Asian Journal of Water, Environment and Pollution, Vol. 10, No. 3 (2013), pp. 51–61.

Spatial Modelling for Nitrogen Leaching from Intensive Farming in Red River Delta of Vietnam

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Received September 13 2012; revised and accepted May 31, 2013

Abstract: In this study, a spatial dynamic model was developed, to simulate nitrogen dynamics in Van Hoi commune, Tam Duong district, Vietnam, for different soil and land use types, under different irrigation and fertilizer regimes. The model has been calibrated using measured nitrogen concentrations in soil solution in March and August 2004 and validated for data from March and August 2005. Lateral flow was low in this level area. Percolation was the main process leading to high nitrogen leaching losses to ground water. Calculated annual leaching losses varied from 88 to 122 kg N ha^{-1} in flowers, 64 to 82 in vegetables of the cabbage group, 51 to 76 in chili, 56 to 75 in vegetables of the squash group, and 36 to 55 in rice.

Key words: Vegetables, rice, lateral flow, percolation, simulation, PCRaster.

Introduction

High fertilizer and manure use in intensive agriculture is one of the main sources of nutrient leaching losses to the environment, and the associated reduction in groundwater quality (Wolf et al., 2005). In many regions the annual leaching load exceeded 20 kg ha^{-1} (Lin et al., 2001). In Vietnam, agriculture is intensified with increasing annually fertilizer use by 7.2% for nitrogen, 13.9% for phosphorus, and 23.9% for potassium from 1985 to 2000 (Hien and Thoa, 2003).

Many researches reported a positive correlation between fertilizer application rates and NO_3 leaching (Zhu et al., 2003). A survey on an area of 800 km^2 in the middle part of the Red River Delta (Minh and Hoc, 1997) reported that the extent of NH_4^+ with concentration higher than 10 mg l^{-1} increased from 22.3 km^2 in 1992, through 41.1 in 1993 to 68.0 in 1994.

Nitrate contamination of drinking water may increase the risk of cancer (Weyer et al., 2001, Yang et al., 1998). It has also been shown that high nitrate-containing vegetables increase the risk of gastric cancer (Kim et al., 2001). Vietnam Cancer Institute (NCI, 2002) showed that stomach cancer is the second leading form of cancer in males, and the third in females, and increases at an annual rate of 4.4% (Anh et al., 2002).

Nitrogen leaching from agriculture is difficult to quantify. At plot scale, various methods for measuring N leaching have been applied (Mai et al., 2010; Riley et al., 2001; Ross et al., 1995; Williamson et al., 1998). N leaching can also be estimated using models at appropriate scales (El-Sadek et al., 2003; Ersahin

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and Rustu Karaman, 2001; Granlund et al., 2000) with spatial and non-spatial data. At watershed scale, N leaching losses vary both temporally and spatially. Following that streamline the objectives of this study were: (i) to develop a spatial-dynamic model for N leaching in an intensive agricultural region and (ii) to apply the model for quantifying N leaching losses from intensive farming systems.

Methodology

Study Area

The study area is located in Van Hoi commune, a flatland area of Tam Duong district (21°26′ N, 105°36′ E), 60 km north of Hanoi. The commune has a total area of 235 ha, with arable land belonging to two soil texture groups (Figure 1): clay loam (126 ha; 53.8%) and sandy loam (109 ha; 46.2%). Representative soil profiles are described in Table 1. Climate data were recorded at Vinh Yen meteorological station, about 2 km from the study area.

Land Use and Fertilizer Use

The main rotation is double rice followed by an upland crop, such as maize, potato, sweet potato, or vegetables during winter (Figures 1 and 2). Vegetables are grown continuously at good irrigation fields. Number of crops and crop types in the rotations are adapted flexibly, depending on market conditions, availability of labour and capital.

Table 1: Saturated hydraulic conductivity (*ks*), porosity and field capacity (FC) of sandy loam (SL) and clay loam (CL) in Van Hoi commune, Tam Duong district, Vietnam

Soil depth (cm)	*ks (cm d^{-1})*		*Porosity (%)*		*FC (cm^3 cm^{-3})*	
	SL	*CL*	*SL*	*CL*	*SL*	*CL*
0–40	146.4	102.1	43.7	45.3	33.3	33.3
40–80	10.3	10.3	39.8	41.2	59.2	60.6
> 80	3.6	2.9	43.0	43.7	63.7	65.0

