Nutrient fluxes at the river basin scale

Forum

The impact of nutrient pollution can be observed in many rivers and coastal seas all over Europe (Stanners & Bourdeau, 1995). This has led to international directives that aim at a reduction of nutrient levels in European rivers and coastal seas (EEC, 2000). Large scale studies of nutrient fluxes are needed to predict and evaluate the effects of the proposed measures.

MARCEL DE WIT

Dr. M.J.M. de Wit, RIZA, P.O Box 9072, 6800 ED Arnhem, The Netherlands.
m.dwit@riza.rws.minvenw.nl

For most applied environmental research the scale (extent and resolution) of the available data (information scale) differs from the scale at which most of the underlying processes typically occur (model scale) and the scale at which the outcome of the research is used (policy scale). Therefore, upscaling and downscaling methods (Bierkens *et al.*, 2000) are often an essential part of environmental research (e.g. Feddes, 1995; Addiscott, 1998). However, the use of scale transfer functions does often not improve the transparency of the linkage between question (policy scale) and answer (policy scale). The aim of this paper is to illustrate that before using scale transfer functions to transpose available models and data into the policy scale one may search for data and model concepts that match the policy scale. This is demonstrated with examples derived from the analysis of Nitrogen (N) and Phosphorus (P) fluxes in the Rhine and Elbe river basins (Figure 1). The search for an appropriate model to analyse nutrient fluxes at the river basin scale involves consideration of the spatial and temporal extent and resolution needed to ans-

Figure 1 The Rhine and Elbe river basins cover an area of approximately 300,000 km2 of which about 45 percent is used for agricultural production. The two river basins have a total population of around 70 million people and they overlap with the borders of 11 different countries. Together these basins cover a wide range of landscape, climatic, and socio-economic zones. The Nitrogen and Phosphorus fluxes in these rivers have increased with time by human activities. This has caused considerable changes in fresh and marine ecosystems and has negatively affected the quality of water for human consumption and other uses (Stanners & Bourdeau, 1995)

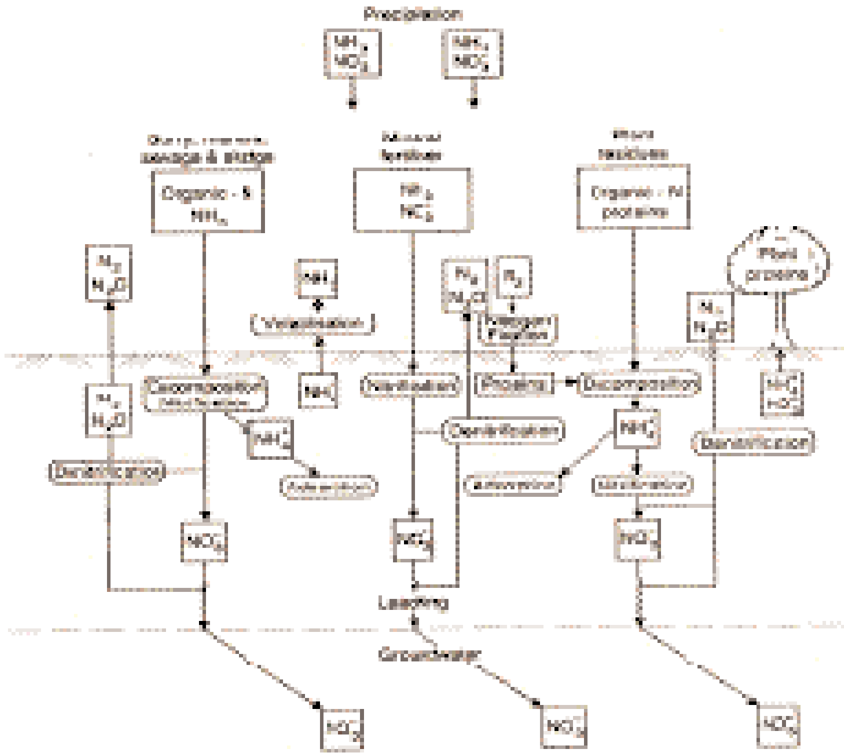

Figure 2. Processes that determine the flux of nitrogen in the soil (Burt *et al.*, 1993)

wer the questions that are relevant for nutrient policy at the river basin scale, and the availability of data to cover the extent of the study at the required resolution. Furthermore, it needs to be determined which factors are the main controls of nutrient fluxes at the river basin scale and how these factors should be represented in the model given the quality and resolution of the available data.

