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Simulating soil erosion and phosphorus transport on loess soils using advanced hydrological and erosional models

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Abstract Within the framework of a multidisciplinary research project in a small rural catchment an operational, event orientated soil erosion model, called PEPP, was developed to simulate erosion and deposition processes on a slope (Schramm, 1994; Gerlinger, 1997). For the calculation of the erosion rate, the model requires a specific erosion coefficient called *erosion resistance*, which is determined by rainfall experiments. The investigations focused on the temporal and spatial analysis of this erosion resistance and its influencing factors. The 60 rainfall experiments conducted on loess soils in an experimental basin demonstrated that the temporal variability of the erosion resistance is less important than the spatial variability. Soil properties, such as clay content, amount of organic matter and moisture content, which influence aggregate stability and crusting, seem to be suitable in revealing the relative spatial differences of erosion resistance. The determination of the required parameters is documented. The simulation results were compared with measurements and show the suitability of the model. The PEPP model can be applied in direct combination with the advanced hydrological model system HILLFLOW, which was developed in the same research project. Currently, the implementation of the PEPP model in the new catchment model CATFLOW and the extension of transport and enrichment of phosphorus is being investigated.

INTRODUCTION

The aim of the multidisciplinary research project "Weiherbach" is the development of an operational, physically-based numerical model for describing transport processes of water, eroded soil, fertilizer and other substances in a small rural catchment. The implementation of an erosion component is required due to the damage that soil erosion causes on agricultural land. Outside the fields, eroded sediment can be a major pollutant and a carrier of polluting chemicals, such as pesticides and plant nutrients (e.g. phosphorus).

Existing soil erosion models are either empirically based (e.g. USLE) or require a large set of input parameters (e.g. WEPP). Therefore, an operational model with high spatial and temporal resolution was required for the transport processes of eroded soil following individual storm events in small rural catchments. Furthermore, intensive field measurements had to be carried out to give a reliable

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database for the model. Since the reliability of the erosion model results depends strongly on the quality of the hydrological simulation, the combination of the erosion model with a sophisticated hydrological model system is required.

PEPP MODEL

As a first step, the slope erosion model PEPP (Process orientated Erosion Prediction Program) was developed (Schramm, 1994; Gerlinger, 1997). In the model, runoff, erosion and deposition are calculated either for rill or for sheet flow. If the overland flow is specified as concentrated flow in rills, the rill geometry is variable and can be computed for deposition areas according to discharge and sediment load.

For modelling the surface runoff, the kinematic wave approach is applied to account for unsteady flow processes. To solve the momentum equation, the energy losses are determined by the Manning-Strickler formula.

Since there is no universal equation for determining transport capacity, four different methods have been implemented in the programme: Engelund & Hansen (1967), Yalin (1977), Yang (1979) and Schmidt (1996). For all methods, the enrichment of the fine particle fraction in the flow due to selective deposition of coarser particles is computed.

The determination of the potential erosion rate follows the basic concept of Schmidt (1996) by calculating the external forces acting on the soil particles. Detachment occurs if the resistance of the soil to erosion caused by internal friction, cohesion, and gravity is overcome.

The forces of the rainfall can be characterized by the momentum flux of rainfall m_r (Fig. 1). It is calculated by:

$$m_r = \rho \cdot r \cdot \cos\alpha \cdot v_f \cdot (1 - C) \tag{1}$$

where m_r = momentum flux of rainfall [kg m^{-1} s^{-2}]; ρ = fluid density [kg m^{-3}]; r =

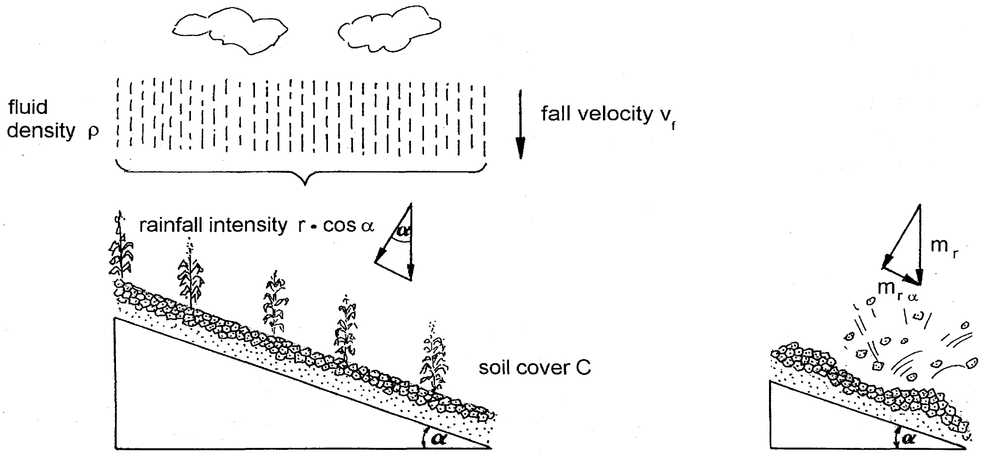

Fig. 1 Representation of an upland profile for calculation of momentum flux of rainfall.

