Comparative computation of soil erosion and reservoir sedimentation on a monthly and on a daily time basis

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Abstract The present study aims to compute sedimentation in Yermasoyia Reservoir in terms of soil erosion in the corresponding basin. Yermasoyia Reservoir is located northeast of the town of Limassol, Cyprus. The storage capacity of the reservoir is 13.6×10^6 m^3. Yermasoyia River drains a basin that, upstream of the reservoir, amounts to 122.5 km^2. Two versions of a mathematical model are used for the computation of the mean annual reservoir sedimentation. The first version consists of three submodels: a rainfall-runoff submodel, a soil erosion submodel and a sediment transport submodel for streams. In the first version, the calculations are performed on a monthly time basis. The second version consists of the same rainfall-runoff submodel and the same soil erosion submodel as the first version. However, instead of the sediment transport submodel for streams, the empirical concept of sediment delivery ratio is used. In the second version, the calculations are performed on a daily time basis. Daily rainfall data from three rainfall stations and other meteorological data from one meteorological station for three years (1987-1989) were available. The arithmetic results of the mean annual soil erosion rate, according to both versions of the mathematical model, are compared with erosion measuring data. Additionally, a comparison between the two model versions is made in relation to the arithmetic results of the mean annual sediment inflow into the reservoir and the mean annual reservoir sedimentation.
Keywords rainfall-runoff; soil erosion; sediment transport; reservoir sedimentation; Yermasoyia Reservoir

INTRODUCTION

Several studies of the first author, regarding the computation of the annual sediment yield due to rainfall and runoff, at the outlet of a large basin, were published in the past (e.g. Hrissanthou, 2002; 2005; 2006). The computation was based on the application of a mathematical model consisting of three submodels: a rainfall-runoff submodel, a soil erosion submodel, and a sediment transport submodel for streams. The calculations were performed on a monthly time basis, because monthly rainfall data were available on the one hand, and reasonable arithmetic values for the annual sediment yield resulted from the above model on the other hand.

In the present study, an attempt to perform the above mentioned computation on a daily time basis is made. In concrete terms, two versions of a mathematical model were applied to the basin of Yermasoyia Reservoir (Cyprus) with an area of 122.5 km^2, in order to compute the annual sediment yield at the basin outlet, namely the annual sediment inflow into the reservoir. The first version of the mathematical model consists of three submodels: a rainfall-runoff submodel, a soil erosion submodel and a sediment transport model for streams. The computation is performed on a monthly time basis. In the second version, the rainfall-runoff submodel and the soil erosion submodel are the same as in the first version; however, the stream sediment transport submodel is replaced by the empirical concept of sediment delivery ratio. The computation is performed on a daily time basis. At this point, it must be noted that the sediment transport from the outlets of the sub-basins to the outlet of a large basin cannot be quantified satisfactorily on a short time basis, e.g. on a daily time basis (Hrissanthou, 1990).

FIRST VERSION OF THE MATHEMATICAL MODEL

The first version consists of three submodels that were tested successfully in the past (Hrissanthou, 2006): a rainfall-runoff submodel (Giakoumakis *et al.*, 1991), a soil erosion submodel (Poesen, 1985) and a stream sediment transport submodel (Yang, 1973).

Rainfall-runoff submodel

A simplified water balance model for the root zone of the soil is used for the computation of the runoff in a sub-basin. The available soil moisture S (mm) in the root zone of the soil increases through rainfall N (mm), and decreases due to evapotranspiration E (mm), deep percolation IN (mm) and runoff h_o (mm). The balancing equation is

$$S_n^{'} = S_{n-1} + N_n - E_{pn} \tag{1}$$

where E_{pn} is the potential evapotranspiration for the time step n.

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

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 $k' = 1 - k$.

In the above relationships, S_{max} (mm) is the maximum available soil moisture and k, k' are proportionality coefficients. The maximum available soil moisture can be estimated as a function of the curve number depending on the soil cover, the hydrologic soil group and the antecedent soil moisture conditions (SCS, 1972).

