Quantification of Non-Point Source Pollution of Surface Waters

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1 Introduction

1.1 The Problem

Although in the last few years considerable successes have been achieved in quantifying non-point source pollution of surface waters (Hamm et al. 1991, Werner and Wodsak 1994, Behrendt 1993 and 1995, Meissner 1996, Mohaupt and Behrendt 1997), the effective reduction of phosphorus and nitrogen output, as demanded by society, has not yet been sufficiently achieved. Not only the seas but also the freshwater biocoenoses suffer from nutrient inputs. Long-term studies in North America show that there is a clear correlation between nutrients (especially phosphorus) and their effects on aquatic habitats. Negative effects on the fish population have been observed as a result of higher nutrient concentrations (total inorganic nitrogen > 0.61 mgN/l and total phosphorus > 0.06 mgP/l). This suggests that the reduction in point source pollutant has not been sufficient to protect aquatic habitats and that measures to reduce the non-point nutrient yields must be taken (Miltner and Rankin 1998).

The two main causes for the unsatisfactory reduction of non-point nutrient yields are:

1. high nitrogen and phosphorus balance surplus and not effective enough measures and implementation strategies to reduce them,
2. components of the water budget (groundwater recharge, base flow, interflow, surface runoff, drainage,) and their effect on the material output from the landscape has not been regionally differentiated enough.

1.2 Objective

To be able to quantify diffuse nutrient output into waters suitable methods must be available. These should meet the following requirements with a prospective towards future river basin planning:

- concrete suggestions referring to a reduction in non-point source pollution must be made for river basin management (e.g. change of land use, management, cultivation technology),
- the procedures should be applicable with generally available data or be able to derive additional parameter values,
- the verification of action must be possible by using measured data.

To understand nutrient output processes and to derive management measures for the reduction of loads on surface waters, it is necessary to link both microscale and mesoscale studies.

2 Quantifying Non-Point Nitrogen and Phosphorus Yields from River Catchments

2.1 Nitrogen

On the microscale, the effect of varying landuse intensity on nitrogen output from the unsaturated zone of the soils can be studied using lysimeters. Linking these studies with detailed work on substance budgets in small representative catchments allows conclusions to be made on the use and retention of nutrients in the landscape unit being studied.

Lysimeter studies have proven to be valuable in hydrological studies, as they allow a relatively short-term analysis of the effects of landuse changes. At the UFZ Centre for Environment Research Leipzig-Halle intensive lysimeter studies are carried out.

To obtain more conclusive statements on long-term nitrogen transport studies in large catchment areas it is possible to combine lysimeter studies with ground-modelling systems in connection with geographic information systems (GIS). For nitrogen output studies in the Parthe catchment area east of Leipzig, the Department of Soil Science at the UFZ, together with the state environmental agency Lysimeterstation Brandis, has carried out lysimeter studies to calibrate and validate the agroecological modelling system CANDY (Franko and Oelschlaegel 1995, Franko et al. 1997). Based on climate, soil type and management data, the model CANDY is able to calculate the C and N turnover, the soil temperature and soil water content down to the depth of three metres in the unsaturated zone of the soil. It has become a very robust model after many years of intensive calibration and validation at UFZ. It can satisfactorily compute the N-output out of the unsaturated zone in the Parthe catchment given the climatic and physical ground conditions (see Fig. 1 for an example). Problems occur, however, when modelling water and material flow in the unsaturated zone in soils with impermeable layers (Krönert et al. 1999).

