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Developing DRAINMOD-EMA Technology for Defining the Nitrogen Dressing as a Function of Environmental Constraints

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ABSTRACT

The objective of this research is to control the nitrate-nitrogen concentration in surface water to 11.3 mg l^{-1} (EU standards) and determine the exact nitrogen amount that has to be applied to achieve this limitation and calculate the corresponding plant uptake. The method used in this study is a combination between DRAINMOD-N model and Environmental Management for Agriculture (EMA), applying the methodology to the Molenbeek and the Mark catchments. The two catchments are situated in the Flemish, northern, part of Belgium. The study illustrates that the EMA in combination with DRAINMOD-N is a powerful and suitable tool for analysing and controlling nitrate leaching to surface waters. Results gave an idea in which way the amount of nitrogen applications has to be adjusted to achieve the plant uptake and the environmental target.

***Keywords**: nitrate leaching, surface water, DRAINMOD-EMA, plant uptake, environmental impact*

1. Introduction

Nitrogen is the nutrient of most concern in the contamination of groundwater and surface water, primarily resulting from NO_3^- leaching (El-Sadek and Vazquez, 2012). Leaching of NH_4^+ is generally not important since it is strongly adsorbed by soil, except for sands and soils that have low retention (cation exchange) capacities. However, NO_3^- is readily leached deeper into the soil profile, below the bottom of the root zone, and may eventually leach into groundwater supplies (Vereecken, 1988; Yang et al., 2007). Agricultural land is the main source of nitrate in rural catchments. The quantity of nitrate lost from an area of land is related to the cropping and practice of farming (El-Sadek et al., 2003). Hence, the concentration of nitrate in a groundwater or river drinking water source depends on the overall balance of agriculture in the catchment (El-Sadek, 2007). This means that the presence of some fields with high losses will not necessarily result in the overall water concentration exceeding 50 mg 1^{-1}. The quantity of nitrate lost from a farming system depends very much on the balance between inputs of nitrogen and the quantity removed in crops (El-Sadek et al., 2013). It is also dependent on whether the farming system protects the soil from over-winter leaching, using for example mainly autumn sown crops, or whether the soil is bare during the main season. No agricultural system can be 100% efficient in its use of nitrogen. Nitrate leaching is a natural process and some loss each year is inevitable. There will always be some loss typically between 10 and 20 kg N ha^{-1} yr^{-1}. According to reports of the European Union, Belgium, after The Netherlands, is the second largest user of nitrogen in agriculture (EU, 1991 and 2000). To reduce the groundwater and surface water pollution in Belgium and control the environmental cost to remove nitrate-nitrogen from water, it is essential to understand fully the nitrate leaching from agricultural fields (El-Sadek et al., 2002). The objective of this research is to control the nitrate-nitrogen concentration in surface water to 11.3 mg l^{-1} (standards limitation) and determine the exact nitrogen amount that has to be applied to achieve this limitation and calculate the corresponding nitrate-nitrogen plant uptake. The method used in this study is a combination between DRAINMOD-N model and Environmental Management for Agriculture (EMA), applying the methodology to the Molenbeek and the Mark catchments. The two catchments are situated in the Flemish, northern, part of Belgium.

2. Site description

Data of two primarily agricultural catchments were used to test and validate the methodology. The approach was developed using data and state variables of the Molenbeek and the Mark catchments. The two catchments are situated in the Flemish, northern, part of Belgium. The catchments are characterised by a dominant flat to slightly undulating topography and a shallow water table. Large areas of the catchments are artificially drained.

2.1 Molenbeek catchment

The river Dender basin is located to the west of Brussels in a region with a rolling landscape. It is a tributary of the river Scheldt having its sources in the Walloon region of Belgium. Because of the rolling topography in the source area and the relatively small water holding capacity of the soils, the flow in the tributaries of the Molenbeek are characterised by relative large discharge fluctuations. The baseflow discharges are small, while the response to rainfall is large. The Flemish part of the basin, the Molenbeek brook sub-catchment at Erpe-Mere, has a total area of 57.44 km^2 (Willems, 2000). It is a narrow and relatively strong indented catchment. The upstream part is rural, while the downstream part is more urbanised (village of Mere, Erpe and Hofstade). One limnigraphic station (hourly water level data and rating curve) is available at Mere (Radwan et al., 1999; Radwan et al., 2000).

