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DISTRIBUTED MODELLING OF SOIL EROSION AND SEDIMENT TRANSPORT

V. HRISSANTHOU[1] AND A. PSILOVIKOS[2]

ABSTRACT

A mathematical model is used for the estimation of the annual sediment yield resulting from rainfall and runoff at the outlet of Nestos River basin (Toxotes, Thrace, Greece), where the ecologically interesting Nestos delta exists. The model is applied to that part of Nestos River basin (838 km^2) which lies downstream of three dams. Two dams (Thissavros and Platanovryssi) have been already constructed, while the third one (Temenos) is under construction. The model consists of three sub-models: a rainfall-runoff sub-model, a surface erosion sub-model and a sediment transport sub-model for streams. This model is also capable of computing the annual erosion amount and sediment yield in the individual sub-basins.

KEY WORDS: River basin, soil erosion, sediment transport, mathematical model.

1. INTRODUCTION

Nestos River flows through two European countries, Bulgaria and Greece, and discharges its water into Aegean Sea. In the Greek part of Nestos River, two dams (Thissavros and Platanovryssi) have been already constructed while a third dam (Temenos) is under construction. The construction of the dams and, therefore, the creation of the corresponding reservoirs implies the decrease of sediment yield at the basin outlet, in relation to the time before the construction of the dams, because of the reservoir sedimentation. It is worth of mention that an ecologically interesting delta at the basin outlet exists. Consequently, the sediment deposition regime of the delta is quantitavely influenced by the reservoir sedimentation.

This paper aims at the estimation of the annual sediment yield, due to rainfall and runoff, at the outlet of Nestos River basin. The main physical processes quantified in the present study are: runoff resulting from rainfall, soil surface erosion due to rainfall and runoff, inflow of soil erosion products into streams and sediment transport in streams. The quantification of the above chain of physical processes leads to the computation of sediment yield at the basin outlet. The sub-models which enable the quantification of the above mentioned physical processes are: a rainfall-runoff sub-model, a soil surface erosion sub-model and a sediment transport sub-model for streams. The individual sub-models are described in the following sections.

2. RAINFALL-RUNOFF SUB-MODEL

A simplified water balance model is used for the computation of the runoff h_o [mm] in a sub-basin (Giakoumakis and Tsakiris, 1992). As is well known, a part of the rainfall water can be stored in the root zone of the soil. If $S_{\max}$ [mm] is the maximum available soil moisture and S_n [mm] the available soil moisture for the time increment *n*, the difference $S_{\max} - S_n$ represents the soil moisture deficit for the time increment considered. It is obvious that the available soil moisture S_n [mm] increases through the rainfall N_n [mm] and decreases through the potential evapotranspiration E_{pn} [mm], the deep percolation IN_n [mm] and the runoff h_{on} [mm], where the index *n* designates the time increment. The balancing equation is written below:

$$S_n' = S_{n-1} + N_n - E_{pn} \qquad (1)$$

The runoff h_{on} [mm] and the deep percolation IN_n [mm] for the time step *n* can be evaluated as follows:

1. Democritus University of Thrace, Department of Civil Engineering, 67100 Xanthi, Greece.
2. University of Thessaloniki, Department of Geology, 54006 Thessaloniki, Greece.

If $S_n^{'} < 0$ then $S_n = 0$, $h_{on} = 0$ and $IN_n = 0$

If $0 \leq S_n^{'} \leq S_{\max}$ then $S_n = S_n^{'}$, $h_{on} = 0$ and $IN_n = 0$

If $S_n^{'} > S_{\max}$ then $S_n = S_{\max}$, $h_{on} = k(S_n^{'} - S_{\max})$ and

$IN_n = k'(S_n^{'} - S_{\max})$, where $k' = 1 - k$.

k and k' are proportionality coefficients.

The maximum available soil moisture $S_{\max}$ [mm] is estimated by the following relationship of Soil Conservation Service (SCS, 1972):

$$S_{\max} = 25.4[(1000/CN) - 10] \quad (2)$$

where CN is the curve number depending on the soil cover, the hydrologic soil group and the antecedent soil moisture conditions ($0 < CN < 100$).

