Estimation of the nutrient inputs into river systems – experiences from German rivers

Horst Behrendt · Matthias Kornmilch · Dieter Opitz · Oliver Schmoll · Gaby Scholz

Abstract The nutrient discharges from point and diffuse sources in more than 200 German river basins were estimated for the periods 1983–1987 and 1993–1997 employing the MONERIS model. This model distinguishes between six diffuse pathways and point source emissions from waste water treatment plants and direct industrial discharges. It was estimated that the total nitrogen input into the German river systems amounts to about 819,000 t N year^{-1} in the period 1993 to 1997. These emissions have decreased since the mid-eighties by about 266,000 t N year^{-1}, mainly caused by the reduction of point discharges. For phosphorus the emissions have been reduced by 56,290 t P year^{-1} and amount to 37,250 t P year^{-1} in the period 1993–1997. Based on emission data a retention module estimates riverine nutrient loads. The comparison of the model output with the observed loads shows a deviation as low as 30% and 50% for nitrogen and phosphorus, respectively. The regional resolution of the model indicates the relative importance of different pathways for phosphorus and nitrogen input into river systems.

Keywords Nutrient discharge · Phosphorus · Nitrogen · German rivers · Multi-pathway modelling

Introduction

Eutrophication of the seas and estuaries in Europe and other parts of the world is mainly caused by nutrient inputs from the land. The reduction of nutrient inputs often is a crucial precondition for the sustainable development of estuaries and the sea. Effective measures to reduce nutrient inputs should be based upon the knowledge of their quantities and of their sources. Rivers are the main carriers of nutrients from the land to the sea. In general the nutrient state of a river system depends on its natural characteristics, the structure and the level of nutrients discharged into the river system, caused by the geogenic background and anthropogenic activities. Analysis of the present state of input and load situation within different scales of a river basin is therefore an important requisite for deriving quality criteria and establishing management plans.

Emissions into the river system from different pathways (point and diffuse sources) have to be estimated. Dynamic models for nutrient emissions do not exist for all possible pathways and have not, until now, been applied to medium and large river basins.

In the following sections, the methods and results of the project "Nutrient balances of the German river basins" are presented briefly. A more detailed methodology description is given in Behrendt et al. (2000).

Material and methods

The Geographical Information System (GIS)-oriented Model MONERIS (Modeling Nutrient Emissions in River Systems) was developed to estimate nutrient inputs by various point and diffuse sources into German rivers with catchments larger than 1,000 km^2 for the periods 1983 to 1987 and 1993 to 1997.

Basic input information entering the model comprises data on river flow, water quality of the investigated basins and GIS-integrating digital maps as well as statistical information for different administrative levels and scales.

Whereas the inputs of municipal wastewater treatment plants (WWTPs) and industrial discharges enter the river system directly, the sum of nutrient inputs into the surface waters from diffuse sources is built from a variety of runoff components taking different pathways in the form of surface runoff, base flow and interflow (see Fig. 1).

The distinction between the inputs from these components is necessary because the concentrations of nitrogen (N) and phosphorus (P) within the runoff components and the

Received: 4 August 2001 / Accepted: 8 February 2002
Published online: 16 April 2002

H. Behrendt (✉) · M. Kornmilch · D. Opitz · O. Schmoll
G. Scholz
Institute of Freshwater Ecology and Inland Fisheries,
Müggelseedamm 310, 12587 Berlin, Germany
E-mail: behrendt@igb-berlin.de

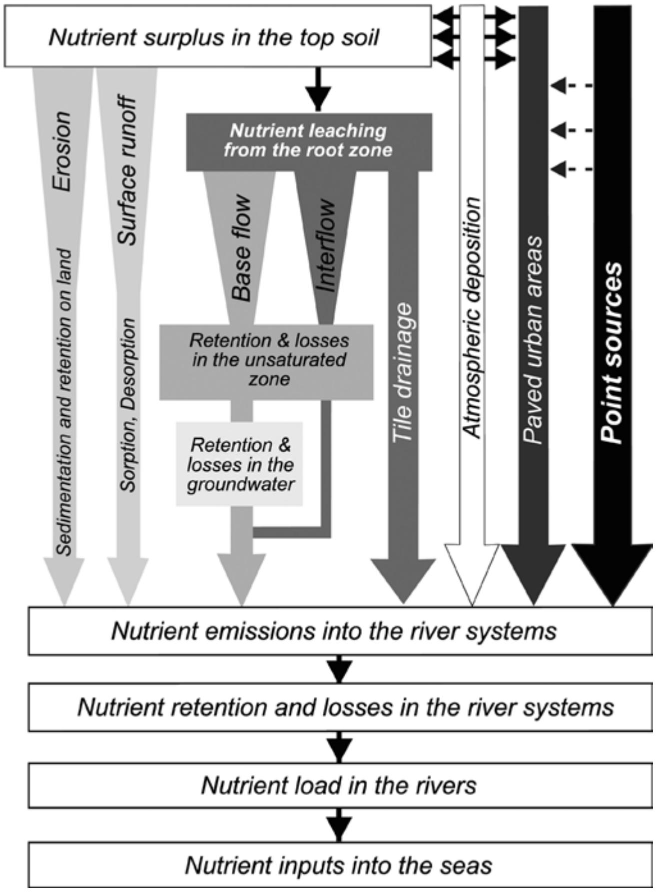


Fig. 1
Pathways and processes in MONERIS

processes are very different. The MONERIS model takes seven pathways into account, including inputs into surface waters by:

- atmospheric deposition
- groundwater
- tile drainage
- paved urban areas
- erosion
- surface runoff (only dissolved nutrients)
- discharges from point sources as municipal waste water treatment plants and industrial discharges

Within the diffuse pathways, various transformations, loss and retention processes are identified. To quantify and forecast the nutrient inputs into river systems in relation to their source requires knowledge of these transformation and retention processes. This is not yet possible in terms of detailed dynamic process models because the current state of knowledge and existing databases are limited for medium and large-scale river basins. Therefore, existing approaches of macro-scale modelling needed to be complemented and modified and, if necessary, attempts had to be made to derive new applicable conceptual models for the estimation of nutrient inputs via the individual diffuse pathways.

An important step in the development of the individual submodels was to validate these models by comparing the results with independent data sets. For example, the groundwater submodel was validated with measured groundwater concentrations.

The use of a GIS gives the possibility for a regionalized estimation of nutrient inputs. The estimations were made using the same methodology for 300 different river basins. The calculation was done for two time periods: 1983 to 1987 and 1993 to 1997. The results for both periods were compared with the estimates from other studies (Behrendt et al. 2000) and analysed for changes of nutrient inputs. These changes were estimated considering both different hydrological as well as comparable hydrological conditions in the two time periods. The assumption of the same hydrological conditions for both time periods can be used to identify the changes caused by anthropogenic activities.

The nutrient inputs from different pathways were estimated as described in the following sections.

Point discharges

The results of the studies of Rosenwinkel and Hippen (1997) and the International Commission for the Protection of Rhine against Pollution (ICPR 1999) were used regarding the direct industrial discharges for the year 1995. For the period before 1990, the published results by Hamm et al. (1991), ICPR (1989), ICPE (1992) and Behrendt (1994) were taken into account.

