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Research paper

Predicting bed load transport of sand and gravel on Goodwin Creek

R.A. Kuhnle*, D.G. Wren, E.J. Langendoen

National Sedimentation Laboratory, U.S. Department of Agriculture, Agricultural Research Service, Oxford, MS 38655, USA

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Abstract

Bed load transport rates are difficult to predict in channels with bed material composed of sand and gravel mixtures. The transport of bed load was measured on Goodwin Creek, and in a laboratory flume channel with a similar bed material size distribution. The range of bed load transport rates measured in the laboratory channel were similar to those measured in the channel of Goodwin Creek; however, the shear stresses calculated on Goodwin Creek were three times greater than in the laboratory channel for similar bed load transport rates. Much of this difference in shear stress was removed by applying the drag partitioning technique of Einstein, although significant differences between the two sets of data remain. Predictions of bed load transport rates using three previously published transport relations were good for most flows for the laboratory data. For the Goodwin Creek bed load data, predicted transport rates were close to measured ones for low flows but diverged by an order of magnitude or more for high shear stresses. Improved methods of shear stress partitioning are needed to improve the performance of bed load transport relations on streams of this type.

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Keywords: Bed load; Grain shear stress; Sand; Gravel

1. Introduction

Experimental watersheds have been operated by the United States Department of Agriculture, Agricultural Research Service (USDA-ARS) for many years. The goals of these watersheds are to understand the movement of water, sediment, nutrients, and other chemicals through the watershed and to determine the impact of the activities involved with agriculture on the movement of these substances through the watershed. Perhaps the most difficult part of determining the sediment load in streams is the determination of an accurate rate for the load moving in contact with the bed. The bed load is generally a small fraction of the total sediment load of streams but serves as an important control on the stability of the channel boundaries and the lands adjacent to the channels. Accurate prediction of the movement of bed material in agricultural watersheds remains elusive, yet knowledge of the rate of bed material transport is critical to determining accurate total sediment load and for predicting the stability of channel banks, which have been shown to be major sources of sediment in many watersheds (e. g. Grissinger et al., 1991; Kuhnle et al., 1996; Wilson et al., 2008).

Goodwin Creek experimental watershed (GCEW) drains an area of 21.3 km^2 (Fig. 1) in Panola County, Mississippi, and has been operated by personnel from the USDA-ARS, National Sedimentation Laboratory since 1981. The watershed is located in the bluff-hills region of the Yazoo River basin just east of the Mississippi River alluvial flood plain. Elevation ranges from 71 to 128 m above sea level, and the average slope of the main channel is 0.004. Supercritical flow flumes, which provide a stable platform for measuring flow rates and sampling sediment during runoff events, have been positioned at 14 subbasins (Fig. 1) (Alonso and Binger, 2000). The bed material of the main channel is predominantly composed of sand in the upstream portions of the watershed (median diameter of 0.5 mm), has increasing amounts of gravel in the middle portion (median diameter of 7 mm), and has progressively less gravel (median diameter of 1 mm) in the downstream part of the watershed (Kuhnle, 1996). The fraction of

* Corresponding author.
E-mail address: roger.kuhnle@ars.usda.gov (R.A. Kuhnle).

