Mapping Nitrogen Concentrations in Shallow Groundwater Under Intensive Farming in Northern Vietnam

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Abstract: A study was carried out in Vanhoi commune, Tam Duong district, in the Red River Delta, North Vietnam, to determine N concentrations in shallow groundwater (NO_3-N and NH_4-N) under various environmental conditions (soil and topography) and land uses. Water samples were taken at one meter depth during the growing season using open porous pipes and a hand pump. Samples were analyzed for NO_3-N and NH_4-N at three moments (March and August 2004 and March 2005). Explanatory variables were used in a stepwise backward linear regression to improve the predicted spatial distribution of N concentrations in groundwater. Semi-variograms were computed and appropriate models were established for original N concentrations as well as for the residuals derived from regression analysis. N concentrations were predicted using both, ordinary block kriging and regression block kriging. Regression block kriging yielded more accurate results, as the additional information, taken into account in the multiple linear regression, explained part of the spatial variation. NH_4-N concentrations were substantially lower than NO_3-N concentrations. Temporal changes in N concentrations in the groundwater were mainly the result of variations in environmental conditions, such as rainfall and in land use with different irrigation and fertilizer regimes. Results indicate a proportional correlation of N concentration with the amount of fertilizer applied and an inverse correlation with crops grown in the field.

Keywords: Nitrate pollution, groundwater, geostatistics, regression-kriging, Vietnam

1. Introduction

In recent years, groundwater pollution due to human activities has been recognized as an increasing environmental threat in many countries throughout the world. In Asian countries where intensive farming systems have developed in recent decades, water for drinking and other domestic uses for many of the rural poor originates from polluted sources, such as shallow aquifers under agricultural land (Pingali and Roger, 1993). A national survey of the Vietnam Cancer Institute (NCI, 2002) showed that stomach cancer is the second leading form of cancer in males, with an age-specific rate of 23.7 per 100 000 and the third one in females with an age-specific rate of 10.8 per 100 000, increasing at an annual rate of 4.4% for both males and females (Anh et al., 2002), and about 5 700 and 3 400 diagnosed patients in the country in 2000. The main causes of this disease are food (in particular, vegetables) and water with high contents of nitrate and nitrite. Extensive research on groundwater quality problems has been conducted by both agricultural and environmental scientists at farm, regional and national scales (cf. van Keulen, 2001; Ondersteijn et al., 2002; Sheldrick et al., 2002; Wolf et al., 2005). In Japan, Kumazawa (2002) found NO_3-N concentrations as high as 100 mg l^{-1} in water drawn from wells and NO_3-concentrations tended to decrease, following reductions in fertilizer application rates. In China, nitrate concentrations in ground- and drinking water exceeding 50 mg NO_3 l^{-1} (at two locations exceeding 300 mg l^{-1}) were found in more than half of the water samples (37) collected in 1993 and 1994 at 69 locations distributed through 14 cities and various counties, covering an area of about 140,000 km^2 (Zhang et al., 1996). Xing and Zhu (2000) estimated that NO_3-leaching from uplands in the north of China accounted for 0.5–4.2% of the applied chemical N-fertilizer. Values for paddy fields in the south ranged from 6.75 to 27.0 kg N ha^{-1} yr^{-1}. Studies at farm level (Hack-ten Broeke and de Groot, 1998; EI-Sadek et al., 2003), corroborating that agriculture is a major contributor to NO_3 leaching to groundwater. Fuentes et al. (2003) found in Washington State (USA) that after harvest, up to 90 kg NO_3-N ha^{-1} can be leached to depths of 1.5 to 2.5 m, which was attributed to inefficient or excessive use of fertilizer.

Groundwater quality varies spatially and temporally, under the influence of inputs, and factors such as elevation, soil type, land use and geohydrological conditions (Pebesma and de Kwaadsteniet, 1997). Spatial variation can be mapped by interpolation from point observations. Different interpolation methods have been applied, such as moving averages, Thiessen polygons or distance-related algorithms (Goovaerts, 2000). Currently, geostatistics is the recommended method, in particular kriging techniques (Goovaerts, 1994; 2000; Hengl et al., 2004, Leopold et al., 2005). Geostatistical methods have been applied in various scientific disciplines for mapping soil properties (Goovaerts, 1994; Lemke et al., 2004), rainfall distribution (Goovaerts, 2000), erosivity (Goovaerts, 1999), and groundwater quality (Pebesma and de Kwaadsteniet, 1997; Cinnirella et al., 2005). Kriging belongs to the family of generalised linear models; it uses weighted point observations to predict on the point or block support. The weights are determined from the semi-variogram model and are calculated in such a way that the estimation error in each output pixel is minimized. For natural conditions, simple kriging can be applied for interpolation of N concentrations in shallow groundwater. As Pebesma and de Kwaadsteniet (1997) point out, in agricultural areas, many environmental factors can influence groundwater quality – such as soil type, land use and geohydrological conditions (e.g. depth of groundwater table, infiltration or seepage, marine influence, precipitation) which have to be taken into account in interpolation procedures. In this paper, a study on N concentration in shallow groundwater is described in Tam Duong district in northern Vietnam, where very intensive agriculture is practiced with high fertilizer application rates.

