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Computation of Lake or Reservoir Sedimentation in Terms of Soil Erosion

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1. Introduction

Lake or reservoir sedimentation, which decreases the useful life of the lake or reservoir, is closely associated with soil and stream bed erosion in the corresponding basin. Sediment inflowing into the lake or reservoir, through the river which feeds the lake or reservoir, originates mainly from the products of soil and stream bed erosion in the corresponding basin. Therefore, the computation of lake or reservoir sedimentation requires, in a previous step, the computation of soil erosion and stream sediment transport in the lake or reservoir basin. The computation of soil erosion, in turn, requires, in a previous step, the computation of runoff due to rainfall, because both rainfall and runoff cause soil erosion.

According to the above mentioned process chain, the physical processes, that should be quantified, are: runoff resulting from rainfall, soil erosion due to rainfall and runoff, inflow of eroded particles into streams, sediment transport in streams, sediment inflow into the lake or reservoir, and sediment deposition in the lake or reservoir. Since the centre of gravity of the present chapter falls into the quantification of soil erosion and stream sediment transport, an overview and classification of soil erosion models and stream sediment transport (total load) models will be given in Sections 2 and 3, respectively.

The physical processes mentioned above could be included in a mathematical simulation model, which will compute the inflowing sediment quantity into a lake or reservoir from the surrounding basins. For the verification of the mathematical model, usually, no systematic, long-term sediment yield measurements of the rivers, streams or torrents, discharging their water into the lake or reservoir, are available. Contrarily, rainfall and, in general, meteorological data, which serve as input data of the mathematical models, can be found. Additionally, model parameters, which serve also as input data, can be estimated by means of topographic and geologic maps. However, the lack of output data, e.g. sediment yield measurements, leaves the computational results unchecked.

In the present chapter, four case studies, regarding the computation of the mean annual sediment inflow into two reservoirs and two natural lakes, will be described. The mathematical simulation model, used in all cases, consists of three submodels:

- a hydrologic rainfall-runoff submodel
- a soil erosion submodel
- a stream sediment transport submodel

In the following paragraph, the names of the lakes (artificial or natural), the submodels used and the available output data are given:

Forggensee Reservoir (Bavaria, Germany)

- Rainfall-runoff submodel of Lutz (1984)
- "Universal Soil Loss Equation" (USLE)
- Stream sediment transport submodel of Yang & Stall (1976)

Available output data: values of sediment yield (suspended load) at the reservoir inlet for 12 years (1966 – 1977).

Yermasoyia Reservoir (Cyprus)

- Rainfall-runoff submodel (Giakoumakis et al., 1991)
- Soil erosion submodel of Schmidt (1992)
- Stream sediment transport submodel of Yang & Stall (1976)

Available output data: mean annual rate of soil erosion in the corresponding basin.

Kastoria Lake (Greece)

- Rainfall-runoff submodel (Giakoumakis et al., 1991)
- Soil erosion submodel of Schmidt (1992)
- Stream sediment transport submodel of Yang & Stall (1976)

No available output data.

Vistonis Lake (Greece)

- Rainfall-runoff submodel (Giakoumakis et al., 1991)
- Soil erosion submodel of Schmidt (1992)
- Stream sediment transport submodel of Yang & Stall (1976)

Available output data: topographic maps with isobath contours of Vistonis Lake for the years 1949 and 1970.

2. Classification of soil erosion models

Two broad categories of mathematical soil erosion models are the deterministic and the stochastic ones (e.g. Smith et al., 1977). In this chapter, a deterministic approach to the soil erosion, as well as to the other physical processes, is made. Therefore, a further classification of the deterministic erosion models is given below:

- empirical models (e.g. Universal Soil Loss Equation, USLE, Wischmeier & Smith, 1978; Santos et al., 1977; Johnson & Julien, 2000; De Vente et al., 2005)
- physically-based models (e.g. Hairsine & Rose, 1992a, 1992b; Flanagan & Nearing, 1995; De Roo et al., 1996; Lukey et al., 2000; Bathurst, 2002; De Aragão et al., 2005)
- models based on the concept of unit sediment graph (e.g. Das & Agarwal, 1990; Sharma et al., 1993)

The empirical models are simple, but they do not go into the mechanisms of the physical processes. In the physically-based models, the soil surface is subdivided into rills and interrill areas, while the soil erosion process is also decomposed into physical subprocesses. Gully erosion is not quantified in the above models. The physically-based models require, apart from rainfall data and physiographic characteristics of the basin, numerous other data, i.e. field measurements, for the determination of the parameters (constants, exponents) in the corresponding equations; therefore, these models are difficult to apply to large basins. By contrast, the empirical models require mostly rainfall data and maps (topographic, soil, vegetation etc.).

RUSLE (Revised Universal Soil Loss Equation, Renard et al., 1996) is the newest improved version of USLE and could be considered as a transition from the empirical to the physically-based models. However, the detailed information required for estimating the

individual factors of RUSLE, with the exception of the topographic factor, renders the application of RUSLE to large basins practically impossible.

The unit sediment graph, as well as the unit hydrograph in hydrology, is a system function describing the sediment behaviour of a basin. It enables the conversion of the effective rainfall or soil detachment (system input) in the basin into sediment yield (system output). Generally, models based on a system function have the possibility to follow the time variation of sediment yield.

3. Classification of stream sediment transport models

The last physical process in the process chain simulated by the mathematical model is the stream sediment transport. In concrete terms, a total load model (bed load plus suspended load) is used for the quantification of sediment transport capacity by streamflow. Therefore, a classification of total load models is made below (Vetter, 1992):

- stochastic and regression models (e.g. Einstein, 1950; Karim & Kennedy, 1983)
- energy and power models (e.g. Engelund and Hansen, 1967; Yang, 1973)
- shear stress models (e.g. Zanke, 1982; van Rijn, 1984a, 1984b)

Additionally, Einstein and van Rijn calculate bed load and suspended load separately.

Sediment transport is considered by Einstein (1950) as probability problem. The probability that a grain will be lifted, is related with two dimensionless parameters: the intensity of bed load transport and the shear intensity of the flow. The Total Load Transport Model (TLTM) of Karim and Kennedy (1983) contains two multiple regression equations that compute the dimensionless total load transport and the dimensionless mean flow velocity as functions of different auxiliary dimensionless parameters.

Engelund and Hansen (1967) compare the rate of energy needed in lifting the grains with the rate of work being done by the resistance forces to the transported grains in the same time. Finally, they result to a relationship between the dimensionless total load transport and a dimensionless mobility parameter. According to Yang (1973), the "unit stream power", namely the mean flow velocity - energy slope product, is the basic parameter for the description of sediment transport. By means of a multiple regression, he results to a relationship between the total sediment concentration and the dimensionless effective unit stream power, among other dimensionless parameters. It is noted that the effective unit stream power is the difference between the dominant unit stream power and its critical value characterizing the incipient motion.

According to Zanke (1982), bed load transport and suspended load transport are functions of the difference between the existing shear velocity and its critical value characterizing the incipient motion. Particular for the suspended load transport, the critical shear velocity for the lifting of the grains to the suspension zone is taken additionally into account. In the model of van Rijn (1894), two dimensionless parameters characterizing the grain diameter and the incipient motion, respectively, dominate. The incipient motion is designated by the difference between the existing shear velocity and its critical value.

4. Mathematical simulation model

As mentioned before, the mathematical simulation model consists of three submodels: (a) a rainfall-runoff submodel, (b) a soil erosion submodel, and (c) a stream sediment transport submodel.

In order to realize the connection of the submodels with each other, the input and output of each submodel are summarized below:

- The input of the rainfall-runoff submodel is the rainfall depth in each sub-basin, while the output is the runoff depth in each sub-basin.
- The input of the soil erosion submodel is the rainfall depth and the runoff depth in each sub-basin, while the output is the soil erosion amount in each sub-basin and the inflowing sediment quantity from the surrounding sub-basin into the main stream of the sub-basin considered.
- The input of the stream sediment transport submodel is the inflowing sediment quantity into the main stream of the sub-basin considered from the surrounding sub-basins, while the output is the sediment yield at the outlet of the sub-basin considered.

In the following sections, the submodels used in the four case studies are described shortly.

4.1 Hydrological submodels

4.1.1 Rainfall-runoff submodel of Lutz

The rainfall-runoff submodel of Lutz (1984) 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:

$$h_o = (N - A_v)c + \frac{c}{k} [e^{-k(h_o - A_v)} - 1] \quad (1)$$

where

h_o : daily rainfall excess (mm)

N : daily rainfall depth (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 depth of about 250 mm and depending on the land use and the hydrological soil group

k : proportionality factor (1/mm) which is given by the following equation:

$$k = P_1 e^{-2.0/WZ} e^{-2.0/q_B} \quad (2)$$

where

P_1 : region-dependent parameter

WZ : week number which designates the season

q_B : baseflow rate which designates the antecedent moisture condition [l/(s km²)]

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

$$q_p = 0.278 \frac{A_E h_o}{T_A} \quad (3)$$

where

q_p : peak runoff rate (m^3/s)

A_E : sub-basin area (km^2)

h_o : rainfall excess (mm)

T_A : time of rise of the hydrograph (hr)

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.

4.1.2 Rainfall-runoff submodel of water balance

The hydrologic submodel described in this section is a simplified water balance model (Giakoumakis et al., 1991), in which the variation of soil moisture due to rainfall, evapotranspiration, deep percolation and runoff is considered. The basic balancing equation is:

$$S_n' = S_{n-1} + N_n - E_{pn} \quad (4)$$

where

S_{n-1} : available soil moisture for the time step $n - 1$ (mm)

N_n : rainfall depth for the time step n (mm)

E_{pn} : potential evapotranspiration for the time step n (mm)

S_n : auxiliary variable (mm)

The direct runoff depth 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 and k' are proportionality coefficients ($k' = 1 - k$).

