

SEDIMENT YIELD ESTIMATES IN NORTH-WESTERN GREECE AND ANALYSES WITH HYDROLOGIC AND GEOMORPHOLOGIC FACTORS

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

¹ *Department of Water Resources, School of Civil Engineering, National Technical University of Athens, 5 Heroon Polytechniou St., 15780, Athens, Greece, zarris@itia.ntua.gr, dpanag@central.ntua.gr*

² *Department of Geological Sciences, School of Mining Engineering and Metallurgy, National Technical University of Athens, 5 Heroon Polytechniou St., 15780, Athens, Greece, mmgpel@central.ntua.gr, elykoudi@metal.ntua.gr*

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 11 river catchments in North-Western Greece are computed with the application of the mean daily discharges to the sediment discharge rating curves and compared to the earlier estimates published by other researchers. For these catchments a number of hydrologic and geomorphologic parameters have been computed using advanced mapping methodologies. An attempt is made to correlate the suspended sediment estimates mainly with geomorphologic parameters, that rarely has been carried out in the international literature.

Key words: *sediment yield, hydrology, geomorphology, Western Greece.*

Περίληψη

Στην παρούσα εργασία γίνεται προσπάθεια προσδιορισμού του βαθμού και του τρόπου που επηρεάζεται η στερεοαπορροή από υδρολογικές και γεωμορφολογικές παραμέτρους, σε 11 ποτάμια συστήματα της βορειοδυτικής Ελλάδας. Η μέση ετήσια στερεοπαροχή και στερεοαπορροή υπολογίζεται από τη μετατροπή των μέσων ημερήσιων παροχών σε στερεοπαροχές μέσω των καμπυλών παροχής – στερεοπαροχής. Οι καμπύλες υπολογίστηκαν με την εφαρμογή της τεθλασμένης παλινδρόμησης, που αποδίδει την αποδόμηση του στρώματος θωράκισης αφού γίνει υπέρβαση μιας οριακής τιμής της παροχής, όπου η στερεοπαροχή αυξάνεται με πολύ μεγαλύτερο ρυθμό.

Για τις λεκάνες αυτές υπολογίστηκαν με την εφαρμογή κατάλληλου λογισμικού ένα πλήθος γεωμορφολογικών παραμέτρων, αφού πρώτα είχαν ψηφιοποιηθεί οι ισούψεις καμπύλες και το υδρογραφικό δίκτυο από τα τοπογραφικά διαγράμματα 1:50000 της ΓΥΣ. Ενδεικτικά αναφέρονται ο λόγος διακλάδωσης, το υψομετρικό ολοκλήρωμα, η συχνότητα και η πυκνότητα του υδρογραφικού δικτύου και άλλα. Με βάση τις τιμές αυτές έγινε μη – γραμμική ανάλυση παλινδρόμησης ώστε να προκύψουν καταστατικές εξισώσεις υπολογισμού της στερεοπαροχής με βάση τις παραμέτρους αυτές.

Για τις ελληνικές συνθήκες είναι η πρώτη φορά που εξετάζεται ένα τόσο μεγάλο δείγμα στερεοαπορροών στον ελληνικό χώρο. Βέβαια το πλήθος του δείγματος δεν είναι τέτοιο που να δικαιολογεί την κατάστρωση καταστατικών εξισώσεων με γενικότερη εφαρμογή, αποτελεί όμως ένα σαφές δείγμα για τη ποιοτική έκφραση των διαδικασιών της διάβρωσης και της στερεομεταφοράς.

Λέξεις κλειδιά: Στερεοαπορροή, Υδρολογία, Γεωμορφολογία, Δυτική Ελλάδα.

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 (S_Y , in t/km^2) to catchment properties, including drainage area, topography, climate and vegetation characteristics (e.g. Jansen and Painter 1974, Dendy and Bolton 1976, Walling 1983). Catchment sediment yield usually decreases with basin scale, mainly because sediment sinks, such as floodplains, will generally increase, assuming the concept of source – transport – deposition continuum as the ideal fluvial system.

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:

Equation 1 – Sediment discharge rating curve

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

where Q_s 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. Catchment sediment yields in NW Greece

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.

