NITRATE CONCENTRATIONS AND FLUX IN DRAINAGE WATER: IMPACTS OF TILE SPACING AND PRECIPITATION EVENTS AND IMPLICATIONS FOR TMDLS

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Abstract

In the humid region of the eastern cornbelt efforts to optimize productivity of poorly drained soils has led to increased spatial intensity of agricultural tile drains. This intensification in installation of drainage tile is often a primary management consideration when field cultivation is being minimized or eliminated entirely. The objective of this study was to quantify the effects of tile spacing on the concentration and flux of nitrate in tile effluent. Continuous corn was grown on a well-structured, poorly drained soil with subsurface tile drainage spacing treatments of 33, 66 and 100 ft (10, 20 and 30 m). Hourly rainfall and tile flow volumes were measured and a flow-weighted water sample was analyzed for nitrate nitrogen concentration. Within discrete flow events in March, April, May and June (1995-2000), significant effects of tile spacing on nitrate concentration were occasionally observed. However, for low to moderate rainfall events, nitrate flux was proportional to flow and the slope of the relationship was not significantly different for the tile spacing treatments. Decreasing distance between tile lines significantly increased the drainage flow volume and thus the mass loss of nitrate to surface water. Measurements in surface waterways in a predominantly agricultural watershed also demonstrate that flux can be predicted from flow volume alone. Current approaches to water quality management and TMDLs are based on monitoring concentration not flow. Our data suggest that if nutrient load management is the objective of regulation, flow volume and its assessment should be the monitoring/management focus.

Introduction

Analysis of agricultural contributions to surface and ground water pollution continue to identify the north central region of the US as the geographic region with the largest nutrient, especially N, loss (Burkart and James, 1999). In the humid region of the eastern Corn Belt, artificial subsurface drainage is common for removing excessive soil moisture from highly-productive, fine-textured soils and creates a conduit for soluble agricultural chemicals to move into surface waters (Kladivko et al., 2001). Water from subsurface drains is a documented source of nitrates (e.g. Logan et al., 1993; Randall and Iragavarapu, 1995; Randall et al., 1997).

This intensification in installation of drainage tile is often a primary management consideration when field cultivation is being minimized or eliminated entirely. Kladivko et al., (1999) found that annual losses of NO_3-N to subsurface drains ranged from 14 to 105 kg ha^{-1}, with the exact amount of loss reflecting factors such as yields, drain spacing, environmental conditions and drainflow volume. Farmers seeking to optimize productivity across a field realize that correcting drainage problems represents the management investment most likely to provide productivity returns, but, at present, this estimation of return on investment does not include any assessment of potential environmental impacts. With the advent of nutrient management plans and regulations to protect surface water quality farmers will also need to have access to information for evaluating the environmental costs of drainage intensification.

In a watershed water quality assessment, Hatfield et al. (1998) demonstrated that cumulative nitrate loads parallel water discharge patterns which both closely track precipitation. In this study, concentrations of nitrates in surface waters were highest when rates of drainage discharge were greatest, suggesting reductions in flux (total mass loss) would require management strategies that significantly reduce overall nitrate concentrations and/or that reduce concentrations in the early part of the crop growth season when flux is highest. Yet, knowledge concerning quantitative impacts on watershed water quality following the implementation of management options such as the spatial intensity of tile lines remains imperfect, a knowledge gap with potentially significant negative consequences for corn belt profitability. Pending enforcement of the Total Maximum Daily Load (TMDL) component of the Clean Water Act and development of regulations related to management practices in the landscape are both predicated on the assumption that implementation of a specific management strategy will produce a quantitatively predictable effect on surface water nutrient loading rates. The need for science to inform developing policy and generate real improvements in rural landscape management while maintaining farm profitability has become critical (Houck, 1999; Jones, 1999).

This study is part of a larger, multidisciplinary Purdue University research program dedicated to enhancing our understanding of the relationships between resource management strategies, crop productivity and surface water quality. The specific objectives of this study were to determine the effects of distance between subsurface tile drains on (1) the nitrate concentrations in drainage water, (2) the volume of water that is removed by the artificial drains, and (3) the flux of nitrate from fields to surface waterways. On-going watershed scale studies are focused on quantifying relationships between nutrient concentration, surface water discharge volume and total nutrient load loss in agricultural landscapes.

Materials and Methods

Small Plot Studies

Small plot studies were conducted at the Water Quality Field Station (WQFS) located at Purdue University's Agronomy Research Center in Tippecanoe County, Indiana. The WQFS site is typical of the tile-drained, intensively cropped areas of the humid region of the eastern corn belt. The soil is a well structured Mollisol (Drummer silty clay loam; fine-silty, mixed mesic Typic Haplaquoll). In 1991, agricultural tile drains were installed at a depth of 33 inches (1 m) at spacings of 33, 66 and 100 ft (10, 20, and 30 m) with two replications of each tile spacing treatment (figure 1). In 1992 a monoculture (continuous) corn cropping system was established. This study reports on crop production years 1995 through 2000.