The regionalized estimation of nutrient inputs from municipal WWTPs is based on a country-wide GIS-supported inventory. This inventory includes more than 8000 WWTPs (80% of all WWTPs allowing for 99% of treated wastewater) for both time periods. It comprises the following information: rate of utilization of WWTPs (AU), treated population equivalents (EW_{AU}), treated population equivalents (on inhabitant basis) (E_{KA}), treated industrial discharges into the municipal sewer systems expressed as population equivalents (EGW). The yearly quantity of treated water is separated into domestic wastewater (Q_H), industrial and commercial wastewater (Q_{GEW}), external water (Q_F), urban wastewater (Q_T), storm wastewater (Q_N) and total wastewater (Q_{GES}). The N and P emissions of a WWTP were estimated based on different methods for each plant depending on the data available. For all WWTPs the emissions could be estimated on the basis of inhabitant-specific nutrient emissions and the treatment efficiency for different types of wastewater treatment (see Table 1). The inhabitant-specific N emission was 11 g N day^{-1} for 1985 and 1995 for all German Federal States. According to the investigations of Schmoll (1998) it was assumed that the specific P emission was 1.8 g P day^{-1} for 1995. For 1985 different values for the phosphorus emissions per inhabitant for East and West Germany need to be taken into account, because the P content in the detergents was different. Schmoll (1998) assumed for East Germany 4.0 g P day^{-1} and for West Germany 3.3 g P day^{-1}. For nitrogen it was further assumed that

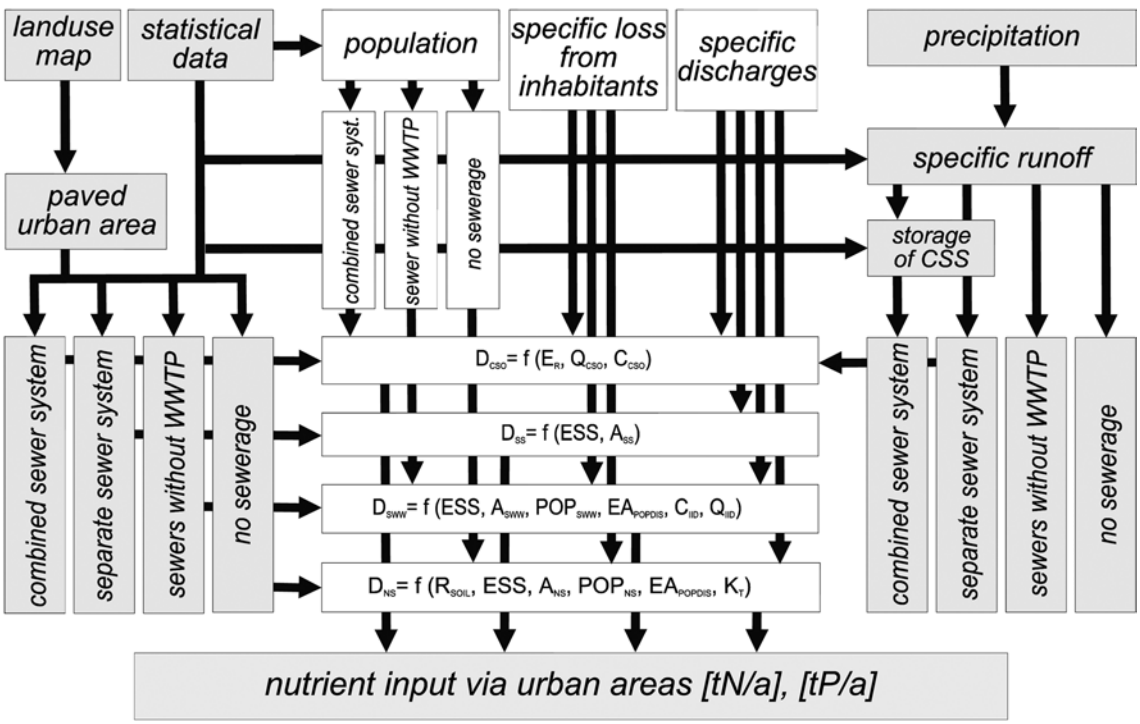
Table 1
N removal performance for various types of treatment plants (see Behrendt et al. 2000)

Plant type	N removal (%)		
	1985/East Germany	1985/West Germany	1995/Whole Germany
Wastewater pond (unaerated)	50	50	50
Wastewater pond (aerated)	30	30	30
Activated sludge plant	30	30	30
Activated sludge plant (partly biological)	20	–	–
Activated sludge plant (fully biological)	30	–	–
Mechanical treatment	10	10	10
Submerged trickling filter/ percolating filter plant	25	25	25
Treatment using plants	45	45	45
Treatment on wastewater farms	80	–	–
Nitrification	–	45	45
Denitrification	–	75	75

the emission of industrial discharges into the sewer systems was 6.5 g N $(\text{day}\cdot\text{EGW})^{-1}$.

The population connected to a WWTP was estimated depending on the size of the WWTP according to the sewage statistics for all medium and large German rivers. Additionally, for some of the WWTPs, the nutrient emissions could be estimated on the basis of annual mean measured nutrient concentrations at the outlet of a WWTP and the amount of treated sewage water.

Fig. 2
Scheme for the estimation of nutrient inputs from paved urban areas



Inputs from paved urban areas

Within this pathway nutrient inputs stem from four different routes: (1) inputs from paved urban areas connected to separate sewer systems, (2) inputs from paved urban areas by combined sewer overflows, (3) inputs from households and paved urban areas connected to sewers without WWTPs and (4) inputs from households and paved urban areas which are not connected to sewer systems. These four different routes of discharges from urban areas include rainwater from streets and roofs.

The paved urban area is calculated from the CORINE land-cover map but also takes into account the population density according to the approach of Heaney et al. (1976). The total paved urban area is split into the different sewer systems according to the length of the different sewer systems in the river basins. The total discharge from the different sewer systems was estimated from the mean precipitation and the sewer system's specific share of paved urban area in a river catchment (Heaney et al. 1976). A schematic overview of the applied method is given in Fig. 2.

The nutrient inputs via separate sewer systems were estimated by means of area-specific emissions. Referring to Brombach and Michelbach (1998) we used an area-specific P emission of 2.5 kg P ha^{-1} $year^{-1}$. The area-specific N emissions were calculated from the sum of the atmospheric N deposition and a value for litter fall and excreta from animals (4 kg N ha^{-1} $year^{-1}$). The N and P inputs were calculated by multiplying the area-specific emissions by the paved urban areas that are connected to separate sewer systems.

The estimation of the nutrient inputs from combined sewer overflows is based on the approaches of Mohaupt et al. (2001) and Brombach and Michelbach (1998). The quantity of water discharged during storm events from combined sewer overflows is dependent on the specific runoff from the paved urban areas, the number of people connected to combined sewers, the inhabitant-specific water discharge (130 l $inh.^{-1}$ day^{-1}), the proportion of industrial areas in the total paved urban area (0.8%), the area-specific runoff from these industrial areas (432 m^3 ha^{-1} day^{-1}) and the number of the days on which storm water events occur (50).

