The influence of drainage network formation and characteristics on a catchment's sediment yield

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ABSTRACT: The influence of certain geomorphologic parameters, such as the bifurcation ratio, on a catchment's sediment yield is rarely reported in the literature in contrast to the catchment area, which is assumed as a predominant morphological parameter for quantifying catchment sediment yields. In this paper, the influence of the catchment bifurcation ratio on the sediment yield is examined. Specifically, the mean weighted bifurcation ratio is proposed so as to give more weight to the first order streams of the overall drainage pattern in the context of sediment productivity and delivery. Mean annual sediment yields from four adjacent catchments in Western Greece have been estimated. It is shown that in catchments with higher bifurcation ratios there is an increase in sediment yield estimates, which is mainly accounted for the neo-tectonic activity and the geomorphologic processes in the area.

1 INTRODUCTION

1.1 *Global sediment yield estimates*

At present, sediment yield estimations 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. Flaxman 1972, Jansen & Painter 1974, Dendy & Bolton 1976, Walling 1983). In some cases, catchment area (A in km^2) seems to be the only explanatory variable used to predict sediment yield (Dendy & Bolton 1976, Higgit & Lu 1996, Webb & Griffiths 2001, Verstraeten et al. 2003). 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 (Schumm 1977). However, there is a significant variability of sediment yield with catchment area. For two catchments with the same area but contrasting climates and geomorphologic regimes will likely exhibit completely different sediment yields. Indeed, Parker & Osterkamp (1995) compiled mean annual sediment discharges from 24 gauged rivers in the United States. Drainage areas ranged from 1.6×10^3 to 1.8×10^6 km^2. Mean annual sediment yields ranged from less than 5 to more than 1480 t/km^2. Linear and non-linear regression analyses of mean annual sediment yields with drainage area indicate no statistical significant relationships. Furthermore, Avendano Salas et al. (1997) presented a dataset of sediment yield values from 60 catchments based on reservoir sedimentation rates throughout Spain. The relation between S_Y and A for the 60 catchments is:

$$S_Y = 4139A^{-0.43}, R^2 = 0.17 \quad (1)$$

That means that the drainage area explains only the 17% of the observed variability of the sediment yield estimates, even within the same region. On the contrary, Dendy and Bolton (1976) presented data from sediment deposits in reservoirs for 800 catchments throughout the USA. There was a statistically significant relation between mean annual sediment yields and drainage areas of the form of the equation (reprinted from Lane et al. 1997):

$$S_Y = 674A^{-0.16}, R^2 = 0.68 \quad (2)$$

Additionally, data from 37 catchments in northern Arizona show a remarkably good correlation with catchment area (Webb & Griffiths 2001). Sediment discharge (Q_S in t/yr) exhibits a power function with catchment area of the form:

$$Q_S = 193A^{1.04}, R^2 = 0.86 \quad (3)$$

Lu et al., 2003 reported that from 248 sediment discharge measurement sites within the Upper Yangtze catchment in China, sediment yield exhibits a fairly good correlation with subcatchment drainage area in the form of the equation:

$$S_Y = 849.15 A^{-0.0785}, R^2 = 0.7735 \quad (4)$$

Moulder and Syvitski (1996) showed that Q_S is strongly correlated to catchment area and the maximum catchment elevation (H_{max}) as:

$$\log(Q_S) = 0.406 \log(A) + 1.279 \log(H_{\max}) - 3.679, R^2 = 0.67 \quad (5)$$

It is likely that the increasing trend of sediment discharge with maximum elevation is a surrogate of tectonic activity. Milliman and Syvitski (1992) concluded that the strong correlation between sediment and topographic relief may not indicate that the second is the cause of the first, but rather that both are caused by another factor less susceptible to numerical modeling, namely tectonism. 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.

Someone might have to consider the random or systematic errors that are associated with such estimates used in the regression equations described above. For instance, if a catchment sediment yield is derived from reservoir sedimentation rates, this estimation is subject to quite a lot of parameters that can induce significant errors, depending on the extend of the reservoir and the available instrumentation. More specifically, errors can be accounted during the hydrographic survey of the reservoir (e.g., GPS selected availability, varied velocity of hydrographic vessel) and during the post-processing of the hydrographic data (e.g., inaccurate Digital Terrain Models (DTMs) for old reservoirs before the dam impoundment, obscure definition of mud – water interface). Moreover, significant errors are connected with estimation of deposits' density, especially if it is not possible to collect undisturbed samples from the reservoir's invert. Moreover, the same applies to sediment yield estimates from sediment discharge rating curves, especially as a design practice in Greece. Simultaneous measurements of river discharge 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.