2.2 Mark catchment

The Mark catchment with an area of 93.62 km^2 is situated in the north, at the border between Belgium and the Netherlands. The catchment is drained by the Mark river discharging into the Netherlands. The catchment is completely flat, soils are mainly sandy, and the water table fluctuates between a depth of 30-50 cm in the winter and 80 to 120 cm in the summer. A large fraction of the basin is drained by a network of ditches and subsurface drains. The land uses are field crops (maize for silage and fodder beets) and pasture, and the main agricultural revenue comes from dairy and pig farming. The pressure to get rid of the animal waste is the main pollution source in the catchment. Slurry rates of over 100 ton ha^{-1} $year^{-1}$ are not an exception.

3. METHOD

3.1 DRAINMOD

The DRAINMOD (Skaggs, 1981) model was used to simulate for the two catchments the performance of drainage system and related water table management. DRAINMOD-N (Brevé et al., 1997a and b), an add on module to DRAINMOD for simulating the nitrogen dynamics in drained soils, was used to model the nitrate-nitrogen leaching from the rootzone into the subsurface drainage system. Nitrate-nitrogen (NO_3-N) is the main N pool considered. The model is a quasi two-dimensional model because the nitrogen movement component considers only vertical transport in the unsaturated zone and both vertical and lateral transport in the saturated zone. The controlling processes considered by the model (Brevé et al., 1992) are rainfall deposition, fertiliser dissolution, net mineralisation of organic nitrogen, denitrification, plant uptake, and surface runoff and subsurface drainage losses.

3.2 ENVIRONMENTAL MANAGEMENT FOR AGRICULTURE (EMA)

Environmental Management for Agriculture, EMA (AERU, 2000) is a computer software that aims to encourage farmers to improve their environmental performance. The approach is based on the principles and philosophy of formal environmental management standards. The system uses auditing techniques to assess and review the environmental performance of a business. Carried out on a regular basis (e.g. annually) the aim is to establish a cycle of continuous improvement in environmental performance. EMA provides an environment audit (evaluation system) to help identify the key impacts of the farm, opportunities for improvement and thus environmental objectives. Advisory and technical systems are available to help the business achieve those objectives by providing useful information and decision support on the best practice for the farm. EMA has three main modes of action: the evaluation system which takes an auditing approach to farm assessment. It determines a series of eco-ratings that help identify strengths and weakness of farming practices. Second, the technical system is a collection of decision support modules that help to identify solutions to the problems identified by the auditing. Third, the advisory system is the EMA library which will help to identify best practice, legislation and answers to ad hoc queries. Traditionally the technical system is used to help develop an improvement programme which focuses on the weakest areas identified in the auditing system and those which are practically achievable in the next season taking into account the financial position. Following the plan is put into action and at the end of the season, the auditing and the cycle described above is repeated. This will lead to gradual but significant improvements in environmental performance (AERU, 2000).

4. Materials

For the application of the simulation models, DRAINMOD and DRAINMOD-N, the following information was collected for each of the catchments studied: climate, land use, soil type, and fertiliser management. The model input was collected for all fields within each catchment. For the Molenbeek catchment, the period from 1 January 1990 to 31 December 1997 ($0 < t < 2922$ day) was simulated using the measured NO_3-N concentrations on 16 December 1989 as initial condition. Water flow and nitrate leaching are modelled in the flow domain of 12.5 m width, representing half the drain spacing, and a depth of the soil profile of 2 m. The drain was located at 120 cm depth and described as a half circular hole with inner diameter of 5 cm. The inner wall of the drain was described as a seepage face, implying that the drain is always practically empty. As atmospheric conditions daily precipitation and evaporation data were used. The average groundwater level midway between the drains was taken as representative for the depth of the initial water table.

5. Results and discussion

In a first step the water flow and nitrate leaching out of the soil profile is simulated using DRAINMOD-N as a function of soil type, land use and fertiliser application. In a second step the results of NO_3-N leaching is compared with the standards limitations (NO_3-N $\leq$ 11.3 mg l^{-1}). If NO_3-N breaches the standards, the Environmental Management for Agriculture (EMA) is used to produce the optimum nitrogen applications to achieve NO_3-N limitations. These optimum nitrogen applications recommendations are used as input to DRAINMOD-N to simulate NO_3-N leaching and achieve both, plant uptake and environmental objective. These procedures are shown in Fig. 1. The DRAINMOD-EMA modelling approach was validated using data of the Mark catchment. The leaching period from 1 January 1994 to 31 December 1998 (0 < t < 1826 day) was simulated using the measured NO_3-N concentrations on 8 December 1993 as initial condition.

