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Tracing river gravels: Insights into dispersion from a long-term field experiment

J.K. Haschenburger *

Department of Geological Sciences, University of Texas at San Antonio, San Antonio, TX 78249, United States

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ABSTRACT

Sediment dispersion is a fundamental component of the sediment transfer process in gravel-bed rivers. Modeling this process requires an understanding of the collective movement of mixed-size clasts. This study explores the temporal evolution of gravel dispersion to underscore the importance of field observation in informing modeling efforts. Magnetically tagged gravels deployed in Carnation Creek have been monitored repeatedly over 17 years. Four metrics used to describe the extent of dispersion document that the overall shape in the spatial distribution of grain location changes over time. The general trends mask the complexity of the dispersion process, expressed by channel sections where tracers are concentrated regardless of grain size. The distribution of total grain displacement responsible for dispersion evolves as tracers become well mixed. Results demonstrate that observations from the field are crucial to the understanding and modeling of sediment dispersion because they provide key insights into the dispersion process that must be known *a priori* for mathematical modeling and similar observations cannot be collected using laboratory flumes.

1. Introduction

Over the last few decades grain kinematics have become increasingly recognized as a critical component in the comprehensive explanation of the sediment transfer process in gravel-bed rivers (e.g., Wong et al., 2007) and the control these transfers exert over the evolution of river landscapes (e.g., Stark et al., 2009). A key process is sediment dispersion, which is accomplished through the collective movement and storage of the grain size ensemble (Church and Hassan, 1992; Wathen et al., 1997; Pyrce and Ashmore, 2003b) that distributes grains downstream. Advancing the capability to model sediment dispersion requires improved understanding of grain displacement (Ganti et al., 2010) so the process can be accurately incorporated into the increasingly sophisticated mathematical models of river channels and their evolution.

Early attempts to model sediment dispersion are grounded in the fundamentals of grain step length and rest period (Einstein, 1937; Hubbell and Sayre, 1964). For example, using the assumption that steps of variable length and rest periods of different duration are both described by exponential density functions (Fig. 1a) along with conditional probability, Hubbell and Sayre (1964) derived a function that describes the spatial concentration of grains over time as

$$f_t(x) = k_1 e^{-(k_1 x + k_2 t)} \sqrt{\frac{k_2 t}{k_1 x}} I_1\left(2\sqrt{k_1 x k_2 t}\right)$$

where $f_t(x)$ = density function for distance x at time t, k_1 and k_2 = coefficients that are equal to the inverses of the mean step length and mean rest period, respectively, and I_1 = modified Bessel function of the first kind of order one. This model is equivalent to the one derived by Einstein (1937). A key issue in using this dispersion model is establishing the mean step length and rest period of the specified probability density function.

Taking a different approach, Ganti et al. (2010) developed a modeling framework for mixed size gravel dispersion based on the stochastic Exner equation, which is given as

$$\left(1-\lambda_p\right)\frac{L_a}{E_b}\frac{\partial f_a(x,t)}{\partial t} = \int_0^\infty f_a(x-l,t) f_s(l) dl - f_a(x,t)$$

where λ_p = porosity, L_a = thickness of the active layer, E_b = volume rate per unit area of entrainment of bed load particles, f_a = fraction of tracer particles in the active layer, f_s = probability density function of step lengths, l = length of steps, x = streamwise coordinate, and t = time. Based on model simulations lasting 500 days, a thin-tailed exponential distribution of step lengths produced a much slower rate of dispersion compared to a heavy-tailed generalized Pareto distribution (Fig. 1b). Thus, a key outcome of this work is that gravel dispersion depends on the probability function used to model the step lengths of the grains and, in turn, this function determines the rate of dispersion.

Both modeling approaches rely on models for the statistical distribution of grain displacement represented by individual steps and rests. Based on flume experimentation, the exponential function initially proposed by Einstein (1937) has found some subsequent confirmation (e.g., Nakagawa et al., 1982; Martin et al., 2012) but the gamma function (Fig. 1c) has also emerged as an alternative (e.g., Yang and Sayre, 1971; Stelczer, 1981). Although laboratory investigations can provide valuable insights into the details of the grain

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* Tel.: +1 210 458 4553.
E-mail address: judy.haschenburger@utsa.edu.