Conclusively, it is noted that there is not a "universal expression" between sediment yield and catchment area, not only because there are different types of catchment geology, hydrology and topography but also because regional tectonics and geomorphology play an important role on the sediment availability within the catchment.

1.2 *Catchment bifurcation ratio and sediment delivery ratio*

Horton (1945) stated that the decrease in number and increase in lengths of streams with centripetal order is approximately geometric and hypothesized that the increase in mean subcatchment area is also geometric. These statistical relations are known as the *"Horton's laws"* of stream numbers, lengths and areas. Their respective series ratios are designated as the bifurcation, length and area ratios. The bifurcation ratio (R_B) between successive stream orders, according to Strahler's (1964) classification, is then defined as:

$$R_B = \frac{N_U}{N_{U+1}} \quad (6)$$

where N_U = number of streams with order U. The mean bifurcation ratio is the average value of the corresponding ones for the successive stream orders. Typical values of bifurcation ratios between 2 and 4 are typical for most natural fluvial systems. The ideal number of streams for a basin of a given order, according to Horton (1945), is then as follows:

$$N_U = R_B^{(K-U)} \quad (7)$$

The symbol K is defined as the order of the main trunk stream.

It is supposed that, while calculating the mean bifurcation ratio, the streams of higher order have the same weight with the streams of the first and second order. This is obviously not representative; especially from sediment yield oriented considerations. It could be more appropriate to assign more specific weight to the first order streams (according to the proportion of the number of these streams against the total number of streams) than to the streams of the highest order. This could be rational, since the first order streams are pointing towards the sediment source areas of the specific catchment and contribute more to sediment availability. We then use the mean weighted bifurcation ratio ($R_{B,W}$), which is determined as:

$$R_{B,W} = \frac{\sum_{i=1}^{n} (R_{B:i,i+1}(N_i + N_{i+1}))}{\sum_{i=1}^{n} N_i} \quad (8)$$

The mean weighted bifurcation ratio is not intended to replace the mean bifurcation ratio in Equation 7; this will certainly give wrong results. This ratio intends to give a first estimation on the degree of the catchment's maturity or, in other words, how much the specific catchment has developed all its streams of any order depending on its geomorphologic state.

Bifurcation ratio is by no means involved in any empirical (statistical) regression relations with sediment yield in 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 (reprinted from McCuen, 1998, p. 795):

$$DR = 18620 A^{-0.23} (\frac{L}{R})^{-0.51} R_B{}^{-2.79} \qquad (9)$$

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.

It is evident from Equation 9 that the delivery ratio is a decreasing function of bifurcation ratio. 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.

The objective of this paper is to show that, according to our sediment yield data for four adjacent catchments in Western Greece, sediment yield and delivery is generally an increasing function of bifurcation ratio, in contrast to Roehl's (1962) findings. We argue that (a) the mean weighted bifurcation ratio is the most appropriative indication of catchment bifurcation in terms of sediment yield, because it gives more weight to the first order streams that, in turn, point towards the sediment source areas, and (b) local geomorphologic regime and tectonic activity (e.g. orogenic uplift), that support higher bifurcation ratios, together with the high intensity of storms and runoff events are the driving forces for higher sediment production rates, thus for higher sediment yields.

2 RESEARCH FRAMEWORK

2.1 *Study area*

Four adjacent catchments in western Greece are selected for analysis. Acheloos River, Agrafiotis River and Megdovas River are discharging at Kremasta reservoir, whereas Evinos R. is discharging at the Patraikos Gulf (see Figure 1). Kremasta dam was built at exactly the confluence of Agrafiotis and Megdovas Rivers with the main stem river (Acheloos R.) and was firstly operated at 1965. Sediment yield estimates for the three rivers discharging at Kremasta Reservoir were computed as reservoir sedimentation rates after a comprehensive hydrographic survey (Zarris et al. 2002). The DTMs before the dam impoundment (1964) and the period of hydrographic survey (1998-99) have been subtracted to produce the volume of deposited sediments. The density of the sediments was estimated by the extraction and laboratory analysis of two sedimentary cores from the reservoir's invert. These rivers are discharging separately in the reservoir so as their sediment yield could be estimated independently. Trikeriotis River, actually a subcatchment of Megdovas R, while presented in Figure 1, is computed together with Megdovas R. as one catchment, since their sediment deposits in the reservoir could not be computed independently. Mean annual sediment yield of the Evinos R. at Poros Riganiou measuring discharge station was computed by means of applying the ordinary suspended sediment discharge rating curves to the available sample of mean daily discharges (Nalbantis 1990).

