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- Identification of hydrologic and morphologic controls on effective discharge
- Analytic expression of the ratio between effective and mean discharge
- Flow regime (flow variability) explains the heterogeneity of observed effective discharges

Supporting Information:

- Supporting Information S1

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Climatic and landscape controls on effective discharge

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Abstract The effective discharge constitutes a key concept in river science and engineering. Notwithstanding many years of studies, a full understanding of the effective discharge determinants is still challenged by the variety of values identified for different river catchments. The present paper relates the observed diversity of effective discharge to the underlying heterogeneity of flow regimes. An analytic framework is proposed, which links the effective ratio (i.e., the ratio between effective discharge and mean streamflow) to the empirical exponent of the sediment rating curve and to the streamflow variability, resulting from climatic and landscape drivers. The analytic formulation predicts patterns of effective ratio versus streamflow variability observed in a set of catchments of the continental United States and helps in disentangling the major climatic and landscape drivers of sediment transport in rivers. The findings highlight larger effective ratios of erratic hydrologic regimes (characterized by high flow variability) compared to those exhibited by persistent regimes, which are attributable to intrinsically different streamflow dynamics. The framework provides support for the estimate of effective discharge in rivers belonging to diverse climatic areas.

1. Introduction

The concept of dominant or channel-forming discharge is central to geomorphological sciences, river engineering, and restoration practices. Described as the discharge which shapes the cross section of natural rivers or transports the most sediments over long time periods, the dominant flow is used in the design of stable morphological configuration of channels [Shields *et al.*, 2003; Doyle *et al.*, 2007] and to estimate sedimentation rate and lifespan of reservoirs [Podolak and Doyle, 2015]. Moreover, dominant flows summarize the hydrologic forcing in models studying long-term evolution of rivers [see, e.g., Frascati and Lanzoni, 2009] and the related incision patterns [see Lague *et al.*, 2005, and references therein].

Several methods have been proposed in the literature to estimate the magnitude of the channel-forming discharge. In some cases, the dominant flow is identified with the bankfull discharge, evaluated from field surveys as the break point between main channel and floodplain [Andrews, 1980]. Other studies suggest equivalence between the channel-forming discharge and flows characterized by suitable return times (e.g., 1.5 years) [Simon *et al.*, 2004]. In order to address the role of both morphological and hydrological factors, Wolman and Miller [1960] proposed to estimate the dominant flow by combining information contained in the frequency distribution of streamflows and the sediment rating curve, giving rise to the concept of effective discharge. Thereafter, empirical, theoretical, and numerical studies on effective discharge flourished in the literature, providing sometimes contrasting results [see, e.g., Bunte *et al.*, 2014]. Effective discharge was found to vary significantly among catchments as a function of climate and sediment rating characteristics, which encapsulate differences of morphology, bed sediment composition, hydrodynamic conditions, and, as a consequence, between dominant transport mechanisms (i.e., suspended versus bedload) [Emmett and Wolman, 2001; Simon *et al.*, 2004]. Previous investigations [e.g., Vogel *et al.*, 2003; Goodwin, 2004; Doyle and Shields, 2008; Quader and Guo, 2009] also suggest the effective discharge to be significantly affected by the variability of river flows. For example, Bolla Pittaluga *et al.* [2014] showed that fluctuations of the hydrodynamic forcing implied by hydrologic variability do not prevent rivers from achieving a quasi-equilibrium morphodynamic state linked to a steady effective forcing, which differs, however, from typical channel-forming estimates (e.g., the bankfull discharge). Notwithstanding many years of studies, a consistent framework that enables

separating hydrologic and landscape controls on the effective discharge and explains the observed patterns of sediment delivery across a gradient of climatic and landscape conditions is still lacking.

In this work, a framework is presented which links the effective discharge to the degree of nonlinearity of the sediment rating curve and to streamflow variability, resulting from climatic and landscape drivers. The framework builds on a physically based stochastic representation of streamflow dynamics and a lumped description of the sediment transport capacity, and is tested using suspended sediment data observed in a set of catchments in the continental United States. The proposed framework gives insight into the major climatic and morphologic controls of sediment transport in rivers.