According to the structure of the above hydrologic submodel, h_o represents the sum of surface runoff depth and interflow depth. The auxiliary variable S_n' includes the quantitative influence of rainfall and potential evapotranspiration for the considered time step n on the available soil moisture for the preceding time step $n - 1$. S_n' is compared with the maximum available soil moisture S_{max} in order to estimate the runoff and the deep percolation for the considered time step.

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

$$S_{max} = 25.4 \left(\frac{1000}{CN} - 10 \right) \quad (5)$$

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

Finally, the potential evapotranspiration E_p is estimated by the radiation method improved by Doorenbos & Pruitt (1977). For this purpose, the following meteorological data are required: mean daily temperature ($^{\circ}C$), sunlight hours per day (hr/day), mean daily relative humidity (%) and mean daily wind velocity (m/s).

The rainfall-runoff submodel described above is applicable on a long-term basis, e.g. on a monthly basis, because it is based on a water balance equation. Performing the calculations

on a monthly time basis may be justified by the fact that the rainfall in most rain days of a year in some countries (e.g. Cyprus, Greece) is not particularly high. Furthermore, it is usual to express the evapotranspiration in monthly or annual values, because the evapotranspiration in this case can also be calculated empirically with a good approximation (Hrissanthou, 2002).

4.2 Soil erosion submodels

4.2.1 Universal Soil Loss Equation (USLE)

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

$$A = RK(LS)CP \quad (6)$$

where

A : soil loss due to surface erosion (t/ha)

R : rainfall erosivity factor (N/hr)

K : soil erodibility factor [(t/ha)/(N/hr)]

LS : topographic factor

C : crop management factor

P : 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:

$$R = 0.5R_{st} + 0.5R_R = 0.5R_{st} + 0.5\alpha h_o q_p^{0.33} \quad (7)$$

where

R : modified erosivity factor (N/hr)

R_{st} : rainfall erosivity factor (N/hr)

R_R : runoff erosivity factor (N/hr)

h_o : runoff volume per unit area (mm)

q_p : peak runoff rate per unit area (mm/hr)

α : a constant depending on the units ($\alpha = 0.70$)

4.2.2 Soil erosion submodel of Schmidt

The soil erosion submodel of Schmidt (1992) is based on the assumption that the impact of droplets on the soil surface and the surface runoff are proportional to the momentum flux contained in the droplets and the runoff, respectively.

The momentum flux exerted by the falling droplets, φ_r (kg m/s²), is given by:

$$\varphi_r = Cr\rho A_E u_r \sin \alpha \quad (8)$$

where

C : soil cover factor

r : rainfall intensity (m/s)

ρ : water density (kg/m³)

A_E : sub-basin area (m^2)

u_r : mean fall velocity of the droplets (m/s)

α : mean slope angle of the soil surface ($^\circ$)

The original relationship of Schmidt for the momentum flux exerted by the droplets is valid for bare soils. Therefore, an additional factor is necessary to express the decrease of the momentum flux because of the vegetation. It is believed that the dimensionless crop management factor C of the USLE is appropriate to express the vegetation influence.

The fall velocity of the droplets, u_r (m/s), is a function of the rainfall intensity r (mm/hr) according to the following equation (Schmidt, 1992):

$$u_r = 4.5r^{0.12} \quad (9)$$

The momentum flux exerted by the runoff, ϕ_f ($kg\ m/s^2$), is given by:

$$\phi_f = q\phi_bu \quad (10)$$

where

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

b : width of the sub-basin area (m)

u : mean flow velocity (m/s)

The mean flow velocity u can be obtained from the well-known Manning formula, while the runoff rate per unit width q can be calculated from the mean flow velocity u and the runoff depth h_o , which is assumed to be uniformly distributed over a sub-basin.

The structure of Equations (8) and (10) indicates that the model of Schmidt is based on fundamental physical concepts. Nevertheless, the basic variable u_r is evaluated by the empirical Equation (9).

4.3 Estimate of sediment inflow into the main stream of a sub-basin

Sediment from the soil erosion transported to the main stream of a sub-basin is computed by the concept of overland flow sediment transport capacity. At this point, it must be noted that only the main stream of the sub-basin is considered because large amounts of unavailable data for the geometry and hydraulics of the entire stream system would otherwise be required.

The amount of sediment due to soil erosion transported to the main stream of a sub-basin, ES , is estimated by means of the following controls: If the available sediment in a sub-basin, q_{rf} , exceeds overland flow sediment transport capacity q_t , deposition occurs, and the sediment transported to the main stream 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 stream of the sub-basin equals the available sediment. It is symbolized by the following relationships:

$$ES = q_t, \quad \text{if } q_{rf} > q_t \quad (11)$$

$$ES = q_{rf}, \quad \text{if } q_{rf} \leq q_t \quad (12)$$

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

$$ESI = ES + FLI \quad (13)$$

4.3.1 Relationships of Beasley et al.

The following relationships of Beasley et al. (1980) are used to compute the overland flow sediment transport capacity in a sub-basin:

$$q_t = 146sq^{1/2} \quad \text{for } q \leq 0.046 \text{ m}^3/(\text{min m}) \quad (14)$$

$$q_t = 14600sq^2 \quad \text{for } q > 0.046 \text{ m}^3/(\text{min m}) \quad (15)$$

where

q_t : overland flow sediment transport capacity [kg/(min m)]

s : mean slope gradient

q : flow rate per unit width [m³/(min m)]

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.

Since the relationships of Beasley et al. (1980) are combined with USLE, the quantity q_{rf} is computed on the basis of the soil erosion amount A .

4.3.2 Relationships of Schmidt

The available sediment discharge per unit width, q_{rf} [kg/(s m)], due to rainfall and runoff, in a sub-basin is given by (Schmidt, 1992):

$$q_{rf} = (1.7E - 1.7)10^{-4} \quad (16)$$

where

$$E = \frac{\varphi_r + \varphi_f}{\varphi_{cr}} \quad (E > 1) \quad (17)$$

φ_{cr} : critical momentum flux (kg m/s²)

The critical momentum flux φ_{cr} , which designates the soil erodibility, can be calculated from:

$$\varphi_{cr} = q_{cr}\rho bu \quad (18)$$

where q_{cr} [m³/(s m)] is the direct runoff rate per unit width at initial erosion.

The critical runoff rate q_{cr} is determined from the critical erosion velocity depending on soil roughness. Equation (17) suggests the concept of critical situation characterizing the initiation of sediment motion on the soil surface.

The sediment transport capacity by overland flow, q_t [kg/(s m)], is computed as follows (Schmidt, 1992):

$$q_t = c_{\max} \rho_s q \quad (19)$$

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} results from the equation (Schmidt, 1992; Hrisanthou, 2002):

$$c_{\max} = \frac{(\phi_r + \phi_f) \sin \alpha}{\rho_s A_E w^2} \quad (20)$$

where w (m/s) is the terminal fall velocity of suspended particles.

Equation (20) is obtained from the equilibrium condition between the vertical component of the total momentum flux $[(\phi_r + \phi_f) \sin \alpha]$ and the critical momentum flux of the suspended particles $(c_{\max} \rho_s A_E w^2)$. The critical momentum flux results by multiplying the mass rate of settling particles $(c_{\max} \rho_s A_E w)$ by the settling velocity w . If the critical momentum flux is exceeded, the particles do not remain in suspension. The equilibrium condition is valid when the sediment transport capacity is achieved

The sediment supply ES to the main stream of a sub-basin is estimated by means of Equation (11) or (12), as described above.

4.4 Estimate of sediment yield at the outlet of a sub-basin

The sediment yield at the outlet of a sub-basin, FLO , reflects the same basic controls as the sediment supply ES from soil erosion:

$$FLO = q_{ts}, \quad \text{if } ESI > q_{ts} \quad (21)$$

$$FLO = ESI, \quad \text{if } ESI \leq q_{ts} \quad (22)$$

where q_{ts} is the sediment transport capacity by streamflow. In the first case, if the available sediment in the main stream of the considered sub-basin, ESI , exceeds sediment transport capacity by streamflow, q_{ts} , deposition occurs. In the second case, if the available sediment ESI is less than sediment transport capacity by streamflow, q_{ts} , bed detachment may occur.

4.4.1 Relationships of Yang & Stall

The following relationships of Yang & Stall (1976) are used to compute sediment transport capacity by streamflow:

$$\log c_t = 5.435 - 0.286 \log \frac{wD_{50}}{v} - 0.457 \log \frac{u_*}{w} + (1.799 - 0.409 \log \frac{wD_{50}}{v} - 0.314 \log \frac{u_*}{w}) \log \left(\frac{us}{w} - \frac{u_{cr}S}{w} \right) \quad (23)$$

$$\frac{u_{cr}}{w} = \frac{2.5}{\log(u_*D_{50}/v) - 0.06} + 0.66, \quad \text{if } 1.2 < \frac{u_*D_{50}}{v} < 70 \quad (24)$$

$$\frac{u_{cr}}{w} = 2.05, \quad \text{if } \frac{u_*D_{50}}{v} \geq 70 \quad (25)$$

where

c_t : total sediment concentration (ppm)

w : terminal fall velocity of suspended particles (m/s)

D_{50} : median grain diameter of the bed material (m)

ν : kinematic viscosity of the water (m²/s)

u_* : shear velocity (m/s)

u : mean flow velocity (m/s)

u_{cr} : critical mean flow velocity (m/s)

s : energy slope

Equation (23) was determined from the concept of unit stream power (rate of potential energy expenditure per unit weight of water, u_s) and dimensional analysis. The variable u_{cr} in Equation (23) suggests that a critical situation is considered at the beginning of sediment particle motion, as in most sediment transport equations. But the relationship of Yang and Stall has the advantage, in contrast to other published equations, that it was verified in natural rivers.