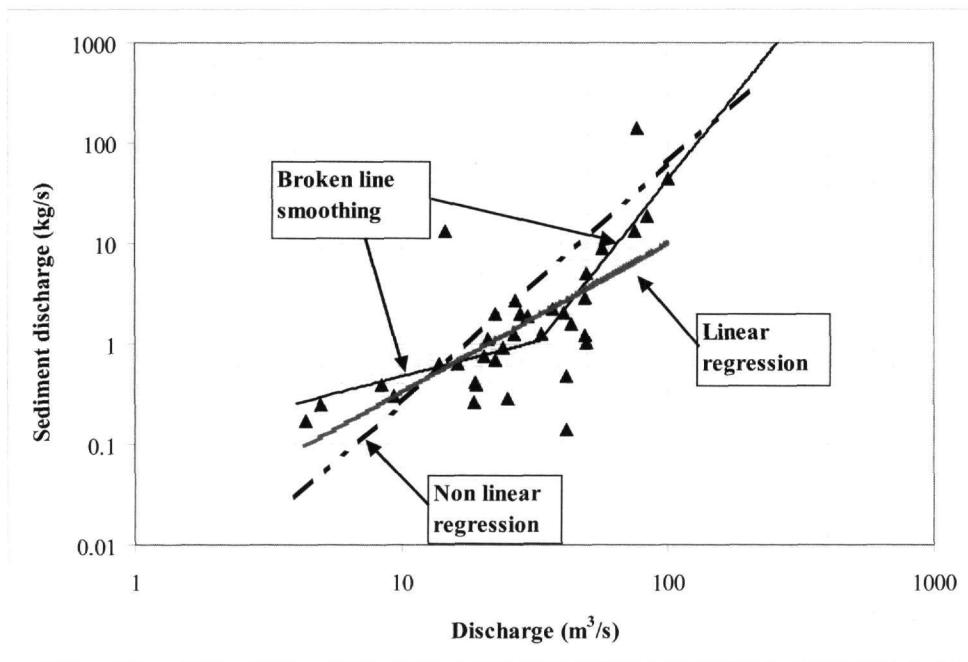


Figure 1 - Comparison of the broken line smoothing technique in contrast to the ordinary power curve and the non-linear regression for the Poros Riganiou cross section

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 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.

2.2. Study area

11 river sites in North-Western Greece have been examined. The original 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 Bridge*) and the frequency of measurement is highly variable. The general map of the catchments and the associated cross sections is shown on Figure 2. Table 1 presents the general characteristics of the examined catchments. 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 (Zarris *et al.* 2002), whereas for the rest of the cross sections the rating curves have been constructed using the broken line interpolation method. Mean daily discharges are available for each of the remaining 8 cross sections for nearly the same period as the sediment discharge measurements (also available from the PPC). Therefore the mean annual sediment discharge and sediment yield have been computed and presented in Table 1.