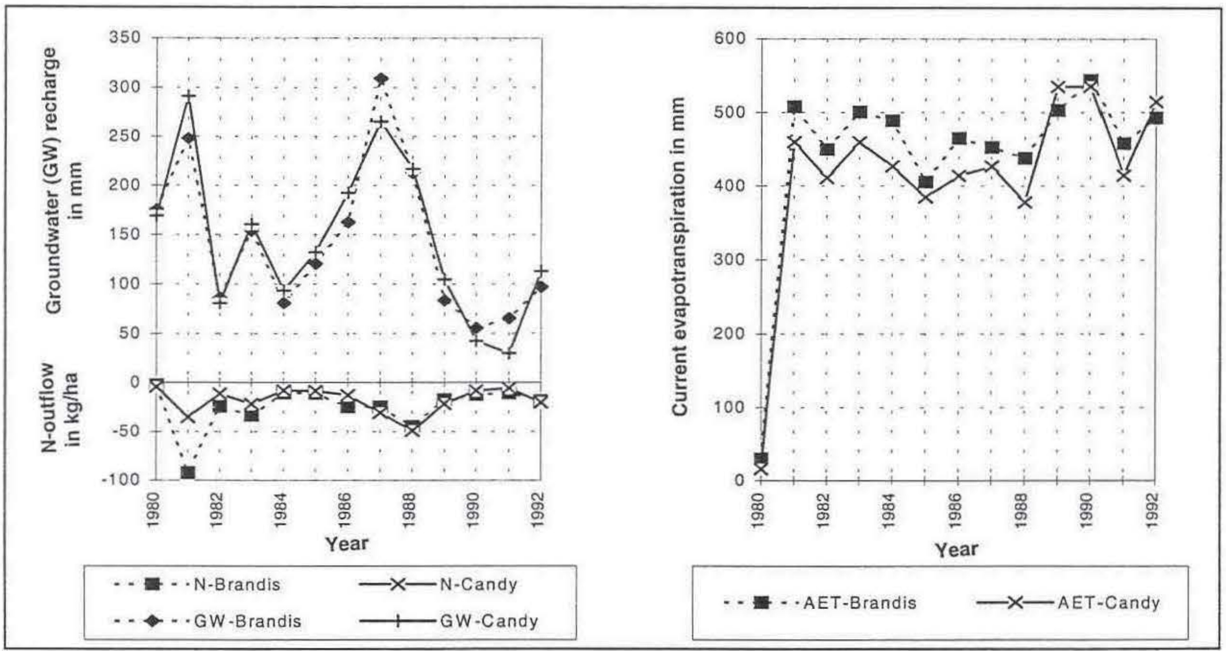

Fig. 1. Comparison of measured (Brandis) and calculated (CANDY) values; soil type is sandy loess - brown soil

The model CANDY can be combined with a GIS allowing a regionalisation of the results for larger mesoscale catchments such as the Parthe with a catchment size of 366 km^2 (Fig. 2). The average nitrogen output, calculated for the agricultural areas is 70 kg N/ha. The groundwater recharge is on average 100 mm/a. Despite low fertilisation, the results are higher than those from before German reunification (50 kg N/ha). This is due to the significantly-delayed effect of over-fertilisation in the years before 1990 (Krönert et al. 1999). These results are a superb example of how the right agro-ecological modelling system can simulate the causal relationship between climate, soil, management and nitrogen output from the unsaturated zone of soils, and the influence of changing landuse on nitrogen transport.

The present regionalisation procedure is limited to the simulation of vertical flows. There are also serious uncertainties in the description of transport and turnover processes along the path from the unsaturated zone to the surface waters. This is especially pronounced for lowlands areas. Based on process studies, areas with short flow times should be calculated separately from those with long flow durations and transport times should be placed in relationship to material transport. For this case, isotope studies in connection with conservative tracers could be used (see Fig. 3).

Tab. 1. Selected N-transport models (from Starck et al. 1997)

Criterion \ Model	CANDY	DYNAMIT	MESO-N	EXPERT-N	HERMES	MINERVA	SIMULAT	SWIM	WASMOD
Hydrology									
Soil hydrology	+	+	+	+	+	+	+	+	+
Link to groundwater	-	o	o	-	-	-	+	+	+
lateral fluxes	-	o	+	-	--	-	-	+	+
connection to channel	-	+	+	-	-	-	-	+	+
Nitrogen dynamics									
plant uptake	+	+	+	+	+	+	+	+	+
Mineralisation	+	+	+	+	+	+	+	+	+
Immobilisation	+	+	+	+	+	+	+	+	+
Denitrification	+	+	+	+	+	+	+	+	+
Nitrogen transport									
Root zone	+	+	-	+	+	+	-	-	-
To groundwater	-	-	-	-	-	-	+	-	-
To receiving water	-	-	+	-	-	-	-	+	+
Carbon cycle	+	-	+	-	-	-	+	-	+
Utilities									
Linked to GIS	+	+	+	+	+	+	+	+	+
Parameterisation tool	+	+	-	+	-	+	+	+	+