5. Application of the mathematical model to artificial or natural lakes

5.1 Application to the basin of Forggensee Reservoir

The mathematical model, consisting of the rainfall-runoff submodel of Lutz, the USLE and the stream sediment transport submodel of Yang & Stall, was applied to the 1500 km² basin of the Forggensee Reservoir (Bavaria, Germany). The storage capacity of the reservoir is 168 x 10⁶ m³. The largest part of the basin is in Austria and the main stream is the Lech River. The basin consists mainly of forest (36%), of meadow (49%), and of rock (11%) over 2000 m in altitude (Fig. 1, Hrisanthou, 1990). Information about the soil texture class was available only for a small part of the basin where it consists of loamy sand, sandy loam, and clay loam.

The following data were available:

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

The quantification of the runoff, erosion and sediment transport 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:

- the precision of the calculations and results;
- 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. According to the above considerations, the study basin was divided into 88 natural sub-basins (Fig. 2), about 25 km² in area.

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

Regarding the application of USLE to the basin considered, the tables of Schwertmann (1981), which are valid especially for Bavaria, were used for the evaluation of the factors K , C and P .

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. the sub-basins of this example, results in only a rough estimate of soil erosion. Moreover, USLE and any equation for classical erosion due to rainfall and runoff are not appropriate to be applied to rock areas without vegetation. As mentioned before, a part (11%) of the basin area consists of rock without vegetation, over 2000 m in altitude.

In Fig. 2, the mean annual erosion amount (t/ha) in each sub-basin is given.

Sediment yield at the outlet of the basin considered was computed by the mathematical 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 soil and stream bed 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 soil and stream bed erosion, to the measured values of sediment yield at the outlet of the whole basin are presented in Table 1 (Hrissanthou, 1988).

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

Year	Measured value (t)	Computed value/ Measured value	Year	Measured value (t)	Computed value/ Measured value
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	1 165 200	0.88	1976	315 772	1.36
1971	326 052	1.59	1977	312 025	2.18

Table 1. Ratio of computed to measured values of sediment yield

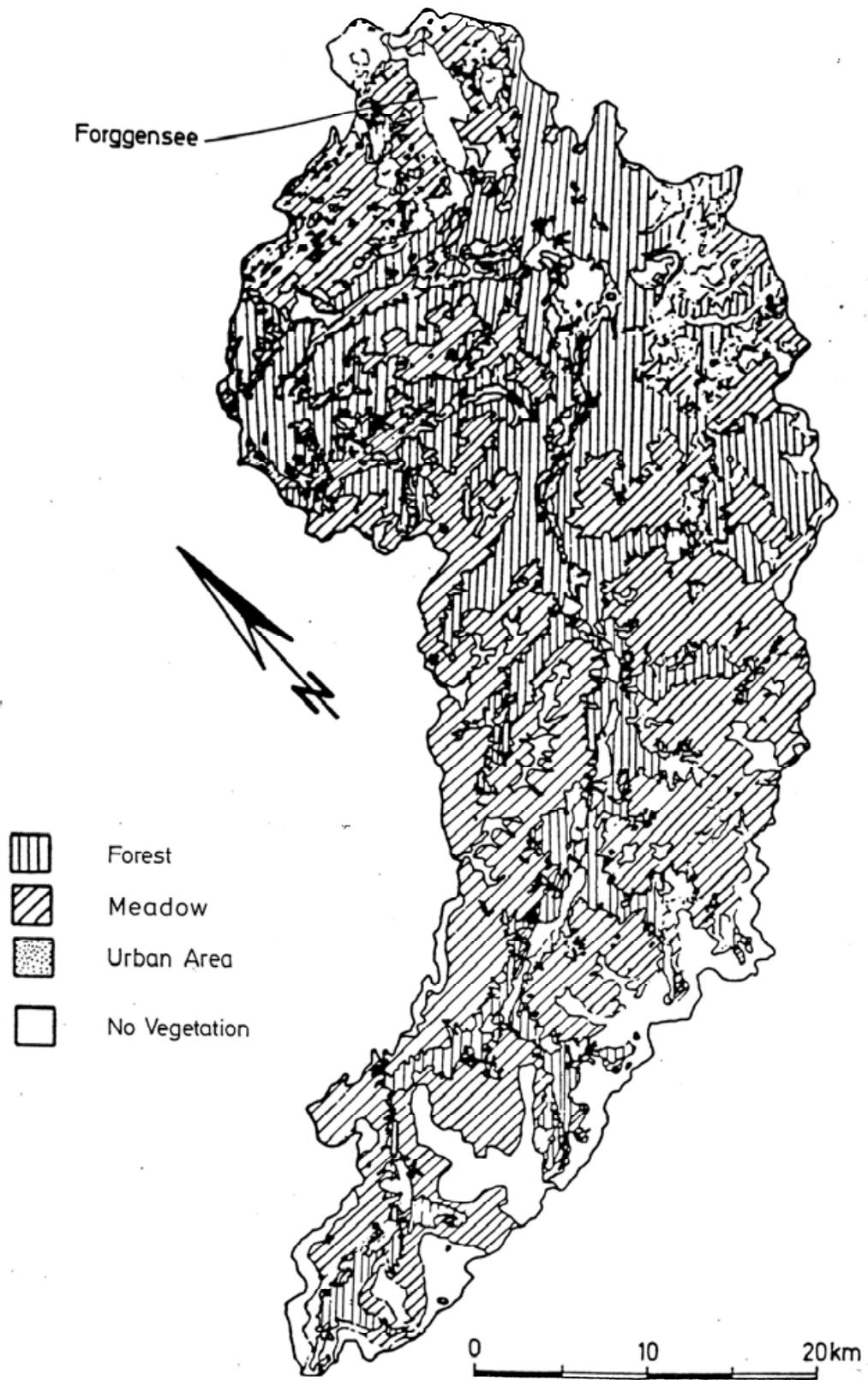


Fig. 1. Soil cover map of the basin of Forggensee Reservoir

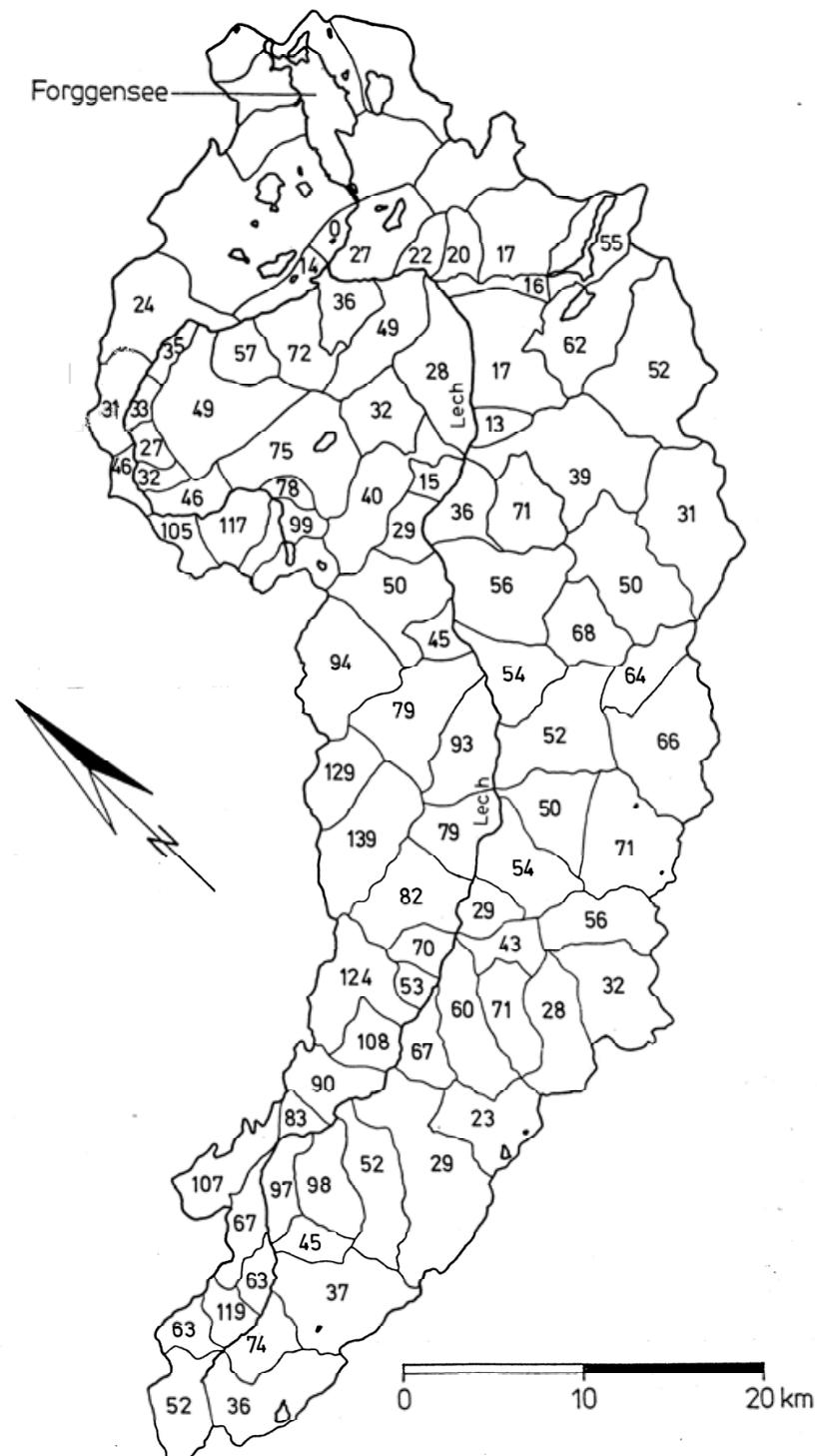


Fig. 2. Mean annual erosion amount (t/ha) in each sub-basin (years: 1966-1977)

5.1.1 Discussion - conclusions

The arithmetic 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 soil erosion was taken into account and the whole basin was subdivided into sub-areas 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 the model, in sub-basins with very low slope gradients or in streams with very low bed slopes. In the other sub-basins or streams, with greater slopes, all the detached soil mass is transported to the main streams of the sub-basins or to the next sub-basins.

