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Modeling temporal trends in bedload transport in gravel-bed streams using hierarchical mixed-effects models

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ABSTRACT

In this paper, we used a bedload transport data set collected at North Fork Caspar Creek, California, to examine temporal variation in sediment transport rate over a 7-year period. Using a hierarchical mixed-effects model, we examined across and within-event variation to determine whether the bedload–shear stress relation trends over time. The relation between bedload transport and shear stress was modeled using $\log(Q_b) = \alpha + \beta^{*}\log(\tau) + \varepsilon$, where α and β are constants and ε is an error term. Depending on the length of observation, α and β can vary over several orders of magnitude, making modeling of transport based on flow challenging and highly inaccurate. We found a higher order yearly relation between bedload and shear stress, indicating systematic changes to the system over time. In the absence of significant additions to the system, α decreases roughly linearly over time, while β does not show any trend. From the systematic decline in α, we infer changes to sediment availability in the stream over time. Mixed-effects models have the potential to be a useful predictive tool in fluvial geomorphology, as they are more powerful at detecting trends in sediment transport rates than individual linear regressions.

1. Introduction

Over the last three decades increased attention has been devoted to the study of erosion, sediment transport, and deposition in gravel-bed streams. The interest in the topic has been motivated by the importance of sediment transport and channel stability for river management, aquatic habitat, and river restoration. In spite of a large body of research on sediment transport, however, there is no agreement on an appropriate governing equation for the estimation of sediment movement in stream channels. In part, this is caused by temporally and spatially variable fluid forces, bed surface structures and armoring, and episodic changes in sediment supply and storage, all of which play important roles in controlling channel stability and regulating sediment transport (e.g., Hassan et al., 2008; Pryor et al., 2011).

In gravel-bed streams, the fluid shear stress on the bed is mostly near the threshold for sediment entrainment and rarely exceeds twice the critical value for mobilizing sediment during sediment transport events (Parker et al., 1982). Small variations in the flow and bed surface composition may cause large fluctuations in sediment transport rates (e.g., Paintal, 1971; Church et al., 1991; Recking, 2013). Furthermore, field and flume data under steady flow show a wide scatter in the relation between hydraulic parameters and sediment transport rates (e.g., Gomez and Church, 1989). Within individual storm events, marked fluctuations in sediment transport rates have been observed (e.g., Hayward, 1980; Hoey, 1992; Warburton, 1992; Moog and Whiting, 1998; Whiting et al., 1999). In most cases, peak bedload transport rates do not correspond directly with peak discharge (Reid et al., 1985; Adenlof and Wohl, 1994). Temporal and spatial variation in sediment transport rates have been attributed to heterogeneity in sediment (e.g., texture, sorting, and shape), bed surface structures (e.g., pebble clusters, cells), bed morphology, flow turbulence (fluctuations in near bed velocity), and interactions among these factors (e.g., Ashworth and Ferguson, 1987).

The traditional approach to sediment transport has focused on the relations between sediment transport rate and hydraulic variables such as discharge, however, field observations suggest that sediment transport rate may not always be directly related to flow discharge because of the major role of sediment supply (e.g., Hassan et al., 2008). During low flows, scour and fill in streams are localized (e.g., Carling and Hurley, 1987), most of the bed remains intact, and mainly sand and fine gravel are transported (e.g., Jackson and Beschta, 1982; Ashworth and Ferguson, 1987; Hassan and Church, 2000). At intermediate flows, larger particles are entrained but a large proportion of the coarse fractions are partially mobile (i.e., less than their proportion in the bed) (Ashworth and Ferguson, 1987; Wilcock and McArdell, 1993, 1997). At the highest flows, full mobility conditions may prevail and almost all sizes are mobile in its proportion in the bed (Parker et al., 1982; Wilcock and McArdell, 1993, 1997).

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A common method for prediction of sediment transport rates uses hydraulically based functional relations that are based on theoretical principles and/or empirical correlations. The most frequently used deterministic approach is based on fixed values for model parameters yielding a single outcome (Schmelter and Stevens, 2013). This approach can result in more than an order of magnitude difference between the measured and calculated sediment transport in streams (Gomez and Church, 1989). These discrepancies have been explained by the dynamic nature of bed surface structures and armoring (Church et al., 1998), sediment supply and storage differences between entrainment and distrainment thresholds, and sediment mobility. Bed state (Hassan and Church, 2000; Pryor et al., 2011) and sediment storage play an important role in regulating sediment transport and channel stability and are hence the focus of the current research (Lisle and Church, 2002; Church, 2006).

The stochastic method is another approach that is based on assigning probability density distributions to model parameters (Schmelter and Stevens, 2013). The advantage in using such a model is the ability to represent the uncertainty of the underlying fixed parameter assumptions (Schmelter and Stevens, 2013). An example of the stochastic approach is Einstein's (1937) pioneering work on probability of particle dispersion in streams. Similar approaches were developed by Hamamori (1962) and Turowski (2010). Bayesian statistics is another approach that has been used to model channel morphology (Griffiths, 1982), sediment entrainment (Wu and Chen, 2009), sediment transport (Schmelter et al., 2011), and sediment budgeting (Schmelter et al., 2011). In a recent paper, Schmelter and Stevens (2013) discussed the use of a Bayesian approach to model sediment transport in streams highlighting advantages of using such an approach.

