Evaluation of strategies to reduce nitrate pollution of groundwater – assessing the needs and efficiencies of agri-environmental measures for selected groundwater bodies in Germany

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Abstract: Within the EU-Life project WAgriCo (Water Resources Management in Cooperation with Agriculture) nitrogen management options adapted to hydrological and agro-economic site properties are developed and implemented for three pilot areas in the Federal State of Lower Saxony using new participation approaches and technologies suitable for programmes of measures to reduce diffuse pollution from agriculture. As a target value for water protection measures a nitrate concentration in percolation water of 50 mg/l as an average for a larger area defined by the groundwater bodies and their hydrogeological subdivisions has been defined. An integrative emission model is used to simulate the interactions between agricultural practice, nitrogen surpluses and the nitrogen flow through the soil and aquifer to the outflow into surface waters. The actual nitrate concentrations in percolation water are calculated for the entire Federal State of Lower Saxony considering site-characteristics, N-surpluses, water balance and denitrification in the soil. The tolerable N-surpluses needed to meet the environmental target are quantified as averages for each of the hydrogeological subdivisions by "inverse" calculation using this model system. The required reduction of N-surpluses can then be estimated by comparing the tolerable N-surpluses to the actual state of nitrogen emission. For the evaluation of the amount and efficiency of water protection measures, the required reduction of N-surpluses to accomplish the environmental target is quantified, using the current status as a reference.

Keywords: Catchment management, diffuse source pollution, mitigation methods, river basin management, Water Framework Directive

1. INTRODUCTION

The fundamental objective of the Water Framework Directive (WFD) of the European Union (European Parliament and Council of the European Union, 2000) is to attain a good status of water resources in the member states of the EU by 2015. The environmental targets for chemical status of groundwater bodies according to the Water Framework Directive are specified in the Groundwater Directive (European Parliament and Council of the European Union, 2006). Following the time table of implementing the Water Framework Directive, EU member States carried out a review about the qualitative and quantitative status for all river basins in the EU. For river basins, whose good status can not be guaranteed by 2015, catchment wide operational plans and measurement programs have to be drafted and implemented until 2009.

In the Federal State of Lower-Saxony, Germany, the achievement of the good status is unclear, or rather unlikely for about 70 % of the groundwater bodies. Inputs from diffuse sources and most of all nitrate losses from agriculturally used land have been identified as the main reasons for exceeding the groundwater quality standard for nitrate and for failing the „good qualitative status" of groundwater. This does not mean necessarily that Nitrate drinking water quality standards are exceeded but the chemical status of groundwater is decreased in special groundwater bodies. For this reason the drafting and implementation of measurement programs in Lower-Saxony is primarily focussed on nitrate.

The WAgriCo-project (Water Resources Management in Cooperation with Agriculture), is a collaborative project funded by the European Commission Life Fund within the period October 2005 to September 2008, involving six British and four German institutions. The aim of the project is to develop a suite of measures or solutions which can be implemented in agri-environmental schemes to achieve and/or sustain good water quality according to the WFD. Based on an assessment of the pollution risk the environmental objectives will be specified and measures for endangered water bodies will be specified, discussed with the local stakeholders and implement at farm level. The results achieved in the pilot areas and the socio-political, financial, geographical and hydrological factors influencing the impact of the measures are evaluated. On the basis of an extrapolation to Federal State level the administrative requirements for state-wide implementation are specified and evaluated.

For macroscale areas, i.e. large river basins or Federal States, the achievement of good qualitative status of groundwater bodies entails a particular challenge as the complex ecological, hydrological, hydrogeological and agro-economic relationships in a catchment area have to be considered simultaneously. In this framework combined agroeconomic-hydrologic models, that can be applied for macroscale areas are powerful tools to analyse the actual pollution loads and "hot spot" areas and to predict the impact of reduction measures. The use of hydrological models to support the implementation of the WFD in larger river basins has been promoted for several years, and has lead to a clear improvement of the models being used (Lindenschmidt *et al.*, 2007). Parallel to this, economic approaches for the support of the WFD have also en developed. These consider mainly the macro-economic effects of the improvement of water quality under the conditions of the WFD (Brouwer *et al.*, 2005; Mysiak & Siegel, 2004; Pulido *et al.*, 2005).

The development of model tools aiming at the derivation of measures to support the implementation of WFD is still the weakest area of the modelling (Lindenschmidt *et al.*, 2007). First steps in this direction have been done already by the authors in a project conducted in the river Ems basin and sub catchments of the river Rhine basin. In this project a combined emission model was developed by coupling results from N-balancing using data from agricultural statistics with the hydrological model GROWA (Kunkel & Wendland, 2002), the DENUZ model approach (Kunkel *et al.*, 2004) for assessing denitrification rates in the soil and the reactive nutrient transport model WEKU for groundwater (Kunkel & Wendland, 1997).

In this paper we want to show how the combined agroeconomic–hydrologic emission model may be used:

- To predict nitrate concentrations in the leachate at the scale of large catchments,
- To identify the maximal permissible diffuse nitrogen loads to guarantee nitrate concentrations in groundwater below 50 mg/l,
- To delineate priority areas for implementing nitrogen reduction measures at the scale of large catchments.