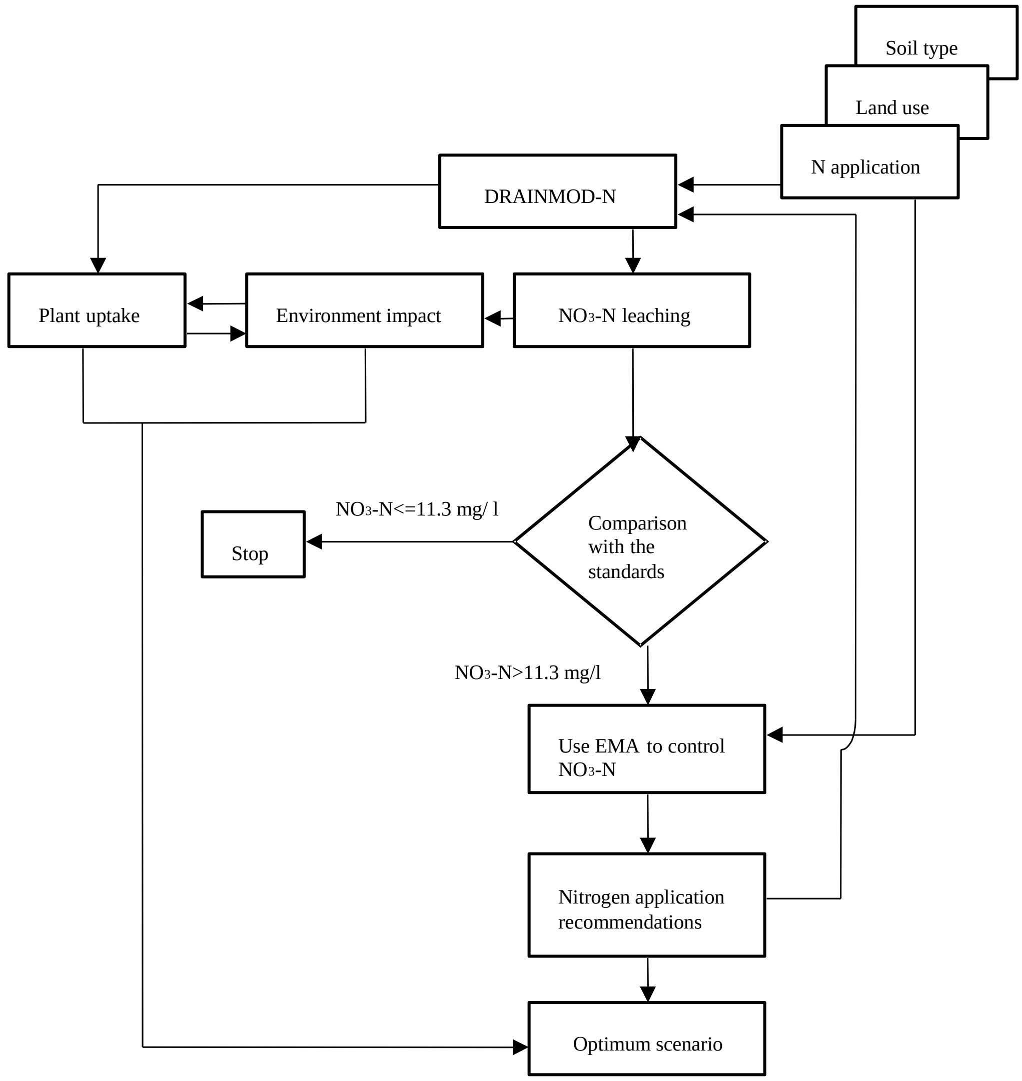

Figure 1: The DRAINMOD-EMA technology model

Since the exact fertiliser package per field for the period of analysis could not be reconstructed the threshold values for N-fertilisers, as specified in the fertilisation standards of the Flemish Government were applied. 320 kg ha^{-1} nitrogen application rate was applied for determining the nitrate-nitrogen leaching in the Molenbeek catchment using DRAINMOD-N. NO_3-N leaching output exceeded the standard as shown in Fig. 2. The EMA was used to recommend the optimum nitrogen application rate that can be applied safely as a combination of mineral and organic nitrogen to keep NO_3-N leaching to the standards level. The EMA recommended a 80 kg ha^{-1} as a nitrogen applications rate (47.5 mineral-N and 32.5 organic-N). A third scenario (160 kg ha^{-1}) in between the two nitrogen applications was simulated to test the EMA model and if NO_3-N leaching will breach the standard or not. The results of the three scenarios are shown in Fig. 2. The results in this figure indicate that only the EMA recommended nitrogen amount is achieving the limitations (a line at 11.3 mg l^{-1} in Fig. 2 was plotted to indicate the limitation level). The same methodology was applied in the Mark catchment. The results of the DRAINMOD-EMA combination model (as shown in Fig. 3) indicated that, the methodology may be applied in the agricultural catchments in Flanders for controlling NO_3-N pollution and achieving the environmental objective.

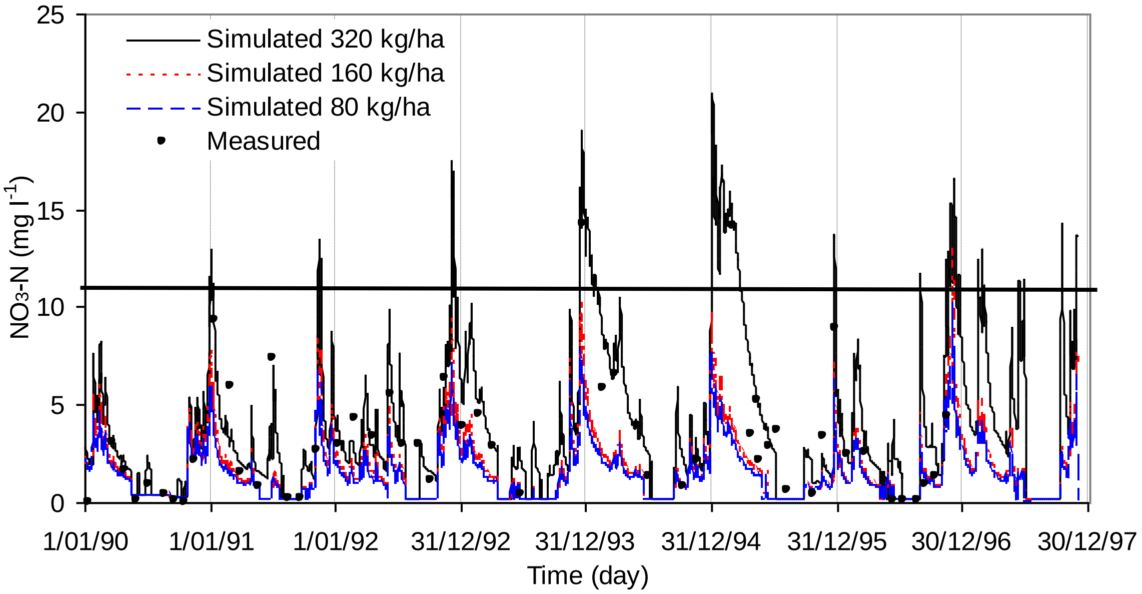

Figure 2: NO_3-N (mg l^{-1}) for the three nitrogen application scenarios in the Molenbeek catchment