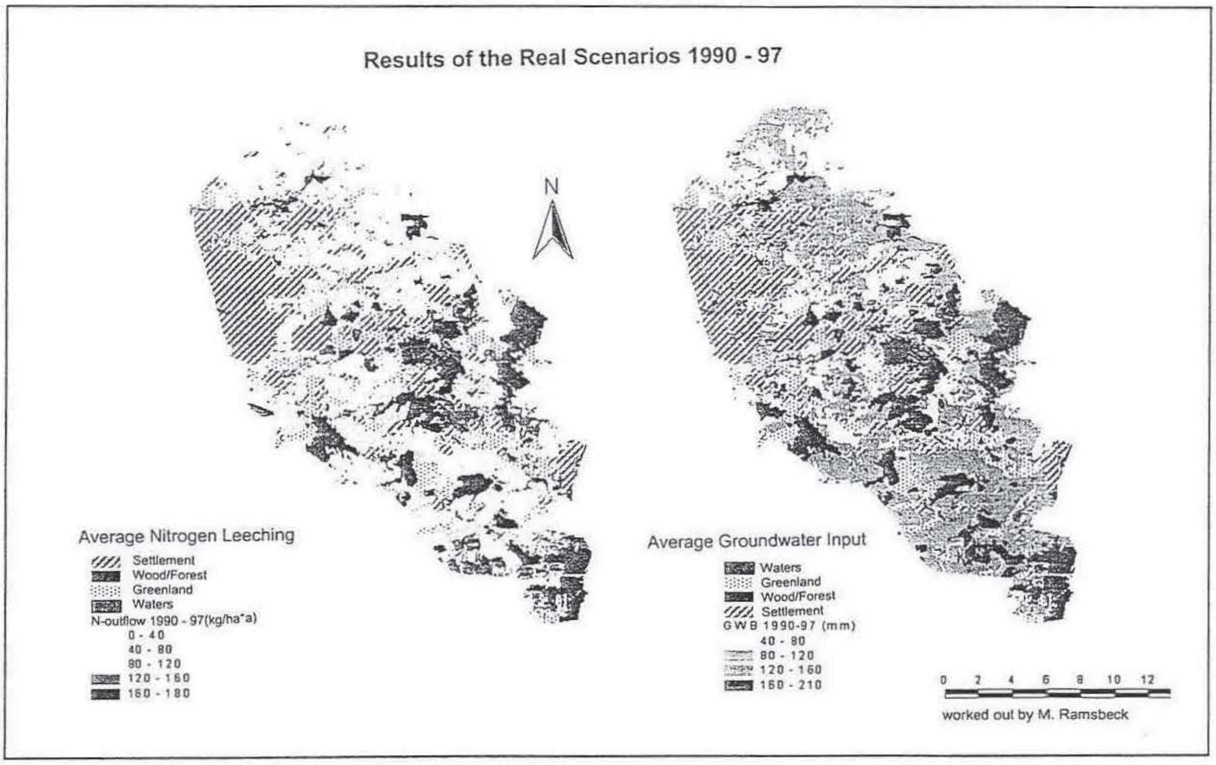

Fig. 2. Average nitrogen leaching levels & groundwater recharge in the Parthe catchment, calculated with CANDY

