The Role of Erosion and Sediment Transport in Nutrient and Contaminant Transfer (Proceedings of a symposium held at Waterloo, Canada, July 2000). IAHS Publ. no. 263, 2000.

Modelling phosphorus transport processes in a small southern German rural catchment

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Abstract The prediction of non-point source phosphorus inputs to surface waters is investigated within the framework of a multidisciplinary research project in a small rural catchment in southern Germany. Release and migration of phosphorus into surface water is predominated by particulate phosphorus eroded with sediments. A hydrological distributed model (CATFLOW) was used for the precise numerical simulation of water transport. This model was extended to determine erosion and deposition of sediment-associated phosphorus and to calculate phosphorus enrichment ratios. Simulation results correlate well with values measured in rainfall experiments. For a natural erosive rainfall event the total sediment loss was calculated with 16 t ha^{-1} for a 160 min rainfall event with a maximum intensity of 92 mm h^{-1}. The total phosphorus content in the eroded sediments was calculated with 2070 mg P kg^{-1} leading to an enrichment ratio of 1.7.

INTRODUCTION

The removal of phosphorus from agricultural land is important from both a water quality and soil fertility aspect (Sharpley, 1985).

The aim of this study, which was developed within the framework of a multidisciplinary research project, was to develop a process based numerical model to predict the transport of water, sediment and phosphorus in a small rural catchment (Plate, 1995). The study area is the 6.3 km^2 Weiherbach catchment in the hilly Kraichgau region located in southwest Germany. The Weiherbach catchment is primarily used for agriculture and is representative for loess covered catchments. The area of distribution of loess soils in middle Europe is a belt from Belgium to south Poland. Erosion occurs very often on loess soils because of their particle size distribution and their intensive agricultural use.

The phosphorus loading of streams from agricultural land is clearly predominated by phosphorus bound to sediment particles (Beudert, 1997). Therefore the annual non-point source phosphorus input is dominated by a few erosive rainfall events. Table 1 shows the variability of surface runoff, sediment yield and particulate phosphorus load in the overland flow in the Weiherbach catchment for the years 1991–1994. In 1994 two rainfall events were responsible for 99% of the annual particulate phosphorus load in the stream. Due to the importance of single rainfall events, the precise simulation of water and sediment transport is a prerequisite for the successful modelling of phosphorus removal.

Table 1 Runoff, sediment yield, dissolved and particulate phosphorus load caused by overland flow of the Weiherbach catchment in the years 1991–1994 (Beudert, 1997).

Year	Runoff (m^3)	Sediment yield (kg)	$o\text{-}PO_4\text{-}P$ (kg)	Particulate P (kg)
1991	8 651	10 454	3	17
1992	14 547	28 303	6	38
1993	9 197	8 326	4	15
1994	55 512	1 889 299	24	1 173

MODEL STRUCTURE

A physically-based distributed CATchment FLOW model, CATFLOW, has been developed for the Weiherbach project. CATFLOW describes the flow dynamics of water in small rural catchments and permits the simulation of specific events as well as long-term processes (Maurer, 1997). The modelling scale is close to the process scale, which permits the consideration of the interaction between all relevant hydrological processes based on field observation. These are: evapotranspiration, infiltration in micro- and macropores, two-dimensional (2-D) soil water movement (saturated/unsaturated), surface runoff and channel flow.

The model is based on subdividing the three-dimensional (3-D) landscape into patches of 2-D hillslopes connected to a drainage network. The hillslope areas are idealized as vertical longitudinal sections of variable width along the steepest gradient of the topography.

For calculating erosion and deposition processes, a sediment transport component was added to the surface runoff component of CATFLOW based on the Process orientated Erosion Prediction Program (PEPP) model developed by Schramm (1994). The sediment model is used to calculate phosphorus transport (Fig. 1).

