MANAGEMENT OF REGIONAL GERMAN RIVER CATCHMENTS (REGFLUD) IMPACT OF NITROGEN REDUCTION MEASURES ON THE NITROGEN LOAD IN THE RIVER EMS AND THE RIVER RHINE

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ABSTRACT

The REGFLUD-project, commissioned by Germany's Federal Research Ministry (BMBF), addresses the problem of reducing diffuse pollution from agricultural production. The objective of the project is the development and application of multi-criteria scientific methods, which are able to predict diffuse pollution in river basins subject to economic feasibility and social acceptability. The selected river basins (Ems and Rhine basins) cover a variety of landscape units with different hydrological, hydrogeological and socio-economic characteristics. This paper focuses on the analysis of the effects of certain policy measures to reduce diffuse pollution by nitrogen. For this purpose a model system consisting of an agricultural sector model, a water balance model and a residence time/denitrification model was developed and applied. First results indicate a wide range of annual nitrogen surpluses for the rural areas between less than 10 kg N/ha up 200 kg N/ha or more depending on the type and intensity of farming. Compared to the level of nitrogen surpluses the level of nitrogen inputs into the surface waters is relatively moderate because of degradation processes during transport in soil and groundwater. Policy impact analysis for a nitrogen tax and a limitation of the livestock density stress the importance of regionally tailored measures.

Keywords Diffuse water pollution, river basin management, multi-criteria assessment, agri-environmental policy evaluation, denitrification, nitrate leaching

INTRODUCTION

In Germany, considerable progress has been achieved towards the improvement of water quality. However, diffuse water pollution, a source largely attributed to agricultural production, continues to be of concern. As described by Goemann et al. (2003, in this volume), a wide range of problems concerning nutrient pollution of water bodies are prevalent in the river catchment areas Rhine and Ems. It is to be expected that political measures towards a solution of these problems will have different effects on the reduction of nitrogen in the different water bodies. Thus, the efficiency of measures has to be evaluated, taking into account both socio-economic conditions as well as natural site conditions. On one hand the different historically evolved and partly established socio-economic conditions in the study area, such as agricultural farm structures or the structure of water protection, as well as water supply and sewage disposal are an important prerequisite for the development of effective nitrogen reduction measures. On the other hand the natural conditions, which determine pathways and transport of diffuse nitrogen surplus into surface waters have to be considered. By the coupling of an agricultural sector model RAUMIS and the hydrological/hydrogeological models GROWA and WEKU the definition of relevant indicators for the detection or classification of "hot-spot" regions is improved.

METHODOLOGICAL APPROACH

Agricultural nitrogen surpluses are quantified using the agricultural sector model RAUMIS (Henrichsmeier et al., 1996). 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. The long-term nitrogen balance averaged over several vegetation periods is calculated considering the organic nitrogen fertilization, the mineral nitrogen fertilization, the symbiotic N-fixation, the atmospheric N-inputs and the N-extractions with the crop substance. 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 balance Goemann et al. (2003, in this volume).

The displacement of N-surpluses into surface waters is coupled to the runoff components. Against the background of a long-term treatment for the hydrological period 1961-1990, runoff was distinguished into direct runoff and groundwater runoff. Whereas direct runoff reaches the surface waters within short time periods (within about a week), groundwater runoff needs much more time (years) to percolate into surface waters. The runoff components were quantified area-differentiated as a function of climate, soil, geology, topography and land use conditions using the GROWA98 model (Kunkel & Wendland, 2002). The ratio between groundwater recharge and total runoff was taken as a measure for the extent diffuse nitrogen surpluses, which are displaced from soil to groundwater.

During transport through the soil and the groundwater nitrogen surpluses may be denitrified to molecular nitrogen. Denitrification losses in the soil occur mainly in the effective root zone. These were modelled by a Michaelis-Menten kinetics as a function of nitrogen surpluses, average field capacity, runoff level and denitrification conditions (Köhne & Wendland, 1992). Reactive nitrate transport in groundwater was modelled using the stochastical WEKU model (Kunkel &

Wendland; 1997, 1999) on the basis of a first order reaction depending on the nitrogen inputs into the aquifer, denitrification conditions in groundwater and groundwater residence times.

For the determination of groundwater residence times the groundwater velocity field was calculated according to Darcy's law. These velocities were combined with the results of an analysis of the lateral flow dynamics along the flow paths from all intake locations to the outflow into the groundwater-effective recipients. This is done by paying attention to information on the water network as well as groundwater discharge or transfer areas.

