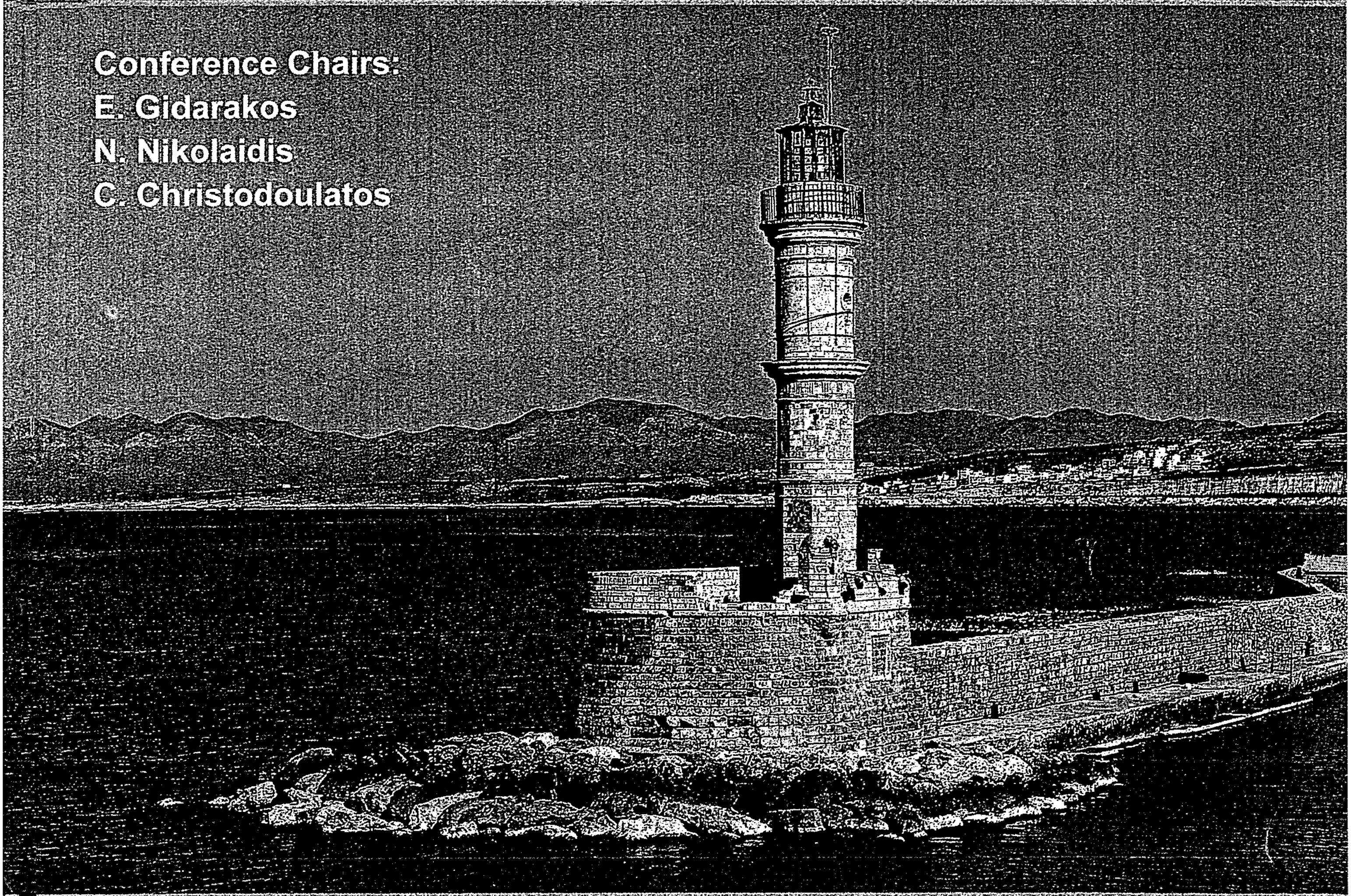
Proceedings

PROTECTION AND RESTORATION OF THE ENVIRONMENT VIII

Conference Chairs:
E. Gidarakos
N. Nikolaidis
C. Christodoulatos



Organised by the
Technical University of Crete - Department of Environmental Engineering
STEVENS Institute of Technology
Stevens Institute of Technology - Center for Environmental Systems