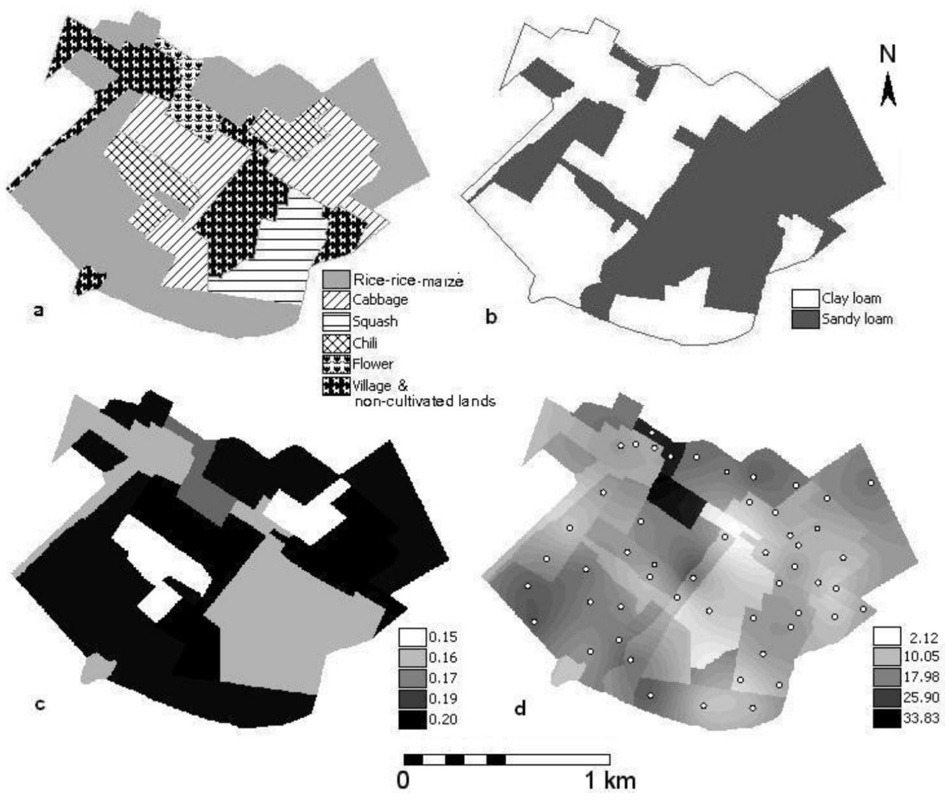

Figure 1: Land use map (a), soil map (b), initial soil moisture content (c) (cm^3 cm^{-3}), and initial soil Nmin (d) (mg kg^{-1}) with measurement points (100 cm depth) in Van Hoi commune, Tam Duong district, Vietnam.

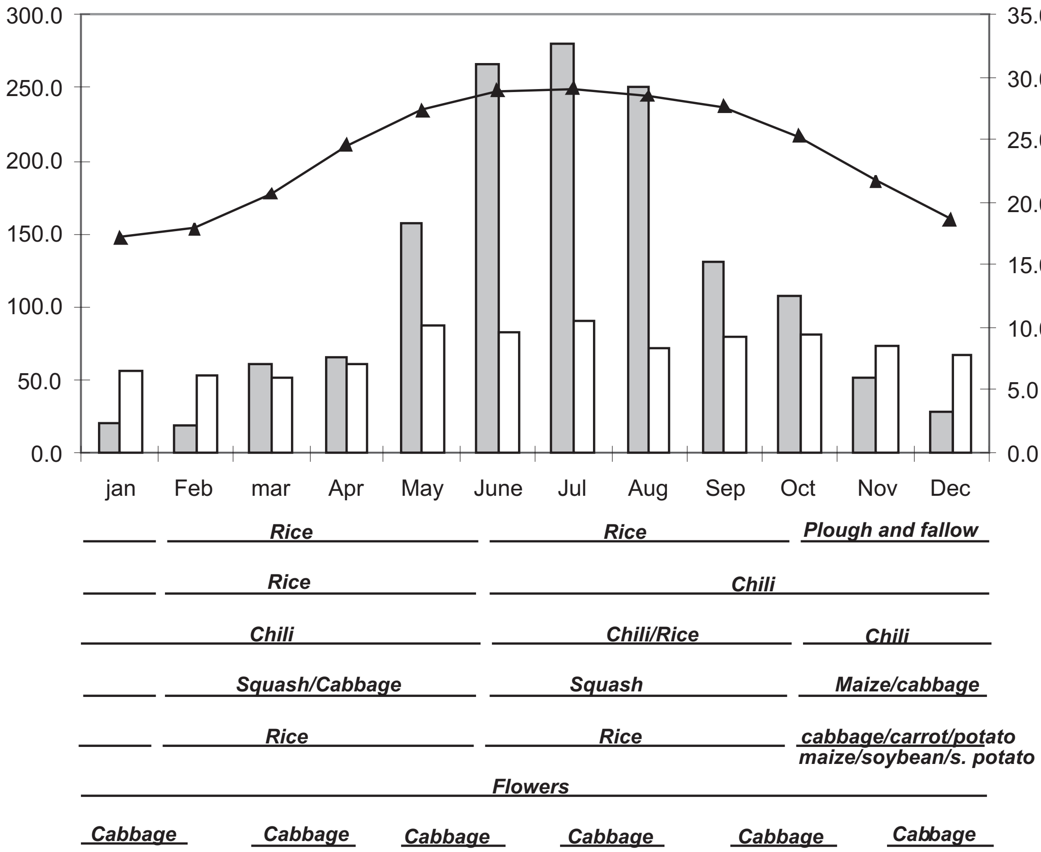

Figure 2: Weather conditions in the study area: monthly rainfall (solid bar; mm) and monthly evaporation (blank bar; mm) referring to left hand Y-axis. Monthly temperature (triangles; °C) referring to right hand Y-axis. Lower part: Cropping calendars of land use systems in Van Hoi commune, Tam Duong district, Vietnam.

