DEVELOPMENT OF A GIS-BASED MODEL FOR THE ANALYSIS OF THE DIFFUSE PHOSPHATE FLOW IN LARGE LOWLAND RIVER BASINS

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ABSTRACT
A model concept for calculating the total phosphorus output from diffuse sources through drainage, overland flow, groundwater and soil erosion is presented. It is developed by the example of the river Ems, a catchment in the lowland of North-West Germany 12,900 km^2 in size, which is characterized by high portions of bog and sandy soils with intensive agricultural usage. Large-scale livestock farming takes place in parts of this catchment.
The model works on an emissions approach, which uses area units with homogeneous P output potential for which export coefficients are calculated. These are adapted to the agricultural and hydrological conditions in the Ems catchment and thus differ from the literature's usual standard values used in connection with emissions approaches.

KEYWORDS: Diffuse P entries, water quality, modelling, catchment management, political nutrient reduction measures

INTRODUCTION
The authors are involved in the interdisciplinary research project "REGFLUD", which is part of the research programme "River Basin Management" funded by the Federal Ministery for Education and Research. REGFLUD aims at the development of policy options leading to a reduction of phosphate inputs from diffuse sources into the surface waters.
One of the areas investigated under this project is the catchment area of the river Ems, 12,900 km^2 in size, which drains the north-west German lowland into the North Sea. In the Ems catchment, bog and sandy soils are widespread, and are agriculturally used after in part extensive melioration. In the north, grassland occupies most of the catchment area, whereas arable land usage dominates in the central and southern parts, where in recent decades the arable land has been extended at the expense of grassland to increasingly cultivate silo maize. This is related to intensified animal production in parts of the catchment area, where in addition to intensive pasture usage large-scale livestock farming especially of poultry and pigs is performed. Large-scale livestock farming is particularly pronounced in the rural districts of Vechta and Cloppenburg, where the highest stocking densities of poultry and pigs in Europe are to be found (Leinweber et al. 1993). As a consequence of these developments, disproportionately high phosphate surplus is present on the soils in the catchment area and high P concentrations in flowing waters in parts of the Ems catchment area.

Within the framework of the REGFLUD project, a GIS-based model for the analysis of diffuse P outputs in macroscale river basins is to be developed. In order to develop management measures for the reduction of P outflow into surface waters in a goal-oriented manner and apply them efficiently, modelling requires a differentiation according to output pathways, the identification and localization of individual subareas with output risk within the area investigated and simultaneously the quantification of output from these subareas. This is not currently achieved by any of the existing models for the calculation of large-scale P output in lowland areas, so that the development of a new P model is required.

MODELLING CONCEPT
The model for calculating the output of total P in large river basins comprises the four pathways of drainage, overland flow, groundwater and soil erosion. For each of these pathways, site factors are specified which control the macroscale outflow, see Table 1.

Tab. 1: Factors controlling the macroscale P outflow (selection)

Overland flow	Drainage	Erosion	Groundwater
surface runoff level	drainage runoff level	erosion risk	groundwater recharge level
slope	drainage intensity	distance from surface water	soil type
risk for soil surface sealing	soil type	P fertilizer excess	depth to groundwater
waterlogging tendency	land use		P fertilizer excess
distance from surface water	P fertilizer excess		groundwater residence time
land use			
P fertilizer excess			

These factors can be quantified area-wide for the catchment of the river Ems using either appropriate data sets evolved by federal and regional state authorities, e.g. soil map 1:50,000, drainage networks, or the data sets were calculated in-house, e.g. runoff components, soil erosion risk, risk for soil surface sealing, map of drainage area. The calculation of the runoff and its components, i.e. total runoff, drainage runoff and groundwater recharge, was performed using the GROWA water balance model (Kunkel and Wendland 2002). For the area-wide calculation of soil loss risk, the universal soil loss equation (USLE) was used including the extensions recommended for the area investigated (AG Boden 2000). The Research Association for Agricultural Policy and Rural Sociology provided the P fertilizer excess values for the time series 1979-1999 calculated by the RAUMIS model.

Moreover, a database was set up with P inputs from point sources, i.e. from sewage treatment plants and industrial polluters. This information is needed to adjust the P loads determined for a gauging station for the fraction from point sources, so that the fractions from diffuse sources are exclusively included in model calibration.