2. Observed Effective Discharge and Streamflow Variability

In this paper, the effective discharge is defined as the constant water flow rate resulting in the same long-term sediment load generated by the complete frequency distribution of streamflows. Doyle and Shields [2008] termed it functional-equivalent discharge q_f , to distinguish it from alternate definitions proposed in the literature [e.g., Wolman and Miller, 1960 and Vogel et al., 2003]. Mathematically, the functional-equivalent discharge q_f is defined as follows:

$$\int_0^{+\infty} q_s p_s(q_s) dq_s = \beta q_f^\delta \quad (1)$$

where q_s is a stochastic variable representing the flow of sediments at a station and $p_s(q_s)$ its probability density function. The empirical coefficients δ and β describe the instantaneous power law relation between water and sediment flows, $q_s = \beta q^\delta$ (hereafter termed sediment rating curve), whose physical interpretation has been the goal of extensive research [e.g., Syvitski et al., 2000]. The validity of such a relation is a basic assumption of this work. Therefore, cases where the power law relation between water and sediment flows may be significantly distorted (e.g., supply-limited catchments, rivers with extensive floodplains or strongly varying sediment storage) are not considered.

In order to introduce dimensionless quantities, we define the functional-equivalent ratio (R_f) as follows:

$$R_f = \frac{q_f}{\langle q \rangle} = \frac{\left[\frac{1}{\beta} \int_0^{+\infty} q_s p_s(q_s) dq_s \right]^{\frac{1}{\delta}}}{\langle q \rangle} \quad (2)$$

R_f scales the functional-equivalent discharge q_f by the average discharge $\langle q \rangle$ [see also Tucker and Bras, 2000], which is a common statistic of river flows, relatively simple to estimate also in poorly gauged regions based on climatic data [e.g., Hrachowitz et al., 2013]. Since the sediment flow q_s is a nonlinear function of q , its probability density function, $p_s(q_s)$ (right-hand side of equation (2)) should strongly depend on the underlying streamflow distribution. As a consequence, the streamflow variability constitutes a major driver of R_f . The effective ratio can be profitably used to infer long-term (e.g., annual or decadal) sediment transport rates from instantaneous load-discharge relations, correctly accounting for the actual range of streamflows experienced by rivers.

The relation between R_f and streamflow variability is here analyzed by using a data set of 18 catchments in the continental U.S. (Figure 1a), for which synchronous data of water and suspended sediment flows were available (summary information for the case studies are reported in Tables S1 and S2 in the supporting information). Morphological and climatic attributes of the catchments are diverse, ranging from the semiarid South Central to the humid Eastern U.S. and spanning rugged mountainous terrains, gently rolling hills, and flatter plains. The land cover is primarily agricultural and forest, with some catchments including urbanized areas. The analyzed rivers are not impacted by significant flow regulation. In some cases, river reaches have undergone straightening and channelization, and topsoil or bank and streambed erosion is a known issue. The mean grain size of sediments transported in suspension (d_{50}) ranges from less than 0.001 to 0.029 mm.

Figure 1b displays (white dots) observed R_f as a function of the coefficient of variation of streamflows, CV_q (defined as the ratio between standard deviation and mean of the observed flows), for every season of the considered case studies. Despite some scattering, a clear pattern emerges from the plot shown in Figure 1b: low values of the functional-equivalent ratio are associated to low CV_q , whereas R_f increases significantly for increasing values of the coefficient of variation of flows. Accordingly, the functional-equivalent discharge q_f is only slightly larger than the average discharge for rivers exhibiting weak variability of flows, whereas it increases (up to 5 times the average flow) for rivers characterized by pronounced streamflow variability.

