Sediment Yield Assessment in Greece

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Abstract Sediment discharge measurements in Greece have absolutely been stopped during the 1980s and are yet at a standstill. Any initiatives for the commencement of a nation-wide sediment discharge measuring program find obstacles, apart from the investment costs, in the unavailability of the experienced personnel to carry out the sediment discharge measurements. However, the hydrographic survey of the Kremasta Reservoir of the Acheloos R. in Western Greece at the end of the 90's was a milestone because it was the first time when the mean annual sediment yield was actually measured by means of reservoir deposits. Sediment yield calculations for other river sites derived from suspended sediment rating curves that have been adjusted by considering estimates from the hydrographic survey of the Kremasta Reservoir.

Keywords: Greece, sediment yield, sediment discharge rating curves, daily discharges

1. INTRODUCTION

Sediment yield is the sediment load normalized for the catchment area and is the net result of erosion and depositional processes within a basin. Thus, it is controlled by those factors that control erosion and sediment delivery, including local topography, soil properties, climate, vegetation cover, catchment morphology, drainage network characteristics and land use. 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) (Verstraeten and Poesen, 2000; de Vente et al., 2005) as well as 39000 large dams. At present, sediment yield estimates are achieved mainly from simple empirical models that relate mean annual sediment yield (SY, in t/km2) to catchment properties, including drainage area, topography, climate and vegetation characteristics (e.g. Jansen & Painter 1974, Dendy & Bolton 1976, Walling 1983). 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:

$$Q_{si} = aQ_i^b n_i$$

where Qs is the sediment discharge (kg/s), Q is the river discharge (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 (Ferguson, 1986). The exponent parameter, b, is very important when determining the sediment yield of a catchment and it normally assigns values between 0.5 and 3; the higher the parameter the more intense transport capacity of the river flow. 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 (Walling, 1977; Asselman, 2000) have analysed 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 (1977) 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%.

2. METHODOLOGY AND STUDY AREA

2.1. Study Area

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. Nestos R. is also studied but it is a transboundary river shared between Greece and Bulgaria and drains through Northern Greece. 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.

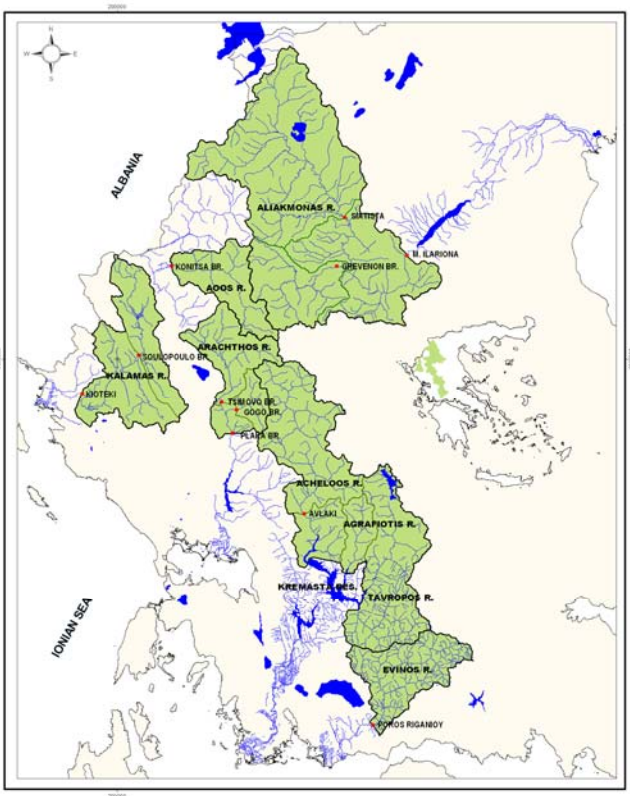

Figure 1. Map of the examined catchments

Skoulikidis (2009) has divided the area of South Balkans in three geotectonical zones: the External (zone 1) and Internal zones (zones 2 and 3) as presented in Figure 2. Zones 2 & 3 are dominated by the Alpine orogenesis and reveal a rather simple geotectonic structure made up of sedimentary sequences. They are additionally affected by older orogenic movements and reveal a complex geotectonic structure dominated by metamorphic massifs, plutonic and volcanic intrusions, and ophiolite suture zones. Due to its relatively young geology, the Peninsula is characterized by highly fragmented hydrographic networks. It is thus drained by many small and medium-sized mountainous rivers running through steep, narrow valleys, with flashy flow and sediment regimes, descending abruptly to the coast. However, there are a few larger low-gradient rivers crossing the Balkans along prevailing thrust belts and related rift valleys that form extensive flood and deltaic plains. It will be shown that catchments which belong to Zone 3 exhibit significantly higher sediment yields than the rest of the available data set.