Tillage operations at the WQFS included chisel plowing in the fall and disking followed by a pass with a field cultivator in the spring. Pioneer 34G81 was planted in '95, '96 and '98 - '00 (27,000 seeds/A) and Pioneer 3491 was planted in '97 (29,600 seeds/A). Planting dates ranged from the last week in April to the third week of June depending on soil temperature and moisture conditions. Insecticides and herbicides were applied as needed. Soil samples were collected each year following harvest, and P, K and lime were fall-applied following Tri-State Fertilizer Recommendations (Vitosh et al., 1995). A liquid knife applicator was used to apply 160 lb. N/A (28% UAN solution) 1 wk before planting. At planting, 20 lb. N/A (19-17-0) starter were placed (2 x 2) below the seed. The total N rate of 180 lb. N/A was based on university recommendations for a yield goal of 155 bu/A (Vitosh et al., 1995). In 1996, excessively wet spring conditions delayed all field operations until June and N was applied as a sidedress application (120 lb./N acre) on July 1st. Grain yield was collected in 4 row (10 ft) x 160 ft passes across the plots so that yields collected directly over a tile drain could be compared with yields at 10 foot increments away from the tile drain. Grain subsamples were collected from each harvest pass and analyzed for moisture (Dickey John GAC 3000 Moisture Meter), and yields were corrected to 15.5% moisture content. Grain was analyzed for total nutrient content according to recommended protocols.

Tile water flow and nutrient content was quantified year round. A magnetic sensor switch mounted on a tipping bucket (volume of 1 liter/tip) was used to quantify tile drainage volume discharged. Sensor data was recorded with Campbell CR10 data loggers (Campbell Scientific, Logan, Utah) and stored on an hourly basis. Ten-millimeter samples were collected from every other tip event and composited in a covered receiving bucket (20 gallons) placed adjacent to the tipping bucket. Every 24 hours the receiving bucket was emptied and a subsample of this cumulative composite water sample was taken to the lab for analysis. These samples were filtered (Whatman #2) and immediately analyzed for nitrate and ammonium (Lachat QuikChem Flow Injection Analyzer, Lachat Instruments-Zelleweger Inc., Milwaukee, WI). If analysis could not be completed immediately, samples were frozen and stored.

Tipping bucket rain gauges (Campbell Scientific, Logan, Utah) were installed at the north and south ends of the experimental site. Hourly rainfall volumes were electronically recorded with the Campbell CR10 data loggers. Rainfall and tile flow volume data were downloaded biweekly using Campbell Scientific PC208 software.

Thirty-year averages show that March through July are typically the wettest months of the year. Preliminary analysis of the data from the WQFS indicates that tile drainage flow volumes (amount following specific rainfall events as well as monthly averages) are greatest in March, April and May (figure 2). Tile flow volumes begin to fall off in June when evaporation increases with increasing daily mean temperatures, and they become almost negligible in July when rainfall inputs are lower, evaporation rates are high and crop transpiration rate becomes significant. Therefore, we focused the flow, concentration and flux data analysis on discrete 3 wk intervals in March through June. Selecting 3 wk intervals permitted us to avoid occasional periods in time where flow or concentration data were missing due to instrumentation failure. Analysis of variance and t-tests were used to evaluate the impacts of tile spacing on crop productivity and nitrate concentration in drainage water. Regression analysis was used to evaluate the correlation between flux of nitrate and flow volume of water.

Watershed Scale Studies

In order to extend the results from plot studies on management practice impacts on water quality such as those described at the WQFS to the watershed scale, related research on flow and nutrient concentration in agricultural ditches and surface waterways is currently ongoing in two rural watersheds located in White County, Indiana. The adjacent watersheds are tributaries to Lake Shafer, a major recreational lake in northern Indiana (figure 3). The land use in the Hoagland Ditch and Honey Creek watersheds is predominately agricultural with 92% of 70.2 mi^2 and 85% of 41.6 mi^2 in row crops, respectively. In spring 2000, twenty-one sampling locations were established for collection of weekly samples for nutrient content analysis. Four of these locations were also equipped with automated data loggers to measure stage (water level) at 30 minute increments. Discharge (flow volume) at these locations was estimated from the stage measurements using the power function:

$$Q=p\ (h-e)^b$$

where Q is water discharge (m3/s), p and b are constants, h is the observed stage (m) and e is the stage at zero flow (m). Initial calibration of the equation involved making manual discharge measurements at different low flow stages according to procedures outlined by the U.S. Geological Survey (Buchanan and Somers, 1969) and using Manning's Equation to calculate high flow discharge. For complete details on watershed land-use characterization, sampling locations and discharge quantitative methods, see DeBroka et al. (2001).

Regression was used to evaluate the relationship between nitrate concentration and discharge (as measured directly and corrected for the area of cropland above the point of discharge measurement) at the two stage measurement locations in Hoagland Ditch.

Results and Discussion

Effect of Tile Spacing on Yield

Average corn yields ranged from under 100 bu/A (1995) to over 160 bu/A (1997) and the significant differences in yields among years (figure 4) can be related to differences in weather conditions. Specifically, lowest yields were observed in years when May (1995) or April (1996 and 1999) rainfall totals are well in excess of 30 yr averages (figure 5) and planting dates were delayed. For the six years of the study tile spacing did not significantly affect average crop yields (figure 4). Analysis of yield as a function of distance from the tile drain within a treatment plot also showed no effect of tile spacing (figure 6). While analysis of interaction of tile spacing with spring rainfall totals is not yet complete, this preliminary analysis suggests that advantages of narrow inter-tile distances will need to be related to management operation considerations alone as they may not translate into a yield advantage.