2. STUDY REGION

Within the Federal State of Lower Saxony three Pilot areas, Lager Hase, Große Aue and Ilmenau/Jeetzel, have been selected (see figure 1). The pilot areas are located in the North German Lowland within different large European river basins and cover approximately 300 000 hectares of agricultural land. The aquifers consist mainly of Pleistocene sand and gravel deposits. According to the first review of the qualitative and quantitative status of the groundwater bodies in Lower Saxony, for all of the three pilot areas the achievement of the good status is unclear or rather unlikely. Table 1 gives a short overview about the agricultural structure in the pilot areas in Lower Saxony.

The size of the pilot areas is in a range of 1500 to 2000 km^2. The land use structure, however, is very different. Lager Hase and Große Aue are dominated by animal husbandry. In the Lager Hase pilot area the average size of the area per farm and the area of the adjacent arable land is smaller than in the Große Aue pilot area. The Ilmenau/Jeetzel pilot

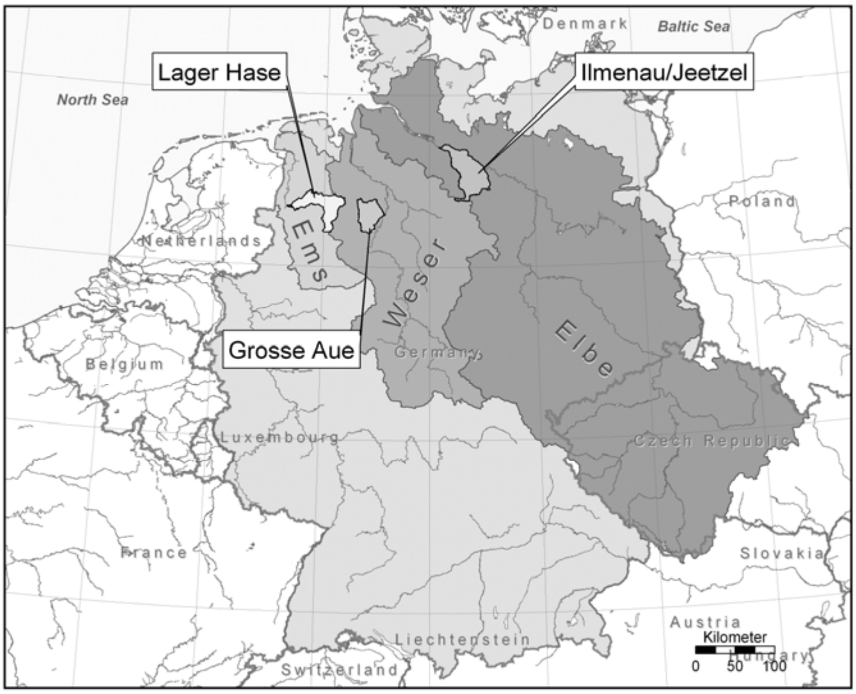

Figure 1. Location of the pilot areas of the WAgriCo project.

area is different to the other two pilot areas, since it is dominated by arable land and not by animal husbandry. In all pilot areas 55 % or more of the land surface is used agriculturally. Therefore, the natural conditions in groundwater and surface waters are significantly influenced by anthropogenic interferences into N- and water balance and runoff regimes.

Table 1. Agricultural structure in the pilot areas in Lower Saxony.

Pilot area	Lager Hase	Große Aue	Ilmenau/Jeetzel
Area (km^2)	1420	1517	2052
Number of farms	3000	1620	1640
Animal husbandry	67 %	67 %	27 %
Arable	14 %	33 %	68 %
Other	19 %	0 %	5 %

3. THE EMISSION MODEL

The main target of the emission model is to analyse the complex interactions between the driving-force indicator “diffuse nitrogen surpluses” and the state indicator “nitrate loads in percolation water” in a consistent and regionally differentiated way. The synergetic effects of the emission model are used for the derivation and implementation of agri-environmental measures aiming at the sustainable management of nitrogen inputs into groundwater. As the emission model consists of modules from different scientific disciplines, a common model interface for data exchange was developed, which guaranteed for a uniform definition (e.g. scope of representation, spatial and temporal dimension) of variables being exchanged.

In this context it has to be considered that the models are using different regional resolutions: raster cells in the hydrological models and administrative units in the agro-economic model. This is due to the different data sources: while the hydrological models GROWA and DENUZ use (digital) maps to derive spatial inputs, the agroeconomic model employs agrarian statistical data (Schmidt *et al.*, 2007). For this reason, regional nitrogen balances calculated by the N balance model as averages for the agricultural areas on a community level cannot be directly used as input variables in the hydrologic models.

For this purpose GIS supported model interfaces has been developed which enable not only the disaggregation and geographical referencing of N surpluses, but also the exchange of data, parameters and results between the models (Gömann *et al.*, 2005). The process of adjusting the different spatial resolution of the models is based on commonly used landcover data, which enables a land cover classification into arable land, pasture, forests and urban areas.