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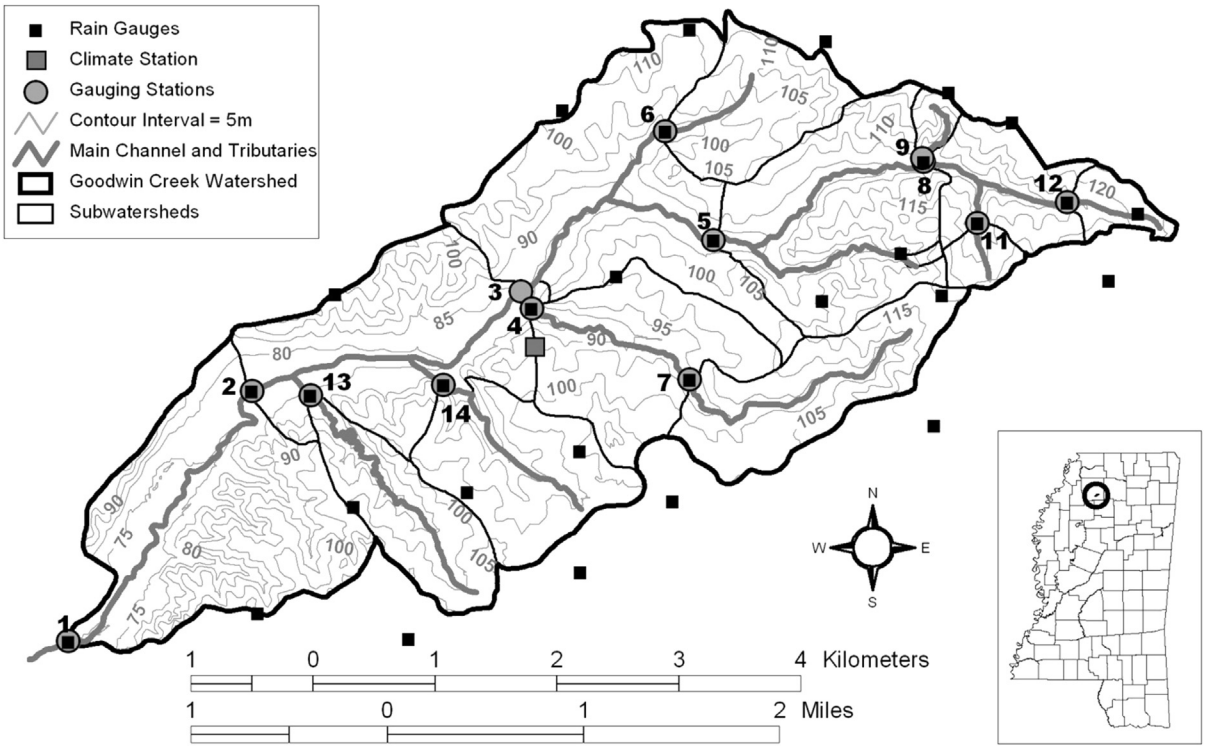

Fig. 1. Map of Goodwin Creek experimental watershed.

sand in the bed of a channel has been shown to have a major effect on the transport rate of the sand-gravel mixture (Iseya and Ikeda, 1987; Curran and Wilcock, 2005).

During the past several years, there have been a number of studies focusing on the challenges of measuring and calculating the transport of bed load on streams with bed material consisting of sand and gravel (McLean et al., 1999; Kleinhans and Ten Brinke, 2001; Habersack and Laronne, 2002; Bunte et al., 2004; Claude et al., 2012). These studies have made progress on the measurement of long-term changes in bed load (McLean et al., 1999), on characterizing error in bed load measurements (Kleinhans and Ten Brinke, 2001), and on the methodology for collecting representative data sets of bed load (Bunte et al., 2004; Habersack and Laronne, 2002; Claude et al., 2012). Streams in which the bed material has well defined modes in the sand and gravel sizes often have a range of flows in which sand is the dominant size of the bed load. As flow strength increases the bed load generally becomes progressively coarser as the gravel size fractions become entrained (e.g. Kuhnle, 1992; Recking, 2010). The sand and gravel modes in the bed material can cause the sampler to over-sample at lower flows due to the scouring of sand from the bed near the sampler intake (Potyondy et al., 2010). The sand and gravel modes also make accurate predictions of the bed load rate difficult because more than one grain size is necessary to characterize the bed (Claude et al., 2012). Research has been conducted by several workers to improve bed load transport rate predictions for streams with sand and gravel in the bed material without having to individually calculate the transport rate of multiple size fractions (e.g. Kuhnle, 1992; Wilcock, 1998; Recking, 2010). Success in this endeavor has been mixed.

