

Simulation model for the computation of sediment yield due to upland and channel erosion from a large basin

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Abstract A mathematical simulation model for the computation of sediment yield due to upland and channel erosion from a large basin on a daily basis is presented in this paper. The model was tested with suspended load data obtained at the inlet of the Forggensee Reservoir (Bavaria, FR Germany), i.e. at the outlet of the corresponding basin ($\approx 1500 \text{ km}^2$). For more detailed calculations of the sediment yield the basin was divided into natural sub-basins. Components of this model are the Universal Soil Loss Equation (USLE; Wischmeier & Smith, 1978) used to compute soil detachment in each sub-basin, the rainfall-runoff model of Lutz (1984) used to estimate the runoff parameters of the USLE, the concept of overland flow sediment transport capacity used to compute sediment transported to the main channel of each sub-basin and the concept of channel flow sediment transport capacity used to compute sediment transported from a sub-basin to the next sub-basin.

Modèle de simulation pour calculer le débit solide résultant de l'érosion en surface et dans les lits du réseau hydrographique

Résumé Un modèle mathématique de simulation est présenté dans cet article pour calculer sur une base journalière le débit solide résultant de l'érosion en surface et dans les lits d'un grand bassin versant. Le modèle a été contrôlé à l'aide de données des solides en suspension à l'entrée du réservoir Forggensee (Bavière, RF Allemagne), c'est-à-dire à la sortie du bassin versant correspondant ($\approx 1500 \text{ km}^2$). Le bassin versant a été divisé en sous-bassins naturels pour calculer en détail le débit solide. Les composants du modèle sont l'Equation Universelle de Pertes en Sol (USLE; Wischmeier & Smith, 1978) pour calculer l'érosion du sol sur chacun des sous-bassins, le modèle précipitation-écoulement de Lutz (1984) pour estimer les paramètres de l'écoulement dans l'équation universelle, le concept de la capacité de transport de sédiments en surface pour calculer les sédiments apportés au cours d'eau principal de chaque sous-bassin et le concept de la capacité de transport de sédiment fluvial pour calculer les sédiments transportés d'un sous-bassin au sous-bassin suivant.

INTRODUCTION

The title of the present paper indicates the main objective of the model; but the wider objectives of the model include:

- (a) the computation of reservoir sedimentation if a reservoir lies at the outlet of the basin investigated, i.e. the computation of the input sediment rates for a reservoir sedimentation model;
- (b) the computation of transport rates for other pollutants e.g. phosphorus, nutrients, heavy metals etc., existing in the sediment.

The erosion in a basin may be divided into two general types: upland erosion and channel erosion. Erosion by water embodies the processes of detachment, transportation and deposition of soil particles (sediment) by the erosive and transport agents of raindrop impact and runoff over the soil surface (Foster, 1982).

The quantification of the erosion processes can be made more exact, if it is applied to small land areas. The specification of the size of the sub-areas is the result of a compromise between the following conflicting criteria:

- (a) the precision of the calculations and results;
- (b) the effort and time available for the performance of the calculations.

The smaller the area and time unit the more exact the calculations and results will be and the greater the effort and time that will be required for the performance of the calculations.

The processes quantified in this work are:

- (a) surface runoff (overland and channel flow) in each sub-area;
- (b) upland erosion and especially soil detachment by raindrop impact and runoff in each sub-area;
- (c) sediment delivery due to upland erosion from a sub-area to the main channel of the sub-area; this process includes implicitly the sub-processes of transportation, deposition and detachment of sediment over the soil surface;
- (d) sediment delivery due to channel erosion at the outlet of each sub-area; this process includes implicitly also the sub-processes of transportation, deposition and detachment of sediment over the main channel bed of each sub-area.

The model was applied to the 1500 km² basin of the Forggensee Reservoir (Bavaria, FR Germany) (Fig. 1). The largest part of the basin is in Austria and the main stem channel is the River Lech. The basin consists of forest, pasture, urban and rocky areas (over 2000 m in altitude). According to the above considerations the study basin was divided into 88 natural sub-basins (Fig. 1).

The following data were available:

- (a) suspended load at the outlet of the basin for 12 years (1966–1977), on a daily basis;
- (b) daily rainfall amounts from five rainfall stations in the basin for these same 12 years.

