Design of best management practice applications for diffuse phosphorus pollution using interactive GIS
A. S. Kovacs, M. Honti and A. Clement

ABSTRACT

The paper presents a complex environmental engineering tool, which is appropriate to support decision making in watershed management. The PhosFate tool allows planning best management practices (BMPs) in catchments and simulating their possible impacts on immissions. The method has two parts: (a) a simple phosphorus (P) fate model to calculate diffuse P emissions and their surface transport, and (b) an interactive tool to design BMPs in small catchments. The fate model calculates diffuse P emissions via surface pathways. It is a conceptual, distributed parameter and long-term (annual) average model. The model also follows the fate of emitted P from each cell to the catchment outlets and calculates the field and in-stream retention. The fate model performed well in the Zala River catchment as a case study. Finally, an interactive design tool was developed to plan BMPs in the catchments and simulate their possible impacts on diffuse P fluxes. Different management scenarios were worked out and their effects evaluated and compared to each other. The results show that the approach is suitable to test BMP scenarios at small catchment scale.

Key words | BMP, diffuse emission, distributed parameter, phosphorus, transport

INTRODUCTION

Best management practices (BMPs), as measures and activities to control the diffuse water pollution have become a cornerstone of watershed management plans. Numerous BMPs reducing the diffuse phosphorus (P) emissions and loads have been published (Ritter & Shirmohammadi 2001; Novotny 2003; Campbell et al. 2004). Interventions have two main groups, source and delivery control. Source control includes minimizing the introduction of pollutants into the environment and preventing mobilization of pollutants. Delivery or transport control tries to reduce the transfer of pollutants from soil to water bodies. Efficiency of applied practices has been evaluated in different case study areas (Campbell et al. 2004).

However, design of BMPs in complete catchments extending to several thousand square kilometres can not miss the quantification of the pollutant fluxes. Since diffuse emissions are immeasurable at source, their regulation must be based on modeling. Catchment simulation models are able to calculate diffuse emissions as well as their transport at the field and in the stream network. After calibration and validation, the models can be used for scenario analyses according to different management plans including various BMPs.

Several watershed models can be found in the literature based on either the empirical or the physical approach (Donigian & Huber 1991; Novotny 2003). Empirical models have major simplifications and they are mostly lumped parameter and long-term average methods. These models do not provide detailed information on spatial and temporal variability of the emissions. Physically based, dynamic models with distributed parameters are theoretically the most useful approaches to simulate the non-point pollutions due to the detailed mathematical description of environmental processes. However, their applicability is often limited by the availability of data.

Besides modeling, practical application of BMP concept must be accompanied by a cost–benefit analysis and...
economical feasibility study as well as legal regulation. There are BMP alternatives at nearly the same emission reducing efficiency, therefore costs can play an important role in decision making. There can be areas with high economic or natural value, where landuse form should not be changed. Finally, farmers should be interested in changing their management practices by economic and/or legal programmes.

This paper presents the PhosFate (Phosphorus Fate) design tool for planning BMPs based on a distributed parameter, long-term (annual) average P fate model calculating diffuse P emissions and their surface transport and an interactive BMP design tool. The tool was applied in the Hungarian Zala River catchment to evaluate the impacts of different management practices on the water quality.

BACKGROUND

Lake Balaton, which is the greatest shallow lake in the Central European region, is sensitive to eutrophication (Somlyody & Hock 2002). First signs of heavy eutrophication occurred during the seventies due to the increased nutrient loads reaching the high priority recreational lake (the highest algae biomass reached a value of 200 mg chl-a/m³, Somlyody & Hock 2002). Since then several investments have been conducted to protect the water quality. Most of the wastewater treatment plants on the watershed were expanded with P removal technology. In addition, since the early 1990’s, an artificial wetland area (Kis-Balaton reservoir) was constructed close to the lake inlet. It was intended to retain nutrients transported by the main influent Zala River, which carries most of the nutrient loads of the lake. Due to the control of point sources, the major portion of P emissions is now associated with diffuse sources. Since the current P load is about two times higher than the desirable value, future water quality management of the lake must reduce the non-point pollution (Somlyody & Hock 2002). Consequently the region is a highly feasible area to study the impacts of diffuse loads.

The Zala River catchment is located in the western, hilly part of Hungary (see Figure 1). The area of the selected part of the watershed (upstream of Kis-Balaton reservoir) is 1528 km². The elevation range is between 90 and 325 m above the Baltic Sea level. The area has moderate slopes (the average value is 4.2%). The long-term average discharge and P load at the outlet is 4.4 m³/s and 34 t/a, respectively. The dominant physical soil type is loam having poor to moderate hydraulic conductivity. The area is sensitive to soil erosion by water (the estimated average soil loss from agricultural lands is about 15 t/ha/a). The majority of the watershed is agricultural area, in particular arable land, which is 54% of the catchment. Forests are relatively important, covering approximately one third of the whole catchment.