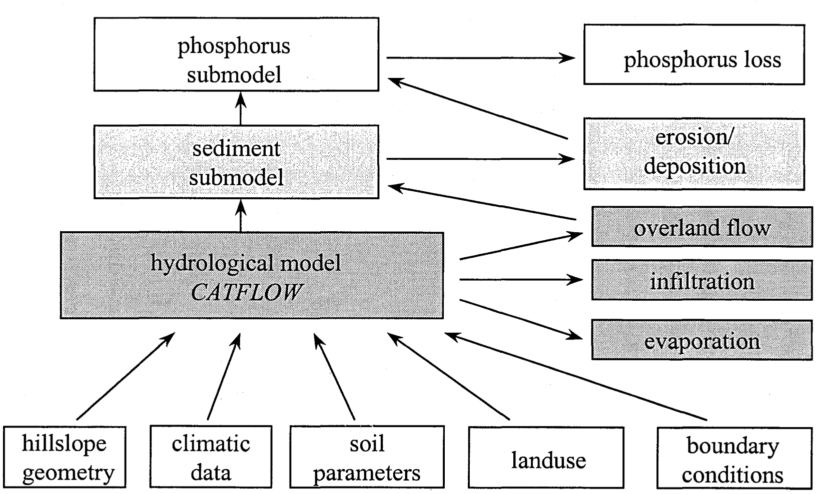

Fig. 1 Model structure.

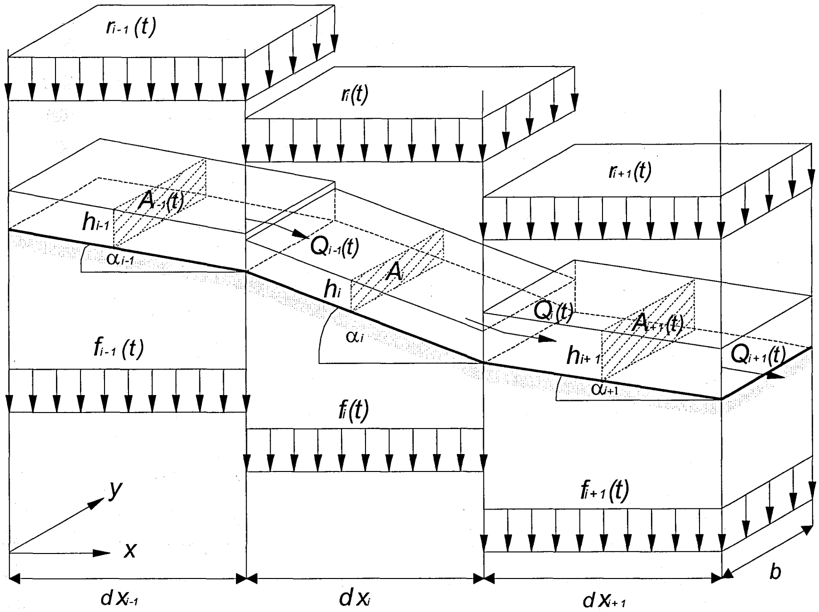

Fig. 2 Calculation of overland flow by dividing the slope into discrete elements (Gerlinger, 1997).

Surface runoff

The kinematic wave approach is applied to model surface runoff. The conservation form of the continuity equation for one dimensional flow is given by:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q(x,t) \quad (1)$$

where Q is discharge ($m^3\ s^{-1}$), A is the cross-sectional area (m^2) and q is lateral inflow ($m^2\ s^{-1}$). The lateral inflow corresponds to the rate of surface flow resulting from the difference between rainfall and infiltration rates. Flow velocities are determined by using the Manning-Strickler formula (Chow, 1959). The continuity equation is solved in discrete steps in time and space by considering the slope segments as storage elements of length Δx with constant flow area A. The flow area is calculated using the effective rainfall (difference between rainfall and infiltration) and the difference between the inflow $Q_{i-1}(t)$ and outflow $Q_i(t)$ of the segment (Fig. 2).

Erosion and deposition processes

In order to obtain sufficient data for soil loss caused by erosive precipitation, a portable rainfall simulator (12 m × 2 m) was incorporated into the Weiherbach study. Usually, a rainfall intensity of approximately 60 mm h^{-1} was applied to the plots. (Gerlinger, 1997; Gerlinger & Scherer, 1998).

