Comparative study of two watershed scale models to calculate diffuse phosphorus pollution

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Abstract The aim of this study was to compare and assess models having different principles to calculate diffuse phosphorus emissions on a selected watershed. The empirical MONERIS model and the physically based SWAT model were evaluated for comparative purposes. The approaches were applied for a sub-basin of the Hungarian Zala River watershed for five years. The calculated river loads were checked by the measured values at the catchment outlet. Due to the dissimilar results of water balance and erosion calculations, a highly different phosphorus emission was computed. It was also concluded that in the case of transport-limited watersheds, the SWAT model calculates phosphorus river loads slightly inaccurately, since it does not include the description of fate of inorganic phosphorus interacting with sediment during the channel transport. When these processes are taken into account, modeling results fit better the measured loads. The MONERIS model calculates acceptable river load by assuming very intensive in-stream retention. Additionally, the empirical method can be useful for long-term investigations as a decisions support tool for preliminary design. However, for detailed emission assessment and scenario development the physically based approach seems to be more appropriate.

Keywords MONERIS; non-point pollution; phosphorus; SWAT; watershed modeling; Zala River catchment

Introduction

Emissions from non-point sources have great importance regarding the water pollution nowadays. One of the current water quality problems related to diffuse pollution is eutrophication. Despite controlling the point sources (i.e. nutrient removal), a significant load of nutrients still reaches surface waters. Diffuse phosphorus emissions from watersheds provide nutrient supplies for the aquatic plants. Therefore knowledge of phosphorus emissions from different pathways and sources is a key issue concerning the protection of water quality and sustainable watershed management practice.

Several watershed modeling approaches are reviewed in the literature (e.g. Donigian and Huber, 1991; Novotny, 2003). They differ from each other primarily in the temporal and spatial scale, i.e. in the details of the resolution. Lumped parameter models consider the watershed as a uniform region and they do not have information on spatial differences within the watershed. In contrast, distributed parameter models divide the watersheds into smaller units. All units are individual having their own parameter set. Long-term yield models calculate the average nutrient fluxes according to a longer time period, typically several years. Dynamic models provide temporary information on the nutrient loads (time series) either as a continuous (daily time step, long-term impacts) or as an event-based (hourly or sub-hourly time-step, short-term impacts) approach. Model selection depends mainly on the aim of the examination, the characteristics of the studied water body, the availability of data, the expected accuracy and the temporal and financial costs.

This paper presents the evaluation of two different watershed models used for a Hungarian case study region, to calculate phosphorus emissions from the drainage area as well as river loads at the catchment outlet for five years (1997–2001).

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Background

Lake Balaton, which is the greatest shallow lake in the Central-Eastern European region, is sensitive to eutrophication (Somlyody and 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/m^3 (Somlyody and Hock, 2002). Sisak and Pomogyi (1994) found that the contribution of point and non-point sources during the period 1975–1987 was 55% and 45%, respectively. Since then, several investigations have been conducted to protect the water quality. Most of the wastewater treatment plants on the watershed were expanded with phosphorus removal technology. In addition, 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 the phosphorus emissions is now associated with diffuse sources. Since the current phosphorus load is about two times higher than the desirable value, future water quality management of the lake needs the reduction of the non-point pollution (Somlyody and Hock, 2002). Consequently the region is a highly feasible area to study the impacts of non-point pollution.

The Zala River catchment is located in the western hilly part of Hungary. The area of the selected part of the watershed (upstream of Kis-Balaton reservoir) is 1,528 km^2. The elevation range of the region is between 90 and 325 m above the Baltic Sea. The hilly area has moderate slopes (the average value is about 6%). The average discharge at the outlet was 4.3 m^3/s during the period of 1997–2001, i.e. the average yearly runoff volume was 89 mm/a. The average phosphorus river load was 35 t/a, which means 0.23 kg/ha/a area specific flux. In the period of 1997–2001, the average annual precipitation was 651 mm. The dominant physical soil type is the loamy soil having poor to moderate hydraulic conductivity. The area is sensitive to water erosion processes (the estimated long-term average soil loss is about 6.1 t/ha/a). The majority of the watershed is an agricultural area, in particular arable land, which is 54% of the catchment area. Forests are relatively important, covering approximately one third of the area.

Methods

Two different watershed modeling tools were selected to estimate phosphorus emissions: the MONERIS model (Modeling Nutrient Emissions in River Systems, Behrendt *et al.*, 2000) and the SWAT model (Soil and Water Assessment Tool, Neitsch *et al.*, 2002).

