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Effective discharge in Rocky Mountain headwater streams

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SUMMARY

Whereas effective discharge (Q_{eff}) in mountain streams is commonly associated with a moderate flow such as bankfull discharge (Q_{bf}), this study found that the maximum discharge (Q_{max}), and not bankfull discharge, is the channel forming or effective flow for gravel transport in plane-bed streams where partial bed mobility causes steep gravel transport rating curves. Q_{eff} may approach bankfull flow in some step-pool channels where gravel moves over a static cobble/boulder bed. Our conclusions are based on magnitude–frequency analyses conducted at 41 gauged Rocky Mountain headwater streams. Because these gauged streams lacked gravel transport data, as is typical, comparable streams with measured transport rates were used to develop scaling relations for rating curve exponents with stream and watershed characteristics. Those scaling relations were then used to estimate the steepness of gravel rating curves at the 41 gauged but unsampled sites. The measured flow frequency distributions were characterized by two fitted power functions. The steepness of the flow frequency distributions and the estimated steepness of gravel transport relations were combined in magnitude–frequency analyses to compute Q_{eff}.

1. Introduction

1.1. Background

Magnitude–frequency analysis, first devised by Wolman and Miller (1960), is used to compute the stream flow that transports the largest amount of sediment over the long run. That flow is referred to as effective discharge (Q_{eff}) and is thought to predominantly shape the channel. Effective discharge is computed by multiplying the flow frequency for a given flow (F_{Qi}) with the bedload transport rate assigned to that flow (Q_{Bi}), and the computations are repeated over the range of recorded discharges Q. The peak of the product function $F_{Qi} \cdot Q_{Bi} = f(Q)$ is defined as effective discharge (Q_{eff}) (Fig. 1). The units selected for F_Q and Q_B evenly affect all values of the $F_{Qi} \cdot Q_{Bi}$ product but not the Q at which the peak occurs, hence the units are inconsequential for determining Q_{eff}.

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River engineers, watershed managers, and fluvial geomorphologists need to know the flows that are most important for shaping and maintaining the channel morphology as a background for channel design and stream restoration (e.g., Biedenharn et al., 2000; Shields et al., 2003; Doyle et al., 2007; Soar and Thorne, 2011), for flow management, and for better understanding of stream responses to changes in flow and bedload transport regimes.

Bankfull discharge (Q_{bf}), either calculated or determined from field observations, is commonly used as a surrogate for effective discharge and as the design discharge in river restoration projects. One reason for assuming Q_{bf} as the channel forming and design discharge (e.g., Biedenharn et al., 2000; Doyle et al., 2007) is that the information required to compute Q_{eff} is not available at unmeasured sites. Another reason for the substitution is that many magnitude–frequency analyses, including those performed in coarse-bedded mountain streams, have reported a similarity between Q_{eff} and moderate flows such as Q_{bf} (e.g., Wolman and Miller, 1960; Nolan et al., 1987; Andrews, 1980; Nash, 1994; Andrews and Nankervis, 1995; Batalla and Sala, 1995; Whiting et al., 1999; Pitlick and Van Steeter, 1998; Torizzo and Pitlick, 2004; Doyle et al., 2007; Barry et al., 2008). However, several studies observed a difference between Q_{bf} and Q_{eff} and suggested that Q_{eff} systematically increases with sediment rating curve steepness

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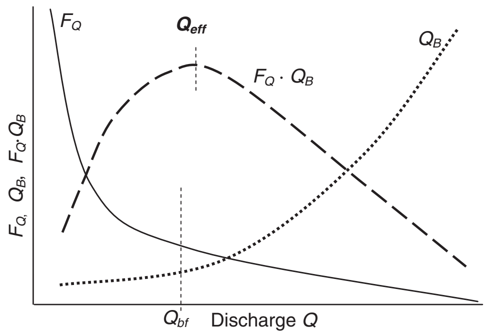

Fig. 1. Concept of a magnitude–frequency analysis.

(Nash, 1994; Bunte, 1995, 2002; Emmett and Wolman, 2001; Vogel et al., 2003; Barry et al., 2008; Doyle and Shields, 2008; Quader and Guo, 2009; Soar and Thorne, 2011) and led the authors to question the commonly held belief that Q_{bf} and Q_{eff} are always approximately equal. In this paper we apply a revised magnitude–frequency procedure and provide additional evidence, which suggests that effective discharge for gravel transport is not equivalent to a moderate or bankfull flow in all stream types but that effective discharge is controlled to a significant degree by channel characteristics and the steepness of the bedload sediment rating curve. An improved understanding of the magnitude of effective discharge and knowledge that the relation of Q_{eff} to bankfull flow varies with stream type, channel characteristics, and bedload transport relations will improve stream channel management.