2. Methodology

2. 1. Study area

Located in the flat land of Tam Duong district, 60 km north of Hanoi (Fig. 1), Vanhoi commune has a total area of 290 ha, comprising two main soil types: Endogleyi district plinthosols (224 ha; 77.4%) and Albi district plinthosols (66 ha; 23.6%) (FAO classification; FAO/UNESCO, 1974). Climate is characterized by two main seasons: a hot rainy season (May-September) and a cold dry season (October-April), with differences in rainfall, evaporation, temperature and solar radiation (Fig. 1).

2. 2. Land use and fertilizer use

Land use in the area consists of paddy rice, vegetables and other dryland crops. The main rotation is rice–rice followed by a winter crop. In well-irrigated soils, vegetables can be grown continuously. The number of crops in such vegetable rotations depends on the market, availability of labor and of capital. The commune is located very close to the provincial center, where purchasing power and consumption of food and vegetables is high, which allows the farmers to implement intensive cultivation systems with new high-value crops, using high levels of external inputs, such as fertilizers. Nitrogen fertilizer is applied at different rates to different crops: the highest doses are applied to flowers (about 50-75 kg ha^{-1} mineral N and 60 kg ha^{-1} N in manure and sludge), followed by vegetable group 1, consisting of chili, cucumber, tomato, pumpkin (about 115 kg N ha^{-1}), vegetable group 2 consisting of paprika, cabbage, eggplant, kohlrabi (about 65 kg N ha^{-1}) and paddy rice (about 80 kg N ha^{-1}). During the main cropping season, from February till the end of September, paddy fields are flooded and non-paddy fields are adequately irrigated and are ponded sometimes in the rainy season (from June till August). Under these conditions, with downward movement of water, nitrogen can be leached below the root zone and cause nitrogen pollution of the groundwater.

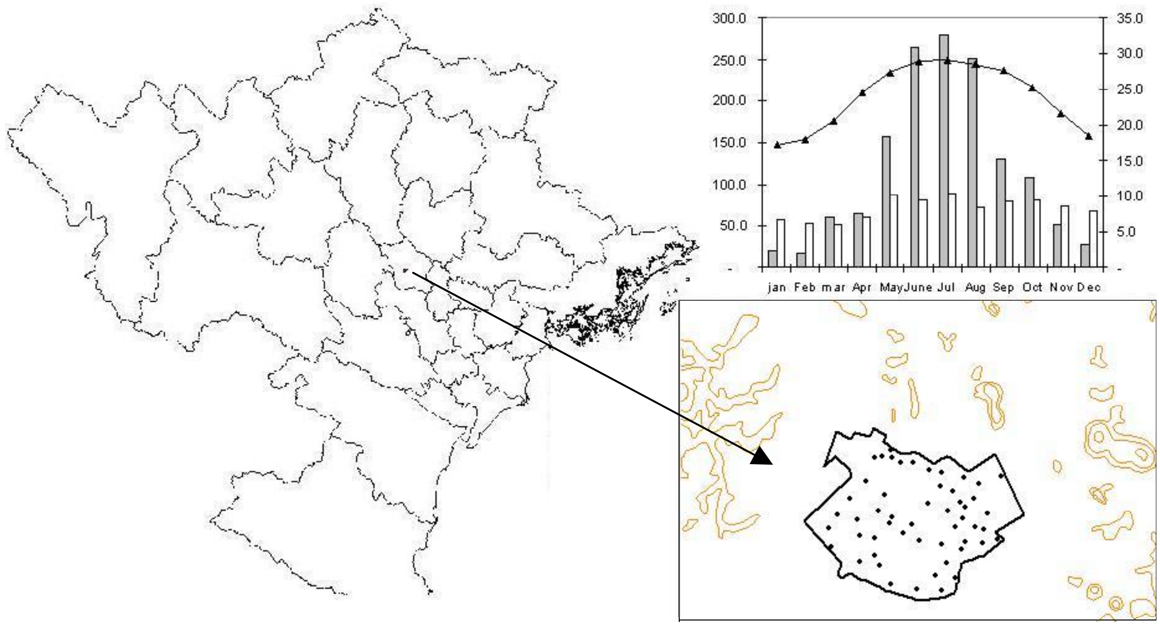

Figure 1: Study area location in the north of Vietnam and its sampling point map overlay topography map with contour lines. Average weather conditions in the study area are shown on the inset graph with monthly rainfall (solid bar) and monthly evaporation (blanc bar) in mm on the left Y-axis. Monthly temperature (line) in ^{o}C on the right Y-axis