Chania - Crete - Greece, July 3-7, 2006

INTERNATIONAL CONFERENCE
PROTECTION AND RESTORATION OF THE ENVIRONMENT VIII

EDITORS

E. Gidarakos
D. Mantzavinos
E. Paleologos
N. Nikolaidis
A. Koutsospyros
M. Lazaridis
C. Christodoulatos
D. Dermatas
A. Koungoulos
E. Karatzas
E. Psillaki
T. Tsoutsos
E. Diamandopoulos

CHANIA – CRETE – CREECE

3 – 7 JULY 2006

ASSESSING THE IMPACTS OF SEDIMENT YIELD ON THE SUSTAINABILITY OF MAJOR HYDRAULIC SYSTEMS

D. Zarris(1), E. Lykoudi(2) and D. Panagoulia(1)

(1) **Department of Water Resources, School of Civil Engineering, National Technical University of Athens, 5 Heroon Polytechneiou St., 15780, Athens, Greece**
(2) **Department of Geological Sciences, School of Mining Engineering and Metallurgy, National Technical University of Athens, 5 Heroon Polytechneiou St., 15780, Athens, Greece**

ABSTRACT

Erosion and sediment yield form a crucial issue within the integrated water resources management context; however are often neglected during the design of major water systems. Sediment yields in 14 river sites in Western Greece are re-computed and compared to the earlier estimations. It is shown that in certain locations there is a serious inconsistency of the sediment yield estimates. This inconsistency is extremely crucial when, for instance, designing a reservoir's dead storage volume. The inaccurate estimation of the dead storage has a potential impact on the sustainability of the reservoir especially when the deposition of sediment occurs in the useful storage of the reservoir.

1. INTRODUCTION

1.1. General overview of sediment yield issues

Predicting the sediment discharge of a river section or the sediment yield of an upstream catchment has always been an ambitious goal for a number of different earth scientists, such as engineers, hydrologists, geomorphologists and others. In particular, estimation of sediment discharge is a vital key point for the assessment and design of major hydraulic systems, such as irrigation dams, hydroelectric projects and flood attenuation structures. It is estimated that throughout the world, there are probably more than a few million small ponds (up to several thousand cubic meters volume of stored water) [1] as well as 39000 large dams [2].

It is estimated that the annual loss in storage capacity of the world's reservoirs due to sediment deposition is around 0.5–1% [3]. For many reservoirs, however, annual depletion rates are much higher and can go up to 4% or 5%, such that they lose the majority of their capacity after only 25–30 years. These high rates of storage loss pose a serious threat to the economic sustainability of the reservoir. This implies that within about 50 years, the world's water storage in reservoirs will be half of the current storage, which will have large economical and environmental consequences, especially in (semi-) arid environments where many reservoirs have been built for irrigation, water supply, flood control and production of electricity. Besides, this sediment storage can have large implications for ecosystem and coastal development downstream of large river systems. On the other hand, an accurate estimate of reservoir sediment deposition rates should be made during the planning of new reservoirs. Therefore, it is of ultimate importance to predict sediment yield at the basin scale and understand which factors determine the sedimentation rate of reservoirs. This knowledge will allow estimating the probable lifespan of a reservoir and moreover to take proper measures against reservoir sedimentation, watering shortage and river bank erosion. At the moment, the prediction of sediment yield at the basin scale (>50 km^2) is still one of the largest challenges in soil erosion research [4].

1.2. Methods determining sediment yield and discharge

Sediment yield is the sediment load normalized for the catchment area and is the net result of erosion and depositional processes within a basin. At present, sediment yield predictions are achieved mainly through simple empirical models that relate the annual sediment delivery to a river with catchment properties, including drainage area, topography, climate and vegetation characteristics (e.g. [5], [6]). Catchment area is probably the most important of all and, in many cases, is the only explanatory variable used to predict sediment yield. Sediment discharge rating curves have been widely used for determining the sediment yield of the catchment under consideration within the last decades. The statistical expression of suspended sediment discharge and stream discharge is called a sediment discharge rating curve and most commonly takes the power-law form of:

$$Q_{si} = aQ_i^b n_i \quad (1)$$

where Q_s is the sediment discharge (M/T, kg/s), Q is the river discharge (M^3/T, m^3/s), a and b are the sediment rating coefficient and exponent correspondingly, and η is the multiplicative error term which exhibits a lognormal distribution [7]. Estimates of sediment yield based on rating curve calculations will in most cases involve greater error than those obtained from direct measurements, and this can be ascribed primarily to the scatter associated with the rating relationship. Several researchers ([8], [9]) have analyzed such scatter in detail and have described controls associated with season, water temperature, hysteretic effects related to rising and falling stage of the hydrograph, exhaustion effects and varying patterns of tributary inflow. The mathematical technique which is used to construct the rating curve and the adequacy of the number of data points have also been shown to be significant controls on the accuracy of resultant calculations of sediment yield. Walling [8] shows that by using a single rating curve for the river Creedy in the UK may involve overestimation of the annual sediment discharge up to 60%.

Rating curves are suffering serious criticism from various researchers. For instance, Ferguson [7] argues that when the rating parameters are resulted from a log-log regression between suspended sediment and river discharges, an underestimation of sediment yield is resulted. Another cause of the inaccuracies associated with the use of rating relationships is the fact that a large proportion of the total suspended sediment load is transported by a few major flood events, which represent only a very small proportion of the total time. In most cases, particularly in Mediterranean type catchments, most of the annual sediment load is transported in a few days around peak flow conditions. These observations indicate two important implications for the likely accuracy of rating curve estimates of suspended sediment load. Firstly it means that a regular sampling programme is unlikely to provide samples representatives of those periods when the majority of the load is transported. Secondly it means that because the rating plot is fitted by least squares to the whole range of the available data, its trend maybe largely determined by the main mass of samples representative of low flows and sediment discharges, and may therefore be unrepresentative of the conditions during which the majority of the load is transported.

Another point of interest in determining the sediment rating curves that has not attracted much attention in the past is the definition of outliers. Unlike stage – discharge rating curves where the hysteretic effects (same stage at different discharges for the rising or falling part of the hydrograph) do not deviate significantly from the general curve, suspended sediment discharge is less dependent by the explanatory variable (river discharge) and the scatter of measurements is always significant. Therefore the rate of suspended sediment transport depends largely on the sediment supply and availability in the catchment and involves the complex interaction between the sediment production and transport processes.

The broken line smoothing was introduced by Koutsoyiannis [10] as a simple alternative to numerical smoothing and interpolating methods and is treated here as a replacement for the ordinary single rating curve. The main concept is to approximate a smooth curve that may be drawn for the data points with a broken line, which can be numerically estimated by means of a least squares fitting procedure. If the only objective used for fitting the broken line is the minimization of total square error then the result might be a very rough broken line, depending on the arrangement of the data points. However, the roughness of the broken line can be controlled by introducing as a second objective the minimization of the roughness. The broken line is a concatenation of straight-line segments, where the number of the straight-line segments is numerically the outcome of the compromise between the two objectives of minimizing the fitting error and the roughness of the broken line. Considering that the prevailing fluvial form in upstream Greek rivers is the gravel-bed river form, we assume a broken line with two segments. In such a fluvial form, there is a distinct threshold discharge for sediment motion. Below this threshold there is no exchange of the suspended sediment with the riverbed. Once the surface, coarse material, armor layer fully breaks up beyond the threshold discharge and exposes a larger range of particle sizes underneath, the transport rate significantly increases. Alternatively, bank erosion during high discharges will enhance the sediment availability in the river bed. Figure 1 shows an example of the broken line rating curve and the application of equation (1) with the non-linear regression and the linear regression of the log-transformed variables Q_s and Q and back-transformed to equation (1) for the set of sediment discharge measurements for the Poros Riganiou cross section of Evinos River.

