EFFECTS OF SUBSURFACE DRAINAGE DESIGN ON THE WATER QUALITY

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Abstract

Some of the highest losses of nitrate to surface waters come from drained agricultural land. Given previous this article studied for Belgian farming conditions (i) the effect of subsurface drainage density on nitrate losses and (ii) the economics of nitrate emissions, using the nitrogen version of DRAINMOD (Brevé et al., 1997 a and b). DRAINMOD (Skaggs, 1997) was used to simulate the performance of the drainage system of the Hooibeekhoeve experiment, situated in the sandy region of the Kempen (Belgium), and this for a 14-year (1985-1998) period. In the analysis a continuous cropping with maize was assumed. Daily NO_3-N losses were predicted for a range of drain spacings and depths, two drainage strategies (conventional and controlled) and three fertilizer application dressings (225, 275, 325 kg N ha^{-1}). Losses of N in subsurface drainage occur almost entirely in the NO_3-N form. Losses of organic and inorganic N in the form of NO_3-N in surface runoff are small and can be neglected. Hydrologic results indicated that increasing drain spacing or decreasing drain depth reduces drainage discharge while it increases runoff. The use of controlled drainage reduces subsurface drainage and increases runoff. Results also revealed that increasing the drain spacing or decreasing the drain depth reduces nitrate-nitrogen (NO_3-N) drainage losses and net mineralization, while increasing denitrification and runoff losses. Controlled drainage caused a predicted reduction in drainage losses and an increase in denitrification and runoff losses. The optimal combination of drain density and management is one that maximizes profits and minimizes environmental impacts. Simulated results indicated that NO_3-N losses to the environment could be substantially reduced by reducing the drainage density below the level required for maximum profits based on grain sales. The study concluded that, if the environmental objective is of equal or greater importance than profits, the drainage systems can be designed and managed to reduce NO_3-N losses while still providing an acceptable profit.

Keywords: hydrology, water quality, conventional drainage, controlled drainage, economic analysis

1. Introduction

Although fresh water and nutrients are essential components, they may become unbalanced as a result of anthropogenic activities. Artificial drainage is frequently criticized as the primary cause of surface water quality problems. This criticism often occurs, without consideration or knowledge of documented drainage water characteristics, simply because soils with drainage improvement are in close proximity to environmentally sensitive waters (Evans et al., 1995).

Nutrients are delivered to estuaries and lakes by discharge from river, atmospheric deposition through rainfall and groundwater discharge. They are derived from point sources (wastewater treatment plants, industrial and municipal discharges) and from non-point sources (runoff from agricultural and forested lands, rural communities and atmospheric deposition) (Skaggs and Chescheir, 1999). The design and management of drainage and associated water table control systems have a substantial effect on drainage water quality (Skaggs et al., 1994). The challenge in current drainage research is to design and manage drainage and related water table control systems with the combined goal of satisfying both production and water quality objectives.

The research presented herein aimed at studying and comparing the characteristics of conventional and controlled drainage in relation to their effect on agricultural profit and water quality. Furthermore, the effects of the subsurface drainage density and N-fertiliser practice on nitrate losses to surface waters were studied, using DRAINMOD-N (Brevé et al., 1997 a and b). DRAINMOD (Skaggs, 1997) was used to simulate the performance of the drainage system of an experimental field at the Hooibeekhoeve, situated in the Kempen, Belgium, using a 14-year period of climatological data.

2. Method

DRAINMOD-N was applied in this research to examine the effects of subsurface drainage on water quality, with application to a study area in the northern part of Belgium. DRAINMOD-N is based on the water balance calculations of DRAINMOD (Skaggs, 1997). DRAINMOD model is used to simulate the performance of drainage and related water table management systems. It uses modifications described by Skaggs et al. (1991) to determine average daily soil-water fluxes and water contents by breaking the profile into increments and conducting a water balance for each increment. In the saturated zone, vertical fluxes are linearly decreased from Hoodghout's drainage flux at the depth of the water table to zero at the impermeable layer depth. In addition, a water content profile is generated using soil-water characteristic data, based on the assumption of hydrostatic conditions above the water table at the end of the day. This approach for computing fluxes and water contents proved to be reliable for soils with shallow water table as indicated by comparisons with numerical solutions of the Richards equation for saturated and unsaturated flow (Karvonen and Skaggs, 1993). Since DRAINMOD fluxes are computed at midpoint between the drains or as the average vertical flux in the zone between drains depending on the drainage algorithm used, the predicted solute concentrations correspond to the same location.