Rather simple indicators, such as the presence of Fe (II), Mn (II) and the absence of dissolved oxygen and nitrate, can be used to decide whether denitrification in groundwater is possible or not (Wendland & Kunkel, 1999). On the basis of a statistical analysis of groundwater samples the groundwater bearing formations occurring in the investigated area were classified as belonging to the predominantly reduced aquifers, in which denitrification may occur. In this case, a halving of the nitrogen leached to the groundwater after a residence time between 1.2 and 4 years was considered. In the other areas displaying oxidized groundwater conditions significant nitrate reduction can be neglected.

RESULTS AND DISCUSSION

Nitrogen surpluses and pathways of nitrate displacement

The nitrogen surpluses represent the amount of nitrogen that potentially leaches into groundwater and surface waters. From the RAUMIS model the nitrogen surpluses from agriculture were calculated on district level. The surpluses were calculated for a projection of the development under the current Common Agricultural Policies (Agenda 2000) of the European Union for the year 2010. This is used as reference scenario instead of the actual situation, because it allows a direct comparison to the effects of the investigated nitrogen reduction measures leaving all other policies constant. Comparison to the actual situation would lead to a convolution between the effects of these already implied policies and the effects of the investigated reduction measures.

On average, the calculated nitrogen surpluses for the agricultural acreages based on this reference scenarios amounts to about 130 kg N/ha a in the Ems basin, whereas the average for the investigates sub basins of the Rhine basin is much less (74 kg N/ha a), due to the generally less intensive agriculture. In Figure 1 the nitrogen surpluses from agriculture are plotted, normalized to the portion of agricultural areas within each district to take into account the different portion of agricultural areas. Especially in regions with area-independent animal processing (intensive animal production) large annual nitrogen surpluses up to more than 75 kg N/ha result from the animal excretions. This kind of land use management occurs mainly in the north-western part of the Ems basin. In addition, the western sub basins of the Rhine basin, dominated by fertile loamy soils and favourable climatic conditions display significant nitrogen surpluses because of intensive growing of commercial and specialty crops. Low nitrogen surpluses are calculated for regions with mostly forage crops production, which is typical for the eastern parts of the Rhine basin.

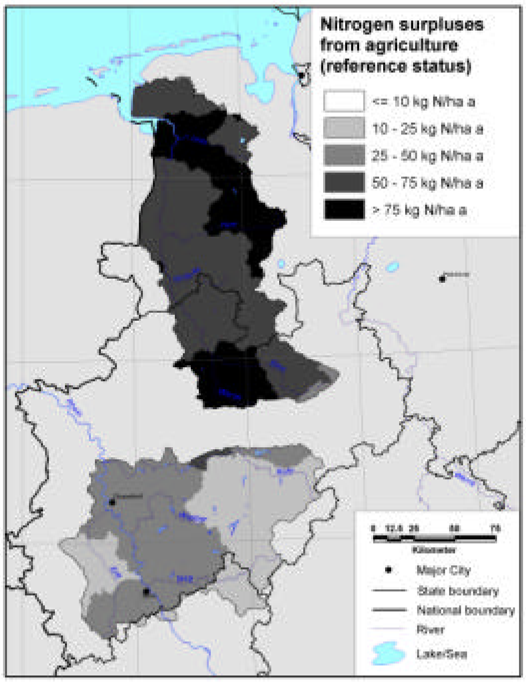

Figure 1: Annual nitrogen surpluses from agriculture.

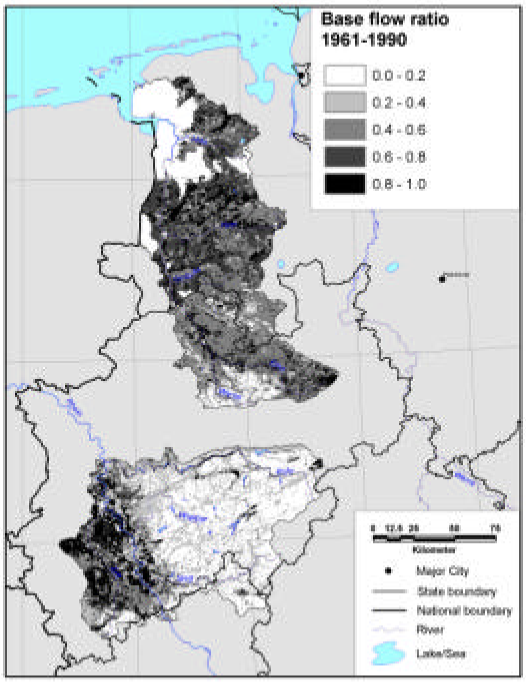

Figure 2: Calculated ratio between groundwater runoff and total runoff.

