Sediment control in the basin of Kastoria Lake

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Abstract

Kastoria Lake is located in northwestern Greece. The whole basin of the lake is about 253 km^2. The torrents of the sub-basins located around Kastoria Lake transport considerable sediment quantities that inflow to the lake and are deposited on the lake bottom. The sediment load reaching the lake arises from the soil erosion, due to rainfall and runoff, of the sub-basins and from the bed erosion of the torrents. In this paper, a mathematical model for the computation of sediment load inflowing to the lake is described. The model consists of three sub-models: a rainfall-runoff sub-model, a soil erosion sub-model and a sediment transport sub-model for streams. On the basis of the mathematical model, those sub-basins are identified which deliver most sediment load to the lake. Additionally, control measures for the reduction of soil erosion and torrent bed erosion are proposed at certain places of the sub-basins.

1 Introduction

Kastoria Lake is located in northwestern Greece, near the borderline between Greece and Albania. The mean water surface area of the lake is about 28 km^2, while the whole basin of the lake is about 253 km^2. The torrents of the sub-basins located around Kastoria Lake transport considerable sediment quantities inflowing to the lake and deposited on the lake bottom. This fact causes the reduction of the water volume capacity with time. The sediment load inflowing to the lake arises from the soil erosion, due to rainfall and runoff, of the sub-basins and from the bed erosion of the torrents.

The reduction of the sediment quantity inflowing to the lake can be achieved by means of erosion control measures in the sub-basins. In order to identify those sub-basins which delivet most sediment load to the lake, a mathematical model for the computation of sediment yield at the outlet of the sub-basins is used. The model consists of three sub-models: a rainfall-runoff sub-model, a soil erosion sub-model and a sediment transport sub-model for streams. In each sub-basin, only the main stream is considered. The sub-models are described in the following sections.

2 Rainfall-runoff sub-model

As is well known, both rainfall and runoff can induce erosion of the soil surface. The rainfall-runoff sub-model aims at the estimation of runoff in a sub-basin on the basis of the rainfall amount.

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 [mm] increases through the rainfall N [mm] and decreases through the potential evapotranspiration E_p [mm], the deep percolation IN [mm] and the runoff h_o [mm]. The balancing equation is written below [1]:

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

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 $0 \le S_n' \le S_{\max}$ 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, k': proportionality coefficients).

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

$$S_{\max} = 25.4\left(\frac{1000}{CN} - 10\right) \tag{2}$$

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

3 Soil erosion sub-model

The erosive impact of droplets and overland flow is proportional to the momentum flux contained in the droplets and the flow, respectively [2].

The momentum flux exerted by the falling droplets φ_r [kg (m/s^2)] is given by the relationship:

$$\varphi_r = CrAu_r \sin a \tag{3}$$

where

C : soil cover factor

r : rainfall intensity [m/s]

A : sub-basin area [m^2]

u_r : mean fall velocity of the droplets [m/s]

a : mean slope gradient of a sub-basin [°]

The fall velocity of the droplets u_r [m/s] is a function of the rainfall intensity r [m/s] according to the following equation [2]:

$$u_r = 4.5 r^{0.12} \tag{4}$$

The momentum flux exerted by the overland flow φ_f [kg (m/s^2)] is given by the relationship:

$$\varphi_f = q\rho bu \tag{5}$$

where

q : runoff rate per unit width [m^3/(s m)]

ρ : water density [kg/m^3]

b : width of a sub-basin [m]

u : mean flow velocity [m/s]

The available sediment discharge q_{rf} [kg/(s m)], due to rainfall and runoff, in the sub-basin considered is given by the following equation [2]:

$$q_{rf} = (1.7E - 1.7)10^{-4} \tag{6}$$

where $$E = \frac{\varphi_r + \varphi_f}{\varphi_{cr}} \quad (E > 1) \tag{7}$$

The critical momentum flux φ_{cr} [kg (m/s^2)], which designates the soil erodibility, can be calculated from the equation:

$$\varphi_{cr} = q_{cr}\rho b u \tag{8}$$

where

q_{cr} : runoff rate per unit width at initial erosion [m^3/(s m)]

4 Sediment supply to the main stream of a sub-basin

The sediment supply to the main stream of a sub-basin is estimated by means of a comparison between the available sediment discharge q_{rf} [kg/(s m)] in the sub-basin and the sediment transport capacity by overland flow q_t [kg/(s m)]: If q_{rf} exceeds q_t, deposition occurs on the sub-basin soil, and the sediment transported to the stream equals sediment transport capacity. If q_{rf} is less than q_t, detachment may occur, and the sediment transported to the stream equals the available sediment.

