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iEMSs 2008: International Congress on Environmental Modelling and Software
Integrating Sciences and Information Technology for Environmental Assessment and Decision Making
4th Biennial Meeting of iEMSs, http://www.iemss.org/iemss2008/index.php?n=Main.Proceedings
M. Sànchez-Marrè, J. Béjar, J. Comas, A. Rizzoli and G. Guariso (Eds.)
International Environmental Modelling and Software Society (iEMSs), 2008

Large-scale modelling of P-inputs from point and diffuse sources in German river basins

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Keywords: P-inputs, eutrophication, river basin management, EU-WFD

Mean annual P-inputs from diffuse and point sources in large river basins can be quantified with the MEPhos model. Its emission approach is described, which distinguishes between both eight different input pathways (municipal waste water treatment plants, industrial plants, combined sewer overflows, rainwater sewers, artificial drainage, erosion, wash-off, groundwater-borne runoff) and various types of critical source areas named phosphotopes.
Then, the results of a model application to two large-scale river basins are presented and discussed. The river basins (ca. 12,500 km²) each show contrasting natural conditions, land use patterns as well as population and industry densities. Total P-emissions from each river basin range around 1,600 tonnes per year but the importance of sources varies significantly. While in the Ems river basin 87 % of all P-inputs originate from diffuse sources, their portion achieves only 32 % in the Rhine river sub-basin. Due to the fact that diffuse entries are mainly made up by erosion (11 % of all P-inputs), measures for tackling P-inputs will aim at erosion prevention and sediment retention.

1. INTRODUCTION

As the inventory of the EU-water framework directive (EU-WFD) revealed in 2004, high nutrient inputs are a major concern for most inland and coastal waters in Germany. As a result the “good status” will not be achieved for 62 % of rivers and 86 % of coastal waters (BMU 2005). To improve water quality until 2015 the EU-WFD demands the drawing-up of detailed river basin management plans and programmes of measures until 2009 (EC 2000). This provokes a demand for instruments and models applicable at the river basin scale for the quantification of nutrient inputs (actual state) and for the prediction of potential future states. Model applications should aim at the localization of critical source areas within river basins as a basis for proposing reduction measures which are adapted to site properties. This requires modelling approaches differentiating between sub-areas and input pathways.

The authors were involved in an interdisciplinary research project named ‘REGFLUD’ commissioned by the Federal German Research Ministry (BMBF) and finished in 2005. REGFLUD was part of the BMBF-research programme “river basin management”. The aim of the project was to develop policy reduction measures for tackling eutrophication in German river basins. In this context the pathway- and area-differentiated phosphate model MEPhos was developed (Tetzlaff 2006, Tetzlaff et al. 2008a). The model was applied to two study areas, the catchments of the River Ems (12,900 km²) and parts of the River Rhine (12,160 km²), located in the north western part of the Federal Republic of Germany. Both study areas are of similar size but show contrasting natural conditions. The Ems catchment is mainly characterized by its lowland situation with sandy and boggy soils under intensive agricultural use. In accordance with the relatively low soil fertility intensive animal husbandry is conducted with partly more than three livestock units per hectare. The investigation area Rhine is dominated by upland conditions with forest and grassland use. Arable land use is restricted to the flat Rhenish bight with fertile loess soils. Furthermore the area comprises sub-regions with high population and industrial densities.

2. GENERAL DESCRIPTION OF THE P-MODEL MEPHOS

The empirical model MEPhos was developed to calculate mean annual total-P inputs from point and diffuse sources to surface waters (Tetzlaff 2006). The model distinguishes between eight different pathways (artificial drainage via moles, pipes or channels), groundwater-borne runoff, erosion, wash-off, rainwater sewers, combined sewer overflows, municipal waste water treatment plants, industrial effluents) as shown in figure 1.

