Environmental Hydraulics – Christodoulou & Stamou (eds)
 ISBN 978-0-415-58475-3

Analysis of the environmental flow requirement incorporating the effective discharge concept

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ABSTRACT: The determination of a river reach's environmental flow is a key point for the sustainable development of water resources and environmental restoration. The effective discharge is theoretically the discharge that forms and maintains in the long term the shape of the river section. It is linked with various ecological processes in streams that assure good ecological status. The effective discharge is calculated for the Evinos R. catchment in Central Greece and conclusions are drawn in respect to the management of Evinos Dam upstream of the gauging station.

1 INTRODUCTION

1.1 *The environmental flow concept*

The determination of a river reach's environmental flow is a key point for the sustainable development of water resources and environmental restoration (McMahon & Finlayson 1995, Richter et al. 1997, Katopodis 2005). A key challenge for environmental flow assessment is to determine how much of the original flow regime should continue to flow down a river and onto its floodplain in order to maintain the valued features of an ecosystem. Discharge has been suggested to be a "master variable" that limits the distribution and abundance of species (Power et al. 1995) and regulates the ecological integrity of flowing water systems (Poff et al. 1997). However, despite the recognition of the importance of discharge to both stream ecology and fluvial geomorphology, there is surprisingly little effort in how these two disciplines are joined together in order to develop a coherent methodological framework in analyzing environmental flow requirements.

A plethora of formal methodologies now exists for evaluating environmental flow requirements. These include methods that link geomorphologic forms and processes with the geomorphological impacts of flow regulation, techniques for determining the flooding requirements of wetland vegetation, methods used to assess the flow requirements of fish, including maintenance of habitat and reproductive processes, flushing flows and fish passage requirements as well as influence of river flows on estuarine fishery production and finally methods for assessing the environmental flow requirements of aquatic invertebrates. Depending on the objectives of each methodology, the computed environmental flows could deviate significantly one another. In this paper, the analytical method of the effective discharge (i.e. the discharge that maintains the form of the cross section in the long term) from fluvial geomorphology is used to analyze the interaction between frequency and magnitude of discharge events that drive suspended sediment and organic matter transport, algal growth, nutrient retention, macroinvertebrate disturbance and habitat availability.

1.2 *The effective discharge concept*

Many ecological processes are known to be discharge-dependent, such as the flux of nutrients and organic material, while others have the potential to be discharge dependent, such as macroinvertebrate drift. The utility of effective discharge in geomorphologic analysis of fluvial landforms suggests that it may be usable in aquatic ecology as well. The concept of magnitude and frequency characteristics of river discharges was introduced in geomorphology by Wolman & Miller (1960). This classic work has initiated a number of studies which emphasized the effectiveness of fluvial events in modifying fluvial forms. Wolman & Miller (1960) argued that the amount of sediment transported by flows of a given magnitude depends upon the form of the relationship between river and sediment discharge as well as on the frequency distribution of the discharge events. Using

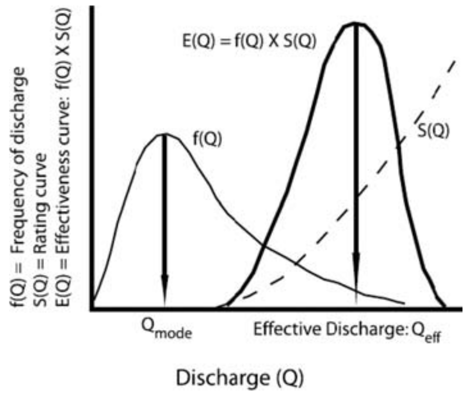

Figure 1. Relation between flow frequency and sediment transport (adapted from Wolman & Miller, 1960).

suspended sediment data they showed that the largest portion of the total sediment load is carried by flows that occur, on the average, once or twice a year.

For actual calculation, the long-term geomorphic effectiveness of a flood of a particular magnitude is the product of the effect of that flow multiplied by its frequency of occurrence. A flow duration curve can be created using historic discharge records (f(Q) in Figure 1); then the geomorphic effect of a given flood is determined from the sediment discharge rating curve (i.e. sediment load vs. discharge over the entire range of discharges experienced by the channel, S(Q) in Figure 1). The product of the hydrologic frequency curve and the sediment rating curve is the effectiveness curve, which represents the proportion of the total annual sediment load carried by each increment of discharge. The maximum value of this product is then the effective discharge. Thus the effective discharge depends on the statistical representation of stream flows, the shape of the sediment rating curve and the threshold at which transport begins (Baker 1977, Andrews 1980, Goodwin 2004, Doyle et al. 2005).