3.1 Regionalised differentiated agricultural economic modelling

Regarding diffuse water pollution the indicator "nitrogen surplus" is of particular importance. Agricultural statistics with data, e.g. on crop yields, livestock farming and land use, were used to balance the nitrogen supplies and extractions for the agricultural area. Nitrogen supply from manure is derived from nitrogen contents of the excrements of farm animals. The N balancing model differentiates between several processes of manure and its application, e.g. dung and liquid manure from cattle, hogs and poultry. Coefficients representing nutrient contents in manure, as well as utilization factors of plants, are taken from the literature and are also provided by experts of Federal Ministry of Food, Agriculture and Consumer Protection.

As a rule, the difference between nitrogen supplies, primarily by mineral fertilizers and farm manure, and nitrogen extractions, primarily by field crops, leads to a positive N-balance (Gömann *et al.*, 2003). Thus, nitrogen surpluses represent a risk potential since they indicate the amount of nitrogen potentially leaching into groundwater and surface water. Starting from these agricultural nitrogen surpluses, hydrogeological modelling is required in order to get closer to the problem of diffuse nitrate pollution of surface waters and groundwater.

3.2. Modelling of denitrification in soils based on DENUZ model

As a rule, not al of the mineral N surpluses in soils are displaced to surface waters via the different transport pathways. A certain amount is degraded in soils to molecular nitrogen by denitrification processes. Denitrification losses in the soil occur mainly root zone in case of low oxygen and high water contents as well as high contents of organic substances (Köhne & Wendland, 1992). In contrast low denitrification rates can be expected in soils displaying high oxygen contents and low contents of water and organic substances and in soils which are vulnerable to acidification.

In the DENUZ model (Kunkel & Wendland, 2006) denitrification losses in soils are calculated according to a Michaelis-Menten kinetics. In this approach, denitrification losses in the effective root zone of soils are assessed as a function of diffuse N-surplus (N), denitrification conditions and related maximal denitrification rates per year (D_{max}) and the residence time of percolation water in the soil (t):

$$\frac{dN(t)}{dt} + D_{max} \cdot \frac{N(t)}{k + N(t)} = 0 \qquad \text{eq. 1}$$

Using observed denitrification rates in German soils (NLfB, 2005) as reference, D_{max} was assessed based on a ranking of the occurring soil types according to their geological substrate, the influence of groundwater and perching water and the average residence time of perching water in the soil as differentiation criteria. In this way the soil types were assigned into four classes ranging from D_{max} = 13.5 $kg \cdot ha^{-1} \cdot a^{-1}$ to D_{max} = 250 $kg \cdot ha^{-1} \cdot a^{-1}$. Denitrification rates larger than 50 $kg \cdot ha^{-1} \cdot a^{-1}$ can be expected for the carbon rich and water saturated soils in the flood plains near the rivers and above all for all areas where fens and bogs occur. In contrast, low denitrifcation rates can be expected in areas where well aerated soils, e.g. Podzol soils, predominate.

The Michaelis constant (k) determines the decrease of denitrification rates in case of small (remaining) N-surpluses. This parameter have been set to values between k = 18 $kg \cdot ha^{-1} \cdot a^{-1}$ (good denitrification conditions) and k = 2.5 $kg \cdot ha^{-1} \cdot a^{-1}$ (bad denitrification conditions).

3.3. Modelling of percolation water rates

The coupling of the N-surpluses occurring in the soil after denitrification to hydrological input pathways is carried out based on the grid-based water balance model GROWA (Kunkel & Wendland, 2002), which has been developed to support practical water resources management issues of large river basins and has already been applied in different regions of different sizes with different perspectives (Bogena *et al.*, 2005; Kunkel *et al.*, 2005; Tetzlaff *et al.*, 2007; Wendland *et al.*, 2005; Wendland *et al.*, 2007; Wendland *et al.*, 2003). It employs an empirical approach with a temporal resolution of one or more years. Annual averages of the main water balance components in mm/a have been quantified as a function of climate, soil, geology, topography and land use conditions. One important element is the calculation of the total runoff (Q_{tot}), which is based on an extended approach of (Renger & Wessolek, 1996), see (Kunkel & Wendland, 2002):

$$Q_{tot}(\ell) = P_y - h_{relief}\left\lfloor a_\ell \cdot P_{wi} + b_\ell \cdot P_{su} + c_\ell \cdot \log(W_{pl}) + d_\ell \cdot ET_{pot} + e_\ell \cdot S + f_\ell \right\rfloor \qquad \text{eq. 2}$$

with:	h_{relief}:	topography correction function [-]
	a, b, c, d, e, f:	land-use-specific coefficients [-]
	P_y, $P_{wi,}$ P_{su}:	annual, winter and summer precipitation [mm/a]
	W_{pl} :	soil water content available to plants [mm]
	ET_{pot} :	annual potential evapotranspiration [mm/a]
	S:	degree of imperviousness [%]

The coefficients a,…,f in eq. 2 depend on the type of land cover. Currently six different land use classes - arable land, pasture, coniferous forest, deciduous forest, bare surfaces and water covered areas - as well as their combinations are considered. The lateral resolution of the model can be chosen variable. However, in order not to loose any information, the grid is in general adapted to the data set which displays the highest spatial differentiation. For this study the spatial resolution was set to 50x50 m^2, thus reflecting on the spatial differentiation of the land use data set. For the climate data, the time period of 1961-1990 have been used as a temporal reference period.

