Journal of Hydrology 402 (2011) 297–305

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

An equation for bed-load transport capacities in gravel-bed rivers

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ARTICLE INFO

Article history:
Received 16 September 2010
Received in revised form 6 March 2011
Accepted 19 March 2011
Available online 12 April 2011
This manuscript was handled by K. Georgakakos, Editor-in-Chief, with the assistance of Ehab A. Meselhe, Associate Editor

Keywords:
Bed-load transport
Transport capacity
Armor layer
Gravel-bed rivers

SUMMARY

Detailed hydraulic and sedimentary information is needed to accurately predict bed-load transport rates in natural gravel-bed rivers. Yet, being able to estimate maximum transport rates from simple measurements would greatly benefit various sediment-related river management practices. To this end, a new concept of bed-load transport capacity for heterogeneous grains in gravel-bed rivers was introduced as the maximum possible transport rate a gravel-bed river can have for a given value of dimensionless shear stress, calculated using the median size of bed-load grains. Flows that can transport bed load at capacity may be identified by the criterion that the median size of bed-load grains must be greater than or equal to that of the bed substrate. Then, a single coefficient, power equation was developed to predict such capacities using bed-load capacity data covering both low flows with an armor layer and high flows without it. The good performance of this empirical equation was confirmed by comparing its predictability with that of Mayer Peter and Muller's and Bagnold's bed-load equations. Using an independent data compiled from six gravel-bed rivers in Idaho, not only was the empirical equation validated but also the criterion for identifying the condition under which bed load is transported at capacity was tested. In practice, the empirical equation can be used to estimate the maximum possible bed-load transport rates during high flow events, which is useful for various sediment-related river managements.

1. Introduction

Estimating bed-load transport rates in natural gravel-bed rivers without collecting large amounts of detailed data on river hydraulics, bed material size distribution, and channel bedforms is very difficult and remains a major problem with respect to managing rivers for both ecosystem functions and navigation (Bunte et al., 2008). The complexity of determining bed-load transport rates in natural gravel-bed rivers mainly stems from: (a) variable upstream sediment supply (e.g., Dietrich et al., 1989), (b) unsteady flows that may result in cross-channel variations of bed shear stress, flow velocity, and transport rates (e.g., Ferguson, 2003; Powell et al., 2006, 1999), and (c) heterogeneous sizes of grains both on the bed surface and in the bed substrate. The heterogeneous grains are mostly responsible for the renowned hydraulic phenomena in gravel-bed rivers: (i) hiding effect and bed armoring (i.e., bigger grains on bed surface preventing smaller ones beneath from being transported and forming a coarser bed surface layer) (e.g., Andrews and Parker, 1987; Egiazaroff, 1965; Einstein and Chien, 1953; Gomez, 1983; Lisle and Madej, 1992; Montgomery et al., 2000; Sutherland, 1987), (ii) selective transport (i.e., grains of different sizes on the bed being transported by different flow intensities) (e.g., Bridge, 2003; Buffington and Montgomery, 1999; Dietrich et al., 1989; Wathen et al., 1995), and (iii) equal mobility (i.e., grains of different sizes may be transported by the same flow intensity) (e.g., Lenzi et al., 1999; Parker et al., 1982; Parker and Toro-Escobar, 2002).

In the past three decades, research done to predict bed-load transport rates in gravel-bed rivers has focused on how bed surface texture and grain sizes vary in response to the change of sediment supply (e.g., Buffington and Montgomery, 1999; Dietrich et al., 1989) and how vertical grain exchange among bed load, bed surface, and substrate happens during transport (e.g., Wilcock, 2001). These efforts have led to many equations that predict bed-load transport rates if detailed information on flow hydraulics, bed surface and substrate characteristics and size distribution, and bed-load grain composition are available (e.g., Parker et al., 1982; Recking, 2010; Wilcock and Kenworthy, 2002). In practice, however, no equation can be universally applied to all rivers (e.g., Barry et al., 2004; Bathurst et al., 1987; Reid et al., 1996) and accurate prediction of bed-load transport rates necessitates a try-and-error procedure to identify the best suitable equation (e.g., Wilcock et al., 2009), as well as the above-mentioned detailed information. Consequently, predicting bed-load transport rates requires considerable effort even in a small stream.

