Water fluxes and diffuse nitrate pollution at river basin scale: coupling of agro-economic models and hydrological approaches

*Research Centre Jülich, Systems Analysis and Technology Evaluation, D-52425 Jülich, Germany
**Federal Agricultural Research Centre, D-58116 Braunschweig, Germany

Abstract An integrated model system has been developed to estimate the impact of nitrogen reduction measures on the nitrogen load in groundwater and in river catchment areas. The focus lies on an area-wide, regionally differentiated, consistent link-up between the indicator “nitrogen balance surplus” and nitrogen charges into surface waters. As a starting point of the analysis actual nitrogen surpluses in the soil were quantified using the agro-economic RAUMIS-model, which considers the most important N-inputs to the soil and N-removals from the soil through crop harvest. The most important pathways for diffuse nitrogen inputs into river systems are modelled with the water balance model GROWA. Additionally, the time-dependent nitrogen degradation along the nitrogen pathways in soil and groundwater are modelled using the WEKU-model. The two selected river basins in Germany cover a variety of landscape units with different hydrological, hydrogeological and socio-economic characteristics. The results indicate a wide range of annual nitrogen surpluses for the rural areas between than 10 kg N ha$^{-1}$ and 200 kg N ha$^{-1}$ or more, depending on the type and intensity of farming. The level of nitrogen inputs into the surface waters is reduced because of degradation processes during transport in soil and groundwater. Policy impact analyses for a nitrogen tax and a limitation of the livestock density stress the importance of regionally adjusted measures.

Keywords Agro-environmental policy evaluation; denitrification; diffuse water pollution; multicriteria assessment; nitrate leaching; river basin management

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 Gömann et al. (2004), a wide range of problems concerning nutrient pollution of water bodies are prevalent in the Ems basin and sub-catchments of the Rhine. It is to be expected that political measures towards a solution of these problems will have different effects on the reduction of nutrients in the different water bodies. Thus, the efficiency of measures has to be evaluated, taking into account both socio-economic conditions and 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, natural conditions, which determine pathways and transport of diffuse nutrient surplus into surface waters, have to be considered. The linkage of the agricultural sector model RAUMIS (Henrichsmeyer et al., 1996) with the hydrological model GROWA (Kunkel and Wendland, 2002) and the reactive nutrient transport model WEKU (Kunkel and Wendland, 1997) represents a consistent link-up of the environmental pressure indicator “agricultural nutrient surplus” with the environmental state indicator “nutrient loads of water bodies” and the environmental...
response indicator “nutrient reduction measure”. This paper focuses exclusively on the application of the integrated agro-economic/hydro(geo)logic model system for the management of diffuse nitrogen fluxes.

**Methodological approach**

Combining agro-economic and hydro(geo)logical models is a scientific challenge. The most efficient way to homogenize and adjust models from different scientific disciplines is the development of a common model interface for data exchange. This interface has to guarantee a uniform definition (e.g. scope of representation, spatial and temporal dimension) of variables being exchanged within the model network. Figure 1 shows the integration of the agricultural economic model RAUMIS with the hydrological models GROWA and WEKU.

A central interface between RAUMIS and GROWA/WEKU is the regional nutrient surpluses and land use patterns. According to requirements specified above, it has to be considered that the two models are using different regional resolutions: raster cells in the hydrological models and administrative units in the RAUMIS model. This is due to the different data sources: while GROWA/WEKU uses land use maps, RAUMIS employs agrarian statistical data. For this reason, regional nitrogen balances calculated by RAUMIS as averages for the agricultural areas (AA) in the individual administrative units cannot be directly used as input variables in GROWA/WEKU. As a first step, these nitrogen surpluses are disaggregated and geographically referenced on raster cells as required by GROWA/WEKU.

In the agricultural sector model RAUMIS (Henrichsmeyer et al., 1996), a set of agro-environmental indicators is linked to agricultural production. Currently, the model comprises indicators such as fertilizer surplus (nitrogen, phosphorus and potassium), pesticide expenditures, a biodiversity index, and corrosive gas emissions. These indicators help to evaluate direct and indirect environmental impacts of policy driven changes in agricultural production. With regard to 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

---

**Figure 1** Integrated agro-economic/hydro(geo)logic model system
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 N-balance (Goëmann et al., 2003).

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 run-off 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 GROWA model (Kunkel and Wendland, 2002). The ratio between groundwater recharge and total runoff was taken as a measure for the extent of diffuse nitrogen surpluses, which are displaced from soil to groundwater (Wendland et al., 2002; Kunkel et al., 2004).