The output of P through a pathway is influenced by a combination of individual site factors. For example, the output by drainage is determined by the drainage runoff level, but the soil type, culture type and level of fertilizer excess additionally also play a role (Tab. 1). The final composition of a combination and the weighting of the individual site factors are governed by the intensity of their correlative relation to the load fraction from diffuse sources. For this purpose, first of all the factors are individually tested for dependence on load. If the correlation between both quantities is sufficiently close, combinations are formed from a multitude of factors, whose composition may vary within certain limits until the strongest correlation is obtained. The result of this iterative process are combinations of site properties with a significant correlation to the load from diffuse sources, which can be mapped as areas using GIS. Due to the unambiguous relation between the share of an area in the catchment area and the load from diffuse sources, the areas formed by the combination of site properties will be termed area units with homogeneous P output potential in the following. For each pathway, a multitude of such area units can be determined.

For each area unit with homogeneous output potential, export coefficients are then calculated by multiple regressions between the load fraction from diffuse sources and the area portions of the units in the catchments. In doing so, retention is taken into account, which is calculated by classes as a function of the runoff volume and the catchment area size of a water quality gauging station (see Behrendt et al. 1999). The output through a pathway is then obtained from the sum of the products of area units with homogeneous P output potential and the export coefficients determined for them across all catchment areas available (eq. 1):

$$O_{P_i} = \sum_{ij=1}^{n} EC_{ij} \bullet HU_{ij} \qquad (1)$$

with O_{P_i} = P total output through pathway P_i, EC_{ij} = export coefficient of an area unit with homogeneous P output potential ij and HU_{ij} = area unit with homogeneous P output potential ij.

The steps in deriving the area units and export coefficients are performed for all output pathways. The complete P output from diffuse sources through the pathways of drainage, groundwater, overland flow and erosion is then obtained from equation 2.

$$L_{total} - L_p = \sum_{i=1}^{n} P_i \left(\sum_{ij=1}^{n} EC_{ij} \bullet HU_{ij} \right) \qquad (2)$$

with L_{total} = total load, L_p = load from point sources, P_i = output pathways, EC_{ij} = export coefficient of a area unit with homogeneous P output potential ij and HU_{ij} = area unit with homogeneous P output potential ij.

Only one pathway is regarded as essential per area unit. Thus, for example, drainage reduces both the groundwater recharge rate and the surface runoff, so that overland flow and erosion risk are clearly reduced. Modelling of the P output with the aid of the derived export coefficients is followed by a validity check of the calculated inputs using measured values.

SELECTED RESULTS AND DISCUSSION

Due to melioration measures performed in the Ems catchment area for more than 50 years, drainage is a potentially important pathway for total phosphorus. In the following, the procedure already outlined will be applied to the drainage output pathway.

In order to derive the area units, the location of drained areas must be known. In contrast e.g. to the United Kingdom, where drainage maps were already compiled by state agencies decades ago (Robinson 1990), this information is not available area-wide in North-West Germany. Therefore, a methodology was developed for determining the drained fraction of the area under agricultural use. First of all, large-scale drainage maps of areas in the Ems river basin were procured. For these areas, comparisons with the digital soil and land use data and with drainage networks were performed in order to find out for which combination of site properties drainage of an agriculturally used area can be inferred. Moreover, data were used to exclude drainage of agricultural areas, e.g. nature reserves, peat mining fields. With the aid of the plans of melioration measures realized and by means of a few field inspections, the estimation accuracy was verified for more than 30 areas.

In order to derive area units for the description of P output by drainage, in principle, combinations come into consideration which distinguish between raised bog, fen, deep-ploughed bogs, marshy, sandy and cohesive mineral soils. Added to this are factors of influence such as soil type, land use, drainage runoff level, drainage intensity and the level of fertilizer excess. These site factors were first examined for their relation to the load from diffuse sources, revealing strong dependencies on raised bog, fen and deep-ploughed bog soils, but also on land use and drainage runoff level (Figs. 1 and 2). No significant correlations to the area fractions of sandy soils and cohesive mineral soils were found and no correlations to marshy soils. The uncertain estimation of annual loads in regions influenced by tides may play a role here.