In the GROWA model total runoff can be separated into direct runoff (i.e. surface runoff, interflow and drainage runoff) and groundwater runoff (Wendland *et al.*, 2007). Percolation water rates are modelled as mean long-term averages by subtracting mean long-term surface runoff rates from total runoff. Surface runoff is modelled based on an empirical formula derived by the (US Soil Conservation Service, 1972), in which it is quantified as a precipitation dependant portion of total runoff:

$$Q_S = 2 \cdot 10^{-6} \cdot Q_{tot} \cdot \left(500 - P_y\right)^{1,65} \qquad \text{eq. 3}$$

with:	Q_S:	Mean annual surface runoff level [mm/a]
	P_y:	Mean annual precipitation level [mm/a]
	Q_{tot}:	Mean annual total runoff level [mm/a]

Based on the calculated percolation water rates, N surpluses and denitrification rates in the soil, the nitrate concentration in the percolation water can be calculated directly.

3.5. Input data

A prerequisite for the integrated modelling is the compilation, updating and harmonizing of a digital data basis for the study region. The agrarian statistical data necessary to run the N-balancing model were provided by the Federal Ministry of Food, Agriculture and Consumer Protection or taken from the literature. The input data for the GROWA and DENUZ model, i.e. data on climate, topography, soil cover, soil parameters, hydrogeological parameters, water quality and groundwater bodies, have been made available for the whole Federal State of Lower Saxony and the German Meteorological Service. Many of these parameters were derived from digital maps, whose scale ranged from 1:50,000-1:200,000 (see table 2).

Table 2. Input data for modelling

	Data set	Scale
Land cover	Landcover categories	1 : 25.000
Agricultural production	animals, cultivation harvest mineral fertilizer	Agrarian statistical data
Climate	Summer precipitation levels winter precipitation levels Potential Evaporation	Interpolated point data
Topography	slope exposition	50 x 50 m² raster
Soil parameters	Plant-available water denitrification capacity of soils groundwater influence	1 : 50.000
Hydrogeology	hydrogeological units geological profiles hydraulic conductivity	1 : 200.000
Hydrodynamics	Depth to groundwater runoff in rivers river network, drainage systems	1 : 200.000 or point data
Hydrochemistry	Groundwater monitoring data	Point data

4. MODEL RESULTS

The Emission model has been set up and used to characterize the present status of the N-emissions to groundwater and surface waters for the three pilot areas of the WAgriCo project. Here, the model results will be presented on the example of the Große Aue pilot area, located in the Weser basin (see figure 1).

4.1 Regionally differentiated N surpluses and denitrification in the soil

The nitrogen surpluses from agriculture, as averages on a district level for the time period 1999-2003, are disaggregated with respect to the current land use. For this purpose the land cover classes arable land and pasture are used as disaggregating criteria. In addition to the N-surpluses by agriculture, as provided by the N-balancing model, atmospheric inputs are considered as lumped inputs of 15 kg·ha^{-1}·a^{-1}. In forests, a higher atmospheric deposition of 30 kg·ha^{-1}·a^{-1} have been considered. For areas in non agricultural regions, i.e. urban areas and forests, only atmospheric inputs have been applied.

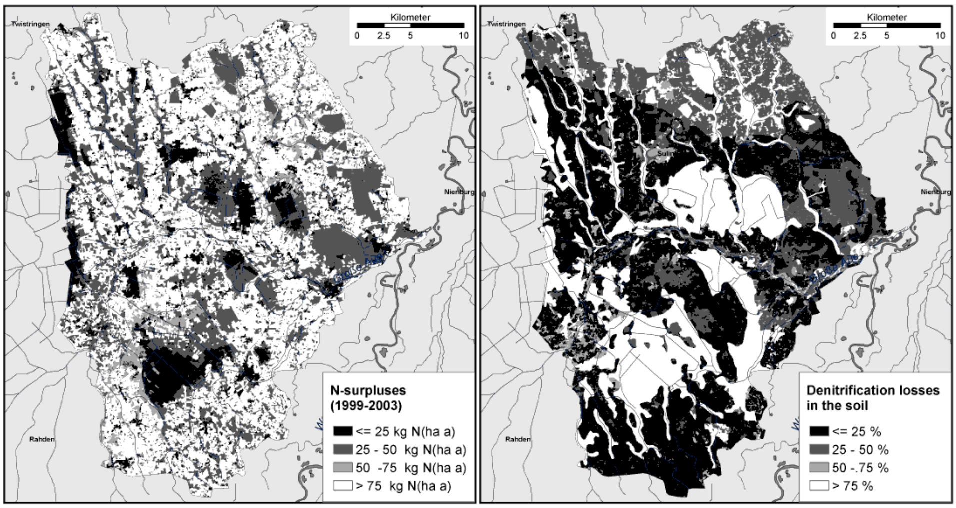

Figure 2. Regionally differentiated Nitrogen surpluses and denitrification losses in the soil for the Große Aue pilot area.