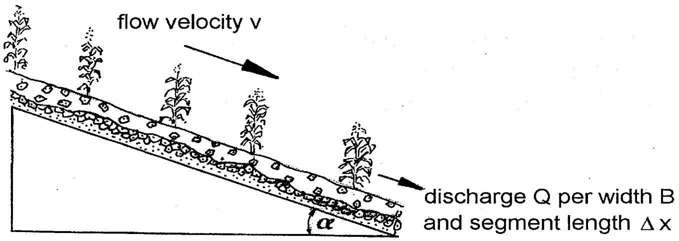

Fig. 2 Representation of an upland profile for calculation of momentum flux of overland flow.

rainfall intensity [m s^{-1}]; v_f = fall velocity of raindrops [L T^{-1}] (can be approximated by a function of rainfall intensity: $v_f = 4.459 + 0.613 \cdot \ln(r \cdot \cos\alpha)$); C = soil cover [ ]. It is assumed that the momentum of the raindrops augments the momentum flux of the runoff. But the exact share of increase is not calculable. Therefore, only the component of the momentum flux of rainfall pointing downslope is considered, by multiplying m_r with sinα, because the vectors of both rainfall and runoff then point in the same direction. This is a crude approximation of the natural processes.

The forces of the overland flow are described by the momentum flux of overland flow m_q per unit area (Fig. 2):

$$m_q = \frac{\rho \cdot v \cdot Q}{B \cdot \Delta x} \tag{2}$$

where m_q = momentum flux of overland flow [kg m^{-1} s^{-2}]; v = flow velocity [m s^{-1}]; Q = discharge [m^3 s^{-1}]; B = distance between rills (1 m for sheet flow) [m]; Δx = length of unit segment [m]. Schmidt (1996) observed by laboratory experiments with a rainfall simulator using loess soil, an empirical relationship between sediment load q_s and the momentum fluxes:

$$q_s = 1.75 \cdot 10^{-4} \left(\frac{m_q + m_r \sin\alpha}{m_{crit}} - 1 \right) \tag{3}$$

where q_s = sediment load [kg m^{-1} s^{-1}]; m_{crit} = critical momentum flux of the soil [kg m s^{-2}]. The critical momentum flux m_{crit} corresponds to an *erosion resistance* of the soil. It is a soil specific parameter which has to be determined by measuring the values of m_r, m_q and q_s from rainfall experiments, solving the equation for m_{crit} and inserting the measured values.

Sensitivity analysis

A sensitivity analysis was performed to examine the effects of variations in 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 model behaviour may change when it is applied to a complete different situation. However, the resulting order of the sensitivity analysis for this standard situation revealed the importance of a precise determination of the effective rainfall per time, the erosion resistance m_{crit} and Manning's n for the model results of soil loss.

DETERMINATION OF THE MODEL PARAMETERS FOR PEPP

A spatial and temporal analysis of Manning's n and especially of the erosion resistance was performed to provide the user with information about the required model input parameters.

The main investigation area is the 6.3 km^2 agricultural Weiherbach catchment in the hilly Kraichgau region (southwest Germany), which is, for the most part, loess covered. In order to obtain sufficient data, a transportable rainfall simulator (12 m × 2 m) was incorporated into the study. Usually, a rainfall intensity of approximately 60 mm h^{-1} was applied to the plots until steady-state runoff conditions had been established for a certain period of time.

The roughness coefficients (Manning's n) were estimated by fitting the recessing limb of the simulated model hydrographs to the observed hydrographs of the rainfall simulations (see Engman, 1986). This leads to a mean roughness coefficient composed of the surface areas with and without rills.

Temporal variability of the erosion resistance

Before the erosion model can be applied, one must know whether the erosion resistance, as a soil specific model parameter, is time invariant.