The potential evapotranspiration E_p is computed by the radiation method improved by Doorenbos and Pruitt (1977).

The necessary input data for this hydrologic submodel concern rainfall, air temperature, sunlight hours, relative air humidity, wind velocity, altitude, latitude, land use, and soil composition. From the above data, the altitude and latitude of the sub-basins considered, and the meteorological data of air temperature, sunlight hours, relative air humidity and wind velocity are required for the computation of the potential evapotranspiration, and the land use and soil composition are required for the estimate of curve number.

Soil erosion submodel

The following relationships of Poesen (1985) are used for estimating soil erosion in a sub-basin:

$$q_{rs} = C(KE)r_s^{-1}\cos a \qquad (2)$$

$$q_r = q_{rs}[0.301\sin a + 0.019 D_{50}^{-0.22}(1 - e^{-2.42\sin a})] \qquad (3)$$

where q_{rs} (kg m^{-2}) is the mass of detached particles per unit area, C is the soil cover factor, KE (J m^{-2}) is the rainfall kinetic energy, r_s (J kg^{-1}) is the soil resistance to drop detachment, a (^{o}) is the mean slope gradient of the sub-basin area, q_r (kg m^{-1}) is the downslope splash transport per unit width, and D_{50} (m) is the median particle diameter.

The original relationship of Poesen for splash detachment is valid for bare soils. Therefore, the dimensionless vegetation factor of USLE (Universal Soil Loss Equation; Wischmeier & Smith, 1978) is used to express the vegetation influence.

The rainfall kinetic energy KE (J m^{-2}) and the resistance of soil material r_s (J kg^{-1}) can be given (Poesen, 1985) by

$$KE = \beta N \quad \text{and} \qquad (4)$$

$$r_s = 1836.5 + 1757\ln D_{50}, \text{ for } 0.0001\text{m} < D_{50} < 0.0007\text{m} \qquad (5)$$

respectively, where β (J m^{-2} mm^{-1}) is a factor proportional to the square of the mean fall velocity of the raindrops, and N (mm) is the rainfall amount.

The sediment transport by runoff q_f (m^3 s^{-1} m^{-1}) can be expressed as follows (Nielsen *et al.*, 1986):

$$q_f = r_e q_t \qquad (6)$$

where r_e is the entrainment ratio and q_t (m^3 s^{-1} m^{-1}) is the sediment transport capacity by overland flow. The entrainment ratio $r_e = 1$ for noncohesive soils and $r_e < 1$ for cohesive soils.

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

$$q_t = 0.04\frac{(2g/f)^{1/6}}{[(\rho_s/\rho) - 1]^2 g^{1/2} D_{50}} q^{5/3} s^{5/3} \qquad (7)$$

where q_t (m^3 s^{-1} m^{-1}) is the sediment transport capacity by overland flow, g (m s^{-2}) is the acceleration due to gravity, f is the friction factor, ρ (kg m^{-3}) is the water density, ρ_s (kg m^{-3}) is the sediment density, q (m^3 s^{-1} m^{-1}) is the runoff rate, and s is the energy slope.

The available sediment on the soil surface of a sub-basin equals the sum of the downslope splash transport plus the sediment transport by runoff. The sediment quantity reaching the main stream of a sub-basin is obtained by means of a comparison between the available sediment in the sub-basin and the sediment transport capacity by overland flow. If the available sediment in the sub-basin exceeds the overland flow sediment transport capacity, then deposition occurs on the sub-basin soil, and the sediment transported to the main stream equals the sediment transport capacity. If the available sediment in the sub-basin is less than overland flow sediment transport capacity, and if the flow's erosive forces exceed the resistance of the soil, then detachment occurs; in this case, it is assumed that sediment transported to the stream is equal to the available sediment.

The additional input data for the soil erosion submodel, with reference to the rainfall-runoff submodel, are: soil slope gradient, sub-basin area, soil cover, main stream length of the sub-basins, soil surface roughness, grain diameter, sediment and water density.