The MONERIS model

The MONERIS model has been developed to calculate nutrient emissions entering river systems at large watershed scale (catchment area larger than 1,000 km^2). It is a lumped parameter model for the estimation of long-term averages based on mostly empirical relationships. The application of the model requires detailed statistical, sampling and literature data, default parameters and digital maps about various characteristics of the watershed. It provides a 5 year-average of water balance components, nutrient emissions and river loads at the main sub-catchment outlets. By this method the nutrient emissions of large sub-catchments into the Danube River and its main tributaries were calculated (Schreiber *et al.*, 2005).

The model does not distinguish phosphorus forms. It focuses only on total phosphorus emissions. It separates seven different pathways resulting in the total amount of phosphorus emissions. Six of these are diffuse sources: atmospheric deposition, overland flow, erosion, tile drainage, groundwater and urban systems. The seventh component is the contamination from point sources. For each pathway the appropriate water balance component (in case of erosion the sediment flux) is computed empirically and after that phosphorus concentration is determined for the water (sediment) flows. These concentrations are determined based on parameters found in the literature and mass balance calculations of the agricultural areas. Phosphorus enrichment in eroded soil is also computed empirically. Additionally, possible field retention is taken into account along the pathways (e.g. sediment deposition on surfaces). From the total emission values of sub-catchments river loads are computed using an empirical in-stream retention model.

The SWAT model

The aim of the SWAT model is to describe the fate of the water, sediment, nutrients and pesticides more accurately in the watersheds and to simulate the impact of management practices on hydrology and water quality. SWAT is physically based, thus the method requires very detailed and specific information on meteorology, topography, soil, land use and management conditions of the watersheds. The method runs on a geographical information system. SWAT is a continuous daily time-scale model; therefore it is particularly useful to simulate long-term yields and impacts. It is not designed to model detailed single-event flood routing and its impacts. It is a spatially distributed parameter model; however, the unit of the calculations is not the grid cell level, but the spatial unit called Hydrological Response Unit (HRU). This means that the grid cells with identical soil and land use types are integrated into a HRU. The number of simulated sub-basins is theoretically unlimited. Many examples of the model application can be found on the SWAT model homepage (www.brc.tamus.edu/swat).

The SWAT approach separates sub-modules for both catchment and river channel processes. In the catchment phase watershed climate and hydrology, plant growth, erosion and phosphorus transformation and transport are modeled. Six different phosphorus forms are separated, i.e. stable, active and fresh organic phosphorus, and stable, active and soluble inorganic phosphorus. The soil phosphorus cycle is modeled in detail. The main transport processes are phosphorus movement via surface runoff (soluble forms), erosion (phosphorus attached to sediment) and leaching. Enrichment of fine particles in eroded soil is also taken into account. Additionally, base flow phosphorus contents can be set to compute the subsurface contribution to the river loads. The channel phase includes water, sediment and phosphorus routing along the main river longitudinal sections, as well as fluxes from point sources. Phosphorus transformations are described with an adapted version of QUAL2-E in-stream water quality model. Mass balance of reservoirs is separately calculated.

Results and discussion

Both models were applied for the Zala River catchment for the period of 1997–2001. While only four sub-catchments were delineated for MONERIS, 40 sub-basins were appointed for SWAT. The SWAT model was calibrated to the measured discharge and water quality data at monthly time steps. The MONERIS model was applied in its original form. Emission results are compared according to the sub-basins in the MONERIS model for the period of 1997–2001 (annual average values). Dynamic results of the SWAT model at monthly time steps as well as yearly average river loads are assessed at the catchment outlet for the same time period.

Emissions of MONERIS model

The calculated area-specific phosphorus emissions and their share in the total emission according to the different pathways are presented in Figure 1. The area-specific phosphorus emissions vary in a wider range (between 0.52 and 1.23 kg/ha/a); the average for