A temporal variability throughout the growing season of other soil erodibility indices was found by several authors (e.g. Coote *et al.*, 1988). For this reason, rainfall experiments were carried out during the growing season on sugar beet and maize fields, which are susceptible to erosion due to the late leaf cover. The results of the five simulations from 1994 on a maize field at the different dates throughout the year are presented as an example (Fig. 3). *At the beginning* of the rainfall experiments, the erosion resistances vary considerably; however, since steady-state conditions *at the end* of the simulations were obtained, the erosion resistances become constant as well. The variation of the erosion resistance values *at the beginning* of the experiments can be explained by the varying initial and unsteady-state conditions throughout the year.

In general, it can be concluded that the erosion resistances for each field at the different dates are relatively uniform. There seems to be only a small temporal variability during the growing season of maize and sugar beet.

Spatial variability of the erosion resistance

In order to simulate erosion in a catchment it is necessary to determine the small-scale variability of the erosion resistance and its influencing factors. Therefore, rainfall experiments were carried out on different slopes in the erodible loess covered regions of the Weiherbach catchment. The selected slopes were divided into strips, and the rainfall simulator was moved onto every strip from the bottom of the slope to

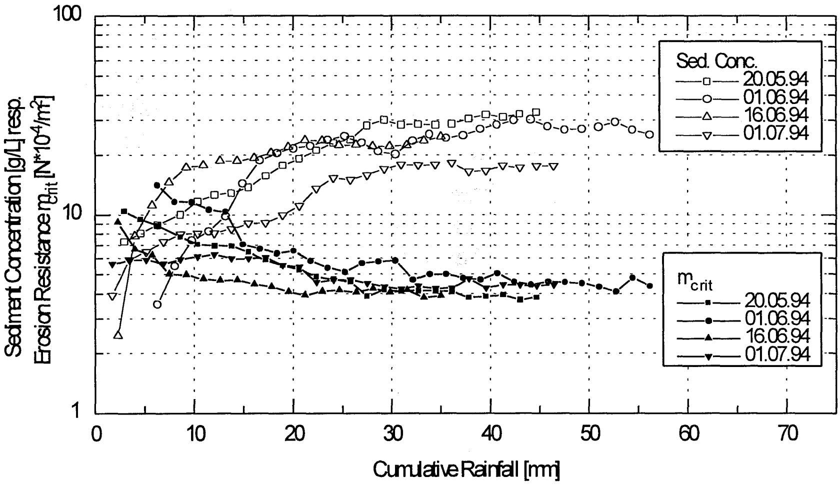

Fig. 3 Values of the measured sediment load and the calculated erosion resistance from the different rainfall experiments during the vegetation growth on a maize field.

the top. The soil moisture contents of the rainfall experiments was different: low water content in summer 1993 and high in spring 1994. Within these two periods the rainfall experiments were carried out over a short period of time so that the initial conditions of the respective experiments would be comparable. These experiments showed that the main influencing parameters of the soil loss and the erosion resistance are the clay content, the amount of organic matter and the antecedent soil moisture content.

The antecedent soil moisture influences infiltration, erosion resistance and sediment concentration in a complex way. On the one hand, rain on a soil with a high moisture content can lead to an early saturation of the soil, creating saturation overland flow. Compared to low initial soil moisture conditions, the amount of rainfall which provokes runoff is less if wet conditions in general prevail (Table 1, experiments 1993 compared to 1994). On the other hand, wet aggregates have a longer resistance to aggregate breakdown and crusting which prevents Hortonian (infiltration-excess) overland flow. Since crusting is the main cause of overland flow on tilled loess soil following individual thunderstorms, a wet soil is able to maintain high infiltration rates while dry areas produce higher discharge and sediment concentration. High moisture content in aggregated soils leads to high erosion resistance. Therefore, the amount of rainfall to produce runoff is higher on the plots with relatively wet conditions compared to the other plots (Table 1, experiments bottom compared to middle).

Since the erosion resistances are not randomly distributed but show a spatial dependency, a determination of the erosion resistance using soil parameters was sought.

Determination of the erosion resistance and Manning's *n*

In addition to the rainfall experiments, investigations of aggregate-size distribution,

Table 1 Initial conditions of the rainfall experiments on 31 August 1993 (dry conditions) and 20 April 1994 (wet conditions) on the same slope. Results of runoff and soil loss after 30 mm of rainfall and at steady-state conditions at the bottom and in the middle of the slope.