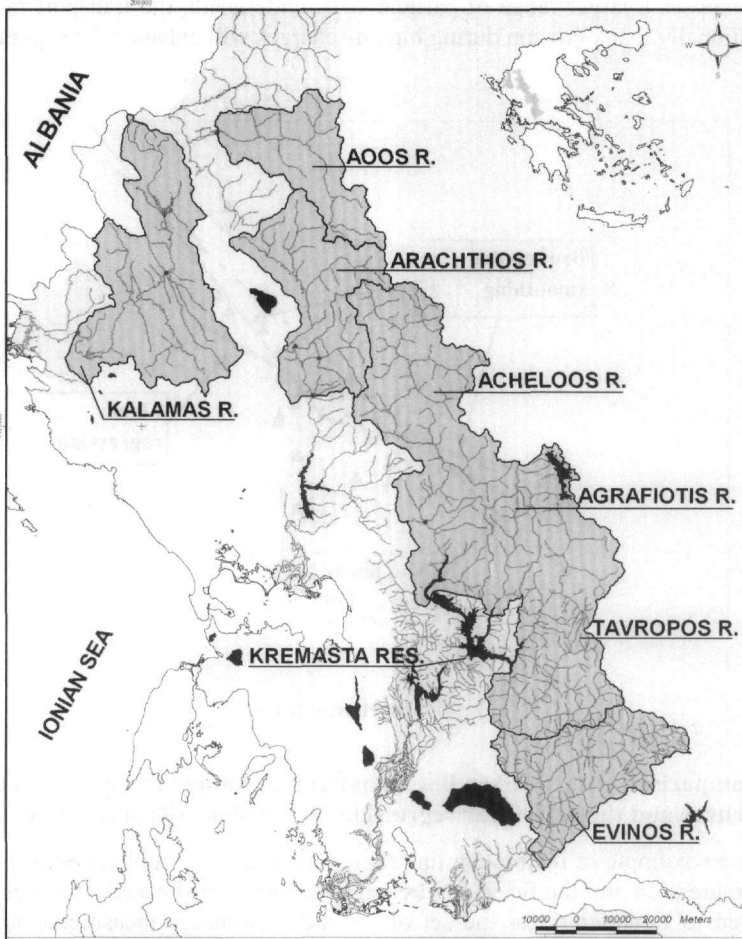


Figure 2 - Map of the study area

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_{av} (m ³ /s)	Q_{max} (m ³ /s)	Q_s (kg/s)	S_y (t/km ²)
1	Acheloos	Avlaki	1355	50.2	561.4	73.3	1706.0
2	Acheloos	Kremasta Res.	1733	-	-	66.0	1201.0
3	Agrafiotis	Kremasta Res.	320	-	-	20.9	2059.7
4	Tavropos	Kremasta Res.	1239	-	-	19.5	496.3
5	Evinos	Poros Riganiou	914	25.3	439.5	42.5	1466.4
6	Arachthos	Tsimovo Br.	640	18.7	314.7	21.3	1049.6
7	Arachthos	Gogo Br.	203	11.4	104.7	10.3	1600.1
8	Arachthos	Plaka Br.	970	36.1	427.2	38.4	1248.4
9	Kalamas	Soulopoulo Br.	660	22.7	130.2	5.9	281.9
10	Kalamas	Kioteki	1481	48.9	419.2	25.4	540.9
11	Aoos	Konitsa Br.	706	24.9	463.5	48.9	2184.3

In order to assess factors affecting sediment yields in NW Greece, key catchment attributes related to erosion were collected. Contour and streams shown in topographic maps 1:50000 were digitized and the Digital Terrain Models (DTM) with cell size equal to 25 m were derived. Major topographic attributes such as the slope, the relief ratio, the bifurcation ratio and the hypsometric integral have been computed using the RiverTools 3.0 software (Rivix 2004). RiverTools provides a specialized set of tools for the analyses of topography, watersheds and river networks. For instance, RiverTools makes it easy to get accurate measurements for things like the lengths and slopes of channel segments, the number of streams of a given order, the contributing area of a catchment, the shape of a longitudinal profile, a basin's hypsometric curve, topographic wetness indices, the shape of a catchment and many others.

3. Results and Discussion

3.1. Sediment yields in NW Greece as compared to universal measurements

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.

For almost the same cross sections, estimates of mean annual sediment discharges have been issued from the PPC and also from Koutsoyiannis and Tarla (1987) and Poulos and Chronis (1997).

Figure 3 presents a comparison of the published estimates of the mean annual sediment discharge between the present paper and the ones from the PPC, Koutsoyiannis and Tarla (1987) and Poulos and Chronis (1997). It is shown that in almost all the cases all the published estimates are quite different. Zarris *et al.* (2006) showed that the inconsistency of sediment yield estimates might provoke an underestimate of the dead storage volume of the *Ag. Demetrios* Reservoir (Evinos River; upstream of the *Poros Riganiou* gauging station) and an overestimate of the corresponding volume of the *Messochora* Reservoir (*Acheloos* River; upstream of the *Avlaki* gauging station).

The present study actually presents significantly higher sediment yields of the Acheloos and Evinos Rivers and less of the Kalamas and Arachthos Rivers. Generally it is often surprising how different sediment yield estimates are derived from nearly the same set of original data. This is in general explained by the serious complexity of the processes involved from the computation of the mean daily discharges to the adequate interpretation of the sediment discharge measurements in order to construct the adequate rating relationship between sediment and stream discharge. However, simultaneous measurements of river and sediment discharge are mainly conducted only in low – flow periods, thus any extrapolation for wash loads at the time of low frequency – high magnitude flood flows will generally give misleading results, unless a correct slope of the rating curve is estimated.