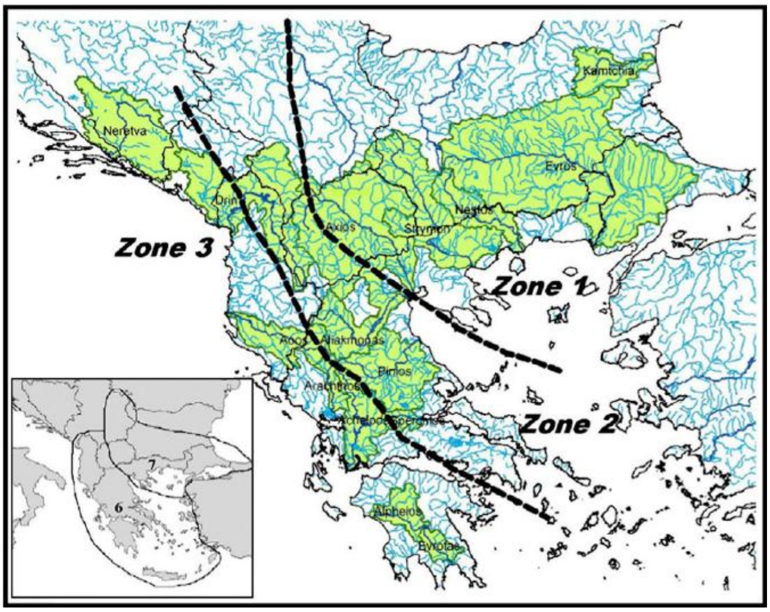

Figure 2. Division of the area into geotectonic zones (after Skoulikidis, 2009)

2.1. Catchment sediment yields in NW Greece

The hydrographic measurement of the 4495 hm^3 Kremasta Reservoir in Western Greece was a milestone (Zarris et al., 2002) in a sense that the actual mass of deposited sediments of the Acheloos (i.e. the catchment's mean annual sediment yield) was measured. Just upstream of the reservoir there is a sediment discharge gauging station (Avlaki gauging station). For this station, the only sediment discharge rating curve that produces sediment yield equal to that measured in the reservoir was the broken line interpolation curve (Zarris and Koutsoyiannis, 2005). All the other available rating curves formulation (i.e. the ordinary power rating curve and with the Ferguson correction, the nonlinear regression, ratings along with dry-wet periods and rising-falling stages) seriously underestimate the measured sediment yield. The broken line interpolation was introduced by Koutsoyiannis (2000) as a simple alternative to numerical smoothing and interpolating methods and is treated here as a surrogate 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 form, we assume a broken line with two segments. In such a fluvial form, there is a distinct threshold discharge for sediment motion, which is attributed to the development of the well-known armour layer. Below this threshold there is no exchange of the suspended sediment with the riverbed. Once the surface, coarse material, armour layer fully breaks up beyond the threshold discharge and exposes a larger range of particle sizes underneath, the transport rate significantly increases. Additionally, bank erosion during high discharges will enhance the sediment availability in the river bed.

Figure 3 presents 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 Qs and Q and back-transformed to Equation 1 for the set of sediment discharge measurements for the Poros Riganiou cross section of the Evinos River. 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. The rating exponent, b, for this specific case is equal to 0.68 for the first segment and 3.3 for the steeper segment of the broken line.