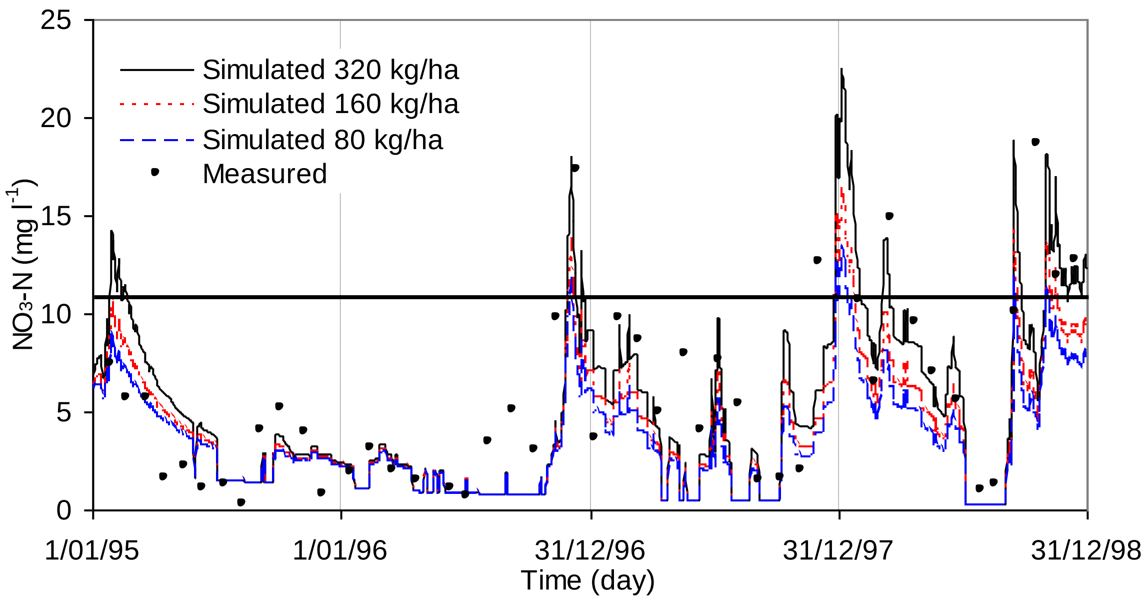

Figure 3: NO_3-N (mg l^{-1}) for the three nitrogen application scenarios in the Mark catchment

Figures 4 and 5 show the yearly NO_3-N in the drainage water, the plant and the soil profile for the Molenbeek and the Mark catchments respectively. In the drainage graphs a line at 15 kg ha^{-1} was plotted to indicate the NO_3-N standards limitation (typically between 10 and 20 kg ha^{-1} yr^{-1}) and show if the yearly NO_3-N leaching resulted from each nitrogen application rate will exceed this standard or not. From these figures, it is obvious that NO_3-N amount in each element is related to the others, this means that, if the NO_3-N in the plant or in the drainage outflow is low, the amount in the soil profile will be high. For instance, in the Molenbeek catchment (Fig. 4), in the year 1990, NO_3-N are 374.13 kg ha^{-1} in the soil profile, 183.14 kg ha^{-1} in the plant and 21.22 kg ha^{-1} in the drainage outflow (for 320 kg ha^{-1} nitrogen application rate scenario). Where the results for 80 kg ha^{-1} nitrogen application rate scenario, are 198.07, 43.64 and 14.53 kg ha^{-1} respectively. Using nitrogen application rate of 80 kg ha^{-1} as recommended with EMA, will lead to 76.2%, 31.5% and 47.1% reduction in NO_3-N in the plant, the drainage outflow and the soil profile respectively compared with using application rate of 320 kg ha^{-1}.