After having verified the site factors listed in Table 1 for significant relationship to the load, combinations were formed from the site factors for renewed verification. The correlations between the fen and raised bog area units under agricultural use are shown in Figures 2 and 3. In total, five area units with homogeneous P output potential were formed to cover the output by drainage specified in Table 2. The location of the five area units with homogeneous P output potential is shown in Figure 3.

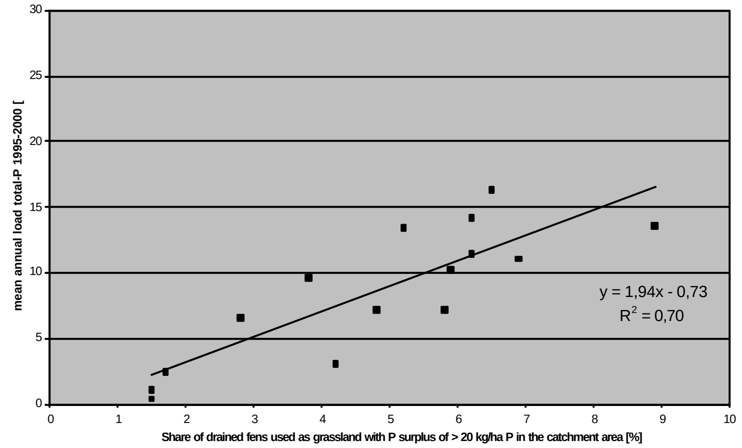

Fig.1: Correlation between area unit 1 (drained fen soils) and mean annual load from diffuse sources

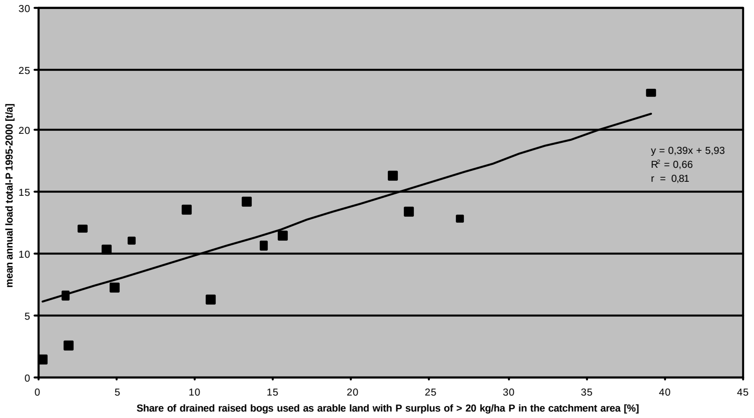

Fig. 2: Correlation between area unit 2 (drained raised bog soils under agricultural use) and mean annual load from diffuse sources

Table 2: Area units with homogeneous P output potential to cover the output by drainage in the part of the Ems catchment area not influenced by tides

Unit No.	Characteristics
Unit 1	Drained fen soils under grassland use with medium fertilizer excess
Unit 2	Drained raised bog soil under agricultural use with medium fertilizer excess and drainage runoff level >100 mm/a
Unit 3	Drained raised bog soil under grassland use with medium fertilizer excess and drainage runoff level >100 mm/a
Unit 4	Deep-ploughed bogs or sand covered bog cultures under agricultural use with medium fertilizer excess
Unit 5	Raised bog with peat mining

By means of multiple regression it is possible to determine export coefficients for the five area units for which significant correlations to the load from diffuse sources were identified. The calculated coefficients are in the range of the results from field studies in northern Germany. The output of P from raised bogs with peat mining and without cultivation is specified by Foerster and Neumann (1981) as 1.5 kg/(ha*a), whereas 1.3 kg/(ha*a) is calculated. From raised bog areas under agricultural and grassland use, between 0.6 and 36 kg/(ha*a) are washed out by drainage, the major portion of the studies specifying outputs between 3 and 12 kg/(ha*a) and the values for agricultural usage being generally higher (Kuntze and Scheffer 1991, Blankenburg 1983). This is in conformity with the export coefficients calculated for the output from raised bog soils under agricultural use, 4.2 kg/(ha*a), and 3.6 kg/(ha*a) for grassland usage. For deep-ploughed bogs, 50-70 % of the outputs are recorded from agriculturally used raised bog cultures (Kuntze and Scheffer 1991). Kuntze and Vetter (1980) measured 6 kg/(ha*a) in young deep-ploughed bogs, but they assume a decrease with increased ageing. The calculated output is 2.9 kg/(ha*a). Outputs from fen soils under grassland use are clearly lower than those from raised bog soils and are normally estimated to be 0.5-3 kg/(ha*a) (Blankenburg 1983). For the area unit "drained fen soil under grassland use with medium fertilizer excess" a P output of 1.1 kg/(ha*a) was determined.