Gully and bank erosion, as well as mass movement were ignored because no information was available about these kinds of erosion. Snowmelt runoff, glacial and snow erosion were not quantified because the research was focused on the classical soil erosion due to rainfall and runoff.

Finally, in this example, the comparison between computed and measured values of sediment yield at the outlet of the entire basin 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:

- the very long sediment travel times from the outlets of the most sub-basins to the outlet of the whole basin;
- the problems of using a total daily rainfall amount;
- 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.

5.2 Application to the basin of Yermasoyia Reservoir

The mathematical model, consisting of the rainfall-runoff submodel of water balance, the soil erosion submodel of Schmidt and the stream sediment transport submodel of Yang and Stall, was applied to the basin of Yermasoyia Reservoir. The Yermasoyia Reservoir is located northeast of the town of Limassol, Cyprus. The storage capacity of the reservoir is 13×10^6 m³. The Yermasoyia River drains a basin that, upstream of the reservoir, amounts to 122.5 km². The length of the main stream of the basin is about 25 km, and the highest altitude of the basin is about 1400 m. The basin which consists of forest (57.7%), bush (33.7%), cultivated land (5.8%), urban area (1.8%) and an area with no significant vegetation (1%) (Fig. 3), was divided into four natural sub-basins for more precise calculations (Fig. 4, Hrissanthou, 2006). The sub-basin areas vary between 14 and 44 km².

The soils of the basin belong to the following types: Calcaric Cambisols, Eutric Cambisols, Eutric Regosols, Calcaric Lithosols, and Eutric Lithosols. These soil types were further divided into three categories: permeable (Calcaric Cambisols, Eutric Cambisols), semi-permeable (Eutric Regosols) and impermeable (Calcaric Lithosols, Eutric Lithosols) soils, because the above distinction is necessary for the estimate of the curve number in the hydrologic submodel.

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

Monthly runoff volumes for the years 1986-1989 were available from a water gauging station, named "Phinikaria" and located at the outlet of sub-basin 3 (Fig. 4). The basin area corresponding to the gauging station amounts to 108 km².

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 mathematical model was applied to each sub-basin separately and on a monthly time basis for a certain year. 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 bed 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 YA, YD and DR for the years 1986-1989 are shown in Table 2.

Table 2 contains also the measured and computed annual values of runoff volume VO at the outlet of sub-basin 3 (Fig. 4), as well as the ratio of computed to measured annual values VR. The computed values of runoff volume result from the hydrologic submodel.

Year	YD (t)	YA (t)	DR (%)	Measured VO (10 ⁶ m ³)	Computed VO (10 ⁶ m ³)	VR
1986	113 000	32 000	28	8.0	9.7	1.2
1987	673 000	224 000	33	19.6	24.6	1.3
1988	618 000	238 000	38	24.7	25.4	1.0
1989	108 000	30 000	28	16.3	9.3	0.6
Mean value	378 000	131 000	32	17.2	17.3	1.0

Table 2. Computational results for YD, YA and DR; annual values of computed and measured runoff volume

The mean annual value of YD, 378 000 t, is transformed into the mean annual rate of soil erosion, 1.16 mm. The latter value is 1.7 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, 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. Considering the storage capacity of the reservoir (13.6 x 10⁶ m³), its useful life thus amounts to 193 years.