Stream sediment transport submodel

The sediment yield at the outlet of the main stream of a sub-basin can be estimated by a similar concept to the sediment supply to the main stream from soil erosion of the sub-basin:

If the available sediment in the stream exceeds sediment transport capacity by streamflow, then deposition occurs and the sediment outflow is equal to the sediment transport capacity.

If the available sediment is less than streamflow sediment transport capacity, then bed detachment may occur and the sediment outflow is equal to the available sediment.

For the computation of the sediment transport capacity by streamflow, the following relationships are used (Yang, 1973):

$$\log c_t = 5.435 - 0.286 \log\frac{wD_{50}}{\nu} - 0.457 \log\frac{u_*}{w} + \left(1.799 - 0.409 \log\frac{wD_{50}}{\nu} - 0.314 \log\frac{u_*}{w}\right)\log\left(\frac{us}{w} - \frac{u_{cr}s}{w}\right) \qquad (8)$$

$$\frac{u_{cr}}{w} = \frac{2.5}{\log(u_* D_{50}/\nu) - 0.06} + 0.66, \text{ if } 1.2 < u_* D_{50}/\nu < 70 \qquad (9)$$

$$\frac{u_{cr}}{w} = 2.05 \text{ if } u_* D_{50}/\nu \geq 70 \qquad (10)$$

where c_t (ppm) is the total sediment concentration by weight, w (m s^{-1}) is the terminal fall velocity of suspended particles, D_{50} (m) is the median particle diameter, ν (m^2 s^{-1}) is the kinematic viscosity of the water, u_* (m s^{-1}) is the shear velocity, u (m s^{-1}) is the mean flow velocity, u_{cr} (m s^{-1}) is the critical mean flow velocity, and s is the energy slope.

Equation (8) derived from the concept of "unit stream power" (rate of potential energy expenditure per unit weight of water, us) and dimensional analysis is a total load equation considering a critical situation at the beginning of sediment particle motion, as most of sediment transport equations.

The additional input data for the stream sediment transport submodel, with reference to the foregoing submodels, are with regard to the streams considered: baseflow, bottom slope, bottom width, bed roughness, diameter of suspended particles, grain diameter of bed material, and kinematic viscosity of water.

SECOND VERSION OF THE MATHEMATICAL MODEL

The second version of the mathematical model consists of the rainfall-runoff submodel and the soil erosion submodel described above in the first version, and of the empirical concept of sediment delivery ratio. It is the annual percetage of soil erosion amount in a basin which reaches the basin outlet.

The following empirical equation of Williams (1977) was used for the estimate of sediment delivery ratio:

$$DR = 1.366 x 10^{-11} F^{-0.0998} s^{0.3629} CN^{5.444} \tag{11}$$

where DR is the sediment delivery ratio, F (km^2) is the basin area, s is the average slope gradient of the main stream of the basin (m km^{-1}), and CN is the curve number.

APPLICATION TO YERMASOYIA RESERVOIR BASIN

Yermasoyia Reservoir is located northeast of the town of Limassol, Cyprus. The storage capacity of the reservoir is 13.6x10^6 m^3. Yermasoyia River drains a basin that, upstream of the reservoir, amounts to 122.5 km^2. The length of the main stream of the basin is about 25 km, and the highest altitude of the basin is about 1400 m. Both versions of the mathematical model described above were applied to the basin of Yermasoyia Reservoir, which was divided into four natural sub-basins for more precise calculations (Fig. 1). The sub-basin areas vary between 14 and 44 km^2. The basin considered consists of forest (57.7%), bush (33.7%), cultivated land (5.8%), urban area (1.8%) and an area with no significant vegetation (1%).

Daily rainfall data for three years (1987 – 1989) from three rainfall stations were available. The mean annual rainfall at these stations amounts to 674 mm. Additionally, mean daily values of air temperature, relative air humidity and wind velocity were available from a meteorological station for the above three years. Daily values of sunlight hours for the three years were obtained from the same meteorological station.

