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Coupling fine particle and bedload transport in gravel-bedded streams

Jungsu Park [1], James R. Hunt [2,*]

Department of Civil and Environmental Engineering, University of California at Berkeley, Berkeley, CA 94720, USA

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ABSTRACT

Fine particles in the silt- and clay-size range are important determinants of surface water quality. Since fine particle loading rates are not unique functions of stream discharge this limits the utility of the available models for water quality assessment. Data from 38 minimally developed watersheds within the United States Geological Survey stream gauging network in California, USA reveal three lines of evidence that fine particle release is coupled with bedload transport. First, there is a transition in fine particle loading rate as a function of discharge for gravel-bedded sediments that does not appear when the sediment bed is composed of sand, cobbles, boulders, or bedrock. Second, the discharge at the transition in the loading rate is correlated with the initiation of gravel mobilization. Third, high frequency particle concentration and discharge data are dominated by clockwise hysteresis where rising limb discharges generally have higher concentrations than falling limb discharges. These three observations across multiple watersheds lead to a conceptual model that fine particles accumulate within the sediment bed at discharges less than the transition and then the gravel bed fluidizes with fine particle release at discharges above the transition discharge. While these observations were individually recognized in the literature, this analysis provides a consistent conceptual model based on the coupling of fine particle dynamics with filtration at low discharges and gravel bed fluidization at higher discharges.

1. Introduction

The transport of fine particles in surface waters is an important topic within the earth and ecological sciences, in the practice of water resources engineering, and within multiple environmental regulatory agencies. Fine particles are defined here as silt, clay and sub-micrometer-sized particles that are transported as suspended particles in surface waters but can accumulate in sediment beds. The earth science community is interested in the release of fine particles from landscapes as a consequence of weathering reactions, and erosive forces ultimately leading to the rates of particle accumulation in sedimentary basins within lakes, coastal zones and the deep ocean (McCave et al., 2001; Paola et al., 2006). Within streams the sediment composition determines ecological habitat where fine particles can block pore spaces in sand and gravel sediments reducing hyporheic exchange of oxygen, nutrients, and organic matter (Packman and MacKay, 2003). However, in estuarine systems, fine particles are essential in the maintenance of mudflats, wetlands, and local redox gradients at the sediment-water interface that determine biogeochemical cycles of carbon, nitrogen, and trace metals (Wolanski, 2007). Water resources managers are interested in fine-sediment transport in streams to measure soil loss from agricultural land, estimate downstream reservoir sedimentation, quantify the transport of particle-associated contaminants (MacArthur et al., 2008) and evaluate costs in the operation of drinking water treatment facilities (Heberling et al., 2015). Receiving water quality is impaired by fine particles and there is continuing regulatory interest in quantifying fine particle loading rates from watersheds through the United States' Clean Water Act, the European Union's approach to environmental quality through the Water Framework Directive, and initiatives in other countries (Bilotta and Brazier, 2008). In spite of the importance of fine particles within watersheds there remains considerable uncertainty in quantifying water quality impacts as well as distinguishing natural from anthropogenic contributions (Horowitz, 2013).

Given the importance of particle transport within surface waters, there has been a steady evolution in analysis methodologies. Prior to the 1940s, fine particle and coarse sediment transport were addressed almost exclusively through field and laboratory measurements. Those data sets led to the development of steady-state bedload transport relationships utilizing either an empirical, dimensionally consistent approach (Meyer-Peter and Muller, 1948)

* Corresponding author.
E-mail addresses: pjs7731@gmail.com (J. Park), JRHunt@berkeley.edu (J.R. Hunt).
[1] Present address: 200 Sintanjin-Ro, Daedeok-Gu, Daejeon, K-water, South Korea.
[2] Present address: 121 Carrot Island Lane, Beaufort, NC 28516, USA.

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or conceptual models based on transport by either a bedload layer (Einstein, 1950) or via siltation (Bagnold, 1956) as summarized by García (2008). At the field-scale the transport rates of silt and smaller-sized particles were not single-valued functions of discharge unlike larger-sized bed sediments (Einstein et al., 1940; Johnson, 1943; Einstein and Chien, 1953). These observations resulted in a bifurcation in modeling approaches with a more fundamental treatment of bedload transport for sand and larger-sized sediments in contrast to an empirical analysis of fine-particle or washload transport.

Since fine-particle releases from watersheds were not single-valued functions of discharge, site specific monitoring programs were adopted to determine particle loading rates. With increased societal demands for quantification of soil erosion rates, nutrient losses from agricultural lands, and the transport of other contaminants associated with fine particles, extensive monitoring programs were initiated through simultaneous measurements of suspended particle concentration, discharge and sometimes particulate carbon and phosphorus concentrations (Hjulström, 1935; Walling, 1977; Verhoff and Melfi, 1978; Leonard et al., 1979; Bilby and Likens, 1979; Meyer and Likens, 1979). Data collection at the daily scale and often more frequently was necessary to resolve the dynamics of suspended particle concentration during flood events (Walling, 1977), although doubts remain on the ability of monitoring programs to generate the data needed for predictive modeling over time within a watershed and for scaling those models to other watersheds (Horowitz, 2013).