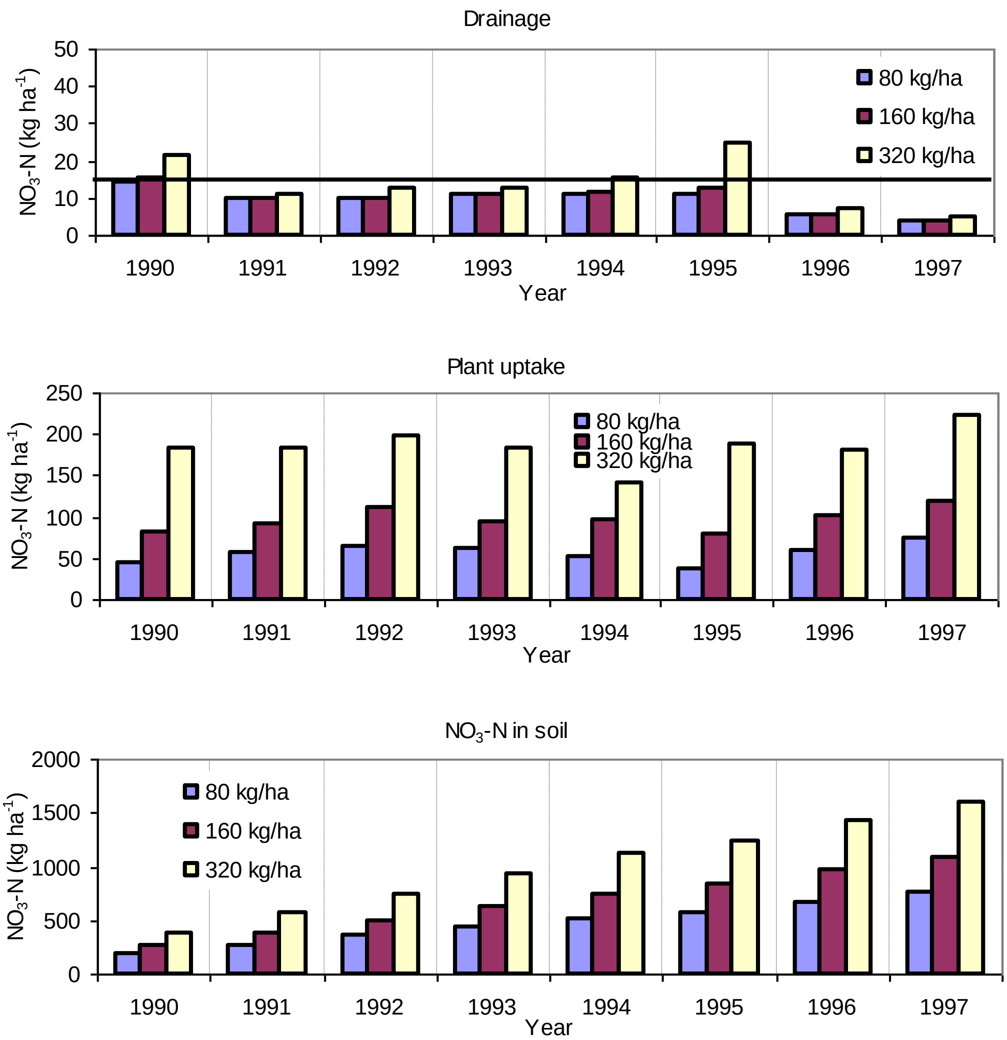

Figure 4: NO_3-N in the drainage water, the plant and the soil profile in the Molenbeek catchment

In 1991, the NO_3-N amount increased to 562.34 kg ha^{-1} in the soil profile (for 320 kg ha^{-1} application scenario). As a result of this, the NO_3-N decreased to 10.90 kg ha^{-1} in the drainage outflow compared with 1990 results while, the NO_3-N amount is still almost the same in the plant (182.26 kg ha^{-1}). A reduction of 68.8%, 9.8% and 51% in the plant, the drainage outflow and the soil profile respectively resulted from using EMA recommendation application rate (80 kg ha^{-1}). A complete NO_3-N output of all nitrogen processes (rainfall deposition, fertiliser dissolution, net mineralisation of organic nitrogen, denitrification, plant uptake, surface runoff and subsurface drainage losses and NO_3-N in the soil profile) are shown in the Appendix. Results analysis indicated that, the maximum yearly nitrogen application rate can be applied is 210 kg ha^{-1}. This amount can be used to keep the yearly nitrate-nitrogen leaching amount to the standards limitation (10-20 kg ha^{-1}). Using this amount can achieve both plant uptake and environmental objectives.

From the economical analysis point of view, in year 1995 (the Molenbeek catchment) using nitrogen application rate of 80 kg ha^{-1} will result in 55.1% NO_3-N reduction in the drainage outflow rather than using 320 kg ha^{-1}, the corresponding plant uptake reduction is 80.3%. El-Sadek et al. (2002) recommended a cost of 320 BEF kg^{-1} to remove NO_3-N from agricultural drainage water in Flanders. Using this rate to release 55.1% NO_3-N from drainage water will cost 4 406 BEF ha^{-1}. A similar analysis was calculated for the Mark catchment (Fig. 5). Results of the scenario-analysis indicate that NO_3-N losses to the environment could be substantially reduced by using the DRAINMOD-EMA modelling approach. That is, if the environmental objective is equal or of greater importance than profits from the agriculture crops, the combination approach can be designed and managed to reduce NO_3-N losses to ground and surface waters. 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.