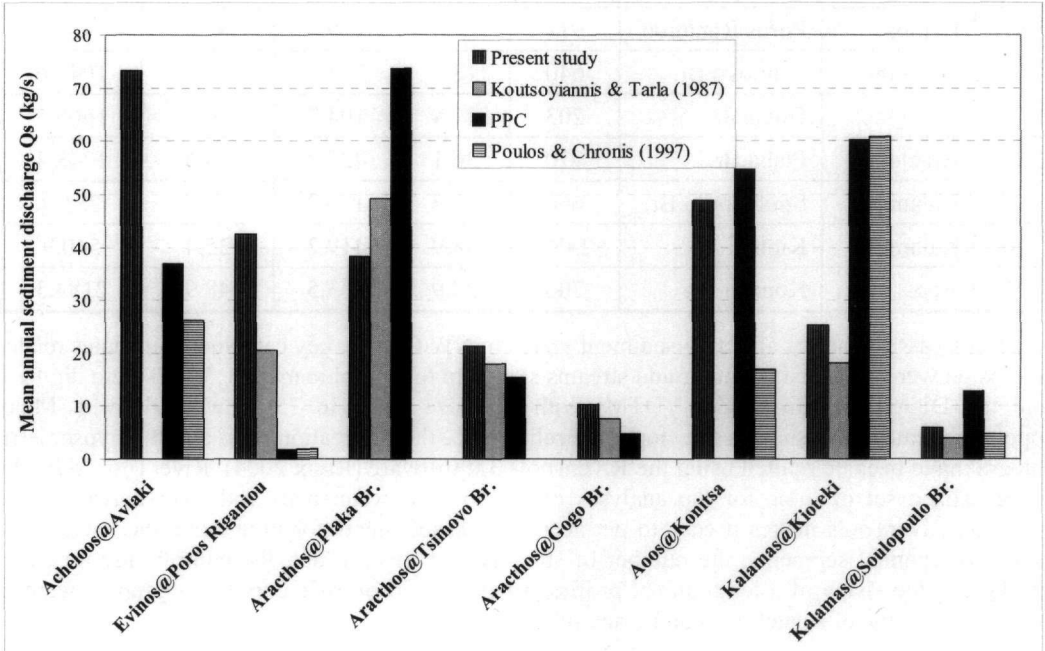


Figure 3 - Comparison of sediment yield estimates in NW Greece as compared with different references

According to our results from the 11 river sites in NW Greece and the data bank with sediment yield measurements from around the globe (823 catchments) that the first of the authors has collected from numerous publications, the box plots of the sediment yields are presented in Figure 4. 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 $2000 \text{ t/km}^2/\text{a}$. It is also shown that a lot of catchments in Asia exhibit sediment yields in excess of $6000 \text{ t/km}^2/\text{a}$. 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.

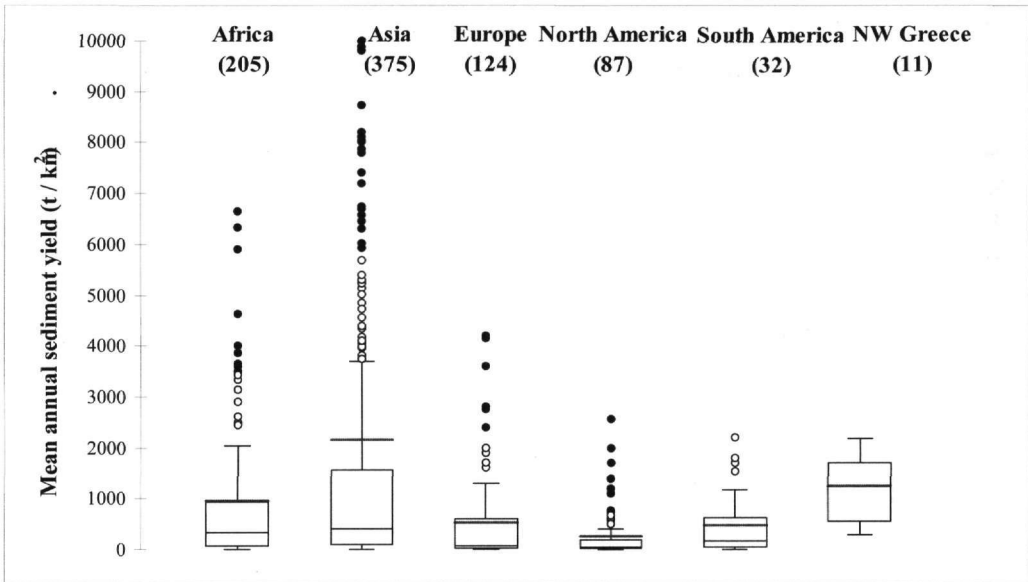


Figure 4 - Box plots of global sediment yield measurements as compared to those from NW Greece (number of catchments in parentheses)