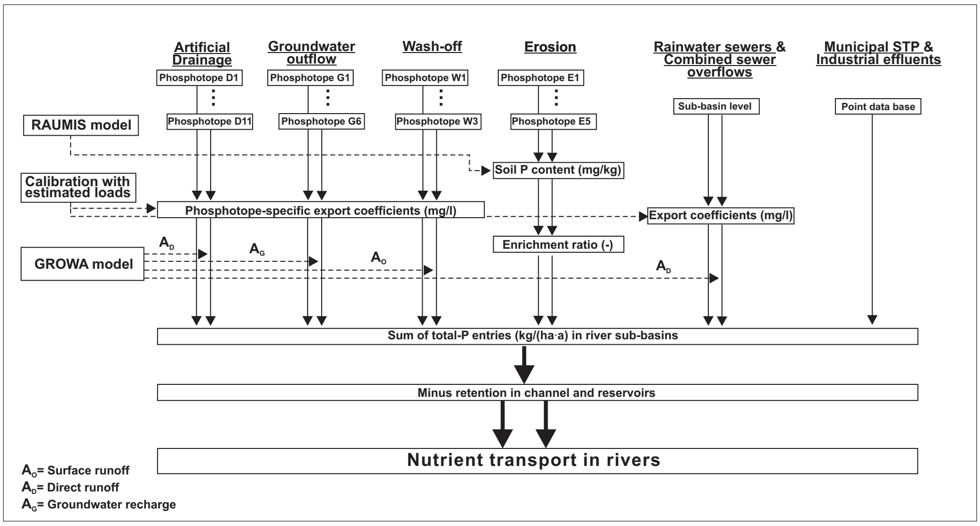

Figure 1. Overview of the MEPhos model

The model approach for each pathway depends on the resolution of input data. Modelling diffuse P-inputs via artificial drainage, groundwater-borne runoff, erosion and wash-off is performed area-differentiated, based on phosphotopes as discontinuous source areas. Phosphotopes are regarded as homogeneous types of sub-areas, defined by a set of different parameters. The coincidence of several parameters on the same area controls the emission potential. For each pathway several phosphotopes are defined (figure 1). The parameters controlling the mean annual P-input from diffuse sources are described in Tetzlaff et al. (2008a) and can be quantified for macroscale investigation areas with already available data sets from federal or state authorities (table 1). Phosphotopes are processed in GIS by classification and overlaying of data sets. This process is explained in greater detail in Tetzlaff et al. (2007b). For modelling diffuse P-emissions via artificial drainage, groundwater-borne runoff, erosion and wash-off 25 different phosphotopes are derived in total (figure 1). In order to model P-inputs to surface waters calibrated export coefficients (unit mg/l) are assigned to all phosphotopes instead of using standard literature values. For determining the pathway-related mean annual runoff components the MEPhos model is coupled to the water balance model GROWA (Kunkel and Wendland 2002). This model provides data about the mean annual sums of surface runoff, drain flow and groundwater runoff needed as transport media for the pathway-differentiated P-modelling (figure 1).

Table 1: Data sets for modelling and validating P-inputs to surface waters

Data sets	Spatial resolution and origin
Mean annual sums of surface runoff, drain flow and groundwater recharge	Results of water balance model GROWA (Grid data, 50·50 m²)
Soil map and parameters (depth of ground-water table, perching water influence, soil water content, clay content, USLE factors)	Soil map 1:50,000 (Geological Surveys)
Land use	CORINE (Federal Statistical Office)
Digital Terrain Model	DTM 10·10 m² and 50·50 m² (State agencies for Land Survey)
Livestock density	Statistical data for municipalities (State statistical offices)
Nutrient balance P	Results of the agro-economic model RAUMIS
Agricultural land with artifical drainage	Derivation procedure described in Tetzlaff et al. (2008b)
River network	ATKIS-DLM 25 (State agencies for Land Survey)
River discharge data	Gauging station network run by state agencies
Surface water and groundwater quality data	Sampling station network run by state agencies
Point data on effluents from municipal sewage treatment plants and industry	Data base from state agencies
- Data about stormwater retention ponds and grade of connection to waste water systems - Reservoir data	Data base from state agencies, literature

Due to the availability of coarser data for modelling mean annual P-inputs via rainwater sewers and combined sewer overflows, no phosphotopes can be derived. Therefore, these emissions are modelled integratively for river sub-basins with sizes between approx. 50 and 500 km² (figure 1). P-inputs from municipal waste water treatment plants and from industry are modelled separately for each site using point data from monitoring data bases from environmental state agencies (figure 1, table 1, equation 1).

$$F_{KA} = \frac{1}{n} \cdot \sum_{i=1}^{n} (Ci_{P_{ges}} \cdot AWM) \quad (1)$$

FKA = Mean annual P-input from MWWTP [t/a]; AWM = mean annual plant discharge [m³/a]; CiPges = mean concentration of total-P in plant discharge [mg/l] for measurement i; n = number of measurements i per year