1.2. Study objectives

1.2.1. Focus on mountain headwaters with snowmelt regimes

Rocky Mountain headwater streams with snowmelt regimes located predominantly in Colorado, USA are the focus of this study. Effective discharge is poorly understood in steep mountain streams because gravel bedload transport dynamics are different than those in less steep and finer grained rivers and are only recently receiving attention and study. Many steep Rocky Mountain streams have limited sediment supply and are not fully alluvial (*in sensu* of full mobility vs. partial mobility as defined by Wilcock and McArdell (1993, 1997)). Here, most bedload transport consists of small and medium gravels moving over a coarse gravel/cobble-bed that is immobile except for the highest flows, and only the finer portion of bedmaterial particle sizes are transported as bedload on a regular basis (e.g., Whiting et al., 1999; Lenzi et al., 2004; Yager et al., 2007, 2012; Bunte et al., 2013). Besides structural bed stability, flow and sediment transport in mountain streams also needs to negotiate immobile obstacles such as boulders, sharp channel bends, and large woody debris. Those obstacles elevate hydraulic friction and cause bedload transport to be controlled by local hydraulics and secondary flows rather than by cross-sectionally averaged flow hydraulics. The resulting complexity of bedload transport processes makes gravel transport rates in those channels nearly impossible to predict from transport equations (Gomez and Church, 1989; Bravo-Espinosa et al., 2003; Barry et al., 2004, 2008; Schneider et al., 2014).

Measuring gravel transport relations in coarse mountain streams is problematic due to limitations in field sampling equipment. Bedload is commonly sampled using a 0.0762 m opening Helley-Smith sampler (e.g., Williams and Rosgen, 1989; Ryan et al., 2002, 2005; King et al., 2004), a device not well suited for sampling low rates of gravel transport in coarse-bedded streams (Bunte et al., 2004, 2008, 2010a,b). Gravel transport relations that are much steeper than those obtained from Helley-Smith samplers are measured with bedload trap samplers designed for coarse-bedded, steep streams (Bunte et al., 2004, 2008, 2010a,b).

This study will conduct magnitude–frequency analyses and compute Q_{eff} based on gravel transport relations derived from bedload traps and other samplers designed for coarse-bedded streams. Two new procedures are employed: flow frequency distributions are described by two separate power functions, and bedload rating curve exponents for unsampled streams are estimated from scaling relations with watershed and channel parameters. Combined, the two procedures provide a straightforward explanation of the magnitude of Q_{eff} in gravel-cobble bed mountain streams.

1.2.2. Extending magnitude–frequency analysis to unsampled streams

A magnitude–frequency analysis is ideally based on measured information for both a flow frequency distribution and a bedload transport relation. However, very few Rocky Mountain streams with long-term flow records have gravel transport measurements obtained from suitable samplers. By contrast, our bedload measurements with samplers designed for the task were mostly taken at ungauged streams. To overcome the lack in overlap, this study extends suitably measured gravel transport relations in mountain streams to unmeasured but well gauged Rocky Mountain streams. The extension is performed by scaling the steepness of measured gravel transport relations (i.e., *b*-exponents) with channel and watershed parameters that may be quantified without field visitation. The scaling relations are then used to estimate gravel rating curve exponents for the unsampled streams, and the estimated *b*-exponents are used to compute effective discharge.

This study employs an analytical approach for magnitude–frequency analyses (e.g., Wolman and Miller, 1960; Nash, 1994; Vogel et al., 2003; Goodwin, 2004; Quader and Guo, 2009) in which both the bedload rating relation $Q_B = f(Q)$ and the flow frequency distribution $F_Q = f(Q)$ are expressed as functions of discharge. However, rather than fitting a commonly used distribution type such as a log normal or gamma distribution, this study expresses flow frequency distributions by two fitted power functions, one for lower flows and one for higher flows. This new procedure offers the advantage that a positive or negative trend for the product curve $F_Q \cdot Q_B$ is indicated by the sum of the exponents of the gravel transport relation and the flow frequency distribution. The numerical value of that sum provides a quick indication of whether Q_{eff} occurs at near bankfull flow or is to be expected at other (higher or lower) flows. Finally, the study discusses stream types and the bedload sampling conditions for which Q_{eff} may be assumed to coincide with bankfull flows or with other discharges.

2. Methods

2.1. Flow frequency distributions

2.1.1. Data selection: mountain streams with long flow records

Time series of mean daily flows were obtained from the USGS flow records (http://waterdata.usgs.gov/nwis/sw) for headwater streams in Colorado, Wyoming, and Montana. Because gravel transport relations (described in Section 2.2) were sampled in coarse-bedded, steep headwater streams with channel gradients S of 0.01–0.14 m/m, basin areas A of 1–260 km^2, and bankfull flows of 0.3–19 m^3/s, flow data were obtained for streams with similar characteristics. Minimum gauge record length was set to 30 years to ensure that the flow frequency distributions represent the highest flows. Gauge elevations range from 2086 to 3180 m, and annual peak flow is due to snowmelt runoff. Excluded from the study are reservoir outflow stations, streams with mixed pluvial–nival flow regimes, streams in arid regions of SW Colorado, heavily diverted streams, as well as streams receiving transbasin diversions which