Influence of hydrologic parameters

Figure 5 presents the correlation of mean annual sediment discharge with catchment area. The correlation is weak ($R^2= 0.39$), which means that catchment area, although is a key element in sediment transport, cannot alone describe adequately the complex physical processes. On the other hand, (Figure 6), the mean annual flood (see also Table 2) has an excellent correlation with mean annual sediment discharge ($R=0.91$) while the correlation with mean annual discharge is not at the same level ($R=0.61$). It is evident that sediment discharges are computed as a function of discharge; so that the mean annual sediment discharges will be highly dependent on the river discharge. The better correlation with the mean annual flood as compared to the mean annual discharge is explaining the fact that the vast majority of the annual sediment yield is transported during few floods during a given year. The apparent difficulty to collect all the available rainfall data for such large catchment scales for the period when the sediment discharge measurements have been carried out prevented the introduction of rainfall into our analyses. This will be done in later stages of this research.

3.2. Influence of geomorphologic parameters

It is extremely rare in the international literature to come across with correlation equations between sediment yield and certain geomorphologic parameters. However, Tamene *et al.* (2006), presented an excellent review on the effect of the geomorphologic variables to the sediment yield measurements in Ethiopia. They found that the development of gullies are primarily responsible for the high sediment yields in the area and produced an index, called Standardized Bank Collapse and Bank eRosion (SBCR) index, for the qualitative description of the gully development within the catchment.