MATERIALS AND METHODS

To calculate diffuse P emissions and impacts on them due to the management change, a complex environmental
engineering tool has been developed. The PhosFate tool supports decision makers to design BMPs in catchments to reduce non-point P emissions. The tool has two main parts: (a) a simple phosphorus (P) fate model to calculate diffuse P emissions and their surface transport and (b) an interactive tool to design BMPs in small catchments.

The fate model aims to calculate diffuse P emissions at their source area. It is a conceptual, distributed parameter model. It utilizes raster maps at 100 × 100 m resolution. The input base maps are the digital elevation model, the soil and landuse type, soil humus content and precipitation. Maps having non-numerical data were filled up with corresponding parameters collected from the literature (see the references below). The outputs are long-term averages of non-point source P fluxes via surface pathways. The time step is one year. For each cell a simple water balance (surface runoff and percolation out of the soil zone) is calculated based on precipitation data and physical properties (slope, landuse and soil type) (Rawls et al. 1993; Batelaan & Woldeamlak 2004). Erosion is computed by the USLE-equation adjusted to local conditions. The R-factor is calculated from precipitation amount and an average distribution of the different rainfall intensities (Salamin 1982; Novotny 2003). Other factors in USLE were derived according to soil, landuse, slope and management practices applied (Salamin 1982; Neitsch et al. 2002; Novotny 2003).

Soil P-content is calculated based on long-term agricultural data, soil humus content as well as atmospheric deposition. Because of the accumulation of P in topsoil, a cumulative P balance calculation was executed to determine the current soil P content. The starting year was 1960, when the fertilizer application rate was very low. For each year the P balance was computed as a summation of inputs and losses. Only the inorganic P is monitored, organic P in humus substances is assumed to be slowly varying. Inputs are the applied fertilizer, manure and humus mineralization (Nemeth 1996; Neitsch et al. 2002) and atmospheric deposition (Schreiber et al. 2003). Outputs are the harvested P amount (Schreiber et al. 2003) and losses via runoff, erosion and leaching. Since meteorological data for the past (back until 1960) were not available, for each year the average precipitation conditions were used. In each year, the P surplus was partitioned between particulate (PP) and dissolved (DP) phase according to Langmuir-isotherm determined by soil properties (clay and humus content and pH value) (Novotny 2003). In case of P deficit (negative balance), adsorbed P amounts were reduced and a new equilibrium was computed. The balance calculation can be also used for future fertilization conditions. In case of paved areas, event mean concentrations were used to characterize the P-content of urban runoff according to the urban landuse types (Novotny 2003).

By multiplying the actual amount of the surface runoff and the soil loss with the proper actual P concentration, emission values for the current time period are calculated for each cell via runoff and erosion. In the case of erosion, enrichment of fine particles is also taken into account based on the soil clay content. Total cell emissions are determined by summing the emissions of the different pathways.

The method is appropriate to discover the areas, which are mainly responsible for diffuse P emissions. The fate of emitted P is further examined by a surface transport model to determine the fluxes arising from the emission sensitive areas. Since P moves towards water bodies primarily by erosion and runoff, subsurface loads were neglected. After filling up the local depressions, flow directions are determined for each cell based on the cell elevation values. In this way flow paths (field and channel) are assigned. After determining the flow lines, average flow velocity of runoff and travel time is computed for each cell by the Manning Equation (Fread 1993; Borah & Bera 2003). Roughness coefficients are determined based on landuse type and channel characteristics (Neitsch et al. 2002; Liu & De Smedt 2004). Time averaged hydraulic radius for each cell was estimated by a power function of the drained area upstream of the cell (Liu & De Smedt 2004). Field and river retention are computed based on the average travel time in the cell and a constant retention coefficient. No retention is assumed in the case of DP. Combining the cell emissions with the transport algorithm, P fluxes at any points within the catchment can be quantified.

Based on the fate model, an interactive design tool was developed to plan BMPs in the catchments and simulate their possible impacts on diffuse P fluxes. There are many BMP alternatives and their combinations, which can be effective in reducing diffuse P contamination. In this tool the landuse management is the targeted group of application. It includes landuse change, cultivation method change, establishment
of buffer zones and wetlands. Landuse conversions (e.g. reforestation, pasture or wetland development from agricultural land, etc.) affect the soil water balance as well as the erosive potential. Cultivation changes (e.g. tilling direction, conservation tillage, strip-cropping, mulching, etc.) have impact on the soil loss values. These are source controlling interventions by reducing runoff and soil loss. Buffer zones, swales and constructed wetlands are transport controlling measures; they are implemented to retain pollutants during their transport in field and river bed. Their impact appears in reducing flow velocity. Annual costs of the different management practices were collected from the “New Hungary” Rural Development Plan (Tar 2006). The tool provides an interface for the users to introduce various BMPs in the examined catchment, and helps to simulate their impacts by running the emission and the transport model according to the designed modifications. Besides load reducing efficiency, expected costs of intervention can be also computed.

RESULTS AND DISCUSSION

The presented modeling tool was applied for the Zala River catchment for the period 1994–2002. Model calibration was executed in the first four years, the rest of the examined period was used for model validation. The verified model was built into the interactive BMP design tool for executing scenario analysis. Different management scenarios were worked out and their effects and costs evaluated and compared to each other.