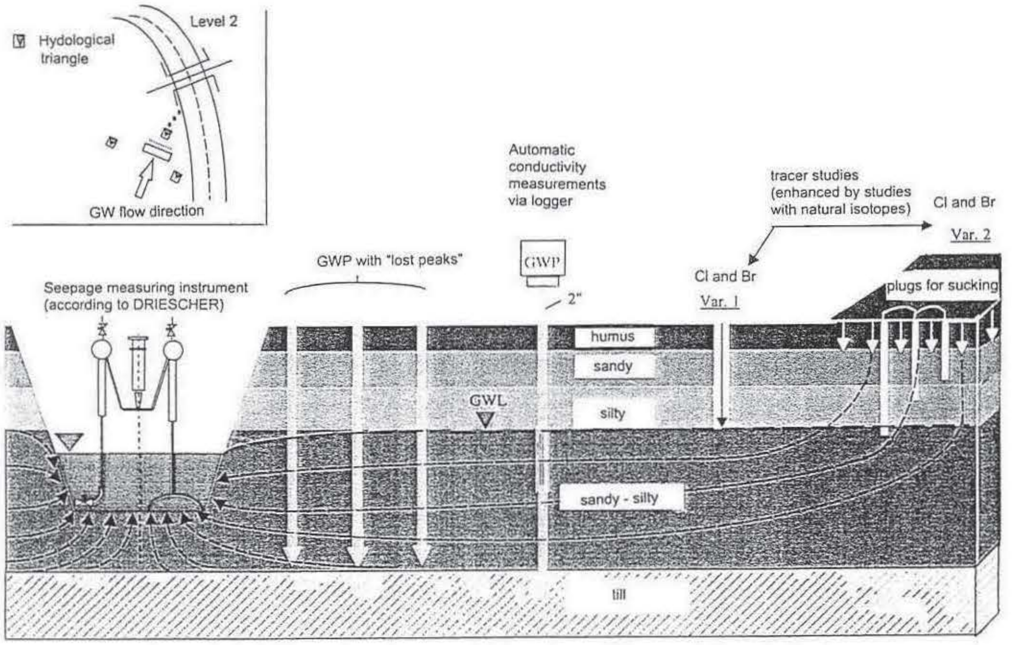

Fig. 3. Experimental study site for investigating the time behaviour of nitrogen transport in the Schaugraben catchment (from Balla and Stratschka)

At present, there is no adequate mesoscale model for dynamic N-modelling available, which completely fulfils the desired management tasks. The model systems SWIM and WASMOD/STOMOD are currently the furthest developed programmes for catchment areas, although certain components, such as the modelling of groundwater flow, are oversimplified. The UFZ is thus trying to couple models for different landscape units in its studies of the Parthe catchment. Agro-ecological modelling systems, precipitation runoff models and groundwater models are being combined in the mesoscale catchment, to calculate the substance budget that is as accurate as possible.

2.2 Phosphorus

As opposed to nitrogen, phosphorus is mainly transported into the waters viarunoff, either as particulate phosphorus (PP) bound to soil particles in connection with erosion or as dissolved phosphorus (DP). Studies by Gburek and Sharpley (1988) as well as our own studies, have shown that DP in surface runoff is generally higher than in other runoff components such as basic runoff and interflow. Exceptions are peat soils (Scheffer 1999). Thus, a requirement for the quantification of nutrient transport to surface waters is a detailed description of the different water flows. This is especially true for the surface runoff as this is the main means of transportation for both DP and PP:

In humid climates such as in central Europe, there are two main mechanisms for surface flow:

1. Horton overland flow, which occurs when the soil surface is saturated from above ground through rainfall. A requirement is that this rainfall intensity must be higher than the infiltration capacity of the top soil layer. The Horton overland flow may occur at any location in the catchment area, but preferentially on soils with low infiltration capacity such as clay soils or sealed arable soils.

2. Saturated overland flow, which occurs when the groundwater level rises and the soil becomes saturated from below. This runoff mechanism tends to occur in the proximity of streams and is the main cause of overland flow in our humid climate conditions.

As a large amount of the phosphorus is transported by runoff waters in particulate form, phosphorus erosion models must be able to adequately describe the transport of suspended substances. Unlike dissolved nutrients, the soil particles transported in the catchment are largely dependant on sediment deposition. Thus, the sediment delivery ratio, i.e. the amount of eroded soil material which is transported out of the catchment under study, diminishes with increasing catchment area size. This relationship is represented in the USDA-ARS diagram (Fig. 4). It is important to note that there is a wide range of results for a specific catchment area size, i.e. the catchment characteristics have a large influence on the sediment delivery ratio. When trying to determine particulate material runoff, emphasis is placed on the problems of soil erosion that arises on agricultural areas. Studies by Osterkamp and Toy (1997) show that channel erosion can also make up a large proportion of the soil loss from a catchment, even in humid climate regions. Furthermore, this transport process is heavily influenced by the size of the scale used. Studies in the lowlands of Denmark have shown that channel erosion can have a large share in PP transport. Kronvang (1997) shows on the basis of Cs-137 studies that this fraction was about 50% of the total soil loss in the catchment. For modelling phosphor transport the model must quantify the following three processes:

1. simulation of the overland flow, both according to Horton and saturated overland flow,
2. calculation of deposition processes of sediments in the catchment,
3. inclusion of transport processes in the channel.