Average fertilizer use for different crops in the commune is shown in Table 2. For vegetables, two groups are distinguished: group 1 ('cabbage' group) consisting of paprika, cabbage, egg plant, and kohlrabi, in which cabbage is the major crop and the farmer can grow seven cabbage crops in the rotation; group 2, including chili, cucumber, tomato, and squash, with chili and squash as major crops.

For rice, all farm yard manure (FYM), all phosphorus, and 20 to 30% of the N fertilizer is applied as basal dressing. The remaining N fertilizer is applied in 2 to 3 splits, at the start of tillering and before booting. For spring rice, in addition to the basal dose, FYM is also applied as top dressing during tillering. For winter maize, FYM and phosphorus fertilizer are applied as basal dressing, while chemical N fertilizers are applied each week, till the 9-leaf stage, through 'bucket irrigation'. For vegetable group 1, all FYM and phosphorus fertilizer are applied at planting. Urea is applied in the early stages through 'bucket irrigation'. For chili, FYM is applied as basal dressing and monthly applied under submerged conditions between the beds; nitrogen fertilizer is applied weekly on the soil surface. For cucumber, tomato and squash, FYM and phosphorus are surface-applied before planting, Sludge and nitrogen is applied weekly through 'bucket irrigation'. Flowers (mainly rose and daisy) require high doses of fertilizers to compensate for nutrient export in the weekly cuttings. Rich N liquid compost are surface-applied each week through 'bucket irrigation'.

The average application rates decreased by 15% in 2005 compared with 2004 due to increasing of fertilizer price.

Field Measurements

Groundwater samples (at 52 locations, randomly selected; Figure 1d), at 1 m depth, were taken on four dates, 6th March and 15th August 2004, and 26th March and 8th August 2005, using an open porous pipe and a hand pump, and were analysed for nitrate- and ammonium-nitrogen content (Mai et al., 2007). Irrigation and fertilizer application were recorded for each land use type. Soil samples were taken on 1st February 2004 (assuming very little change from 1st January to

Table 2: Fertilizer and biocide use for different crops in Van Hoi commune, Tam Duong district, Vietnam

Crop	*N* *kg ha*$^{-1}$	*P* *kg ha*$^{-1}$	*K* *kg ha*$^{-1}$	*FYM*[1] *Mg ha*$^{-1}$	*Herbicide* *(10*^{3} *VND*[2] *ha*$^{-1}$*)*
Spring rice	76.3	28.2	62.0	7.9	111.8
Summer rice	84.2	24.2	66.9	5.4	86.9
Maize	59.5	15.9	30.2	2.9	ND[3]
Soybean	30.0	0.0	0.0	0.0	ND
Peanut	40.0	0.0	0.0	0.0	ND
Vegetable group 1[4]	63.7	25.0	34.1	9.3	ND
Vegetable group 2[5]	254.2	57.8	26.9	20.0	139.0
Sweet potato	20.3	11.7	10.9	4.1	0.0
Flowers[6]	568.0	240.0	360.0	30.0	ND

[1]FYM (Farm Yard Manure) has 0.53% N, 0.025% P_2O_5 and 0.49% K_2O
[2]VND = Vietnamese Dong; 15,000 VND = 1 US$ (in 2002)
[3]ND = Not Determined
[4]Vegetable group 1: paprika, cabbage, egg plant, kohlrabi
[5]Vegetable group 2: chili, cucumber, tomato, squash
[6]Fertilizer dose per year

1st February, because of the very dry conditions), and analysed for Nmin.

Model Description

A spatial dynamic model was developed to simulate N leaching using PCRaster, a computer language for construction of dynamic spatio-temporal environmental models (Karssenberg et al., 1996; Van Deursen, 1995; Wesseling et al., 1996). It includes water and nitrogen modules and calculated in daily time step (Figure 3).

There are three distinguished soil horizons in the soil profile (Table 1), while the model consists of four compartments, with thickness of 40, 40, 20 and 300 cm, respectively (Figure 3).

Water Balance

In the water balance sub-model, net flow into the i^{th} soil layer is calculated as the balance of inflow (FL), outflow (i.e. inflow into the i+1th soil layer), and evapo-transpiration (ET) from that layer:

$$SW_{i,t} = SW_{i,t-1} + NFL_{i,t} \times \Delta t \quad (1)$$

$$NFL_i = FL_i - FL_{i+1} - ET_i \quad (2)$$

For the surface layer, inflow equals:

$$FL_1 = R + IRR - Q \quad (3)$$

where SW_i is soil water (mm) in the i^{th} layer, Δt—the time step of the model (1 d), R—rainfall (mm d^{-1}), IRR—irrigation (mm d^{-1}), ET_i—contribution of i^{th} layer to evapo-transpiration (mm d^{-1}), FL_i, FL_{i+1}—flow over upper and lower boundary of layer i (mm d^{-1}), respectively, and Q is surface runoff (mm d^{-1}).