The potential evapotranspiration E_{pn} [mm] is estimated by the radiation method improved by Doorenbos and Pruitt (1977). For this purpose, the following meteorological data are required: mean daily temperature, sunlight hours per day, mean daily relative humidity and mean daily wind velocity.

3. SOIL EROSION SUB-MODEL

The following relationships of Poesen (1985) are used for estimating soil surface erosion:

$$q_{rs} = C(KE)r_s^{-1}\cos a \quad (3)$$

$$q_r = q_{rs}[0.301\sin a + 0.019 D_{50}^{-0.22}(1 - e^{-2.42\sin a})] \quad (4)$$

where

q_{rs}: mass of detached particles per unit area [kg/m^2]

q_r: downslope splash transport per unit width [kg/m]

C: soil cover factor

KE: rainfall kinetic energy [J/m^2]

r_s: soil resistance to drop detachment [J/kg]

a: slope gradient [°]

D_{50}: median particle diameter [m]

The variables r_s, a and C are the "passive" factors of the detachment process because they refer to the soil surface, while KE is the "active" factor because it refers to the rainfall which induces detachment. At this point, it must be noted that the original relationship of Poesen for splash detachment is valid for bare soils. Therefore, an additional factor is necessary to express the decrease of splash detachment because of the vegetation. It is believed that the dimensionless vegetation factor of the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978) is appropriate to express the vegetation influence.

The rainfall kinetic energy KE [J/m^2] is given by the equation (Poesen, 1985):

$$KE = \beta N \quad (5)$$

where

N: rainfall amount [mm]

β: factor proportional to the square of the mean fall velocity of thec raindrops [J/(m^2 mm)]

The resistance of the soil material r_s [J/kg] can be given as a function of the median particle diameter D_{50} [m] by the equation (Poesen, 1985):

$$r_s = 1836.5 + 175.7 \ln D_{50}, \text{ for } 0.0001m < D_{50} < 0.0007m \quad (6)$$

The sediment transport by runoff q_f [m³/(s m)] is expressed as follows (Nielsen et al., 1986):

$$q_f = r q_t \quad (7)$$

where

q_t: sediment transport capacity by overland flow [m³/(s m)]

r: entrainment ratio; it equals 1 for noncohesive soils, while for cohesive soils it is less than 1.

The well known formula of Engelund and Hansen (1967) for sediment transport capacity by streamflow was modified especially for overland flow:

$$q_t = 0.04 \frac{(2g/f)^{1/6}}{(\rho_s/\rho - 1)^2 g^{1/2} D_{50}} q^{5/3} i^{5/3} \quad (8)$$

where

q: runoff rate [m³/(s m)]

i: energy slope

g: gravity acceleration [m/s²]

f: friction factor

ρ_s: sediment density [kg/m³]

ρ: water density [kg/m³]

D_{50}: [m] q_t : [m³/(s m)]

The friction factor f is given by the equation (Engelund and Hansen, 1967):

$$f = 2gh_o i / u^2 \quad (9)$$

where

h_o: flow depth [m]

u: mean flow velocity [m/s]

4. SEDIMENT INFLOW INTO STREAMS

The available sediment on the soil surface equals the sum "downslope splash transport + sediment transport by runoff". The sediment quantity reaching a stream from the respective basin area results by means of the following controls: If the available sediment in the stream basin exceeds overland flow sediment transport capacity, deposition occurs on the basin soil, and the sediment transported to the stream equals sediment transport capacity. If the available sediment in the 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 stream equals the available sediment.

5. SEDIMENT TRANSPORT SUB-MODEL FOR STREAMS

The sediment yield at the outlet of the stream considered is computed by the concept of sediment transport capacity by streamflow. The following relationships are used to compute sediment transport capacity by streamflow (Yang and Stall, 1976):

$$\log c_t = 5.435 - 0.286 \log \frac{wD_{50}}{v} - 0.457 \log \frac{u_*}{w} +$$

$$+ (1.799 - 0.409 \log \frac{wD_{50}}{v} - 0.314 \log \frac{u_*}{w}) \log(\frac{ui}{w} - \frac{u_{cr} i}{w}) \quad (10)$$

$$\frac{u_{cr}}{w} = \frac{2.5}{\log(u_* D_{50}/v) - 0.06} + 0.66, \text{ if } 1.2 < u_* D_{50}/v < 70 \quad (11)$$

$$\frac{u_{cr}}{w} = 2.05, \quad \text{if } \frac{u_* D_{50}}{\nu} \geq 70 \tag{12}$$

where

c_t: total sediment concentration by weight [ppm]

u: mean flow velocity [m/s]

u_{cr}: critical mean flow velocity [m/s]

u_*: shear velocity [m/s]

w: terminal fall velocity of sediment particles [m/s]

