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Notes

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ABSTRACT

Analysis of suspended sediment transport data for rivers in Yunnan and Tibet shows that monsoon flows control effective discharge. We calculate effective discharge, defined as the discharge that transports the most sediment, for 44 stations for which there is at least one complete year of daily suspended sediment concentration and mean daily discharge data, and find that the effective discharge is approximately the mean monsoon discharge for all stations. The correspondence of the effective discharges with the mean annual flow and monsoon discharge for all stations demonstrates that monsoon flow dominates suspended sediment transport in the region, rather than storm flow during discrete, short-duration storm events. In this region, the monsoon lasts for 4 months (June–September) and during that time transports 86% of the suspended sediment load. In contrast to the general observation from temperate environments that infrequent, stochastic storm events dominate sediment transport (with 90% of the suspended sediment transport occurring in 10% of the time), our findings show that the mean monsoon discharge dominates sediment transport in the rivers draining the southeastern Tibetan Plateau.

INTRODUCTION

Recent interest has focused on the Himalaya and Tibet as a natural laboratory for understanding the interplay of climate, tectonics, and erosion (Brozovic et al., 1997; e.g., Burbank et al., 2003; Finlayson et al., 2002; Galy and France-Lanord, 2001; Thiede et al., 2004). Researchers have variously concluded that mean annual rainfall is strongly correlated with, and possibly drives, average erosion rates (Gabet et al., 2008) or that erosion and precipitation are decoupled (Burbank et al., 2003). Although such analyses typically employ mean annual rainfall, it is widely understood that as much as 90% of suspended sediment transport typically happens during the highest 10% of discharges (Meade, 1982). Although monsoon (Craddock et al., 2007) or storm event (Snyder et al., 2003) rainfall likely controls erosion and sediment transport rates more than mean annual rainfall, the long-standing question of whether frequent events, such as monsoons, or infrequent events, such as large storms, transport more suspended sediment remains little explored in monsoon regions like the Himalaya.

The concept of effective discharge (Q_{eff}) is a useful tool for evaluating the relative roles of large and small storms and the monsoon climate of south and southeast Tibet in transporting suspended sediment. Following Wolman and Miller (1960), we define Q_{eff} as the discharge that transports the most suspended sediment, integrated over the record available. The concept initially was used by Wolman and Miller (1960) to show that large, infrequent events do less work over time than moderate events that occur more frequently. Wolman and Miller (1960) calculated Q_{eff} using a flow-frequency curve and a suspended sediment rating curve, the product of which had a peak they defined as Q_{eff}.

Since this initial analysis, two schools of thought have emerged around the concept of Q_{eff} (Crowder and Knapp, 2005). The first is that Q_{eff} is the dominant discharge in setting channel properties (i.e., channel-forming flow), and is approximately equal to the flow that recurs every 1.5 yr and fills the banks of the channel (e.g., Andrews, 1980; Andrews and Nankervis, 1995; Dury, 1973; Leopold, 1994; Leopold et al., 1964; Rosgen, 1996; Wolman and Miller, 1960). The second is that rivers respond differently to a variety of discharges and the concept of a dominant discharge is virtually meaningless. This view has emerged in part because some researchers have found widely varying recurrence intervals associated with Q_{eff} that are thought to be the result of varying morphology, hydrologic regimes, size of suspended sediment transported, and watershed areas (e.g., Ashmore and Day, 1988; Benson and Thomas, 1966; Castro and Jackson, 2001; Hey, 1998; Nash, 1994; Phillips, 2002; Pickup and Warner, 1976; Williams, 1978). Some have since proposed that rivers have two important discharges, one for suspended sediment that transports the most suspended sediment and one for bedload that forms the channel (Phillips, 2002).

Rivers dominated by monsoon climates have received little attention in this ongoing debate surrounding Q_{eff}. Kale (2002) reported that Indian rivers are dominated by the monsoon climate of the region and that in this environment large floods control channel form. A detailed analysis of discharges and stream power for the Narmada (Kale, 2008) and Tapi Rivers (Kale and Hire, 2004, 2007), both on the Indian Peninsula, reveals that flows are capable of transporting pebbles during most of the monsoon, but that channel-altering flows recur much less frequently (possibly with recurrence intervals longer than 100 yr). However, these analyses are primarily based on potential stream power estimated from discharge and channel cross sections rather than direct measurements of sediment concentration and load.

