

Erosion and sediment transport in the basin of the Yermasoyia Reservoir, Cyprus

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Abstract The Yermasoyia Reservoir is located northeast of the town of Limassol, Cyprus. The basin area of the Yermasoyia River, which feeds the reservoir with water, totals 122.5 km². This study aims to estimate the annual sediment inflow into the Yermasoyia Reservoir from its basin using a mathematical model. The whole model consists of three individual models: a rainfall-runoff model, a physically-based soil erosion model and a sediment transport model for streams. The sediment transport capacity of streamflow, which is incorporated into the sediment transport model, is calculated by the relationships of van Rijn (1984). Monthly rainfall data from three rainfall stations, and data from a meteorological station for four years (1986–1989), were available. The soil erosion estimates are compared with erosion measurement data. Additionally, the estimated values of sediment inflow into the reservoir are compared with values estimated by another model that differs from the present model only in the relationships for sediment transport capacity by streamflow (Yang & Stall, 1976).

Key words reservoir; sediment transport; soil erosion; Yermasoyia Reservoir, Cyprus

NOTATION

| | |
|----------|---|
| α | Slope gradient ($^{\circ}$); reference distance from the bed (m) |
| A | Sub-basin area (m ²) |
| b | Width of the sub-basin area (m) |
| C | Soil cover factor |
| C_a | Reference concentration in distance a (m) from the bed |
| D_{50} | Median particle diameter (m) |
| D^* | Bonnefille number (dimensionless particle diameter) |
| DR | Sediment delivery ratio (%) |
| E | Dimensionless coefficient |
| F | Correction factor for suspended load |
| g | Gravity acceleration (m s ⁻²) |
| h | Flow depth (m) |
| q | Runoff rate per unit width (m ³ s ⁻¹ m ⁻¹) |
| q_{GV} | Bed load transport (m ³ s ⁻¹ m ⁻¹) |
| q_{SV} | Suspended load transport (m ³ s ⁻¹ m ⁻¹) |
| q_{TV} | Total load transport (m ³ s ⁻¹ m ⁻¹) |
| q_{cf} | Available sediment discharge per unit width (kg m ⁻¹ s ⁻¹) |
| r | Rainfall intensity (m s ⁻¹) |
| T^* | Transport stage parameter |
| u | Mean flow velocity (m s ⁻¹) |

| | |
|----------------|---|
| u_f | Mean fall velocity of the droplets (m s^{-1}) |
| u_s' | Shear velocity related to the grain roughness (m s^{-1}) |
| $u_{s,cr}$ | Critical shear velocity (m s^{-1}) |
| YA | Annual value of sediment yield at the basin outlet (t) |
| YD | Annual value of soil erosion amount for the whole basin (t) |
| ν | Kinematic viscosity of water ($\text{m}^2 \text{s}^{-1}$) |
| ρ | Water density (kg m^{-3}) |
| ρ_s | Sediment density (kg m^{-3}) |
| ρ' | Relative sediment density $[(\rho_s - \rho)/\rho]$ |
| φ_{cr} | Critical momentum flux (kg m s^{-2}) |
| φ_f | Momentum flux by the overland flow (kg m s^{-2}) |
| φ_r | Momentum flux by the droplets (kg m s^{-2}) |

INTRODUCTION

The Yermasoyia Reservoir is located northeast of the town of Limassol, Cyprus. The storage capacity of the reservoir is $13 \times 10^6 \text{ m}^3$. The Yermasoyia River feeds the reservoir with water; its basin area upstream of the reservoir amounts to 122.5 km^2 . This study aims to estimate the annual sediment inflow into the Yermasoyia Reservoir from the basin.

The main physical processes quantified in the present study are: runoff resulting from rainfall, soil 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, i.e. at the reservoir inlet.

For the quantification of runoff, a rainfall–runoff model (Giakoumakis & Tsakiris, 1992) is used, while for the quantification of soil erosion, a physically-based soil erosion model (Schmidt, 1992) is applied. Schmidt's model has been applied previously by the first author to basins where no erosion measurement data were available (e.g. Hrissanthou, 2002). However, for the basin considered in this study, estimates of soil erosion are available.

For the quantification of stream sediment transport, the relationships of Yang & Stall (1976), concerning sediment transport capacity by streamflow, have been used by the first author several times. Here a different concept for the computation of sediment transport capacity by streamflow (van Rijn, 1984) is applied.