3. Materials

In this study, the DRAINMOD model was calibrated using historic field data collected for 14-year period (1985-1998) on the experimental site of the Hooibeekhoeve, situated in the community of Geel, the northeastern sandy region, the Kempen, of Belgium. During the period of experimentation the field was cropped with maize. As fertiliser only organic manure was applied. Missing data, required to run the model, such as the soil hydraulic parameters (van Genuchten and Nielsen, 1985), were either supplementary measured on undisturbed soil cores or reconstructed by using the pedo-transfer functions of Vereecken (1988), as indicated by Ducheyne and Feyen (1999). DRAINMOD-N was applied to evaluate long-term effects of several drainage and related water table control systems on nitrogen-nitrate losses.

In the scenario-analysis it was assumed that the field, for which DRAINMOD-N was calibrated, was equipped with a subsurface drainage system consisting of parallel, 10 cm diameter, corrugated plastic drains. The drainage designs evaluated consisted of four drain depths (0.75, 1.00, 1.25, and 1.50 m), four drain spacings (25, 50, 100, and 300 m), and three fertilisers strategies (225, 275, and 325 kg N ha^{-1}). The management treatments included conventional and controlled drainage. Detailed inputs for the maize production practices and NO_3-N transport and transformation variables are listed in Table 1.

Table 1: Summary of inputs for DRAINMOD-N

Soil properties:	
θ_{sat} (cm^3 cm^{-3})	0.48 (0-35 cm)
	0.43 (35-50 cm)
	0.42 (50-100 cm)
	0.42 (100-200 cm)
θ_{wp} (cm^3 cm^{-3})	0.17
Bulk density (g cm^{-3})	1.6
Organic nitrogen in top soil (μg g^{-1})	3200
K_{mnl} (d^{-1})	$3.5x10^{-5}$
K_{den} (d^{-1})	0.40
Lateral Saturated hydraulic conductivity (m d^{-1})	0.55 (0-30 cm)
	0.19 (35-50 cm)
	0.16 (50-100 cm)
	0.13 (100-200 cm)
Drainage system parameters:	
Drain depth (m)	0.75, 1.00, 1.25, 1.50
Drain spacing (m)	25, 50, 100, 300
Surface storage (cm)	2.5
Effective drain radius (cm)	2.5
Maize production parameters:	
Desired planting date	May 4
Length of growing season (d)	120
N-fertiliser input (kg N ha^{-1})	225, 275, 325
Date fertiliser application	April 14, May 14
Depth fertiliser incorporated (cm)	10
Total dry matter production (kg ha^{-1})	14500
Other nitrogen model parameters:	
Dispersivity (cm)	10
NO_3-N content of plant (per cent)	1.55
NO_3-N concentration of rain (mg l^{-1})	0.8

For the experimental site a cost benefit analysis was performed to determine the optimum drain spacing, drain depth, fertiliser strategy and water management combination. The costs considered in the economic analysis include the production costs, and the installation and maintenance costs of the drainage system. A detailed description of the production costs is presented in Table 2. Drainage system costs, as listed in Table 3, are based on estimated prices of drain tubing installation and control structure costs. Annual maintenance costs was taken as a fraction (3%) of the annual amortization costs of the drainage system. Annual income figures are based on a maximum total dry matter production of 14500 kg ha^{-1} and a maize market price of 5.16 BEF kg^{-1}.