2 MATERIALS AND METHODS

2.1 *Magnitude and frequency relationships for river discharges*

Wolman & Miller (1960) developed a hypothesis that the magnitude and frequency of river flows are responsible for the characteristic shape of a river channel. It was assumed that the total work done on the river channel is proportional to the sediment transported. It is thus important to know the distribution density function of the river discharges in an appropriate time scale (e.g. daily). Most data sets of river daily discharges are described by asymmetric distributions (e.g. lognormal or gamma density functions). It is assumed (Nash 1984, Ashmore & Day 1988, Goodwin 2004) that the recurrence interval of the effective discharge should increase with discharge variability. Therefore, in dry climates with strong skewed distributions of river discharges, it is expected that the magnitude of the effective discharge should be a rather high value.

2.2 *Sediment transport rating curves*

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:

$$Q_S = aQ^b n \tag{1}$$

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 n is the multiplicative error term which exhibits a lognormal distribution (Ferguson 1986, Asselman 2000). The exponent parameter, b, is very important when determining the sediment yield of a catchment and it normally assigns values

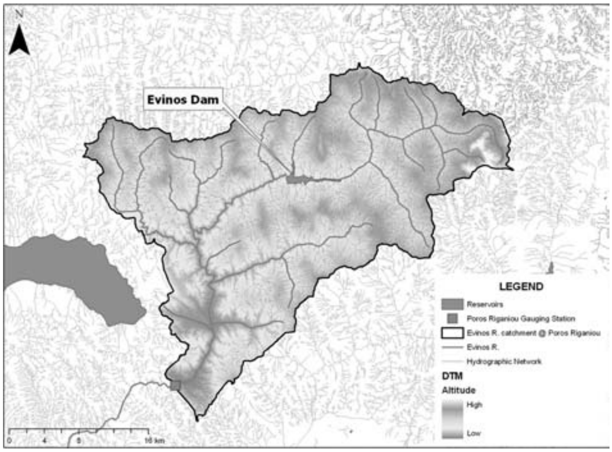

Figure 2. Map of the Evinos R. catchment at the Poros Riganiou gauging station.

between 0.5 and 3; the higher the parameter the more intense transport capacity of the river flow. Commonly for the same river discharge, corresponding sediment discharges could deviate by at least two orders of magnitude or even more. 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. Consequently the use of a unique regression equation for the whole range of possible discharges might be unrealistic (Jansson 1996, Zarris & Koutsoyiannis 2005) because it practically denotes the same sediment source for every flow condition.

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 from 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 coarseness of the broken line can be controlled by introducing as a second objective the minimization of the coarseness. 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 coarseness 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 (Zarris & Koutsoyiannis 2005).

2.3 *Description of the study site*

Evinos R. catchment is situated in Central Western Greece and discharges into the Patraikos Gulf. The total catchment area is about 1164.3 km^2, whereas the corresponding area at the main gauging station in the catchment (Poros Riganiou) is equal to 913.9 km^2. Mean annual precipitation and evapotranspiration are equal to 1200 mm and 498 mm respectively, whereas the mean annual runoff is equal to 22.9 m^3/s, as measured at Poros Riganiou gauging station (see Figure 2). Mean daily river discharge data are available between the hydrologic years 1971–72 and 1989–90. Suspended sediment discharge data for the same site have been collected between the period 1970 and 1982. The mean annual suspended sediment yield and discharge are equal to 1466.4 t/km^2 and 42.5 kg/s respectively (Zarris et al. 2006). Therefore the available data are sufficient for the effective discharge to be calculated. Upstream of the gauging station, the Evinos Dam was constructed and first fully

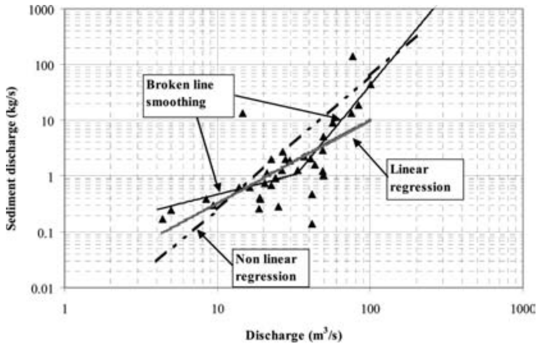

Figure 3. Suspended sediment rating curve for Poros Riganiou gauging station.