These nitrogen surpluses from agriculture, calculated as averages on a district level, are disaggregated with respect to the current land use. In addition, atmospheric inputs as well as denitrification in the soils, which may reduce the total inputs by up to 50%, have been considered. The remaining nitrogen leaching from the root zone is transported to the surface waters either by direct runoff or leaches into groundwater according to the calculated base flow ratio shown in Figure 2. It becomes evident, that in some areas, e.g. the marshy regions in the north-western part of the river Ems basin or in the mountainous regions in the eastern part of the Rhine basin, groundwater runoff is not more than 20 to 40 % of the total runoff. In these regions direct runoff is the dominant pathway of nitrogen input into surface waters. In other areas, e.g. the central part of the Ems basin, the base flow ratios above 0.8 indicate that groundwater runoff is the main pathway for nitrate entries into surface waters.

The results of coupling nitrogen surpluses for the reference status with water balance are shown in Figure 3 and Figure 4. In Figure 3 the nitrate inputs into surface waters from direct runoff are shown. It has been assumed that after denitrification in the root zone no further denitrification occurs. N-inputs to surface waters from direct runoff are important especially in the marshy areas of the Ems basin and the mountainous regions in the Rhine basin, where direct runoff is the most important transport pathway for nitrogen. Figure 4 shows the nitrogen inputs into the aquifer via groundwater recharge. High nitrogen leaching to the groundwater is calculated for regions with a high groundwater runoff portion and high nitrogen surpluses, which is important in particular for the central part of the Ems basin.

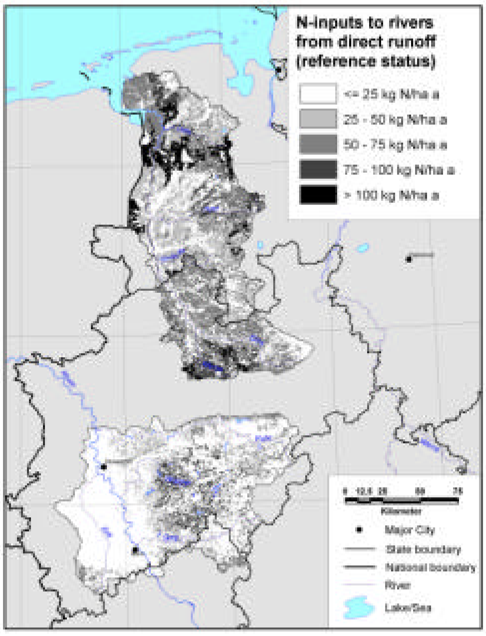

Figure 3: Nitrogen inputs into surface waters from direct runoff for the reference status.

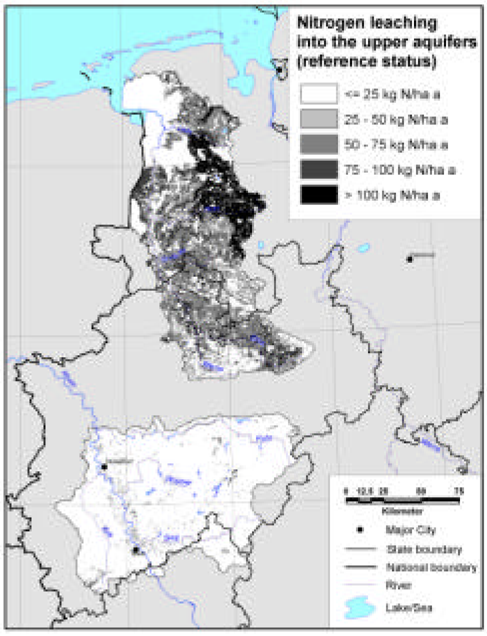

Figure 4: Nitrogen leaching into the upper aquifer for the reference status.