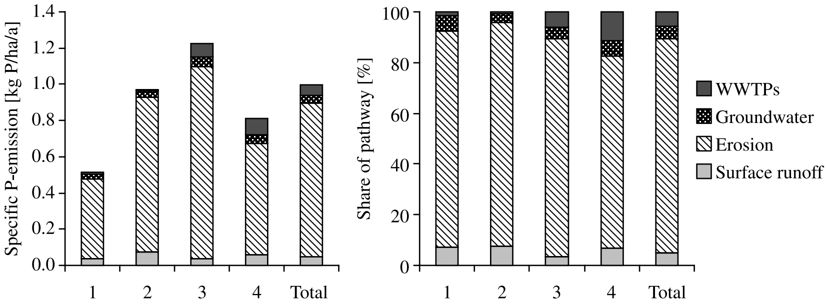

Figure 1 Annual average total phosphorus emissions according to the different pathways calculated by the MONERIS model in the Zala River catchment (1997–2001)

the total area is about 1.00 kg/ha/a, which is 153 t/a. The difference is due to the different volume of eroded soil transported into the river, which is explainable by the varying sensitivity to erosion in the watershed area. However, in sub-basin No. 1 the calculated area-specific flux is low despite the higher specific soil loss value. This is due to lower delivery ratio of sediment in this sub-catchment. Regarding the share of the sources, almost all of the total emission (about 75–85%) is caused by the erosion. Other diffuse sources have minor importance and point source emissions are also non-relevant due to the P-elimination applied in the WWTPs in this region. It is concluded that 94% of the total emitted phosphorus fluxes originate from non-point sources.

Emissions of SWAT model

Figure 2 shows the estimated area-specific phosphorus releases into the river and their proportion compared to the total phosphorus fluxes. The specific emissions have high variation among the sub-catchments ranging between 0.18 and 0.42 kg/ha/a. Emission regarding the whole catchment is 0.31 kg/ha/a, which is equal to 47 t/a. Total emitted phosphorus yield is lower by about 70% compared to MONERIS results. The reason can be found primarily in the highly different amount of sediment yield predicted (discussed later). Difference between the average enrichment ratios computed by the models is not significant. Excluding sub-basin No. 1 the area-specific values are also lower. The higher relative importance of the first sub-watershed is probably due to the decisive role of surface runoff to the river loads in areas located in the upper part of the watershed. Sub-basin No. 4 yields the least phosphorus load into the reach because of its low sensitivity to soil erosion and its low surface runoff contribution. Erosion is the primary pathway regarding phosphorus transport. Groundwater and point sources are less significant; their role is remarkable in sub-basin No. 4 only. Dominance of diffuse pollutions is obvious (90%).

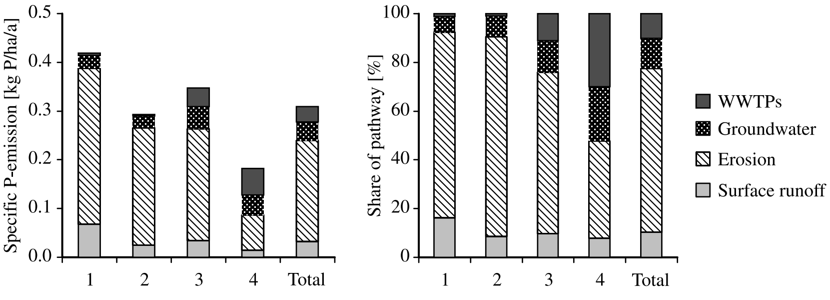

Figure 2 Annual average total phosphorus emissions according to the different pathways calculated by the SWAT model in the Zala River catchment (1997–2001)

Comparison of the river loads

Comparison of simulated river loads to each other and to the measured values at the catchment outlet is presented in Table 1. In the case of the SWAT model, monthly calibration results are shown in Figure 3. Regarding the river flow components, there are remarkable differences between the two methods. SWAT calculates quite well the total river flow based on the watershed features (Figure 3A), MONERIS uses the measured flow to calculate water balance. While MONERIS calculates lower surface water contribution and stronger base flow dominance, SWAT computes a higher amount of direct runoff (see Table 1), which is acceptable considering the topsoil with poor hydraulic conductivity. MONERIS underestimates the surface runoff volume. This is confirmed by the results of a base flow separation technique developed by Arnold *et al.* (1995), which determines an approximate value of 20 mm/a for the surface runoff in the studied time period. The reason for the discrepancy can be found in the extension of empirical equations for areas out of the original calibration range.