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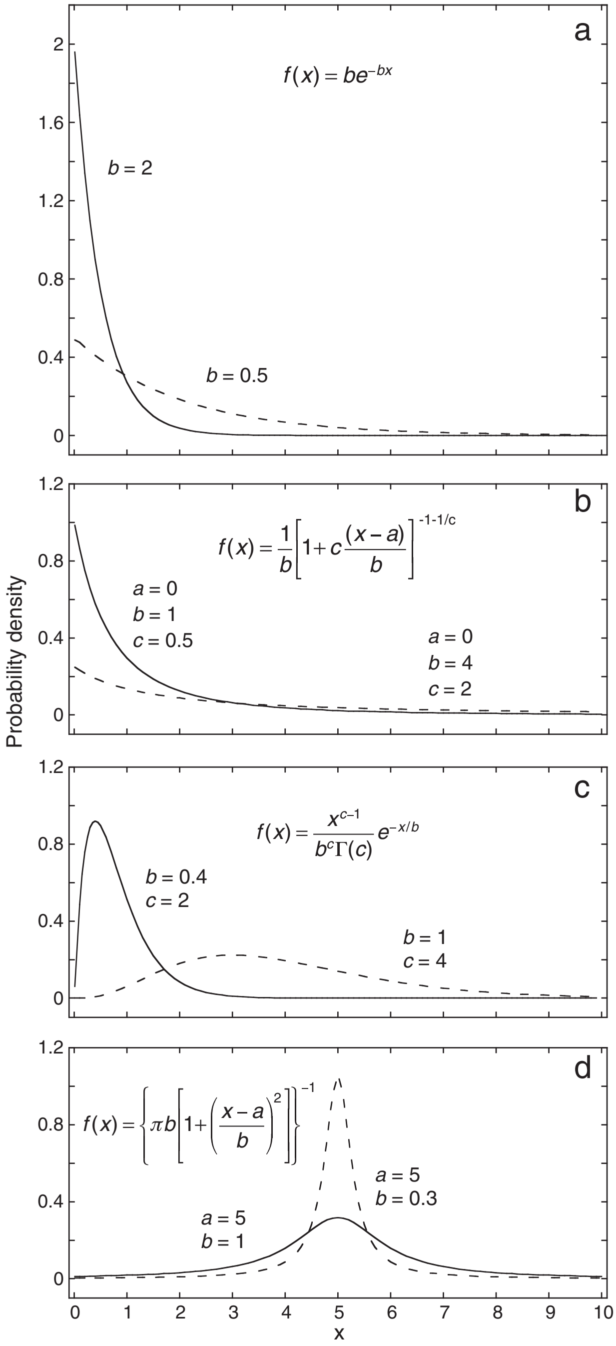

Fig. 1. Probability density functions used to characterize grain displacement. (a) Exponential, (b) generalized Pareto, (c) gamma, and (d) Cauchy. Values of location parameters are given by *a*, scale parameters by *b*, and shape parameters by *c*. Generalized Pareto presented with condition $c \neq 0$.