	Clay [%]	Organic matter [%]	Initial soil moisture [vol. %]	Rainfall to start runoff [mm]	Runoff [mm] 30 mm*	Soil loss [t ha^{-1}] 30 mm*	Runoff rate* [mm h^{-1}]	Soil loss rate* [g m^{-2} min^{-1}]	Erosion resistance [N·10^{-4} m^{-2}]
Bottom 1993	19.8	1.6	12.8	16.6	1.5	0.6	40.1	40.8	8.36
Bottom 1994	23.1	2.2	27.7	13.2	6.6	4.6	56.7	43.6	10.22
Middle 1993	14.7	1.5	7.9	13.8	3.5	2.8	50.2	154.1	2.87
Middle 1994	17.9	1.7	24.3	8.3	16.1	32.5	61.1	125.7	4.72

* Runoff and soil loss are for 30 mm of simulated rainfall; runoff rate and soil loss rate are at the equilibrium flow; slope gradient: for the bottom experiments: 16.2%, for the middle experiments: 18.0%; rainfall intensity 62.2 mm h^{-1}. The plots were tilled one week before the experiments with a rotary hoe.

aggregate stability, plasticity limits and shear strength were carried out to determine the suitability of these soil properties for the estimation of the erosion resistance. But the soil parameters clay content, amount of organic matter and antecedent soil moisture, which are more easily available, showed a better relationship to the erosion resistance. To ease the application of the PEPP model, equations were sought to determine the erosion resistance by this main influencing factor. Multiple step-wise regressions were conducted and by using the correlation coefficients a flow chart was established to estimate the erosion resistance dependent on these factors (Gerlinger, 1997).

For the estimation of Manning's *n* a correlation between Manning's *n* of the rainfall experiments and the soil parameters was sought. But, the calculated correlation coefficients were quite low. Only a table for different crops could be established with ranges of Manning's *n* (Table 2). The model user must decide if the soil is dominated by clayey or wet conditions which result in a higher surface roughness. For dry conditions or mainly small aggregates the respective lower value of Manning's *n* should be applied. In addition, the shortening of a 1 m chain laid on the ground can be helpful to estimate Manning's *n*.

MODEL APPLICATION

Since the model does not implicitly calculate the infiltration, the effective rainfall,

Table 2 Estimated values for the roughness coefficient (Manning's *n*), based on the results of the rainfall experiments.

Land use or soil cover		Manning's *n* [m/s$^{1/3}$]: Low	Mean	High
Corn (seed bed to maturity)		0.015	0.042	0.145
Sugar beet (seed bed to maturity)		0.019	0.036	0.123
Freshly tilled soil (harrowed), crusted		0.015	0.037	0.074
Cereals (height up to 10 cm), crusted		0.010	0.026	0.050
Freshly tilled soil, chain shortening downslope:	<4 cm	0.010	0.030	0.067
	4–8 cm	0.012	0.036	0.123
	8–12 cm	0.020	0.059	0.190

which is one of the most influencing parameters, has to be known beforehand. Alternatively, the model can be applied in direct combination with the advanced hydrological HILLFLOW-2D model for hillslopes (Bronstert, 1994), which was developed in the same research project.

As an example for the model application a comparison of measured and simulated results of a rainfall experiment (plot size 22 m × 4 m) is depicted in Fig. 4. The model parameters for PEPP and HILLFLOW were determined using available soil parameters like the particle soil distribution and the antecedent moisture content. Figure 4 shows the correlation of the simulated and measured results.

Since 1994 the HILLFLOW model has been developed into the new model system CATFLOW (Maurer, 1997) for continuous simulation of catchment water dynamics. At the moment the PEPP model is included in the CATFLOW system with the aim of simulating erosive processes on the scale of small rural catchments.

PREDICTION OF PHOSPHORUS LOSSES

The removal of phosphorus from agricultural land is important from both a water quality and soil fertility aspect. Release and migration of phosphorus into surface water is predominated by particulate phosphorus moved with eroded sediment. Therefore an extension of the PEPP model to calculate transport and enrichment of phosphorus is investigated.

The particulate phosphorus concentration (PP) of runoff can be calculated from the total phosphorus content (TP) of the surface soil (Sharpley *et al.*, 1985):

$$PP = TP * SC * ER \qquad (4)$$

where PP = particulate P-concentration of runoff [mg l^{-1}]; TP = total phosphorus content of the surface soil [mg kg^{-1}]; SC = sediment concentration in runoff [kg l^{-1}]; ER = enrichment ratio [ ]. Following selective erosion and deposition processes, the runoff contains a larger percentage of fine particles which have a higher capacity per unit of sediment to adsorb phosphate. Because of that the enrichment ratio (ER) of