2. 3. Sampling design and analysis

Water samples were taken in paddy fields in March 2004, to represent the early spring season after the long dry period, and in August 2004, to represent the mid-summer period with the highest rainfall and very high crop grow rates. Sampling has been repeated in the same sampling points in March 2005. At each sampling, 52 samples were taken using open porous pipes. Polyvinylchloride (PVC) pipes, 3 cm in diameter, were inserted in pre-drilled holes into soil to 1 m depth. Small PVC pipes (0.5 cm in diameter) were inserted into the wide pipes till the bottom. Before the sample was taken, the water in the porous pipes was pumped off several times. Water from the pipe was collected by hand pump, through a vacuum bottle, transferred to plastic bottles and stored at 4 ^{o}C till chemical analysis. Water samples were filtered through 0.45 mm Watman paper, and the extract distilled for determination of NH_4-N and NO_3-N, using micro-Kjeldahl.

2. 4. Spatial correlation and geostatistical analysis

In the analysis, we used ordinary block kriging (OBK) and regression block kriging (RBK) (Goovaerts, 1997; Hengl et al., 2004; Leopold et al., 2005). Ordinary kriging uses weighted linear combinations of the observations of *Z* to predict *Z* at unobserved locations. The weights are chosen such that the prediction error variance is minimized, under the condition of unbiasedness. The weights are a solution of the kriging system, and can be expressed in terms of semi-variogram values, that describe the spatial autocorrelation structure of *Z*. In mathematical terms, the ordinary kriging predictor is defined as:

$$\hat{Z}(B) = \sum_{i=1}^{n} \lambda_i Z(x_i) \tag{1}$$

where $\hat{Z}$ (*B*) is the predictor of the average value of *Z* over a block B, obtained from the n observations *Z*(x_i), using weights λi. In regression kriging, an extension of ordinary kriging, the mean of *Z* is taken as a non-constant trend, defined as a linear regression on explanatory variables. Thus, in regression kriging the random function Z is defined as the sum of a deterministic trend m and a zero-mean stochastic residual ε:

$$\hat{Z}(x) = m(x) + \varepsilon(x) = \sum_{k=0}^{m} \beta_k y_k(x) + \varepsilon(x) \tag{2}$$

where β_k are regression coefficients and y_k explanatory variables (usually y_0 is taken as 1, so that β_0 is the intercept of the regression). Prediction, using regression block kriging, follows:

$$\hat{Z}(B) = \sum_{k=1}^{m} \hat{\beta}_k y(B) + \sum_{i=1}^{n} \kappa_i \varepsilon(x_i) \tag{3}$$

The regression coefficients are estimated from the observations, using weighted least squares. Note, that we can use here the regression coefficients derived at the point support for estimations on the block support, as the regression model is linear and, thus, the block predictions and the corresponding prediction variance are not affected by a change in support. The kriging weights k_i are solved by the kriging system, and are expressed as semi-variogram values of the residuals. The corresponding regression kriging variance incorporates the uncertainty on the estimation of the regression coefficients (Leopold et al., 2005).

Candidate explanatory variables for RBK of NO_3-N and NH_4-N concentrations in groundwater are soil type, soil texture and land use. Soil and land use maps were obtained by reclassification of the original soil and land use maps. Soil type and land use are categorical variables and were transformed to binary variables of zero and one to be used in Equation (3). Explanatory variables were selected using stepwise backward linear regression. The regression analysis was carried out with the statistical software package Genstat (Lawes Agricultural Trust, 2003). Residuals at observation locations were computed by subtracting the fitted regression line from the observations.

Experimental semi-variograms were computed for the original observations, as well as for the residuals, and variogram models were fitted by selecting the correct values for the parameters nugget, range and sill. Finally, the N concentrations were interpolated and aggregated using OBK and RBK as in Equations (1) and (3). Gstat software (Pebesma, 2001) was used to compute and model the semi-variograms and perform the kriging predictions.

3. Results

3. 1. Data analysis.

Data used in the analysis were NO_3-N and NH_4-N concentrations in groundwater in March and August 2004 and March 2005. As N-concentrations in groundwater are influenced by many spatial variables, such as soil type and land use (Diodato and Ceccarelli, 2004; Hengl et al., 2004), and vary in time, groundwater quality varies and is skewed in managed ecosystems. Analysis of the N concentration histograms showed a normal distribution only for the NO_3-N concentration in March 2004. As a consequence, the other data would have to be log-transformed (Fig. 2) to be normally distributed. In this study, we decided to work with the untransformed data, as the back-transform of N concentrations for averaged block values does not equal the log-transform of the point observations and bias could be introduced (Leopold et al., 2005).