In this paper, a simple bed-load equation that requires simple measurements is developed. This equation is not for estimating specific bed-load transport rates, but the maximum bed-load transport rates (i.e., the transport capacities) of heterogeneous

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0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2011.03.025

grains for given hydraulic and sedimentary conditions in gravel-bed rivers. The paper begins with the definition of transport capacity for heterogeneous grains in gravel-bed rivers. Then, a criterion of identifying such capacities is introduced. A simple bed-load equation is subsequently developed using nonlinear regression based on the compiled data. Both the equation and the criterion are further validated using an independent data from natural gravel-bed rivers. The paper ends with the discussion of the limitations and application of the developed equation.

2. Methods

2.1. Definition of transport capacity

Bed-load transport capacity traditionally refers to "the maximum load of a given kind of debris a stream can carry" (Gilbert, 1914). Engineers and scientists have used the concept of bed-load transport capacity to assess degradation and aggradation rates on river channel beds and to understand if sediment transport is primarily controlled by sediment supply (i.e., supply-limited rivers) or river flow hydrodynamics (i.e., transport-limited rivers) (e.g., Andrew, 1979; Hicks and Gomez, 2003; Jackson and Beschta, 1982; Lisle, 2007; Mackin, 1948; Reid and Dunne, 1996; Sear, 1996). Considerable work to determine what controls bed-load transport capacity has derived from flume experiments that used grains with identical or nearly identical particle size (e.g., Fernandez Luque and van Beek, 1976; Simons and Senturk, 1992; Yalin, 1977), which may be called homogeneous grains. However, bed-load transport in natural gravel-bed rivers never occurs with homogeneous grains, but rather, with grains of mixed sizes, termed heterogeneous grains. Because bed-load transport with homogeneous grains is significantly different from that with heterogeneous grains, the concept of bed-load transport capacity may in fact be different with respect to homogenous and heterogeneous grains.

In a steady, uniform flow transporting homogeneous grains over plane, loose beds, bed-load transport rate is indeed the only transport rate the flow has and can be defined as the transport capacity for homogeneous grains. This capacity has been generally quantified by Abrahams and Gao (2006) using an equation, which can be expressed in a different dimensionless form than used in Abrahams and Gao (2006)

$$B = G^{3.4} \tag{1}$$

where $B = i_b/\omega$, i_b is the bed-load transport rate at capacity (kg m^{-1} s^{-1}), $\omega = \tau u = \rho ghSu$ is the unit stream power per unit bed area (kg m^{-1} s^{-1}) in which τ is the bed shear stress (kg m^{-2}), h is the mean flow depth (m), S is the energy slope, ρ is the density of flow (kg m^{-3}), g is the acceleration of gravity (m s^{-2}), and u is the mean flow velocity (m s^{-1}). The variable G equals to $1 - \theta_c/\theta$ where in $\theta = \rho hS/(\rho_s - \rho)D_{50}$ is the dimensionless shear stress, ρ_s is the density of sediment (kg m^{-3}), D_{50} is the median size of bed-load grains (m), and θ_c is the critical value of θ for the initial movement of sediment. This concept of transport capacity mainly applies to flume experiments with homogeneous grains, though it could also be applicable in sand-bed rivers within a very narrow range of hydraulic conditions (Simons and Senturk, 1992).