One of the key goals for the GCEW has been to measure and predict total sediment load from the channels of the watershed. Rates of bed load transport have been one of the most difficult of the sediment fractions to measure and predict accurately. The purpose of this study was to collect bed load data under controlled conditions in a laboratory flume to improve our understanding of the problems with the prediction of sand and gravel transport in streams of the GCEW. This series of experiments, while designed to model conditions specific to Goodwin Creek, will also provide information on how to predict transport rates on other streams with sand and gravel bed material.

2. Field data

The samples considered here were collected at station 2 (Fig. 1), which drains 17.9 km^2 of the watershed. The channel at station 2 is 25 m wide and 3 m deep, and the bed material surface and subsurface layers have median grain diameters (D_{50}) of 11.7 and 8.3 mm, respectively (Kuhnle, 1992). Mean slope of the channel bed upstream from station 2 is 0.003. Samples of the bed load were collected within a concrete "V"-shape flume with a 4% longitudinal slope, which causes local supercritical flow and prevents sediment deposition on the structure. The V-section of the flume is compound with 5:1 side slopes for 4.7 m each side of the center and 2:1 slopes thereafter. Samples of bed load were collected from a footbridge over the upstream edge of the supercritical flow flume

using a modified version of the Helley-Smith (MHS) sampler (Helley and Smith, 1971) mounted on a rigid streamlined strut.

The entrance nozzle of the MHS samplers was redesigned from a 7.62 cm square to a parallelogram shape with a 5:1 bottom slope to rest firmly on the concrete sloping floor surface of the supercritical flow flume without any void area beneath the sampler (Bowie and Sansom, 1986; Willis et al., 1986). The areas of the inlet and outlet orifices on the MHS samplers were the same as on the original Helley-Smith sampler with an area expansion ratio of 3.54. Laboratory tests have established that the hydraulic efficiencies of the MHS and the original Helley-Smith sampler were about 1.5 for mid to higher flows (Druffel et al., 1976; Kuhnle, 1992). Several workers have reported evidence for oversampling by the original Helley-Smith sampler (Hubbell et al., 1985; Pitlick, 1988; Bunte et al., 2004); however, it has also been shown that if a Helley-Smith sampler is used on a non-erodible bottom, the tendency to oversample is minimized or eliminated (Emmett, 1980; Potyondy et al., 2010). Since the bed load samples collected with the MHS sampler on Goodwin Creek were collected on the non-erodible concrete surface of the supercritical flow flume, it was assumed that the bed load samples were representative of the bed load transport at the time of sampling.

To relate the flow strength to the sampled bed load, bed shear stress (τ_b) was calculated from a 106-m long straight reach 63-m upstream of the supercritical flow structure using a mean hydraulic radius (R) versus flow depth relation derived from 10 surveyed channel cross sections and water surface slope data measured over the reach. Bed shear was calculated from,

$$\tau_b = \rho g R S, \tag{1}$$

where ρ is the density of the water, g is the acceleration of gravity, and S is the slope of the water surface. Water surface slopes were calculated from four USGS-type bubble water-surface gauges located in a 91 m long section of the 106 m long surveyed channel reach (Kuhnle, 1992). Individual bed load transport rates from GCEW were calculated as weighted means from 1 to 4 samples collected across one half of the 1:5 sloping section of the flume over a short period of time (Fig. 2). It was assumed that the distribution of bed load was symmetrical around the centerline of the structure. Sampling yielded 488 individual samples of paired flow strength and mean unit bed load transport rate, which were collected over a period of 4 years from 1984 to 1988 and varied over several orders of magnitude for similar flows (Fig. 2; Kuhnle et al., 1989). All indications are that these large changes in transport rate for similar flows were due to the natural variability of the bed load transport process and not due to errors in the collection of the samples (Hubbell, 1987; Kuhnle and Southard, 1988; Kuhnle et al., 1989; Whiting et al., 1988). Average parameters for 5-*Pa* wide bins of shear stress were calculated for flows from 5 to 20 m^3/s (Table 1). These were the flow ranges where there were enough samples to identify representative mean values of unit transport rate and grain size distribution (Figs. 2 and 3). The mean grain size distributions of the bed load for each flow range were calculated as the average of the size distributions of the samples weighted by the mass of the samples.