Model calibration and verification

Calibration and verification results are presented in Figure 2. To extract diffuse loads arising on the surface, the measured DP and PP loads were separated into strongly variable (surface loads) and slowly variable (subsurface and point source fluxes) categories based on the main flow components. Flow separation was executed by a baseflow
filtering technique (Arnold et al. 1995). After parameter adjustment for the first four years the simulated and measured values fit reasonably in the verification period. Strong correlation was found between the calculated and the observed values (DP: $R^2 = 0.94$, PP: $R^2 = 0.90$). In the fourth and sixth year the PP simulation has higher inaccuracy. Despite the simple hydraulic algorithm the model well simulates the annual P loads via runoff and erosion.

Figures 3–4 show the spatial resolution of the long term average (1994–2002), yearly area specific DP and PP emissions as well as the outflowing fluxes and the local retention. Areas having higher slopes and agricultural cultivation produce remarkable phosphorus emissions due to their greater runoff and soil loss amounts. TP fluxes are increasing as the water flows down, especially in the main channel. High rates of local retention were found in forest areas and local depressions.

**Scenario analysis**

Based on the calibrated model, scenario analysis was performed to assess the possible impacts of different BMP applications. Table 1 presents the examined scenarios.
Interventions were planned in the erosion sensitive areas as well as the riparian zones. Sensitivity to erosion was defined as soil loss value greater than 1 mm/ha/a (approximately 15 t/ha/a). In Scenario I the sensitive areas were completely reforested. Scenario II means establishment of 50–50 m wide riparian buffer zones at the margins of the main channels. In the third and fourth scenario the sensitive areas were protected by erosion controlling activities (Scenario III: contour plow and strip-cropping, Scenario IV: mulching). Finally, Scenario V is a mixture of the previous ones: it includes forestation and erosion control at the sensitive cells as well as buffer zones close to the river beds. Delineation of forest cells was carried out based on the suitability of soils for forestation and the environmental sensitivity of the areas (Angyan et al. 1997). For each scenario the DP and PP loads were computed using the long-term average meteorological conditions and compared to the present values. Besides this, total costs of the interventions and the specific P-removal costs were assessed.

Comparison of the load reducing efficiency of the planned BMPs can bee seen in Table 2. The most effective interventions are the combined scenario and forestation. Mulching and strip-cropping can also remarkably reduce the loads. Riparian zones only do not provide sufficient P retention. Costs of the BMPs were also compared (Table 3) based on specific costs including losses due to the decreasing agricultural products, deployment and technological costs, etc. Forestation has the highest specific and total costs, but it has the best efficiency in load reducing. Buffer zone has the lowest P-specific charges, however, its load reducing capacity is weaker. Erosion control measures have acceptable charges accompanied by effectiveness in P emission reduction. The combined intervention can also be suitable solution if enough financing is available.

**Table 1** | Examined management scenarios
---|---
Scenario | Applied management practice  
I | Forestation  
II | Riparian buffer zone  
III | Contouring and strip-cropping  
IV | Mulching  
V | Forestation + riparian zone + mulching

**Table 2** | Load reduction efficiency of the selected management practices
---|---|---
Scenario | DP load [t/a] | PP load [t/a] | TP load [t/a] | Reduction [%]  
Present | 5.030 | 21.850 | 26.880 |  
I | 4.525 | 4.196 | 8.721 | 67.6  
II | 4.771 | 11.700 | 16.471 | 38.7  
III | 4.937 | 7.644 | 12.581 | 53.2  
IV | 4.940 | 6.031 | 10.971 | 59.2  
V | 4.603 | 3.615 | 8.219 | 69.4

**Table 3** | Costs of the scenarios
---|---|---|---|---
I | 21.600 | 250 | 5.400 | 297  
II | 3.950 | 250 | 0.988 | 95  
III | 21.600 | 130 | 2.808 | 196  
IV | 21.600 | 170 | 3.672 | 231  
V | 15.500 + 8.100 | 170 + 250 | 4.660 | 250

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**CONCLUSIONS**

With the developed PhosFate tool, annual diffuse P emissions via surface pathways at local level can be quantified. The main advantages of the approach are the supportable data demand and the simple algorithm. Based on the calculated emissions the most important source areas can be identified. By the transport model P fluxes can be determined at arbitrary point within the catchment. The model was successfully calibrated and validated in the Hungarian Zala River catchment. Besides emission and load computation, this method can support strategic decisions in water management. The model was built into an interactive design tool to plan various BMPs in the catchment. Applying the tool, impacts of different landuse and cultivation method changes can be easily examined even in complex watersheds. P load reducing capacity and P-removal costs are assessed together. In the pilot area buffer zone establishment was found the most cost effective solution, however, its total P-reduction is the lowest.
Forrestation is the most effective practice, but at high charges. Combining the buffer zone in the erosion sensitive areas with forestation and/or erosion controlling measures, acceptable technical and economical efficiency can be achieved.

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REFERENCES