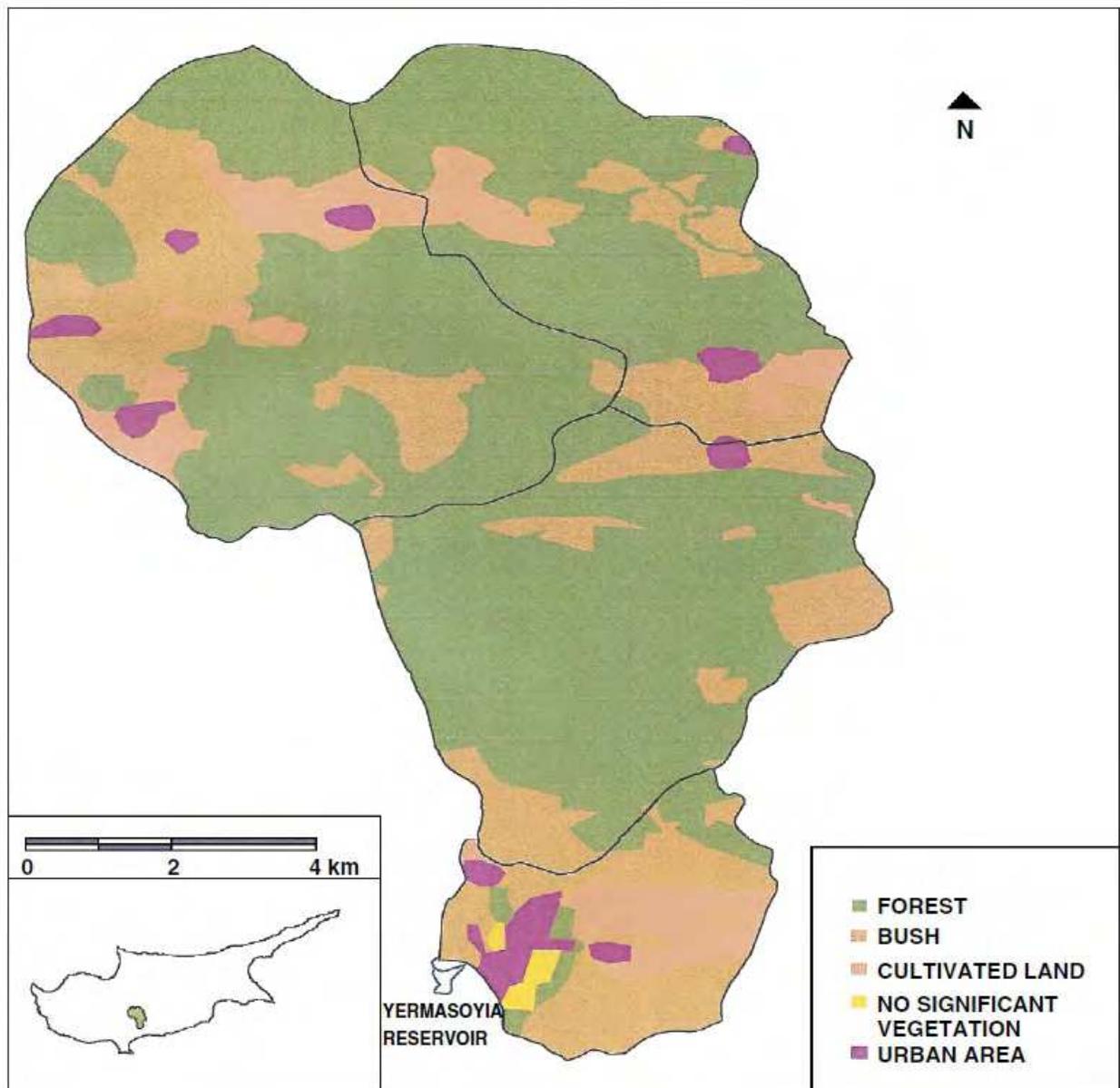


Fig. 3. Soil cover map of the basin of Yermasoyia Reservoir

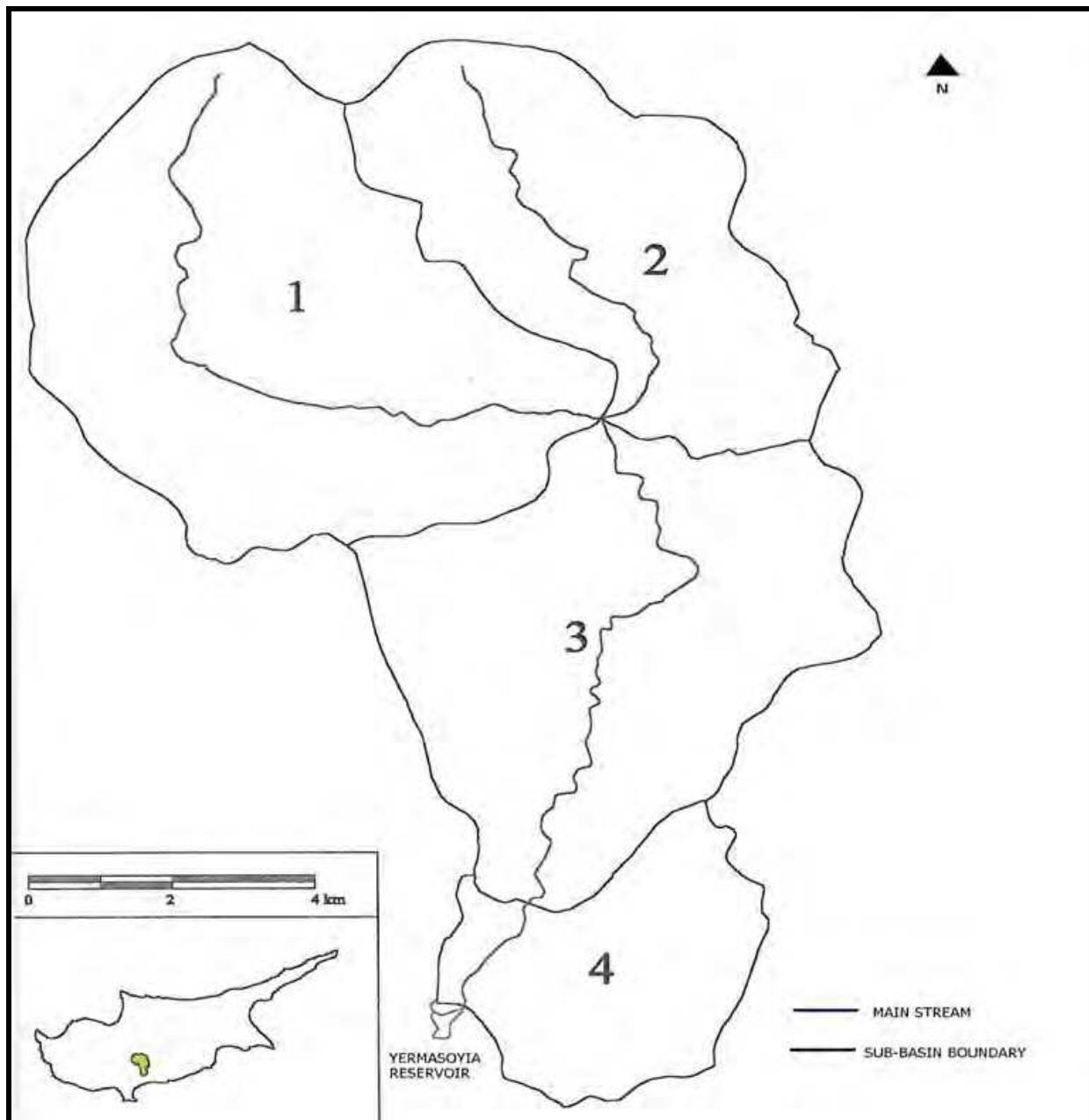


Fig. 4. Main streams of the four sub-basins of Yermasoyia Reservoir basin

5.2.1 Discussion - conclusions

The measured mean annual runoff volume at the outlet of sub-basin 3 is slightly overestimated by the model. Generally, for models of the same structure as the model used in this example, the rainfall volume and the parameter curve number influence the monthly sediment yield at the basin outlet more strongly than the other input data (Hrissanthou, 2002).

The soil erosion submodel also overestimates the mean annual rate of soil erosion for the whole basin. At this point, it has to be noted that runoff resulting from the hydrologic submodel serves as input to the soil erosion submodel. Apart from that, the following factors also contribute to the deviation between the computed and the measured values of soil erosion:

- The equations for soil erosion described above are applied, in this study, to relatively small sub-basins, whereas they were developed initially for small experimental fields.
- Snowmelt runoff, gully and bank erosion are neglected in this study.
- The erosion measurements are indirect, as explained previously.

The sediment inflow into the reservoir resulting from the stream sediment transport submodel is also overestimated, because the overestimated soil erosion quantity serves as input to the stream sediment transport submodel. Apart from that, it must be added that bank erosion was neglected in the stream sediment transport submodel. Moreover, in the present case study, the bed of the main streams of the sub-basins consists of sand and gravel, and the slope of the main streams of two sub-basins exceeds the application limit of the Yang formula, which is valid for sandy beds.

The overestimation of the sediment inflow into the reservoir implies the underestimation of the useful life of the reservoir. In any case, there is no immediate and sharp danger of reservoir filling with sediments.

The mean annual sediment inflow would be more reliable if the computations could be carried out for as many years as possible. Unfortunately, meteorological data were available only for four years.

In the computations performed through the mathematical model, the sub-basin was the space unit and the month was the time unit. However, it has to be stressed that performing the calculations on an event basis is a reasonable way for the quantification of runoff, erosion and sediment transport processes, provided that pertinent detailed data are available.

In the case of large basins, for which mean annual values of soil erosion and sediment yield are required, the monthly time basis of the computations constitutes a temporally detailed approach. Additionally, the computational experience has shown that performing the calculations on a daily time basis, especially in large basins, leads to a disagreement of high order between computed and measured daily values of sediment yield (Hrissanthou, 1990). In contrast, performing the calculations on a monthly time basis results in a relatively good agreement between the computed and measured monthly values of sediment yield, which is due to the integrating effect obtained through use of a sub-basin (as a space unit) and a long simulation period. However, the performance of the calculations on a monthly time basis has as the consequence that some variables of the model equations, e.g. the rainfall intensity, characterizing single storm events lose their physical meaning.

Most parameters of the mathematical model used were estimated by means of tables and topographic, vegetation and soil maps. To take into account the diversity of the sub-basins with respect to soil, topography and vegetation, mean weighted values of the parameters for each sub-basin were computed.

The proportionality coefficient k of the rainfall-runoff submodel was determined on the basis of a value of 35.5% of the runoff coefficient (ratio of rainfall excess to rainfall). This value was estimated from the available rainfall and runoff volume data.

5.3 Application to the basin of Kastoria Lake

The mathematical model, consisting of the rainfall-runoff submodel of water balance, the soil erosion submodel of Schmidt and the stream sediment transport submodel of Yang and Stall, was applied to the basin of Kastoria Lake. Kastoria Lake is located in northwestern Greece, near the Albanian border. The mean water surface area of the lake is about 28 km²,

while the whole basin of the lake is about 253 km². The soil cover of the 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 (Fig. 5). The area of the sub-basins varies between 2 and 64 km². The mean soil slope of the sub-basins varies between 10 and 49%, while the mean slope of the main streams of the sub-basins varies between 0.5 and 13%.

The main streams of the sub-basins located around Kastoria Lake transport both water and sediment into the lake. The inflowing sediment causes the reduction of the water volume capacity of the lake with time, endangering the existence of this environmental resource. The water volume inflowing into the lake through the streams originates mainly from the rainfall-runoff process in the sub-basins. Groundwater recharge contributes significantly to the volumetric budget of the lake, as well as to the budget of the whole basin. The sediment load reaching the lake arises from the soil erosion, due to rainfall and runoff, of the sub-basins and from the stream bed erosion.

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 meteorological stations for 33 hydrologic years (1961/62-1993/94).
- Individual baseflow measurements in some streams 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 and 876 mm. The air temperature data were used for the estimation of the potential evapotranspiration according to the method of Thornthwaite. The baseflow measurements belong to the input data of the stream sediment transport submodel.

The mathematical model was applied to each sub-basin separately and for every month of a certain hydrologic year. The monthly values of total flow volume and sediment yield, due to soil and stream bed erosion, at the outlet of each sub-basin, resulting from the mathematical model for a certain hydrologic year, were added to produce the annual value of total flow volume v_{og} and sediment yield y_a , respectively. As is well-known, the total flow volume is the sum of direct runoff volume and baseflow volume. The annual soil erosion amount for each sub-basin is symbolized with y_d . The ratio of y_a to y_d is called the sediment delivery ratio (dr).

In Table 3, the mean annual values of v_{og} , y_a and y_d for 33 hydrologic years (1961/62-1993/94), for the sub-basins, are given. In the same table, the ratio dr of the mean annual values y_a / y_d is contained (Hrissanthou et al., 2003).

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

The general remarks of Section 5.2.1 concerning the application of the mathematical model to a relatively large basin, are also valid for the application of the model to the basin of Kastoria Lake.

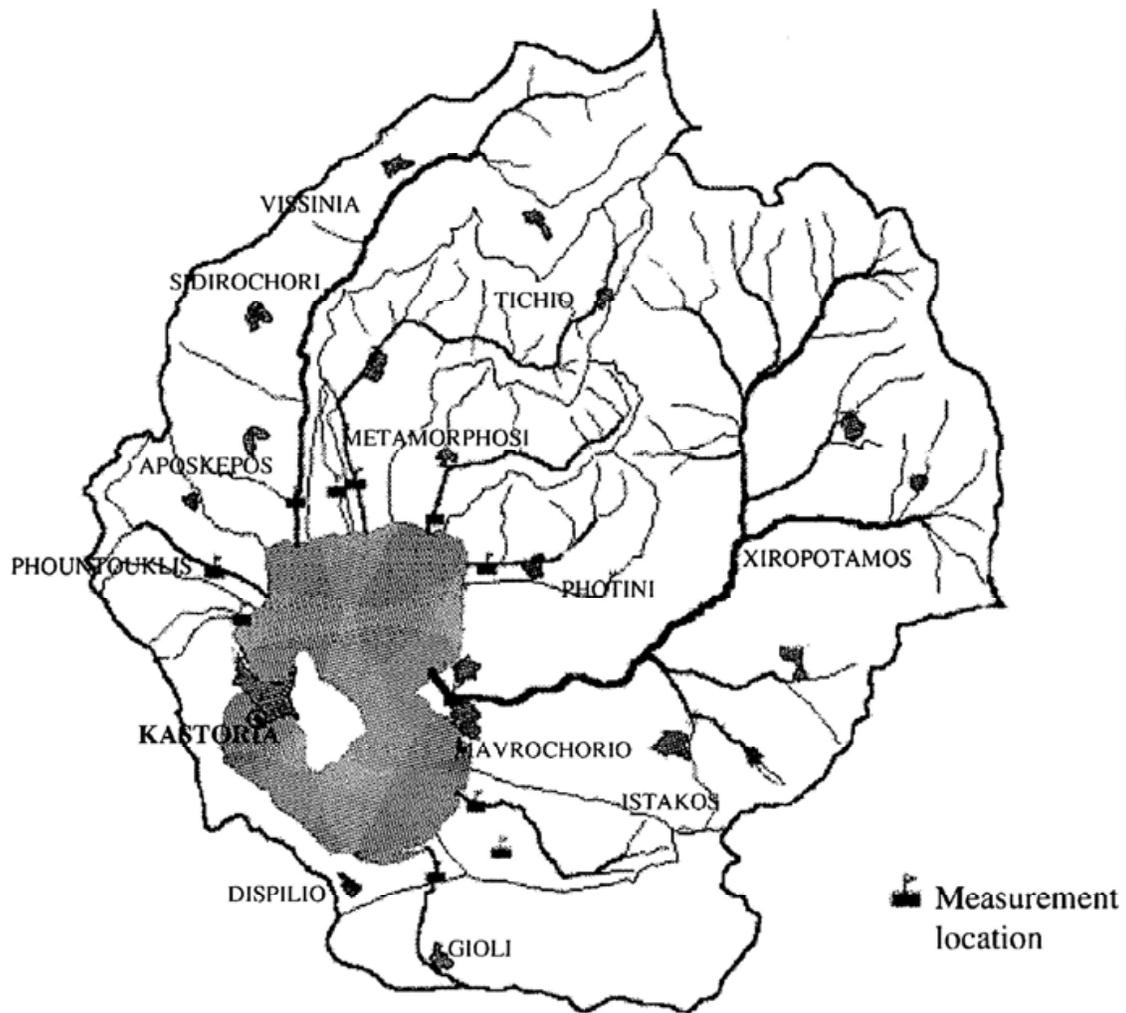


Fig. 5. Sub-basins of Kastoria Lake

Sub-basin	vog (10^6 m^3)	ya (t)	yd (t)	dr (%)
Xiropotamos	23.39	109 200	327 000	33
Vissinia	6.77	45 300	163 100	28
Tichio	7.01	41 000	123 000	33
Kastoria-Dispilio	0.78	27 000	27 000	100
Metamorphosi	3.34	23 500	48 600	48
Aposkepos	2.96	15 400	72 400	21
Photini	1.06	10 200	39 600	26
Istakos	5.16	8 600	48 700	18
Phountouklis	1.04	6 000	17 300	35
Agios Athanasios	1.99	2 400	14 000	17