Effect of Tile Spacing on Flow Volume from Tile-Drained Fields

The percent of rainfall that leaves a given field as tile drainage water is a function of the antecedent soil conditions, rate of water input to the field, soil type and field slope. For example, if the soil is saturated and rain falls at a steady but moderate rate onto a relatively flat field that is naturally or artificially moderately- to well-drained, then the majority of the rainfall in any additional rainfall event will cause an equal amount of water to leave the field as subsurface drainage. If the soil is not at field capacity, then the volume of water leaving the field as drainage will be a smaller proportion of the volume coming in as rainfall. All other conditions being equal, fields with steeper slopes will have a greater percentage of incoming rainfall go to runoff. Likewise, fields with heavier soils or smaller amounts of surface residue will also have greater runoff and/or soil retention versus infiltration when compared to sandier soils or those with more surface residue.

Figure 7 shows a scatter plot of the percentage of the total rainfall volume for a given 3 wk interval that left the treatment plot as drainage water. For specific incoming volumes of rainfall that were relatively low (less than 750,000 L/ha or 80,250 gal/A or ~3 inches of rain), the percent leaving the plot ranged from 0 to 100% (figure 7). This range reflects the differences in antecedent soil conditions but also shows pronounced effects of tile spacing. For example, at lower rainfall totals (<750,000 L/ha) the amount of water leaving the field through drains spaced at 33 ft intervals frequently equaled the incoming rainfall amount (100% removal). However, for the same amounts of incoming rainfall, the percent of water leaving the field as drainage never exceeded 82 and 62 % for tile spacings of 66 and 100 ft, respectively. For the range of total rainfall amounts observed in this study, narrower tile spacings had the potential to permit a greater amount of the incoming rainfall to enter surface waterways. At higher rainfall amounts, the maximum percent of water leaving a field through drainage declines for all tile spacings as the capacity of the drainage system is exceeded and the excess water ponds or runs off the soil surface.

Effect of Tile Spacing on Nitrate Concentration and Flux in Drainage Water

Ranges and average nitrate concentrations in tile drainage water for a given tile spacing are reported by year in Table 1. While the trend is for concentrations from 100 ft tile spacings to be higher than those observed in narrower tile spacings (and these differences were occasionally significant within a given year), average differences over all years were small in magnitude and not statistically significant. Furthermore, concentrations ranges and distributions for the individual daily samples tended to be similar for all tile spacing treatments and there was no apparent relationship between flow and concentration (figure 8).

Plotting flux (total amount of nutrient in the tile drainage water) as a function of the flow shows a strong linear relationship at lower flow volumes that is not affected by tile spacing (figure 9). At higher flow volumes flux appears to level off, an observation that likely reflects that soil profiles have been flushed of nitrate and nitrification of NH_4^+ has not kept pace with leaching.

Relationship between Nitrate Concentration and Flux in an Agricultural Watershed

The WQFS results differ somewhat from relationships between flow and concentration observed at the watershed scale level. Between May 2000 and February 2001, watershed discharge was greatest during June, the month of greatest total rainfall (figure 10 and figure 5). However, nitrate concentrations exhibited two periods of peak concentration. The first coincided with the discharge peak, while the second occurred in winter (Nov. through Feb.) when discharge was relatively low. This bimodal distribution in seasonal nitrate concentrations that does not track discharge in winter suggests that there is another significant source of N to the watershed in addition to cropland leaching. Municipal and highway rest area sewage treatment plant releases are currently being investigated as well as residential septic systems.

However, plotting concentration as a function of flow volume demonstrates that, in general, nitrate concentrations increase linearly with discharge (figure 11a) as in the WQFS small plot data. Furthermore, identical relationships were observed at two different points in the watershed when the discharge values were weighted for the area of cropland contributing to the drainage volume (figure 11b). Calculating flux at selected locations in the watershed and plotting them as a function of flow reveals that, as in the small plot work, the load or mass of nitrates in a surface water could be predicted from the flow volume alone (figure 12). These results suggest that in agricultural watersheds management practices that effect concentration of nitrate in tile drainage water may be less important for nitrate load than practices that significantly alter volume of discharge.

Summary

Small plot studies on drainage tile spacing intensity demonstrated the magnitude to which inter-tile distance alters field discharge volumes from poorly drained soils with high productivity potential. The impact of tile spacing on concentration of nitrates in tile water appeared minimal and mass nitrate loss to surface water was directly correlated with discharge volume. Complimentary watershed studies indicated that nitrate loads in agricultural landscapes could also be predicted from flow volume alone and might not be related to nutrient concentration measurements. Current approaches to water quality management and TMDLs are based on monitoring concentration not flow. Furthermore, there is an expectation that changes in management practices in the landscape will produce measurable changes in surface water nutrient concentrations that will be relevant to load reduction. Our data suggest that if nutrient load management is the objective of regulation, flow volume and its assessment should be the monitoring/management focus.

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Figure and Table Captions

Figure 1. Experimental design for the tile spacing treatments at the Purdue University Water Quality Field Station (WQFS). Only water from the center tile line of each treatment was collected.