A matter of scale

In applied environmental studies research questions are often scale specific. The scale of the research largely determines which method is appropriate to use. Therefore, it is necessary to explicitly define the scale of the research before choosing the methodology. One should consider both the spatial and temporal extent and the spatial and temporal resolution needed to answer the question. In general the larger the extent, the less detailed is the resolution, that is considered for the analysis. At a regional scale nutrient fluxes are not analysed to learn about microscopic processes in the soil, but rather to describe long term and regional patterns. Also, the resolution of the available data generally decreases with increasing size of the study area. For the analysis of nitrogen leaching at the scale of a farm one might use data from field experiments, whereas for a regional analysis of nitrogen pollution one has to work with soil maps and regional administrative data. Finally, different factors dominate at different levels of scale (see for example Figure 2). Temperature might be one of the main variables to describe the variation in N concentrations within a year, but it is of much less importance for the description of the variation between different years.

The framework presented in Table 1 summarises the foregoing discussion and was used to develop a modelling strategy for the analysis of nutrient fluxes from pollution sources to the river outlets at the river basin scale. The nutrient study described in this paper aims at answering two questions: 1) what is the contribution of the different sources (agriculture, industry etc.) and regions to the nu-

Table 1. Examples of the analysis of nutrient fluxes at different levels of scale

Research aim	Extent of research	Resolution	Available data	Dominating factors
understanding processes	point	detailed	laboratory experiments	denitrification,adsorption
protecting the trophic status of a small lake	small region: decade	hectare: month	stream flow data, field measurements	agricultural practices, flow velocity
global/climate change	world: century	country: year	administrative data, climate data	population density, economy