ν: kinematic viscosity of the water [m^2/s]

i: energy slope

D_{50}: median particle diameter of the bed material [m]

The sediment yield at the outlet of the stream considered is estimated by a similar concept as the sediment supply to the stream from soil surface erosion: If the available sediment in the stream exceeds sediment transport capacity by streamflow, deposition occurs, and the sediment outflow equals sediment transport capacity. If the available sediment is less than streamflow sediment transport capacity, bed detachment may occur, and the sediment outflow equals the available sediment.

Figure 1 shows the flow chart of the whole computational process.

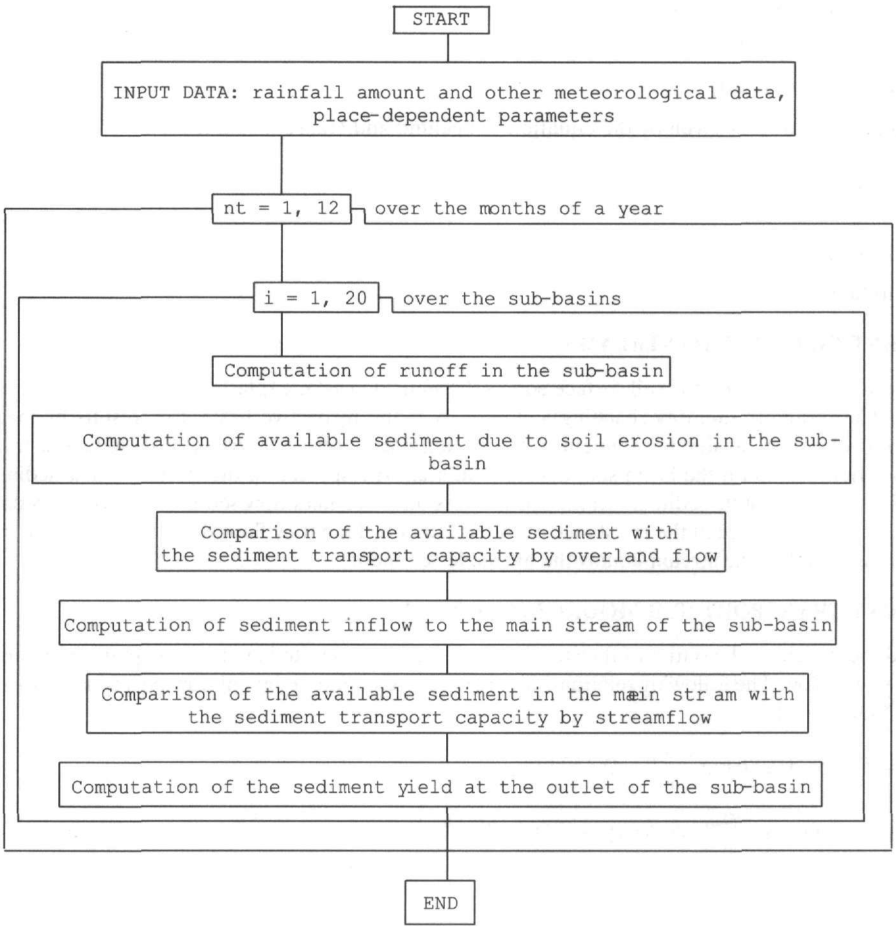

Figure 1: Flow chart of the computational process

6. APPLICATION TO NESTOS RIVER BASIN

The mathematical model described above was applied to that part of Nestos River basin which lies downstream of the dams. The area of this part of Nestos basin is about 838 km^2 consisting of forest (48%), bush (20%), cultivated land (24%), urban area (2%) and an area with no significant vegetation (6%). The highest altitude of the considered basin part is about 1600 m. The length of Nestos River in this part is about 55 km. The rocks were divided into permeable (38%), impermeable (41%) and semi-permeable (21%). The permeable rocks include marble, the impermeable rocks include schist, granite, granite-diorite, gneiss and gneiss-granite, while the semi-permeable rhyolite and lignite.