The discharge rate of a combined sewer system was estimated according to a method developed by Meißner (1991) and is dependent on the storage volume of the combined sewer as well as the annual precipitation. Data on the storage volume of the combined sewers was taken from the sewage water statistics of the German states. The nutrient concentration in a combined sewer can be calculated from the area-specific emission rate of the paved urban area, the inhabitant-specific nutrient emissions and the concentration of indirect industrial effluents. The nutrient discharge into each river system is then calculated from the product of the quantity of water discharged by the overflow and the mean nutrient concentration during such events.

In addition to the inputs from separate and combined sewer systems, the nutrient emission into the river systems from paved urban areas and people who are not connected to a sewer system has to be considered. Whereas the calculation procedure for paved urban areas is similar to the method described for separate sewers, we used only the dissolved portion of the inhabitant-specific nutrient emissions (60% for P and 80% for N), because the particulate fraction will generally be transported to a WWTP.

Inputs by direct atmospheric deposition

Estimations of direct inputs into surface waters by atmospheric deposition were based on the total surface area of all waters within a catchment, which is connected to the river system. The land use map, CORINE land cover, was used for the estimation of larger lakes and rivers. Additionally, the area of the other surface waters in the river systems itself has to be taken into account. This was estimated according to Behrendt and Opitz (2000), where it is assumed that the area of a river system is dependent on the size of the catchment.

The nutrient inputs via atmospheric deposition were calculated from the product of the area-specific deposition and the mean area of surface water in a basin. For phosphorus the deposition rate was estimated from literature data. A single value of 0.37 kg P ha^{-1} $year^{-1}$ was used for the period 1993–1997. For nitrogen the results of the EMEP program were considered for the years 1985 and 1996 (Tsyro 1998a, b; Bartnicki et al. 1998). The EMEP data are available as grid maps with a cell size of 150 km^2 for 1985 and 50 km^2 for the year 1996 as NO_x-N and NH_4-N deposition in kg N ha^{-1} $year^{-1}$. The EMEP grid maps were overlaid with the boundaries of the river basins for the estimation of the mean NO_x-N and NH_4-N deposition within the catchments.

Inputs via tile drainage

The method for the quantification of nitrogen and phosphorus inputs through tile drainage is based on the size of the drained area, the amount of drainage water and the average nutrient concentrations in the drainage water (Fig. 3).

For the estimation of the size of drained areas within a basin, various databases had to be used for East and West Germany. For East Germany, data on the drained area could be partly derived from documents of the German Democratic Republic (GDR) melioration companies, which were responsible for the irrigation and drainage of agricultural area. The drained areas were digitized and overlaid with the soil map of the agricultural area of the former GDR, which includes items characterizing the hydromorphic properties of the soils. The result of the

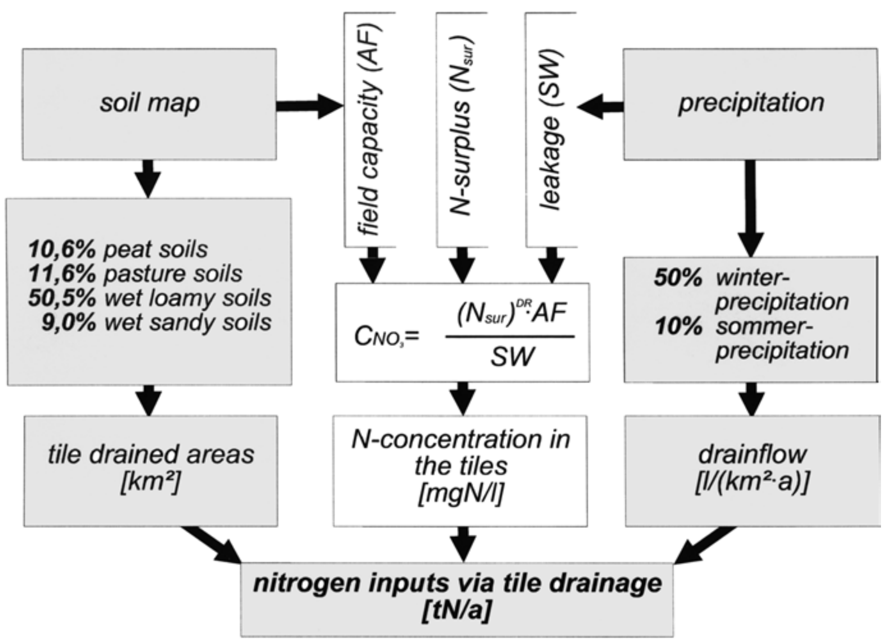


Fig. 3
Nitrogen inputs by tile drainage

overlay was that about 10.6% of peat soils, 11.6% of flood plain soils, 50.5% of wet loamy soils and 9% of sandy soils with low groundwater tables were tile-drained. For West Germany Bach et al. (1998) carried out a survey of agricultural excess N and P in communities and districts concerning the drained area of arable land and pasture. From these surveys the proportion of drained land for the old German states was derived.

The drainage water volume is calculated according to Kretzschmar (1977) under the assumption that the drained water is the sum of 50% of winter and 10% of summer precipitation. This approach takes into account the regional distribution of rainfall and the volume of drainage water. On the basis of measurements, P concentrations in the drainage water for various soil types were determined. The results are shown in Table 2.

The calculation of nitrogen concentrations in drainage water is based on the regionally differentiated N surpluses (Bach et al. 1998). From the N surpluses the potential nitrate concentration in the infiltrating water is calculated according to Frede and Dabbert (1998). According to Fig. 3, this potential nitrate concentration in the upper soil layer is reduced by denitrification, which is dependent on soil characteristics.

The nitrogen concentrations in drainage water are assumed to react very quickly to changes in nitrogen surpluses. These changes in the nitrogen surpluses between both investigated 5-year periods should therefore have a direct effect on change in nitrogen concentrations. For the period 1983–1987 regionalized data on the nitrogen surplus were not available. Therefore for this period, the nitrogen surpluses were determined from the long-term changes of nitrogen surpluses in the old and new German states according to Bach et al. (1998) and Behrendt (1988). From these studies it was concluded that the nitrogen surplus in the period 1983–1987 was 36% larger in the old German states and 50% larger in the new German states (i.e. the former German Democratic Republic) than in 1995.

Table 2
P concentrations used for drainage water for various soil types

Soil type	Term	C_{DRP} [mg P l^{-1}]
Sandy soils	C_{DRSP}	0.20
Loam	C_{DRLP}	0.06
Fen soils	C_{DRNMP}	0.30
Bog soils	C_{DRHMP}	10.00

Inputs via groundwater

The nutrient inputs via the groundwater pathway are calculated from the product of the groundwater outflow and the groundwater nutrient concentration (Fig. 4). The absence of methods for estimating natural interflow means that this pathway includes both the base flow and the natural interflow. The groundwater flow was calculated for each basin from the difference between the observed runoff at a monitoring station and the estimated sum of the other discharge components (drain flow, surface runoff, storm water runoff from paved urban areas).