Groundwater-borne Nitrogen inputs into the surface waters

During transport through the aquifer, nitrate may be denitrified to molecular nitrogen by micro organisms. Transport and denitrification in the aquifer is calculated using the WEKU model taking into account groundwater residence times and natural nitrate degradation in the aquifers. Calculated groundwater residence times range between less than 1 year and more than 150 years. Long residence times result both from small groundwater velocities as well as from long flow paths up to the recipient, pointing at the long time periods, after which nitrate inputs into the aquifer can contribute to the pollution of surface waters in some regions. Short residence times generally result for areas in the vicinity of rivers and/or regions with high groundwater velocities.

The quantification of the parameters of denitrification kinetics in groundwater was done separately for the groundwater bearing formations occurring in the river basins. In total, about 1050 groundwater samples were evaluated and classified with respect to nitrate-degrading capacity. From this analysis the groundwater bearing formations glaciofluviatile sands and moraine deposits, both occurring in the river Ems basin, were classified as nitrate degrading. Most aquifers in the investigated sub basins of the river Rhine, predominantly consolidated rocks (e.g. shists and limestones), showed instead usually non-nitrate degrading conditions.

The remaining nitrogen outputs to surface waters from groundwater were calculated by combining the N-leaching into the aquifers and the reactive N-transport in the aquifers. The result is shown for the reference status in Figure5 for the initial cells for which the inputs into the soil have been calculated. It can be seen that nitrogen intakes in the vicinity of surface waters and high nitrogen leaching levels contribute considerably to the groundwater-borne nitrate inputs to the surface waters. Even with good conditions for a complete degradation of nitrate in the aquifer, the brief residence times are not sufficient for an adequate degradation of high nitrate inputs. There is, furthermore, a hazard potential in many regions where high nitrate inputs are associated with relatively short residence times of the groundwater, as well as restricted and/or insignificant degradation conditions in the aquifer. These regions include almost the whole Rhine catchment area.

The loose rock aquifers in the northern part of the Ems basin show an opposite behaviour. There, even high nitrogen inputs into the groundwater systems result only in very slight nitrate inputs to surface waters after transport through the aquifers. The, as a rule, long groundwater residence times and good denitrification conditions cause high denitrification of up to 99% of the inputs into the aquifer systems. As a consequence, groundwater is almost nitrate-free when it enters the rivers after transport through the aquifer systems.

The validity of the model results was checked according to the procedure described in Behrendt et al. (2000). The modelled groundwater-borne nitrogen inputs into surface waters have been compared to the observed nitrogen concentrations in rivers at low flow conditions and at temperatures below 5° C to avoid effects of nutrient retention in rivers. Comparison with observed data showed a satisfactory agreement (Wendland et al., 2002).

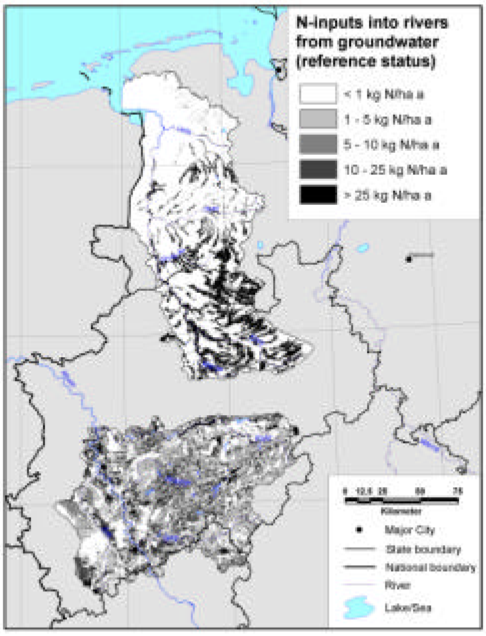

Figure 5: N-inputs to surface waters from groundwater for the reference status.

Evaluation of N reduction measures

Two measures aiming at a reduction of agricultural nitrogen use have been conducted and compared to the simulation of the intakes into surface waters according to the input pathways on the basis of the nitrogen surpluses for the references status. The first scenario (Scenario 1) reflects to nitrogen reduction by rising a tax on the price of mineral fertilizer of 200%. The implementation of a nitrogen tax has been repeatedly discussed since the mid-eighties. The second scenario (scenario 2) reflects on the limitation of the livestock density (LD) to not more than 1.0 livestock units (LU) per ha.