Table 2: Estimated costs for maize production in Geel, Belgium

Variable costs:	BEF ha^{-1}
Costs tillage + planting	13 050
Fertiliser costs	7 988
Pest and weed control	5 689
Harvest costs	11 500
Post-harvest expenses (sillage)	6 500
Total variable costs:	44 727
Fixed costs:	BEF ha^{-1}
Lease and general costs (Machinery replacement, machinery interest, tax and insurance)	10 000
Total fixed costs:	10 000
Total annual production costs:	54 727

Table 3: Estimated drainage costs for Geel, Belgium

Initial costs:	
Drain tubing	60 BEF m^{-1}
Control drainage structure	1 600 BEF ha^{-1}
Annual maintenance costs:	
Subsurface drainage	3% of the initial cost ha^{-1}

The maize production practices used in the simulations are characteristic for the sandy region of the Kempen. The reaction rate coefficients were obtained from ranges published in the literature.

4. Results and discussion

4.1. Hydrology

For the experimental field in the Hooibeekhoeve, Geel, effects of drainage system management, drain spacing and depth on subsurface drainage and surface runoff are shown in Fig. 1. The average annual rainfall of the simulation period (14-year) is 86.75 cm. Simulation results indicate that increasing the drain spacing reduces subsurface drainage while it increases surface runoff and ET. Increasing the drain depth increases drainage and decreases ET and runoff. Furthermore, controlled drainage reduces subsurface drainage and increases surface runoff, as compared to conventional drainage. The magnitude of these changes increases with the intensity of controlled drainage.