For the development of the respective submodel, nutrient concentrations in groundwater were used, supplied by the Environmental Offices of German Federal States. Only stations were considered which represent the upper groundwater aquifer and which are located outside urban or industrial locations. To transfer the individual data for each groundwater well into average concentrations for the basin upstream of an individual monitoring station, each station's mean values were interpolated with a GIS. By using the GIS a regionalized map of nutrient groundwater concentrations was constructed. On the basis of this map and additional literature, concentrations of phosphorus in the groundwater for the various soil types were calculated

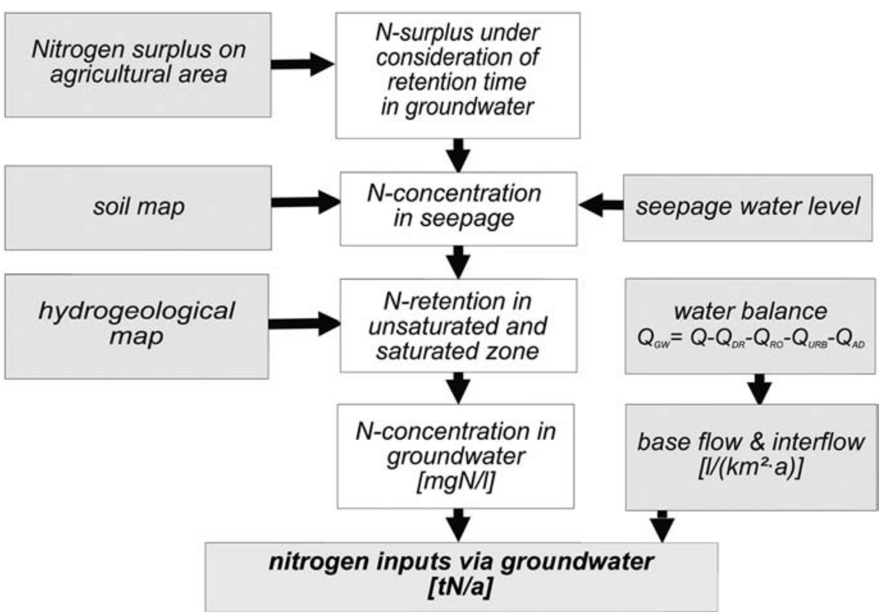


Fig. 4
Nitrogen inputs by groundwater

(see Table 3). The groundwater-watch programme of Mecklenburg-Western Pomerania and the study of Driescher and Gelbrecht (1993) show that in anaerobic groundwater, particularly at deep levels, there are clear differences between the concentrations of dissolved inorganic phosphorus (DIP) and total phosphorus. According to Driescher and Gelbrecht (1993), one can conclude that the total phosphorus (TP) concentrations are two to five times higher than the concentrations of soluble reactive phosphorus (SRP) determined in the normal standard monitoring programmes. Information on areas of anaerobic groundwater is not available. However, one can determine areas with a higher probability of anaerobic conditions through a comparison of nitrate concentrations in the groundwater and those in the infiltration water. For the calculation of total phosphorus concentrations in the groundwater it was assumed that, if nitrogen concentrations in the groundwater are less than 15% of those in the infiltration water, the TP concentrations in the groundwater are 2.5 times greater than the SRP concentrations. With the information given above, the calculated TP concentrations ranged between 0.09 and 0.14 g P m^{-3} in the groundwater of Mecklenburg-Western Pomeranian rivers which is in the same range as the measured values (see Behrendt and Bachor 1998).
The N concentrations in the groundwater are also derived from the potential nitrate concentration in the infiltration water. However, in contrast to tile drainage, the knowledge of the residence time of water on its way from the root-zone to the groundwater and in the groundwater itself is essential for this derivation. An approach for an approximate estimation of the water residence time in the unsaturated zone and in the aquifer was made on the basis of long-term observations of nitrate concentrations and loads in rivers.
Because detailed model results regarding the residence time in the unsaturated zone and in the groundwater aquifers of the German river basins were not available up to now, we tried to estimate this residence time from the comparison of long-term changes of the nitrogen surplus averaged over different periods from previous years with the long-term behaviour of the observed nitrate concentrations in rivers. The result of this comparison was that, within the Rhine, residence times seem to be about 10 years. In the Danube and Elbe, residence times of about 20 and 30 years, respectively, were derived. Based on these results, the nitrogen surpluses for the different basins were corrected and then used for the calculation of the nitrate concentration of the infiltration water. In the next step, this concentration was compared to the mean nitrate concentration in the groundwater of a river basin derived from the interpolated map. The differences in nitrogen concentrations between both maps represent the nitrogen retention (mainly denitrification) within the soil, and the transition between the unsaturated and saturated zones. It was found that the nitrogen retention is dependent on the level of infiltration water and the hydrogeological conditions.
The nitrogen concentration in the groundwater was then calculated from the modified N surplus and the specific N retention of each river basin. In the final calculation the nutrient input by groundwater is estimated from the product of the regionalized nutrient concentrations and the groundwater flow of the basins.

Table 3
P-concentrations in groundwater for various soil types

Soil type	Use	Expression	C_{GWP} [g P m^{-3}]
Sandy soils	Agricultural land	C_{GWS_P}	0.1
Loam	Agricultural land	C_{GWL_P}	0.03
Fen soils	Agricultural land	C_{GWNM_P}	0.1
Bog soil	Agricultural land	C_{GWHM_P}	2.5
All soils	Woodland/open areas	C_{GWWAOF_P}	0.01

Inputs by erosion

Figure 5 shows the procedure for estimating nutrient inputs by erosion, based on the soil loss rate, the sediment

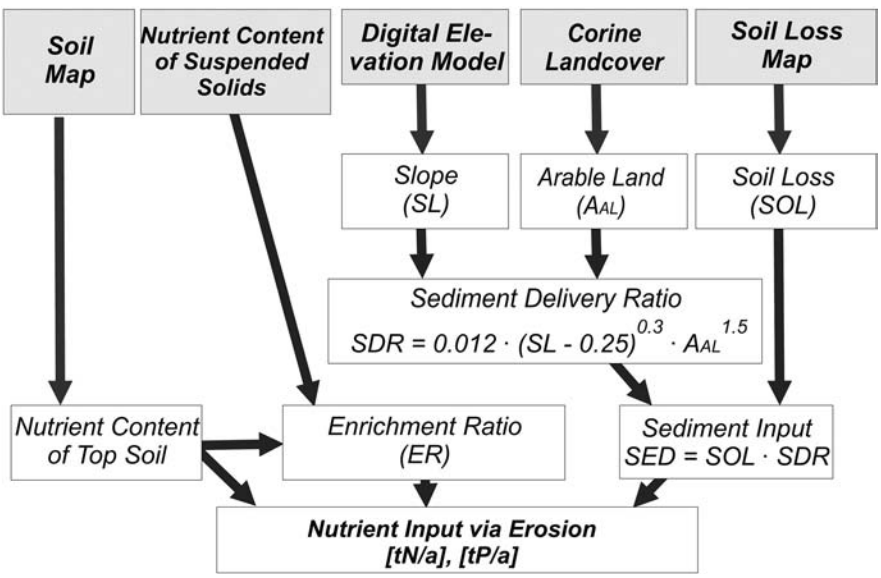


Fig. 5
Scheme for the estimation of nutrient inputs by erosion

delivery ratio and the enrichment ratio of nutrients. To calculate soil loss in the river basins, the digital erosion potential map of the black-fallow area for Germany was used which was calculated according to the modified uniformed soil loss equation (USLE) from the Fraunhofer Institute of Ecotoxicology (Klein, personal communication). For the correction of the values the for black fallow area (C factor=1), C factors of the crops were calculated from statistical information. The attribution of the C factor follows Deumlich and Frielinghaus (1994). Additionally, soil loss data estimated for administrative units by Deumlich and Frielinghaus (1994) for the new German states and by Gündra et al. (1995) for Baden-Württemberg were used for validation.