Bedload data often are limited to few events, and the lack of long-term measurements limits our ability to study temporal variation in the bedload–shear stress relations. The 7-year data set collected at North Fork Caspar Creek, California, provides an opportunity to study temporal variations in bedload transport. In this paper, we use a hierarchical mixed-effects model to determine whether bedload–shear stress relations show trends over time. We use this class of linear model to show that event-to-event variation in the bedload–shear stress relation can be modeled over a period of observation.

2. Study area

The study was conducted in Caspar Creek in Jackson Demonstration State Forest near Fort Bragg, California (Fig. 1). Established in 1961, the watershed is a research site for the evaluation of the impacts of timber harvesting on erosion, streamflow, and sedimentation. The watershed is unique in providing long-term hydrological and geomorphological data on channel dynamics in response to changes in land use and climate variability (Ziemer, 1998).

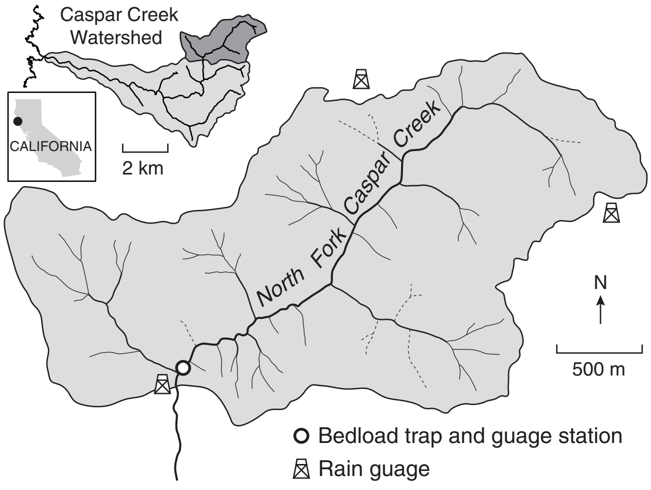

Fig. 1. Caspar Creek Experimental Watersheds, study site and gauge locations.

Caspar Creek drains an 8.97 km^2 (4.73 km^2 North Fork and 4.24 km^2 South Fork) watershed dominated by Mediterranean climate typical of low-elevation terrains of the Pacific Northwest (Ziemer, 1998). The watershed is carved into uplifted marine terraces underlain by a coastal belt of the Franciscan Formation of Cretaceous age, consisting locally of interbedded sandstone and shale. The soils in the watershed are clay loam and 1–2 m in depth. The watershed is dominated by second-growth coast redwood (*Sequoia sempervirens* (D. Don) Endl.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.) (Ziemer, 1998). Over 90% of the precipitation falls between October and April during low-intensity rain storms. The summer is typically dry. Annual precipitation ranges between 300 and 2000 mm with a mean value of 1190 mm for the period 1962–1997. Flow data are available since 1962. Annual floods in the North Fork Caspar Creek for the period 1962–1995 ranged in magnitude between 0.76 and 8.61 m^3 s^{-1} with a mean annual flood of about 4 m^3 s^{-1}. Flows with recurrence interval of 10 and 50 years have a peak discharge of 7 and 10 m^3 s^{-1}, respectively. Near the headwaters, channels are incised into bedrock and saprolite in steeper valleys. Channel longitudinal profiles alternate between steep and low gradient reaches. Sand, silt, and gravel dominate alluvial fill in confined valley bottoms (Ziemer, 1998).

The North Fork Caspar Creek channel at the study reach is single-thread with plane-bed and riffle-pool segments (Lisle and Napolitano, 1998). The channel is strongly affected by large wood, which creates jams, scour holes, and alluvial deposits. The bankfull channel has an average width of 5.2 m and depth of 0.48 m; channel gradient is 0.0123. The bed of the channel typically consists of a thin (<0.5 m) layer of cobbles, gravel, and finer material overlying bedrock. Much of the bed consists of a framework of subangular lag material of coarse cobbles that is derived from streamside landslides and debris flows. Alluvial bars of rounded pebble gravel and sand overlie the lag material upstream and downstream of logjams and in reaches widened by bank erosion. Bars furnish the bulk of bedload material during peak flows. Fine bedload (sand and fine gravel) is stored in pools and mobilized during lower winter flows. Otherwise, the channel is generally armored; the median size of the surface and subsurface material are 12 and 7 mm, respectively (Fig. 2). Most of the mobile material is delivered from upstream

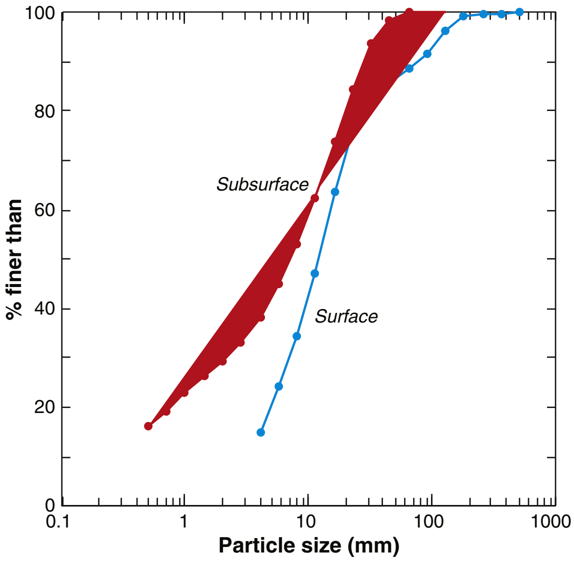

Fig. 2. Size distributions of surface and subsurface bed material in the study site of North Fork Caspar Creek.