Figure 2. Volume of water flow from drainage tiles spaced 66 ft (20 m) apart in 1998, 1999 and 2000. Typically, the majority of the flow occurs in a one hundred day period between Julian Date (JD) 61 (March 1st) and JD 161 (the end of the first week of June).

Figure 3. Sampling and stage measurement sites for the agricultural watershed assessment study that is currently ongoing in Hoagland Ditch and Honey Creek, White County, Indiana.

Figure 4. Annual variation in crops yields at the WQFS experimental site. Groups of columns with the same letter indicate annual average yields that were not significantly different. Analysis of variance found no tile spacing treatment effect on whole plot yield in any year of the study.

Figure 5. Cumulative monthly rainfall totals for each year of the study. The red line shows the 30-year average.

Figure 6. Yields for individual combine passes as a function of distance from a tile line. Values are means across tile spacing treatments over the six years of the WQFS study. The effect of distance from a tile line on yield was not significant.

Figure 7. Percent of rainfall that was measured leaving the plots as tile drain flow. Each data point represents a 3-wk interval during March, April, May or June for a replicate of a given tile spacing treatment. All six study-years are shown.

Table 1. Mean nitrate concentrations and nitrate concentration ranges measured in each tile spacing treatment at the WQFS.

Figure 8. Nitrate concentration plotted as a function of the flow volume for both replicates of tile spacing treatments of 33 ft (10 m) and 100 ft (30 m) in 1998 at the WQFS.

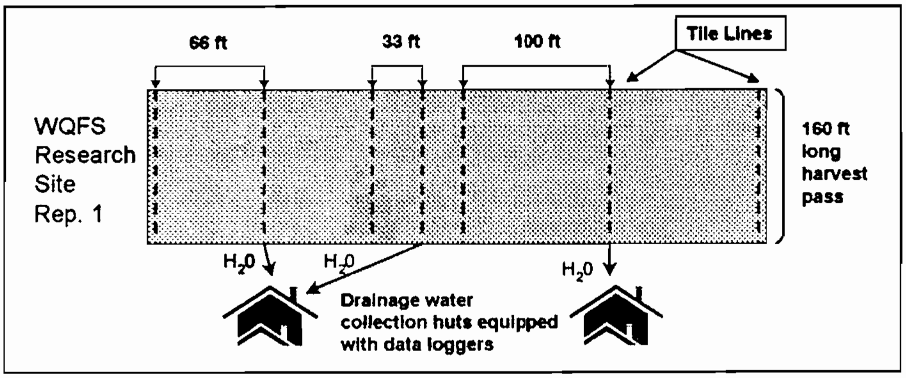
Figure 9. The relationship between nitrate flux or mass loss and water loss (tile drain water removal) per unit area of field at the WQFS (1 liter/ha = 0.11 gal./A; 1 kg/ha = 0.89 lb/A).

Figure 10. Water flow (discharge rate) and nitrate concentration at one of the monitoring locations (Hoagland Ditch No. 10 (HD10)) in the watershed study plotted as a function of date of collection.

Figure 11. Nitrate concentration shown as a function of discharge at watershed sample locations HD 10 (shown in figure 10) and HD 5. Figure 11a shows concentration as a function of measured rate of discharge while figure 11b shows concentration as a function of discharge rate weighted for the area of cropland potentially drained by the agricultural ditch at the separate geographical sample points (discharge per unit row crop area in that portion of the watershed). Note that discharge data are plotted on a log scale for ease of visual interpretation.

Figure 12. Calculated nitrate flux or mass loss at watershed sample locations HD 5 and HD 10 plotted as a function of discharge per unit row crop area in that portion of the watershed. Note that flux and discharge data are plotted on a log scales for ease of visual interpretation.

Figure 1



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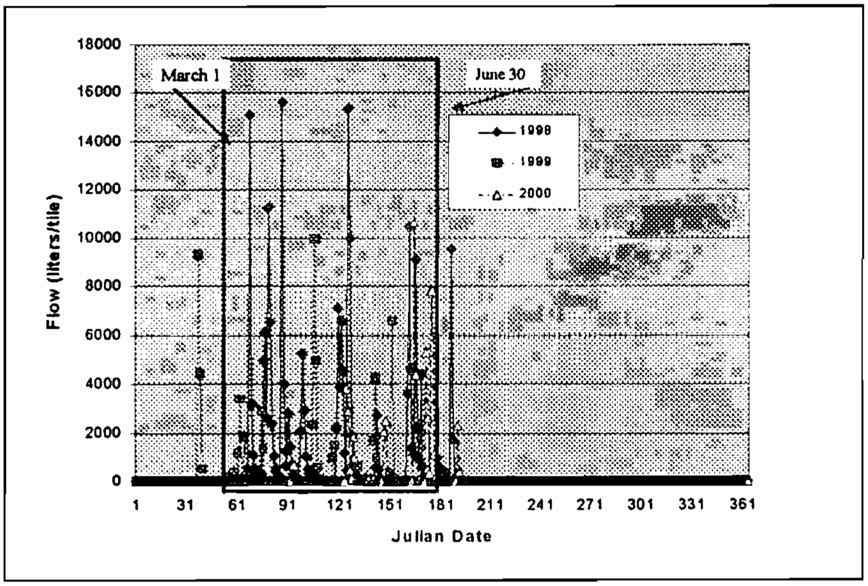