Total ET was calculated using the Penman-Monteith method (Allen et al., 1998). Total root water extraction is partitioned in the proportions 0.4, 0.3, 0.2 and 0.1 over the four successive quarters of the total rooting depth, starting from the top (Hasegawa and Kasubuchi, 1993; Mai et al., 2010; Molz, 1981; Molz and Remson, 1970).

Flow into the i^{th} soil layer (Radcliffe et al., 1998) is described by Darcy's law:

$$FL_i = -k_i \frac{dh_i}{dz} \quad (4)$$

$$k_i = ks_i \quad \text{if } \theta_i = \theta s_i \quad (5)$$

$$k_i = kr_i \times ks_i \quad \text{if } \theta_i < \theta s_i \quad (6)$$

$$kri = \left(\frac{\theta_i - \theta r_i}{\theta s_i - \theta r_i}\right)^{\lambda} \text{(Averjanov, 1950; Brutsaert, 1966)} \quad (7)$$

where k_i is soil hydraulic conductivity of soil layer i (mm d^{-1}), dh_i/dz—the moisture potential gradient (unitless) between layers i and i–1, kr_i—the proportionality factor between actual and saturated soil hydraulic conductivity ($0 \le kr_i \le 1$), θ_i, θr_i, θs_i—water content in the layer to which ks applies, residual water content and water content at saturation, respectively (cm^3 cm^{-3}); and θr is defined as the water content in the soil that does not participate in flow (immobile water). In practice, θr corresponds to the water content at which the soil moisture capacity approaches zero ($d\theta/dh \to 0$) (Zaradny, 1993) and varies from 0.005 for light-textured soils to 0.1 for heavy-textured soils (Lal and

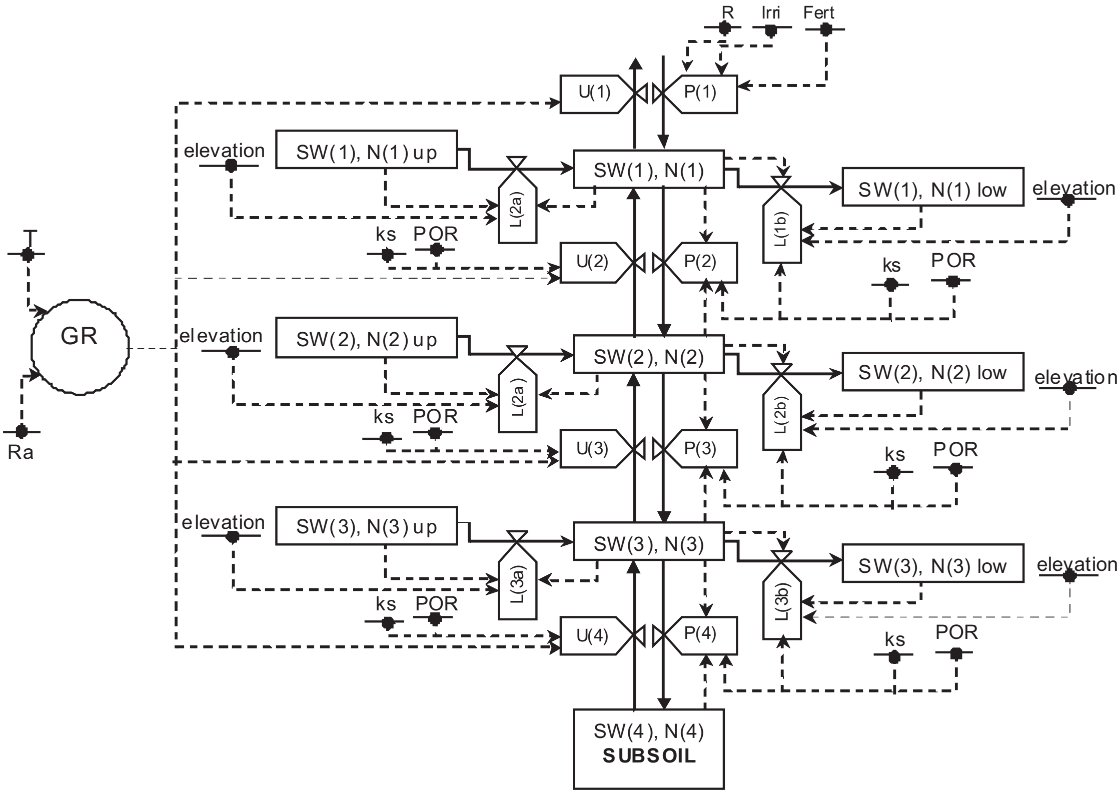

Figure 3: Relational diagram for soil moisture and nitrogen dynamics in the soil; where R is rainfall; Irri, irrigation; Fert, fertilizer; SW(1), soil water content (layer); L(1a), lateral inflow rate; N, nitrogen concentration; P, percolation and leaching rates; U, evapo-transpiration and nitrogen uptake rates; T, temperature; Ra, radiation; GR, crop growth; ks, soil conductivity; L(1b), lateral outflow; and POR is soil porosity.