The sediment transport capacity by overland flow q_t [kg/(s m)] is computed as follows [2]:

$$q_t = c_{\max}\rho_s q \tag{9}$$

where

$c_{\max}$: concentration of suspended particles at transport capacity [m^3/m^3]

ρ_s : sediment density [kg/m^3]

The concentration $c_{\max}$ [m^3/m^3] results from the equation:

$$c_{\max} = \frac{1}{x}\frac{\varphi_r + \varphi_f}{\rho_s A w^2} \qquad (10)$$

where

x : factor depending on the soil slope gradient

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

5 Sediment transport sub-model for the main streams

The sediment yield at the outlet of the main stream of a sub-basin can be computed by the concept of sediment transport capacity by streamflow. The following relationships are used to compute sediment transport capacity by streamflow [3]:

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

$$+ (1.799 - 0.409\log\frac{wD_{50}}{\nu} - 0.314\log\frac{u_*}{w})\log(\frac{ui}{w} - \frac{u_{cr}i}{w}) \qquad (11)$$

$$\frac{u_{cr}}{w} = \frac{2.5}{\log(u_* D_{50}/\nu) - 0.06} + 0.66, \quad \text{if } 1.2 < u_* D_{50}/\nu < 70 \qquad (12)$$

$$\frac{u_{cr}}{w} = 2.05, \quad \text{if } \frac{u_* D_{50}}{\nu} \geq 70 \qquad (13)$$

where

c_t : total sediment concentration by weight [ppm]

D_{50} : median particle diameter [m]

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

u_* : shear velocity [m/s]

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

i : energy slope

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

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6 Application of the sub-models to Kastoria Lake basin

The sub-models described above were applied to the basin of Kastoria Lake. The soil cover of this basin consists of forest (29%), pasture (44%), cultivated area (24%) and urban area (3%). The highest altitude of the basin is about 1900 m. The rocks were divided into permeable (34%), impermeable (50%) and semi-permeable (16%).

For a more precise computation of runoff, soil erosion and stream sediment transport, the whole basin was divided into ten natural sub-basins, which contribute to the sediment inflow to the lake (Fig. 1). The relatively large sub-basin of Xiropotamos was further divided into two sub-basins. The area of the sub-basins varies between 2 and 64 km^2. In the sub-basin including Kastoria City, there are not well defined streams. The mean soil slope of the sub-basins varies between 10% and 49%, while the mean slope of the main torrents of the sub-basins varies between 0.5% and 13%.

The following data were available:

- Monthly rainfall data from six rainfall stations for 33 hydrologic years (1961/62 - 1993/94).
- Monthly air temperature data from four meteorologic stations for 33 hydrologic years (1961/62 - 1993/94).
- Individual baseflow measurements in some torrents discharging into the lake, for the years 1998 and 1999.

The mean annual value of the rainfall amount from the six stations varies between 563 mm and 876 mm. The air temperature data were used for the estimation of the potential evapotranspiration according to the method of Thornthwaite [4]. The baseflow measurements belong to the input data of the sediment transport sub-model for streams.

The sub-models 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, soil erosion and sediment transport processes.

7 Computational results

The monthly values of sediment yield at the oulet of each sub-basin, resulting from the mathematical model for a certain year, were added to produce the annual value of sediment yield ya due to soil and stream bed erosion. The annual soil erosion amount for each sub-basin is symbolized with yd. The ratio of ya to yd is called the sediment delivery ratio.

In Table 1, the mean annual values of ya and yd for 33 hydrologic years (1961/62 - 1993/94), for the sub-basins (Fig. 1), are given. In the same table, the ratio dr of the mean annual values ya / yd is contained. It is obvious from

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Table 1 that the sub-basins of Xiropotamos, Vissinia and Tichio deliver most sediment load to the lake.

Table 1: Mean annual values of ya and yd - Ratio dr.

Sub-basin	ya [t]	yd [t]	dr [%]
Xiropotamos	109 200	327 000	33
Vissinia	45 300	163 100	28
Tichio	41 000	123 000	33
Kastoria -Dispilio	27 000	27 000	100
Metamorphosi	23 500	48 600	48
Aposkepos	15 400	72 400	21
Photini	10 200	39 600	26
Istakos	8 600	48 700	18
Phountouklis	6 000	17 300	35
Agios Athanasios	2 400	14 000	17

The mean annual value of soil erosion for the whole basin amounts to 881 000 t, while the mean annual value of sediment yield at the outlets of the sub-basins amounts to 289 000 t. This means that the sediment delivery ratio of the whole basin is 33%.