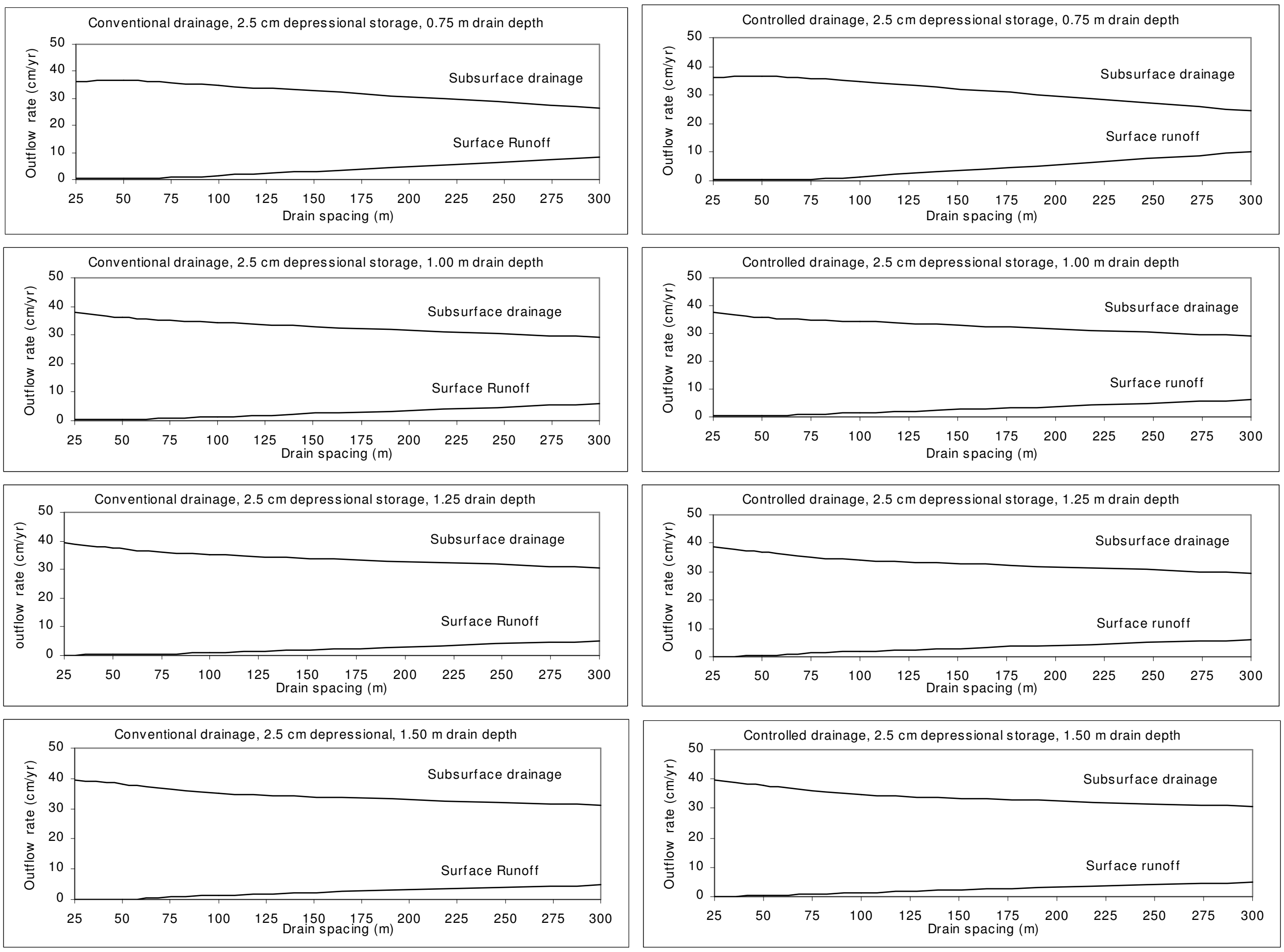

Figure 1: Predicted average annual subsurface drainage and surface runoff as affected by system management, drain depth and spacing

4.2. Water quality

Effects of drainage system management, drain spacing and depth on the nitrogen budget components (drainage losses and runoff losses) are show in Fig. 2. Simulation results reveal that increasing the drain spacing reduces NO_3-N drainage losses and net mineralization, but it increases NO_3-N runoff losses and denitrification. On the other hand, increasing the drain depth increases drainage losses and net mineralisation, and it decreases runoff losses and denitrification. Furthermore, increasing fertiliser application increases drainage losses, runoff losses and all nitrogen components. The effect on net mineralization is not evident. The use of controlled drainage decreases the subsurface drainage intensity. Hence it reduces drainage losses and increases denitrification and runoff losses, as compared to the use of conventional drainage. The effect of controlled drainage on net mineralization is not clear.

Results of the simulation analysis show that total NO_3-N losses (subsurface drainage plus surface runoff) can be substantially reduced with controlled drainage during the winter season. This can be explained by the climatological conditions in Belgium where drainage is usually maximum during the winter and early spring months.