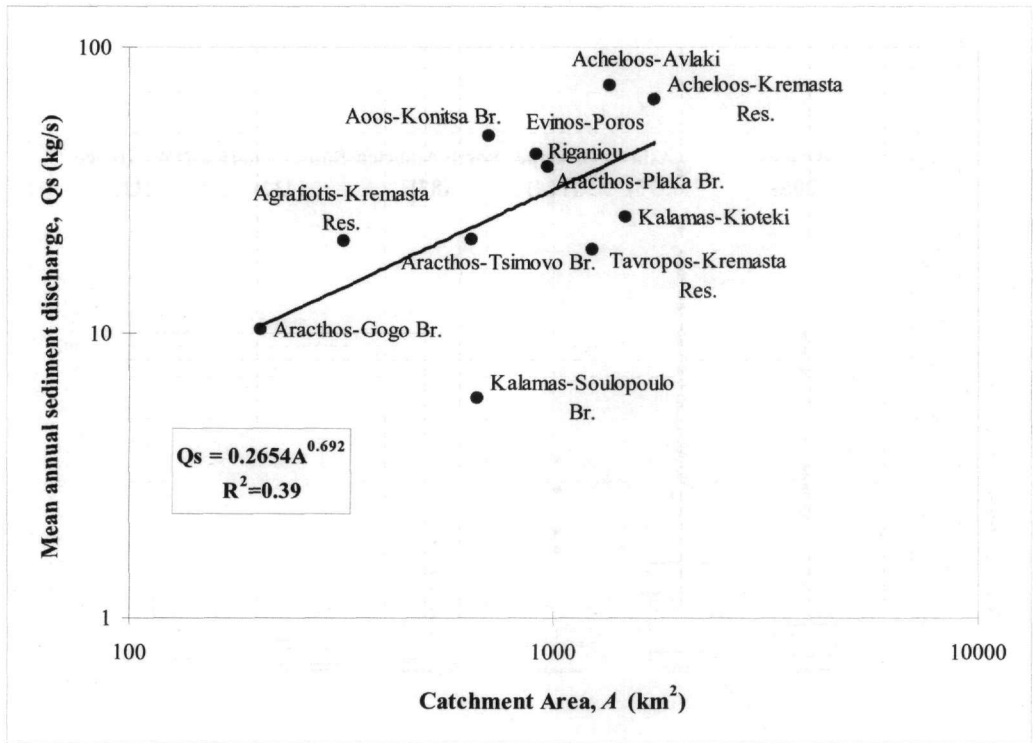


Figure 5 - Relation between mean annual sediment discharge with catchment area

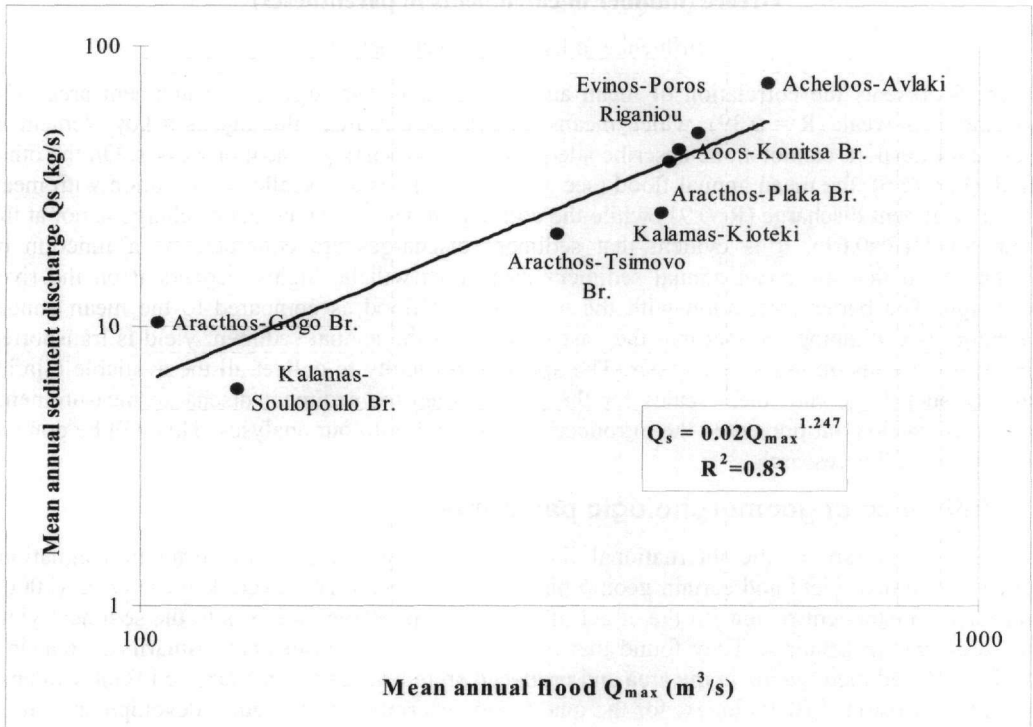


Figure 6 - Relation between mean annual sediment discharge and mean annual flood

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. The bifurcation ratio, for instance, is by no means involved in any empirical (statistical) regression relations with sediment yield in the international literature, according to the authors' knowledge. It is included, however, in statistical relations with catchment sediment delivery ratio, DR, (i.e. the proportion of eroded sediment that finally reaches the catchment's outlet).

Roehl (1962) using sediment yield data from 15 catchments from the Southeast USA and source erosion estimates derived from the Universal Soil Loss Equation (USLE), stated that the catchment's delivery ratio is computed by the equation: (reprinted from McCuen 1998, p. 795):

Equation 2: Relation of sediment delivery ratio with geomorphologic characteristics (Roehl, 1962)

$$DR = 18620A^{-0.23} \left(\frac{L}{R}\right)^{-0.51} R_B^{-2.79}$$

where L = watershed length; and R = watershed relief (or the elevation difference), all in English units and DR expressed as a percentage. The concept of delivery ratio might be valuable in conceptualizing sediment yield processes but is highly uncertain in its application. Indeed, source erosion is at least as difficult to be computed (usually with the USLE) as the sediment yield itself. Equation 2 implies that the bifurcation ratio is inversely proportional to the catchment sediment yield. It is supposed that higher bifurcation ratios are likely to reveal elongated catchments with long, thin drainage networks that forces sediment to deposit within the stream network, especially if moderate magnitude flood events are prevailing and/or the vegetation cover is dense. However, Lykoudi and Zarris (2004) presented preliminary evidence that this statement does not hold and apparently the R_B should be proportional to the sediment yield. This was verified with the non-linear correlation analysis shown in Equation 3, where mean annual sediment yield is proportional to the R_B , the Hypsometric Integral and the USLE's K-factor. The coefficient of determination (after testing several combinations with other physically independent parameters) ensures that the equation explain the 74 % of the observed variance in the dataset.