The current state of mesoscale phosphorus transport modelling can excellently be shown using the model system ASGi, which was developed by the work group of Prof. Kleeberg at the military academy in Munich. It is a combination of the hydrological model WaSim, developed by Schulla (1997), and the erosion and nutrient transport model AGNPS. It is a distributed model, which can simulate both the water balance and single flood events. Based on calculated PP detachment in the catchment area, it calculates PP export in connection with the calculated overland flow. Detached P compunds can only leave the grid or subcatchment under observation when there is overland flow available. Phosphorus transport is only calculated for areas where there is overland flow. Fig. 5 shows that in the investigated catchment only a small part of the arable fields contributes to the PP yieldeven with comparatively high precipitation.

Tab 2. Selected erosion and P-transport models

Model	SEM/ SHE	ERO- SION3D	WEPP	EURO- SEM	Ann- AGNPS	OPUS	SWAT	ASGi	SWIM
Components									
Horton overland flow	*	*	*	*	*	*	*	*	*
Saturated overland flow								*	
Overland flow (total)					*	*	*	*	*
Erosion	*	*	*	*	*	*	*	*	*
Deposition	*	*	*	*	*	*	*	*	*
Crop growth			*			*	*		*
Nutrient yield					*	*	*	*	*
Time interval									
Single event	*	*	*	*		*		*	
Water balance			*		*	*	*	*	*
Area unit									
slope		*	*		*	*			
< 10 km^2	*		*	*	*	*	*	*	*
< 100 km^2					*		*	*	*
< 1000 km^2							*	*	*
Distributed model	*	*	*	*	*		*	*	*

The results presented are plausible, but still need a comprehensive comparison with measured data, so that a conclusion of this work cannot yet be made. Initial studies, however, suggest that especially the suspension-particle transport model is oversimplified.

As the overview of currently available phosphor-transport models shows (Tab. 2), there are still no models which fulfil all the main demands on mesoscale modelling.

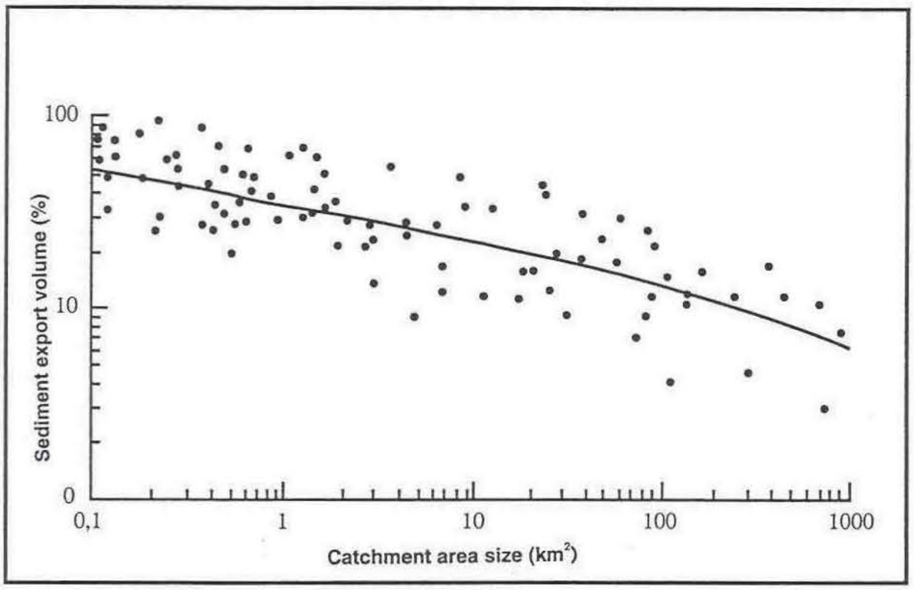

Fig. 4. Relationship between sediment delivery ratio and catchment size (from USDA-ARS)