Sediment yield at the outlet of the basin was computed by the model on a daily basis because the rainfall amounts (input data) were available on a daily basis. Apart from this, the selection of the "day" as the time unit in the

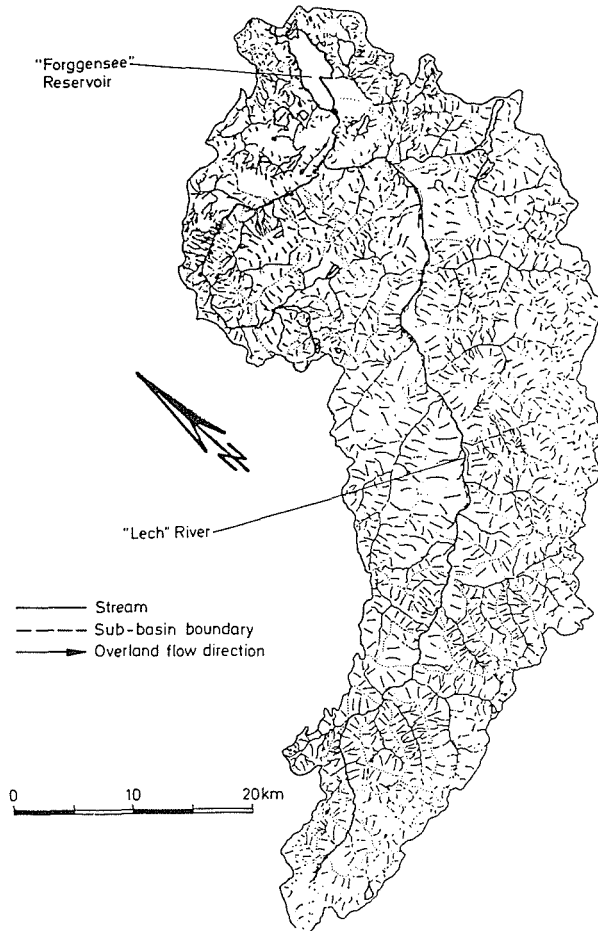


Fig. 1 Basin of the Forggensee Reservoir.

calculations is a very good approximation of the sediment delivery problem of a large basin.

It was assumed that uniform conditions exist in each sub-basin and that steady conditions exist throughout each day for the runoff and erosion processes. Daily rainfall occurrences were treated as individual storm events.

THE RAINFALL-RUNOFF MODEL

A rainfall-runoff model represents the first step in the development of a sediment transport model because raindrop impact and runoff shear stresses cause soil detachment and transportation. The rainfall-runoff model of Lutz (1984) was used to compute runoff parameters included in the sediment sub-models. It predicts rainfall excess for a given storm by using region-dependent and event-dependent parameters. Region-dependent parameters are the land use and the hydrological soil group which reflects the

infiltration rate.

The model of Lutz is expressed mathematically by the following equation:

$$Q = (N - A_v) c + (c/ao) \{ \exp [-ao(N - A_v)] - 1 \} \quad (1)$$

where:

N = daily rainfall amount (mm)

Q = rainfall excess (mm),

A_v = initial abstraction consisting mainly of interception, infiltration and surface storage and depending on the land use (mm),

c = maximum end runoff coefficient expected for a rainfall amount of about 250 mm and depending on the land use and the hydrological soil group

ao = proportionality factor (mm^{-1}) which is given by the following equation:

$$ao = P_1 \exp(-2.0/WZ) \exp(-2.0/QB) \quad (2)$$

where:

P_1 = a region-dependent parameter,

WZ = week number which designates the season,

$WZ = 1$ for week 31 of a year,

$WZ = 2$ for weeks 30 and 32 of the year etc., and

QB the baseflow rate which designates the antecedent moisture condition ($1 \text{ s}^{-1} \text{ km}^{-2}$).

The region-dependent parameters of the rainfall-runoff model were estimated by means of both topographic and geological maps and tables valid for the southern part of the FRG.

Another typical parameter required to estimate upland erosion resulting from runoff is the peak runoff rate. The following formula developed by the US Soil Conservation Service (SCS) was used to determine the peak runoff rate from a sub-basin (Huggins & Burney, 1982):

$$q_p = 0.278 FQ/T_A \quad (3)$$

where:

q_p = peak runoff rate ($\text{m}^3 \text{ s}^{-1}$),

F = sub-basin area (km^2),

Q = rainfall excess (mm) and

T_A = time of rise of the hydrograph (h).

This formula is based upon the SCS triangular hydrograph analysis procedure for approximating the manner in which an incremental volume of rainfall excess is translated into a time distribution of runoff at the sub-basin's outlet.