After calculating mean annual P-inputs via all eight pathways the emissions are summed up for river sub-basins related to water quality gauges (figure 1). Then the mean annual load of an upstream sub-basin is added and the P-retention is subtracted (equation 2). In MEPhos P-retention in both running and standing waters is considered. This enables a validation of the modelled P-loads by comparison with mean annual P-loads estimated from measured water quality and discharge data.

$$F_{bas} = \left[\left(\sum F_{dr} + \sum F_{gw} + \sum F_{wash} + \sum F_{eros} + \sum F_{rws}\right) + \sum F_{mwwtp} + \sum F_{id} + \sum F_{cso}\right] + F_{upbas} - R_r - R_s \quad (2)$$

F_{bas} =estimated load for river sub-basin, F_{dr} = P-inputs via artificial drainage, F_{gw} = P-inputs via groundwater-borne runoff, F_{wash} = P-inputs via wash-off, F_{eros} = P-inputs via erosion, F_{rws} = P-inputs via rainwater sewers, F_{mwwtp} = P-inputs from municipal waste water treatment plants, F_{id} = P-inputs from industrial effluents, F_{cso} = P-inputs via combined sewer overflows, F_{upbas} = P-load of an upstream river sub-basin, Rr = P-retention in running waters, Rs = P-retention in standing waters

The retention of P during the transport phase in surface waters is modelled separately for running and standing waters. Behrendt and Opitz (2000) have developed an approach to describe the retention in rivers integratively, which is applied in the MEPhos model. The increased P-retention occuring e.g. in reservoirs due to reduced flow velocity, increased travel time as well as higher sedimentation rate is modelled according to Molot and Dillon (1993).
In the following chapter an example will be given about modelling erosion-related P-inputs with MEPhos.

3. EXAMPLE: MODELLING DIFFUSE P-INPUTS VIA EROSION

The controlling factors for P-inputs to surface waters via erosion are soil loss from arable land within river catchments, sediment delivery ratio, P-content in the top soil as well as by P-enrichment during the erosion process. Diffuse P-inputs to surface waters via erosion are modelled after equation 3. This equation follows in general the universal soil loss equation adapted to German conditions by Schwertmann et al. (1990), but implies several modifications in order to take into account the high sensitivity of relief features.

$$E = SSF \bullet \left[(R \bullet K \bullet LS \bullet C) \right] \bullet SDR \bullet PC \bullet \frac{P_S}{P_{OA}} \quad (3)$$

E = mean annual P-inputs via erosion [kg/(ha·a)]; SSF=slope shape factor after Prasuhn and Grünig (2001); R = rain erosivity factor [N/(h·a)]; K = soil erodibility factor [t·h/(ha·N)]; LS = combined slope steepness and slope length factor after Moore and Wilson (1992) [-]; C = crop and management factor [-]; SDR = sediment delivery ratio [%/100]; PC = content of total-P in the top soil [mg/kg]; ER = enrichment ratio [-]; P_S = P-content of suspended matter given at high discharge levels [mg/kg]; P_{OA}= P-content in the top soil of sediment delivering arable land [mg/kg]

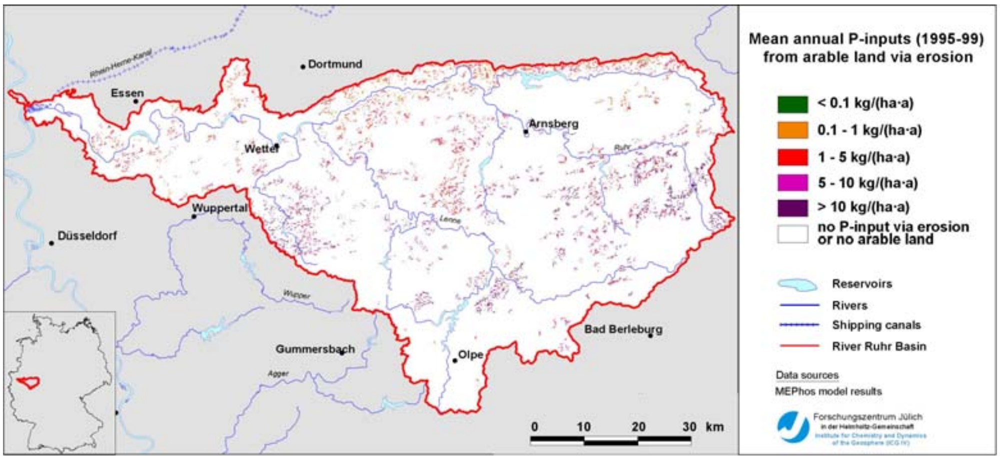

Figure 2. Example for MEPhos results for modelling mean annual P-inputs (1995-1999) via erosion: the River Ruhr catchment