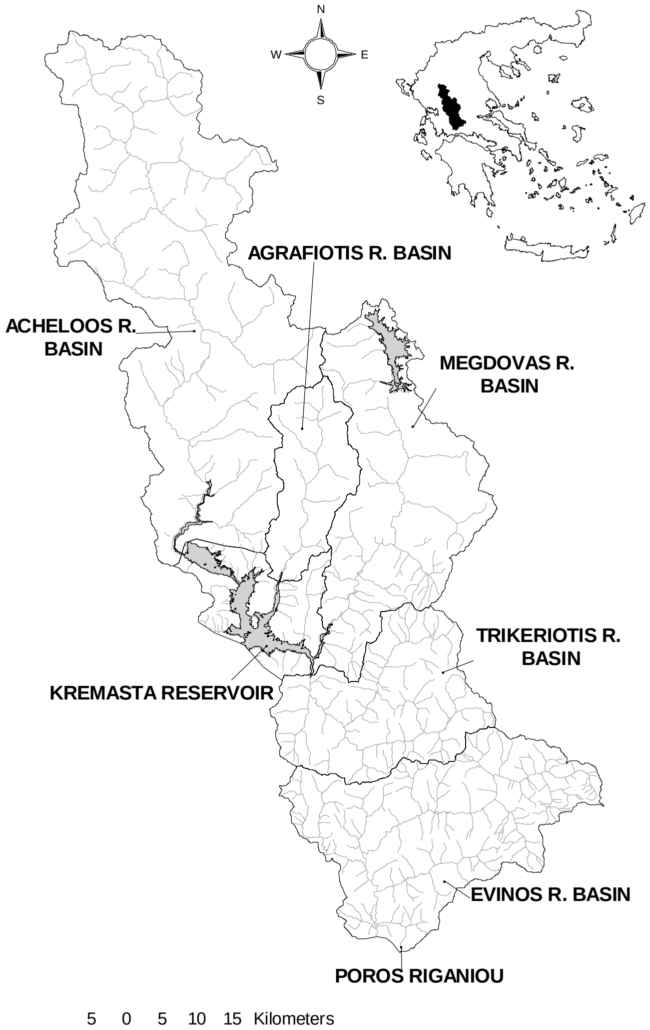

Figure 1: Map of the selected catchments with drainage network (only shown 3rd, 4th, 5th and 6th order streams).

The source erosion of the three basins discharging at the Kremasta reservoir was estimated by applying the USLE on a GIS platform. The sediment delivery ratios were then estimated for all but the Evinos R. catchment.

Mean annual inflow at the Kremasta reservoir is 76.6 m^3/s, a significant portion of which belongs to Acheloos River itself (49.9 m^3/s). The mean annual discharge of Evinos River at Poros Riganiou measuring site is estimated as 24.75 m^3/s. Poros Riganiou is located upstream of the river's delta in the Patraikos Gulf, but the catchment can be considered as an ideal conceptual system of erosion – transport – deposition continuum. All streams are perennial but are subject to severe floods because of the intense storms that are enhanced by the orographic uplifting of the Pindos mountain range. All streams are sixth order catchments (according to Strahler's classification system) except Agrafiotis R., which is a fourth order catchment, due to its relative small area.

Table 1 presents the sediment yields and delivery ratios estimated for the catchments under consideration. The results generally follow the trend of higher sediment yields and delivery ratios with decreasing catchment areas, except the sediment yield from Acheloos catchment. Particularly, Agrafiotis R. sediment yield is in the same order of magnitude even with the majority of Japanese rivers (Oguchi et al. 2001), which are famous for their pronounced sediment yields.