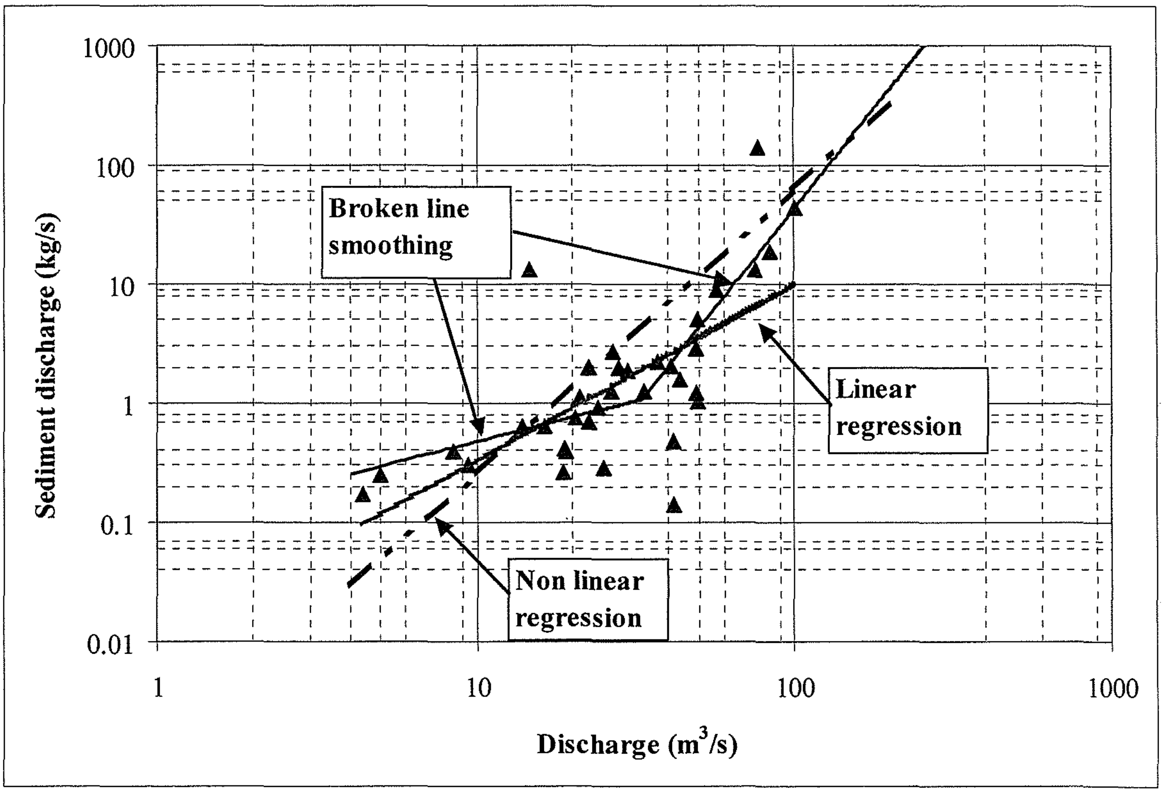


FIGURE 1: Comparison of the broken line smoothing technique in contrast to the ordinary power curve (1) for the Poros Riganiou cross section

The broken line shows an excellent fit to the data in contrast to single rating curves for the whole set of measured discharges. Particularly for the linear regression of the log-transformed variables it is illustrated that for high discharges the rating curve significantly underestimates the sediment discharge of the measurements.

2. RESEARCH METHODOLOGY

2.1. Description of research framework

14 river sites in North-Western Greece have been examined. The suspended sediment measurements have been collected from the Public Power Corporation (PPC) and normally cover a time span from 1965 to 1980. The number of measurements varies from site to site (e.g. 36 measurements at Poros Riganiou to 121 at Plaka Br.) and the frequency of measurement is highly variable. The general map of the catchments and the associated cross sections is shown on Figure 1. Table 1 presents the general characteristics of the cross sections. The mean annual suspended sediment discharge and sediment yield for cross sections 2, 3 and 4 have been resulted from the measurement of the Kremasta reservoir sedimentation rate [11], whereas for the rest of the cross sections the rating curves have been constructed using the broken line smoothing method. Mean daily discharges are available for each of the remaining 11 cross sections for nearly the same period as the sediment discharge measurements. Therefore the mean annual sediment discharge and sediment yield have been computed and presented in Table 1.