Table 1
Mean conditions for Goodwin Creek bed load transport at station 2.

Sequence number	Flow discharge (m^3/s)	Flow depth (m)	Bed shear stress (Pa)	Mean bed load transport rate (kg/s m)	Median diameter of bed load (mm)
1	4.82	0.80	12.95	0.0021	0.52
2	8.79	1.04	17.33	0.0116	0.90
3	12.33	1.22	22.33	0.0574	1.60
4	14.80	1.36	27.37	0.1855	4.23
5	16.57	1.46	32.69	0.7462	8.06
6	18.89	1.57	36.99	0.7293	6.92

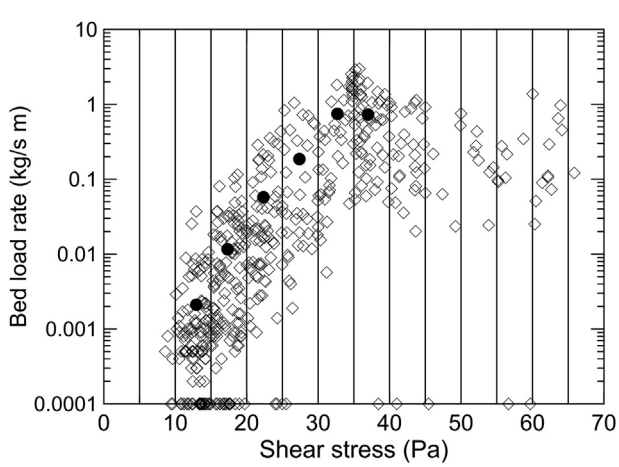

Fig. 2. Binned bed load transport data from Goodwin Creek, station 2. The solid circles represent the mean shear stress and transport rate for the respective bin.

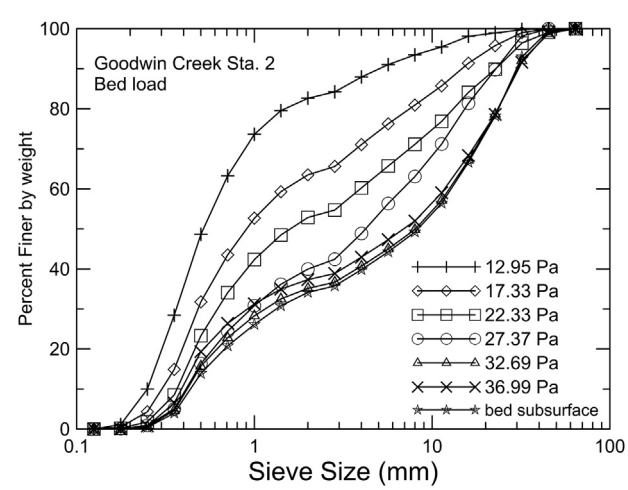

Fig. 3. Grain size distribution of bed load on Goodwin Creek near station 2. The size distributions were calculated as the weighted average for the samples in the bins of shear stress shown in Fig. 2. Shear stresses in the legend are average values for the samples in each bin.

Table 2
Characteristics of bed forms.

	Period (hr)	Height (m)	Migration rate (cm/s)	Spacing (m)
Goodwin Creek	0.20–0.68	0.08–0.24	0.4–1.0	5.28–19.65
Laboratory channel	0.075–0.58	0.019–0.033	0.9–3.0	7.07–17.84

Potential errors in the mean bed load transport rates on Goodwin Creek were estimated to be within 20 percent based on the work by Hubbell and Stevens (1986). The analyses conducted by Hubbell and Stevens indicated that approximately thirty traverses were required to reduce potential errors below 20 percent for cross sections with moderately non-uniform distributions of bed load. More than 30 samples were collected (ranging in number from 35 to 113) for each of the six flow ranges on Goodwin Creek (Fig. 2). According to the analyses by Hubbell and Stevens (1986), potential errors for each flow range were within 20 percent (Kuhnle, 1992).