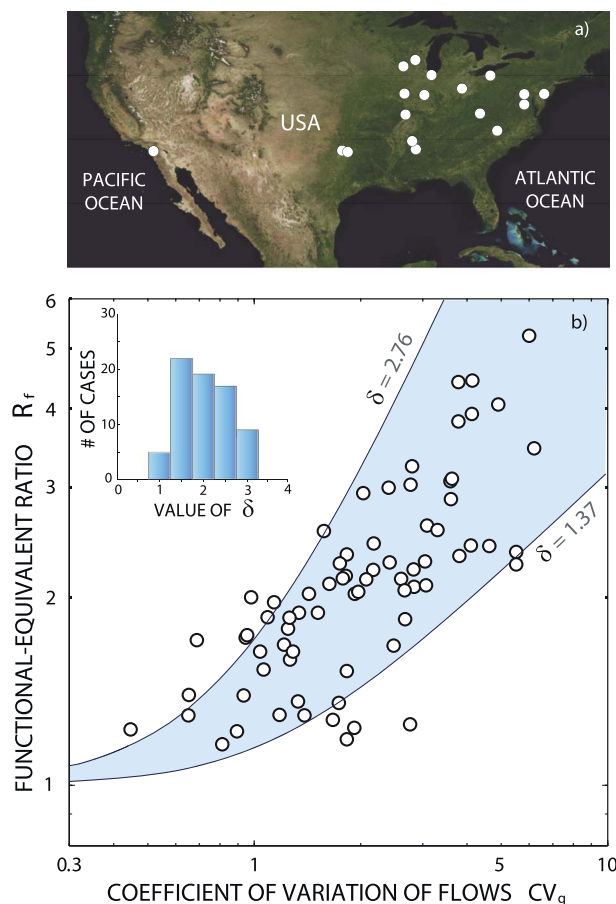


Figure 1. (a) Outlet locations of catchments considered in this study. (b) The observed functional-equivalent ratio R_f scales with the coefficient of variation of streamflows CV_q . Solid lines containing most of the observations (shadowed area) represent estimate of the analytical model (equation (3)) for δ equal to the 0.1 ($\delta = 1.37$) and 0.9 ($\delta = 2.76$) quantiles of its observed distribution (shown in the inset).

3. An Explanatory Framework

The observed variations of the functional-equivalent ratio as a function of streamflow variability are explained by adopting a lumped framework recently proposed by Botter *et al.* [2013] to characterize and classify flow regimes. According to this framework, the variability of river flows results from the interplay between the frequency of effective (i.e., streamflow-producing) rainfall events (λ) and the mean catchment response time ($1/k$). Censoring of rainfall events by soil moisture deficit controls the value of λ , which is bounded from above by the rainfall frequency and chiefly depends on catchment-scale evapotranspiration rates (in turn determined by vegetation cover and climate). The parameter k expresses the flow decay rate when recessions are assumed exponential, and its value embeds catchment-scale morphological and hydrological features, like the mean length of hydrologic pathways and soil conductivity [Botter *et al.*, 2007b].

When the mean interarrival time of flow-producing rainfall events is shorter than the mean catchment response time ($\lambda > k$), the river is continually fed by pulses delivered from the contributing catchment, and the range of streamflows observed between pulses is reduced. River flows are weakly variable around the mean, and the arising flow regime is termed persistent. When $\lambda < k$, effective rainfall events are interspersed in between long periods of flow recession, and a wider range of streamflows is observed. In this case an erratic regime emerges, characterized by high flow variability. The ratio λ/k (termed persistency index) fully determines the coefficient of variation of streamflows, since $CV_q = \sqrt{k/\lambda}$ in this framework (see supporting information).