For the estimation of the sediment delivery ratio, a new GIS-supported method was proposed through a separation of areas which contribute to soil loss into the river systems. Because the GIS-supported method needs digital records (water networks, land use, soil and elevation information) with a high resolution, the application of this method was limited to 30 river basins. On the basis of a digital relief analysis, grids were selected, which include a distance of 30 m from a water-body, an agricultural usage and a slope greater than 1%. For these areas, their watersheds or source areas were estimated with the GIS function WATERSHED. It is assumed that in the case of erosion events in these areas, the possibility exists of movement of eroded soil material into the neighboring water body. The "sediment/area" ratio (SAR_{GIS}), which is related to the sediment delivery ratio, is defined as the sum of the "source areas" divided by the area of the catchment. For a transfer to other river basins, a modification of this method is necessary. For that, relationships between the SAR_{GIS} and easily available parameters characterizing the basins and which are available for all German catchment areas were investigated. Through regression analysis, the mean slope of a basin and the proportion of arable land were identified as the parameters that explain the greatest part of the variance.

In the next step, the SAR_{GIS} model was validated using the long-term records of daily measurements of suspended solids for 23 river basins located in Bavaria and Baden-Württemberg. For the validation only loads of suspended solids above a critical discharge were used to prevent the particles discharged by point sources and autochthonous growth processes from influencing the relationship. To adapt the estimations for differences in hydrological conditions between the time periods, a weighting factor, which considers the number of days with high flow rates, was introduced according to Rogler and Schwertmann (1981). The approach for the sediment delivery ratio assumes that the riverbed itself is in a steady state, i.e. periods of resuspension of river sediments are followed by periods of sedimentation.

The P content of the topsoil was calculated on the basis of a start value for the middle of the 20th century and the cumulative P surplus since this time for each German state. The start value is regionalized by a dependency on the silt content of different soil types. The N contents were derived from the German soil map. The ratio between the observed P content of suspended solids at high flows and the estimated P content of the soil was the basis for the calculation of the enrichment ratio. It was found that the enrichment ratio is inversely proportional to the square root of the specific sediment input. For nitrogen, the enrichment ratio of phosphorus was modified according to the N/P ratio in the soil. Finally, the nutrient inputs by erosion are calculated as the product of the nutrient content of soil, the enrichment ratio, the sediment delivery ratio, the weighting factor and the soil loss.

Inputs by surface runoff

The inputs of dissolved nutrients by surface runoff were determined according to the scheme presented in Fig. 6. The specific surface runoff itself was calculated according to the approach of Liebscher and Keller (1979). In this method, the mean summer and winter precipitations are the main variables controlling the volume of this flow component. Further, it was assumed that surface runoff of unpaved areas does not occur. This includes forest, wetlands, surface waters and mining areas.

The concentrations of dissolved nutrients in the surface runoff were estimated as area-weighted means for each basin. It was assumed that the phosphorus concentration in the surface runoff depends on the land use, because the level of long term P surplus in agricultural soil determines the level of particulate and dissolved phosphorus in the upper soil. Therefore, dissolved P concentrations are high for cropland, medium for grassland and low for non-agricultural areas. For nitrogen, the concentrations in the surface runoff were derived from the atmospheric deposition rates and, for cropland alone, an additional contribution from the soil was assumed.

Nutrient retention in the surface water system

The nutrient inputs are often not in correspondence with the observed load because retention and losses of nutrients occur within the surface waters of a river system. From the comparison of estimated nutrient inputs with the observed load of about 100 different river systems Behrendt and Opitz (2000) have shown that the nutrient retention of a river system strongly depends on the specific runoff and the hydraulic load. The authors derived submodels for the retention of nitrogen and phosphorus, which were used to estimate the nutrient load from the inputs.

Results and discussion

Nitrogen

In the period 1993–1997, it was estimated that 818.6 kt year^{-1} nitrogen were discharged into the river basins of Germany (see Fig. 7). Compared with the situation in 1983–1987 the estimated nitrogen inputs were

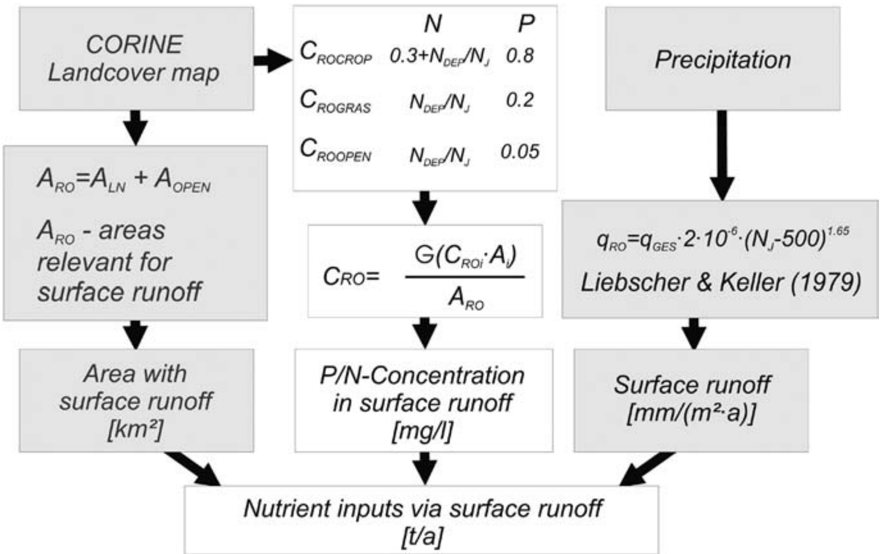


Fig. 6
Scheme for the estimation of nutrient inputs by surface runoff

reduced by 24.5%. The nitrogen emissions were dominated by groundwater (48%) followed by discharges from WWTPs (25%) and inputs caused by tile drainage (15%). All other estimated emissions of nitrogen into German surface water systems comprise only a small share of the total inputs. The reduction of all N-inputs is mainly caused by the decrease of point source discharges (–46%).