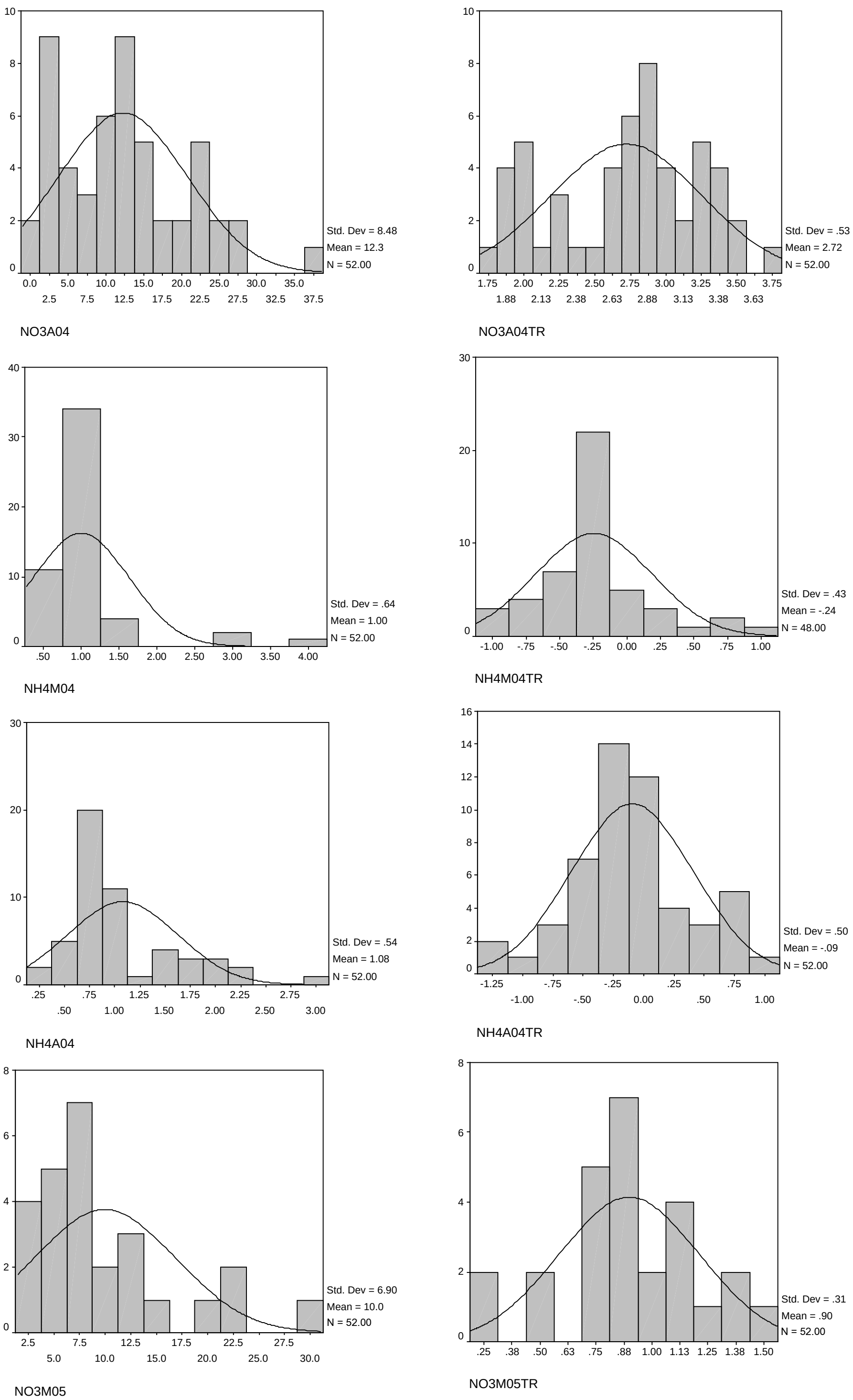

Figure 2: Histogram of N concentration (left) and its log-transformation (right) for NO3-N in August 2004, NH4-N in March 2004, NH4-N in August 2004 and NO3-N in March 2005.

Fig. 3(a–d) show the spatial distribution of the explanatory variables selected for regression, i.e. land use type (a), elevation (b), soil texture (c) and soil type (d). In the central part, soils are suitable for non-rice crops, such as cabbage, chili, flowers and squash, because of their low clay content, while elevation gradually declines from north east to south west. Irrigation and drainage systems are designed in association with this topography. Soil type and soil texture are classified as two separate characteristics as shown in Fig. 3.