Table 1: Characteristic elements of selected catchments

Catchment	Area (km^2)	S_Y (t/km^2)	DR	(Mean) Bifurcation ratio	Mean weighted bifurcation ratio
Acheloos R.	1733	1184.6	0.17	4.20	4.94
Agrafiotis R.	320	2034.8	0.42	5.62	5.86
Megdovas R.	1239	489.4	0.22	3.89	4.75
Evinos R.	884	734	-	3.86	5.27

Applying the Equation 9 to the data of Table 1, delivery ratios are calculated equal to 0.13, 0.12 and 0.24 for the Acheloos R., Agrafiotis R. and Megdovas R. catchments respectively. It is shown that Roehl's equation not only gives misleading results for these basins (except for Megdovas R.) but also changes completely the order of the basins with higher delivery ratios. Indeed, Agrafiotis R., which exhibits the highest delivery ratio, according to our estimates from the Kremasta reservoir sedimentation rates, seems to have the least corresponding value according to Roehl's equation. The authors are unaware of any similar work by other researchers on that issue and this paper is dedicated to give some insight on the possible correlation of bifurcation ratio with sediment yield and delivery ratio.

2.2 *Geology of the study area*

The geologic structure of the catchments under consideration has directly affected the formation of the drainage network and the morphology of the relief. The geologic setting of the study area is covered by formations of the *"Gavrovo"* and the *"Pindos"* geotectonic zones, which belong to the external *"Hellenides"*, as well as post-alpine formations, ophiolites and igneous rocks. More specifically, the Acheloos River catchment is mainly formed by flysch and thickly bedded limestone of the *"Gavrovo"* zone, and alternations of the flysch with thinly bedded limestone, irestone and clastic sediments of the *"Pindos"* zone, which are intensely folded. The catchments of the rest of the rivers under consideration are consisted of the intensely folded formations of the *"Pindos"* zone. More specifically, an extended part of the northeastern part of the Evinos catchment is formed only by the *"Pindos"* flysch with depth on excess of 1000 m. Figure 2 presents a synoptic view of the geologic formations of the region.

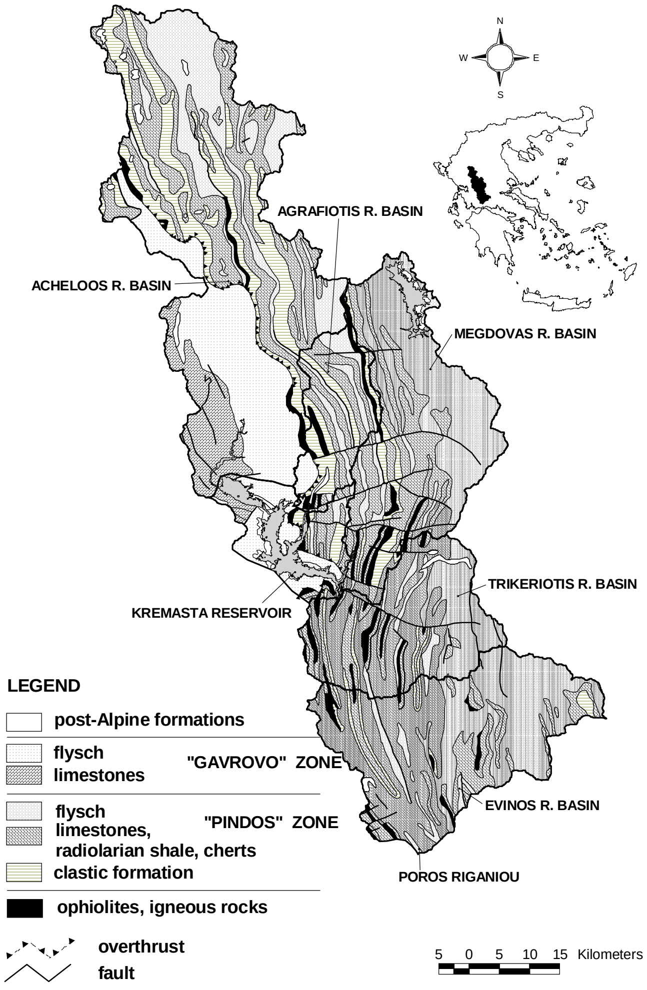

Figure 2: Geo-tectonic map of the study area.