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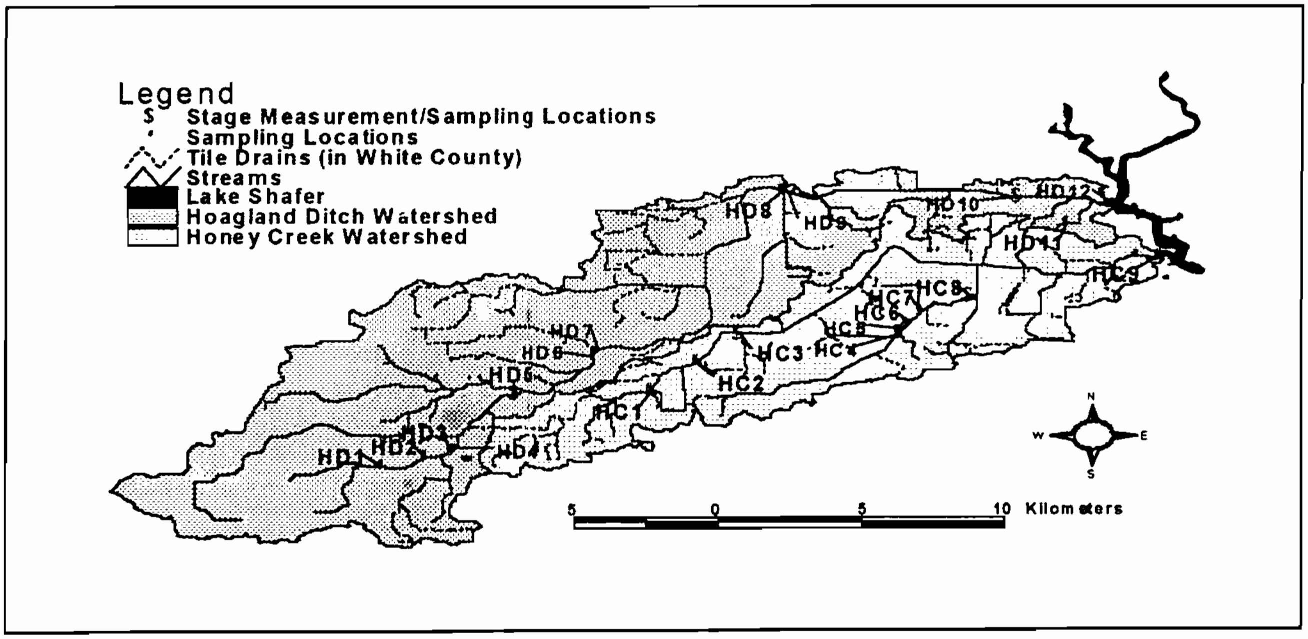

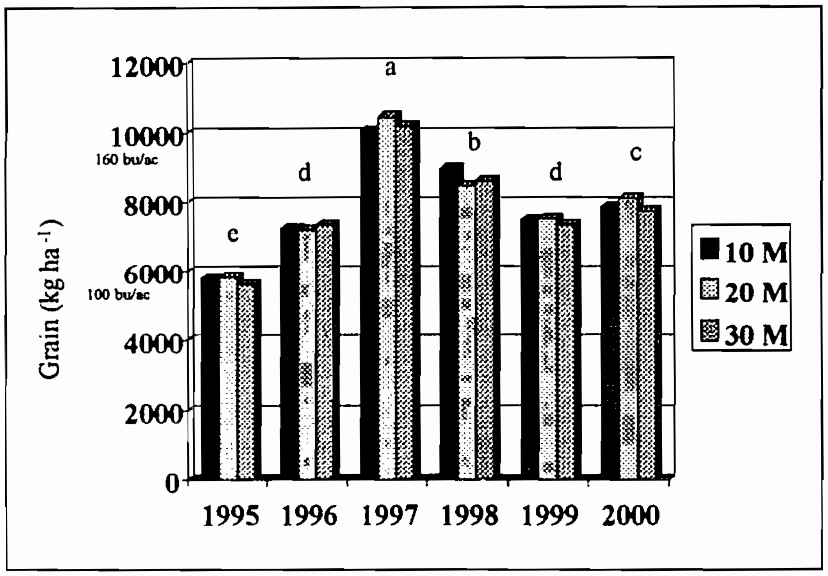

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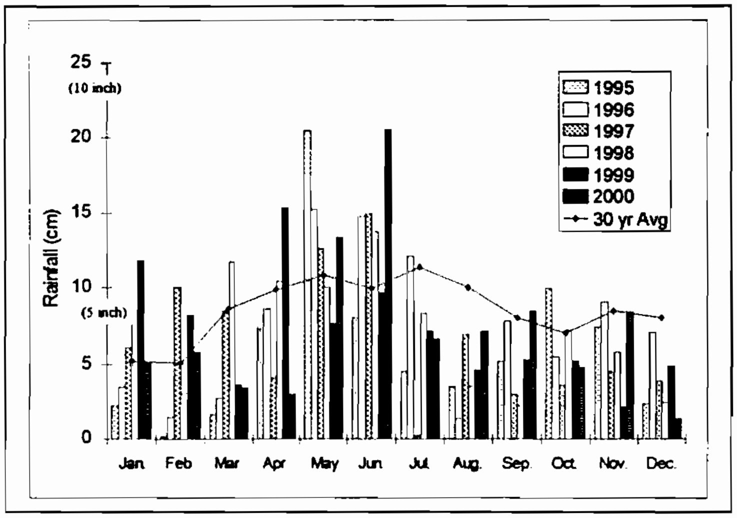