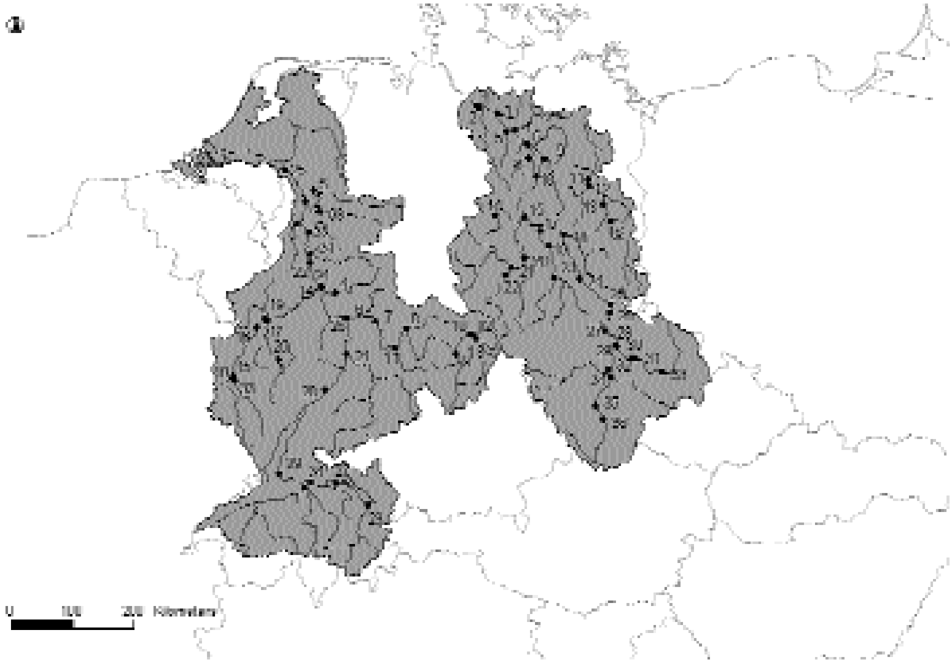

Figure 3 Location of monitoring stations used in this study

trient load in the river?, and II) what will be the effect of source control measures (e.g. reduction of fertiliser use or the improvement of wastewater treatment plants) on the nutrient load in the river? For large areas such as the river basins analysed in this study (10^5 km²) these questions need to be evaluated over long time periods (decades rather than years). From a (European) policy point of view a spatial resolution of 10^3-10^4 km² (upstream basins of major tributaries) and a temporal resolution of five years are a reasonable resolution to analyse the past (since 1970) and future (up to 2020) changes in nutrient sources and nutrient loads in the Rhine and Elbe river networks.
The next step is to explore what data are available at the scale (extent and resolution) of the research question. It appeared that for the analysis of nutrient fluxes in the Rhine and Elbe basins a lot of data were available that cover the entire river basins and have the required (or even more detailed) resolution. An overview of the data available for the analysis of nutrient emissions and nutrient transport (from pollution sources to river outlets) are given in Table 2. Water quality and water quantity data were available for 70 stations spread over the Rhine and Elbe river networks (see Figure 3). The area upstream of these monitoring stations varies between 10^3-10^5 km². These data were available to calibrate and validate the models. More detail about the data used for the nutrient study is given in De Wit (1999a).
The quality and resolution of the available data should be seen as a precondition for the type of model to be developed and not as an excuse afterwards for why an advanced and intricate model does not perform well. There is no point in using a model for which the appropriate data are not available. Moreover, the model should consider those factors that dominate at the scale of the analysis. The question now is: which factors are dominating for nutrient fluxes at the river basin scale and how should these factors be represented in the model given the quality and resolution of the available data?

The balance between data availability and model complexity

The search for an appropriate model at the river basin scale was done by comparing the results of four different models that represent increasing complexity (De Wit & Pebesma, 2001). In the first model only one variable is used, in the second model two variables are used, in the third model three variables are used and in the fourth model a large number of variables are included. The five year average N and P loads measured at 34 different mon-

itoring stations in the river Rhine network (1970-1995) were used to calibrate the models. The model parameters were tuned in such a way (trial and error) that the difference between measured and modelled five year average river load was minimised. The five year average N and P loads measured at 36 different monitoring stations in the river Elbe network (1980-1995) were used to validate the models. A comparison of the predictive capability of the four models can be used to determine the utility of increasing model complexity. The errors in the data that were used to run and validate the models were quantified and it was analysed to what extent the model validation errors could be attributed to data errors, and to what extent to shortcomings of the model. For more details the reader is referred to De Wit & Pebesma (2001).

In the first model it is assumed that the five year average river load at a certain monitoring station in the river network and for a certain time period (e.g. 1970-1975 or 1990-1995) is proportional to the size of the upstream basin. This model serves as a starting point. It lacks any description of the upstream basin. It represents the level of knowledge that was available before the analysis of pollution sources and transport conditions in the Rhine and Elbe basins.

The second model is based on the assumption that the river load is proportional to nutrient emissions in the upstream basin or in other words: ‘the larger the nutrient input the larger the nutrient output’. A distinction is made between direct nutrient emissions to the surface water (e.g. discharge of wastewater) and nutrient surplus at the soil surface (input from fertilisers, manure, and atmospheric deposition minus output from yield). Both were mapped for the entire Rhine and Elbe basins at a resolution of 1 km^2 for all five year periods from 1970 to1995 (see De Wit, 1999a) and have been used as input for models two, three and four. The ratio of transport of nutrients through the soil/groundwater system and the ratio of transport through the river network are constant in this model for all regions and time periods. This second model represents the level of knowledge available after the inventory of pollution sources and before the analysis of transport conditions.