Finally, the distribution of mean annual erosion rates over the island of Cyprus was obtained from the Water Development Department (Nicosia, Cyprus). According to this authority, the erosion rates have been deduced and assigned to the various geomorphologic areas of Cyprus on the basis of existing, randomly obtained, suspended sediment samples and mainly on the basis of estimates derived by surveying three dams.

The first version of the mathematical model was applied to each sub-basin separately and on a monthly time basis for a certain year. Only the main stream of each sub-basin was considered in the sediment transport model for streams. The second version of the mathematical model was also applied to each sub-basin separately, but on a daily time basis for a certain year.

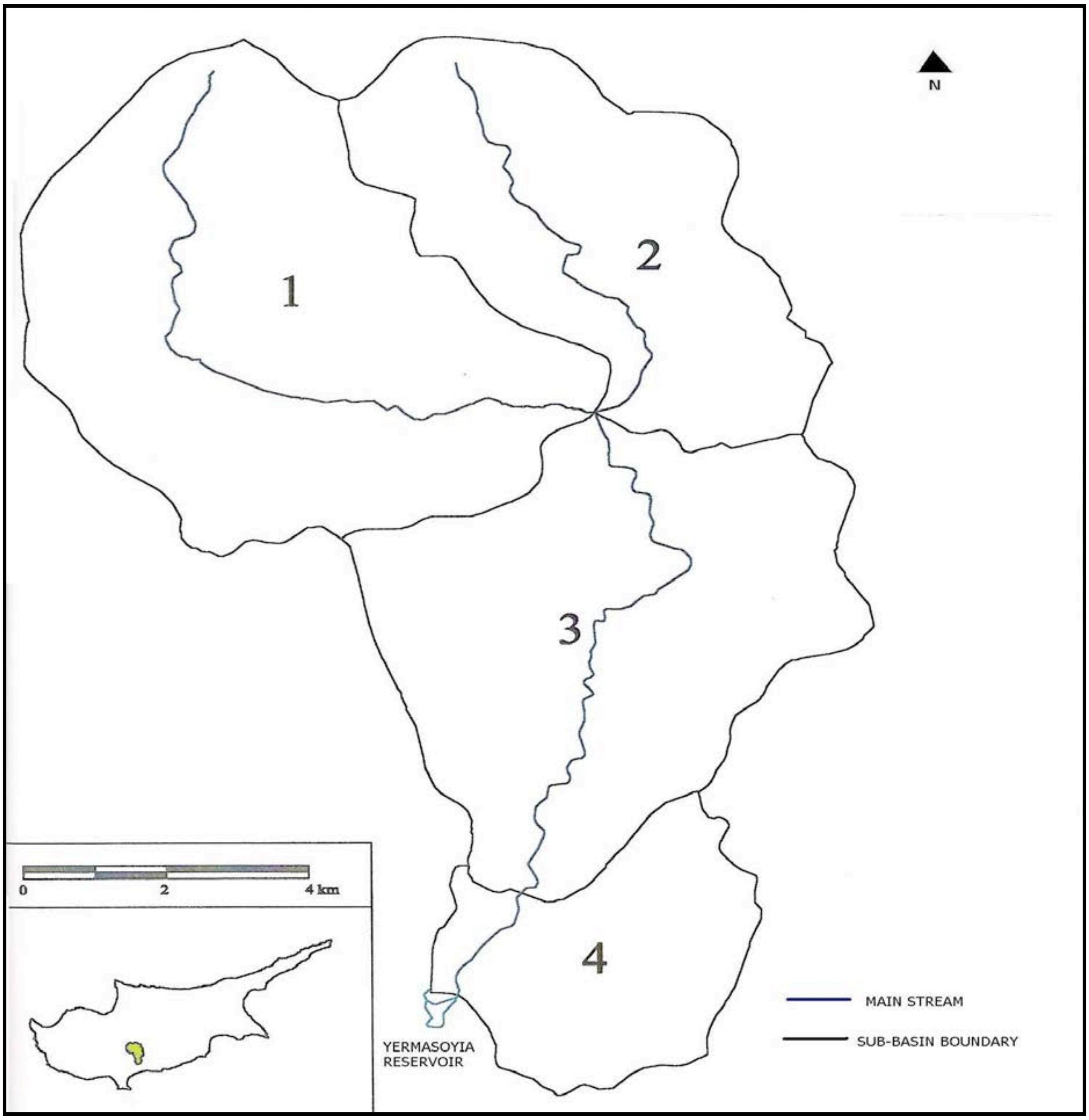

Fig. 1 Yermasoyia Reservoir basin divided into four sub-basins.