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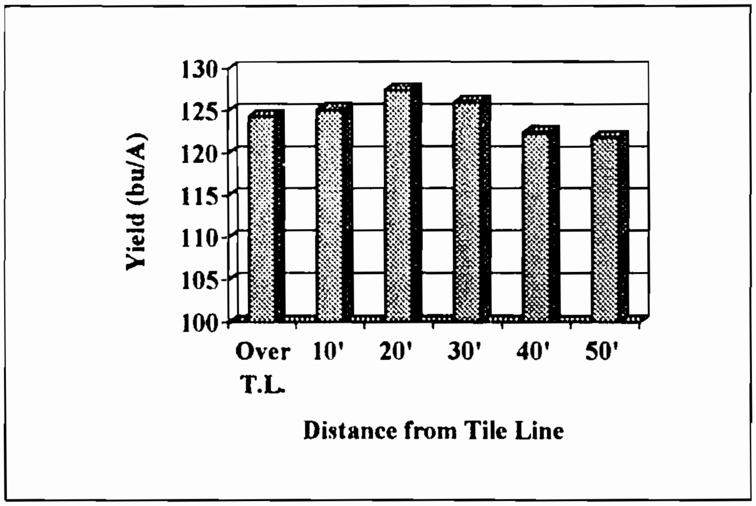

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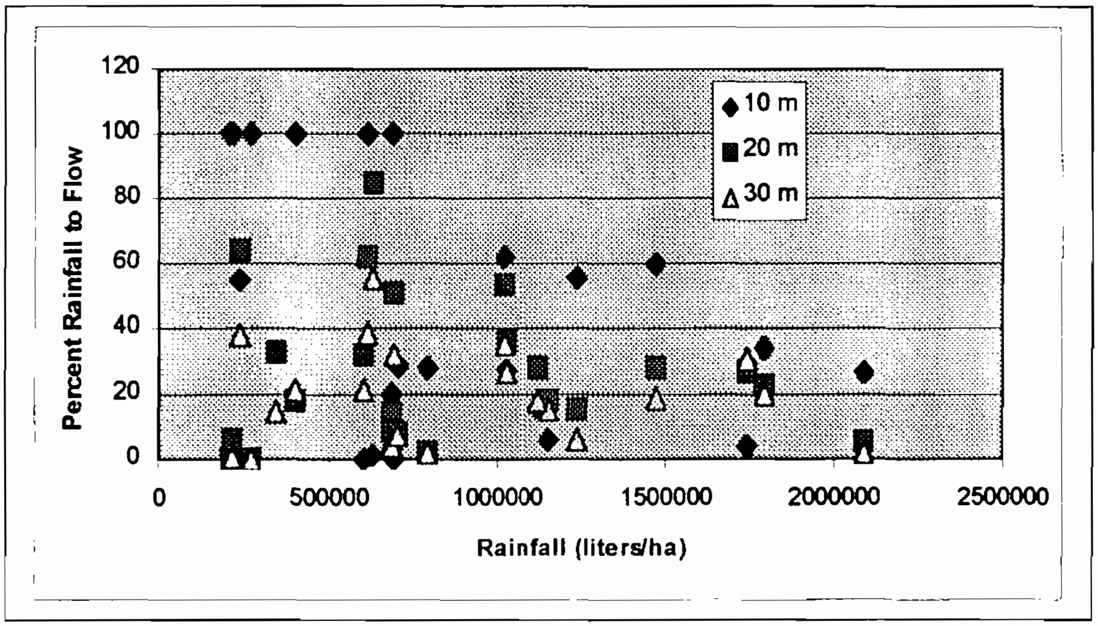


Figure 7

Table 1. Nitrate concentrations (ppm) in drainage water for tile spacings of 33 ft (10m), 66 ft (20 m) and 100 ft (30m).

Spacing	1995	1996	1997	1998	1999	2000
10	19.1	39.4	30.5	26.2	7.1	20.1
	(3.4-36.2)	(7.9-64.7)	(18.1-33.7)	(18.1-33.7)	(1.3-12.9)	(4.9-36.8)
20	15.4	35.1	23.3	20.0	8.3	21.6
	(1.0-29.9)	(12.6-66.6)	(9.1-38.6)	(0.4-28.7)	(0.2-14.8)	(5.3-31.7)
30	22.6	46.0	30.9	24.2	9.7	25.3
	(6.3-32.6)	(18.3-79.2)	(16.5-43.7)	(12.5-47.9)	(1.6-13.5)	(10.6-47.1)