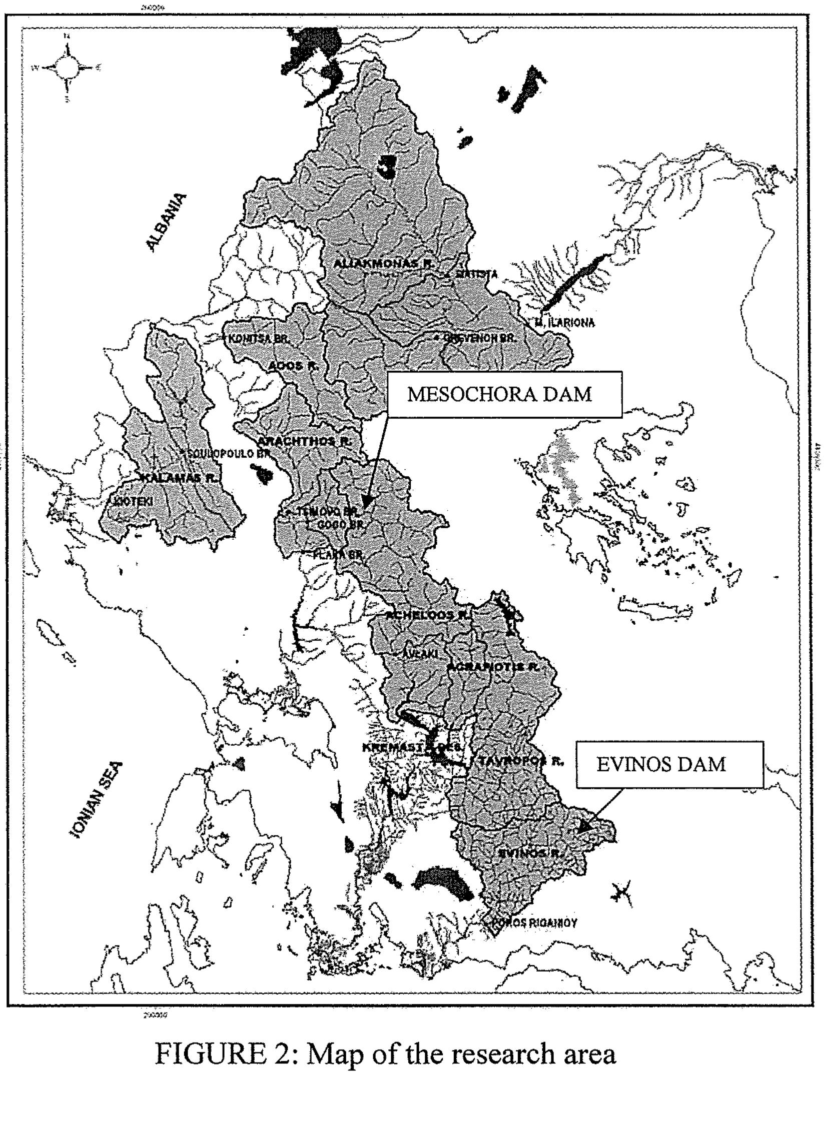


FIGURE 2: Map of the research area

For almost the same cross sections, estimates of mean annual sediment discharges have been issued from both the PPC and from Koutsoyiannis and Tarla [12]. These estimates originate from (1) for two single rating curves (for the whole set of measured discharges); one for the dry and the other for the wet period of the year. Based on these approaches, the dead storage volumes for a number of dams in Greece have been computed. Here we will restrain to the Evinos Dam, upstream of the Poros Riganiou cross section, and the Mesochora Dam at Acheloos River, upstream of the Avlaki cross section (see Figure 2). The Evinos Dam (catchment area of 351.9 km^2) has been designed within the Athens' water supply scheme and the Mesochora Dam (upstream area of 640.4 km^2) is a hydroelectric project and part of the Acheloos diversion scheme. The dead storage volume for the Evinos Dam has been assigned equal to 25.4 hm^3 for a projected economic life of 100 years. This consists of total mass of deposited sediments equal to 35.5 Mt assuming a density of deposited sediments equal to 1.4 t/m^3 (according to the design study). The expected sediment load for the Mesochora Dam has been calculated equal to 130 hm^3 (or 182 Mt with a density equal to 1.4 t/m^3) for 50 years period. We will show that both dead storage volumes as calculated with the simplistic rating curves are not realistic and deviate significantly from the values calculated with the broken line rating curves.

Table 1: Characteristic values of mean annual sediment discharge (Q_s) and sediment yield (S_y) for the cross-sections under consideration.