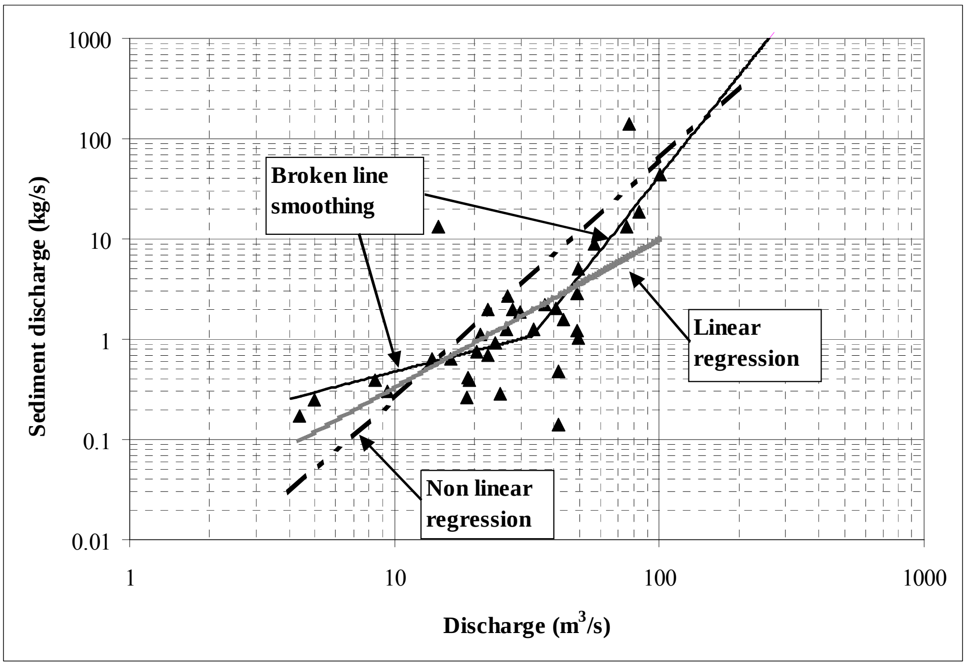

Figure 3. Comparison of the broken line smoothing technique in contrast to the ordinary power curve and the non-linear regression for the Poros Riganiou cross section

3. RESULTS AND DISCUSSION

The application of the mean daily discharges to the sediment rating curves are resulting in the values of mean annual sediment yield (S_Y) and mean annual sediment discharge (Q_s). The corresponding values as well as the catchment area, the mean annual discharge and the mean annual maximum flood (in terms of mean daily discharges) are presented in Table 1. Sediment yields for catchments No. 1 to 4 can be found at Zarris et al., (2002), No. 5 to 14 at Zarris et al. (2006) and No. 15 at Zarris et al., 2011.

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	Zone (Fig. 2)	Area (km^2)	Q (m^3/s)	Qs (kg/s)	S_y (t/km^2)
1	Acheloos	Avlaki	3	1355	50.2	73.3	1705.5
2	Acheloos	Kremasta Res.	3	1733	-	66.0	1184.6
3	Agrafiotis	Kremasta Res.	3	320	-	20.9	2034.8
4	Tavropos	Kremasta Res.	2	1239	-	19.5	489.4
5	Evinos	Poros Riganiou	3	914	25.3	42.5	1447.3
6	Arachthos	Tsimovo Br.	3	640	18.7	21.3	1049.5
7	Arachthos	Gogo Br.	3	203	11.4	10.3	1592.1
8	Arachthos	Plaka Br.	3	970	36.1	38.4	1249.0
9	Kalamas	Soulopoulo Br.	3	660	22.7	5.9	279.6
10	Kalamas	Kioteki	3	1481	48.9	25.4	532.6
11	Aoos	Konitsa Br.	3	706	24.9	48.9	2150.7
12	Aliakmonas	Grevenon Br.	2	847	17.0	2.2	81.3
13	Aliakmonas	Siatista	2	2724	22.8	20.2	233.3
14	Aliakmonas	M. Ilariona	2	5005	48.7	65.8	414.6
15	Nestos	Temenos	1	4954	31.0	31.9	203.4

Table 2 presents the examined geomorphologic parameters under consideration with a synoptic explanation of the role of each parameter in conceptualizing sediment yield processes and the correlation coefficients with the sediment yield estimates. In bold characters, the most influential parameters are being denoted that are statistically significant at the 5% significance level. Obviously, the available dataset is not adequate in order to generalize the conclusions, but it seems that sediment yield is strongly correlated to mean annual discharge depth, the hypsometric integral, the catchment's mean slope, the bifurcation ratio and the USLE's rainfall erosivity factor. Sediment yield is decreasing with increasing catchment area but according to a relatively weak correlation.