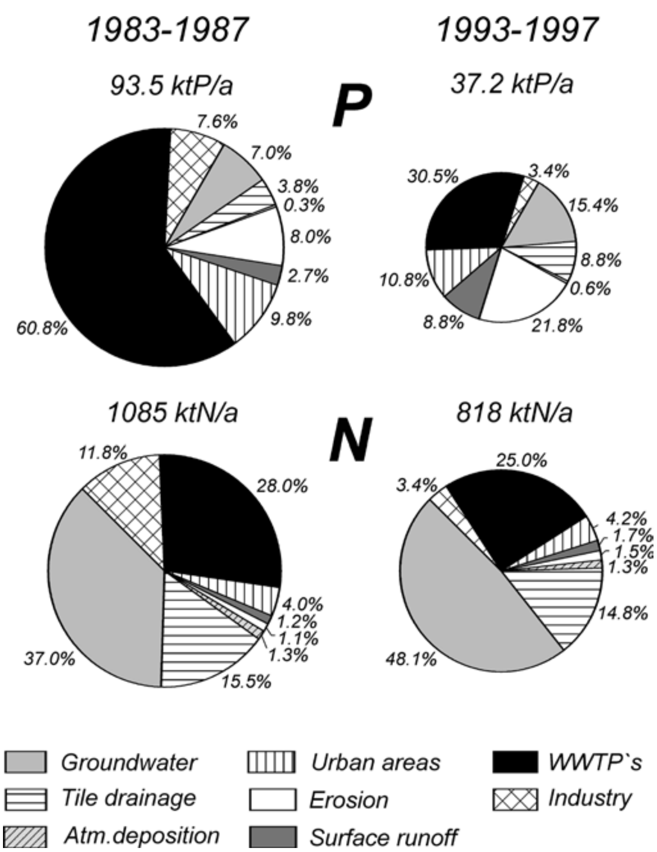


Fig. 7
Nitrogen and phosphorus inputs into the German river basins

In contrast to that, the reduction of diffuse sources accounts for about 10% only. That is the reason why the relative contribution of diffuse sources has increased since the mid-1980s.

The greatest reduction of nitrogen inputs was achieved in the Elbe basin (33%) whereas the decrease in the Danube basin was only 13% (Table 4). The highest share of point source discharges was estimated for the Rhine basin (40%), but point source inputs caused only 20% of total nitrogen inputs in the Danube basin. The target of a 50% reduction of inputs into the North Sea and the Baltic set by the conference of the Ministers of the Environment of the bordering countries, ICN, and HELCOM for the time between 1985/87 and 95 was not achieved for all river catchments.

The hot-spots of nitrogen emissions (N inputs>2,500 kg km^{-2} $year^{-1}$) were those areas with very high population densities (e.g. the region of Berlin and the catchment of the River Ruhr) where the proportion of point sources is high. The same levels of total N inputs occur in the rivers Lippe and Ems, but here the diffuse inputs are very high, caused by the very high N surplus in agriculture (Bach et al. 1998).

The lowest area-specific nitrogen inputs (lower than 1,000 kg km^{-2} $year^{-1}$) were calculated for the river basins in the north-east German flatlands, where the population density is low and a high denitrification potential occurs.

Although the nitrogen surplus in agriculture was substantially reduced in the old and especially in the new German states, a decrease in the nitrogen inputs by groundwater was achieved only in the Rhine basin. In the other river basins a further increase of the inputs by this pathway occurred up to the middle of the 1990s, because the residence times in the unsaturated zone and in the groundwater are more than 20–30 years. Wendland and Kunkel (1999) by means of their stochastic retention time model, WEKU, estimated for the German part of the Elbe basin an average residence time in the groundwater of

Table 4
Total nitrogen inputs into the basins of Danube, Rhine, Weser and Elbe as well as into the basins of Seas and all of Germany (D) for the period 1983–1987 and 1993–1997

Basin		Danube	Rhine	Weser	Elbe	Black Sea	North Sea	Baltic Sea	D
Total N inputs 1983–1987	kt year^{-1}	150.1	395.6	107.0	219.3	150.4	873.1	61.1	1,084.6
Share of diffuse sources	%	75.0	47.5	70.8	56.2	75.0	56.6	74.8	60.2
Total N input 1993–1997	kt year^{-1}	131.3	277.7	85.1	147.5	131.7	642.1	44.9	818.6
Share of diffuse sources	%	80.4	59.8	78.4	72.1	80.5	69.1	81.1	71.6
Changes	%	–12.5	–29.8	–20.5	–32.7	–12.5	–26.5	–26.6	–24.5

29 years. This model result agrees with our assumption developed from the different long-term changes of the nitrogen surplus in agricultural soils and the nitrate concentrations in the river. Under these conditions even a small reduction of the nitrate concentrations in the groundwater of these river basins cannot be achieved before the middle of this decade.

Phosphorus

The phosphorus inputs for all of Germany including the catchments were reduced by at least 50% in comparison to the period 1983–1987 (Fig. 8). The estimated decrease in detail was 60.2% to a level of 37 kt year^{-1}. This was mainly due to an 80% input reduction from point sources. The diffuse P inputs were only reduced by 17%. Although the point source reduction was very high, the discharges into the German river basins from WWTPs represent the dominant pathway with 31% of the total P inputs followed by erosion (22%) and inputs via groundwater (15%). Also the other pathways, tile drainage, surface runoff and emissions from paved urban areas constitute significant P inputs.

The greatest observed reduction of total P inputs was 68% in the Rhine basin. In the Danube, the decrease was the lowest at 50% (Table 5). In general, because of the significant reduction of point sources, the relative contribution of diffuse sources to the total P inputs is now more than 50% in all investigated river basins whereas the share of point sources ranges between 28% (Danube) and 46% (Rhine).