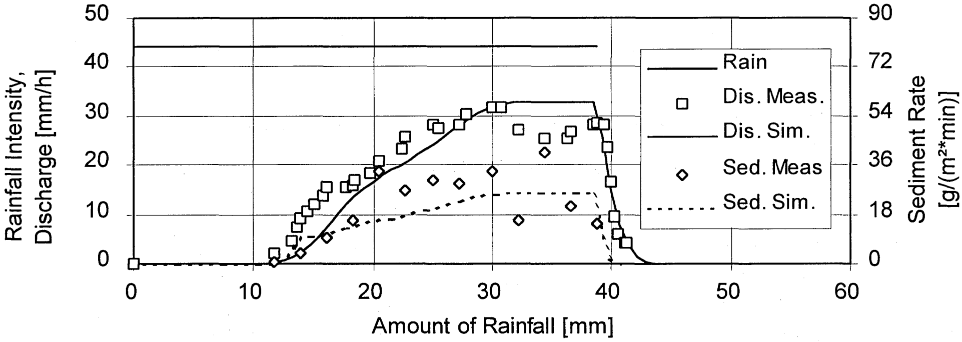

Fig. 4 Rainfall, discharge and sediment rate of the rainfall experiments at Neuenbürg on 19 October 1990. Comparison of measured and simulated results from PEPP-HILLFLOW.

Table 3 Values of the enrichment ratio (ER) of phosphorus for several rainfall experiments.

Rainfall experiment	Eroded sediment [kg ha^{-1}]	ER1 measured	ER2 deterministic calculation method	ER3 calculation method: Sharpley
Maize field 3 May 1993	4 483	0.93	1.14	1.23
Maize field 26 May 1993	14 167	1.16	1.07	0.9
Maize field 17 June 1993	3 125	1.37	2.05	1.36
Potato beet 4 May 1993	2 000	1.16	1.06	1.53
Sugar beet 4 May 1993	3 729	0.99	1.31	1.3
Sugar beet 26 May 1993	3 750	1.21	1.01	1.29

ER1: measured. ER2: calculated with the deterministic method. ER3: calculated with the equation of Sharpley *et al.* (1985) (König, 1994).

the phosphorus content of sediment (eroded soil) to that of source soil has to be known. Two possibilities to estimate the enrichment ratio (ER) have been tested:

(a) ER can be calculated by the following empirical equation developed by Sharpley *et al.* (1985):

$$\ln(\mathrm{ER}) = 2.48 - 0.27 \ln(\text{soil loss}) \tag{5}$$

where the units of soil loss are kg ha^{-1}.

(b) A deterministic calculation of ER is possible if the particle size distribution in runoff and the phosphorus content of the particle fractions of the source soil is measured.

To approve these equations for the Weiherbach catchment, the phosphorus contents of sediment samples from rainfall experiments have been analysed and compared to calculated values of ER (Table 3) and PP (Fig. 5) (König, 1994). The measured (ER1) and calculated (ER2, ER3) enrichment ratios have all been of the same magnitude, which seems to be typically for the erodible loess soils in the Weiherbach catchment (Table 3). Nevertheless there is a good correlation of measured and predicted particulate P-concentrations (PP) of runoff. Figure 5 shows

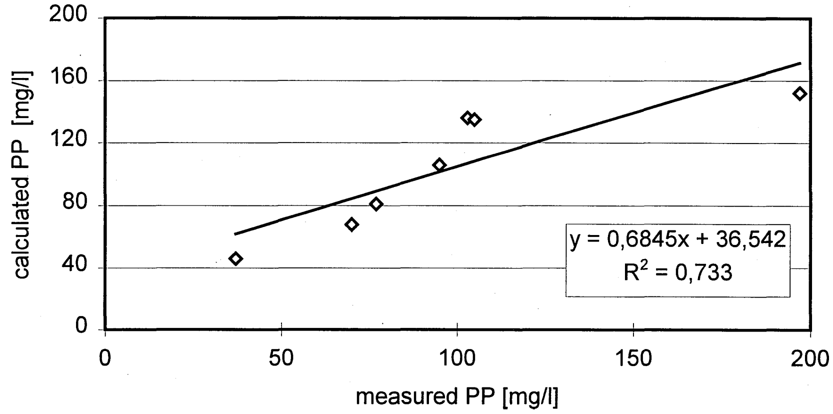

Fig. 5 Correlation between measured and calculated particulate phosphorus concentration (PP). Values of enrichment ratio (ER) calculated with the deterministic method.

the linear correlation of calculated and measured values of PP by using the deterministic method for the calculation of ER.

Accordingly the enrichment ratio (ER) is not a sensitive parameter for the calculation of particulate P-concentration (PP) of runoff. The amount of soil loss and the phosphorus content of the source soil are more important. Therefore the prediction of phosphorus removal in small rural catchments requires a precise simulation of water and sediment transport, which is expected from the combination of PEPP and CATFLOW.

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