Table 2. Major terrain characteristics and their relation to erosion and transport processes

Geomorphologic parameter	Influence on erosion and transport processes	Correlation Coefficients	
		Sediment Yield Sy	Sediment Discharge Qs
Catchment Area (A)	Global parameter	-0.45	0.49
Mean annual discharge (Q_{av})	Runoff Potential	-0.14	**0.73**
Mean annual runoff depth (Hq_{av})		**0.64**	-0.11
Mean annual flood (Q_{max})	Stream Power, Transport Potential	0.14	**0.89**
Hypsometric Integral (HI)	Distribution of elevation with catchment	**0.81**	0.27
Catchment Length Lb_{max}	Catchment size index	-0.16	**0.67**
Mean Slope	Flow velocity and momentum	**0.61**	-0.15
Drainage Density (DD)	Balance between erosive forces and surface resistance	0.20	-0.33
Drainage Frequency (DF)	Stream network texture, Relief disruption	-0.31	-0.35
Circularity Index (CI)	Rate of sediment delivery, deposition potential	-0.09	-0.50
Elongation Ratio (ER)		-0.38	-0.40
Bifurcation Ratio (R_B)	Internal processes index, branches development grade, stream network dynamic equilibrium	**0.55**	0.14
USLE Rainfall Erosivity Factor (R)	Driving force of erosion	**0.76**	-0.004
USLE Soil Erodibility Factor (K)	Main source of erosion processes	-0.37	0.005

On the other hand, sediment discharge is strongly correlated to the mean annual flood and discharge and the catchment length. The inconsistency of regression coefficients between sediment yield and discharge is due to the catchment area (i.e. sediment yield is sediment discharge divided by catchment area), that acts as a distorting parameter. It is also evident that the geologic setting of the catchments under consideration is averaging out in medium to large catchments as other mechanisms in the erosion-transport-deposition continuum play dominant role. However, the strongest correlation of all parameters is the sediment discharge with the mean annual flood (i.e. the average of the maximum daily discharge for a given number of hydrologic years). The power equation is presented in Figure 4 and has been used with relative success in a number of hydrologic design studies in Greece.