The basin was divided into 20 natural sub-basins (Figure 2) for more precise calculations. The area of the sub-basins varies between 13 and 67 km^2.

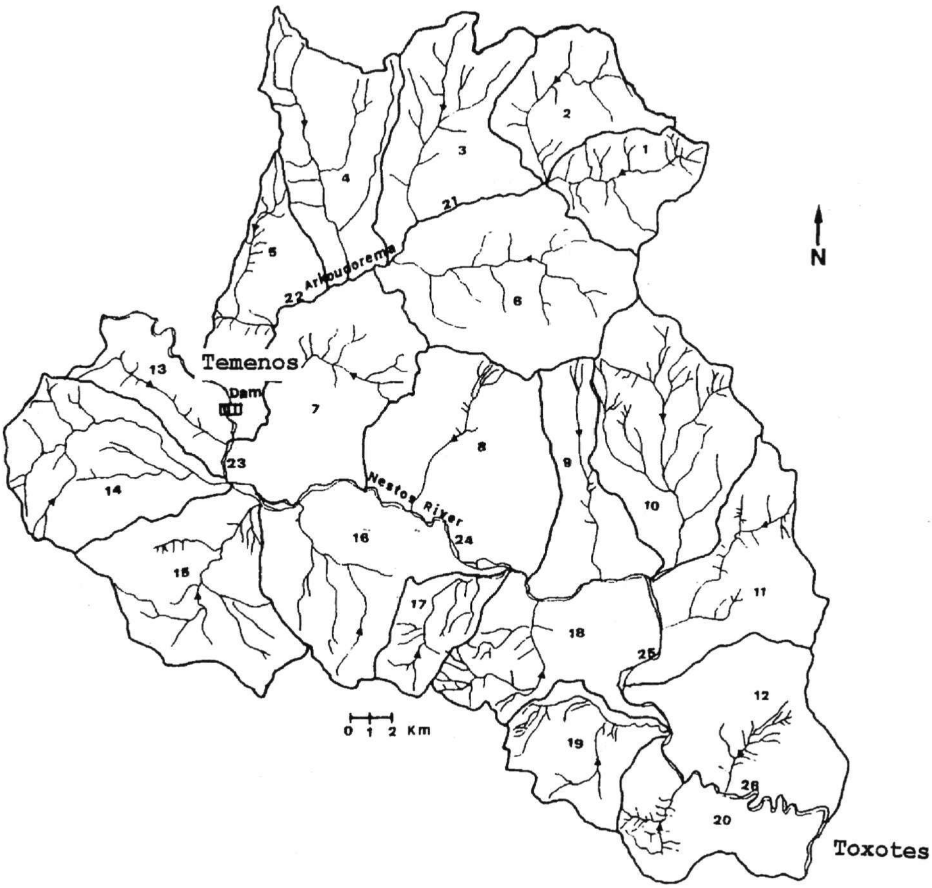

Figure 2: Stream system map of Nestos River basin (20 sub-basins)

Only the main stream of each sub-basin was considered for the sediment transport process. A sediment routing plan is necessary in order to specify the sediment motion from sub-basin to sub-basin.

Monthly rainfall data for 11 years (1980 - 1990) from eight rainfall stations were available. The mean annual value of the rainfall amount from the eight stations is 814 mm. For every month of the 11 years, mean daily values of air temperature, relative air humidity and sunlight hours from a meteorological station located near the basin outlet were also available. Mean daily values of wind velocity only for two years were obtained from the same meteorological station.

The sub-models described in the previous sections were applied to each sub-basin separately and for every month of a certain year. This way of working renders necessary the following assumptions: uniform conditions exist over a sub-basin and steady-state conditions exist throughout each month for the runoff, erosion and sediment transport processes.