Here we calculate effective discharges using complete years of daily measurements of discharge and suspended sediment concentration for 44 hydrology stations in Yunnan and Tibet (Fig. 1). We use these data to investigate climatic controls on suspended sediment load in monsoon rivers. Based on the results of previous studies discussed above, we hypothesize that Q_{eff} will approximately equal the mean monsoon discharge and that the majority of suspended sediment load and water will move through the system at these flows. In addition, we expect that Q_{eff} will be exceeded only during the monsoon.

METHODS

Reported values of Q_{eff} are highly dependent on the way the calculation is performed (Crowder and Knapp, 2005). In particular, the discharge must be binned to create a histogram, and the value calculated for Q_{eff} depends on the size and number of bins used (Biedenharn and Copeland, 2000). Typically, discharge measurements are made much more frequently than suspended sediment concentration measurements, meaning that suspended sediment concentration must be estimated from discharge data. The method used to estimate suspended sediment load has been the subject of much debate and can greatly affect the calculated Q_{eff} (Benson and Thomas, 1966; Crowder and Knapp, 2005; Pickup and Warner, 1976; Wolman and Miller, 1960). To avoid many of these problems, we use suspended sediment concentrations and discharges measured daily over periods of complete years.

We use data from rivers in southwest China and Tibet collected by the Chinese Ministry of Hydrology and compiled in a series of books by the ministry from 1962 to 1989 (Ministry of Hydrology, 1971, 1978; http://depts.washington.edu/shuiwen); we digitized the data for this analysis. The stations have upstream areas ranging in size from 14 to 203,904 km^2 and 1–27 yr of data

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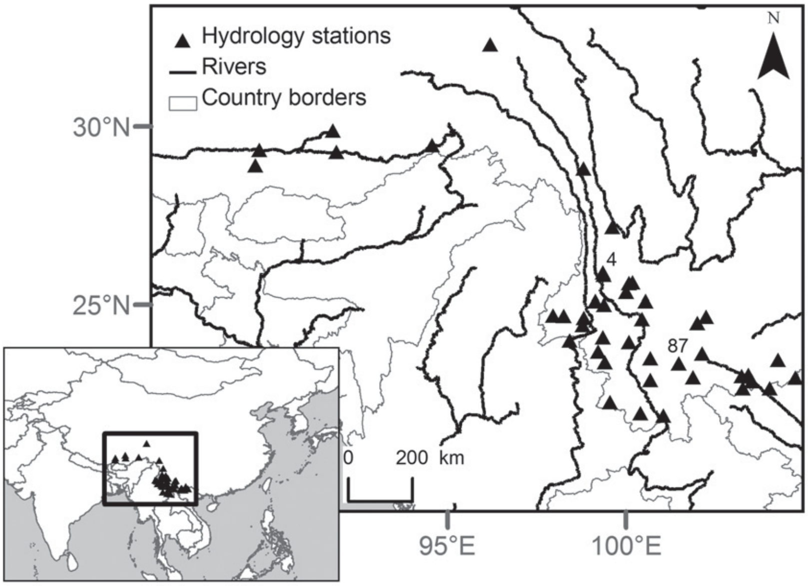

Figure 1. Map showing location of stations analyzed. Stations 4 and 87 are labeled; data about them are shown in more detail in Figure 2.

(see the GSA Data Repository[1]; Fig. 1). Suspended sediment concentration and discharge data were collected daily using a Jakowski sampler and the 0.2–0.8 sampling method (Ministry of Water Conservancy and Electric Power, 1962, 1975). No error estimates are reported for these data in the original sources. To ensure that calculations capture major events, we only analyze complete years of data, defined as at least 365 daily suspended sediment concentration and discharge measurements within the same year. Stations with at least one complete year of data are included in the analysis.

Because no bedload data were reported by the Chinese Ministry of Hydrology, we must restrict our analysis to suspended sediment load. We recognize that this means we do not consider coarser sediment, which only moves during larger flood events. Although detailed analyses of when bedload is transported have not been done for this region, suspended sediment likely dominates the total sediment flux, as in other mountain drainage basins worldwide (Milliman and Syvitski, 1992). Thus, we consider analysis of the suspended load to be valuable in furthering our understanding of sediment transport in this region.

The Indian Monsoon occurs during the months of June through September (Krishnamurti, 2010); thus, we define the mean monsoon discharge as the mean daily discharge during this time interval (Burbank et al., 2003; Craddock et al., 2007) in order to directly compare mean monsoon discharge to calculated Q_{eff}. In addition, for each station we calculate the fraction of total annual suspended sediment load and discharge that is transported during these months.