No	River	Cross Section	Area (km^2)	Q (m^3/s)	Qs (kg/s)	Sy (t/km^2)
1	Acheloos	Avlaki	1355	50.2	73.3	1705.5
2	Acheloos	Kremasta Res.	1733	-	66.0	1184.6
3	Agrafiotis	Kremasta Res.	320	-	20.9	2034.8
4	Tavropos	Kremasta Res.	1239	-	19.5	489.4
5	Evinos	Poros Riganiou	914	25.3	42.5	1447.3
6	Arachthos	Tsimovo Br.	640	18.7	21.3	1049.5
7	Arachthos	Gogo Br.	203	11.4	10.3	1592.1
8	Arachthos	Plaka Br.	970	36.1	38.4	1249.0
9	Kalamas	Soulopoulo Br.	660	22.7	5.9	279.6
10	Kalamas	Kioteki	1481	48.9	25.4	532.6
11	Aoos	Konitsa Br.	706	24.9	48.9	2150.7
12	Aliakmonas	Grevenon Br.	847	17.0	2.2	81.3
13	Aliakmonas	Siatista	2724	22.8	20.2	233.3
14	Aliakmonas	M. Ilariona	5005	48.7	65.8	414.6

2.2. Results and Discussion

The application of the broken line rating curves to the mean daily discharges result in values of mean annual sediment discharge and sediment yield as presented in Table 1. We can produce regression equations with catchment area according to Figure 3. Note that the labels in this figure refer to the first column in Table 1. It can be inferred that there is a region (squares in Figure 3) that covers a hypothetical axis from SE to NW including (from south to north) the Evinos R., the Acheloos R. (excluding the eastern Tavropos subcatchment), the Arachthos R. and the Aoos R. catchments that a significant correlation of mean annual sediment discharge and catchment area, A, is exhibited. The equation (see Figure 3) is presented in a power form ($Q_s = c\,A^d$), where A in km^2 is the catchment area and c, d parameters. The coefficient of determination is equal to R^2=0.82.

Accordingly there is a region that covers a hypothetical axis from West to East including the Kalamas R. and the Aliakmonas R. catchments (triangles in Figure 3) with remarkably less value of sediment discharges than the former region. The same type of equation as before is shown in Figure 3. The regression is also very significant and the coefficient of determination is equal to R^2=0.87. The important issue on the second set of catchments is that sediment yield is an increasing function of basin area. This trend clearly controverts the conventional model of sediment yield as decreasing function of catchment area. However, it is reported that there are cases when sediment yield increases with catchment area. For instance, [13] have observed a pattern of increasing sediment yield at all spatial cases up to $3*10^4$ km^2 in British Columbia. The authors suggested that the positive correlation has been attributed to the dominance of secondary remobilization of Quaternary sediments from stream banks and valley bottom areas over primary denudation of the land surface. This result suggests that sediment yield of larger drainage basins remains conditioned by the extraordinary glacial events of the Quaternary period, when large quantities of unconsolidated sediments were delivered to the major valley of British Columbia.