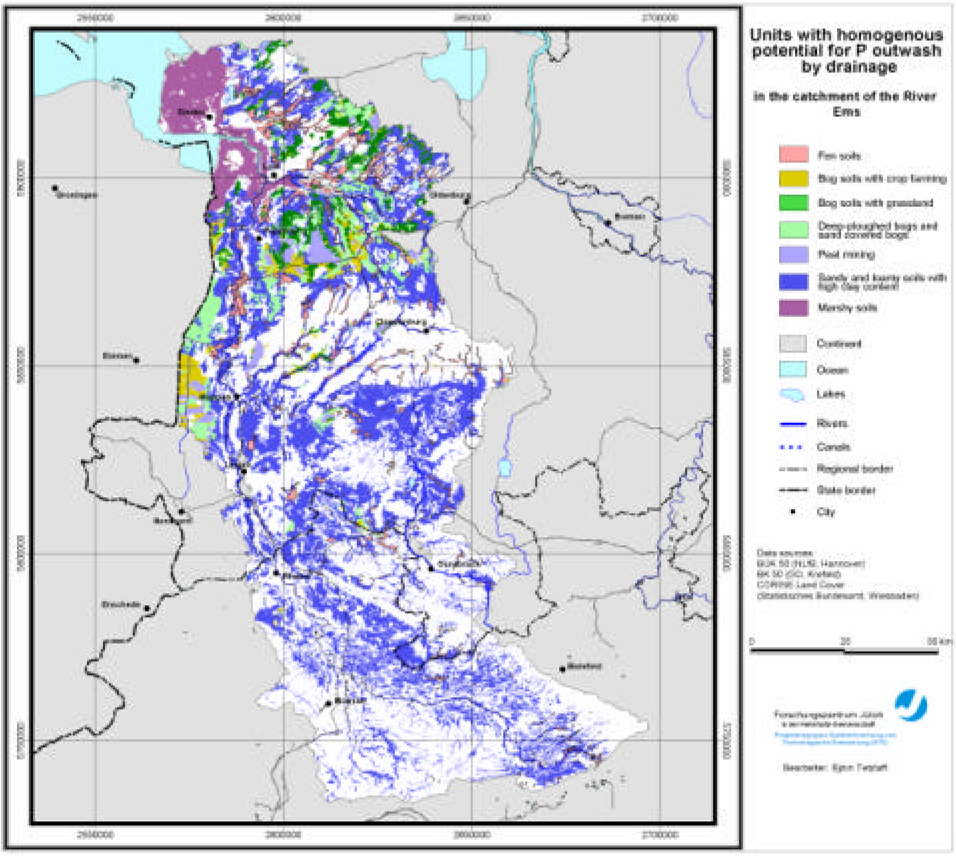

Figure 3: Location of the area units of relevance for P output by drainage in the Ems catchment