The potential erosion rate was calculated following the basic concept of Schmidt (1991, 1996) by calculating the external forces (rainfall and overland flow) acting on the soil particles:

$$qs = 1.75 \cdot 10^{-4} \left(\frac{m_q + m_r \cdot \sin\alpha}{m_{\text{crit}}} - 1 \right) \tag{2}$$

where qs is the potential erosion rate (kg m^{-1} s^{-1}), m_{crit} is the erosion resistance (kg m^{-1} s^{-1}), α is the slope angle, and m_r and m_q are the momentum flux of rainfall and overland flow, respectively (kg m^{-1} s^{-1}). Detachment occurs if the resistance of the soil to erosion (m_{crit}) caused by internal friction, cohesion and gravity is overcome. The erosion resistance is a soil specific parameter which can be determined by measuring qs, m_r and m_q from rainfall experiments and solving equation (2) for m_{crit}. Several rainfall experiments have been carried out to investigate the spatial variability of the erosion resistance. Gerlinger (1997, 1998) has shown that the erosion resistance is mainly influenced by the soil parameters clay content, amount of organic matter and antecedent soil moisture. Using these values, the erosion resistance can be estimated for loess soils.

The transport capacity of overland flow is calculated using the method of Engelund & Hansen (1967). Determining the transport capacity for each class of particle size distribution of the source soil enables the calculation of enrichment of fine particle fractions in the flow due to selective deposition of coarser particles. Therefore the particle size distribution of the source soil was determined using sieves to separate the sand fraction and the pipette method for determining the silt and clay fractions (Scheffer & Schachtschabel, 1992). Then erosion and deposition was calculated for each particle size fraction leading to an enrichment of the particle classes fine silt and clay. Table 2 shows the measured percentages of the particle classes of the source soil and the calculated values of the particle size distribution of eroded sediments for a hillslope of the Weiherbach catchment.

Particulate phosphorus losses

Following selective erosion and deposition processes, the runoff contains a larger percentage (Table 2) of fine particles which have a higher capacity to adsorb phosphate. The particulate phosphorus concentration (*PP*) of runoff can be calculated with the following equation of Sharpley *et al.* (1985):

$$PP = TP \cdot SC \cdot ER \tag{3}$$

where *PP* is the particulate P concentration of runoff (mg l^{-1}), *TP* is the total phosphorus content of the surface soil (mg kg^{-1}), *SC* is the sediment concentration in

Table 2 Measured and calculated values of sediment from a hillslope of the Weiherbach catchment.

	Clay	Fine silt	Medium silt	Coarse silt	Sand
Percentage of source soil (%)	17	5	23	45	10
Calculated percentage of eroded sediments (%)	72	19	8.5	0.06	0.03
Phosphorus content (mg kg^{-1})	2305	1661	1157	926	581

runoff (kg l^{-1}), and *ER* is the enrichment ratio. Since erosion and deposition processes are modelled for each particle size class, the phosphorus loss with eroded sediments is calculated as:

$$TPP = TP_1 \cdot SC_1 + TP_2 \cdot SC_2 + \ldots + TP_n \cdot SC_n \quad (4)$$

where *TPP* is the phosphorus content of eroded sediments (mg kg^{-1}), $TP_{1...n}$ is the phosphorus content of each particle class of the source soil (mg kg^{-1}), and $SC_{1...n}$ is the percentage of each particle class of eroded sediments. The enrichment ratio (*ER*) is defined as the difference between the phosphorus content of the source soil and the eroded sediment.

The phosphorus contents of sediment samples from rainfall experiments and the enrichment ratios have been analysed and compared to calculated values. Measured and calculated values for the enrichment ratios of rainfall experiments ranged from 0.93 to 1.37 (Gerlinger & Scherer, 1998). These values are typical for the erodible loess soils of the Weiherbach catchment and there was little variation in the observed phosphorus enrichment ratios of different rainfall experiments.