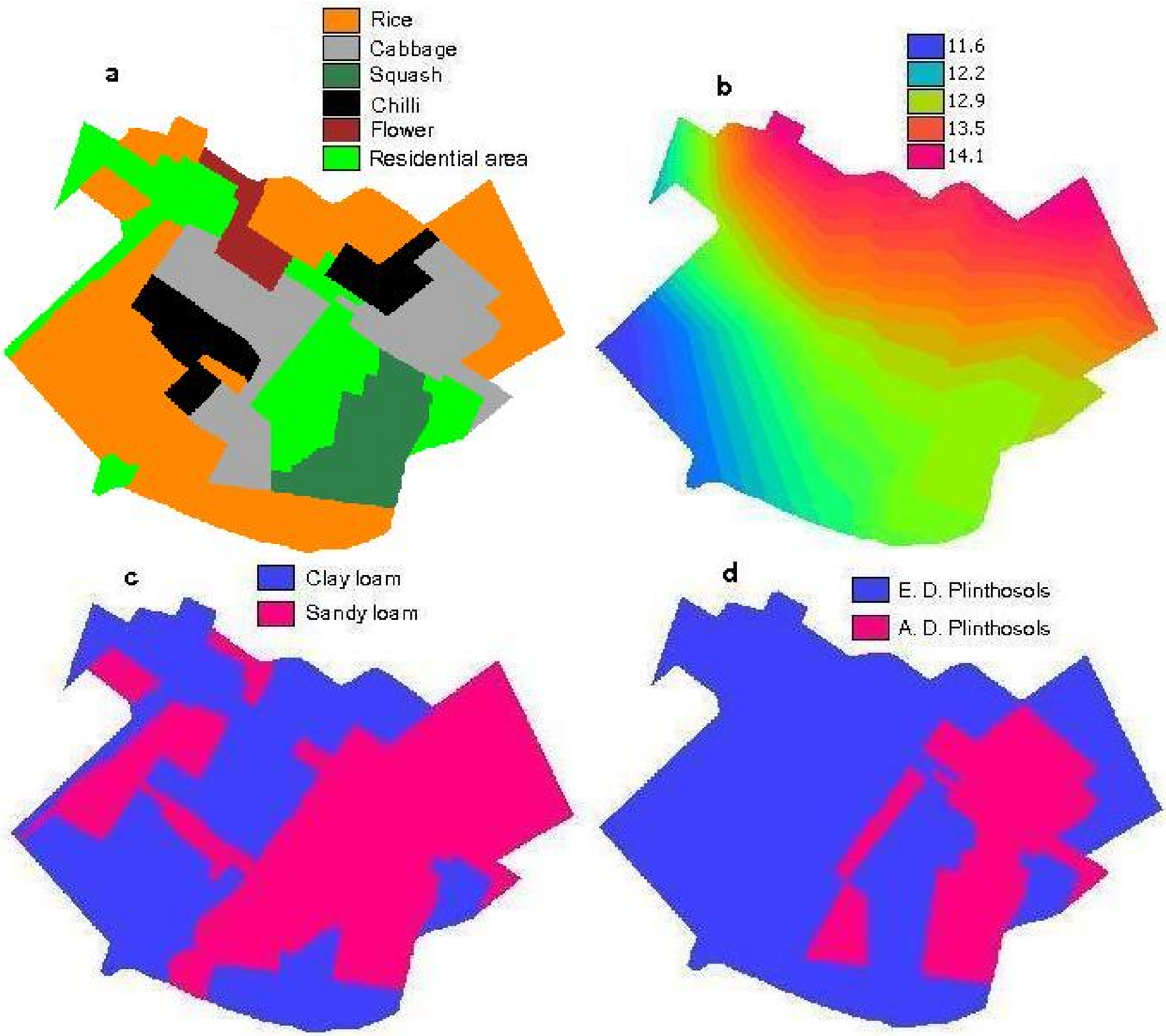

Figure 3: Maps for explanatory variables used in regression block kriging of NO_3-N and NH_4-N. land use (a), elevation (b), soil texture (c) and soil type (d).

The variables selected in the stepwise linear regression are those expected to be correlated with N concentrations: Land use is associated with the fertilization and irrigation regimes, i.e. in flowers and chili input of manure is high, with high risks for N leaching and in (flooded) rice there is continuous downward water movement. Differences in elevation cause lateral flows of percolation- and groundwater in the subsoil. In the sandy loam, rates of percolation are higher than in the clay loam. Regression analysis showed that land use type, elevation, main soil type and the soil texture class sandy loam are significantly ($R^2 = 0.95$) correlated with N concentration. Minor soil type (A. D. Plinthosols) and soil texture class clay loam have no significant influence in the regression analysis, because the number of samples in these classes is low and the variation in N-concentration high.