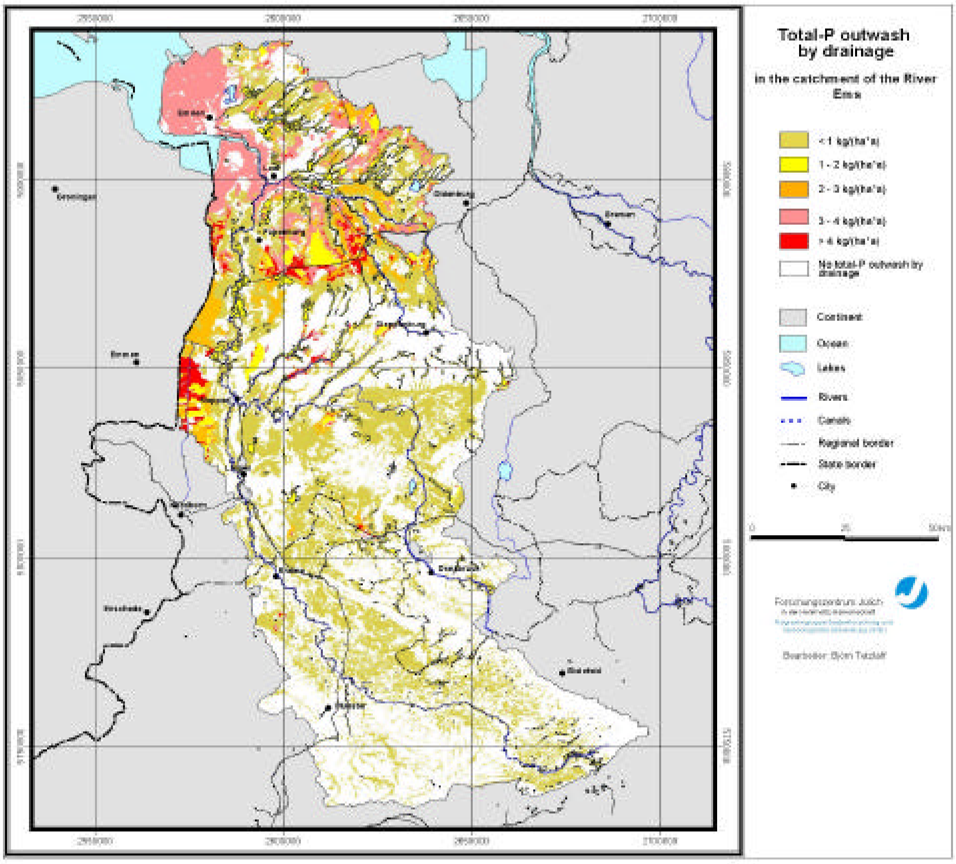

Figure 4: Calculated output of total P by drainage

For artificially drained marshy soils and sandy resp. cohesive mineral soils, e.g. gleys, no units were formed since even widely differing combinations of site properties did not permit any units with significant relation to the load to be derived. In the case of the marshy soils located in the north of the Ems catchment area, this is certainly also due to tidal influence which makes a precise estimation of the loads difficult.

Nevertheless, these soil types exhibit an output potential and should not be neglected in terms of area size, since they account for 38 % of the drained agricultural land. For this reason, two additional area units were formed covering marshy soils, on the one hand, and mineral soils, on the other. Their output potential was estimated on the basis of literature surveys (Dils and Heathwaite 1999, Lennartz and Hartwigsen 2001). With reference to the studies by Neuhaus (1991) an export coefficient of 3.25 kg P/(ha*h) was fixed for P output from marshy soils and of 0.1 kg P/(ha*h) for output from mineral soils (Foerster and Neumann 1981, Scheffer and Kuntze 1991). The location of the two units formed additionally can also be seen from Figure 3.

Figure 4 shows the result of the calculation of the P output by drainage on the basis of area units with homogeneous P output potential and using calculated export coefficients and literature values for sites with similar properties. In Figure 4, the agriculturally used raised bog soils and the marshy soils clearly stand out as areas with a high output potential with respect to drainage. Medium outputs are to be expected from deep-ploughed bogs, whereas the outputs from drained sandy and cohesive mineral soils and from fen soils under grassland use are to be assessed as low. An effective development of management measures for a reduction of output by drainage should therefore primarily concentrate on the raised bog and marshy soils.

CONCLUSIONS

On the basis of the area units derived to describe the P output by drainage, a calculation of area-differentiated export coefficients can be performed, which are adapted to the special situation in the Ems catchment area. In this way, a more precise calculation of the P output can be expected than has been possible to date using typical standard values. Nevertheless for areas with tidal influenced marshy soils and sandy resp. cohesive mineral soils export coefficients have to be taken from field study results. But above all the localization of subareas within a catchment area is possible, for which the output potential for P can be specified in a differentiated manner. This can be taken into account in deriving management measures.

In the next step, further area units are formed for the pathways of overland flow, groundwater and soil erosion and export coefficients also derived for these in order to complete the calculation of the output of total P from diffuse sources in the catchment area of the river Ems.

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