Shukla, 2004); and λ is an empirical coefficient of 3.5 (Averjanov, 1950).

Daily water extraction from layer *i* for transpiration (T_i; mm d^{-1}) is calculated as a function of daily ET_i, time after sowing (d), and duration to maximum leaf area index (Du_LAI_{max}; Table 3):

$$T_i = \frac{\min(t, Du\_LAI_{max})}{Du\_LAI_{max}} ET_i \quad (8)$$

In this area, individual fields are surrounded by bunds; therefore, surface runoff is assumed to only occur when the first layer is saturated and surface water depth exceeds bund height (Chowdary et al., 2004):

$$Q = \max(0, R + IRR + Q_{up} + (SW_1 - POR_1 - BH)/\Delta t) \quad (9)$$

where Q_{up} is runoff from upstream (mm d^{-1}); SW_1, POR_1—soil water content (mm) and saturated soil water content in the first layer; and BH is bund height (mm), in this study set to 50 mm for flowers and cabbage and 100 mm for chili and rice, the crops for which rain water is stored in the field.

Laterally, the flow rate from one cell (the smallest unit of the raster map) to the neighbouring downstream cell, in layer *i* (LF_i, mm d^{-1}) is calculated (Hoffmann et al., 2006) from hydraulic conductivity (*k*, mm d^{-1}) and the difference in hydraulic head (*dh*) between two cells (*dL* = cell size):

$$LF_i = -k\frac{dh_i}{dL} \quad (10)$$

A Digital Elevation Model (DEM) was generated, from which the local drainage network map (ldd; Table 4) was derived. At each layer, for each cell, elevation/soil water content was assigned the value of the neighbouring downstream cell, where downstream cells were determined using the local drain directions on ldd. Differences in elevation/soil water content between upper and lower cells were calculated from original and downstream elevation/soil water content maps (Karssenberg et al., 1996). Outflow from the upper

Table 3: Crop calendars (dates of sowing, maximum LAI and harvest) for various crops in Van Hoi commune, Tam Duong district, Vietnam

Crop	*Date*		
	Sowing	*LAImax*	*Harvest*
Flowers	Sept 15th	Oct 30th	After Oct 30th
Tomato	Sept 15th	December 15th	January 15th
Squash/cucumber*	February 5th	June 5th	August 5th
Cabbage**	Feb 5th	March 15th	March 21st
Chili	Sept 1st	Dec 1st	July 15th
Spring rice	Feb 5th	May 5th	June 5th
Summer rice	June 25th	Aug 19th	Sept 19th
Winter maize	Sept 20th	Dec 5th	Jan 10th

* Squash/cucumber and tomato are in the same rotation.
** Cabbage is transplanted directly following harvest of the preceding cabbage.

Table 4: Input parameters for the model (all maps are in raster mode with a resolution of 5 m)

Input file	*Description*
Rain.tss	Daily rainfall
Irrig.tss	Daily irrigation for each land use type
Evap.tss	Daily evapo-transpiration for each land use type (calculated outside the model)
Fert.tss	Daily fertilizer application for each land use type, 15% reduced in 2005
Soil.map	Soil map
Soil.tbl	Attribute table with different soil properties for each soil type
Dem.map	Digital elevation map
Ldd.map	Local drainage network map derived from Dem.map, which is raster-formatted with codes from 1 to 9 showing drain directions to the neighbouring cells (Karssenberg et al., 1996)
Landuse.map	Land use map that is linked to the irrig.tss, evap.tss and fert.tss files through land use types (Figure 1)
Landunit.map	Overlay from soil and land use type maps
Kslandunit.tbl	Multiplication factor for *ks* values in each land unit
InitSW.map	Initial soil water map (Figure 1)
InitN.map	Initial nitrogen concentration (mg kg^{-1}) map from soil samples taken on 1st February 2004 at 1 m depth

cell is calculated with the accucapacityflux function (Karssenberg et al., 1996). This function calculates outflow from the upstream cell (which equals inflow into the downstream cell) as a function of transport capacity. Water content in a cell is compared to transport capacity, and part of the water that can be transported over the boundary.