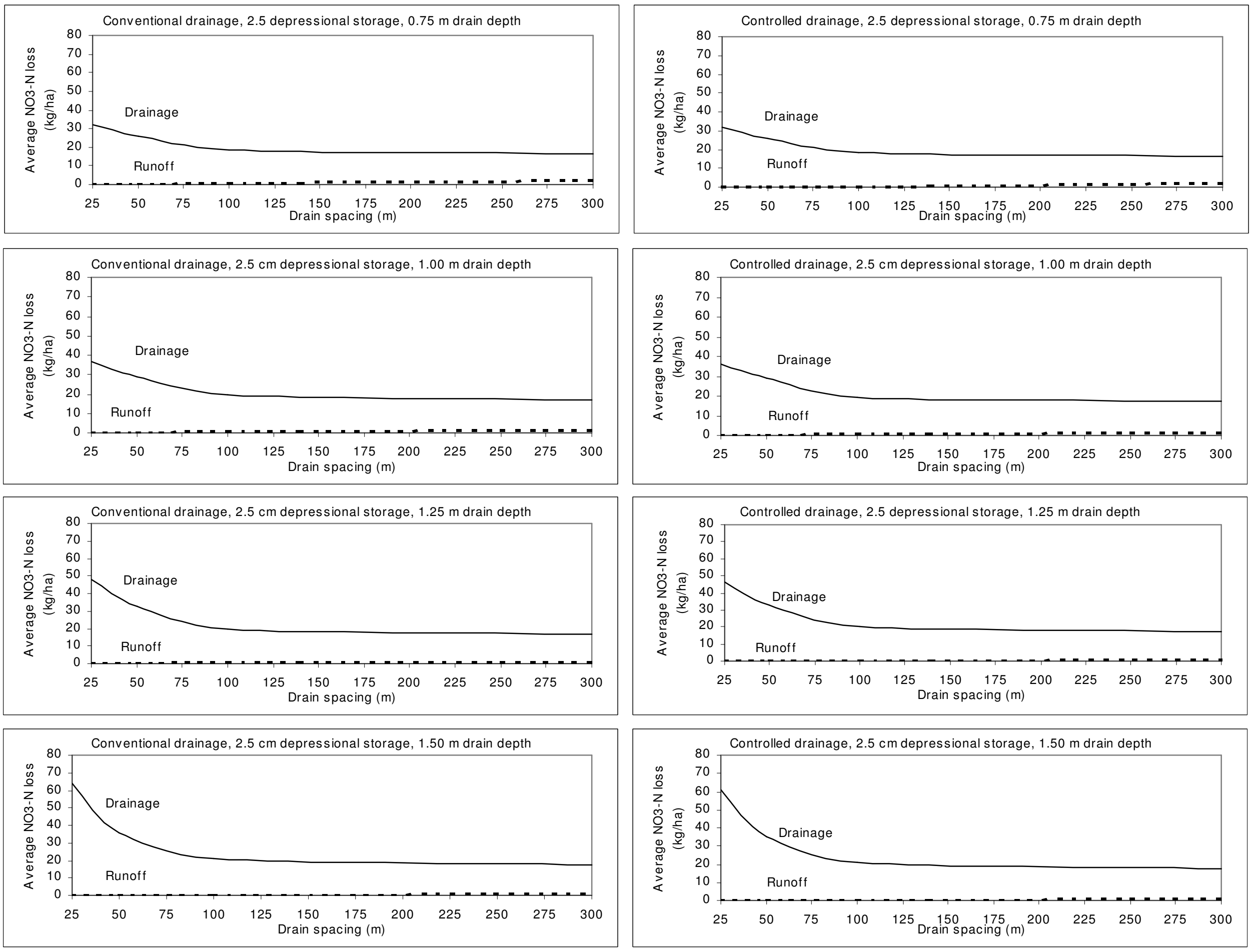

Figure 2: Predicted average annual NO_3-N losses in drainage and runoff as affected by system management, drain depth and spacing. Results are for a 275 kg N ha^{-1} fertilizer strategy

4.3. Economic analysis

Cost benefit results indicate that for the given climate-crop-soil combination a conventionally drained system with 25 m drain spacing and 1.25 m drain depth, is close to optimal. The optimum spacing is 50 m. The predicted net profit associated with this optimum system is 16 687 BEF ha^{-1}. For a drain depth of 1.0 m, profit will be reduced by 1 422 BEF ha^{-1}, but drainage outlets 1.25 m deep may not be available in some cases. Furthermore, the deeper the drains NO_3-N losses increase as will be discussed below.

The economic analysis also reveals that the use of controlled drainage does not increase profits. This is due to a slight decrease in simulated relative yield resulting from the controlled drainage and an increase in the annual drainage system costs as a consequence of the cost of the control structures.

Clearly, the ideal drainage design and management combination is one that maximizes profit and minimizes environmental impact. The economic analysis indicates that the maximum profit for the Geel soil would be obtained with a conventional drainage system, with 50 m drain spacing and 1.25 m drain depth. However, these systems would not be optimum from the water quality perspective. The total nitrate-nitrogen losses associated with the drainage systems producing maximum profit for 225, 275 and 325 kg N ha^{-1} fertilizer application strategies are 28.44, 33.01 and 37.59 kg ha^{-1} yr^{-1}, respectively.