For the Große Aue pilot area, the N-surpluses from agriculture amount to about 100 kg·ha^{-1}·a^{-1}. After disaggregation of the data to the different land use types in the area, high surpluses are obtained only for the arable land areas. For other land use classes (pasture, forest urban or other areas) much smaller N-surpluses down 15 kg·ha^{-1}·a^{-1} are present (see left part of figure 2). The results of the DENUZ model indicate significant denitrification rates of the nitrogen surpluses in areas, where organic soils (bogs, fens) occur. This is the reason for the very high denitrifcation losses in the lowland parts in the central part of the pilot area. (see figure 2, right part). Especially in the sandy Geest areas in the northern and southern part of the pilot area, denitrification in the soil is reduced down to 10 % or less of the initial N-surpluses due to small water storage capacity and a small organic carbon content of the soil

4.2 Percolation water rates

Grid specific information about percolation water rates are a prerequisite for the calculation of nitrate concentrations in the leachate, as they determine the dilution of the nitrogen surpluses specified in section 6.1. The calculated percolation water rates are shown in the left part of figure 3. Percolation water rates vary between less than 100 mm a^{-1} and more than 300 mm a^{-1}. Small percolation water rates occur mainly in the lowland areas, where water balance is influenced by high groundwater tables and where the actual evapotranspiration is close to potential evapotranspiration. Typical values of 200 to 300 mm a^{-1} are calculated for the Geest areas in the Northern and Southern part of the pilot area, which are dominated by agricultural use.

4.3. Potential nitrate concentrations in the leachate

The percolation water rates, nitrogen surpluses and nitrate degradation rates in the soil are used for the calculation of nitrate concentrations in the leachate. The results for the Große Aue pilot area are shown in the right part of figure 3. For the major part of the Pilot area high concentrations of 150 mg NO_3/l and more have been calculated. This is due to the intensive agricultural use, i.e. high N-surpluses of the soils. Especially in the sandy areas in the northern and southern parts of the pilot area significant denitrification in the soil is not possible, thus leading to high nitrate concentrations.

On the other hand, low nitrate concentrations in the leachate (below 50 mg NO_3/l) are calculated for the lowland and the peaty areas. In that case the N surpluses are smaller, on one hand, and denitrification in the soil is much more effective due to high groundwater tables and high organic N-content in the soil, on the other hand.

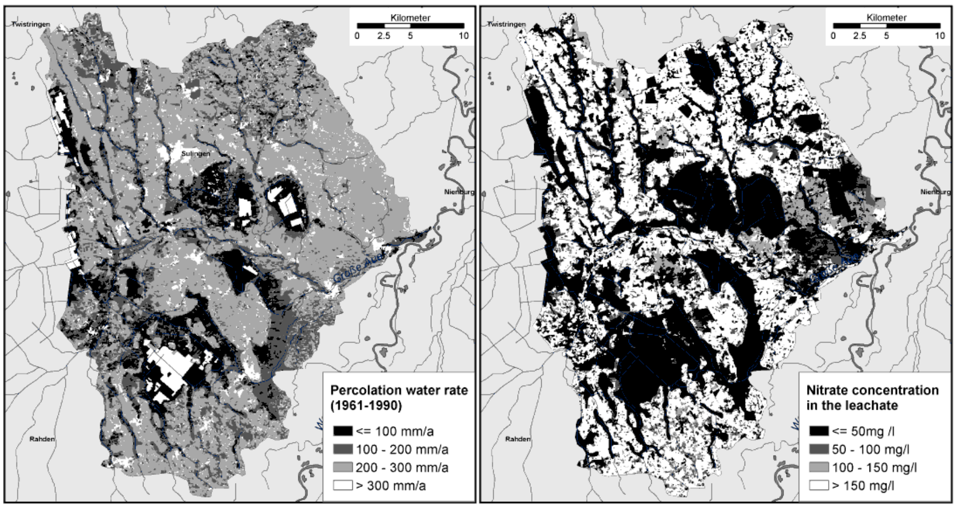

Figure 3. Calculated percolation rates and the nitrate concentration in the leachate for the Große Aue pilot area.

4.4 Validity of the model results

For a use of the emission model to water and nutrient management purposes vadatin of the model results is required. This is necessary both for the modelled percolation water rates and for the calculated nitrate concentrations in the leachate.

Because of the supraregional character of the model, existing data from monitoring networks have to be used. For the water balance, a comparison of the modelled leachate rates with observed runoff values a gauging stations has been performed. For this purpose the grid-wise calculated total runoff levels were summarized for gauged sub-catchments for which observed runoff data (MQ values) was available. This was the case for 68 sub-catchment areas of the Weser basin. The summarized values are then compared to the measured total runoff values at that station. The result, shown in figure 4, illustrates that the calculated and observed runoff values compare quite sufficiently. This is also supported by a mean deviation between measured and total runoff values of 16% and a high coincidence between observed and modelled runoff levels of r^2=0.92. Hence, the derived percolation water levels are representative enough to calculate nitrate concentrations in the percolation water.