Nitrogen Balance

The net rate of change in nitrogen (N_{NFL}) in a cell in layer *i* is defined as:

$$N_{NFLi} = N_{ferti} + N_{lat\_upi} + N_{leach(i-1)} - N_{uptakei} - N_{gasi} - N_{leachi} - N_{lat\_lowi} \quad (11)$$

where N_{fert} is fertilizer application (kg ha^{-1} d^{-1}), N_{lat_up}—inflow from upper cells (kg ha^{-1} d^{-1}), defined as the product of lateral inflows and appropriate N concentrations in the upper cells, N_{uptake}—uptake by the crop (kg ha^{-1} d^{-1}), defined as the product of transpired water and N concentration, N_{gas}—gaseous losses due to volatilization and denitrification (kg ha^{-1} d^{-1}), $N_{leach(i-1)}$, $N_{leach(i)}$—downward transport (kg ha^{-1} d^{-1}) from the appropriate layer, i.e. the product of FL_i, and N concentration in layer *i*–1 and the product of FL_{i+1} and N concentration in layer *i*, respectively, and N_{lat_low} is outflow to the lower cell (kg ha^{-1} d^{-1}), defined as the product of lateral outflow and appropriate N concentration in that cell.

N fertilizer application, comprising N from manure and chemical nitrogen is read daily from the file Fert.tss (Table 4). Organic N from manure is mineralized following first-order kinetics as described by Yang (1996). The Initial map of Nmin in the soil solution was interpolated from point measurements using regression kriging (Mai et al., 2007).

The rates of volatilization (NH_3) and denitrification (NO, N_2O, N_2) depend on the concentrations of NH_4 and NO_3 in the soil, aeration, and soil pH, and mostly follow first-order kinetics (Addiscott and Whitmore, 1987; Chowdary et al., 2004). In the model, these processes are approximated by:

$$N_{gas} = k_{gas} \times N_{min} \times e^{-k\text{gas}\times t} \quad (12)$$

where k_{gas} is a combined rate constant for volatilization and denitrification, set to 0.01 per day.

Model Calibration and Validation

The most important parameter influencing percolation and N transport rates is *ks*. As no data were available for calibration of lateral flows, N mineralization and transformation of nitrogen into gaseous form, only *ks* was used for calibration. Goodness of fit of simulated values was calculated following Jørgensen and Bendoricchio (2001):

$$Y = \sqrt{\frac{\sum \frac{(\chi_c - \chi_m)^2}{\chi_{m,a}}}{n}} \quad (13)$$

where χ_c is simulated Nmin, χ_m—the corresponding measured Nmin, $\chi_{m,a}$—average measured Nmin, and *n* is the number of samples.

Results

Model Calibration and Validation

Data from 2004 were used for calibration; input files with model parameters are given in Table 4.

Model was calibrated in two procedures: (i) using different *ks* values for the two soil types, and (ii) using different *ks* values for 13 land units, derived from overlaying the soil and land use maps.

For each of the two procedures, output maps of simulated Nmin concentration in the soil solution were extracted for two dates, 6th March and 15th August 2004, for which measured values (for the third layer, i.e. 1 m depth) were available. Goodness of fit between simulated and measured Nmin-values was calculated (Figure 4), and the *ks* values were adjusted successively, until no further improvement in goodness of fit was obtained.

The multiplication factors for both, soil type-specific *ks* and land unit-specific *ks* associated with the best fit, are shown in Table 5. Simulated Nmin was closer to the measured values with the second procedure (Figure 4a), with $Y = 1.58$ (Eqn 13), compared to $Y = 2.29$ with the first procedure.

Spatial N Distribution

The spatial distribution of simulated Nmin concentrations in the third layer for March 6th 2004 and March 26th