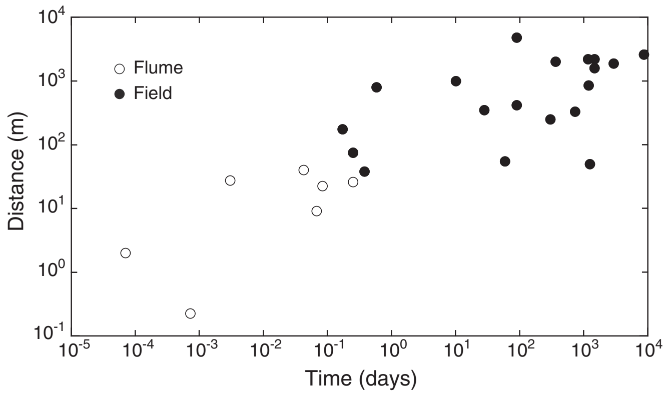

Fig. 2. Spatial and temporal scales of tracing studies drawn from flume and field investigations. Spatial scales are defined by the maximum grain displacement reported or total length of flume or study reach. Temporal scales are delineated by the maximum run times in flume experiments, monitoring times for real-time tracking of field tracers, and elapsed time for passive tracer field studies, either reported or estimated, because competent flow durations are not typically reported. Selected studies (Einstein, 1937; Leopold et al., 1966; Laronne and Carson, 1976; Butler, 1977; Mosley, 1978; Stelczer, 1981; Arkell et al., 1983; Kondolf and Matthews, 1986; Schmidt and Ergenzinger, 1992; Hattingh and Illenberger, 1995; Schmidt, 1995; Sear, 1996; Hassan et al., 1999; Habersack, 2001; Ferguson et al., 2002; Pyrce and Ashmore, 2003a; McNamara and Borden, 2004; Ancey et al., 2006; Wong et al., 2007; Lamarre and Roy, 2008; Hill et al., 2010; Haschenburger, 2011a; Bradley and Tucker, 2012; Liébault et al., 2012; Martin et al., 2012) provide a range in scales rather than constituting a comprehensive compilation of tracing studies.

displacement process, the observations are limited to the length scale of the specific flume and the time scale defined by the speed at which grains move over that distance. Based on a selection of flume tracing studies, maximum spatial and temporal scales equal 40 m and 2 h, respectively (Fig. 2), a short distance and time period compared to typical bedload transport events in natural channels. Moreover, limitations to flow shear stresses relative to sediment mixture characteristics further constrain the range of conditions over which the statistical distributions of steps and rests have been investigated to develop probability functions.

Advances in monitoring technology have facilitated field observations of step lengths and rest periods, with the probability models revealed as being either exponential or gamma (Ergenzinger and Schmidt, 1995; Habersack, 2001; McNamara and Borden, 2004) and, thus, falling generally in line with flume results. Although more realistic observations can be gained by working in channels, because of the naturally water worked streambeds and enlarged spatial scales, field observations are still limited by sample size, which is typically less than 20 clasts, and the duration and range of grain sizes tracked, especially when considered in the context of the stochastic nature of grain displacement. This reflects, in part, the cost and time involved as well as the inherent challenges of flood-based fieldwork. Overall, the paucity of field observations on step lengths and rest periods and a failure to establish generalized relations between hydrologic forcing, channel characteristics, and resulting displacement patterns leave modelers with little guidance from which to generalize the process of grain displacement.

Using step lengths and rest periods to model dispersion necessarily involves scaling up to describe the spatial and temporal scales that are relevant when modeling longer channel reaches over time. Alternatively, it may be advantageous to work directly at a larger scale (Church, 1996) using grain path lengths, which define the total grain displacement achieved by a specified time period (Einstein, 1937) and typically consist of multiple steps and rests. Based on flume observations, exponential and Cauchy functions (Fig. 1d) depict distributions of path lengths (Pyrce and Ashmore, 2003a; Hill et al., 2010). Because of the spatial and temporal constraints of flume experiments, the proposed generalized Pareto function that builds on flume results (Hill et al., 2010) may not characterize path lengths in natural channels.

Short-term field studies reveal that gravels starting from the bed surface are, at times, fitted by the exponential, gamma, and generalized Pareto distributions as well as the compound Poisson model of Einstein–Hubbell–Sayre (e.g., Hassan et al., 1991; Schmidt, 1995; Bradley and Tucker, 2012; Liébault et al., 2012) when individual floods are considered. A reanalysis of field data (Pyrce and Ashmore, 2003b), however, shows a broader range in the shape of path length distributions and a likely control of bed morphology on dispersion, which has been assumed previously in efforts to quantify sediment transfers through morphological approaches (Neill, 1987; Ashmore and Church, 1998).

The reanalysis by Pyrce and Ashmore (2003b) raises two significant points for modeling. First, the body of field evidence raises a question