operated in 2001 to improve the water supply of greater Athens. The dam's catchment area is 351.8 km^2 and the reservoir's useful storage 112.1 hm^3. That means that approximately 30% of the entire catchment area is actually fully diverted outside of the catchment. The environmental flow downstream of the dam was assumed constant and equal to 1 m^3/s according to the water resources management plan of the Evinos R. catchment (Ministry of Environment 1996). Figure 2 presents a synoptic map of the catchment under consideration.

3 DISCUSSION AND CONCLUSIONS

3.1 *Calculations and results*

The mean daily discharges as measured at the Poros Riganiou gauging station present, as expected, a highly skewed distribution with considerable variability. The mean value and the standard deviation are equal to 22.8 m^3/s and 39.9 m^3/s respectively and the coefficient of variation (i.e. the standard deviation divided by the mean) is equal to 1.75. The skewness coefficient is equal to 5.98. The appropriate distribution is the 3-parameter Gamma distribution (or Pearson Type III distribution), as implemented in the Hydrognomon software (Kozanis et al. 2005). The distribution density function takes the form (for $Q > \varepsilon$):

$$f(Q) = \frac{\lambda^n}{\Gamma(\eta)}(Q-\varepsilon)^{\eta-1}\exp[-\lambda(Q-\varepsilon)] \tag{2}$$

where, λ, η and ε are the scale, shape and location parameters of the Pearson Type III distribution and $\Gamma(\eta)$ is the Gamma function.

The suspended sediment rating curves have been computed with the broken line interpolation method with two discharge classes and a threshold value of 33.1 m^3/s (Figure 3). It is clear that the broken line interpolation procedure performs better that the ordinary rating curve and the non linear regression especially at the high 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 (Equation 1) for this specific case is equal to 0.68 for the first segment and 3.32 for the steeper segment of the broken line. Finally, performing mathematical deviations, the Q maximum value of the product of Equations 1 and 2 is the effective discharge (Q_e) takes the following form:

$$\lambda Q_e - [(\eta-1) + b + \lambda\varepsilon]Q_e + b\varepsilon = 0 \tag{3}$$

or, in the case of $\lambda^*\varepsilon \ll b$,

$$Q_e = \frac{\eta + b - 1}{\lambda} \tag{4}$$

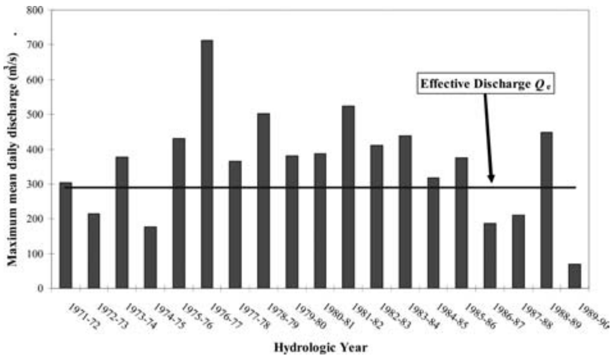

Figure 4. Plot of maximum mean daily discharges against the effective discharge.

In the specific case of the Poros Riganiou gauging station, assuming that *b* is 3.32, the effective discharge equals 290.5 m^3/s.

4 CONCLUSIONS

Figure 4 presents a comparison between the effective discharge and the maximum mean daily discharges for each hydrologic year of the available dataset. The plot illustrates that the effective discharge is a quite common value that, on average, takes place once or twice in a given year. This finding is actually in accordance with the original paper of Wolman & Miller (1960) who proved that the largest portion of the total load is carried by flows that occur once or twice per year on average. They also proved that the high storage capacity of sediments in gravel-bed reaches tends to establish higher values of the effective discharge.

Nevertheless, after the construction and the full operation of the Evinos R., it is essential for the geomorphologic stability of the river reach at Poros Riganiou vicinity and for good ecological status that at least a discharge equal to 290.5 m^3/s must be provided once or twice on an average year. Therefore, the Water Resources Management Plan of the Evinos R. catchment should make provisions for the effective discharge, along with regular flow releases from Evinos Dam, at least once or twice a year.

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