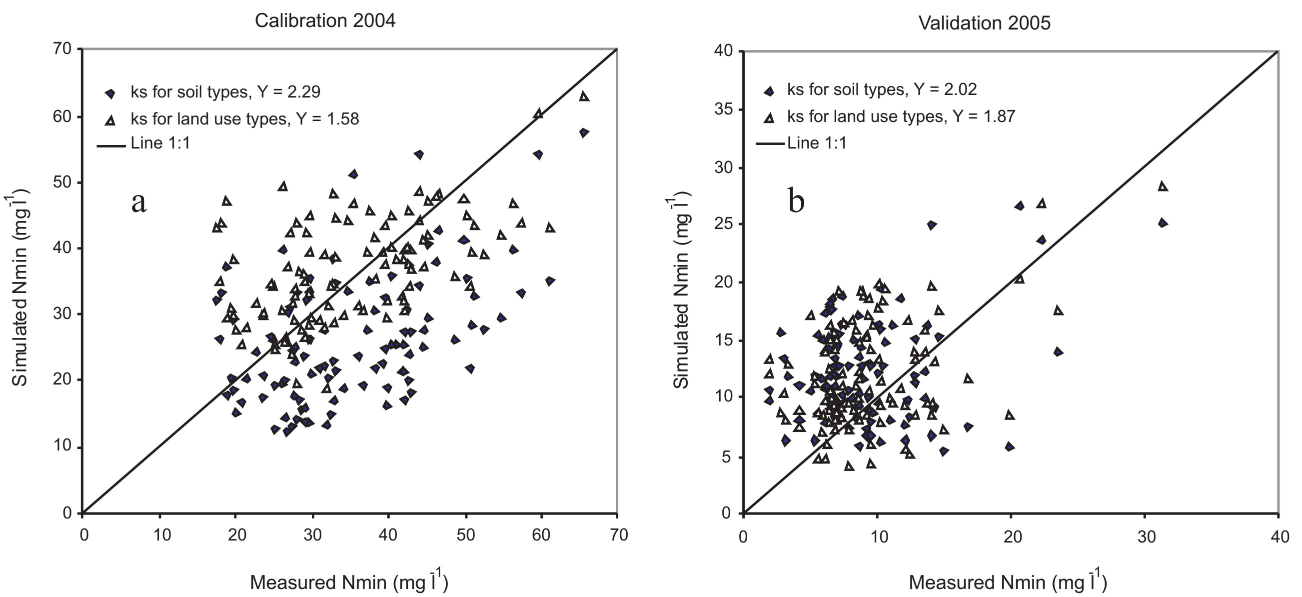

Figure 4: Calibration 2004(a) and validation 2005(b) results: correlation between measured soil mineral nitrogen concentration (Nmin, mg l^{-1}) at 52 points and four sampling dates and (solid symbols) simulated Nmin (mg l^{-1}) with different *ks* for the two soil types and (open symbols) simulated Nmin with different *ks* for 13 land units, created by overlaying soil and land use maps.

Table 5: Calibration factors for soil type-specific *ks* and soil and land use type-specific *ks*

Soil compartment	*Sandy loam*		*Clay loam*	
For soil type-specific ks				
	Rice	*Other*	*Rice*	*Other*
Compartment 1	0.0003	0.0049	0.0003	0.0075
Compartment 2	0.030	0.130	0.030	0.130
Compartment 3	0.310	0.455	0.310	0.364

For soil and land use type-specific *ks*

	Flowers	*Squash*	*Cabbage*	*Chili*	*Rice*	*Flowers*	*Squash*	*Cabbage*	*Chili*	*Rice*
Compartment 1	0.0049	0.0049	0.0049	0.0049	0.0024	0.0075	0.0075	0.0075	0.0075	0.0024
Compartment 2	0.120	0.120	0.120	0.120	0.003	0.130	0.130	0.130	0.130	0.003
Compartment 3	0.457	0.447	0.437	0.455	0.478	0.400	0.354	0.361	0.341	0.437

2005 is shown in Figure 5. In general, Nmin was lower in 2005 than in 2004. Overall, the spatial patterns were similar, but in 2004, Nmin was similar in rice soil and in vegetable soil, whereas in 2005 it was lower in rice.

In the simulations, the rate of lateral nitrogen transport along the local drainage network (ldd; Table 4) was low, i.e. lateral water and N flows were less than 0.2 mm d^{-1} and 0.032 kg ha^{-1} d^{-1} in the first, 0.11 and 0.06 in the second, and 0.03 and 0.012 in the third layer, respectively. The highest rates usually occurred during irrigation of specific crops, creating moisture content gradients between plots with different land use types. However, at some locations, cumulative lateral Nmin transport was substantial (Figures 5c and d), due to frequent soil moisture gradients between the upper and lower cells.

Nitrogen Transport and Leaching

Simulated percolation rates reached values up to 55.1 mm d^{-1} in the first layer, 1.74 in the second, and 0.9 in the third, with associated N leaching rates of 0.7 kg ha^{-1} d^{-1} in the first layer, 0.65 in the second, and 0.45 in the third. Percolation was more frequent than lateral flow and strongly associated with rainfall events.

Total annual N leaching was higher in 2004 than in 2005 (Figures 5e and f) and varied among crops (Table 6), as a result of differences in percolation volume under different irrigation and fertilizer regimes, i.e. from 88 to 122 kg N ha^{-1} yr^{-1} in flowers, 64 to 82 in the cabbage group, 51 to 76 in chili, 56 to 75 in the squash group, and 36 to 55 in rice.

Discussion

Up-scaling from individual plot level is essential in environmental assessment, and requires taking into account topography, spatial variability, temporal dynamics and interactions among factors that do not play a role at plot level (El-Sadek et al., 2003). Land use is the single most important factor influencing N leaching, as shown by significant differences in N-concentrations in the profile among crops (Mai et al., 2010). Among the cropping systems in this study, flowers showed the highest susceptibility to N leaching,

Table 6: Simulated annual nitrogen leaching losses (kg ha^{-1}) for different crops on sandy loam (SL) and clay loam (CL)

Land use	*N leaching*			
	2004		*2005*	
	SL	*CL*	*SL*	*CL*
Flowers	121.5	121.0	89.8	87.9
Squash	75.4	71.2	58.7	55.7
Cabbage	81.6	76.7	69.9	63.9
Chili	76.1	72.6	56.1	51.1
Rice	36.7	36.1	54.8	52.9