RAINFALL–RUNOFF MODEL

A simplified water balance model of the root zone of the soil is used for the computation of the runoff in a sub-basin (Giakoumakis & Tsakiris, 1992). The available soil moisture in the root zone of the soil increases through rainfall, and decreases due to potential evapotranspiration, deep percolation and runoff. The available soil moisture for the time increment considered is compared with the maximum available soil moisture. The equations of the model are given in Hrissanthou (2002).

SOIL EROSION MODEL

According to Schmidt (1992), the erosive impact of droplets and overland flow is proportional to the momentum flux contained in the droplets and the flow, respectively. The momentum flux exerted by the falling droplets, φ_r , is given by the relationship:

$$\varphi_r = Cr\rho Au_r \sin a \quad (1)$$

The original Schmidt relationship for rainfall erosion is only valid for bare soils. Therefore, an additional factor is necessary to express the decrease of rainfall erosion because of vegetation. It is believed that the dimensionless vegetation factor C of the USLE (Wischmeier & Smith, 1978) is appropriate to express the vegetation influence.

The momentum flux exerted by the overland flow, φ_f , is given by the relationship:

$$\varphi_f = q\rho bu \quad (2)$$

The available sediment discharge q_{rf} , due to rainfall and runoff, in a sub-basin area is given by the following equation:

$$q_{rf} = (1.7E - 1.7)10^{-4} \quad (3)$$

where:

$$E = (\varphi_r + \varphi_f) / \varphi_{cr} \quad (E > 1) \quad (4)$$

The critical momentum flux φ_{cr} designates the soil erodibility.

The sediment supply to a stream is estimated by means of a comparison between the available sediment in the corresponding basin area and the sediment transport capacity of the overland flow (Hrissanthou, 2002).

STREAM SEDIMENT TRANSPORT MODEL

The sediment yield at the outlet of the stream considered can be computed by the concept of sediment transport capacity by streamflow. This capacity is estimated by means of the relationships of van Rijn (1984), who computes the bed load transport and the suspended load transport separately.

The bed load transport, q_{GV} , is given by the relationship:

$$q_{GV} = 0.053 \frac{T^{*2.1}}{D^{*0.3}} \sqrt{\rho'g} D_{50}^{1.5} \quad (5)$$

The transport stage parameter T^* is defined as:

$$T^* = \left(\frac{u'_*}{u_{*cr}} \right)^2 - 1.0 \quad (6)$$

The Bonnefille number D^* (dimensionless particle diameter) is defined as follows:

$$D^* = \left(\frac{\rho' g}{\nu^2} \right)^{1/3} D_{50} \quad (7)$$

The suspended load transport, q_{SV} , is given by the equation:

$$q_{SV} = FuhC_a \quad (8)$$

The reference concentration C_a in a distance a from the bed results from the equation:

$$C_a = 0.015 \frac{D_{50} T^{*1.5}}{a D^{*0.5}} \quad (9)$$

The correction factor F takes mainly into account the damping of turbulence.

The total load q_{TV} , which is identical with the sediment transport capacity of the streamflow, is the sum of q_{GV} and q_{SV} .

The sediment yield at the outlet of the stream considered is estimated by comparing the available sediment in the stream with the sediment transport capacity by streamflow (Hrissanthou, 2002).

APPLICATION TO THE YERMASOYIA RESERVOIR BASIN

The three models described above were combined to form a composite mathematical model. This model was applied to the basin of Yermasoyia Reservoir (122.5 km²), consisting of forest (57.7%), bush (33.7%), cultivated land (5.8%), urban area (1.8%) and an area with no significant vegetation (1%). The highest altitude of the basin is about 1400 m. The length of the main stream of the basin is about 25 km. The basin was divided into four natural sub-basins for more precise calculations (Fig. 1).

Monthly rainfall data for four years (1986–1989) from three rainfall stations were available. The mean annual rainfall at these stations amounts to 662 mm. For every month of the four years, mean daily values of air temperature, relative air humidity and sunlight hours were also available from a meteorological station. Mean daily values of wind velocity only for one year (1988) were obtained from the same meteorological station.

The mathematical model was applied to each sub-basin separately and for every month of a certain year. Only the main stream of each sub-basin was considered in the sediment transport model for streams, because numerous unavailable data for the geometry and hydraulics of the entire stream system would otherwise be required.