Coupling the analytical expression for the probability distribution of streamflows derived by Botter *et al.* [2007a] (see supporting information) and the sediment rating curve $q_s = \beta q^\delta$, analytical expressions for the

probability distribution of sediment flows, $p_s(q_s)$, and its statistical moments can be derived (equations (S4) and (S5) in the supporting information). The integral in equation (2) can thus be expressed as a function of climate and landscape attributes of the catchment. Accordingly, the functional-equivalent ratio R_f can be expressed as follows:

$$R_f = \frac{k}{\lambda} \left[\frac{\Gamma\left(\frac{\lambda}{k} + \delta\right)}{\Gamma\left(\frac{\lambda}{k}\right)} \right]^{\frac{1}{\delta}} = CV_q^2 \left[\frac{\Gamma\left(CV_q^{-2} + \delta\right)}{\Gamma\left(CV_q^{-2}\right)} \right]^{\frac{1}{\delta}} \quad (3)$$

Notice that the functional-equivalent ratio only depends on the persistency index λ/k (or, alternatively, on the coefficient of variation of streamflows) and on the exponent δ of the sediment rating curve. The ratio λ/k embeds the effects of rainfall variability and soil drainage, whereas δ summarizes sediments size (i.e., suspended or bedload transport), erodibility of hillslopes, and local conditions of river bed (e.g., armoring) [Bunte *et al.*, 2014].

When δ is an integer, equation (3) can be written in a simpler way:

$$R_f = \begin{cases} 1 & \text{if } \delta = 1 \\ \sqrt{1 + \frac{k}{\lambda}} & \text{if } \delta = 2 \\ \sqrt[3]{\left(1 + \frac{k}{\lambda}\right)\left(1 + 2\frac{k}{\lambda}\right)} & \text{if } \delta = 3 \end{cases} \quad (4)$$

Equation (4) clarifies that when the catchment hydrologic response is flashy (high k), the rainfall frequency is low or the soil water deficit in the root zone is pronounced (i.e., low λ , as it might happen in semiarid climates) the value of R_f increases (i.e., the functional-equivalent discharge is larger than the mean). However, the sensitivity to λ/k is modulated by the value of δ , as discussed later.

In Figure 1b, the analytical expression for R_f (equation (3)) is plotted as a function of CV_q , by assuming δ equal to the 0.1 ($\delta = 1.37$) and 0.9 ($\delta = 2.76$) quantiles of its empirical distribution across the case studies (shown in the inset). The analytical curves (contours of the shadowed area) contain most of the observations, thereby suggesting that the proposed model is able to capture the first-order controls on the effective discharge.

Figure 2a displays (continuous lines) theoretical patterns of the functional-equivalent ratio R_f as a function of the persistency index, for different values of δ . R_f tends to one for very stable (persistent) regimes and significantly increases for low values of the persistency index (i.e., high values of CV_q characteristic of erratic flow regimes), approaching infinity for extremely variable flows ($\lambda/k \rightarrow 0$). The higher the exponent of the sediment rating curve, the higher the effective ratio and the smoother its increment with decreasing λ/k (increasing flow variability). High values of δ ($\delta > 3$, see Figure 2a) are typically associated to bedload transport [Emmett and Wolman, 2001] and correspond to highly nonlinear sediment rating curves which mimic the effect of a minimum threshold of movement. Interestingly, Bunte *et al.* [2014] and Lanzoni *et al.* [2015] suggested that the effective discharge for gravel transport should correspond to the maximum observed discharge, which implies $R_f > 1$ (in agreement with the theoretical analysis presented here). On the other hand, $\delta < 1$ causes a decrease of the functional-equivalent ratio with increased flow variability. Values of δ smaller than 1 are uncommon in sediment transport [Sholtes *et al.*, 2014], but may be appropriate for characterizing the flushing of geogenic and anthropogenic solutes [Neal *et al.*, 2012], where, in fact, upscaled load-discharge relations need to be suitably adjusted to account for hydrologic variability [e.g., Basu *et al.*, 2010].