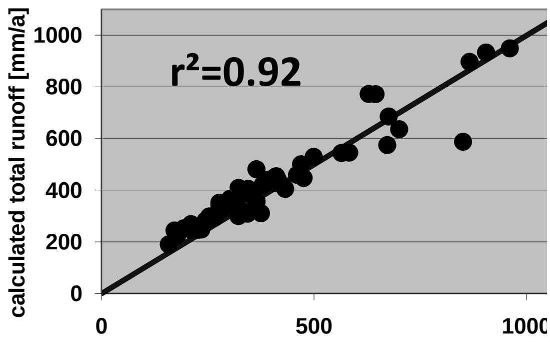

Figure 4. Comparison of calculated mean percolation water rates with observed total runoff levels in 68 gauging stations in the Weser basin.

For the nitrate concentrations in soil profiles, data from permanent soil observation sites (BDF sites), established in 1991 in the Federal State of Lower Saxony (Bartels *et al.*, 1991), could be used. In this monitoring network 14 long-term soil observation sites under agricultural land use have been established, in which the nitrate concentration in percolation water is recorded up to 24 times per year.

Because the observed nitrate concentrations in the leachate vary not only with time but also with the sampling depth, a temporal and spatial averaging of the observed data in the range of depth 1.0-1.4 m below surface was necessary. The comparison of the calculated and observed values, shows a quite good agreement, which is indicated by a correlation coefficient of 0.79. Differences between individual values at some sites can be addressed to several reasons, e.g. the strong depth dependency of the nitrate concentrations, regionalization effects of the input data, errors attributed to the temporal variability and

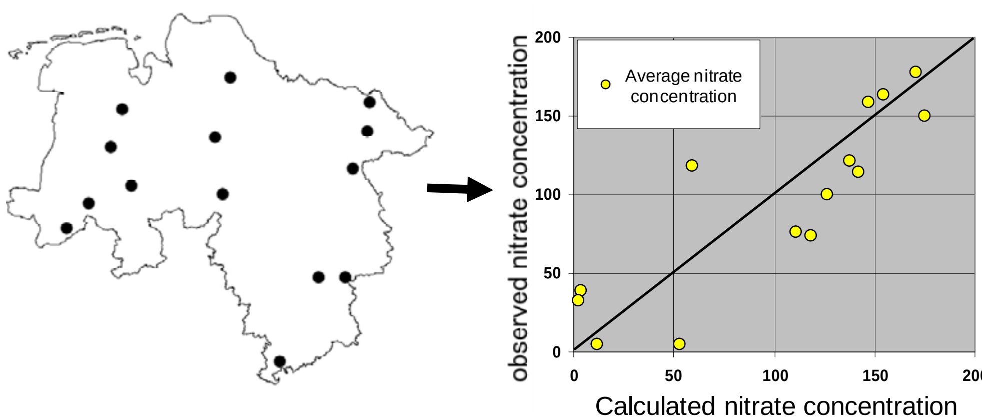

Figure 5. Location of the BDF sites in Lower Saxony (left part) and the comparison of modelled nitrate concentrations with mean observed values (right part).

model uncertainties. The agreement of the calculated runoff rates and nitrate concentrations in the leachate allows the conclusion that the model, which is designed to be a small-scale model applicable to large areas represents the real situation sufficiently.

5. ASSESSING THE REQUIRED AMOUNT AND EFFICIENCY OF WATER PROTECTION MEASURES

As required by the EU water framework directive, the good status of groundwater requires a nitrate concentration of groundwater less than 50 mg/l. In general, this value is the target value for all groundwater protection measures, by definition. In order to support policy measures to reduce the nutrient inputs to groundwater by models, the nitrate concentration in groundwater needs to be calculated. For supraregional applications, e.g. on a level of Federal States or large river basins, this is not possible within the required accuracy.

Therefore, other indicators have to be used, which are able to be represented by models properly. In the WAgriCo-project a mean long term nitrate concentration in percolation water of 50 mg/l was defined as a suitable environmental target for protecting groundwater against an exceeding of the EU quality standard for nitrate . This value is without any doubt appropriate for oxidized, i.e. not nitrate degrading, aquifers as it guarantees a nitrate concentration in groundwater below the EU quality standard for drinking water.

In reduced aquifers often low nitrate concentrations in groundwater have been observed, even in case of high inputs by percolation water. This is due to denitrification processes in the aquifer, takinge place in the absence of oxygen and the presence of pyrite and/or organic carbon material. Most of the aquifers of the North German Lowland, where the pilot areas are located in, show a high denitrification potential (Wendland *et al.*, 2005).