In natural gravel-bed rivers containing heterogeneous grains both on the bed surface and in the bed substrate, bed-load transport rates are typically limited by an armor layer developed on the bed surface and hence are lower than those predicted using Eq. (1) for the same θ values. When flow rates are high, which means corresponding θ values calculated based on the median size of bed surface grains, D_{s50}, are roughly above the range of 0.1–0.2 (Ashworth and Ferguson, 1989; Lisle and Smith, 2003; Parker and Klingeman, 1982; Wilcock and Southard, 1989), the armor layer may break out and bed-load transport can occur at capacity (Gomez, 2006; Laronne et al., 1994; Parker, 2006; Powell et al., 1999, 2001; Wilcock and Crowe, 2003). In practice, the breakout of the armor layer most possibly occurs with peak discharges (i.e., big flows) (e.g., Clayton and Pitlick, 2008; Wilcock and DeTemple, 2005) during which bed-load measurement is very difficult to deploy. Thus, there are not many data representing transport capacities in natural gravel-bed rivers available. The widely accepted capacity data are those collected from a natural gravel-bed river, the Nahal Yatir River of Israel (Reid et al., 1995). In this desert ephemeral river, intensive storm events and sufficient bed materials assure that bed load is transported along the bed without an armor layer (Laronne et al., 1994; Powell et al., 2001) and both bed-load transport rate and efficiency are high. Hence, equal mobility is achieved and fractional bed-load transport rates should be described by the same transport equation (Parker, 2006; Powell et al., 2001; Wilcock and Crowe, 2003). In other words, bed load in this river is transported at capacity. If this capacity is conceptually the same as the one predicted by Eq. (1) for homogeneous grains, then the bed-load data collected from the Nahal Yatir River should be predicted reasonably well by Eq. (1).

Based on the data compiled from Reid et al. (1995), bed-load transport rates in Nahal Yatir river were predicted using Eq. (1) and compared with the measured ones. Fig. 1 showed that bed-load transport rates in gravel-bed rivers without the armor layer were consistently lower than the transport capacities predicted using Eq. (1). It follows that bed-load transport rates in gravel-bed rivers with and without an armor layer are generally less than those predicted using Eq. (1). This suggests that the transport capacity in natural gravel-bed rivers transporting bed-load grains of mixed sizes is different from that of homogeneous sizes and needs to be defined separately. Therefore, *bed-load transport capacity for heterogeneous grains is herein defined as the maximum possible transport rate a gravel-bed river can have for a given value of θ calculated using the median size of bed-load grains D_{50}*. According to this definition, though a gravel-bed river with an armor layer may have several different available transport rates for a given θ value, it only has one maximum possible transport rate (i.e., the transport capacity).

2.2. Data compilation and analysis

To develop an equation for bed-load transport capacities in natural gravel-bed rivers, data representing the transport capacities

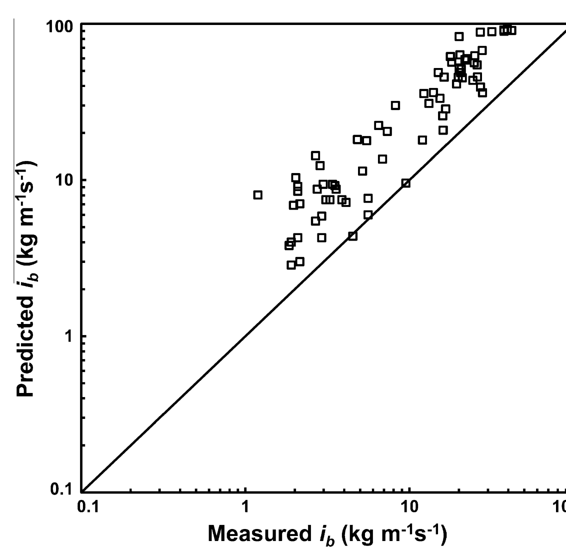

Fig. 1. Comparison of bed-load transport rates in Nahal Yatir River with the transport capacities predicted by Eq. (1) for the same θ values. This gravel-bed river transports bed load of heterogeneous grains without an armor layer and at capacity (Laronne et al., 1994).