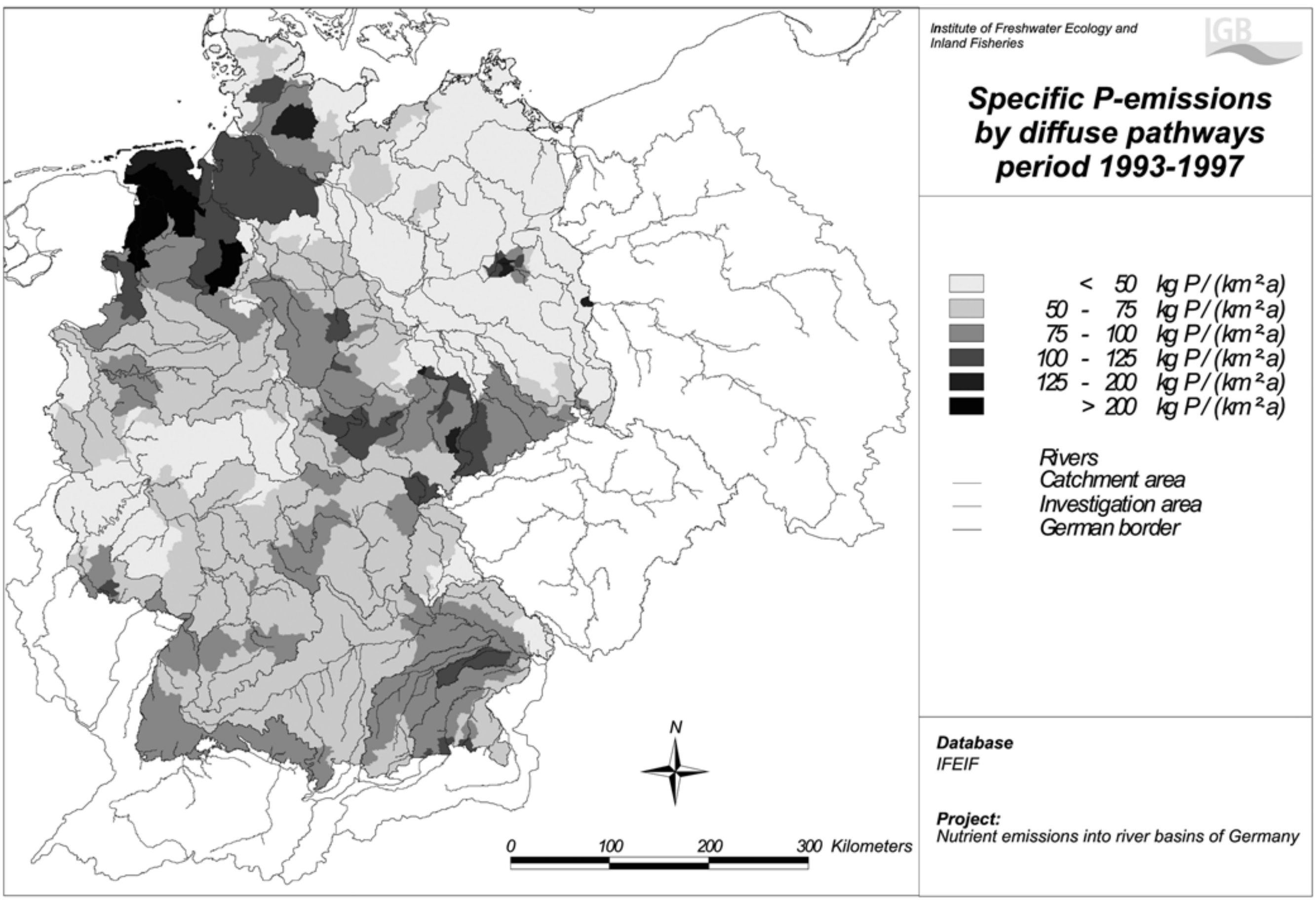


Fig. 8
Total specific phosphorus emissions into German river basins in the period 1993–1997

Table 5
Total phosphorus inputs into the basins of Danube, Rhine, Weser and Elbe as well as into the basins of Seas and all of Germany for the periods 1983–1987 and 1993–1997

Basin		Danube	Rhine	Weser	Elbe	Black Sea	North Sea	Baltic Sea	Germany
Total P inputs 1983–1987	t $year^{-1}$	10,630	37,550	8,510	18,800	10,640	78,770	4,130	93,540
Share of diffuse sources	%	36.7	21.9	37.7	33.1	36.7	31.0	30.3	31.7
Total P inputs 1993–1997	t $year^{-1}$	5,300	12,040	3,810	7,160	5,310	30,320	1,620	37,250
Share of diffuse sources	%	71.5	53.7	70.6	64.5	71.6	65.0	71.0	66.1
Changes	%	–50.1	–67.9	–55.2	–61.9	–50.1	–61.5	–60.8	–60.2

The highest area-related P inputs (Fig. 8) were found in the regions with high population densities, where either large areas are drained and used for agriculture (Ems basin and smaller catchments flowing directly into the North Sea) or a large share of the population is connected to sewers but not to WWTPs (Saale, Mulde).
A comparison of the model results with the results of other studies and the immission approach shows good agreement. But still this comparison shows that the possible deviation of the estimated diffuse inputs is in the range of about 30%.
For the large transboundary river basins (Danube, Elbe and Rhine) the nutrient inputs were also calculated for the parts outside Germany. The total inputs into these upper basins of the Danube, Elbe and Rhine were 213 tk N $year^{-1}$ and 16 kt P $year^{-1}$ for the period 1993–1997. For the Danube, upstream of the gauging station Jochenstein the share of nutrient inputs from the basins outside Germany was 15% (nitrogen) and 29% (phosphorus). The share of nutrient inputs outside Germany for the Elbe upstream of Zollenspieker was 37% for nitrogen and 43% for phosphorus. For the Rhine it was estimated that the tributaries in Switzerland, France and Austria cause 30% of the total nitrogen inputs and 41% of the phosphorus emissions into the river systems.

Comparison with the observed nutrient loads

The calculated nutrient inputs into the river basins were converted into loads by the application of the retention equations according to Behrendt and Opitz (2000). These calculated nutrient loads were then compared with the loads estimated from measurements of flow and nutrient concentrations. This comparison was possible for about 170 river basins and is shown in Fig. 9 for the load of dissolved inorganic nitrogen. For more than 90% of the investigated river basins the deviation between calculated and observed DIN load is lower than 30%. Larger deviations only occur in river basins smaller than 1,000 km^2 and seem to be caused by problems in the measurement of flow and basin size (the groundwater catchment can be smaller or larger than the catchment derived from the elevation). Comparison of the loads of total phosphorus also shows the tendency of larger deviations with decreasing size of the catchments. Additionally, it was found that larger deviations occur for basins, which comprise for example large lakes directly upstream of the gauging station or in the upper catchment. From this it can be concluded that the differences in the distribution of surface

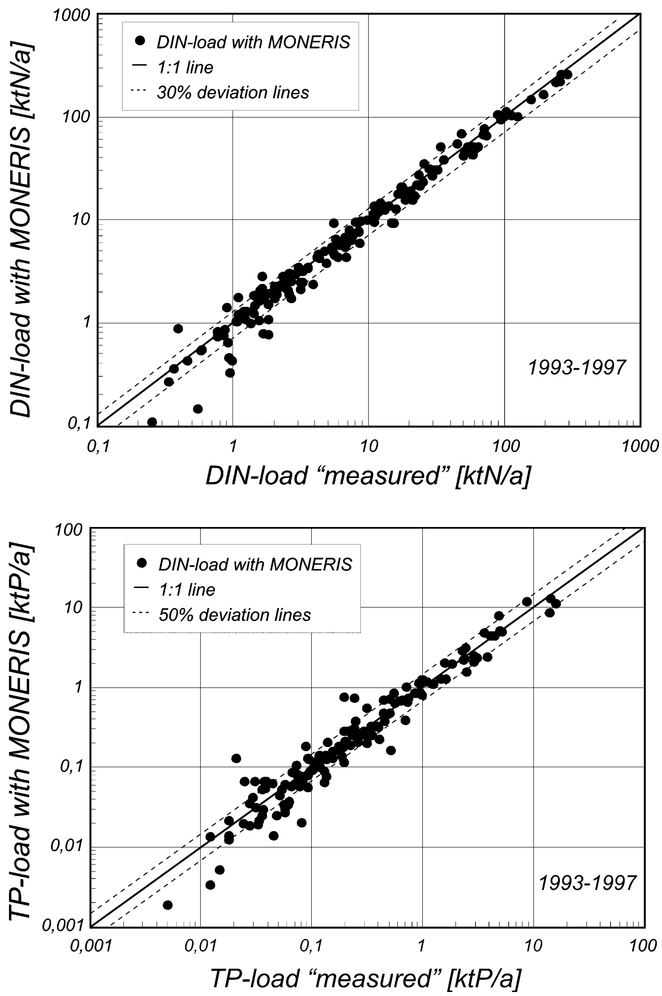


Fig. 9
Comparison of measured and calculated loads of dissolved inorganic nitrogen and total phosphorus

waters within a catchment have not been taken into account sufficiently up to now in the retention approach. The MONERIS model further enabled the calculation of scenarios for changes of point and diffuse sources. Such scenarios show that, in a time perspective of 10–20 years, measures focused alone on the reduction of point and diffuse inputs into the river basins are in most cases not sufficient to achieve a 50% reduction of nitrogen load compared with the middle of the 1980s. Additional measures are needed to increase the quantities of nitrogen retained in catchments (e.g. buffer strips, conversion of drained areas, establishment of reservoirs and reconstruction of former lands). In response the latter is increasingly being picked up by regional and national legislation and agricultural administration.