2.3 *Regional tectonics*

The *"Gavrovo"* zone is characterized by a gentle tectonism, with synclines and anticlines, of which the axes follow a NW-SE direction as well as faults with a NW-SE and NE-SW direction. The *"Pindos"* zone is characterized as a gigantic tectonic cover, heavily cracked. This tectonism is demonstrated with micro-plications with axial direction NW-SE, thrusts of the same direction as well as faults, which are contemporary of the alpine structures following the same directions or more recent following a W-E direction.

Generally, the *"Pindos"* zone has been undergone intensified tectonic strain due to the considerable movement of the *"Pindos"* formations over the *"Gavrovo"* zone. Particularly, over the thrusting front (where the whole of the Agrafiotis R. and the eastern part of the Acheloos R. catchments are situated), the tectonic stress is pronounced.

The main faults and thrusts are presented synoptically in Figure 2.

3 DISCUSSION

We consider, like Milliman and Syvitski (1992), that the topographic/tectonic character of a river catchment plays an important role in determining its sediment yield and that catchment area plays only a supplementary role. For instance, both Japan and New Zealand are characterized by high-relief mountains on active margins, coupled by tropical cyclones, which are assumed as the driving forces for the world's highest recorded sediment yields under natural conditions.

3.1 *Mean bifurcation ratio and mean weighted bifurcation ratio*

Bifurcation ratios are normally assigning the values between 2 and 4, whereas 4 should be suggested as the "ideal" value of a catchment's bifurcation (Leopold & Langbein 1962, Costa-Cabral & Burges 1997). Yang (1971) measured 14 basins in the maturity stage in the middle-western USA. The bifurcation ratio of those basins ranges from 3.29 to 4.79, with a mean value of 4.05, which is nearly equal to 4.0. Other researchers (e.g. Eyles 1968, Gustafson 1973) reported less bifurcation ratio values for areas such as Germany (3.98), Australia (3.45) and Israel (3.75). The catchments of Northern Europe and North America were formed in a much older geologic period; therefore their catchments and rivers are stable, so that channel streams consisted mainly of the most probable networks in which the bifurcation ratio is close to a value of 4.0. As noted in Table 1, the mean bifurcation ratios of the examined catchments are quite high, higher than the average value of most catchments in other countries with less tectonic activity. The Agrafiotis R. bifurcation ratio value is even higher than the corresponding value observed even in Japanese catchments. For instance, Shimano (1992) measured the morphometric parameters of 180 catchments all over Japan. The values of bifurcation ratios range from 3.2 and 5.4 while most of them range between 3.6 and 4.8. Agrafiotis R. also exhibits a quite significant sediment yield and sediment delivery ratio, which is one of the highest values ever reported in the literature, particularly for the European region.

There are two basic elements, which are important to be carefully noticed. Firstly, there is a deficit of the first order streams for all the catchments between the observed number of these streams and the supposed number according to the first Horton's law. The arithmetic values are given in Table 2.

Table 2: Comparison between observed first order streams against simulated ones as resulted from Horton (1945).

Basin	Observed first order streams	Simulated first order streams (from Horton, 1945)	% Deficit
Acheloos R.	1195	1308	9.45
Agrafiotis R.	172	177	3.20
Megdovas R.	840	888	5.70
Evinos R.	817	854	4.48

Secondly, another interesting point comes from the comparison between the mean bifurcation ratio and the mean weighted one (from Table 1). It is evident that for the Agrafiotis R. the difference between these values is almost infinitesimal, while the same differences for the other catchments are significant. It is implied, however, that these observations are in some way interconnected.

Agrafiotis R., which exhibits the highest bifurcation ratio, has the lowest deficit of the first order streams. In pure numbers, it needs only 5 first order streams in order to reach the ideal state, as described by Horton's scaling law. At the same time, the difference between the mean and the weighted mean bifurcation ratio is very small. We argue that these observations are closely related to the high sediment yield of this particular basin. Since Agriafiots R. has developed almost the total number of the first order streams that it could be possible to develop, then, giving more weight to the first order streams, does not considerably increase the mean weighted bifurcation ratio of the catchment. This is also explained by the high bifurcation between the first and second order streams (4.53) for that particular catchment. It could be concluded that this catchment reaches the state of full maturity; it has developed almost the whole of its drainage network and finally exhibits high sediment yield values.