Sediment yield and load calculations also have differing results. MONERIS despite its lower surface runoff volume calculates almost four times higher sediment input than SWAT (Table 1). This inconsistency is caused by the sediment yield generation approach of MONERIS, which does not depend on the surface runoff volume and the soil and land coverage properties. It calculates empirically the sediment input from the mean soil loss and average delivery ratio determined from the catchment slope and proportion of arable lands. SWAT erosion calculation (MUSLE method) is based on surface flow amount, soil erodibility, topography and land use characters. A study on the impacts of the spatial aggregation on sediment generation found that sediment generation can vary by 44% between the coarsest and the finest watershed delineation and it decreases substantially with decreasing sub-watershed size (FitzHugh and Mackay, 2000). Consequently, further examination of the impacts of spatial scaling in the Zala River watershed is needed to clarify the possible changes in sediment generation.

Only the SWAT model contains a sediment channel routing sub-model. The calculated sediment loads approximate well the measured values (Figure 3B). The results indicate clear net sedimentation of the suspended solids (Table 1), e.g. the model computes remarkable sediment retention in the reach system (about 50%). This means, if the results of MUSLE approximate well the realistic sediment yield values, the total examined watershed is a transport-limited area, where the generated amount of eroded soil in the catchment exceeds the sediment transport capacity of the channel system (FitzHugh and Mackay,

Table 1 Comparison of annual average runoff components, sediment and phosphorus fluxes at the catchment outlet of the Zala River (1997–2001)

Component	Unit	MONERIS	SWAT
Surface runoff	mm/a	11.9	17.6
Subsurface flow	mm/a	74.3	69.9
Waste water discharge	mm/a	3.0	3.0
Total river flow	mm/a	–	90.5
Measured river flow	mm/a	89.2	
Sediment yield	t/ha/a	0.334	0.088
Sediment deposition	t/ha/a	–	0.042
Sediment load	t/ha/a	–	0.046
Measured sediment load	t/ha/a	0.045	
Phosphorus emission	kg/ha/a	0.999	0.309
Phosphorus rentention	kg/ha/a	0.817	0.022
Phosphorus load	kg/ha/a	0.182	0.288
Measured phosphorus load	kg/ha/a	0.227	

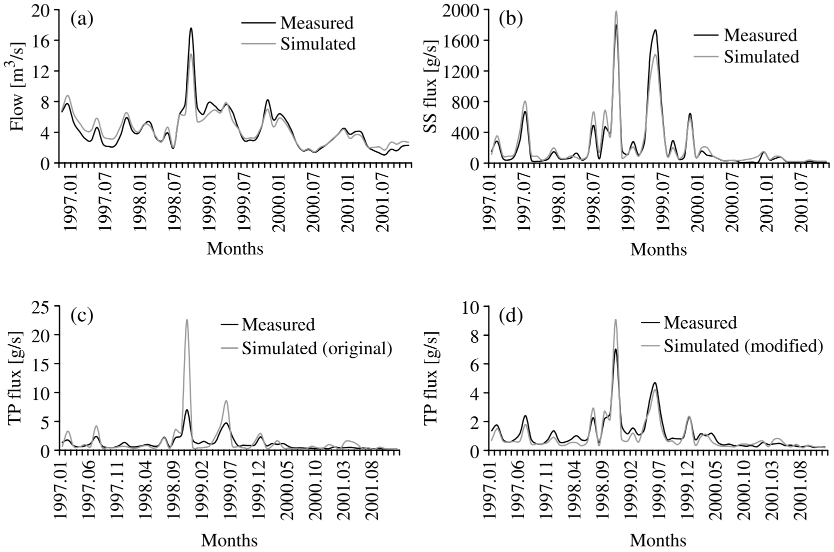

Figure 3 Monthly river flow, sediment flux and total phosphorus load values calculated by the SWAT model at the catchment outlet of the Zala River (1997–2001)

2000). In a geomorphologic sense, the stream channels are only temporary storages of the transported sediment and over a long period of time a natural river transports all sediment delivered into it from the drainage area (Novotny, 2003). Thus, long-term (more than 100 years) sediment delivery ratio for streams is 1. However, at the time step of water quality studies (less than 10 years) the deposition of sediment and the fate of settled contaminants related to it must be considered (Novotny, 2003). In many streams the sediment delivery ratio is less than 1 if the examinations concern short periods without extreme flood events. Sediment settles in the downstream reaches of the river with lower flow velocity (where the texture of sediment becomes finer), in small ponds located on the river network and primarily on the floodplains during flood events and in the reservoirs.