The third model (De Wit, 1999b) describes the ratio of transport of nutrients through the river network as a function of the area specific runoff. The ratio of transport of

Table 2. Data available for the analysis of nutrient fluxes at the river basin scale

Data available for the analysis of nutrient emissions

Data	Resolution	Period	Source
Population numbers	Regions	1990-1995	National Statistical Agencies
Connection rate sewage systems	Regions	1990-1995	,,
Connection rate WWTP [a]	Regions	1990-1995	,,
Information WWTP [a]	WWTP [a]	1990-1995	,,
Industrial emissions	Regions	1990-1995	,,
Livestock numbers	Regions	1970-1995	,,
Agricultural land use	Regions	1990-1995	,,
Crop yields	Regions	1990-1995	EUROSTAT [b]
Crop yields	Country	1970-1995	FAO
Fertiliser use	Country	1970-1995	FAO
Land Cover	1 km^2	1990-1995	Corine, USGS [c]

Data available for the analysis of nutrient transport in soil, groundwater, and river network

Data	Resolution	Period	Source
Average annual precipitation	9 km^2	long term	PIK [d]
Average annual temperature	9 km^2	long term	PIK [d]
Soil type	1:1 M	-	ESB [e]
Lithology	1:1 M	-	Derived from soil map, IAH [f]
Elevation	1 km^2	-	USGS [c]
Slope (relief)	1 km^2	-	Derived from elevation map
River network (LDD[g])	1 km^2	-	Derived from elevation map

[a] Wastewater treatment plant
[b] European Statistical Office
[c] United States Geological Survey
[d] Potsdam Institute for Climate Impact Research
[e] European Soil Bureau
[f] International Association of Hydrogeologists
[g] Local drain direction map