Values of δ in the catchments analyzed in this study well represent the range of values reported in the literature for suspended sediment flows ($\delta \in [1, 3]$) [Nash, 1994]. Case studies displaying $\delta \sim 1$ ($\delta < 1.20$, tagged with squares in Figures 2a) lay near the corresponding analytical curve ($R_f = 1$) and thus confirm that in these circumstances the functional-equivalent discharge is almost insensitive to flow variability, being $q_f \sim \langle q \rangle$ regardless of the type of flow regime. Colored dots in Figure 2a represent observed R_f versus $CV_q^{-2} = \lambda/k$ for the same set of catchments shown in Figure 1. Most of the observations fall within the range predicted by the analytical model (shadowed area in Figure 2a). Case studies exhibiting δ lower than the average observed value ($\delta < 2.03$) are tagged with blue dots, while red dots correspond to cases with $\delta > 2.03$. Though considerable scatter appears for high flow variability (left side of the plot), the stratification of the two groups of observations seems to support the layering predicted by the model for different exponents of the sediment rating curve, with larger values of R_f associated to larger values of δ .

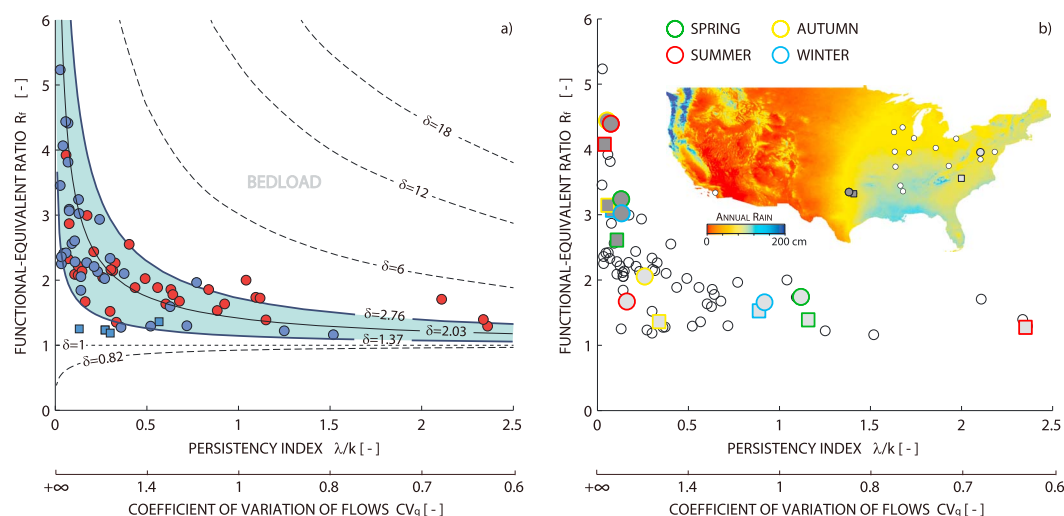


Figure 2. (a) Functional-equivalent ratio R_f as a function of the persistency index λ/k . Thick solid lines represent estimate of the analytical model for δ equal to the 0.1 ($\delta = 1.37$) and 0.9 ($\delta = 2.76$) quantiles of its observed distribution and contain most of the observations (shadowed area), which refer to suspended sediment transport. Blue squares are cases with $\delta \sim 1$ ($\delta < 1.20$). Blue dots tag catchments with observed δ lower than the mean value ($\delta < 2.03$), while basins with $\delta > 2.03$ are marked by red dots. The analytical estimate for the discriminating δ value is represented with a thin solid line. Analytical estimates for other values of δ usually associated to bed or dissolved loads are also displayed with dotted lines. (b) Clustering of R_f values of catchments belonging to different climatic areas. Dark gray dots and squares represent basins in South Central U.S. (respectively Elm Fork and Little Elm Creek in Texas), while light gray dots and squares tag catchments in Eastern U.S. (respectively Conococheague Creek in Maryland and South Yadkin River in North Carolina). Locations of their outlets are displayed in the map, which also shows total annual rainfall throughout the United States. Green, red, yellow, and blue contours of markers, respectively, indicate spring, summer, autumn, and winter seasons.