Table 3. Mean annual values of vog , ya and yd - Ratio dr

5.3.1 Practical use of the model

The simulation model described above can be used for the identification of those sub-basins where sediment control measures have to be implemented. The sediment control measures, which aim at the reduction of sediment inflowing into Kastoria Lake from the sub-basins, are classified into three groups:

- Soil erosion control measures in the sub-basins through the 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 streams.

According to Table 3, the sub-basins, which deliver most sediment load to the lake, are those of Xiropotamos, Vissinia and Tichio. Therefore, the 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.

5.4 Application to the basin of Vistonis Lake

The mathematical model, consisting of the rainfall-runoff submodel of water balance, the soil erosion submodel of Schmidt and the stream sediment transport submodel of Yang and Stall, was also applied to the basin of Vistonis Lake (Thrace, northeastern Greece), which is one of the most important wetlands in Greece. The water surface area of the lake is about 45 km². In concrete terms, the model was applied separately to the mountainous part of the three basins of Kompsatos, Kossynthos and Travos (Aspropotamos) Rivers, respectively, which discharge their water into Vistonis Lake (Fig. 6).

The application of the mathematical model to the basin of Vistonis Lake is given, in this section, in more detail compared to the three foregoing case studies. For each of the three basins, five maps were drawn and digitized: a stream system map, a contour map, a vegetation map, a geologic map, and a map of Thiessen polygons. On the basis of the first four maps, the physiographic characteristics for each sub-basin of the three basins (e.g. main stream length, main stream bottom slope, soil slope gradient, sub-basin area, soil cover, rock classification), as well as parameter values depending on the physiographic characteristics (e.g. curve number, soil cover factor, soil roughness coefficient, critical erosion velocity of the soil surface) were calculated. At this point, it must be noted that both soil permeability and rock permeability are of importance for the quantification of the runoff process, because soil moisture variation is influenced by both soil permeability and rock permeability. Therefore, the soils and rocks were divided into permeable, impermeable and semi-permeable on the basis of soil texture and deep percolation percentage, respectively. By means of the fifth map (Thiessen polygons), a mean weighted value of rainfall depth for each sub-basin of the three basins was computed. The parameter values serve as input data to the mathematical model.

The input data for the rainfall-runoff submodel are: monthly rainfall depth, mean daily air temperature, sunlight hours per day, mean daily relative humidity of the atmosphere, mean daily wind velocity, altitude, latitude, soil cover - land use, and hydrologic soil group. The additional input data for the soil erosion submodel, with reference to the rainfall-runoff submodel, are: mean slope angle of soil surface, sub-basin area, soil cover factor (C-factor of USLE), length of the main stream of the sub-basins, roughness coefficient of soil surface,

critical erosion velocity, water and sediment density. The additional input data for the stream sediment transport submodel, with reference to the foregoing submodels, concern the main stream of the sub-basins: baseflow, bottom slope, bottom width, bed roughness, diameter of suspended particles, grain diameter of bed material, and kinematic viscosity of water.

Finally, a sediment routing plan is necessary in order to specify the sediment motion from sub-basin to sub-basin.

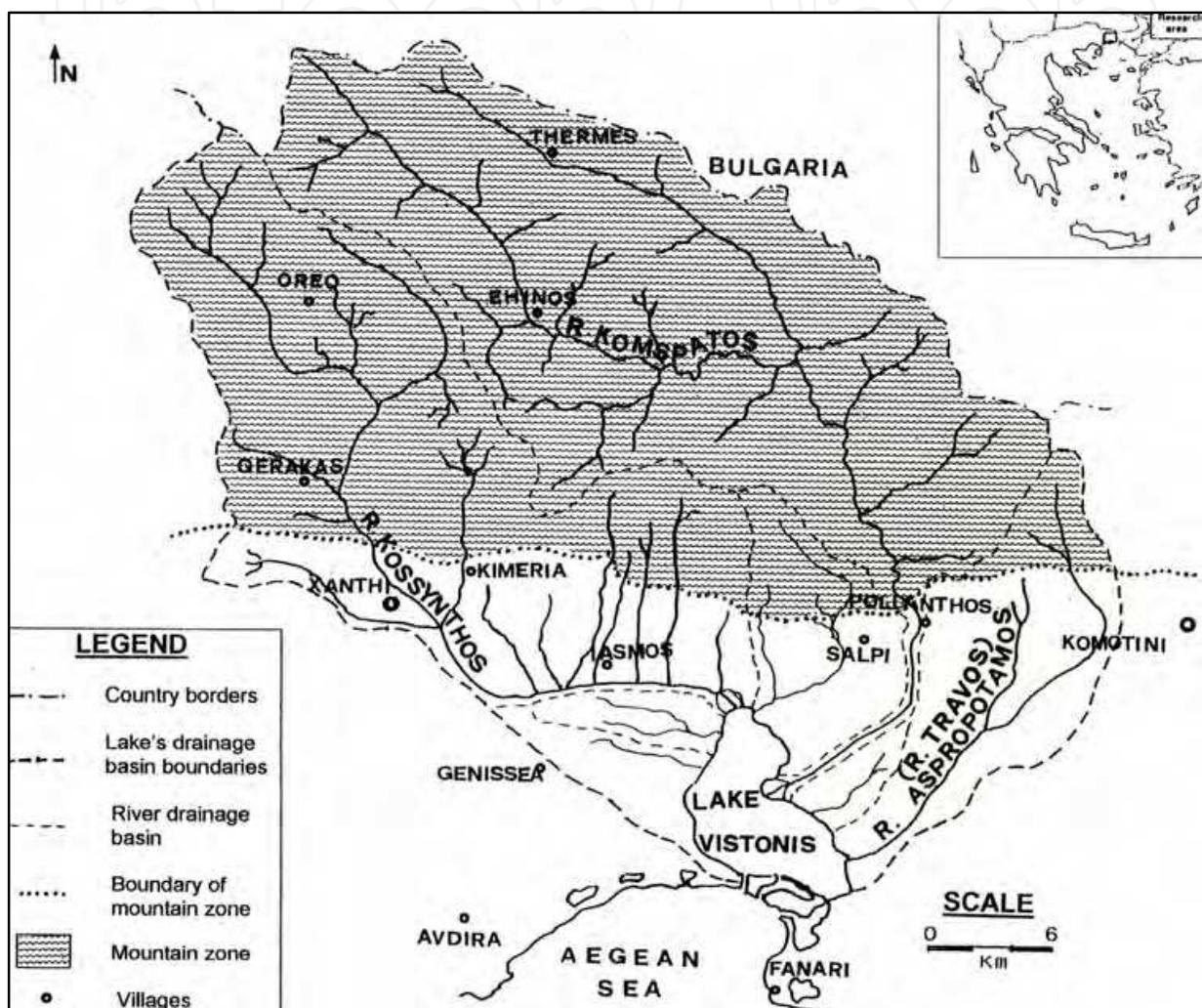


Fig. 6. Rivers discharging into Vistonis Lake

5.4.1 Application of the model to Kompsatos River basin

The basin of Kompsatos River has an area of about 567 km² consisting of forest (37.3%), bush (36.1%), cultivated land (26.1%) and urban area (0.5%). The dominant rocks are marble, amphibolite, rhyolite and gneiss-granite. The highest altitude of the basin is about 1200 m. The length of the main stream of the basin is about 57 km. For more precise calculations, the basin was divided into 18 natural sub-basins (area: between 13 and 50 km², Fig. 7). The mean soil slope gradient of the sub-basins is about 26%.

Monthly rainfall data for 27 years (1966-1992) from four rainfall stations (Dimario, Thermes, Ehinios and Trikorpho, Fig. 6) were available. The mean annual rainfall at these stations

amounts to 1038 mm. For every month of the 27 years, mean daily values of air temperature from three meteorological stations (Thermes, Ehinis and Xanthi, Fig. 6) and mean daily values of sunlight hours from a meteorological station (Egiros) were available. Additionally, mean daily values of relative humidity of the atmosphere for every month of the year 1985 were obtained from the meteorological station of Xanthi, and mean daily values of wind velocity for every month of the year 1995 were obtained from the meteorological station of Genissea (Fig. 6). Finally, daily baseflow data were available from measurements for the years 1991 and 1992.