Figure 3 shows the effect of drain spacing and system management on net profit and total NO_3-N losses. The results depicted in Fig. 3 illustrate the benefit of simulation modeling for deriving for the given climate-crop-soil system the drainage density that meets simultaneously the production and environmental objectives. Although it was found that the maximum predicted profits were obtained for 50 m spacing, in practice smaller spacings are applied based on conservative design considerations. The applied conservative drain spacings satisfy the production objective, as indicated by crop yield, even though profits are somewhat reduced.

Results in Fig. 3 show clearly that NO_3-N losses are smaller as the drain density is reduced. Given previous, the NO_3-N losses to the environment can reduced by fitting the drainage system design of the crop-soil system such that the drainage density is not smaller than the required (i.e., drain spacings as wide as possible and drain depths as shallow as possible). Results also indicate that NO_3-N losses to the environment could be substantially reduced by reducing the drainage density below the level required for maximum profits from grain sales. That is, if the environmental objective is of equal or greater importance than profits from the agriculture crops, the drainage systems can be designed and managed to reduce NO_3-N losses while still providing an acceptable profit.

For example, increasing the drain spacing from 50 to 100 m with conventional drainage, with a 275 kg N ha^{-1} fertiliser application and 1.0 m drain depth would reduce total NO_3-N losses by 20%, from 36.58 to 29.26 kg ha^{-1}, while reducing profits by only 260.40 BEF ha^{-1}. Under those conditions the risk of large losses in yields and profits during wet years will increase, but the reduction in NO_3-N losses to surface waters will decrease, which overall might be of greater value.

The NO_3-N losses presented in Fig. 3 show that a substantial reduction is achieved by decreasing the drain depth. If a 1.0 m drain depth is used the projected reduction in total NO_3-N losses is estimated at 17.3%. This would result in a reduction in profit of about 1 122.3 BEF ha^{-1}, but this may be warranted by the accompanying significant reduction in NO_3-N losses. That is, from a societal point of view, it may become less expensive to pay greater prices for grain compared to treating the water to remove excessive NO_3-N. The cost for the removal of 17.3% NO_3-N is estimated at 1 955.2 BEF ha^{-1}. Another way to decreasing total NO_3-N loss is by improving the surface conditions. However, the obtained decrease is not substantial as compared to the associated decrease in profit.

Simulated results indicate that using controlled drainage could reduce total nitrate-nitrogen loss, with however an additional sacrifice in profit. If controlled drainage is used, total NO_3-N losses can be decreased by 4.6% (from 75.94 to 72.43 kg ha^{-1}) for 1.50 m drain depth, 25 m drain spacing and 275 kg N ha^{-1} fertiliser application, as compared to the conventionally drained system. The decrease in profit associated with this management modification is not substantial (15.16 BEF ha^{-1}). Although the controlled drainage may not affect profits, it may substantially decrease NO_3-N losses, and thus, meet both the production and environmental objectives.