Bed forms have been characterized for a wide range of flows using bed-height records collected from a set of four acoustic distance measurement sensors deployed on a tethered floating platform in the reach just upstream of the flow measuring structure at station 2 (Kuhnle and Derrow, 1998; Kuhnle et al., 2006). Distances between successive crests of the bed forms were generally about 70 times their height (Table 2). The period of bed forms was defined as the mean time between successive bed form crests as determined from bed height records. Most of the bed forms identified occurred under relatively low flow strengths due to the infrequency and extreme difficulty of collecting data during large runoff events. Smaller bed forms at the site have been classified as a form of pre-dunes, while the larger ones have been classified as dunes (Kuhnle et al., 2006).

3. Scale modeling considerations

When collecting bed load data in natural streams, many associated field variables cannot be well quantified, which makes strong conclusions of cause and effect difficult. The flow strength in the channel at Goodwin Creek was seldom steady, and information about the size distribution of the bed surface during bed load transporting flows was not available. Samples of the bed surface size distribution were collected after the stage returned to base flow following runoff events. There was an unknown amount of change from the size distribution of the bed surface during the different stages of the runoff event to its end. The availability of sediment sizes coming from upstream reaches and tributaries was also unknown in this study. Because information on bed material composition and upstream sediment supply is important for understanding bed load dynamics, which may, in turn enhance or aid in their prediction, it was decided to model the transport of bed load on Goodwin Creek under carefully controlled conditions in a laboratory flume.

Conventional scale models of streams are generally designed to be similar geometrically, kinematically, and dynamically (Pugh, 2008). Geometric similarity is achieved when the ratios of the dimensions of the model and field site are the same. In this study strict geometric similarity is not required, as only a vertical slice of the channel is being modeled. As long as the width of the model channel is several times the flow depth and the flow depth is significantly greater than the sediment size, it can be argued that a reasonable representation of a slice of a larger stream may be made.

Kinematic similarity is achieved when the ratios of velocities and accelerations between model and prototype are equal, while dynamic similarity is achieved when the ratios of the hydraulic forces caused by gravity, viscosity, pressure, surface tension, and elasticity in the model and prototype are equal. The ratios between the most important forces are represented by the Reynolds number (Re),

$$\mathrm{Re} = \frac{Uh}{\nu}, \tag{2}$$

and the Froude number (Fr),

$$\mathrm{Fr} = \frac{U}{\sqrt{gh}}, \tag{3}$$

where U is the mean flow velocity, h is the depth of flow, and ν is the kinematic viscosity of the fluid. Arranging to have both Reynolds and Froude numbers equal between the model and prototype is very difficult for reasonably sized models. However, in many situations it is not necessary to have Reynolds number similarity between model and prototype as long as the Reynolds number is above a minimum value to assure that turbulent flow exists in the model (Townsend, 1976; Flack et al., 2005). Equivalence of the Froude numbers between model and prototype was not required as long as both were in the sub-critical range (<1).

It is important for this study to insure that the forces involved in the transport of sediment were in the same range for the model and prototype. The motion of sediment occurs when the forces of the fluid on the sediment grains exceed the forces holding the grains in place. The weight of the grain and the friction angle required to move the grain combine to form the forces preventing motion of the particles, while the lift and drag forces of the moving fluid combine to create the forces which cause grains to move. Shields (1936) defined the following parameters:

$$\tau_c^* = \frac{\tau_c}{(\rho_s - \rho)gD} \tag{4}$$

$$R_* = \frac{u_* D}{\nu} \tag{5}$$

where τ_c is the critical shear stress for initiation of the bed material sediment, ρ_s and ρ are the density of the grains and fluid, respectively, D is the diameter of the sediment in the bed material, R_* is the boundary Reynolds number, and u_* is the shear velocity ($u_* = \sqrt{\tau_0/\rho}$). The first parameter (τ_c^*) approximately represents the ratio of the entrainment forces on a sediment grain to the forces keeping the grain stationary,