On the other side, the other catchments need a considerable number of first order streams to reach the ideal state of maturity. Acheloos R. needs 113 first order streams, Megdovas R. 48 streams and Evinos R. 37 streams. For these catchments, the mean weighted ratio gives more substantial differences compared with the simple mean ratio. Based on the local geotectonic regime, the fate of these catchments is to further develop their drainage basins so as to reach the maturity that Agrafiotis R. has already reached. Therefore the sediment yields of these catchments will further increase, especially the Acheloos R. catchment, which has the most considerable hysteresis in terms of its drainage network formation, but it already exhibits a quite impressive sediment yield, constituting a possible exception to the general approved relation of increasing area – decreasing sediment yield.

3.2 *Interrelations of geomorphologic and tectonic elements with sediment yields*

The Agrafiots R. catchment is situated over the thrusting front of the "Pindos" cover; therefore its formations are heavily cracked. Additionally, all the river catchments are being undergone neo-tectonic movements, particularly orogenic uplift, which is characteristic of their geologic age. Agrafiotis R. catchment is already in an early mature state while the rest of the catchments are in a younger state.

Orogenic movements are also responsible for the high sediment yields, because the equilibrium between the excess available sediment (from rock weathering) and the transport downstream should be reached at all times. Channel incision through tectonic forcing is evident which keeps the catchment in a mature state, while constantly rejuvenated. Channel incision adds more first order streams in the drainage system, increasing the order of the whole catchment and re-arranging the overall drainage network; thus finally conveying new sediment source areas to the catchment outlet. Moreover, the uplift creates steeper stream slopes that, in turn, develop higher stream power of the flow, especially in large infrequent floods, which are typical in Mediterranean environments. Indeed, Snyder et al. (2003) stated that, comparing basins from high uplift zones (uplift rates around 4 mm/yr) to the ones in the low uplift zones (uplift rates approximately 0.5 mm/yr), streams in high uplift zones are about twice as steep for a given drainage area, therefore exhibit an increase of the catchment response to rainfall and sediment. Significant stream power values in V-shaped streams can easily transport sediment downstream (as wash load), increasing sediment delivery to the catchment's outlet. These processes of orogenic uplifting and increasing sediment yield are seem to be probably everlasting leading to continuously changing catchments and drainage patterns.

4 CONCLUSIONS

This paper has introduced the bifurcation ratio concept in the context of sediment yield and delivery ratio processes of a catchment in order to draw useful interconnections between these geomorphologic parameters. Primarily, it was shown that the Roehl's (1962) equation, that assumed the sediment delivery ratio as a decreasing function of the bifurcation ratio does not hold, at least for the four adjacent catchments in Western Greece. On the contrary, it was shown that it is, in fact, an increasing function of the bifurcation ratio and was assumed that the regional neo-tectonic activity coupled with the state of maturity that these basins exhibit, are the influential factors for the relatively high sediment yield.

It was shown that, for active tectonic areas, the increase of the bifurcation ratio entails greater sediment yields because there are more first order streams encouraging the conveyance of detached sediments to reach the drainage network. Additionally, the axial erosion in V-shaped, first order, streams with high stream power – low frequency flood peaks, transports the wash load further downstream, so as the residence times of the sediments within the catchment will be relatively low. This of course is a prerequisite for higher catchment sediment yields.

Finally, it was proposed that the mean weighted bifurcation ratio is a better indicator for qualitatively describing the drainage pattern in terms of sediment production, availability and transport. For catchments, that have fully developed their drainage patterns, according to Horton, the difference between the mean and the mean weighted bifurcation ratio is insignificant. On the contrary, for young catchments, which are still developing their drainage forms, the difference is significant because there is also a considerable deficit of the first order basins relative to the ideal value for the perfect fluvial system.

The observations of this paper, especially the contradicting results with Roehl's equation, could give a motive to the geomorphologists, engineers and other earth scientists to cast their shadows over the real influence of the geomorphologic pattern of the catchment (e.g., drainage network formation, tectonic activity) over the long – term evolution of sediment yield. It is important to notice that there are no equations with global applicability but any approach will be tailored and specified for any particular catchment or region with homogenous geomorphologic characteristics.

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AKNOWLEDGMENTS

This work is a continuation of the research project "Appraisal of river sediment deposits in reservoirs of hydropower dams" funded from the General Secretariat of Research and Technology (GSRT) and the Public Power Corporation (PPC) of Greece. The authors would like to thank Demetris Koutsoyiannis, research coordinator of the project, for his valuable comments and supervision during the research project.