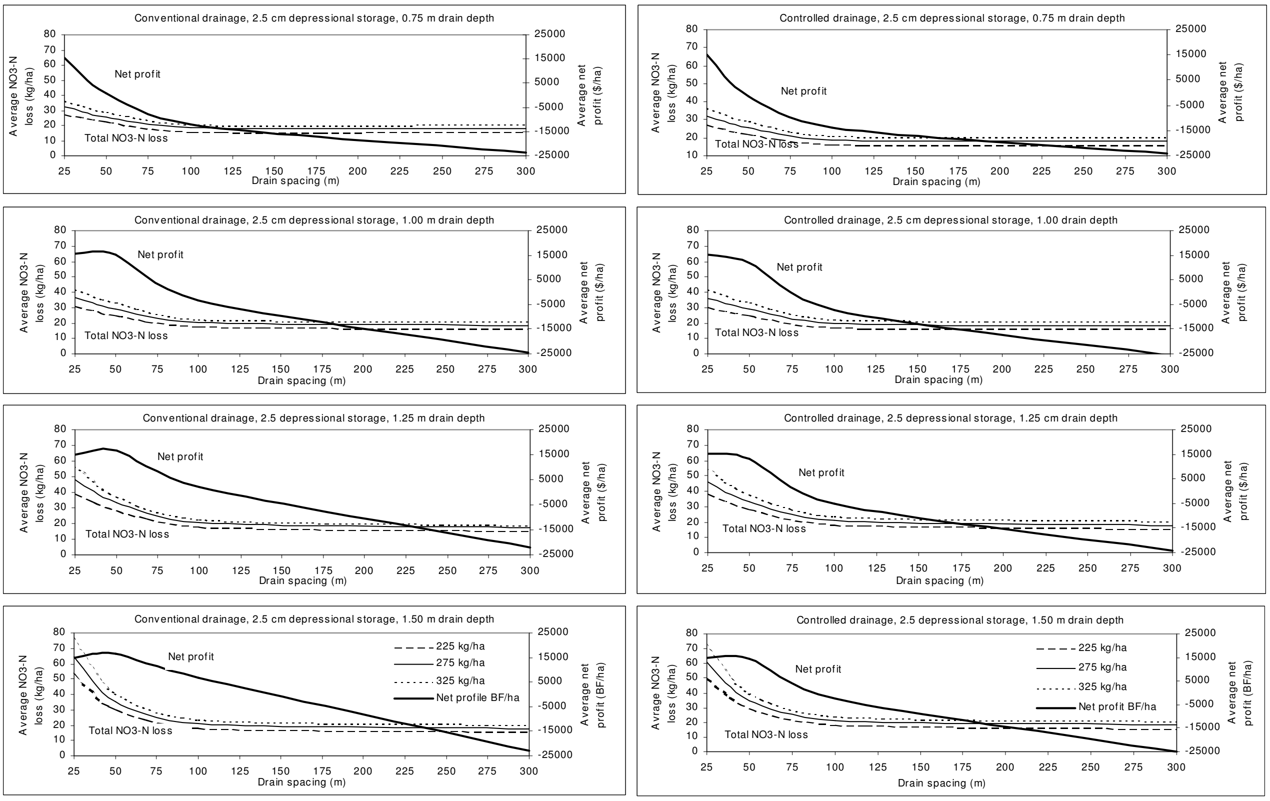

Figure 3: Predicted annual profit and total NO_3-N losses as affected by system management, drain depth and spacing. Results are for different fertilizer application strategies

Maximum annual profit and corresponding NO_3-N losses are plotted as functions of drain depth in Fig. 4. This figure reveals that annual NO_3-N loads could be reduced by 25.19 kg ha^{-1} by using drain depths of 0.75 m rather than 1.50 m. Agricultural profits for this alternative are reduced because shallow drains require a closer drain spacing, which increases costs. However, the net profit does not consider the environmental costs of releasing NO_3-N to the receiving waters.

The cost of releasing NO_3-N to receiving streams is difficult to determine, in the general sense, because it depends on many factors (Skaggs and Chescheir, 1999). Schwabe (1996) investigated the costs of several alternatives for reducing N loading to the Neuse River in North Carolina. He found the costs for non-point source N to range from US\$ 5.80 kg^{-1} to US\$ 10.40 kg^{-1}. Costs for removing N in municipal water treatment plants varied from US\$ 5.30 kg^{-1} to more than US\$ 100 kg^{-1}, depending on the concentration and the level of treatment. Based on these data, Skaggs and Chescheir (1999) concluded that a relatively low cost of US\$ 8 kg^{-1} could be used to assess the overall economic impacts of drain depth. Based on these data, a cost of 320 BEF kg^{-1} was used in this study to remove NO_3-N from agricultural drainage water. The treatment cost was applied to losses greater than 10 NO_3-N kg ha^{-1} as to account for all nitrogen present in the drainage water, including the nitrogen through natural drainage.