Dissimilarity of phosphorus emissions calculated by the two methods has already been discussed; phosphorus river load calculations have different results also. The SWAT model overestimates the observed river load (Table 1) and generates high phosphorus peaks (Figure 3C). Although sediment routing is modeled by SWAT in the river net, the fate of the inorganic phosphorus associated with the sediment particles is not tracked along the main river sections except in the reservoirs. Only organic phosphorus is accounted for in deposition in streams by a settling rate. Consequently, in watersheds where sediment retention is remarkable, SWAT is not feasible to calculate adequately the phosphorus river loads due to the lack of in-stream transport modeling of inorganic particulate phosphorus and calculation of floodplain impacts. In contrast, MONERIS gives more appropriate results for the river load compared to the measured one (Table 1). The model includes an empirical river retention model for the total phosphorus based on the specific runoff of the catchment, which results in a good fit to the measured load, though the total emissions are quite high (see Figure 2). Thus, the degree of the retention (80% of the emission) is assumed to be very intensive. As was shown by Zessner *et al.* (2005), flood events transport only a few percent of the total yearly average phosphorus loads of the Zala River, which indicates remarkable phosphorus retention in the river system. Since most of the phosphorus in soils is contained in the particulate phase and moves with eroded soil (Novotny, 2003), phosphorus can be retained in the reaches by sediment deposition. Although settled phosphorus reenters by resuspension of sediment caused by the flow turbulence and biological benthic activity, the delivery ratio for phosphorus in streams can be also less than 1 for a short time period.

To take into account the sedimentation of inorganic phosphorus attached to the sediment a simple correction was executed to improve the SWAT model performance. Assuming that the settling rate of sediment and adsorbed mineral phosphorus is approximately equal, a value for the possible river retention regarding the adsorbed inorganic phosphorus form was calculated by the ratio of daily sediment flux at the catchment outlet to the daily sediment yield from the watershed. Then, particulate inorganic phosphorus emission was multiplied with the retention ratio for each day. This slight correction resulted in smaller peaks (Figure 3D) and an additional average retention of 0.072 kg/ha/a, consequently the original value for the river load (0.288 kg/ha/a) reduced to 0.216 kg/ha/a. This value approximates better the measured one. The corrected phosphorus retention (30% of the emission) is lower than in the case of MONERIS. Based on the results it can be concluded that additional examinations are necessary to reveal the possible impacts of the in-stream retention processes regarding both sediment and phosphorus.

Conclusions

Both methods detect the dominance of diffuse sources, especially the erosion on the phosphorus pollutions of the Zala River. However, there are remarkable differences between the calculated emissions for the major sub-catchments and also for the total watershed. The MONERIS model predicts more than three times higher phosphorus emissions from the total watershed. The differences are due to the lower surface runoff volume and the huge amount of sediment yield of MONERIS. These results are explainable by the extension of the empirical equations without calibration as well as by the model application for sub-basins smaller than the originally proposed catchment size. Therefore recalibration of the empirical equations according to the local conditions and to higher resolution is needed. SWAT simulates better the water balance and sediment generation as well.

River load calculations of SWAT are slightly inaccurate due to the lack of in-stream modeling of inorganic phosphorus attached to the sediment. In watersheds where sediment deposition is significant, this shortcoming can lead to imprecise determination of phosphorus river loads, because retention primarily on the floodplains and in the river channels is not taken into account. Consequently SWAT can overestimate the observed phosphorus river loads. By a simple estimation of retention of mineral particulate phosphorus, the results fit better the measured values. Despite the high value of estimated emissions MONERIS simulates good results compared to the observed loads due to the computed very intensive river retention. Further studies are needed to clarify the accuracy of the erosion calculations and the related phosphorus emissions depending on the spatial resolution of the catchment as well as the possible river sediment and phosphorus retention.

Considering the extension problem of empirical formulas, the MONERIS model is capable of establishing the existence of the diffuse pollution problem in general. Nevertheless, regarding the accurate calculation of emission values as well as important processes (surface runoff and erosion) it has significant uncertainties. For precise emission estimations and determination of cause–effect relationships, SWAT seems to be more appropriate due to its physically based structure. However, in large basin scale, where the effects of different sub-regions are more balanced, the MONERIS model can be suitable to calculate long-term impacts of management practices. It can be useful in the phase of preliminary design of watershed management planning to evaluate the possible effects of the designed changes in the river basin management. For detailed examination of the source areas and pathways at particular temporal and spatial resolution, the SWAT model is more feasible. However, due to its high data demand, temporal and financial costs, it cannot be applicable in regions without detailed data collection. In such cases, it should be replaced even at higher resolutions with simpler methods, like the MONERIS model.

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