This fact, however, should not be deceived into thinking that a possible denitrification capacity of groundwater is an argument to allow higher nitrate inputs into groundwater Denitrification in groundwater is associated with the irreversible consumption of substances in the groundwater, such as pyrite and organic carbon. Once these substances are exhausted nitrate can not be denitrified in groundwater any more. As a consequence, nitrate concentrations would start to rise, like it is described for many sites since many years (Rohmann & Sontheimer, 1985). Consequently, the denitrification buffer of groundwater systems has to be prevented from damage, which implies a reduction of N-intakes into groundwater. A capable environmental target may be the nitrate concentration in the leachate. A limit of 50 mg NO_3/l would ensure a “good groundwater quality status” with respect to general quality standards even in the case of missing or exhausted nitrate degradation capacities in the aquifer.

Assuming the quantified percolation water levels and the nitrate degradation capacities of the soils to be constant, the nitrate concentration in percolation water depends exclusively on the nitrogen surplus level. Hence, by means of a backward calculation (inverse modelling), the maximal permissible N surplus for guaranteeing a mean nitrate concentration in percolation water of 50 mg NO_3/l has been calculated.

The according N-reduction level to reach 50 mg NO_3/l in the percolation water for every raster cell in the Große Aue pilot area is shown in the left part of figure 6. It can be seen directly that in many parts of the pilot area the amount of water protection measures needs to around 50 $kg \cdot ha^{-1} \cdot a^{-1}$ or even more. This high reduction need, however, is a typical value for almost all intensively used agricultural areas in Northern Germany. Especially in regions with area-independent animal production the required N surplus reduction would be significant.

The Water framework directive is related to groundwater bodies and not to individual raster cells. Therefore, the influence of dilution areas with smaller nitrate concentrations in the leachate was considered by defining the individual target (50 mg NO_3/l in the leachate) not for individual raster cells, but for areas characterized by the groundwater bodies and the different hydrogeological settings within each groundwater body. In figure 6 (right part), the required N surplus reduction level is shown for the case that the average nitrate concentration in the leachate for each of the subdivisions needs to be 50 mg/l or less. It

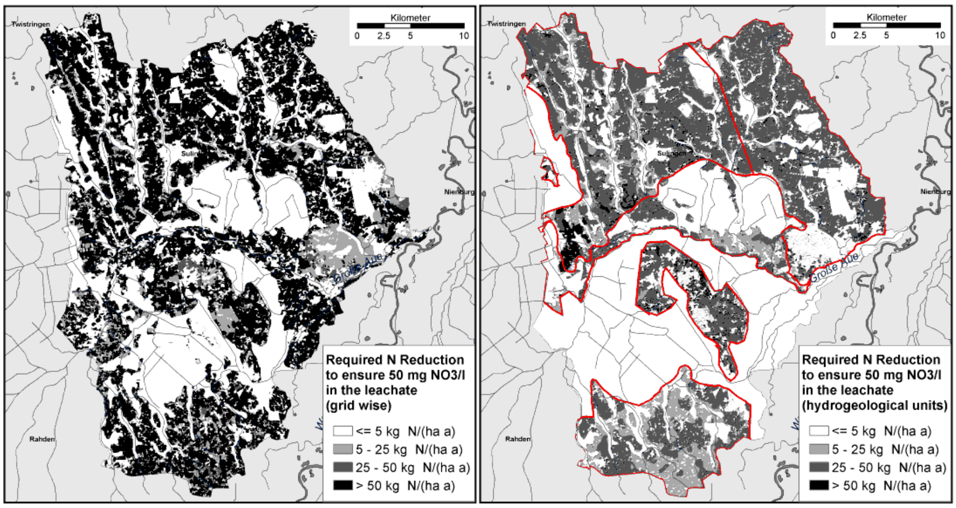

Figure 6. Required Reduction of N-surpluses to ensure a nitrate concentration in the leachate of 50 mg/l for the Große Aue pilot area with respect to individual grids (left part) or to on average for a subdivision (red lines).

becomes clear directly that the overall reduction amount reduces significantly to roughly 25 kg·ha^{-1}·a^{-1} due to the effect of the dilution areas. Secondly, even in the case of local high inputs, there may be no reduction necessary to meet the environmental target since the average nitrate concentration in the leachate in the subdivision is below 50 mg/l.

Compared to the grid wise quantified N reduction levels, the required N reduction levels for subdivisions show the same hot spots areas, e.g. the Geest part in the northern part of the pilot area. Under deduction of compensation areas between the agriculturally used land within a groundwater body, the required degree of reduction is smaller.

Finally, figure 7 shows the calculated reduction to ensure 50 mg NO_3/l in the leachate for the subdivisions in the groundwater bodies at risk for all three pilot areas of the WAgriCo project as well as for the whole Federal State of Lower Saxony. It can been seen that the required reduction of N surpluses to meet the environmental target varies significantly between the different regions of Lower Saxony. First of all, for the two pilot areas Lager Hase and Große Aue, both characterized by a high portion of animal husbandry, the required N-reduction still amounts to around 50 kg·ha^{-1}·a^{-1}. It can be doubted that a reduction of N surpluses in this extent can be achieved realistically by measures which still allow a cost-effective land-cultivation. In the Ilmenau-Jeetzel pilot area as well as for the whole north-eastern part of Lower Saxony, the necessary N reduction to meet the environmental target is much smaller. This can be attributed to the different type of land use, which is more coupled to arable land cultivation.