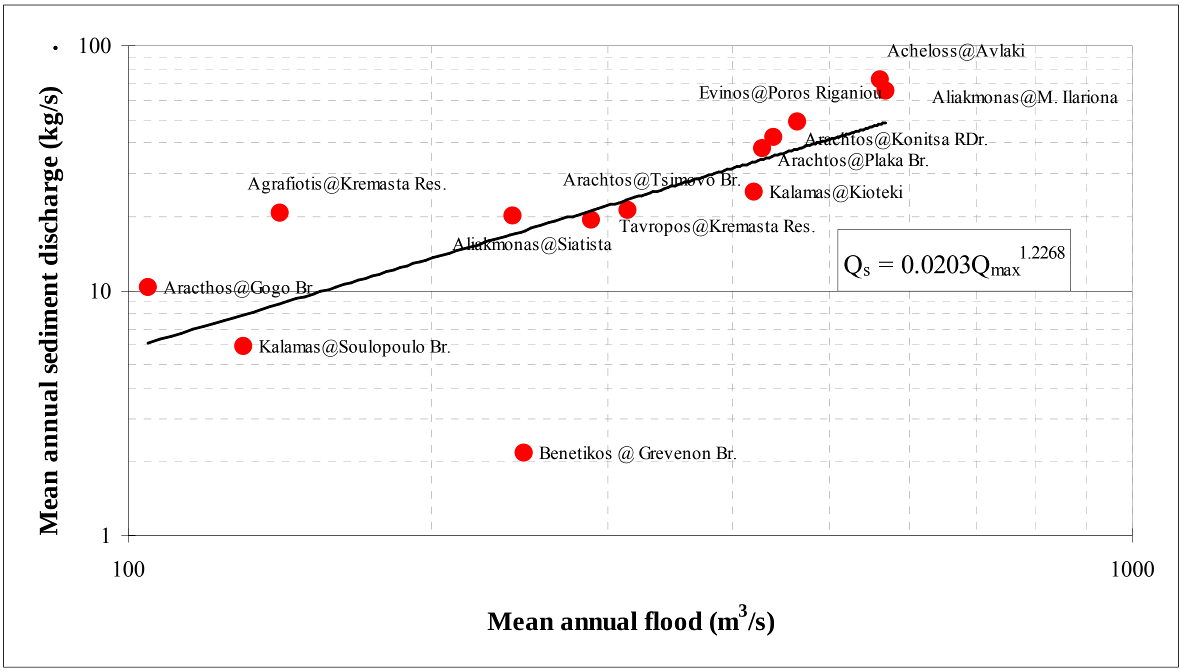

Figure 4. Relation between mean annual sediment discharge and mean annual flood

According to our results from the 15 river sites in NW Greece and the data bank with sediment yield measurements from around the globe (823 catchments) that the authors has collected from numerous publications, the box plots of the sediment yields are presented in Figure 5. These circles are filled in when the values are more than three times the distance between the quartiles ($Q_{75\%}$-$Q_{25\%}$) otherwise they are empty. It is evident that the highest sediment yields in the world are found in Asia with mean value around 2000 t/km^2/a. It is also shown that a lot of catchments in Asia exhibit sediment yields in excess of 6000 t/km^2/a. The estimated sediment yields in our study naturally are higher than those measured in the rest of Europe (mostly from the northern Europe) and from the Americas, largely because tectonic activity seriously affects the sediment yield of such catchments. Furthermore, rivers that drain active edges of continental margins (e.g., western South and North America) or collision margins (e.g., southern Europe and southern Asia) are generally much smaller, but collectively they transport similar amounts of sediment as do large passive margin rivers. It is also evident that the small number of sediment yield estimates in NW Greece does not allow for arbitrary generalizations.

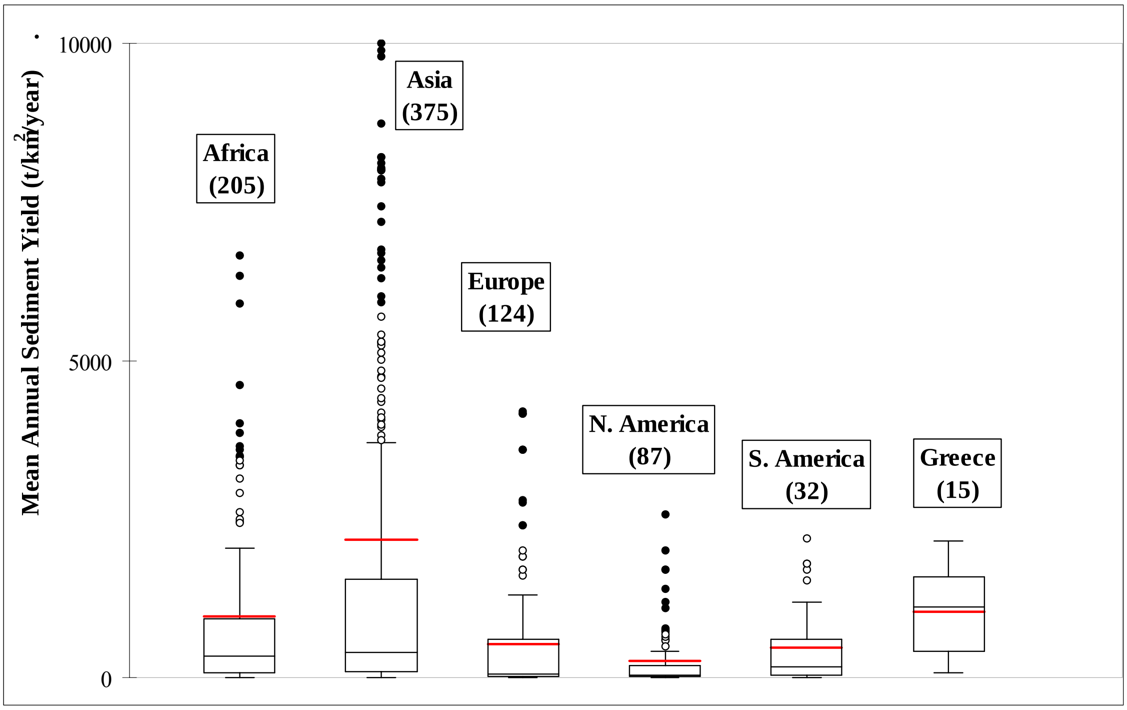

Figure 5. Box plots of global sediment yield measurements as compared to those from NW Greece (number of catchments in parentheses)

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