For the Q_{eff} calculations, we are in the unique position of having suspended sediment concentration data available for entire years of the data record. Therefore, we did not have to estimate suspended sediment loads and instead used measured concentrations and discharges to calculate daily suspended sediment load. We then binned the daily suspended sediment load by discharge to create a histogram. The discharge value with the highest percentage of sediment transported is the Q_{eff} for that station. Following Crowder and Knapp (2005), we initially used 25 bins for discharge and added bins until the peak of the histogram did not occur in the first bin (for more details on calculating Q_{eff} and for examples of histograms for stations along the Mekong River, see the Data Repository).

RESULTS AND DISCUSSION

The monsoon in this region lasts for only one-third of the year, but transports >80% of the annual suspended sediment load and >60% of the discharge and thus dominates the suspended sediment transport for the region (Fig. 2). During the monsoon, the rivers transport an average of 86% of the annual suspended sediment and 62% of the annual discharge (see the Data Repository). The fraction of suspended sediment load transported during the monsoon and fraction of annual discharge

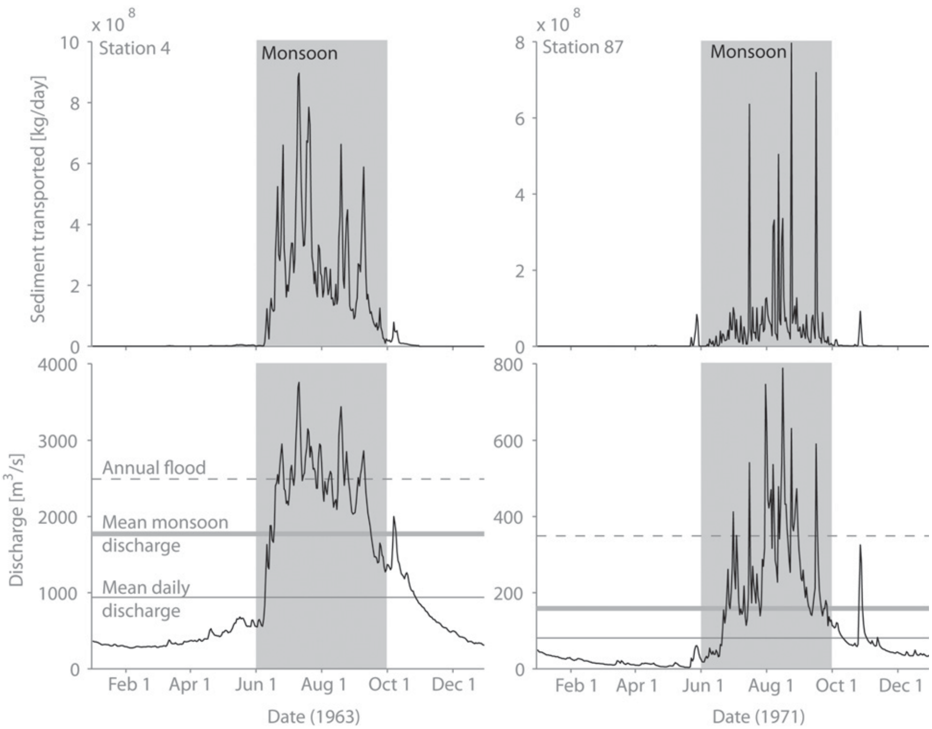

Figure 2. Upper panels show sediment transported per day and lower panels show hydrographs (thin black line), mean daily discharge (thin gray line), mean daily monsoon discharge (wider gray line), and annual (1 yr recurrence interval) flood (dotted line) for station 4 in A.D. 1963 (left) and station 87 in 1971 (right). In addition, sediment transport curves show that majority of sediment is transported during monsoon. These years and stations are typical among stations analyzed.

[1]GSA Data Repository item 2010272, Tables DR1 and DR2, details of Q_{eff} and monsoon characteristic calculation, and Figure DR1, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

that occurs during the monsoon are independent of the mean monsoon discharge (Fig. 3). Analysis of annual hydrographs for individual stations shows that nearly all the sediment and most of the discharge are transported during the monsoon months.

We find an ~1:1 relationship between monsoon discharge and calculated Q_{eff} (r^2 = 0.94, slope of the best fit line is 1.13 ± 0.04; Fig. 4A). The ratio of mean monsoon discharge to Q_{eff} is independent of number of years of data available and upstream basin area (Fig. 4B). Although the relatively short duration of our data set (<30 yr) may be expected to bias our Q_{eff} estimates toward more frequently recurring discharges, the lack of a correlation between ratio of the mean monsoon discharge to the effective discharge and the length of data available, or between the fraction of sediment and water transported during the monsoon and the mean monsoon discharge, suggests that the results are not biased toward more frequent floods. The robust correlation between Q_{eff} and mean monsoon discharge also supports this interpretation.