8 Sediment control measures

The sediment control measures for the reduction of sediment inflowing to Kastoria Lake from the sub-basins can be classified into three groups:

- Soil erosion control measures in the sub-basins through establishment of vegetative cover (e.g. afforestation).
- Check dams in the torrents (mountain part of the sub-basins) to trap bed load and to prevent bed degradation.
- Detention basins for bed load in the alluvial fans (cone-shaped depositions) of the torrents.

These sediment control measures must be implemented, in order of priority, in the sub-basins of Xiropotamos, Vissinia and Tichio. In the other sub-basins, of course, sediment control measures can also be performed.

The proposed new control measures are [5]:

- Check dams in the sub-basins of Xiropotamos, Vissinia, Tichio and Aposkepos (Fig. 1).
- Detention basins in the sub-basins of Xiropotamos and Vissinia (Fig. 1).
- Vegetative cover in the sub-basins of Vissinia, Xiropotamos and Photini.

It must be noted that check dams have been constructed, in the past, in the sub-basins of Xiropotamos, Vissinia and Photini, while a forest cover has been established at certain places of the sub-basin of Xiropotamos. The old sediment control measures have not been taken into account during the computation of sediment yield at the outlets of the sub-basins.

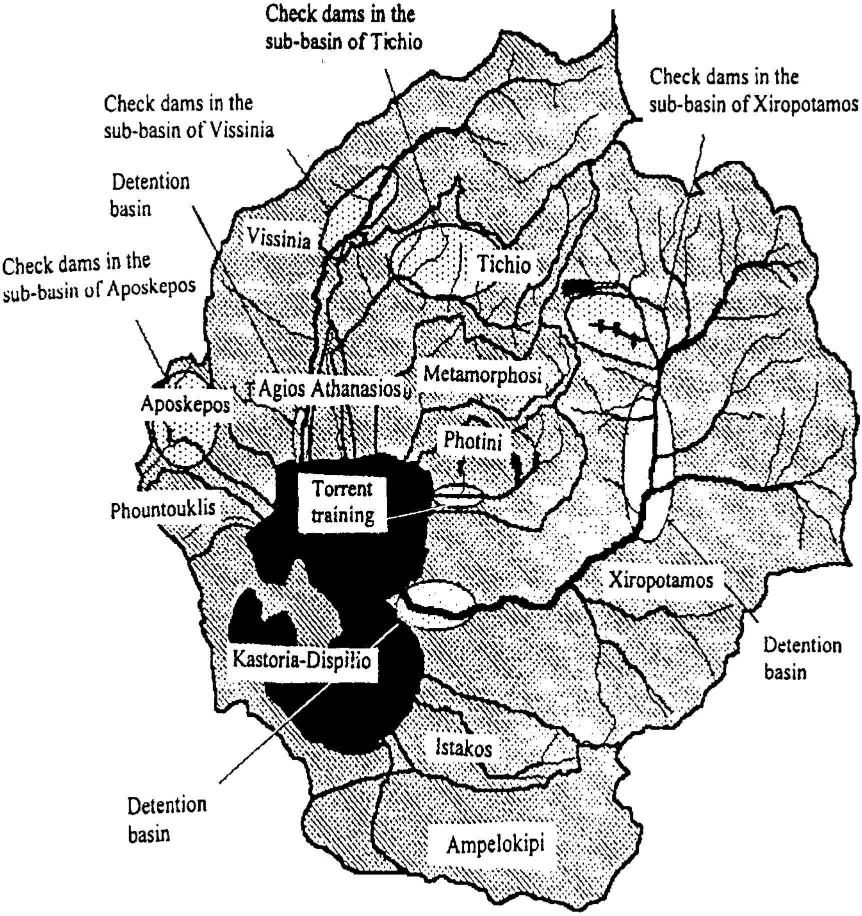

Figure 1: Proposed new sediment control measures in the sub-basins of Kastoria Lake.

9 Remarks and conclusions

The most important drawbacks of the computational model described above are quoted below:

- The model computes only total values of runoff, soil erosion and sediment transport. The temporal development of the physical processes over the considered time period (month) is not followed.
- 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.

However, the objective of this study is the identification of those sub-basins which deliver most sediment load to the lake. For this purpose, a rough estimation of the mean annual soil erosion in the sub-basins and of the mean annual sediment yield at the outlets of the sub-basins is sufficient.

Because of lack of sediment yield data at the outlets of the sub-basins, the mean annual value of sediment yield (289 000 t) resulting from the model presented above is compared with the respective value (361 000 t) resulting from another model that contains a different soil erosion sub-model [6]. The relatively small deviation between these values is an encouraging indication for the order of magnitude of the computed sediment yield.

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