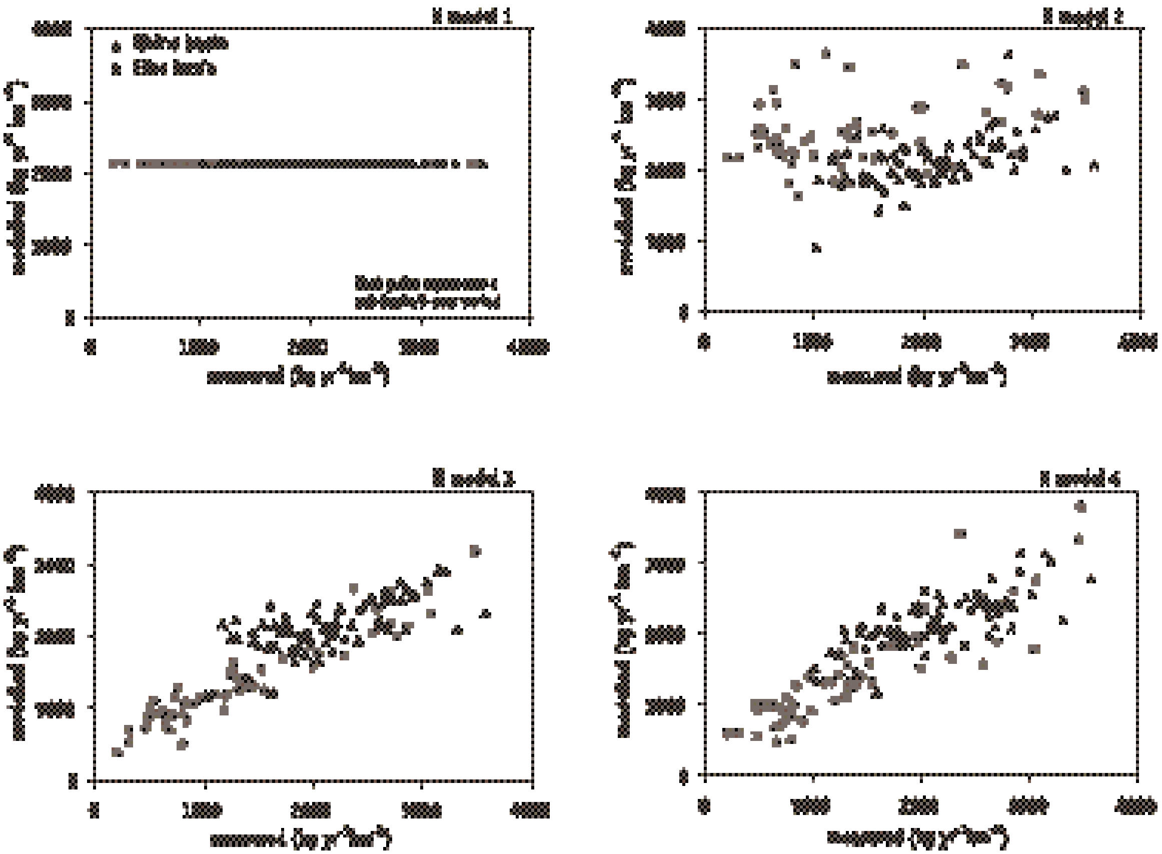

Figure 4 Measured and modelled area specific nitrogen load. The figure shows that the model performance increases when moving from model 1 to model 3. The shift to model 4 does not improve the model outcome. Similar results were obtained for phosphorus. For more details about the performance of the four models, the reader is referred to De Wit & Pebesma (2001).

nutrients through the soil/groundwater system is described as a function of lithology. Here, a different parameter value is used for regions with consolidated and regions with unconsolidated rocks. This model describes the river nutrient load as a function of nutrient emissions in the upstream basin, where the fraction of the nutrients that reaches the outlet of the river is positively related to runoff, and the ratio of transport through the soil/groundwater system is larger for regions with consolidated rocks than for regions with unconsolidated rocks.

The fourth model is a conceptual model that is described in detail in De Wit (2001). It is linked to a GIS environment. The fraction of the nutrient surplus at the soil surface that leaches, erodes, volatises or is stored in the soil/groundwater system is related to the total runoff, groundwater recharge, groundwater travel times (see De Wit *et al.*, 2000), slope, soil type, and aquifer type at each specific location (km^2). Dynamic functions are used to account for the delay of nutrient transport in the soil and the groundwater. A drain direction map is used to route the nutrients through the river network. In each river segment (1 km) a certain fraction of the nutrient load is lost, depending on the flow regime in the specific cell.

From a comparison of the models, it was concluded (De Wit & Pebesma, 2001) that although the addition of more process description is interesting from a theoretical point of view, it does not necessarily improve the predictive capability. Although the analysis is based on an extensive pollution sources-river load database (see Table 2) it appeared that the information content of this database was only sufficient to support a model of a limited complexity. However, this model (model three) successfully described most of the observed spatial and temporal variation in nutrient fluxes at the river basin scale. Moving from model one to model two to model three appeared to be improvements. The step from model three to model four did not yield better simulations of nutrient fluxes (see Figure 4).


Foto: Saxifraga, Jules Philippona

The balance between the quality of the available data and the complexity of the model had been reached.

Discussion

A challenging aspect of this study is its spatial and temporal extent; river basins of the order 10^5 km² and a time period of interest of 50 years. The pathways, and fate of nutrients in soil, groundwater, and river network are a complex function of biological, chemical, and physical processes. Nonetheless it appeared to be possible to simulate most of the observed spatial and temporal variation of nutrient fluxes in the Rhine and Elbe basins. This good result can be attributed to the following points:

• A consideration of the resolution needed to answer the research question resulted in the choice to model at a temporal resolution of five-year periods. This resolution is detailed enough to monitor the effects of large scale policy and very much simplified the analysis since short-term variation in nutrient fluxes were not considered. In the same way the use of a less detailed spatial resolution may prevent the researcher from being drawn in small scale variation that are not relevant at the scale of an entire river basin.

• The search for data at the river basin scale was more successful than expected. Due to advances in technique there is a growing amount of digital spatial data available for environmental research. Data derived from satellite images, supranational mapping programs (e.g. Corine, European soil map), uniform administrative data (e.g. Eurostat), and long term monitoring programs (e.g. water quality monitoring) continuously offer new opportunities for the modelling of environmental issues (Burrough & Masser, 1998).