Acknowledgements We would like to thank the German Environmental Agency for funding the project. Further we would like to thank all of the institutions that have supported the project by supplying data and helpful discussions. Our special thanks are related to Dr. Herata, Dr. Mehlhorn and Dr. Mohaupt from the German Environmental Agency for the helpful critical discussions during the project.

References

Bach M, Frede H-G, Schweikart U, Huber A (1998) Regional differenzierte Bilanzierung der Stickstoff- und Phosphorüberschüsse der Landwirtschaft in den Gemeinden/ Kreisen in Deutschland. UBA-Texte, 75/99 Annex, pp 1–45

Bartnicki J, Olendrzynski K, Jonson JE, Uer S (1998) Description of the Eulerian acid deposition model. In: Transboundary acidifying air pollution in Europe. EMEP/MSC-W Status Report 1/98. Part 2, Oslo

Behrendt H (1988) Changes in nonpoint nutrient loading into European freshwaters: trends and consequences since 1950 and not impossible changes until 2080. IIASA, Working paper WP-88-026, 28 pp

Behrendt H (1994) Phosphor- und Stickstoffeinträge über punktförmige Quellen. In: Werner W, Wodsak H-P (eds) Stickstoff- und Phosphoreintrag in Fließgewässer Deutschlands unter besonderer Berücksichtigung des Eintragsgeschehens im Lockergesteinsbereich der ehemaligen DDR. Agrarspectrum 22, Frankfurt/Main, pp 137–164

Behrendt H, Bachor A (1998) Point and diffuse load of nutrients to the Baltic Sea by river basins of north east Germany (Mecklenburg-Vorpommern). Water Sci Technol 38:147–155

Behrendt H, Opitz D (2000) Retention of nutrients in river systems: Dependence on specific runoff and hydraulic load. Hydrobiologia 410:111–122

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, 261 pp

Brombach H, Michelbach S (1998) Abschätzung des einwohnerbezogenen Nährstoffaustrages aus Regenentlastungen im Einzugsgebiet des Bodensees. Bericht Internationale Gewässerschutzkommission Bodensee, 49, 47 pp

Deumlich D, Frielinghaus M (1994) Eintragspfade Bodenerosion und Oberflächenabfluß im Lockergesteinsbereich. In: Werner W, Wodsak H-P (eds) Stickstoff- und Phosphoreintrag in Fließgewässer Deutschlands unter besonderer Berücksichtigung des Eintragsgeschehens im Lockergesteinsbereich der ehemaligen DDR. Agrarspectrum 22, Frankfurt/Main, pp 48–84

Driescher E, Gelbrecht J (1993) Assessing the diffuse phosphorus input from subsurface to surface waters in the catchment area of the lower River Spree (Germany). Water Sci Technol 28:337–347

Frede HG, Dabbert S (1998) Handbuch zum Gewässerschutz in der Landwirtschaft. Ecomed Landsberg, 451 pp

Gündra H, Jäger S, Schröder M Dikau R (1995) Bodenerosionsatlas Baden-Württemberg. Ulmer Verlag, Stuttgart

Hamm A, Gleisberg D, Hegemann W, Krauth K-H, Metzner G, Sarfert F, Schleypen P (1991) Stickstoff- und Phosphoreintrag in Oberflächengewässer aus "punktförmigen Quellen". In: Hamm A (ed) Studie über Wirkungen und Qualitätsziele von Nährstoffen in Fließgewässern. Academia Verlag, Sankt Augustin, pp 765–805

Heaney JP, Huber WC, Nix SJ (1976) Storm water management model level I – preliminary screening procedures. EPA 600/2-76-275

ICPE (International Commission for the Protection of Elbe) (1992) Inventar der wichtigsten Abwassereinleiter im Einzugsgebiet der Elbe in Jahr 1989. ICPE, Magdeburg, 12 pp

ICPR (International Commission for the protection of Rhine) (1989): Programme d'Action "Rhin" – Inventaire des rejets de substances prioritaires en 1985. ICPR, Brussels, 69 pp

ICPR (1999) Bestandsaufnahme der punktuellen Einleitungen und der diffusen Einträge 1996. IKSR-Document, Cd 20–98d

Kretzschmar R (1977) Stofftransport in ländlichen Entwässerungsgräben und Vorflutern. Landwirtschaftliche Forsch 30:231–238

Liebscher HJ, Keller R (1979) Abfluß. In: Keller R (ed) Hydrologischer Atlas der Bundesrepublik Deutschland (Textband). Bonn, pp 90–159

Meißner E (1991) Abschätzung der mittleren Jahresschmutzwasserfrachten aus Mischwassereinleitungen. Wasser-Abwasser-Abfall, Kassel 7:69–78

Mohaupt V, Sieber U, Van De Roovaart J, Verstappenn CG, Langenfeld F, Braun FM (2001) Diffuse sources of heavy metals in the German Rhine catchment. Water Sci Technol (in press)

Rogler H, Schwertmann U (1981) Erosivität der Niederschläge und Isoerodentkarte von Bayern. In: Zeitschrift für Kulturtechnik und Flurbereinigung, p 22

Rosenwinkel K-H, Hippen A (1997) Branchenbezogene Inventare zu Stickstoff- und Phosphoremissionen in die Gewässer. Forschungsbericht, Institut für Siedlungswasserwirtschaft und Abfalltechnik, Universität Hannover

Schmoll O (1998) Nährstoffeinträge aus kommunalen Kläranlagen in die Flussgebiete Deutschlands: Notwendigkeiten und Möglichkeiten ihrer weiteren Verminderung. Diplomarbeit, Technische Universität Berlin, Institut für Technischen Umweltschutz, 113 pp

Tsyro SG (1998a) Transboundary fluxes and exceedances to critical loads. In: Transboundary acidifying air pollution in Europe. EMEP/MSC-W Status Report 1/98. Part 1, Oslo

Tsyro SG (1998b) Description of the Lagrangian acid deposition model. In: Transboundary acidifying air pollution in Europe. EMEP/MSC-W Status Report 1/98. Part 2, Oslo

Wendland F, Kunkel R (1999) Das Nitratabbauvermögen im Grundwasser des Elbeeinzugsgebietes. Schriften des Forschungszentrum Jülich, Reihe Umwelt/Environment, vol 13, 166 S