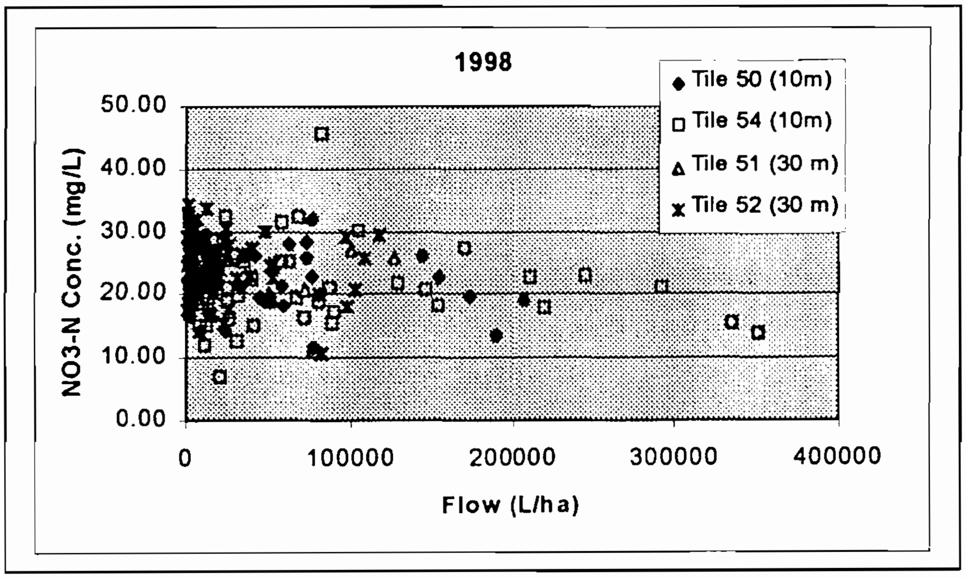
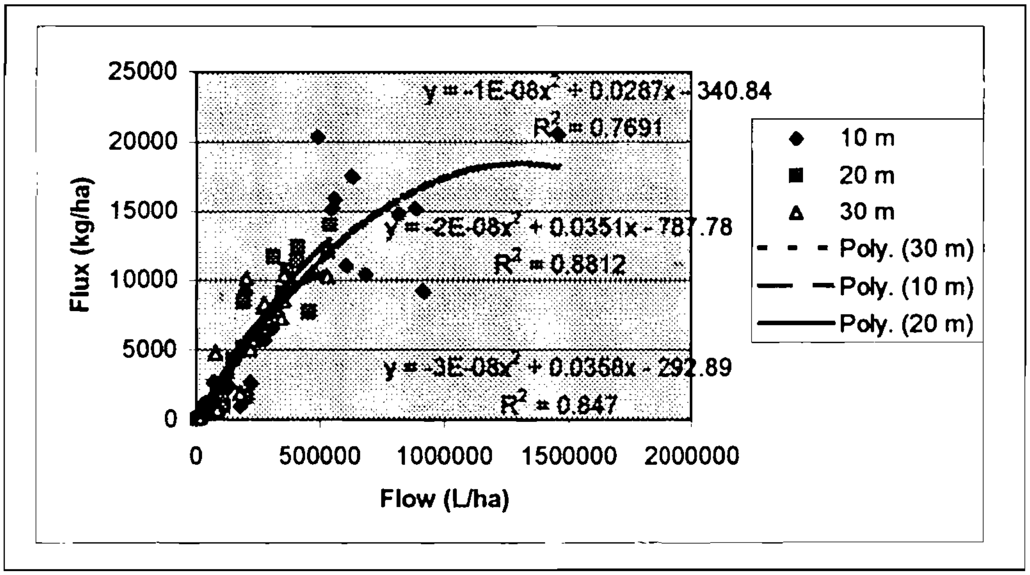


Figure 8



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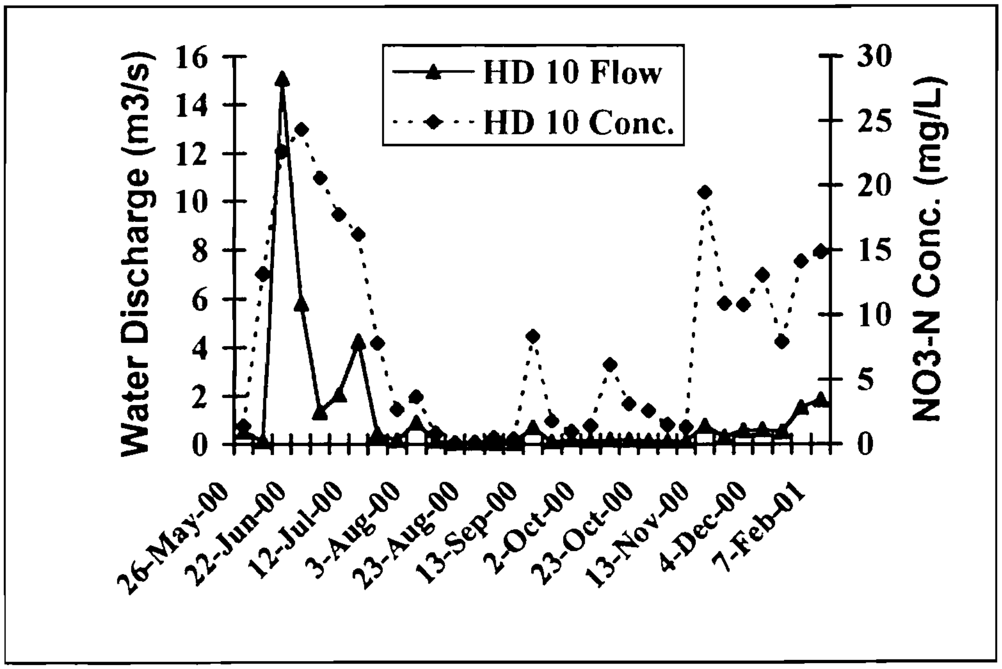