The effects of these scenarios on the potential reduction of N-surpluses from agriculture compared to the reference status (Figure 1) is shown in Figure 6 and Figure 7. It can be seen easily that the measures affect the nitrogen surpluses in the two selected study areas differently. The nitrogen tax (scenario 1) noticeably reduces nitrogen use in all arable farm regions such as the western part of the Rhine sub basin and the southern part of the Ems basin by at least 10 kg N/ha a. It has a minor effect on the N-surpluses in the central parts of the Ems basin, which are characterized by intensive animal production and the associated animal food production areas. Thus, a nitrogen tax does not mitigate the hot-spot problems since the manure supply in regions with intensive livestock production is not affected. From Figure 7 it becomes clear that especially in these regions a limitation of livestock density would be much more effective, since it would lead to a potential reduction of the N-surpluses to at least 25 kg N/ha a. On the other hand, scenario 2 has almost no effect in regions with extensive animal production like in the major parts of the Rhine sub basins.

In Figure 8 and Figure 9 the effects of the implementation of a nitrogen tax on the price of mineral fertilizer (scenario 1) on the potential reduction of the N-inputs into surface waters are shown compared to the reference status. It can be seen that a significant reduction of the N-inputs to surface waters can be achieved only for the inputs from direct runoff components (see Figure 8). In the Ems basin, even large N-inputs into groundwater are denitrified to a large extent. This has the effect that potential reductions of groundwater-borne N-inputs to surface waters are obtained only for areas in the vicinity of surface waters with incomplete nitrate reduction (see Figure 9).

Figure 10 and Figure 11 show the effects of the limitation of the livestock density (LD) to not more than 1.0 livestock units (LU) per ha (scenario 2) on the potential reduction of the N-inputs into surface waters. On the first sight, the results seem to be quite similar, since significant N-reductions are obtained almost exclusively for inputs from direct runoff components. These reductions, however, are much larger than in the first scenario and can amount up to 100 kg N/ha a. Secondly, because scenario 2 affects areas with intensive animal production, significant N-reduction can be achieved only in the Ems basin. In the Rhine sub basins almost no reduction of the N-inputs to river can be obtained, in contrast to scenario 1.

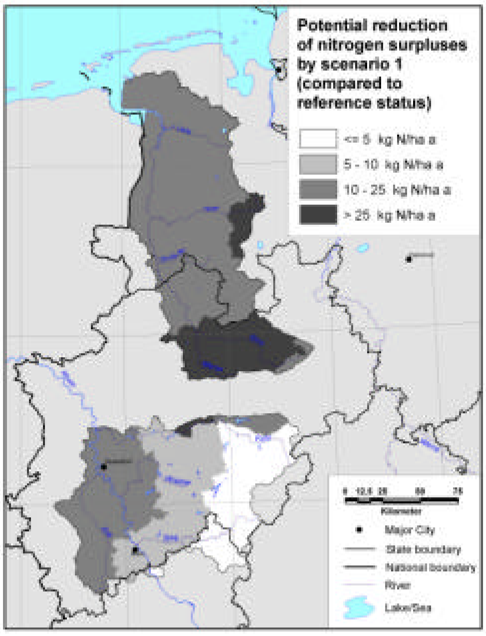

Figure 6: Potential reduction of N surpluses from agriculture by rising a fertilizer tax of 200% compared to the reference status.

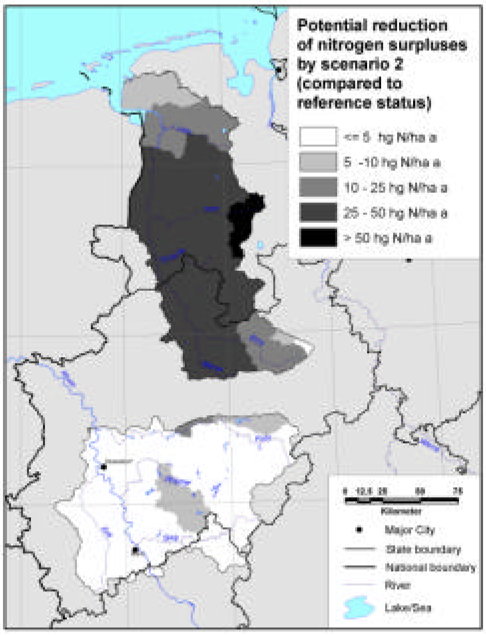

Figure 7: Potential reduction of N surpluses from agriculture by limitation of livestock density compared to the reference status.