THE UNIVERSAL SOIL LOSS EQUATION (USLE)

The classical form of the USLE (Wischmeier & Smith, 1978) is:

$$A = R K L S C P \quad (4)$$

where:

- A = soil loss due to upland erosion (mass per unit area),
- R = the rainfall erosivity factor (energy per unit area \times rainfall intensity unit),
- K = the soil erodibility factor (A -unit/ R -unit),
- LS = the topographic factor,
- C = the crop management factor and
- P = the erosion control practice factor.

The USLE is intended to estimate average soil loss over an extended period, e.g. mean annual soil loss (Foster, 1982). However, only raindrop impact is taken into account in this equation to estimate soil loss. An improved erosivity factor was introduced by Foster *et al.* (1977) to take also into account the runoff shear stresses effect on soil detachment for single storms:

$$R = 0.5 R_{st} + 0.5 R_R = 0.5 R_{st} + 0.5 a Q q_p^{0.33} \quad (5)$$

where:

- R = modified erosivity factor ($\text{kgm m}^{-2} \text{ mm h}^{-1}$),
- R_{st} = rainfall erosivity factor ($\text{kgm m}^{-2} \text{ mm h}^{-1}$),
- R_R = runoff erosivity factor ($\text{kgm m}^{-2} \text{ mm h}^{-1}$),
- Q = runoff volume per unit area (mm),
- q_p = peak runoff rate per unit area (mm h^{-1}) and
- a = a constant depending on the units ($a = 0.70$).

Schwertmann (1981) converted the USLE from its original English units to metric units and presented tables for the evaluation of the factors K , C and P for Bavaria. The units and tables of Schwertmann were used in this work.

The rainfall erosivity factor is defined as the product of two rainstorm characteristics: kinetic energy and the maximum 30-min intensity. The computation of this factor for a rainfall event requires a continuous record of rainfall intensity. Only daily rainfall amounts were, however, available for the example basin. A regression analysis was therefore used to estimate the factor R_{st} as a function of the daily rainfall amount. Data for the rainfall erosivity factor and rainfall amount were available from a small basin ($\approx 14 \text{ km}^2$) in the neighbouring state of Baden-Württemberg. The topographic factor LS was evaluated as a function of the slope gradient and slope length (Wischmeier & Smith, 1978). In addition to the tables of Schwertmann, soil, topographic and vegetation maps were required for estimating the K , LS and C factors. The USLE was developed for small agricultural fields; therefore, the application of this equation to large areas, e.g. to the sub-basins of this example, results in only a rough estimate of soil erosion.

OVERLAND FLOW SEDIMENT TRANSPORT CAPACITY

Sediment from the upland erosion transported to the main channel of each sub-basin was computed by the concept of overland flow sediment transport capacity. The following relationships of Beasley *et al.* (1980) were used to compute the overland flow sediment transport capacity in each sub-basin:

$$TF = 146 sq^{1/2} \quad \text{for } q \leq 0.046 \text{ m}^3 \text{ min}^{-1} \text{ m}^{-1} \quad (6)$$

$$TF = 14\,600 sq^2 \quad \text{for } q > 0.046 \text{ m}^3 \text{ min}^{-1} \text{ m}^{-1} \quad (7)$$

where:

TF = overland flow sediment transport capacity ($\text{kg min}^{-1} \text{ m}^{-1}$),

s = slope gradient,

q = flow rate per unit width ($\text{m}^3 \text{ min}^{-1} \text{ m}^{-1}$).

The first equation is valid for laminar flow and the second for turbulent flow. The relationships of Beasley *et al.* (1980) are based upon the equation developed by Yalin (1963), who assumed that the mechanism of sediment transport by a shallow flow, e.g. by the overland flow, is similar to the mechanism of bed load transport in channels and that a critical shear stress exists acting on the soil at the beginning of sediment transport.