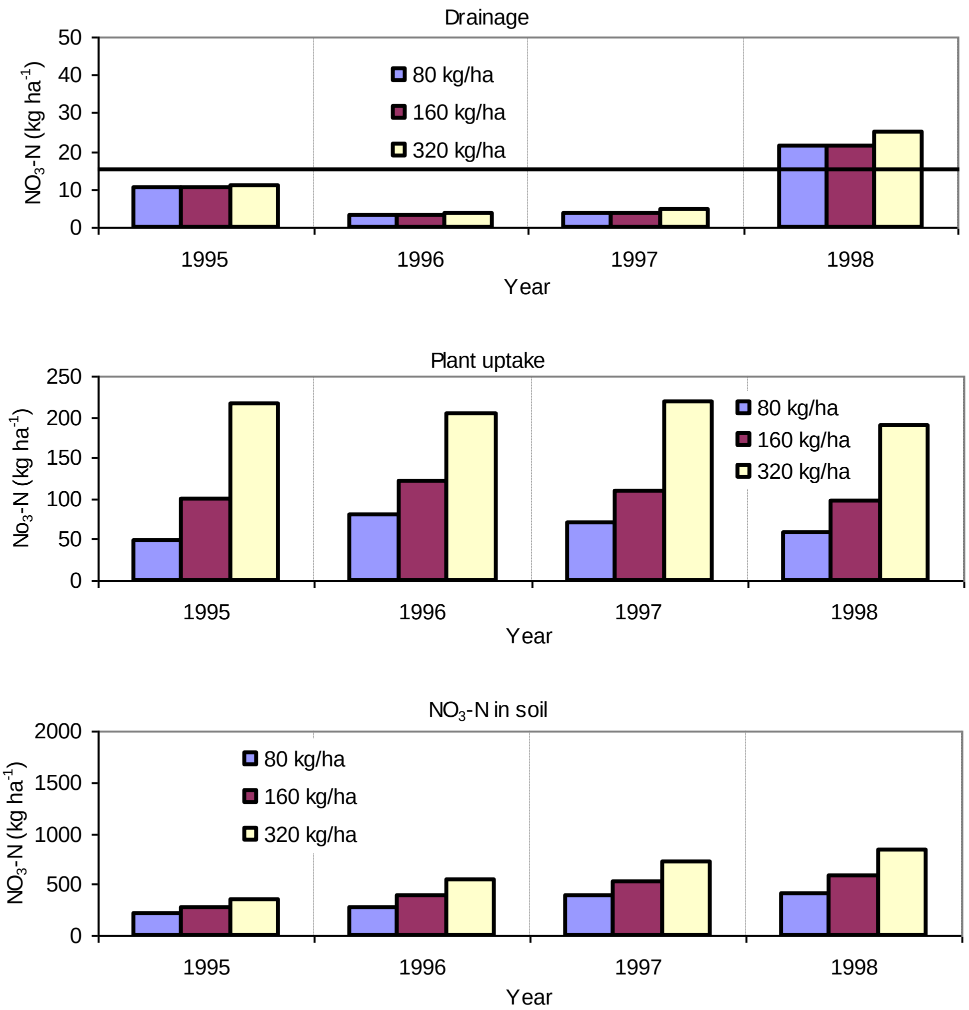

Figure 5: NO_3-N in the drainage water, the plant and the soil profile in the Mark catchment

6. Conclusions

DRAINMOD-N is linked to the Environmental Management for Agriculture (EMA) in order to define from environmental point of view safe nitrogen fertiliser procedures. The procedures were applied in two catchments situated in the Flemish, northern, part of Belgium. The model seeks to encourage continuous improvement in environmental performance, tackling issues and problem areas in steps which are practically manageable and financially affordable. The benefits include: reduction in pollution risk and so the potential for fines; protection and enhancement of farm biodiversity; and finally, save money through better management of agrochemicals, wastes and water. The optimal combination management is one that maximises profit and minimises environmental impact. Results of the scenario-analysis indicate that NO_3-N losses to the environment could be substantially reduced by using the DRAINMOD-EMA in an iterative way. That is, if the environmental objective is equal or of greater importance than profits from the agriculture crops, the combination model 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 55.1% NO_3-N is estimated at 4 406 BEF ha^{-1}. The study revealed that for the given climate-crop-soil combination different scenarios of nitrogen application rates exist resulting in a reduction of the NO_3-N loss to surface waters. The foregoing enables the decision maker to adjust the nitrogen applications according to the real field situation and the need to control water quality. The analysis presented in this study further demonstrates the applicability of the combination modelling as a management tool to design and manage the agriculture profits and NO_3-N losses to the environment for a specific combination of climate, crop and soil.