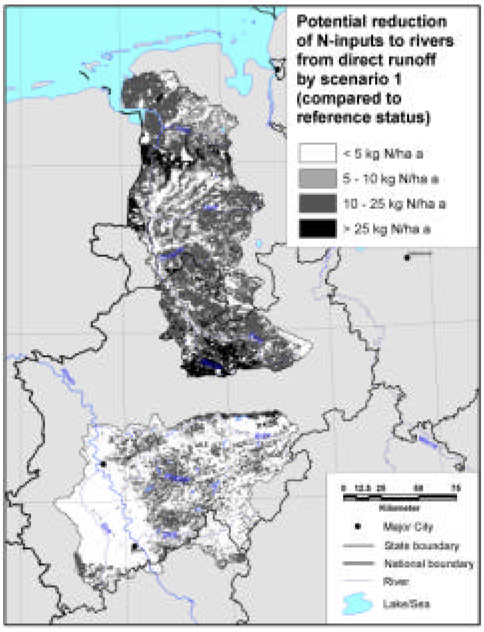

Figure 8: Potential reduction of N-inputs to rivers from direct runoff by scenario 1 compared to the reference status.

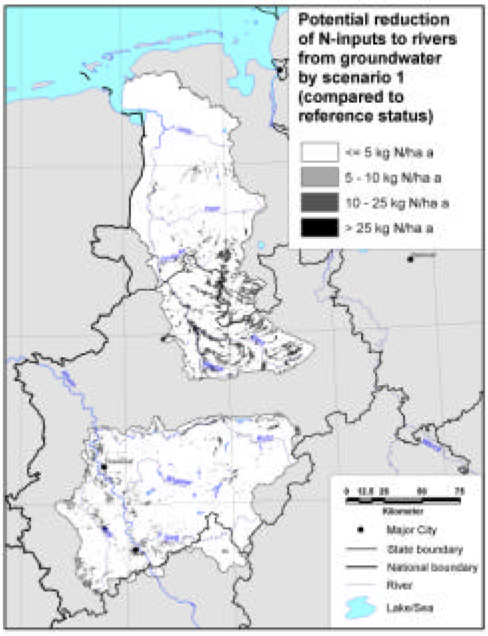

Figure 9: Potential reduction of N-inputs to rivers from groundwater runoff by scenario 1 compared to the reference status.

CONCLUSIONS AND OUTLOOK

In Germany, the problems of diffuse water pollution with nitrogen from agriculture are regionally different. Using the nitrogen surpluses as an indicator to detect or classify "hot-spot" regions, the Ems catchment seems to be quite endangered by N-inputs from agriculture. However, a direct inference from the risk indicator "nitrogen surplus" being calculated with the agricultural sector model RAUMIS to actual depositions of nitrogen into water bodies is limited since natural site conditions (e.g. nitrogen degradation capacities, residence times, etc.) vary considerably among regions.

These natural conditions are accounted for in the hydrological and hydrogeological models GROWA98 and WEKU, which were used to quantify the nitrogen inputs into the surface waters from the different transport pathways. From the results of this study we conclude that in the groundwater systems of the river Ems basin about 90% of the diffuse nitrogen input into the ground water is degraded in groundwater due to long ground water residence time and favourable denitrification conditions. There, groundwater borne nitrate input into the surface waters turned out to be relatively low even if the region were addressed as a “hot-spot” in terms of total nitrogen surplus from agriculture.

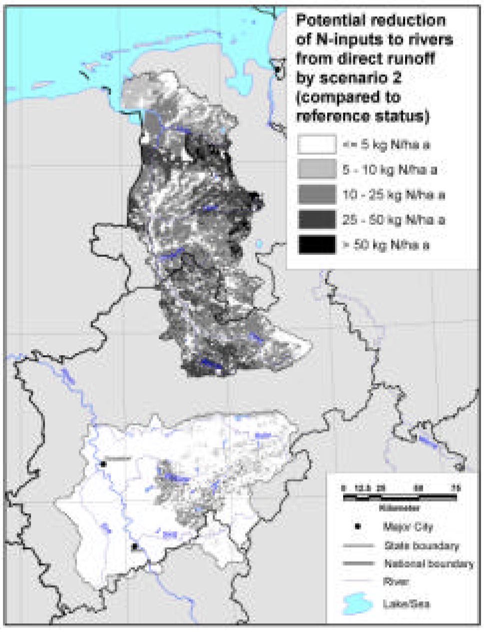

Figure 10: Potential reduction of N-inputs to rivers from direct runoff by scenario 2 compared to the reference status.