• The relatively good performance of model three in the analysis of nutrient fluxes shows that most of the spatial and temporal variation in nutrient loads in the river Rhine and Elbe can be explained by an inventory of nutrient emissions and a description of the transport of nutrients as a function of two variables; precipitation surplus and lithology. Apparently these two variables are large scale 'surrogate' variables that reflect the most important processes that determine the pathways and fate of nutrients from pollution sources to river outlets.

An alternative to the method presented in this paper would have been to use existing process-based models for water and nutrient fluxes in soil, groundwater, and rivers and combine these models (using scale transfer functions) to derive a tool that can be used for the entire river basin. It would be interesting to compare the results of such a methodology with the results of the river basin models (three and four) presented in this paper. Such a comparison is however, beyond the scope of this study.

The message of this paper is that before using scale transfer functions to transpose available models and data into the policy scale one may search for data and models that match the policy scale. This appeared to be a successful approach for the analysis of long-term nutrient fluxes at the river basin scale and may also be a useful strategy for some other environmental studies. Still, for many other studies (e.g. the influence of global warming on regional flooding) the need for scale transfer functions will probably appear to be unavoidable.

Acknowledgements

Most of the work presented in this paper has been performed at the department of Physical Geography of Utrecht University with support of RIVM. Three anonymous reviewers are acknowledged for their valuable comments.

Abstract

The impact of nutrient pollution can be observed in rivers and coastal seas all over Europe. Much is known about the biological, chemical, and physical processes that determine the pathways and fate of nutrients in soil, groundwater, and surface water. However, there is a large gap between the scale at which these processes typically occur and the understanding of nutrient fluxes at the scale of entire river basins. This paper shows how the scale issue was considered for the analysis of long-term nutrient fluxes in the Rhine and Elbe river basins. Although this analysis is based on an extensive pollution sources-river load database it appeared that the information content of this database was only sufficient to support a model of a limited complexity. Nevertheless, this model successfully described most of the observed spatial and temporal variation in nutrient fluxes in the Rhine and Elbe river basins.

References

Addiscot, T.M., 1998. Modelling concepts and their relation to the scale of the problem. Nutrient cycling in Agroecosystems 50: 239-245.

Bierkens, M.F.P., P.A. Finke & P. de Willigen, 2000. Upscaling and downscaling methods for environmental research. Developments in Plant and Soil Sciences, volume 88. Kluwer, Dordrecht.

Burrough, P.A. & I.Masser, 1998. European Geographic Information Infrastructures: opportunities and pitfalls. Taylor & Francis, London.

Burt, T.P., A.L. Heathwaite & S.T. Trudgill, 1993. Nitrate: processes, patterns and management. Wiley, Chichester.

De Wit, M.J.M., 1999a. Nutrient fluxes in the Rhine and Elbe basins. Netherlands Geographical Studies (NGS): 259. PhD Thesis Utrecht University.

De Wit, M.J.M., 1999b. Modelling nutrient fluxes from source to river load: a macroscopic analysis applied to the Rhine and Elbe basins. Hydrobiologia 410: 123-130.

De Wit, M.J.M., C. Meinardi, F. Wendland & R. Kunkel, 2000. Modelling water fluxes for the analysis of diffuse pollution at the river basin scale. Hydrological Processes 14: 1707-1723.

De Wit, M.J.M., 2001. Nutrient fluxes at the river basin scale. Part I: The PolFlow model. Hydrological Processes 15: 743-759

De Wit, M.J.M. & E.J. Pebesma, 2001. Nutrient fluxes at the river basin scale. Part II: The balance between data availability and model complexity. Hydrological Processes 15: 761-775

EEC, 2000. Council Directive 2000/86/EEC of 23 October 2000 establishing a framework for Community action in the field of water policy. European Commission, Bruxelles.

Feddes R.A., 1995. Space and time variability and interdependencies in hydrological processes. International Hydrological Series. University Press, Cambridge.

Stanners, D. & P. Bourdeau, 1995. Europe's environment. The Dobris Assessment. European Environmental Agency. EEA, Copenhagen