Equation 3: Correlation of mean annual sediment yield with the Hypsometric Integral (HI), Bifurcation Ratio (R_B) and USLE Soil Erodibility Factor (K)

$$S_y = 40.23 * HI^{1.06} * R_B^{1.40} * K^{0.59} \quad R^2=0.74$$

In the stream networks under consideration, the mean bifurcation ratio is around 4.2, which is almost two times the ideal value of $R_B=2.0$ (Strahler 1952) and marginally higher of the corresponding «theoretical» value ($R_B=4.0$) (Leopold and Langbein 1962, Shreve 1966) of a stream network which is in a state of dynamic equilibrium. The high values of R_B is mainly ascribed to the high slopes of the terrain, due to the neo-tectonic activity, which results in a significant development grade of the stream network.

This illustrates the fact that the stream networks under consideration are in a state of dynamic equilibrium with a tendency of further sediment transport and erosion than of deposition. In catchment with higher bifurcation ratios sediment yield is also higher. This is due to the fact that lower order streams that are joined into higher order streams are more in absolute numbers than those according to the ideal values. This results in the case where the sediment availability is higher than the transport capacity of the higher order streams. Equation 4 shows that the mean annual sediment discharges are proportional to the catchment length and inversely proportional to the catchment's drainage density, explaining the 83 % of the variance of the data set. The inverse

proportionality with the drainage density, although it seems that has no physical meaning, will be further explored in later stages of our research.

Equation 4: Correlation of mean annual sediment discharge with the Catchment Length (Lb_{max}) and Drainage Density (DD)

$$Q_s = 173.4 * Lb_{max}^{0.76} * DD^{-3.6} \quad R^2=0.79$$

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	-0.41	0.49
Mean annual discharge (Q _{av})	Runoff Potential	0.12	0.61
Mean annual flood (Q _{max})	Stream Power, Transport Potential	0.43	0.91
Hypsometric Integral (HI)	Distribution of elevation with catchment	0.75	0.35
Catchment Length Lb _{max}	Catchment size index	0.25	0.75
Mean Slope	Flow velocity and momentum	0.31	-0.28
Drainage Density (DD)	Balance between erosive forces and surface resistance	-0.57	-0.74
Drainage Frequency (DF)	Stream network texture, Relief disruption	-0.27	-0.62
Circularity Index (CI)	Rate of sediment delivery, deposition potential	0.23	-0.47
Elongation Ratio (ER)		-0.60	-0.52
Bifurcation Ratio (R _B)	Internal processes index, branches development grade, stream network dynamic equilibrium	0.69	0.00
Relief Ratio (RR)	Intensity of erosion process	-0.31	-0.63
USLE Soil Erodibility Factor (K)	Main source of erosion processes	0.66	0.27

4. Conclusions

The main scope of the research presented in this paper is to compute the mean annual sediment yield and discharge for eleven river cross-sections in NW Greece. The basic data were the sediment discharge measurements and the mean daily stream discharges, all available from the PPC. Sediment discharge was statistically associated with the simultaneous river discharge, namely the sediment discharge-rating curve, by means of the broken line interpolation method that represents realistically the process of the break up of the armour layer in gravel-bed rivers when a certain discharge threshold is exceeded. Then mean daily sediment discharges were computed from the mean daily stream discharges and the mean annual sediment discharge is finally estimated. The cornerstone of this approach is the correspondence of the mean annual sediment discharge of Acheloos River at *Avlaki* gauging station computed by the broken line rating curve

with the corresponding value computed by the sediment deposits in the Kremasta Reservoir located just downstream of the *Avlaki* gauging station (Zarris and Koutsoyiannis 2005)

Certain geomorphologic parameters have been computed from the catchments' DTMs and their values were introduced in non-linear correlation analyses with the mean annual sediment yield and discharge. Two equations with high values of the coefficient of determination have been calculated in order to, at least, qualitatively describe the phenomena in terms of the relation between sediment yield and catchment geomorphology.

5. Acknowledgments

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