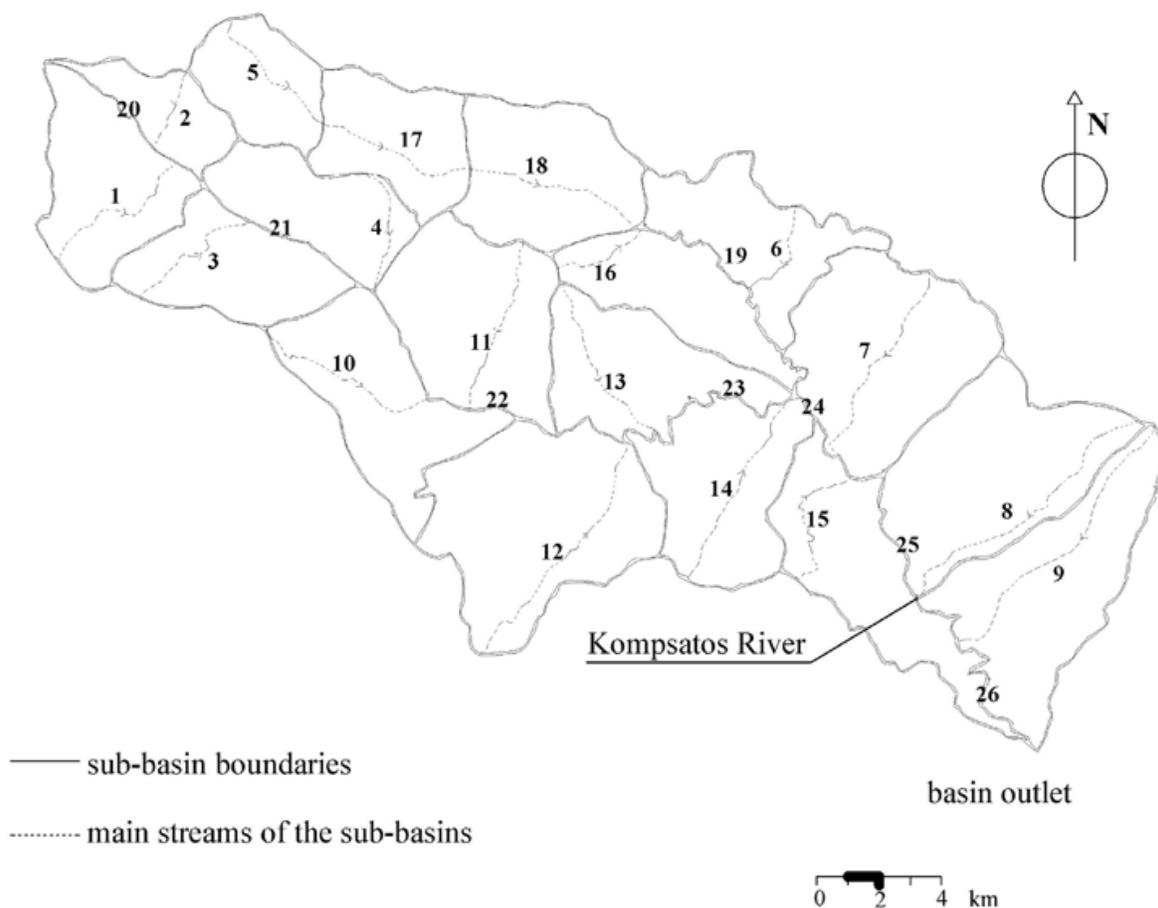


Fig. 7. Kompsatos River basin – Sub-basins with main streams

5.4.2 Application of the model to Kossynthos River basin

The basin of Kossynthos River has an area of about 237 km² consisting of forest (74%), bush (4.5%), urban area (1.5%) and an area with no significant vegetation (20%). The dominant rocks are granite-diorite, marble, gneiss-granite and migmatite. The highest altitude of the basin is about 1700 m. The length of the main stream of the basin is about 35 km. For more precise calculations, the basin was divided into ten natural sub-basins (area: between 16 and 35 km², Fig. 8). The mean soil slope gradient of the sub-basins is about 37%.

Monthly rainfall data from six rainfall stations (Livaditis, Ehinis, Xanthi, Gerakas, Oreo and Lykodromio, Fig. 6) for eleven years (1980-1990) were available. The mean annual rainfall at these stations amounts to 883 mm. Apart from the rainfall data, mean daily values of air temperature, sunlight hours and relative humidity of the atmosphere from

the meteorological station of Xanthi (Fig. 6) for every month of the years 1980-1990 were available. As far as the wind velocity is concerned, the same data were used as for the basin of Kompsatos River. Daily baseflow data were available from measurements for the years 1991 and 1992. Finally, median values of grain diameters of bed material were available from samples taken in the lower and upper parts of Kossynthos River basin, in June 1997.

5.4.3 Application of the model to Travos River basin

The basin of Travos (Aspropotamos) River has an area of about 40 km² consisting of forest (15.7%), bush (82.1%), urban area (0.8%) and an area with no significant vegetation (1.4%). The dominant rocks are granite-diorite, gneiss, marble and amphibolite. The highest altitude of the basin is about 1400 m. The length of the main stream of the basin is about 8.5 km. The mean soil slope gradient of the basin is about 53%.

Monthly rainfall data for 27 years (1966-1992), as well as mean daily values of air temperature, sunlight hours and relative humidity of the atmosphere for every month of the above years were available from the meteorological station of Egiros, which is located near the basin, but in the flat part of the region. The mean annual rainfall at this station amounts to 665 mm. Moreover, mean daily values of wind velocity for certain months of the years 1997 and 1998 were obtained from the meteorological station of Xanthi (Fig. 6).

5.4.4 Computational results

The mathematical simulation model was applied separately to each sub-basin of the three basins. The computations were performed on a monthly time basis, because monthly rainfall data were available. The discussion on the monthly time basis is found in Section 5.2.1.

The monthly values of sediment yield at the outlet of each of the three basins for a certain year were added to produce the annual value of sediment yield. The mean annual value of sediment yield, YA , for the three basins has as follows (Hrissanthou et al., 2010):

- Kompsatos River basin, $YA = 447\ 000\ t$
- Kossynthos River basin, $YA = 192\ 000\ t$
- Travos River basin, $YA = 28\ 000\ t$

The monthly values of erosion amount in each of the three basins for a certain year were added to produce the annual value of erosion amount. The mean annual value of erosion amount, YD , for the three basins has as follows (Hrissanthou et al., 2010):

- Kompsatos River basin, $YD = 1\ 026\ 000\ t$
- Kossynthos River basin, $YD = 409\ 000\ t$
- Travos River basin, $YD = 112\ 000\ t$

The ratio of the annual sediment at the outlet of a basin to the annual erosion amount in the basin is called the sediment delivery ratio, as mentioned in the other case studies. The mean annual value of the sediment delivery ratio, DR , for the three basins has as follows (Hrissanthou et al., 2010):

- Kompsatos River basin, $DR = 38\%$
- Kossynthos River basin, $DR = 49\%$
- Travos River basin, $DR = 25\%$

On the basis of the above arithmetic results, the calculated total mean annual sediment yield, which flows into Vistonis Lake, is 667 000 t. For the most unfavourable case, that the

whole sediment inflowing into the lake is trapped by the lake, the mean annual volume of the deposited sediment will be 445 000 m³. The conversion of mass to volume was made on the basis of the assumption that sediment bulk density is 1.5 t/m³. This is a typical value for submerged reservoir deposits consisting of a sand-silt mixture.