3. 2. Geostatistical aggregation and prediction

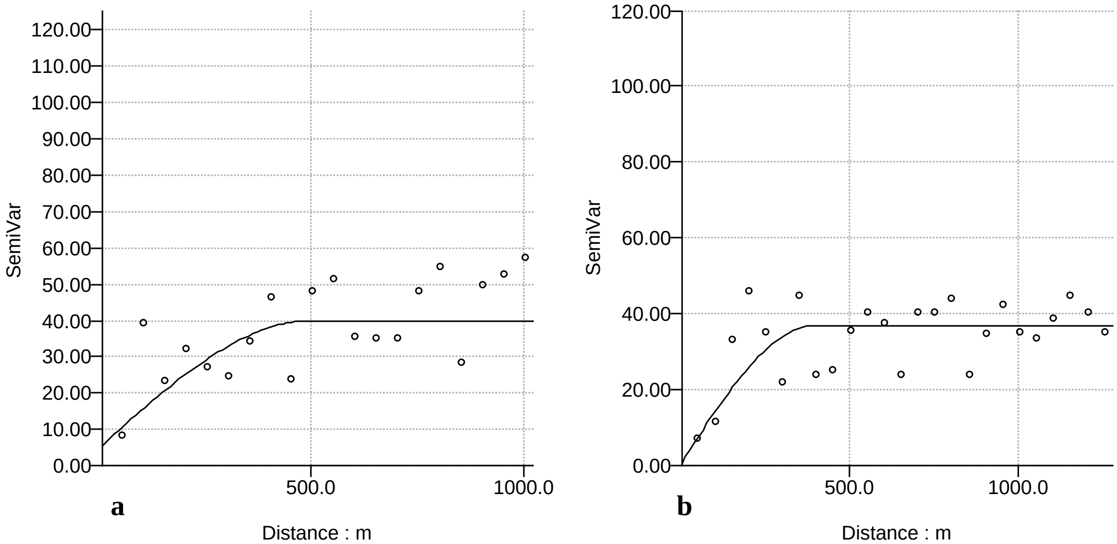

Figure 4: Experimental semi-variogram (dots) and fitted model (solid line) of NO_3-N observations (a) and NO_3-N residuals (b) in August 2004.

The experimental variograms and the fitted models for the ordinary and regression kriging are shown in Fig. 4a and b, respectively. The nugget-, sill- and range values in the variogram for the observations are relatively larger than for the variogram of the residuals in Fig. 4b. This is in accordance with observations of Hengl et al. (2004) and Leopold et al. (2005) that variograms for residuals result in lower nugget and sill values when the deterministic trend has been removed by regression.