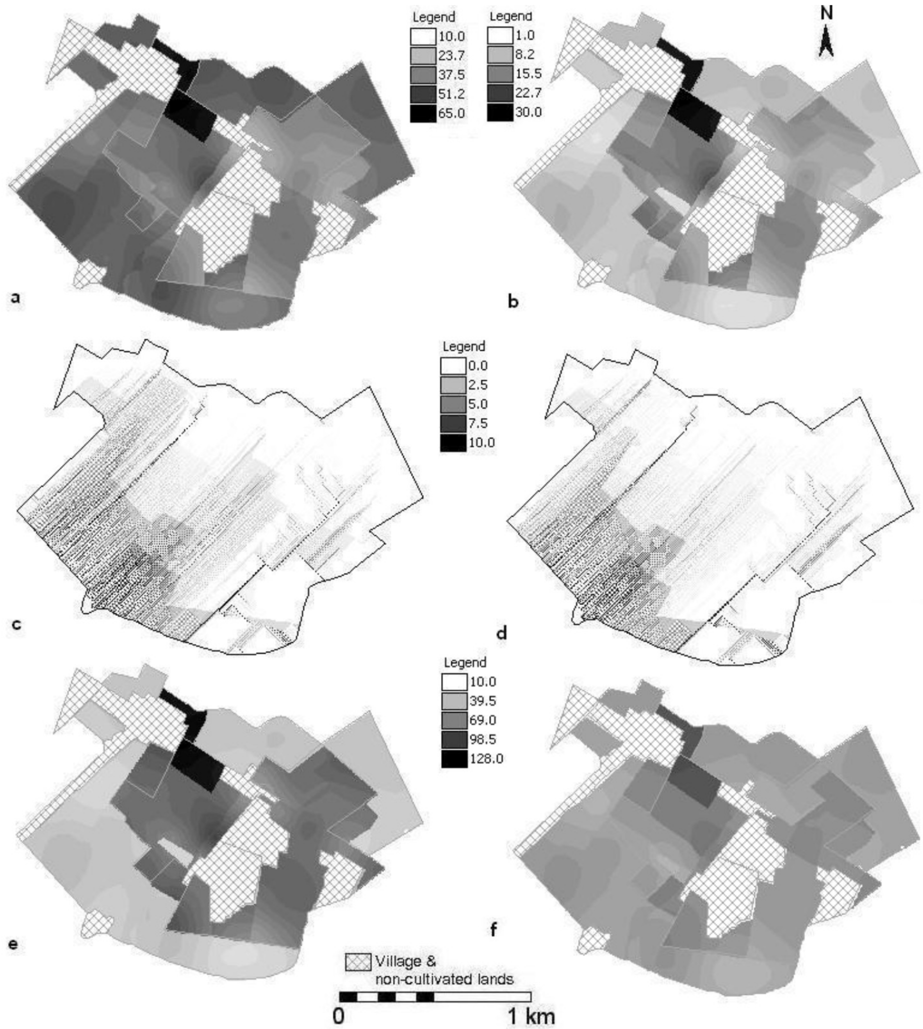

Figure 5: Simulated soil mineral nitrogen concentration (Nmin, mg l^{-1}) on 6th March 2004 (a), and 26th March 2005 (b); simulated cumulative lateral N transport (kg ha^{-1} yr^{-1}) in 2004 (c) and in 2005 (d); and simulated annual N leaching (kg ha^{-1} yr^{-1}) in 2004 (e), and in 2005 (f).

because of the very high fertilizer doses applied. Vegetables have a similar range in N leaching, with the higher values for cabbage, associated with short-duration rotation and the high frequency of fertilization. N leaching is lowest in rice, because of the presence of the low-permeability layer.

Land use type strongly influences the water and nitrogen balances in the soil, through irrigation, evapotranspiration, and fertilization. Soil moisture status varies among crops and soil-type. Therefore, *ks* should be calibrated for each soil horizon in combination of soil type and land use type.

For integrated environmental assessment, a large number of system characteristics have to be combined. These results show that the methodology is flexible and provides facilities for easily linking to and extracting information from spatial and non-spatial databases (Karssenberg et al., 1996).

Conclusions

A spatial dynamic model was developed in the PCRaster software environment to simulate nitrogen dynamics and leaching under intensive agriculture with high fertilizer use, and was applied for a period of two years to Van Hoi commune in a flatland area of Tam Duong district in Vietnam. The model is shown to be a suitable tool for quantifying nitrogen losses from agriculture and for environmental assessment at regional scale. It has been calibrated on the basis of measurements in March and August 2004 and validated for March and August 2005. Simulated result shows that lateral flow was low, and that nitrogen leaching due to percolation was high. Simulated annual N leaching losses varied from 88 to 122 kg N ha^{-1} yr^{-1} in flowers, 64 to 82 in the cabbage group, 51 to 76 in chili, 56 to 75 in the squash group, and 36 to 55 in rice.

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Asian Journal of Water, Environment and Pollution

Volume 9 Number 3 **July – September, 2012**

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