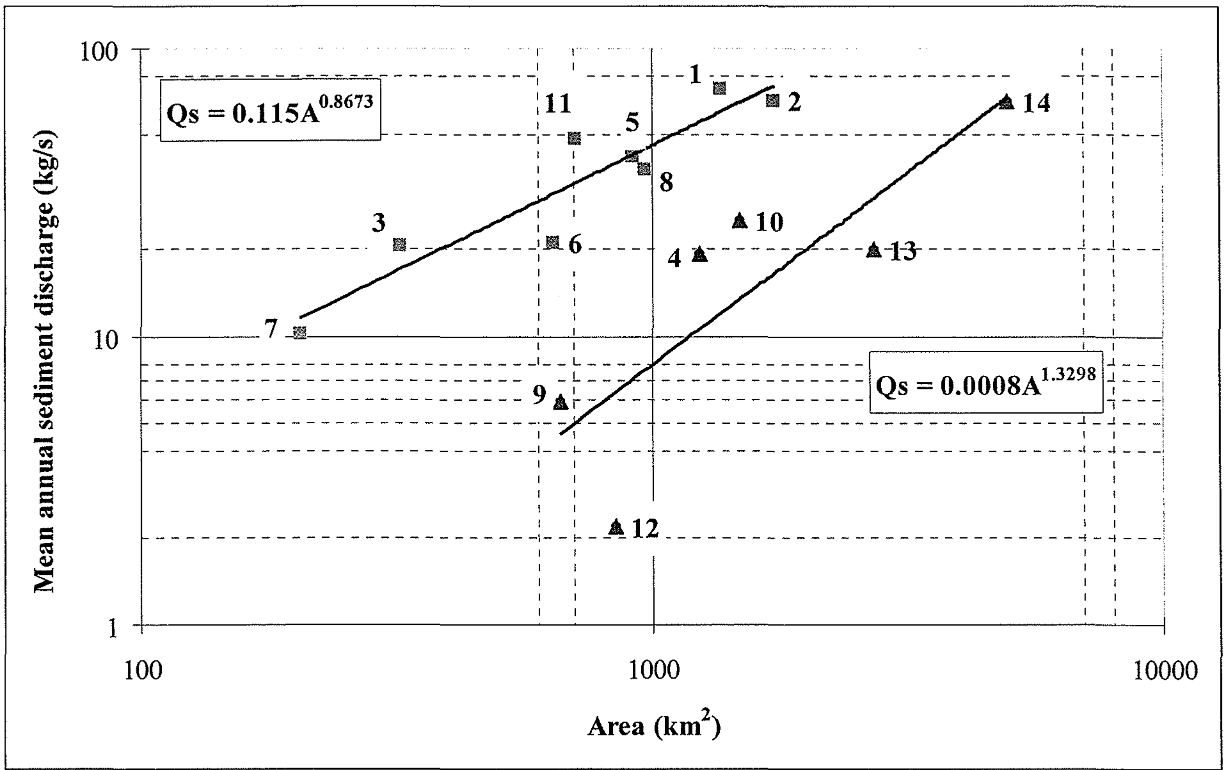


FIGURE 3: Mean annual sediment discharge for two distinct regions in NW Greece.

We can rationally assume that the Evinos Dam and Mesochora Dam catchments belong to the first region of catchments and that the retention efficiency of both the reservoirs is equal to unity; i.e. the whole of the incoming sediment load is retained within the reservoirs. By applying the equation ($Q_s = 0.115A^{0.8673}$) we conclude that for Evinos Dam and Mesochora Dam the mean annual sediment discharge is equal to 18.6 kg/s and 31.2 kg/s respectively. For 100 and 50 years projected time period respectively, the expected accumulated sediment load for Evinos Dam should be equal to 58.6 Mt and for the Mesochora Dam should be equal to 49.3 Mt. These values are referring only to the suspended load and for bed load an increase of 10 to 15% should be accounted for. Considering that the dead and useful storage of the Evinos reservoir is only 25.4 and 112 hm^3 respectively and the projected deposited sediments' volume is 41.9 hm^3 at the end of the economic life for the same sediments' density, it is obvious that a part of the useful storage will be occupied by the deposited sediments. Needless to say, if the water supply intake is close enough to the inlet of the Evinos River in the reservoir, then a serious threat for the reliability of the dam as a whole is posed. On the contrary, the dead storage of the Mesochora Dam is significantly overestimated. The expected sediment load after 50 years according to the design study of the reservoir is 182 Mt whereas the computed value from this study is only 49.3 Mt. This overestimation, although is not a threat to the sustainability of the project as designed, leads to a waste of valuable water resources because, as proved by [11], sediment deposits are mostly occurred at the reservoir's delta and not in front of the dam where the dead storage is conceptually set up. Therefore, in such reservoirs overestimated dead storage volumes remain empty and the incoming sediment load occupy part of the useful storage.

Therefore for Evinos Dam we conclude that the original expected accumulated sediment load without counting the bed load fraction is significantly underestimated (35.5 instead of 58.6 Mt). That raises serious questions for the sustainability of the reservoir to undertake its purpose for the Athens' water supply. Therefore, it of the utmost urgency to launch a program of sediment discharge measurements upstream of the reservoir in order to evaluate the true sedimentation rate of the reservoir and to re-assess the economic life of the reservoir in front of the new evidence. On the other hand, the dead storage volume for the Mesochora Dam was overestimated at the original design study; where less conservative dead storage estimation would enhance the production of hydroelectric energy.