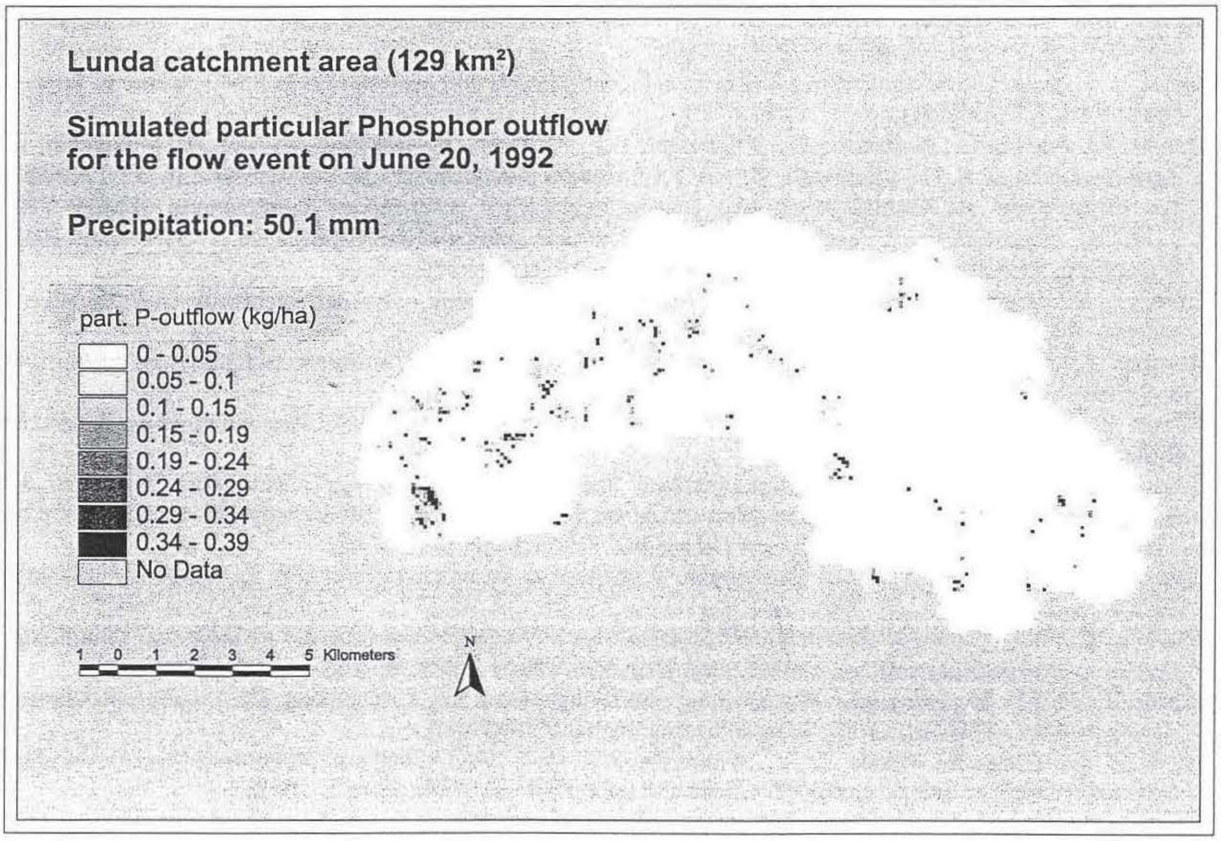

Fig. 5. Simulated particular phosphorus yields for the runoff event on June 20, 1992, in the Lumda catchment (sub-catchment of the Lahn river) in the state of Hessen, Germany

3 Conclusion

There are still large gaps in the knowledge base in understanding the processes of nutrient transport for the modelling of catchment areas in mesoscale dimensions. An additional problem is the availability of data extensive enough for use in modelling exercises. The following research requirements are needed to fill these gaps:

- For the calibration and validation of nutrient transport models, combined microscale and mesoscale studies are required.
- Deeper understanding of the temporal behaviour of nitrogen transport and turnover in representative landscape units (lateral material transport) is needed.
- Contributions from various landuses on surface runoff and phosphor transport (especially DP) still need to be determined.
- Phosphorus transport in mesoscale catchment areas with separated observations of surface runoff processes must be further studied and identified.

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