Sensitivity analysis

A sensitivity analysis was performed to examine the effects of variations of input parameter values upon the model behaviour and output. To conduct the sensitivity analysis a standard slope was defined and the values of each input parameter were modified within a certain range. The resulting order for the sensitivity analysis for this standard situation revealed the importance of a precise determination of the effective rainfall per time (difference between rainfall and infiltration), the erosion resistance m_{crit} and the roughness coefficient Manning's *n*. For calculating the particulate phosphorus loss, the amount of soil loss has been the most sensitive parameter (Gerlinger, 1997; Gerlinger & Scherer, 1998).

MODEL APPLICATION

The model was tested by simulating rainfall experiments which have shown a good correlation for calculated and measured values for erosion and phosphorus removal (Gerlinger & Scherer, 1998).

As an example of the model application, an erosive rainfall event in June 1994 was modelled for a slope of the Weiherbach catchment. The rainfall event lasted 160 min with a total rainfall of 72 mm and a maximum 5-min intensity of 92.1 mm h^{-1} (Fig. 4(a)). In the model, the slope length of 198 m was discretized into 40 lateral segments. The density of discretization is highest at the bottom of the slope, because this is the most active area for the infiltration process (Fig. 3(a)).

The total erosion/deposition rates on the hillslope are shown in Fig. 3(b). Negative values indicate erosion and positive values represent deposition zones. The erosion maximum at 150 m corresponds with the location of the highest gradient of the slope (9%). The total calculated sediment output of the hillslope for the storm event in June 1994 was 16 t ha^{-1}. Gerlinger (1997) measured a total sediment loss of

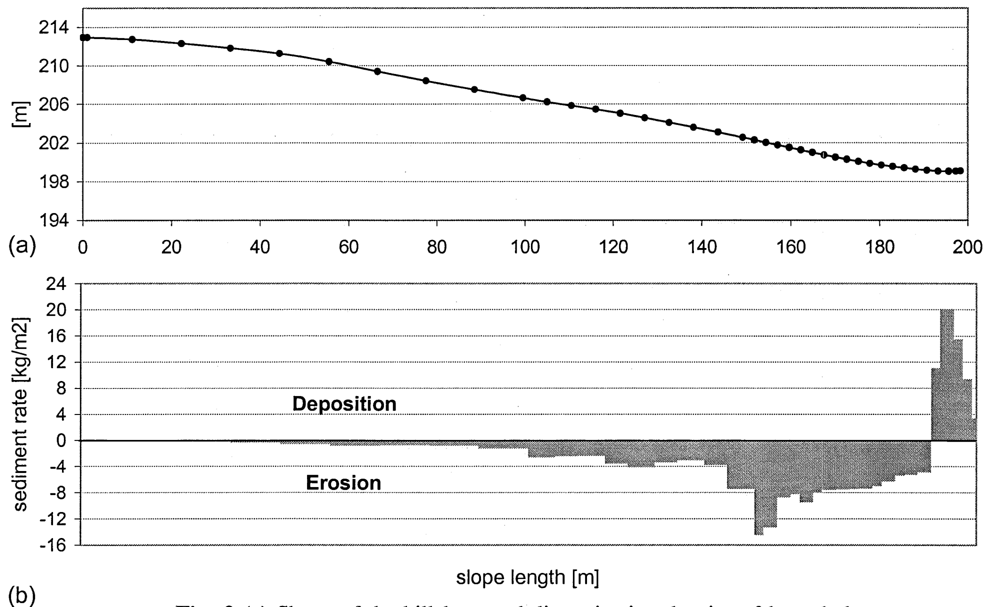

Fig. 3 (a) Shape of the hillslope and discretization density of lateral slope segments, and (b) calculated total erosion/deposition rates along the hillslope (kg m^{-2}) (values < 0: erosion, values > 0: deposition).

42 t ha^{-1} for this event for an instrumented 70 m slope length without a distinct deposition zone. The simulation result for the 70 m slope was 39 t ha^{-1}. The lower value of 16 t ha^{-1} for the 198 m slope is plausible because this slope has a deposition zone at the bottom leading to a lower sediment output.