while the boundary Reynolds number describes the nature of the flow near the bed as a function of flow strength and grain size as related to the viscosity of the water. These parameters have been shown to yield a reasonable prediction of the initiation of motion of cohesionless grains under flowing water (e.g. Vanoni, 1975; Miller et al., 1977; Middleton and Southard, 1984; Buffington and Montgomery, 1997; Garcia, 2008). Although the depth and slope of the flume are smaller in the model, if the forces controlling the movement of the bed sediment grains, as represented by the Shields parameters, are the same for flows in the model and the field site, the flume should recreate the meso-scale characteristics of the field site and allow a controlled exploration of bed load transport in the laboratory that would be representative of the conditions at the field site. It was assumed that the flume channel provided a reasonable model of the transport of bed load through a slice of the channel at station 2 of Goodwin Creek.

4. Laboratory experiments

Experiments were conducted in a laboratory flume channel 30-m long by 1.2-m wide by 0.6-m deep located at the USDA-ARS National Sedimentation Laboratory during the fall and winter seasons of 2011 and 2012. Water and sediment were recirculated in all of the experiments. The bed material sediment used in the flume was obtained from Goodwin Creek and had a similar median size and spread of grain sizes as the channel at station 2 (Fig. 4). Depth of flow was measured as the difference between profiles of the bed and water surfaces measured with in-air and underwater acoustic distance measurement devices that were mounted on a motorized programmable instrument carriage that rode on stainless steel rods over the channel. Water surface slopes were determined as the sum of the slopes of the flume and the water surface relative to the stainless steel rods based on measured longitudinal water surface transects. Most of the flow discharge was driven by an in-line impellor pump in a 0.41 m diameter return pipe. The rest of the discharge traveled through 0.15 m diameter pipe and was driven by a centrifugal slurry pump. Flow discharge in the channel was measured using a calibrated Venturi meter and a calibrated elbow meter in the 0.41 m and the 0.15 m diameter pipes, respectively. The pressure differences from the Venturi and elbow meters were measured using pressure transducers recorded continuously on a personal computer during experiments.

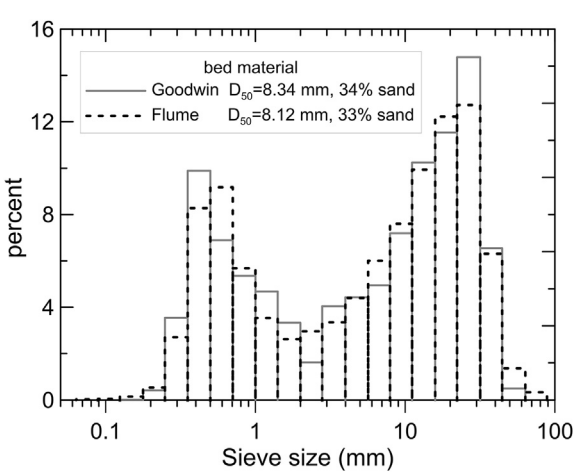

Fig. 4. Sediment size distribution of the bed material of Goodwin Creek and in the laboratory flume.

Bed load transport rate was measured using two drum devices suspended from load cells over a 1.2 m wide by 0.57 m long sediment trap. The outputs from the load cells were recorded at 1 Hz. After falling through the trap, the centrifugal slurry pump, which can pass gravel up to 100 mm in diameter, returned the gravel to the upstream end of the channel through a 0.15 m diameter pipe. Accumulation rates of the bed load were measured continuously except for intervals of 20 s after the drums had dumped the 30 kg of accumulated sediment into the trap which led to the slurry pump. The value of 20 s was determined empirically from the recorded data as a sufficient amount of time for the signal from the load cells to stabilize after dumping. Suspended sediment was defined as the sediment that overpassed the sediment trap and was sampled isokinetically from a 0.011 m diameter sampling port in the main return pipe just downstream of the pump and run through a 50 micron sieve. A sample of the sediment in transport was collected just before the end of the experiment by manually triggering the dumping of both drums and diverting the sediment and water mixture to a 3800-L tank. Water was replaced to the channel at the same rate it was diverted to maintain steady flow in the channel during the collection of the bed load sample. The mass of the bed load transport samples ranged from 27 to 102 kg.