ARITHMETIC RESULTS

The monthly values of sediment yield at the basin outlet resulting from the 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 arithmetic results for YA , YD and DR for the years 1986–1989 are shown in Table 1.

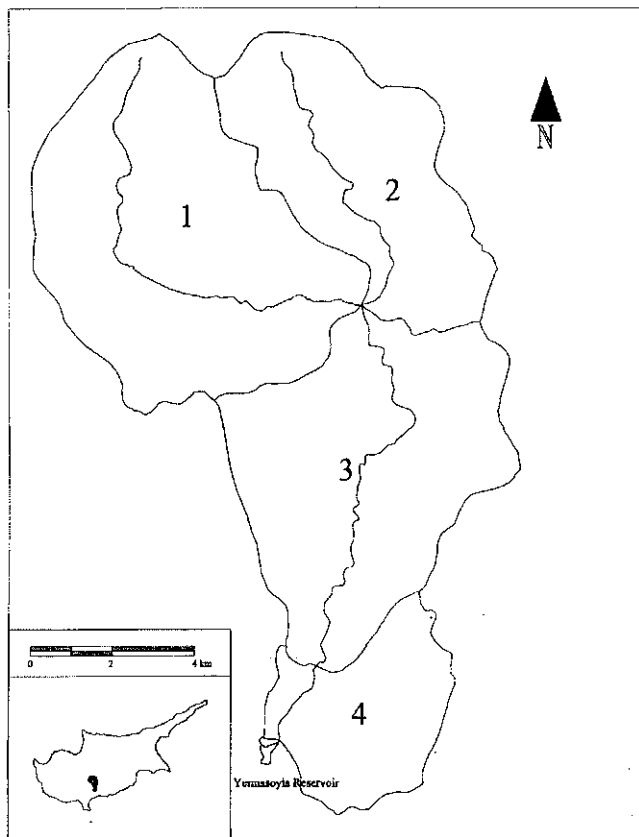


Fig. 1 Main streams of the sub-basins of Yermasoyia Reservoir basin.

Table 1 Results for YD , YA and DR for different years.

| Year | YD (t) Schmidt | YA (t) van Rijn | DR (%) van Rijn | YA (t) Yang-Stall | DR (%) Yang-Stall |
|------------|---------------------|----------------------|----------------------|------------------------|------------------------|
| 1986 | 113 000 | 28 000 | 25 | 32 000 | 28 |
| 1987 | 673 000 | 368 000 | 55 | 224 000 | 33 |
| 1988 | 618 000 | 299 000 | 48 | 238 000 | 38 |
| 1989 | 108 000 | 27 000 | 25 | 30 000 | 28 |
| Mean value | 378 000 | 180 500 | 38 | 131 000 | 32 |

The mean value of YD (378 000 t) is transformed into the mean annual rate of soil erosion (1.2 mm). The latter value is 1.7 times greater than the corresponding measured value of 0.70 mm (Water Development Department, Nicosia, Cyprus).

Table 1 also shows the YA and DR values estimated by another model which differs from the present model only in the relationships used for the computation of sediment transport capacity by streamflow (Yang & Stall, 1976). The model with the relationships of Yang & Stall is described in Hrisanthou (2002). The mean annual value of YA resulting from the model using the relationships of van Rijn is 1.4 times

higher than the corresponding value resulting from the model using the relationships of Yang & Stall.

According to the diagram of Brune (1953), the trap efficiency of the Yermasoyia Reservoir is 100%. It means that all of the sediment yield at the basin outlet is deposited in the reservoir. The useful life of the Yermasoyia Reservoir thus amounts to 140 years according to the present model (van Rijn), and to 190 years according to the second model (Yang & Stall).

DISCUSSION

The comparison between the two models focuses on the comparison between the total load models of Yang & Stall and van Rijn.

The relationships of Yang & Stall constitute a regression model based on the “unit stream power” concept. Additionally, they include the difference between flow velocity and its critical value in a dimensionless form, and are valid for a certain range of bed width, bed slope, flow depth, flow velocity and grain size. It should be noted that the bed slope of the main stream in two of the sub-basins, in this case study, exceeds the application limit of this model.

In the van Rijn model, the bed load transport and suspended load transport are calculated separately. In the bed load equations, the shear velocity is compared with its critical value, while in the suspended load equations, the shear velocity is compared with the settling velocity of the particles.

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