7. References

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Appendix

Molenbeek catchment

Year	Miner.	Denit.	Plant up.	N applic.	Drainage	Runoff	Rain dep.	Soil profile
1990	85.85	44.66	43.64	80.00	14.53	0.00	4.48	198.07
1991	97.32	37.36	56.78	80.00	9.83	0.00	4.25	275.67
1992	113.58	44.44	63.57	80.00	9.90	0.02	4.84	356.16
1993	113.77	48.75	63.11	80.00	11.10	0.34	4.61	431.25
1994	99.82	39.02	52.84	80.00	10.84	0.00	5.29	513.66
1995	64.62	36.16	37.09	80.00	11.22	0.13	4.44	578.12
1996	99.29	26.83	58.20	80.00	5.28	0.17	3.72	669.92
1997	107.57	23.72	74.15	80.00	3.70	0.00	3.27	759.19

Year	Miner.	Denit.	Plant up.	N applic.	Drainage	Runoff	Rain dep.	Soil profile
1990	85.85	47.47	81.89	160.00	15.27	0.00	4.48	266.12
1991	97.32	37.61	91.47	160.00	9.93	0.00	4.25	388.67
1992	113.58	44.51	111.45	160.00	9.92	0.02	4.84	501.19
1993	113.77	48.77	94.54	160.00	11.11	0.34	4.61	624.81
1994	99.82	43.51	96.74	160.00	11.59	0.00	5.29	738.08
1995	64.62	40.16	78.79	160.00	12.90	0.13	4.44	835.15
1996	99.29	27.33	101.64	160.00	5.40	0.17	3.72	963.61
1997	107.57	23.80	117.74	160.00	3.72	0.00	3.27	1089.18

Year	Miner.	Denit.	Plant up.	N applic.	Drainage	Runoff	Rain dep.	Soil profile
1990	85.85	71.95	183.14	320.00	21.22	0.00	4.48	374.13
1991	97.32	40.20	182.26	320.00	10.90	0.00	4.25	562.34
1992	113.58	55.25	197.56	320.00	12.52	0.02	4.84	735.42
1993	113.77	54.93	181.99	320.00	12.49	0.34	4.61	924.06
1994	99.82	63.89	141.34	320.00	15.29	0.00	5.29	1128.65
1995	64.62	73.42	188.29	320.00	24.99	0.14	4.44	1230.86
1996	99.29	36.00	181.59	320.00	7.14	0.17	3.72	1428.97
1997	107.57	31.76	223.16	320.00	4.85	0.00	3.27	1600.04

Miner.: net mineralisation of organic nitrogen; Denit.: denitrification; Plant up.: plant uptake; N applic.: fertiliser dissolution; Drainage: subsurface drainage losses; Runoff: surface runoff losses; Rain dep.: rainfall deposition and Soil profile: NO_3-N in soil profile. Units in kg ha^{-1}.

Mark catchment

Year	Miner.	Denit.	Plant up.	N applic.	Drainage	Runoff	Rain dep.	Soil profile
1994	87.90	106.32	47.85	80.00	42.17	0.00	4.69	137.69
1995	85.60	39.00	48.99	80.00	10.18	0.00	3.79	208.90
1996	94.40	22.50	80.30	80.00	3.16	0.00	3.35	280.70
1997	117.75	29.22	69.70	80.00	3.81	0.00	3.67	379.39
1998	89.75	68.24	57.15	80.00	21.21	0.00	7.04	409.58

Year	Miner.	Denit.	Plant up.	N applic.	Drainage	Runoff	Rain dep.	Soil profile
1994	87.90	106.35	96.57	160.00	42.17	0.00	4.69	168.94
1995	85.60	39.03	98.33	160.00	10.19	0.00	3.79	270.77
1996	94.40	22.51	122.40	160.00	3.16	0.00	3.35	380.43
1997	117.75	29.22	108.66	160.00	3.81	0.00	3.67	520.15
1998	89.75	68.33	96.50	160.00	21.26	0.00	7.04	590.85

Year	Miner.	Denit.	Plant up.	N applic.	Drainage	Runoff	Rain dep.	Soil profile
1994	87.90	107.00	209.85	320.00	42.21	0.00	4.69	214.97
1995	85.60	43.28	216.09	320.00	10.95	0.00	3.79	354.05
1996	94.40	25.20	204.79	320.00	3.40	0.00	3.35	538.42
1997	117.75	38.25	217.44	320.00	4.60	0.00	3.67	719.54
1998	89.75	78.78	190.35	320.00	25.23	0.00	7.04	841.97

Miner.: net mineralisation of organic nitrogen; Denit.: denitrification; Plant up.: plant uptake; N applic.: fertiliser dissolution; Drainage: subsurface drainage losses; Runoff: surface runoff losses; Rain dep.: rainfall deposition and Soil profile: NO_3-N in soil profile. Units in kg ha^{-1}.