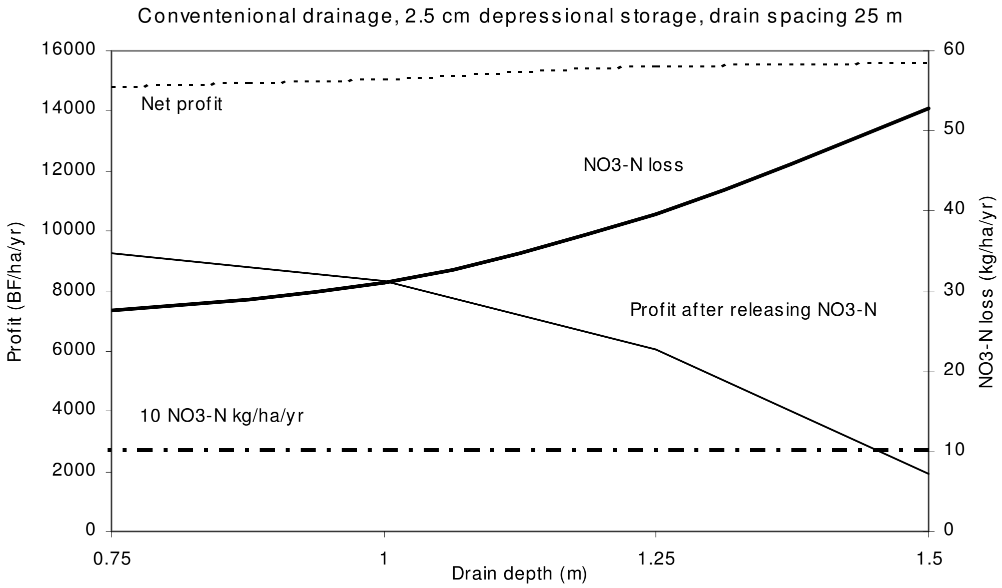

Figure 4: Effect of drain depth on profit as impacted by environmental costs of NO_3-N loss. Results based on 225 kg ha^{-1} fertiliser application

5. Conclusion

DRAINMOD-N was used to study for an experimental field in the Hooibeekhoeve, Geel (Belgium) the effects of drainage system design and management on yield and NO_3-N loss, using DRAINMOD-N as simulation tool. The analysis revealed that increasing the drain spacing and/or decreasing the drain depth reduces subsurface drainage while it increases surface runoff. Controlled drainage is associated with a reduction in subsurface drainage and an increase in surface runoff. Simulated results also indicated that increasing the drain spacing reduces NO_3-N drainage losses and net mineralization, but it increases NO_3-N runoff losses and denitrification. Increasing the drain depth increases drainage losses and net mineralization, and it decreases runoff losses and denitrification. Increasing the fertilizer application causes an increase in all nitrogen components in the subsurface drainage and surface runoff water. Controlled drainage is associated with a reduction in drainage losses and an increase in denitrification and runoff losses.

The optimal combination of drainage design and management is one that maximizes profit and minimizes environmental impact. Results of the scenario-analysis indicate that NO_3-N losses to the environment could be substantially reduced by reducing the drainage density below the level required for maximum profits from grain sales. That is, if the environmental objective is equal or of greater importance than profits from the agriculture crops, the drainage systems can be designed and managed to reduce NO_3-N losses while still providing an acceptable profit. From a societal point of view, it may become less expensive to pay higher grain prices than paying the costs for removing NO_3-N in excess of the tolerance level. The cost to remove 17.3% NO_3-N is estimated at 1 955.2 BEF ha^{-1}.

The study revealed that for the given climate-crop-soil combination different scenarios of drain depth and spacing exist resulting in a similar reduction of the NO_3-N loss to surface waters. The foregoing enables the decision maker to adjust the drainage system design according to the real field situation and the need to control water quality. The analysis presented in this paper further demonstrates the applicability of DRAINMOD-N for quantifying effects of drainage design and management on agricultural profits and NO_3-N losses to the environment for a specific combination of climate, crop and soil.

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