The amount of sediment due to upland erosion transported to the main channel of each sub-basin ES is estimated by means of the following controls. If the available sediment in a sub-basin VS exceeds overland flow sediment transport capacity TF , deposition occurs, and the sediment transported to the main channel of the sub-basin equals sediment transport capacity. If the available sediment in a sub-basin is less than overland flow sediment transport capacity and if the flow's erosive forces exceed the resistance of the soil to detachment by flow, detachment occurs; in this case sediment transported to the main channel of the sub-basin equals the available sediment. It is symbolized by the following relationships:

$$ES = TF \quad \text{if } A > TF \quad (8)$$

$$ES = A \quad \text{if } A \leq TF \quad (9)$$

However, sediment from the preceding sub-basin FLI is also transported to the sub-basin under consideration. The total sediment transported to the main channel of the sub-basin $ES1$ is therefore:

$$ES1 = ES + FLI \quad (10)$$

CHANNEL FLOW SEDIMENT TRANSPORT CAPACITY

The sediment yield from a sub-basin to the next sub-basin was computed by the concept of channel flow sediment transport capacity. The following relationships (Yang & Stall, 1976) were used to compute channel flow

sediment transport capacity:

$$\begin{aligned} \log c_t = & 5.435 - 0.286 \log (wD/v) - 0.457 \log (u_*/w) + [1.799 \\ & - 0.409 \log (wD/v) - 0.314 \log (u_*/w)] \log [(uJ/w) \\ & - (u_{cr}J/w)] \end{aligned} \quad (11)$$

where:

c_t = total sediment concentration, in parts per million by weight,

w = terminal fall velocity of sediment particles,

D = median sieve diameter of bed material,

ν = kinematic viscosity,

u_* = shear velocity,

u = average water velocity,

u_{cr} = critical average water velocity,

J = energy slope,

uJ = unit stream power and

$u_{cr}J$ = critical unit stream power at incipient motion.

$$u_{cr}/w = \frac{2.5}{\log(u_*/D/v) - 0.06} + 0.66, \text{ for } 1.2 < u_*/D/v < 70 \quad (12)$$

$$u_{cr}/w = 2.05, \text{ for } u_*/D/v \geq 70 \quad (13)$$

The basic form of equation (11) was determined from the concept of unit stream power and dimensional analysis. The rate of sediment transport in an alluvial channel is dominated by the rate of potential energy expenditure per unit weight of water, i.e. the unit stream power (Yang & Stall, 1976). From equation (11) is clear that a critical situation is considered at the beginning of sediment particle motion, as in most sediment transport equations. But the relationship of Yang has the advantage, in contrast to other published equations, that it was verified in natural rivers.

The sediment yield at the outlet of a sub-basin FLO reflects the same basic controls as the sediment transport rate ES :

$$FLO = TFH \quad \text{if } ES1 > TFH \quad (14)$$

$$FLO = ES1 \quad \text{if } ES1 \leq TFH, \quad (15)$$

where TFH is the channel flow sediment transport capacity, computed by means of equation (11). In the first case, if the available sediment in the main channel of the considered sub-basin $ES1$ exceeds channel flow sediment transport capacity TFH , deposition occurs. In the second case, if the available sediment $ES1$ is less than channel flow sediment transport capacity TFH , bed detachment may occur.

In this example only the erosion occurring in the main channel of each sub-basin was considered because large amounts of unavailable data for the geometry and hydraulics of the entire stream system would otherwise be required.

SYNTHESIS

The four component submodels, i.e. the rainfall-runoff model, the USLE, and the concepts of overland and channel flow sediment transport capacity, were combined to form the final model represented by the flow chart in Fig. 2.