During transport through the soil and the groundwater nitrogen surpluses may be denitrified to molecular nitrogen. According to a review by Köhne and Wendland (1992) denitrification losses in the soil occur mainly in the root zone in the case of low oxygen and high water contents as well as high contents of organic substances. In a Michaelis–Menten kinetics approach these denitrification conditions were combined with the nitrogen surpluses given by RAUMIS and the residence times of the percolation water in the root zone calculated as a function of average field capacity and the percolation runoff level (Behrendt et al., 2003). Reactive nitrate transport in the groundwater was modelled using the stochastic WEKU model (Kunkel and Wendland, 1997) on the basis of a first-order reaction depending on the nitrogen inputs into the aquifer, denitrification conditions in groundwater and groundwater residence times.

In the first step groundwater velocities are calculated according to Darcy’s law from hydraulic conductivity, effective yield of pore space of the aquifer and the slope of groundwater surface (hydraulic gradient). The calculation of the residence times of the groundwater runoff is performed in a second step. Based on groundwater contour maps, a digital relief model of the groundwater surface is generated. This is analysed paying attention to information on the water network as well as the groundwater discharge or transfer areas with respect to lateral flow dynamics and groundwater-effective recipients. The residence times of the groundwater runoff are then obtained for each initial grid by summation over the individual residence times in the grids resulting from the groundwater velocities and individual flow distances along the flow path until they enter a surface water.

The WEKU model was extended by a module for the quantification of nitrate degradation in groundwater. According to a number of field studies a first-order denitrification kinetics has been found. Denitrification leads to a halving of the nitrogen leached to the groundwater after a residence time between 1.2 and 4 years. Rather simple indicators, such as the presence of Fe (II), Mn (II) and the absence of O₂ and NO₃ can be used to decide whether a groundwater province has hydrogeochemical conditions in which denitrification is possible or such transformation of nitrogen can be neglected (Wendland and Kunkel, 1999; Kunkel et al., 2005a).

Case study river basins
Two German river basins, the Ems basin (12,900 km²) and several Rhine sub-catchments, comprising the river basins of the Sieg, Wupper, Ruhr and Erft, (in total 12,100 km²), have been selected as study areas in order to cover a wide range of different landscape...
units with different hydrological, hydrogeological and socio-economic characteristics. The administrative bodies that correspond to the RAUMIS regions ("Landkreise") cover an area of 32,700 km² in total and thus overextend the catchment areas by about 30%.

The river Ems basin is located in the North German Plain. Agriculture plays an important role in comparison to the German average: agricultural area (AA) accounts for about 62% of total area and production is dominated by intensive animal husbandry which is more competitive on the prevailing less fertile sandy soils than cash cropping. Farmers typically grow fodder crops, such as silage maize and corn-cob-mix on arable land. These generate higher yields than permanent grassland and enable a higher livestock production. This production structure explains the visible correlation between shares of arable land and livestock densities (LD) that are displayed for the regions within the Ems catchment.

The situation is quite different in the Rhine sub-catchments. A striking socio-economic difference is that the population density is three times higher than in the Ems basin. Settlements, traffic, and industries, in addition to forests, play an important role such that the agricultural area amounts to 30% of the total area. Eastern parts of the Rhine sub-catchment are located in consolidated Palaeozoic rock areas with high total area runoff levels, dominated by fast (direct) runoff components. These conditions hamper tilling of soil so that permanent grassland dominates land use. Farmers specialise in cattle and milk production on a fairly extensive level. All these regions can be classified as areas with a high risk of surface water pollution e.g. reservoirs. On the other hand it can be expected that nutrient reduction measures will rapidly improve surface water quality in these areas. Western parts of the Rhine sub-catchment are located in the unconsolidated quaternary rock area of the lower Rhine bay with considerable groundwater recharge levels. Because of the very fertile loess soil, intensive cash cropping is the main agricultural production activity. These regions feature a share of arable land of more than 90% of AA and low livestock densities.

Results and discussion
Nitrogen leaching from the soil

The nitrogen surpluses calculated with the RAUMIS model 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 surplus is used as the reference scenario instead of the actual situation, as comparative static policy impact analyses for a future target year require a scenario of reference because various parameters are changing in the long-run in addition to the variations of policy measures being investigated. Typically the scenario of reference is a projection of the development under “business as usual”. Thus, nitrogen surpluses indicate the amount of nitrogen that potentially leaches into groundwater and surface waters. Deviating from the reference scenario, alternative policies and regulations are imposed on the model keeping all other parameters and constraints 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 scenario amount to about 130 kg N ha⁻¹·a⁻¹ in the Ems basin, whereas the average for the investigated sub-basins of the Rhine basin is much less (74 kg N ha⁻¹·a⁻¹), due to the generally less intensive agriculture. The nitrogen surpluses from agriculture, calculated as averages on a district level, are disaggregated with respect to the current land use. For this purpose the CORINE land cover land use classes, arable land and pasture, are used as disaggregating criteria. In addition, atmospheric nitrogen inputs of 30 kg N ha⁻¹·a⁻¹ and an asymbiotic nitrogen fixation of 1.4 kg N ha⁻¹·a⁻¹ have
been considered as lump sum amounts. For areas representing non-agricultural regions in the REGFLUD study areas, urban areas and forests, only the atmospheric inputs and asymbiotic nitrogen fixation were considered.