Translating field observations of fine particle concentration into predictive relationships is constrained by mechanistic uncertainties in the empirical models. The data on particle concentration (C) and discharge (Q) are often plotted as C vs. Q and referred to as a sediment rating curve. Since loading rate ($Q_s = CQ$) is usually desired, a power law representation of the empirical data is generally adopted of the form

$$Q_s = aQ^b$$

where a and b are empirical coefficients. Fig. 1 illustrates a typical situation, in this case for daily data over multiple years for Redwood Creek at Orick, California. Researchers have expressed reservations about power-law approaches from the beginning because of the vertical scatter in the data (Leopold and Maddock, 1953; Walling, 1974) and the nonlinearity of the log transformed data (Leopold and Maddox, 1953; Müller and Förester, 1968; Nash, 1994; Warrick, 2015). Alternative representations of particle loading as a function of discharge have utilized empirical curve fitting based on nonlinear, log-transformed data (Crowder et al., 2007) or on locally weighted scatter smoothing (LOWESS) (Hicks et al., 2000; Gray et al., 2014). Multi-variable statistical models have attempted to improve model representation through incorporation of season, antecedent conditions, baseflow prior to the flood event, and the rate of change in flow rate during flood events (e.g. Guy, 1964; Walling, 1974; Alexandrov et al., 2009; Gellis, 2013). Alternative methodologies based on time series analysis and machine learning techniques are fitted to the data but these approaches do not provide predictive relationships (Sharma et al., 1979; Zhang et al., 1989; Francke et al., 2014). Empirical approaches often qualitatively attribute variables to specific mechanisms, but process representation of fine particle generation, accumulation, and transport within watersheds has not been quantitative.

There is variability in the loading rate for a given discharge, likely due to event, seasonal (Alexandrov et al., 2007; Cantalice et al., 2013) and inter-annual or even decadal scale (Warrick, 2015; Gray et al., 2015) changes in the channel or watershed system. The event scale scatter is mostly from the hysteresis in the relationship of suspended particle transport rate to discharge

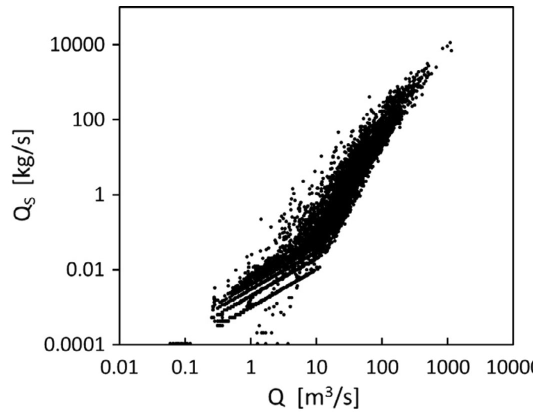

Fig. 1. Particle loading rate, Q_s, vs. flow rate, Q, based on daily data at Redwood Creek at Orick for the period of March 1970 to April 2001.

which caused by the difference in suspended particle concentrations during the rising and the falling limb of flood hydrographs. There are various possible explanations for the hysteresis such as different travel times of peak water discharge and peak suspended particle load (Bača, 2008; Megnounif et al., 2013), dilution of suspended particle concentration by baseflow (Walling and Webb, 1982), differences in water surface slope between rising and falling limb of a flood event, and the exhaustion of fine particles available for transport within the watershed (Wood, 1977; Walling, 1974; Carling, 1983). Thus, various patterns of hysteresis loops (clockwise, counterclockwise, figure eight, and straight line etc.) are observed in the relationship of suspended particle loading rate to discharge during individual flood event (Williams, 1989). For example, clockwise hysteresis is observed when sediment particle peak arrives before the water discharge peak while counterclockwise hysteresis is observed when the water discharge peak arrives earlier than suspend particle peak (Williams, 1989). For example, Bača (2008) observed predominantly counterclockwise hysteresis in the relationship between Q_s and Q in his field study in Rybárik, a small watershed in western Slovakia, and attributed counterclockwise hysteresis to sediment supplied from distant sources such as hillslopes. The variation of the hysteresis patterns are also often qualitatively attributed to various sources of the fine particles within the watershed such as local bed sediments, stream banks, flood plains, nearby tributaries, or distant hillslopes (Wood, 1977; Williams, 1989; Nistor and Church, 2005). The relationship of suspended load rate to discharge is also affected by longer scale (e.g. seasonal and inter-annual or decadal) variations of sediment dynamics in channel system. Depletion of sediment by the earlier floods (Cantalice et al., 2013) and increased discharge by snowmelt (Stubblefield et al., 2009) also affect seasonal changes in suspended particle dynamics. Furthermore, anthropogenic activities such as agriculture and events such as wildfires also alter suspended particle loading rate at given discharge (Gray et al., 2016). Thus, a number of factors at the event, seasonal, and decadal scales will alter the relationship between discharge and suspended particle load for a given flood event, making it difficult to model these relationships. Yet, empirical power-law models have parameterized these observations through the inclusion of season, flood magnitude, the time interval between flood events, the rate of change in flow rate, the imposition of fine particle source terms within the watershed, and even parameter association to individual flood events (VanSickle and Beschta, 1983; Asselman, 1999; Doomen et al., 2008; Mather and Johnson, 2014).

Empirical particle loading rate expressions are often needed to extend models to extreme conditions and to ungauged watersheds both for fine particles and particle-associated nutrients. When