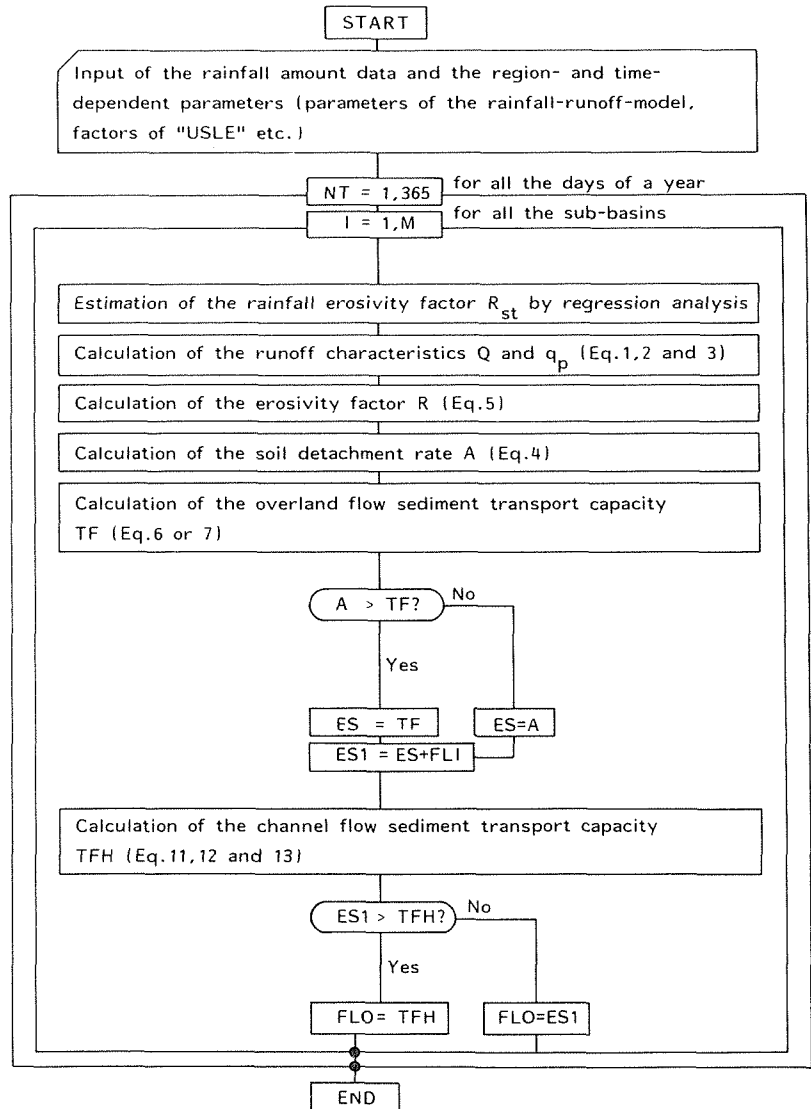


Fig. 2 Flow chart of the final model.

The application of this model requires the use of a sediment transport routing plan, which specifies the sediment motion from sub-basin to sub-basin.

RESULTS

Sediment yield at the outlet of the basin was computed by this model on a daily basis. The daily values of sediment yield were added to produce the annual value of sediment yield at the outlet of the basin. These computed annual values of sediment yield due to upland and channel erosion were compared with the measured values of "annual suspended load" plus "annual bed load" at the outlet of the basin. Annual bed load was assumed to be 20% of the annual suspended load (Schröder & Theune, 1984).

The ratios of the computed annual values of sediment yield associated with upland and channel erosion, to the measured values of sediment yield at the outlet of the whole basin are presented in Table 1.

A sensitivity analysis showed that rainfall amount and sub-basin area strongly affect daily sediment yield at the outlet of the whole basin.

Table 1 Ratio of computed to measured values of sediment yield

<i>Year</i>	<i>Measured value (t)</i>	<i>Computed value/ measured value</i>	<i>Year</i>	<i>Measured value (t)</i>	<i>Computed value/ measured value</i>
1966	585 600	1.46	1972	79 046	5.30
1967	351 600	2.45	1973	408 352	1.23
1968	374 400	1.78	1974	324 037	2.48
1969	246 000	1.74	1975	745 586	0.91
1970	1165 200	0.88	1976	315 772	1.36
1971	326 052	1.59	1977	312 025	2.18

CONCLUSIONS

The results are satisfactory considering the large basin area and the fact that the computation was performed on a daily basis and that no rainfall, runoff or sediment yield data were available for the sub-basins. These results are much better than those obtained for the same example when only upland erosion was taken into account and the whole basin was subdivided into subareas by means of a quadrangular grid (Hrissanthou, 1986).

The rainfall, runoff, soil detachment, deposition and transport processes in the large basin area were not considered in detail, but rather in a macroscopic way. It implies, for example, that soil deposition occurs, according to this model, in sub-basins with very low slope gradients or in channel reaches with very low bed slopes. In the other sub-basins or channel reaches, with greater slopes, all the detached soil mass is transported to the main channels of the sub-basins or to the next sub-basins.

Finally, this paper compares computed and measured values of sediment yield at the outlet of the entire basin. The comparison was made on an annual basis, although the calculations were performed on a daily basis. The following reasons are given for using an annual basis for the comparison:

- (a) the very long sediment travel times from the outlets of the most sub-basins to the outlet of the whole basin;
- (b) the problems of using a total daily rainfall amount;
- (c) the lack of runoff and sediment yield data in the sub-basins.

These reasons render the precise computation of daily sediment yield at the outlet of the whole basin difficult. The addition of the daily values of sediment yield at the outlet of the basin causes a decrease in the differences between computed and measured values of sediment yield.

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