With regard to proposals for efficient eutrophication reduction measures modelling of diffuse P-inputs by MEPhos has to be performed area-differentiated, i.e. the eroding arable land area has to be disaggregated. Therefore, phosphotopes for modelling erosion inputs are delineated, they represent source areas for the release of sediment and particulate-P and are made up by erodible arable land which is at the same time hydraulically connected to the network of rivers and flow paths (Tetzlaff and Wendland 2007). These connections are provided by flowpaths determined by the relief. Such morphological flow paths are modelled using a highly-resolved digital terrain model and the algorithm "D infinity" (D∞, Tarboton 1997). Then, those flow paths, which are connected to the river network, are selected and buffered with stripes of 2·30 m width, according to findings of Fried et al. (2000). Only those sub-areas contained in the 60 m stripes are regarded as hydraulically connected. Then, phosphotopes for modelling P-inputs via erosion are derived by intersecting the data sets of erodible arable land with the buffered network of flow paths and rivers. Depending on their erosion potential five different phosphotopes are distinguished (Hydraulically connected arable land with erosion potential of <1 t/(ha·a), 1-5 t/(ha·a), 5-10 t/(ha·a), 10-15 t/(ha·a) and >15 t/(ha·a)).

According to equation 3, the level of particulate P-inputs results not only from the sediment delivery to surface waters, but also from the P-content of the top soil and the enrichment ratio. The calculation of the total-P content in the top soil is based on P-surpluses and clay content following Behrendt et al. (1999). P-surplus is modelled on a county level employing the agro-economic model RAUMIS developed and run by the German Federal Agricultural Research Centre (IAP and FAL 1996), the clay content is given by soil maps on a scale of 1:50,000 (figure 1, table 1). An enrichment ratio has to be determined in order to consider the selective effect of water erosion. For this a method is employed in the MEPhos model requiring measured water quality data, above all, about the P-content of suspended matter (Behrendt et al. 1999). The enrichment ratio for river sub-catchments is given by the quotient of the P-content of suspended matter given at high discharge levels (PS) and the P-content in the top soil of sediment delivering arable land (POA), as shown in equation 3. More details about the erosion modelling routine of MEPhos can be found in Tetzlaff and Wendland (2007a).

An example for the model results achievd by using equation 3 is given in figure 2. Because of the high spatial differentiation a clipping of the map for the River Ems and Rhine sub-catchments is presented, concentrating on the River Ruhr catchment (4,485 km²), being a tributary of the River Rhine. Inputs of total-P vary between less than 0.1 and more than 10 kg/(ha·a). Erosion-related P-inputs are characterised by a small spatial extent of sediment delivery areas with highly differing input levels (figure 2). The small spatial extent of the phosphotopes results from the disaggregation of erodible arable land, its intersection with buffered flow paths and the application of highly-resolved data sets, above all the digital terrain model with a resolution of 10·10 m². High erosion-related P-inputs are to be found mainly in sub-regions with steep slopes and widespread arable land use (figure 2). For the entire River Ems catchment mean annual P-inputs of 34 t/a or 2.94 kg/(km²·a) are modelled, the results for the entire River Rhine sub-catchment are significantly higher with 234 t/a or 14.8 kg/(km²·a). The difference reflects the contrasting natural and land use conditions between the two areas.

4. TOTAL P-INPUTS FROM DIFFUSE AND POINT SOURCES AND VALIDATION OF MODEL RESULTS

After modelling mean annual P-inputs via all eight pathways diffuse and point source emissions can be summed up. This leads to mean annual total loads for the period 1995-1999, which amount to 1,666 t/a in the River Ems catchment and to 1,574 t/a for the River Rhine sub-catchment. Figures 3 and 4 show the relevance of all eight pathways for the mean P-input. In the entire River Ems catchment diffuse P-emissions account for 87 % of all P-inputs to surface waters. It can be stated for almost all of the 56 sub-catchments that diffuse inputs dominate and that the pathway "artificial drainage" is of highest importance in this lowland river catchment. The percentage of inputs via artificial drainage differs between 16 and 89 % in total, it is above 50 % in most sub-catchments (figure 3). The highest loads from non-point sources are modelled for the lower reaches of the River Ems and its tributaries, which correspond with the decreasing population density and the increasing intensity of agricultural activities from south to north. Due to the origin of these high loads from artificially drained agricultural land, i.e. as mainly soluble reactive and therefore highly algae-available P, the agricultural activities on raised bog soils result in a tremendous local and regional eutrophication potential for surface waters. A significant reduction of P-fluxes to the receiving coastal waters due to P-retention during fluvial transport cannot be expected due to the short distance between the source areas and the mouth of the River Ems. As a consequence, also the wadden sea receives a high phosphate input from diffuse sources causing increased eutrophication risks in coastal waters at least, where no limitations due to the nitrogen content exist.