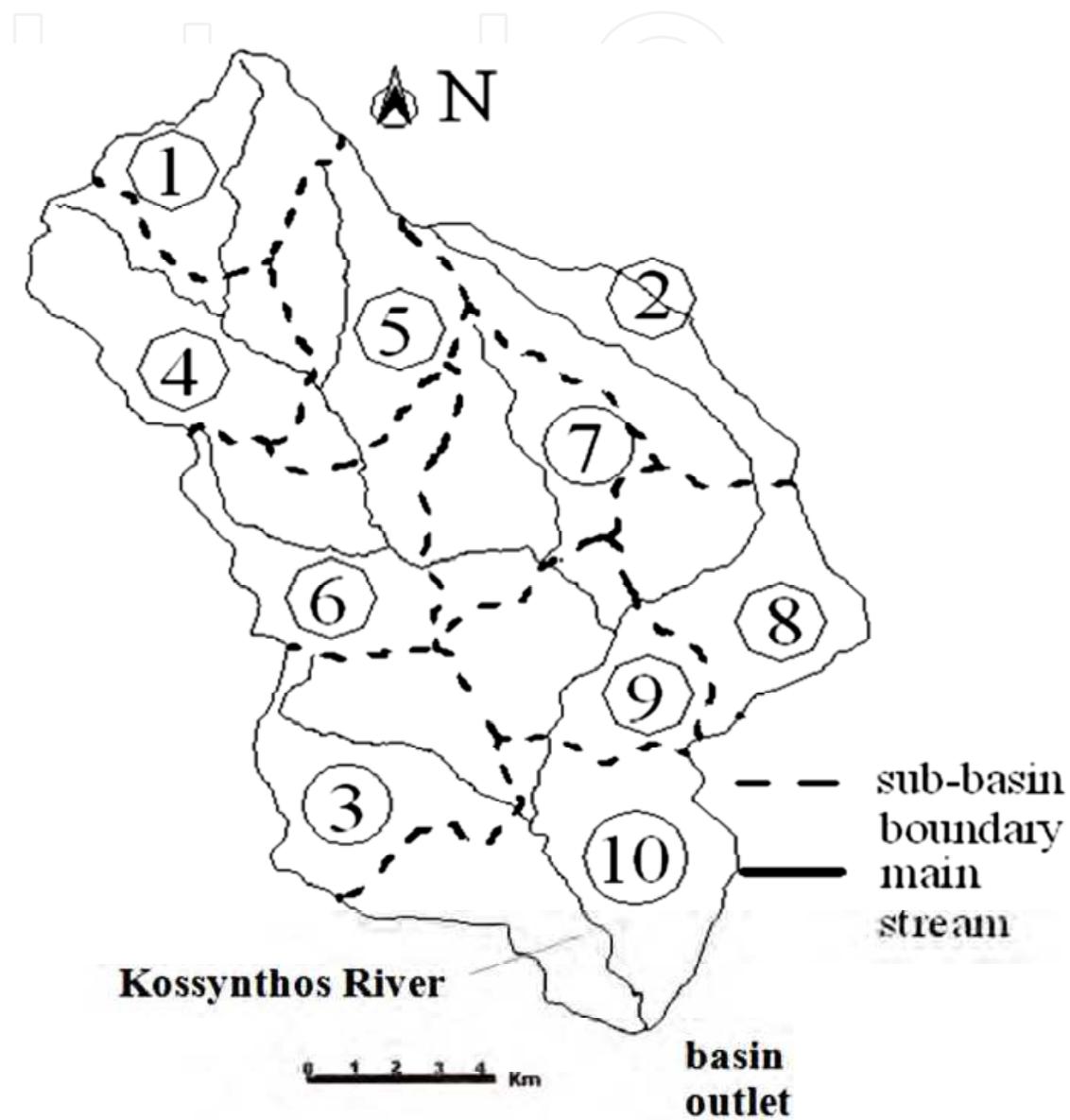


Fig. 8. Kossynthos River basin – Sub-basins with main streams

5.4.5 Estimate of the accumulated sediment in Vistonis Lake

From topographic maps of Vistonis Lake for the years 1949 and 1970, obtained from the Hydrographic Service of the Greek Navy, in which the lake boundaries are also shown (Fig. 9), resulted that the decrease rate of the lake water volume because of sediment deposition is 347 000 m³/year.

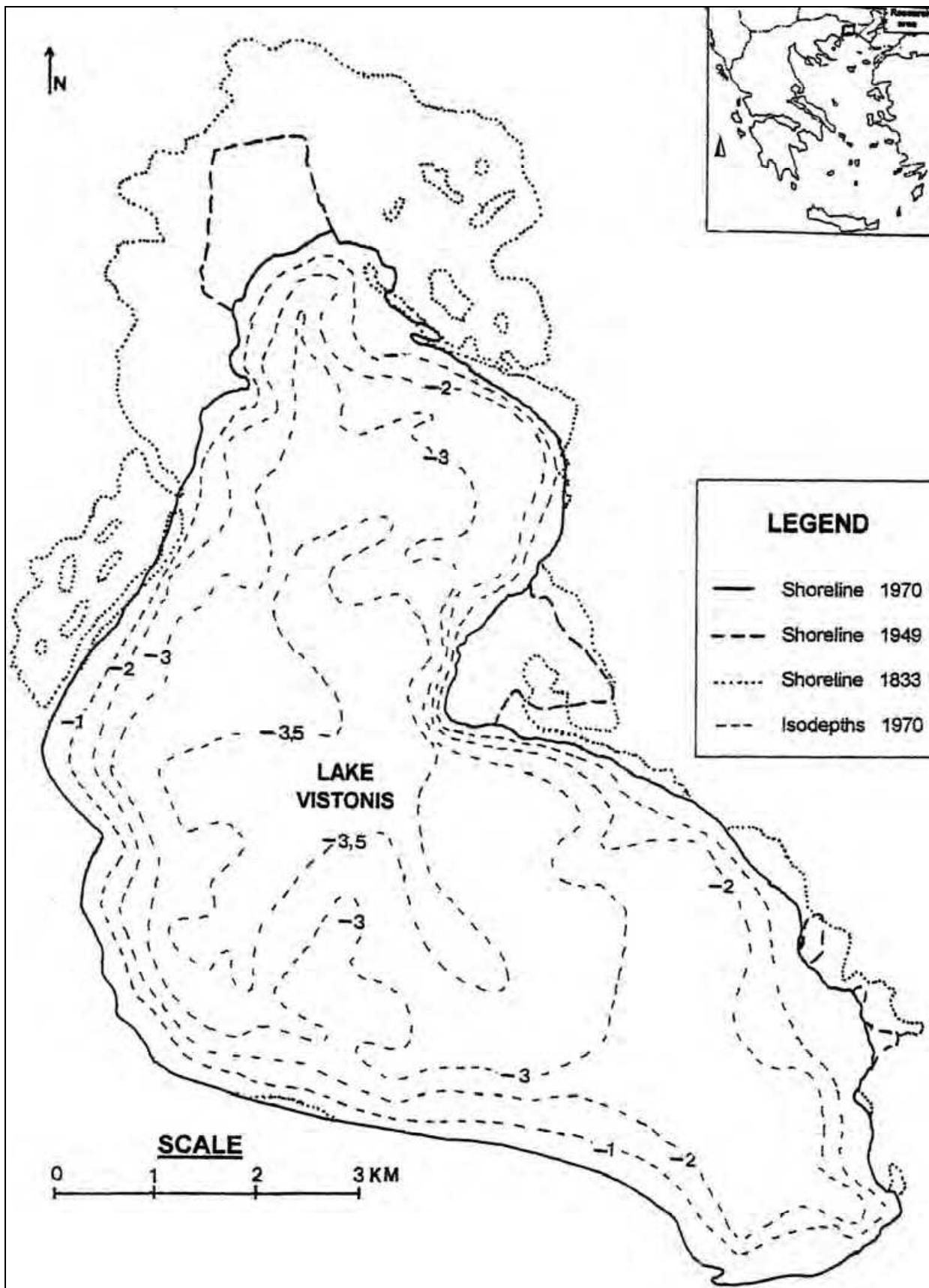


Fig. 9. Shoreline of Vistinis Lake - Isobath contours

5.4.6 Discussion on the comparison between computations and estimates

A comparison between computations by means of the mathematical model and estimates by means of the topographic maps indicates that the mean annual sediment volume accumulated in the lake was overestimated about 28%, according to the computations. The deviations between computations by means of the mathematical model and estimates by means of the maps is attributed, among others, to the following reasons:

- It was not taken into account that a small part of the deposited sediment may be transported to the sea, because the lake communicates with the sea. In other words, the trap efficiency of the lake was assumed to be as equal to 100%.
- The mean annual sediment yield at the basin outlet of Kompsatos and Travos Rivers was computed for the same time period (1966-1992), while the mean annual sediment yield at the basin outlet of Kossynthos River was computed for a different time period (1980-1990). Moreover, the mean annual sediment accumulation in Vistonis Lake was estimated approximatively by means of topographic maps also for a different time period (1949-1970).
- The mean annual sediment yield was computed at the outlet of the mountainous part of the basins considered. It means that the erosion and sediment transport in the flat part of the basins was not taken into account. Anyway, it is believed that a considerable part of sediment load reaching the outlets of the mountainous part of the basins will be deposited in the flat part of the basins. However, in the case of flood events, the sediment deposited in the plains will be transported to the lake.

Finally, the assumptions and simplifications of the mathematical model mentioned in Section 5.2.1, contribute to the inaccurate computation of sediment yield. Additionally, the following remarks are given for the case study of Vistonis Lake basin:

- The proportionality factor k of the hydrological submodel was determined on the basis of the empirical assumption that the runoff coefficient (ratio of rainfall excess to rainfall) amounts to 40% on a monthly time basis, especially for winter months or months with a considerable rainfall amount. The above assumption cannot be avoided, because the factor k is the only parameter of the whole mathematical model that cannot be estimated directly, by means of tables or maps. The final value of factor k used in the hydrologic submodel is a mean value resulting from the k - values determined for different months.
- Some input data (e.g. bottom channel width) of the model used were determined in an empirical way, namely by optical estimation, while the values of other input data (e.g. diameter of suspended particles, sediment density) were determined by assumption. However, these parameters do not influence strongly the sediment yield value at the basin outlet.

6. General conclusion

From the preceding discussions on the computational results of the mathematical simulation models described in this chapter, it is concluded that these models are applicable to lake or reservoir basins for which both hydrometeorological data and topographic, vegetation and soil maps are available, in order to predict roughly lake or reservoir sedimentation in terms of soil erosion.

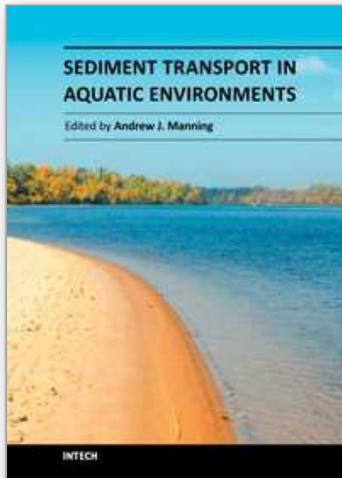
However, it has to be emphasized that some of the model imperfections given above lead to an overestimation and some others to an underestimation of the sediment yield at the basin outlets, which has as a favourable consequence the compensation of the deviations between computations and estimates or measurements.

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Sediment Transport in Aquatic Environments is a book which covers a wide range of topics. The effective management of many aquatic environments, requires a detailed understanding of sediment dynamics. This has both environmental and economic implications, especially where there is any anthropogenic involvement. Numerical models are often the tool used for predicting the transport and fate of sediment movement in these situations, as they can estimate the various spatial and temporal fluxes. However, the physical sedimentary processes can vary quite considerably depending upon whether the local sediments are fully cohesive, non-cohesive, or a mixture of both types. For this reason for more than half a century, scientists, engineers, hydrologists and mathematicians have all been continuing to conduct research into the many aspects which influence sediment transport. These issues range from processes such as erosion and deposition to how sediment process observations can be applied in sediment transport modeling frameworks. This book reports the findings from recent research in applied sediment transport which has been conducted in a wide range of aquatic environments. The research was carried out by researchers who specialize in the transport of sediments and related issues. I highly recommend this textbook to both scientists and engineers who deal with sediment transport issues.

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