The nitrogen surpluses in the soil are plotted in Figure 2. Especially in regions with area-independent animal processing (intensive animal production) nitrogen surpluses result from both animal excretions and mineral fertilizers. 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.

Denitrification in the soils has been modelled using a Michaelis–Menten kinetics. In this way the nitrogen surpluses from agriculture were reduced by up to 50% in some areas, e.g. in areas where loamy soils with a high water storage capacity and high organic carbon content occur. 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. 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 20–40% 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, groundwater runoff is the main pathway for nitrate entries into surface waters.

The results of coupling nitrogen leaching from the root zone with runoff values are shown in Figures 3 and 4. Figure 3 shows the corresponding nitrogen input into surface...
waters via direct runoff. In this case no further denitrification in the unsaturated zone is considered. It becomes clear, that 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. Figure 4 shows the nitrogen inputs into the aquifers 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. In the sub-basins of the Rhine the nitrogen leaching to groundwater is less important due to the low nitrogen surplus level (see Figure 3) on one hand and the large portion of direct runoff in the mountainous regions of the Rhine basin.

Figure 3 Nitrogen outputs into rivers from direct runoff

Nitrogen inputs into surface waters via groundwater runoff
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, indicating 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 3,300 groundwater samples were evaluated and classified with respect to nitrate-degrading capacity. From this analysis the groundwater bearing formations, glaciofluvial sands and moraine deposits, both occurring in the river Ems basin, were classified as nitrate degrading. In contrast, most aquifers in the investigated sub-basins of the river Rhine, predominantly consolidated rocks (e.g. shists and limestones), showed 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. Figure 5 shows the result for the reference situation, for the initial cells whose inputs into the soil have been calculated. It can be seen that the 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 only result in very slight nitrate

Figure 4 Nitrogen leaching into the upper aquifer
inputs to surface waters after transport through the aquifers. Long groundwater residence times and good denitrification conditions cause high denitrification of up to 90% of the inputs into the aquifer systems. As a consequence, the groundwater is almost nitrate-free when it enters the rivers after transport through the aquifer systems.

The observed N-loads in rivers represent the sum of all N-inputs by the different diffuse and point source intake pathways. The residence times of direct runoff and groundwater runoff differ significantly not only between the different input pathways but also from intake site to intake site. Thus, the input to surface waters from a certain intake location via direct runoff refers to an input from of less than 2 years ago in general, whereas the inputs via groundwater for the same location refers to an input from some decades ago. Hence, for the calibration and verification of the integrated RAUMIS-GROWA-WEKU model calculations of nitrogen river loads concerning the past inputs have to be considered as well. This has been done using nitrogen surpluses calculated with RAUMIS for the reference periods of the last decades.

The validity of modelled groundwater-borne nitrogen inputs into surface waters was checked following a procedure suggested by Behrendt et al. (2002). At first the measured N-loads were corrected by the point N-inputs (Behrendt et al., 2000). In order to avoid effects of the N inputs by direct runoff, only observed nitrogen concentrations at low flow conditions were considered. Additionally, only observed values at temperatures below 5°C were taken as references in order to avoid effects of nutrient retention in rivers. Following this procedure the comparison of the modelled groundwater-borne nitrogen inputs into surface waters with the observed river load data of 54 sub-catchment areas show only relatively small differences to the observed values (about 10–20%).
Conclusions
In Germany, the water pollutions caused by diffuse 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 GROWA 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 groundwater is degraded in groundwater due to a long groundwater 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 considered to be a “hot-spot” in terms of total nitrogen surplus from agriculture.

The networking of the agro-economic model RAUMIS with the hydro(logic) models GROWA and WEKU has shown, that the very complex interactions between the driving-force indicator “diffuse nitrogen surpluses” and the state indicators “nitrogen loads in surface waters and groundwater” can be analysed in a consistent and regionally differentiated way. The synergetic effects shows the potential of interdisciplinary model networks for the implementation of political measures aiming at the sustainable management of nitrogen fluxes in river basins.

Acknowledgements
The study is part of the REGFLUD-project, which was funded by Germany’s Federal Ministry of Science and Education (BMBF) within the research program “River Basin Management”.

References