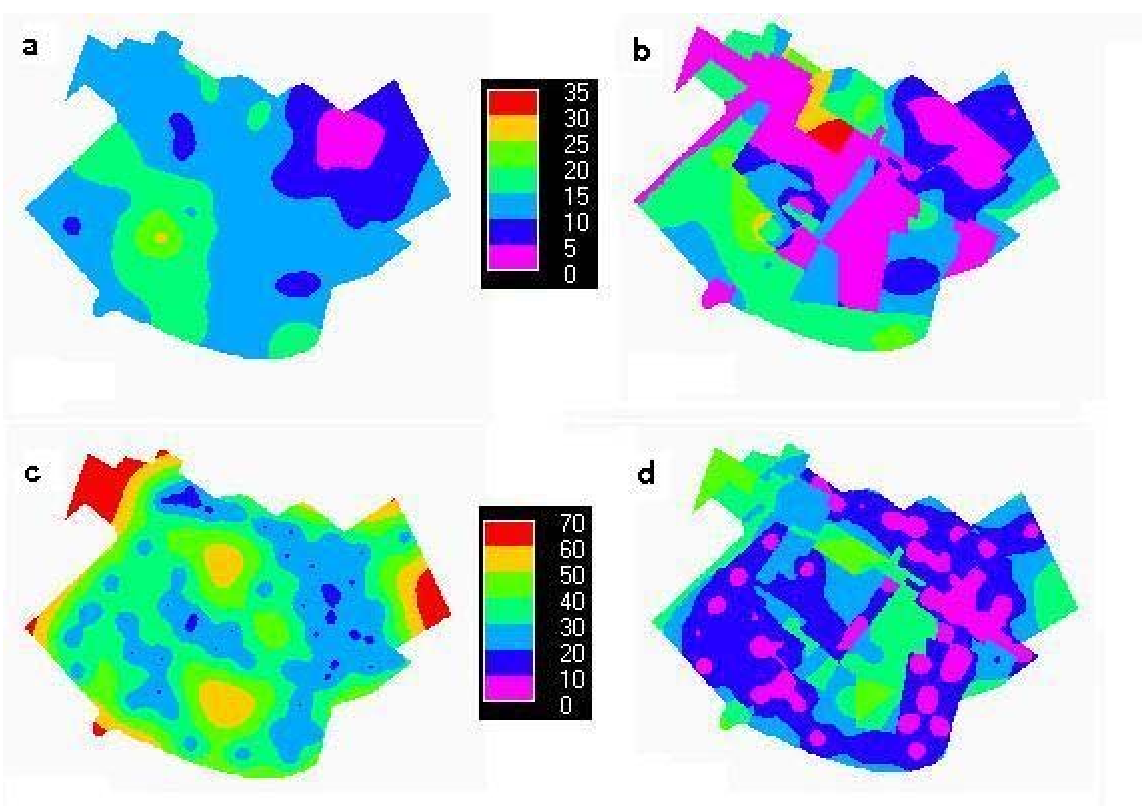

Figure 5: Kriging predictions for NO_3-N (mg l^{-1}) and kriging variances (mg l^{-1})^2 in August 2004; a) ordinary block kriging, b) regression block kriging, c) ordinary block kriging variance and d) regression block kriging variance.

OBK and RBK have first been applied to the NO_3-N concentration in August 2004 with calculation of variances (Fig. 5a-d). Where OBK predicts a smooth spatial distribution of NO_3-N concentration over the area (Fig. 5a), RBK results in a much more detailed picture, where NO_3-N concentration varies under the influence of the explanatory variables (Fig. 5b), especially in the very intensive agro-ecosystems with high inputs of fertilizer. Overall, OBK gives a mean variance of 37.18 (mg l^{-1})^2, compared to 20.78 (mg l^{-1})^2 for RBK and the patterns of variance distributions are clearly illustrated in Fig. 5c and d.

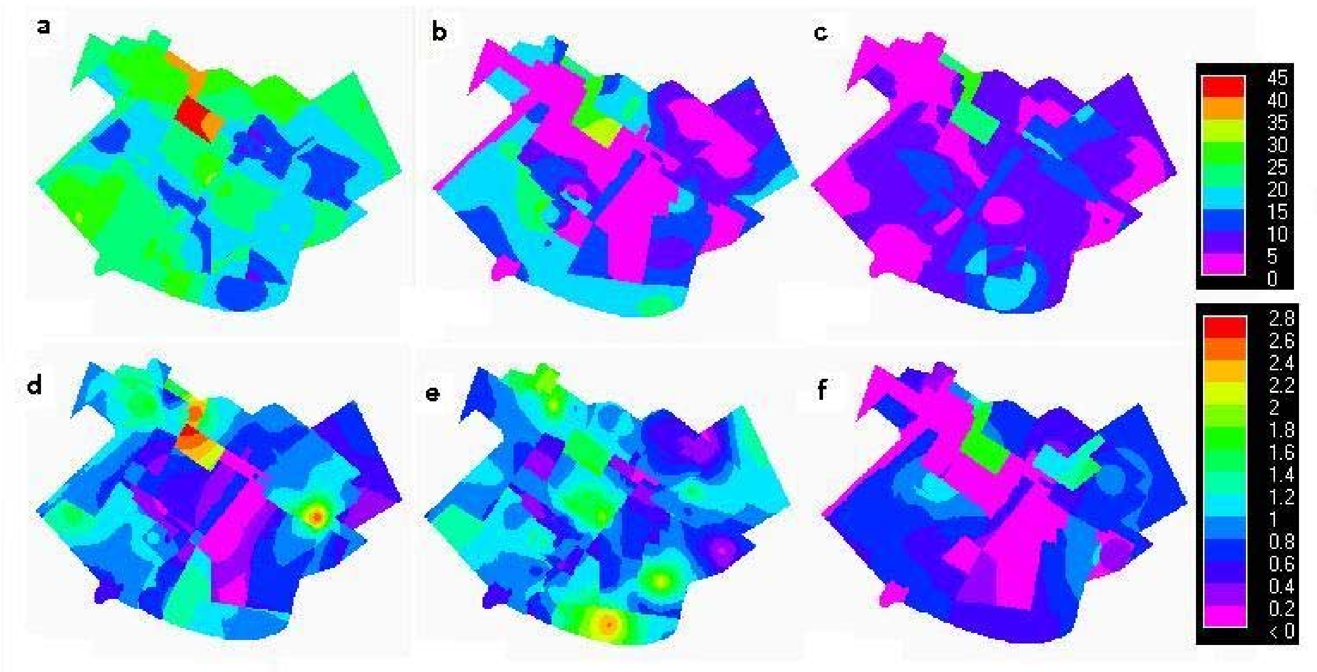

Figure 6: Prediction result of N concentration (mg l^{-1}) in shallow groundwater using RBK for NO_3-N in March 2004 (a), NO_3-N in August 2004 (b), NO_3-N in March 2005 (c), NH_4-N in March 2004 (d), NH_4-N in August 2004 (e) and NH_4-N in March 2005 (f).

