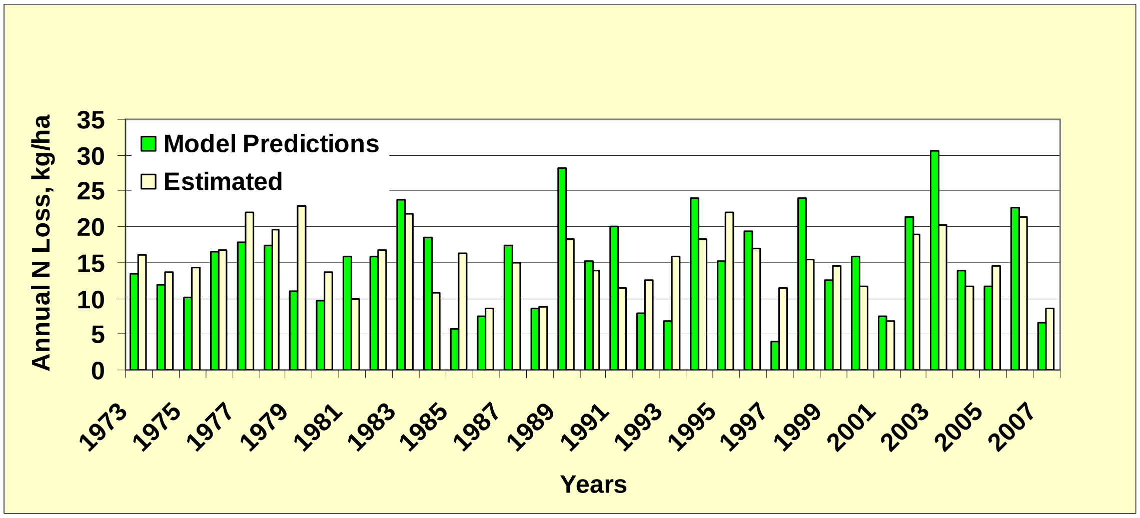

Figure 3. Effect of DWM on annual N loss in drainage water as predicted by DRAINMOD-NII and as estimated by the approximate approach based on DRAINMOD predictions of flow volumes.

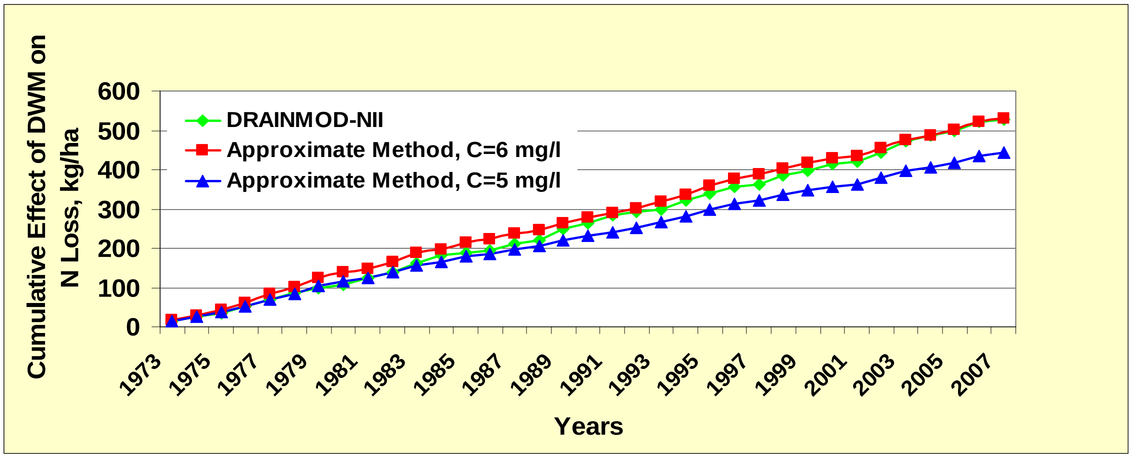

Figure 4. Cumulative effect of DWM as predicted by DRAINMOD-NII and as estimated with the approximate method using two long-time average NO_3-N concentrations in drainage water.

predicted by the two methods (estimated – DRAINMOD-NII predicted) varied from an overprediction of 11.9 kg/ha to an underprediction of 10.2 kg/ha (Figure 3).

If the estimated values were used to determine annual nutrient trading payments for reduction in N loads, the farmer would be overpaid in some years but underpaid in others, with the long-term average about right, based on the above results. The close agreement of the predicted long-term cumulative impacts of DWM resulted from the way the average load weighted N concentration was determined. In this case it was based on DRAINMOD-NII predictions of the annual N losses and drainage volumes for the 35-year period. This insured that the cumulative effect of DWM predicted by the approximate method would be nearly equal to that predicted by DRAINMOD-NII. Other methods, including field monitoring, can be used to determine the average flow weighted concentration (C in Eq.2). The value of C can also be adjusted to provide a factor of safety in nutrient trading calculations. For example, if we use C=5 mg/L, rather than 6 mg/L, the 35 year average load predicted by the approximate method would have been 2 kg/ha/yr less than predicted by the model.

Results plotted in Figure 4 show the cumulative effect of DWM as predicted by DRAINMOD-NII, the approximate method (Eq. 2 with C= 6 mg/L, and drainage volumes predicted by DRAINMOD), and the approximate method with C=5 mg/L. The concentration, C = 5 mg/L is lower than the actual long-term average effective concentration. It might be used in determining credits for nutrient trading as a safety measure; i.e., to insure that the N reduction achieved is greater than that claimed.

CONCLUSIONS Results of a simulation study indicate that approximate methods can be used to estimate effects of Drainage Water Management (DWM) on annual N losses to surface waters. The methods are based on the assumption that the effect of DWM on N loads is proportional to its effect on drainage volumes, which can be predicted with DRAINMOD. A flow weighted average N concentration of the drainage water is used to calculate the effect of DWM on loads. Additional work is needed to test the methods for other soils and regions and to develop methods for determining inputs.

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