ARITHMETIC RESULTS

The monthly values of sediment yield at the basin outlet resulting from the first version of the mathematical model for a given year were added to produce the annual value of sediment yield YA due to soil and stream erosion. The annual soil erosion amount for the whole basin is symbolized with YD. The ratio of YA to YD is called the sediment delivery ratio DR. The computational results for YD, YA and DR for the years 1987 – 1989 are shown in Table 1.

Table 1 Computational results of the first version of the mathematical model.

Year	YD (t)	YA (t)	DR (%)
1987	681 000	229 000	34
1988	533 000	255 000	48
1989	72 000	59 000	82
Mean value	429 000	181 000	55

The daily values of the soil erosion amount for the four sub-basins resulting from the second version of the mathematical model are added to produce the daily value of the soil erosion amount for the whole basin. The daily values of the soil erosion amount of the whole basin for a certain year are added to produce the annual value of the soil erosion amount, YD, for the whole basin.

The sediment delivery ratio (DR), according to equation (11), equals 29%. The annual sediment yield, YA, due to soil erosion at the outlet of the whole basin results by multiplying the YD value by DR. The computational results for YD, DR and YA for the years 1987 – 1989 are shown in Table 2 (Galani & Hrissanthou, 2005).

Table 2 Computational results of the second version of the mathematical model.

Year	YD (t)	DR (%)	YA (t)
1987	807 000	29	234 000
1988	43 000	29	12 500
1989	474 000	29	138 000
Mean value	441 000	29	128 000

The mean annual values of YD, 429 000 t and 441 000 t, are transformed into the mean annual rates of soil erosion, 1.32 mm and 1.36 mm respectively. Both latter values are approximately 1.9 times higher than the corresponding estimated value of 0.70 mm (Water Development Department, Nicosia, Cyprus). This estimated value is assigned to areas with igneous rocks, steep slopes and rainfall rates of the order of 600 – 800 mm year^{-1}, covered by forest, brush and with little cultivation. These climatic and physiographic conditions are fulfilled by the basin of Yermasoyia Reservoir.

According to the classical diagram of Brune (1953), the trap efficiency of Yermasoyia Reservoir is 100%. This means that all of the sediment yield at the basin outlet is deposited in the reservoir. The mean annual sediment volume deposited in the reservoir equals 97 600 m^3 according to the first model version, and 69 000 m^3 according to the second model version. Considering the storage capacity of the reservoir (13.6x10^6 m^3), its useful life thus amounts to 139 years according to the first version of the mathematical model, and to 197 years according to the second version of the mathematical model.

REMARKS AND CONCLUSIONS

The deviation between the two mean annual erosion rates calculated according to the first and the second version of the mathematical model, respectively, is negligible. Consequently, regarding the computation of the annual soil erosion, the time basis of the computations does not play a significant role. However, both model versions overestimate the mean annual erosion rate resulting from measurements.

The mean annual sediment yield at the basin outlet according to the first model version is about 1.4 times higher than the corresponding value according to the second model version. This arithmetic result may be justified by the fact that sediment yield according to the fist model version is due to soil and stream erosion, while sediment yield according to the second model version is due only to soil erosion.

The mean annual deposition volume in the reservoir according to the first model version is about 1.4 times higher than the corresponding deposition volume according to the second model version. The present arithmetic result is a reasonable consequence of the previous arithmetic result.

The mean value of the sediment delivery ratio according to the first model version is about 1.9 times higher than the constant year-independent value of sediment delivery ratio according to the second model version.

Finally, it has to be noted that the small number of years considered in this study does not allow to draw widely representative conclusions.

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