Figure 4(b) shows the mean sediment rate and discharge of the slope. The shape of the sediment rate indicates a strong dependency from discharge. For this event the momentum flux of overland flow was the most influencing force on sediment transport. Only the second and third peaks of the rainfall event at 19:20 and 19:40 h (Fig. 4(a)) caused clear peaks in sediment rate and show the influence of the momentum flux of rainfall (Fig. 4(b)). The maximum sediment rate was calculated as 54 g m^{-2} min^{-1} (Fig. 4(b)). This corresponds with measured maximum sediment rates of rainfall experiments in the Weiherbach catchment (Gerlinger, 1997).

Measured percentages of particle classes for the source soil and calculated percentages of particle classes of eroded material are listed in Table 2. Compared to the source soil, the eroded material shows a distinct enrichment in the clay and silt fractions. The total phosphorus content of the source soil was 1220 mg kg^{-1} and the phosphorus content in eroded sediments was calculated as 2070 mg kg^{-1}, leading to an enrichment ratio of 1.7. This value is higher than the enrichment ratios observed in rainfall experiments (*ER*: 0.93–1.37), but it has to be taken into account that the slope length of the rainfall experiments was only 12 m and the experiments have been performed with maximum rainfall intensities leading only to slight deposition rates. Thus the measured enrichment ratios from rainfall experiments underestimate the enrichment ratios occurring on hillslopes with distinct deposition zones.

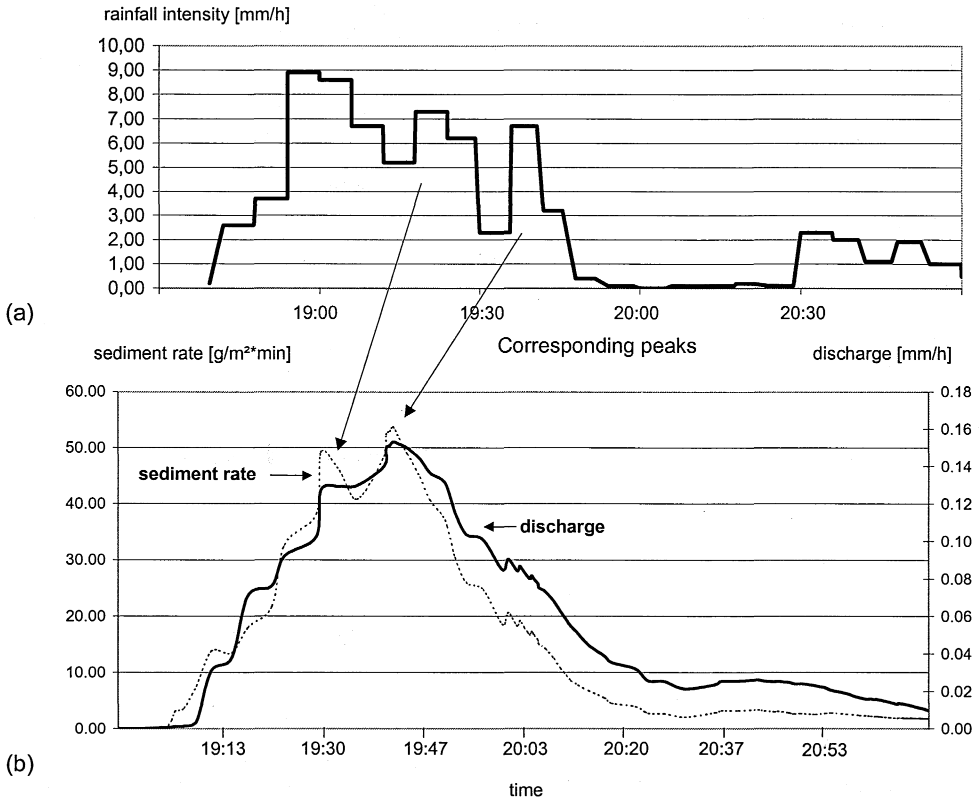

Fig. 4 (a) Measured rainfall intensities for the rainfall event in June 1994; and (b) simulated mean discharge (mm h^{-1}) and sediment rate (kg m^{-2} min^{-1}).

The extended model CATFLOW has shown good simulation results for a natural erosive rainfall event on a slope of the Weiherbach catchment. Currently erosion and phosphorus removal are modelled on the whole catchment scale.

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