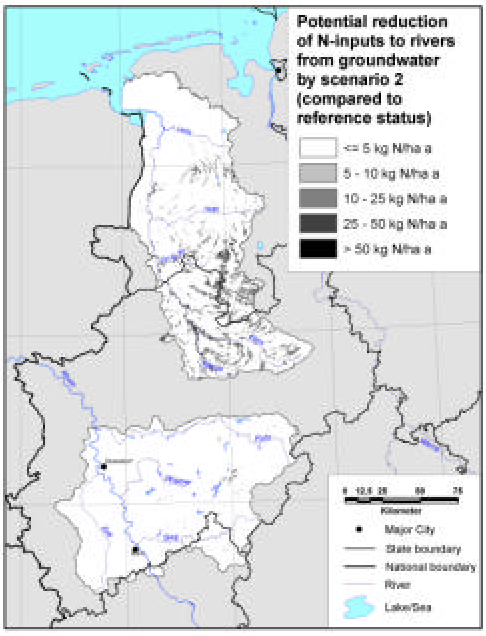

Figure 11: Potential reduction of N-inputs to rivers from groundwater runoff by scenario 2 compared to the reference status.

The agricultural policy impact analysis pointed out that nitrogen reduction measures affect the regional nitrogen use differently. In particular, the investigated effects of a tax on mineral nitrogen or a limitation of the regional livestock density highlight that the mitigation of the diffuse water pollution problems require regionally tailored measures. However, it could also be shown that in areas where natural degradations capacities are missing only very drastic measures lead to a significant improvement of the nitrogen load of surface waters.

The first adaptation of the model network (RAUMIS, GROWA98, and WEKU) has been performed in consecutive but independent steps. The model concept is designed for area-differentiated modelling on a supraregional scale. According to the models applicability to the entire catchment area, the hydrological, pedological and hydrogeological input parameters needed for the GROWA and WEKU model were taken from thematic maps. The scale of these maps, ranging from 1:50,000 to 1:200,000, determine the degree of detail of the model input values and define in connection with the suitable model approaches the validity range of the model results.

This RAUMIS model as well as the policy impact analysis revealed some anticipated methodological improvements. The current spatial differentiation of RAUMIS, presently limited by the availability of agricultural data to district level, has to be refined. Depending on the availability of data a first step is to extend the model to a lower municipality level which is closer to the resolution of the hydrological models. The next step is defining “natural site class farms” below the community level and modelling the adjustment behaviour for these homogenous farms. In this context the intensity of production i.e. input use that is currently computed before the optimising process should be endogenously determined.

REFERENCES

Behrendt, H., Huber, P., Kornmilch, M., Opitz, D., Schmoll, O., Scholz, G. & Uebe, R. (2000): Nutrient balances of German river basins. UBA-Texte,23/2000, 261p .

Henrichsmeyer, W. et al. (1996): Development of the German Agricultural Sector Model RAUMIS96. Final Report of the Cooperation-Project. Research Report for the BMELF (94 HS 021), unpublished, Bonn/Braunschweig.

Köhne Ch. & Wendland, F. (1992): Modellgestützte Berechnung des mikrobiellen Nitratabbaus im Boden, Internal Report, KFA-STE-IB 1/92, Research Centre Jülich.

Kunkel, R. and F. Wendland (2002):, The GROWA98 model for water balance analysis in large river basins – the river Elbe case study. Journal of Hydrology 259, 152-162.

Kunkel, R. & Wendland, F. (1997). WEKU-a GIS supported stochastic model of groundwater residence times in upper aquifers for the supraregional groundwater management. Envir. Geol., 30(1/2), 1-9.

Wendland, F. and R. Kunkel (1999), Das Nitratabbauvermögen im Grundwasser des Elbeeinzugsgebietes. Schriften des FZ Jülich, Reihe Umwelt/Environment, 13, Jülich, Germany.

Wendland, F., Bach, M., Behrendt, H. & Kunkel R. (2002): Integrated modelling of groundwater-borne nitrate intakes into the river Elbe basin (German part). Proceedings of the 9th International Specialized Conference on River Basin Management, Edinburgh, Scotland.