7. ARITHMETIC RESULTS

The monthly values of sediment yield at the basin outlet resulting from the mathematical model for a certain year were added to produce the annual value of sediment yield YA due to surface and stream erosion. The annual surface erosion amount for the whole basin is symbolized with YD. The ratio of YA to YD is called the sediment delivery ratio (DR). The arithmetic results for YA, YD and DR for the years 1980 - 1990 are contained in Table 1.

Table 1: Arithmetic results foray, YD, and DR for different years

Year	*YA* [t]	*YD* [t]	*DR* [%]	Year	*YA* [t]	*YD* [t]	*DR* [%]
1980	298 000	896 000	33	1986	196 000	500 000	39
1981	528 000	1737000	30	1987	638 000	1109000	58
1982	446 000	1513000	29	1988	396 000	442 000	90
1983	80 000	132 000	61	1989	201 000	249 000	81
1984	492 000	1280000	38	1990	75 000	96 000	78
1985	119 000	119 000	100				

The mean values of the variables YA, YD and DR contained in Table 1 are 315 500 t, 734 000 t and 58%, respectively. Because of lack of sediment yield data at the basin outlet, the above mean values are compared with the mean values resulting from another mathematical model described in Hrissanthou et al. (2000). The latter model differs from the model described in the previous sections only in the soil surface erosion sub-model. The mean values of the variables YA, YD and DR , and, according to the mathematical model described in Hrissanthou et al. (2000), are 319 500 t, 672 500 t and 65%, respectively.

The model presented in this paper is also able to deliver erosion and sediment yield values for the individual sub-basins. For instance, sub-basins 2 and 10 (Figure 2) are selected for presentation of arithmetic results. Sub-basin 2 has an area of about 31 km^2 consisting of forest (45%) and no significant vegetation (55%). The mean soil slope gradient amounts to 23%. Sub-basin 10 has an area of about 62 km^2 consisting of forest (72%), bush (10%), cultivated land (12%), no significant vegetation (5%) and urban area (1%). The mean soil slope gradient amounts to 40%.

Table 2 contains the annual values of soil surface erosion (yd) in sub-basins 2 and 10, and the annual values of sediment yield (ya) at the outlets of sub-basins 2 and 10 for the years 1980 - 1990. It is obvious from Table 2 that the values of the variables yd and ya in sub-basin 2 are identical for the years considered. It means that the sediment delivery ratio for sub-basin 2 is 100%.

Table 2: Arithmetic results for yd and ya for different years

Year	Sub-basin 2 *yd* [t]	Sub-basin 2 *ya* [t]	Sub-basin 10 *yd* [t]	Sub-basin 10 *ya* [t]
1980	28 000	28 000	132 000	124 000
1981	15 000	15 000	158 000	141 000
1982	24 000	24 000	192 000	143 000
1983	15 000	15 000	6 000	6 000
1984	14 000	14 000	144 000	144 000
1985	2 000	2 000	15 000	15 000
1986	14 000	14 000	95 000	95 000
1987	25 000	25 000	110 000	110 000
1988	9 500	9 500	49 000	49 000
1989	6 000	6 000	24 000	24 000
1990	3 000	3 000	5 000	5 000

8. REMARKS

The most important drawbacks of the modelling chain are quoted below:

- The temporal development of the physical processes over the considered time period is not followed. The model computes only total values of runoff, soil erosion and sediment transport.
- The equations used for soil erosion and sediment transport were not adapted to local conditions; especially, the equations for soil erosion were developed for small experimental fields.
- Snowmelt runoff, gully and bank erosion were neglected.

9. CONCLUSIONS

- The small deviation between the corresponding mean annual values of soil erosion on the one hand and sediment yield on the other hand, according to two different mathematical models, is an encouraging indication for the size order of these quantities.
- The proportionality factor k of the hydrologic sub-model and the entrainment ratio r of the soil erosion sub-model were determined by calibration. All remaining parameters were estimated by means of tables, topographic or geologic maps and the available meteorologic data.
- It has to be stressed that a "middle behaviour" of the basin with reference to soil erosion and sediment transport is quantified by the model described above.

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