Figure 10

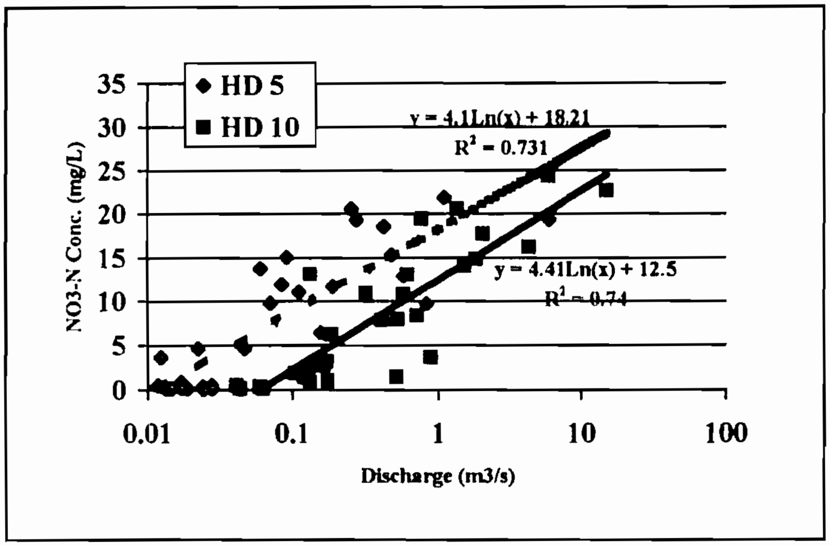

Figure 11a

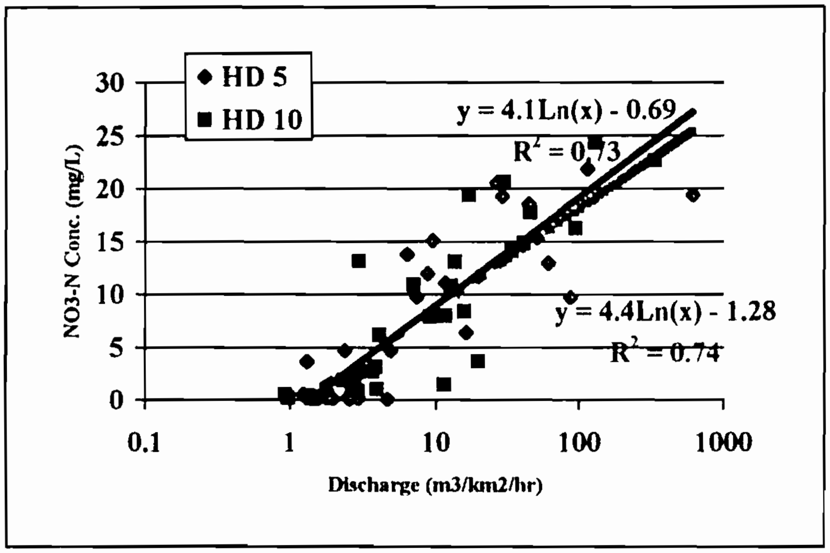

Figure 11b

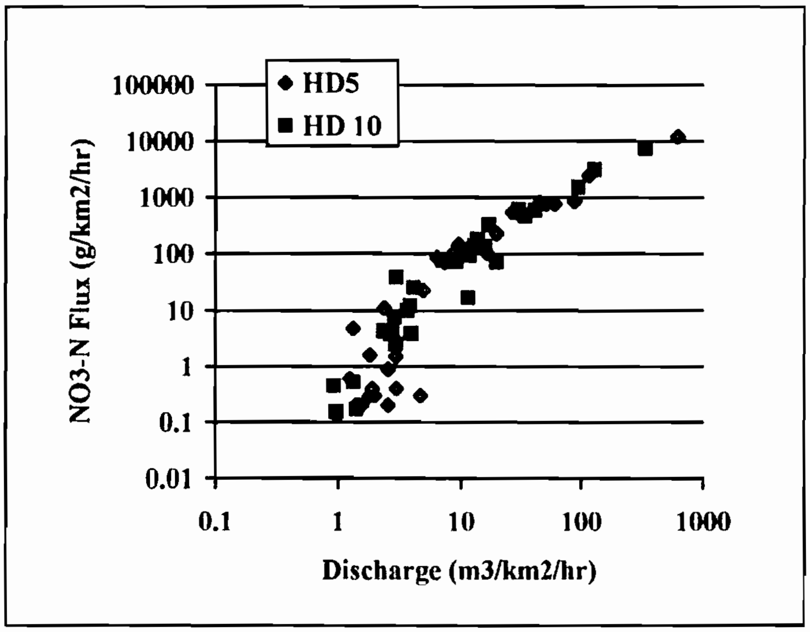

Figure 12

PROCEEDINGS OF THE

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