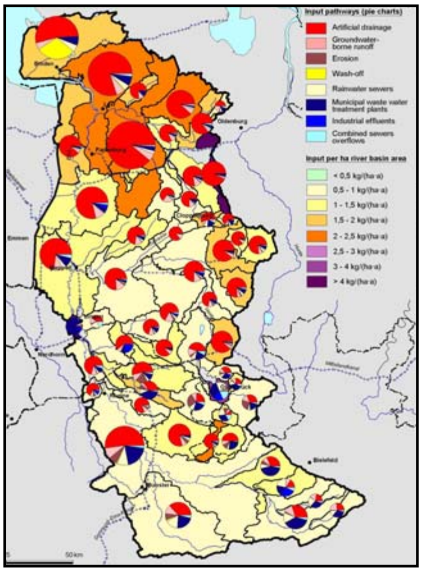
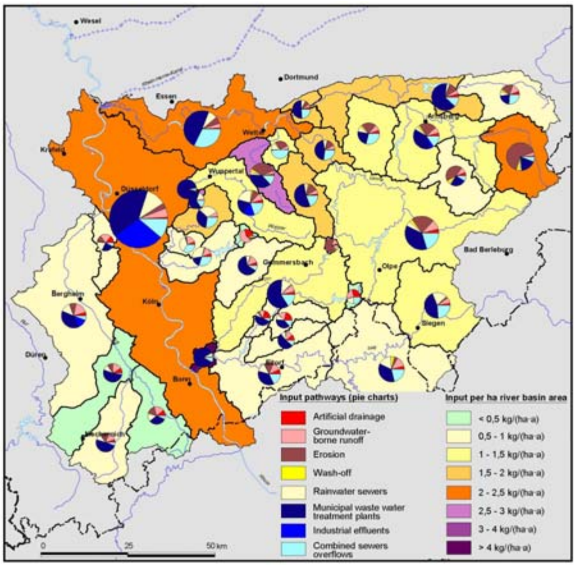

Figure 3. Mean annual P-inputs (1995-1999) of sub-catchments and relevance of pathways for the River Ems catchment (left)

Figure 4. Mean annual P-inputs (1995-1999) of sub-basins and relevance of pathways for the River Rhine sub-basin (right)

While the mean total P-inputs (1995-1999) in the investigation area Rhine equal those in the Ems area, the mean relation between diffuse and point source inputs of 32:68 differs significantly (figure 4). The main reasons are the high densities of population and industry, above all at the River Rhine and along the lower reaches of the River Ruhr. High emissions via combined sewer overflows play an important role, too. When the MEPhos modelling results are examined for river sub-catchments, areas where diffuse emissions are a major concern, are revealed also for the investigation area Rhine (figure 4). They are located in the upper reaches of the Rivers Erft and Ruhr, i.e. in the south-west and east of the investigation area. As a result of arable land use on steeper slopes, partly on loess soils, soil erosion is responsible for these increased diffuse P-loads.