Our results demonstrate that in the monsoon regions of Yunnan and Tibet, rivers move most suspended sediment during the monsoon. Unfortunately we have no information on bedload in this region and cannot evaluate whether the bedload also moves regularly during the monsoon or requires higher flows to move. Nonetheless, in this region, Q_{eff} is not a function of individual stochastic events; it is simply a measure of the sediment transport efficacy of the monsoon. Although one could consider the monsoon to be a single event, its duration greatly exceeds those of effective discharges observed in non-monsoon regions.

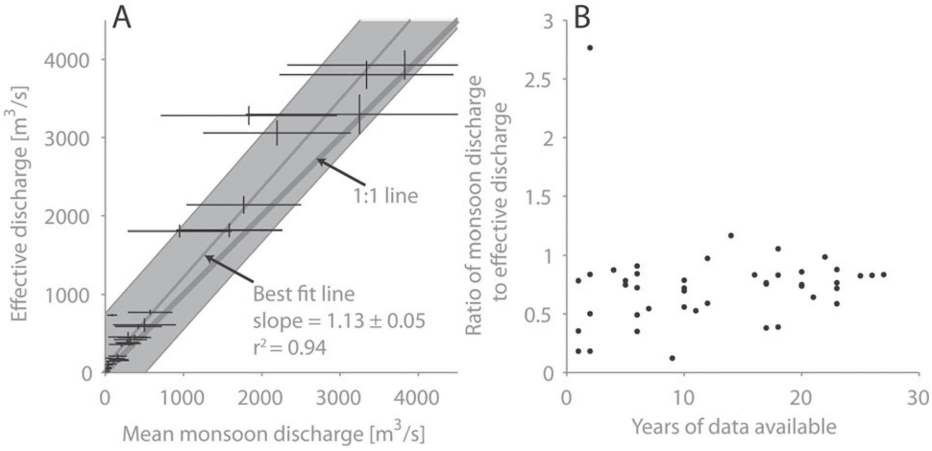

Figure 4. A: Effective discharge, Q_{eff}, as function of mean monsoon discharge for all stations. Error bars shown are standard deviation of monsoon discharge and bin size for Q_{eff} calculations. Thin gray line is best fit line for scatter plot (r^2 = 0.94, slope = 1.13 ± 0.04) and gray area in background is 95% confidence range for best fit line. The 1:1 line (thicker gray line) is contained within range of possible best fit line, suggesting that within error of calculations, Q_{eff} is approximately the mean monsoon discharge. B: Ratio of monsoon discharge to calculated Q_{eff} is independent of years of data available.

CONCLUSIONS

Our analysis demonstrates that mean monsoon discharge is Q_{eff} in Yunnan and Tibet and suggests that monsoon discharge is more important than individual storms in governing suspended sediment transport for rivers in monsoon regions. As the monsoon lasts for four months and recurs annually, it lasts significantly longer than the discrete, short-duration storm events that dominate sediment transport in most temperate systems (Meade, 1982). If our observations in Tibet and Yunnan are characteristic of other monsoon systems, the adage that as much as 90% of the suspended sediment transport takes place in 10% of the time (Meade, 1982) does not hold for monsoon rivers. Instead, in rivers dominated by a monsoon climate, the mean monsoon flow (which occurs for 4 months, or ~33%, of the year) is the discharge that transports the most suspended sediment (86% of the sediment). This discharge recurs for several months a year. In light of these results, models of landscape evolution or erosional processes in the Himalaya and other monsoonal regions could reasonably model suspended sediment transport as happening during monsoon discharges rather than during stochastic large flood events. Moreover, it would appear prudent for studies of correlations between rainfall and erosion rate in the Himalaya and other monsoonal regions to focus on monsoon rainfall rather than mean annual rainfall.

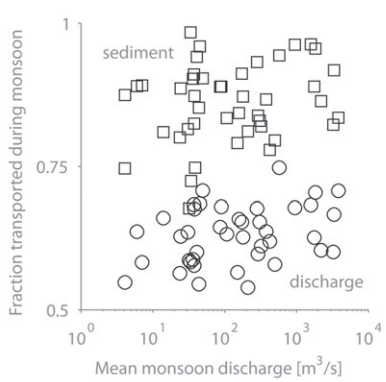

Figure 3. Fraction of annual sediment load (squares) and annual discharge (circles) transported during monsoon as function of monsoon strength.

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