The existence of distinct values of the functional-equivalent ratio for erratic ($CV_q > 1.1$, 59 cases) and persistent ($CV_q < 0.9$, 6 cases) regimes has been quantitatively checked by means of statistical hypothesis testing. Intermediate regimes ($0.9 < CV_q < 1.1$) have been excluded from the analysis, in agreement with Botter *et al.* [2013]. The null hypothesis that observed R_f values in persistent and erratic regimes are sampled from distributions with equal medians has been tested through the Wilcoxon rank sum test. The null hypothesis was rejected at the 5% significance level, thereby implying that the median functional-equivalent ratios of erratic and persistent rivers are statistically different. Because of the different size of the two samples (erratic and persistent regimes), the test has been repeated by dividing cases with CV_q lower or higher than the observed median value across the catchments/seasons considered ($CV_q = 1.92$), with analogous results.

Distinct streamflow dynamics exhibited by erratic and persistent regimes are the physical driver of the different behaviors of these systems. When flows weakly vary around their mean value (persistent regimes), the probability of high flows and even higher magnitudes of sediment transport (implied by nonlinearity of the sediment rating curve) is very low. The magnitude of such events is overshadowed by the corresponding low probability of occurrence, and high flows weakly contribute to long-term sediment transport. Erratic regimes, instead, are composed of a sequence of high flows interspersed in between prolonged periods of low flows (i.e., droughts), which may not be effective in mobilizing sediments (e.g., the shear stress they exercise is under the threshold of movement). As a result, only high flows are responsible for sediment transport, and the functional-equivalent discharge increases significantly.

Spatial patterns of river flow regimes are the complex by-product of large-scale climatic drivers and local heterogeneities (e.g., soil, vegetation, and geology). Nevertheless, when climatic attributes like seasonal rainfall and potential evapotranspiration are the primary controls on streamflow variability [Botter *et al.*, 2013], functional-equivalent ratios of rivers could mirror the underlying climatic patterns. An example of climatic clustering is shown in Figure 2b, which highlights R_f values of two groups of catchments subject to very diverse climatic conditions (map shows total annual precipitation). Light gray dots tag basins in Eastern U.S. (Maryland and North Carolina), while dark gray dots indicate South Central catchments (Texas). Because of their semiarid climate, Texas catchments are characterized by extremely erratic flow regimes throughout

the year and are located in the top left part of the plot. For these rivers q_f is several times larger than the mean streamflow in all cases. R_f is instead less than 2 in every season for rivers of the Eastern Coast of U.S. (bottom right part of the plot in Figure 2b), because of the more frequent rainfall input, which leads the seasonal regime to shift from persistent to slightly erratic.

These results, jointly with recent advances in the prediction of flow regimes using climatic and morphologic data [Doulatyari et al., 2015], support the possibility of applying the present framework for first-order estimates of functional-equivalent discharge in rivers belonging to different geographic and climatic areas, based on rainfall and landscape attributes. This represents the goal of ongoing research.

4. Conclusions

The diversity of effective discharges observed in rivers is here explained in terms of the underlying heterogeneity of flow regimes. The ratio between effective discharge and mean streamflow (effective ratio) is analytically expressed as a function of the exponent of the sediment rating curve and the coefficient of variation of daily flows, which in turn depends on streamflow-producing rainfall frequency and mean catchment response time. The analytic expression captures the first-order controls on the effective ratio for suspended sediment in a set of 18 case studies in the continental U.S. High values of the effective ratio are associated to larger exponents of the sediment rating curve and to more erratic flow regimes (high flow variability). Instead, the effective discharge is only slightly higher than the average flow in persistent regimes (weak flow variability). This is the by-product of distinct streamflow dynamics, which causes high flows to be mainly responsible for sediment transport in erratic regimes. Conversely, the highest discharges weakly contribute to long-term load in persistent regimes. Values of the effective ratio can exhibit climatic signatures because of the strong control of evapotranspiration and rainfall regimes on flow variability. The formal linkage between effective ratio and flow regimes may constitute a valuable tool for preliminary estimates of the effective discharge in rivers belonging to different geographic and climatic settings.

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