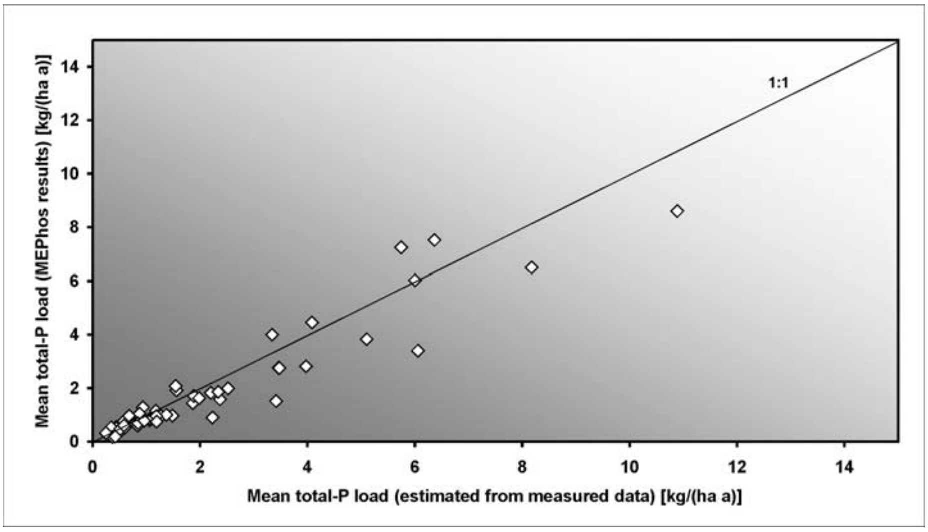

Figure 5. Validation of MEPhos modelling results against mean annual loads (1995-1999)

The validity of the MEPhos modelling results (1995-99) is checked by a comparison with mean annual P-loads estimated from measurements of daily discharge and monthly total-P-concentration following the OSPAR method (OSPAR Commission 1998). When selecting the gauging stations, attention was paid to achieve a great variability with respect to basin size, natural conditions and population density. Furthermore, the extent of gaps in the time series of the measured data should be as small as possible. These requirements are fulfilled for 32 gauge-related sub-catchments in the River Ems basin and 24 sub-catchments in the River Rhine sub-basin. The selected sub-catchments are sized between approximately 50 and 500 km². The general validation process is explained in chapter 2. Figure 5 shows the validation results.

The mean annual P-loads differ between approx. 0.1 kg/(ha·a) and approx. 11 kg/(ha·a) (figure 5). In general, the diagram shows a good correlation between loads estimated from measurements and modelling results. The mean deviation amounts to 7.3 %, the coefficient of determination reaches 89 %. For eight sub-catchments the deviation is below 10 %, for 20 of 56 sub-catchments below 20 %. Errors in this order of magnitude are within the usual variation range of empirical models. Although the most recent data sets with the highest spatial resolution and information content were used in this project, unavoidable measuring and interpolation errors are undoubtedly involved. Systematic errors causing the deviations could not be identified. Because of the restricted data availability in the field of urban drainage and sanitation, the model routines for the quantification of mean annual P-inputs via rainwater sewers and combined sewer overflows have to get by on a limited number of parameters. With respect to these restrictions the model results can be regarded as valid.

5. CONCLUSIONS AND MANAGEMENT OPTIONS FOR TACKLING EUTROPHICATION

As outlined in chapter 1, an overall objective of the EU-WFD is to achieve the good status of surface waters. Important tools in this context are cost-effective measures for the reduction of nutrient inputs (UBA 2004). Based on valid model results, management options for the reduction of eutrophication can be proposed and scenarios calculated. With respect to cost-effective measures the focus for reduction has to be on “hot spots” as priority areas, i.e. critical source areas with small spatial extent and high emission. From the area-differentiated MEPhos model results it can be concluded that in the River Rhine sub-catchment P-inputs via erosion from arable land with soil loss of >15 t/(ha·a) sum up to approx. 24 % of all diffuse inputs, originating from less than 1 % of the catchment area. Published results from field studies were used to assess the level of sediment input reduction to be achieved by various protection measures. The MEPhos results were then reduced due to these findings. On-site and off-site erosion protection measures like mulching combined with riparian buffer stripes would lead to a reduction from 87 t/a to 39 t/a. Converting these highly eroding arable lands into grasslands would reduce the P-inputs by 98 %. But due to the fact that in the River Ruhr catchment a series of reservoirs act as sediment sink and due to the dominance of point sources, tackling diffuse sources in the River Rhine sub-catchment has only little effect on the general water quality situation, especially in the lower reaches, where water quality problems due to eutrophication have been observed (LUA 2002). A far larger improvement would be achieved by taking technical measures for small and medium sewage treatment plants, e.g. P-elimination techniques, and by extension of measures to reduce combined sewer overflows.

By providing area-differentiated model results about diffuse and point source P-inputs to surface waters via eight different pathways, applications of the MEPhos model can contribute to the tasks of the EU-WFD and therefore to a sustainable use of water resources. In the meantime, MEPhos has been applied to the German state of Hesse (21,115 km²) to identify surface water bodies with eutrophication risks due to high inputs of ortho-P. Furthermore, policy advice for the administrative client is provided by quantifying the effects of state-wide mitigation measures for the surface water bodies.

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