3. CONCLUSIONS

The main scope of the research presented in this paper is to re-compute the mean annual sediment yield and discharge for a number of river cross-sections in NW Greece. This approach was based on the broken line smoothing method that represents realistically the process of the break up of the armor layer in gravel-bed rivers when a certain discharge threshold is exceeded. Further research is needed to provide evidence on the frequency and magnitude of this threshold discharge and its relation with certain geomorphologic elements (e.g. bankful discharge). The rating curve consists of two straight lines in a log-log plot with the steepest one occurring at high discharges. Ordinary single-valued rating curves cannot describe the transport mechanisms accurately and result in serious underestimation of sediment discharges during wet periods. A regression analysis with the catchment area is carried out and two distinct regions have been established with strong correlations between mean annual sediment discharge and catchment area. The strong correlation might dictate similar characteristics in terms of rainfall and runoff intensity, geologic formations and land cover. Further research is being contacted so as to include other hydrologic or geomorphologic parameters in a multiple regression analyses in order to explain more of the observed variance of the sediment discharge estimates.

Applying the regression equation to two rivers (Acheloos and Evinos Rivers) impounded by dams (the Mesochora and Evinos Dams), the mean annual sediment discharge is calculated as well as the projected sediment mass and volume at the end of the economic life of the projects. It is shown that the dead storage of the Evinos Dam is underestimated contrary to the Mesochora Dam where a significant overestimation of the dead storage volume is prominent.

ACKNOWLEDGMENTS

This paper is a result of the research program "Assessment of hydrologic catchments' sediment yield by comparative analyses of hydrologic and geomorphologic parameters", which is funded from the National Technical University of Athens under the framework program of basic research "PROTAGORAS". The authors are also indebted in the Public Power Corporation for providing the sediment discharge data.

REFERENCES

1 Verstraeten, G. and J. Poessen (2000) Estimating trap efficiency of small reservoirs and ponds; an overview of existing methods and the implications for the assessment of sediment yield, **Progress in Physical Geography,** 24(2), pp. 219-251.

2. Takeuchi, K., M. Hamlin, Z.W. Kundzewicz, D. Rosbjeg and S. Simonovic (1998) **Sustainable reservoir development and management**, IAHS Publication No. 251,.

3. WCD (2000) **Dams and development. A New Framework for Decision-Making.** Earthscan Publications Ltd, London, 356 pp.

4. de Vente, J., J. Poesen and G. Verstraeten (2005) The application of semi-quantitative methods and reservoir sedimentation rates for the prediction of basin sediment yield in Spain, **Journal of Hydrology**, 305, pp. 63-86.

5. Walling, D.E. (1983) The sediment delivery problem, **Journal of Hydrology**, 65, pp. 209-237.

6. Verstraeten G. and J. Poessen (2001) Factors controlling sediment yield from small intensively cultivated catchments in a temperate humid climate. **Geomorphology** 40 (1/2), pp: 123–144.

7. Ferguson, R.I. (1986) River loads underestimated by rating curves, **Water Resources Research**, 22 (1), pp. 74-76.

8. Walling, D.E. (1977) Assessing the accuracy of suspended sediment rating curves for a small basin, **Water Resources Research**, 13 (3), pp. 531-538.

9. Asselman, N.E.M. (2000) Fitting and interpretation of sediment rating curves, **Journal of Hydrology**, 234, pp. 228-248.

10. Koutsoyiannis, D. (2000) Broken line smoothing: a simple method for interpolating and smoothing data series, **Environmental Modelling & Software**, 15, 139-149.

11. Zarris, D., E. Lykoudi and D. Koutsoyiannis (2002) Sediment yield estimation from a hydrographic survey: A case study for the Kremasta reservoir basin, Greece, Proceedings of the **5th International Conference "Water Resources Management in the Era of Transition"**, Athens, 4-8 September, pp 338-345.

12. Koutsoyiannis, D., and K. Tarla (1987) Sediment yield estimations in Greece. **Technika Chronika**, A 7 (3), 127–154 (in Greek).

13. Church, M., R. Kellerhlals and T.J. Day (1989) Regional clastic sediment yield in British Columbia. **Canadian Journal of Earth Science**, 36, 1267-1280.