6. SUMMARY

A combined agroeconomic-hydrologic emission model has been used to predict nitrate concentrations in the leachate at the meso- and macroscale with the example of three mesoscale pilot areas and the Federal State of Lower Saxony. Model results showed considerable regional differences. Consistently, low nitrate concentrations in the leachate were modelled for areas displaying good denitrification capacities and long residence times of percolation water in the soil. Especially in the sandy Geest areas, which are used area-independent by animal husbandry especially in the western part of Lower Saxony, the nitrate concentrations are consistently more than 100 mg l^{-1} over the entire area. The high nitrate concentrations are a consequence above all of the high N surpluses from agriculture and the relatively low denitrification capacity of the soil.

Due to the manifold of possible factors, which influence the nitrate concentration in the leachate directly or indirectly, a comparison of modelled mean long-term nitrate concentrations in percolation water against averaged random nitrate concentrations

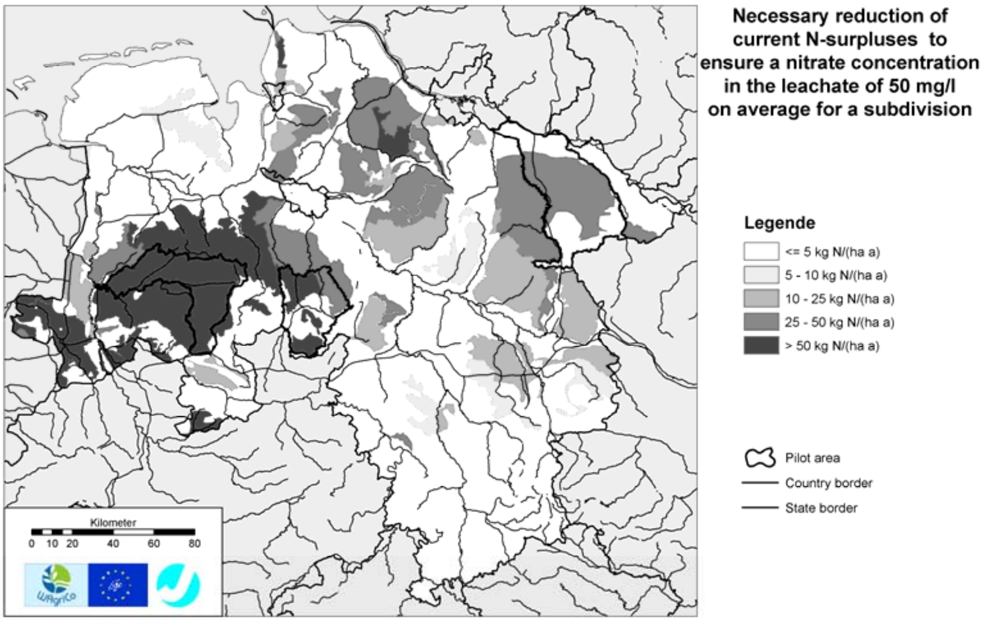

Figure 7. Required Reduction of N-surpluses to ensure a nitrate concentration in the leachate of 50 mg/l as an average for the subdivisions in the Federal State of Lower Saxony compared to the current status.

observed in monitoring stations at a fixed sampling depth and at a fixed time is only possible under consideration of several constraints. Thus, the mean deviation of r^2= 0.79 determined for the BDF – sites can be regarded as a good correlation between modelled and measured concentrations. In any case, the modelled values should not be regarded as fixed values, which trace the specific nitrate concentrations at certain sites and at certain times, but as reference values, which represent mean long-term conditions and comprise regional blurring.

Modelled nitrate concentrations in the percolation water have been used to identify the maximal permissible diffuse nitrogen loads to guarantee nitrate concentrations in groundwater below 50 mg/l, i.e. the drinking water standard for nitrate in groundwater. In case nitrate concentration in percolation water exceeds 50 mg/l, the maximal permissible nitrogen surplus levels in agriculture to guarantee a mean long term nitrate concentration in percolation water below 50 mg/l has been identified based on a backward modelling approach. This has been done for different geographical reference areas, i.e. for individual grids and on the level of groundwater bodies.

Especially in the western part of Lower Saxony which is dominated by intensive animal husbandry, the necessary N-reduction to guarantee 50 mg NO_3/l in the leachate would be significant (> 50 $kg \cdot ha^{-1} \cdot a^{-1}$). In the eastern part of Lower Saxony, a reduction of up to 25 $kg \cdot ha^{-1} \cdot a^{-1}$ would be sufficient to fulfil the environmental target. Consideration of dilution areas reduces the required reduction levels significantly.

As the discussions on environmental targets proceed, it may be necessary to modify the trigger value of 50 mg NO_3/l in percolation water depending on the agricultural and hydrological site conditions in the groundwater bodies. In general however, this procedure is perceived to be particularly innovative since the political relevance of conclusions of this type of approach is gaining importance and the accuracy of recommended environmental policy instruments is improving.

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