RBK was selected for continuous interpolation of NO_3-N and NH_4-N for the other data sets. Fig. 6 shows the dynamics of the NO_3-N and NH_4-N concentrations in shallow groundwater for different soil conditions and under different intensive farming systems, as interpolated using RBK on the basis of various explanatory variables, such as soil, elevation and land use. These explanatory variables influence the N concentration under intensive cropping systems, where high inputs of fertilizer contribute significantly to N-leaching to the groundwater.

4. Discussion

Regression block kriging yielded more accurate results than ordinary block kriging as shown in Fig. 5. The spatial patterns resemble much more the actual environmental conditions. The kriging variance in Fig. 5b appears lower for RBK than OBK, which can be used as a criterion for the goodness of prediction. As spatial patterns and accuracy seem to be reproduced better with RBK we continued to use RBK only to predict N concentrations in groundwater for the other sampling times. Comparing Fig. 6a and 6b, shows higher NO_3-N concentrations in March 2004 than in August 2004, as in March 2004 a basal fertilizer, comprising manure and chemical nitrogen fertilizer had been applied to almost all crops. As temperatures were very low in this period, crop growth was slow, as was crop nitrogen uptake, while in August, in the rainy season, fertilizer application was lower and temperatures were higher, so that crop growth rates and nitrogen uptake rates were higher. Hence, quantities of NO_3-N and NH_4-N available in the soil solution for leaching were smaller and consequently N concentration in the groundwater lower. The consequence of the much warmer spring in 2005, with crops starting early and in good condition at the time of sampling, shows up when comparing Fig. 6a and c: NO_3-N in March 2005 is much lower than in March 2004. The trends are similar for NH_4-N in Fig. 6d, e and f, but the NH_4-N concentration is much lower, because nitrification generally proceeds fast under these conditions and NH_4, being a cation, is adsorbed at the soil colloids (Mulvaney, 1994). Results from the spatial analysis show higher spatial correlation and lower variance for N concentrations in August to for those in March 2004. This can be explained from rainfall, that in the wet season is the major factor determining N leaching. Rainfall is evenly distributed and as growth and nutrient status of most crops is similar, leaching rates are comparable. In spring, following the winter crops, soil moisture status depends on the preceding land use (fallow without irrigation, maize with a high cover and weekly irrigated, vegetables irrigated at two-day intervals). Hence, following the fallows, soils are very dry with many cracks and macro-pores, causing strong leaching in spring, in contrast to plots cultivated to winter crops. For flowers, the main growth period is from the end of September until April, which is characterized by weekly applications of liquid compost and mineral fertilizer, hence N leaching in this period is high. During summer, the crop is kept alive, with lower inputs and production. However, the remaining compost on the surface continues to decompose and the mineralized N results in higher N leaching than on other land use types.

5. Conclusions

Predicting N concentrations in shallow groundwater from various explanatory variables, regression block kriging gave more accurate results than ordinary block kriging as the kriging variance is lower for RBK than OBK. RBK results appeared to resemble the true spatial variation better, which is in agreement with expert knowledge.

Land use appeared the most influential factor for the spatial distribution of N concentrations, because it determines the water balance components, such as runoff, evapotranspiration and percolation. The fertilization and irrigation regimes also strongly affect the magnitude of N leaching. In addition to their spatial variability, N-concentrations in groundwater also varied temporally, under the influence of varying environmental conditions, such as rainfall, and management practices, such as irrigation and fertilizer application and their effects on crop growth. Concentrations in groundwater were very low for NH_4-N and fairly high for NO_3-N, associated with their relative mobility in the system. The accuracy of the predictions depends not only on the additional information taken into account, but also on the number of sampling points. Furthermore, the predictions are only representative for a given period of time with similar environmental conditions. Therefore, the accuracy could be improved by increasing the sample size in space and by increasing the frequency of sampling, to account for variations in environmental conditions, such as rainfall and evaporation/evapotranspiration, as well as in plant performance. Hence, we could improve the modeling of N loss due to leaching under various land use and environmental conditions as soil type, rainfall, and evapotranspiration.

In predicting N concentrations in shallow groundwater from various explanatory variables, regression block kriging gave better results than ordinary block kriging. RBK yielded more heterogeneous results, in agreement with expert knowledge about the spatial distribution of N concentrations in groundwater.

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