Shear stress was calculated using the depth-slope product and was corrected for the effect of the sidewall using the method of Vanoni and Brooks (1957) and will hereafter be referred to as the bed shear stress (τ_b). Experiments were run for at least 8 h to ensure that the flow and bed had come to a steady-state before the collection of bed load transport data. Experiments with low shear stress and low bed load transport rates were run for proportionally longer times to make sure that the bed was at a steady condition. Bed load transport rates varied dramatically with time, similar to observations on Goodwin Creek. To ensure that transport rates were representative of the flow, means were calculated from load cell readings collected over at least 8-h. According to the study by

Table 3
Conditions in Laboratory experiments.

Run number	Flow discharge (m^3/s)	Flow depth (m)	Wall corrected bed shear stress (Pa)	Mean bed load transport rate (kg/s m)	Median diameter of bed load (mm)
1	0.215	0.246	4.149	0.0013	0.88
2	0.264	0.236	6.639	0.0146	0.89
3	0.285	0.234	7.732	0.0695	0.92
4	0.322	0.235	9.559	0.2205	1.48
5	0.367	0.234	10.257	0.3693	3.92
6	0.412	0.243	11.688	0.4494	4.96

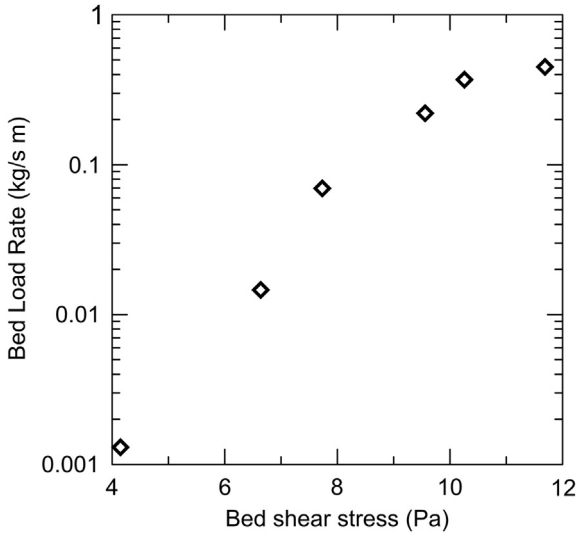

Fig. 5. Unit bed load transport rate versus bed shear stress for laboratory flume experiments.

Hubbell and Stevens (1986), the minimum of eight hours of near-continuous measurements of bed load transport across the entire channel-width used to calculate the mean bed load rates, indicates that the probable errors in mean bed transport rates are likely less than 10 percent.

5. Laboratory bed load transport data

Bed load transport data were collected after the establishment of equilibrium conditions from six different flow rates during experiments in the laboratory flume (Table 3). Flow depth was maintained at about 0.24 m in all experiments while bed shear stress ranged over a factor of 2.8 and mean bed load transport rate ranged over more than two orders of magnitude (Fig. 5). The range of unit bed load transport rates was similar to measured rates in Goodwin Creek; however, the range of bed shear stresses was substantially less. The bed load in the laboratory flume (Fig. 6) increased in particle size as the shear stress increased, similar to the trend in bed load particle size observed in Goodwin Creek. The size distribution of the bed load in the flume experiments approached the size distribution of the subsurface bed material, however; in contrast to Goodwin Creek, the maximum flow available in the flume was insufficient to mobilize all of the sizes present in the bed. The maximum particle size entrained in the flume was 41 mm in diameter.

Bed forms were detected in all of the experimental runs except the one with the lowest bed shear stress (run 1). Bed forms were measured using bed elevation data collected using two stationary underwater acoustic distance measuring devices during the experimental runs. The two transducers were 1.30 m apart in the streamwise direction, and data was collected for several hours during each of the experiments. Cross correlations were calculated for the paired bed elevation records. These were then used to calculate the period, migration rate and spacing using the techniques of Willis (1968). Heights were calculated as the mean difference between the local maximum and minimum heights from the bed elevation records. The bed forms observed in the laboratory were of similar length, spacing, and periodicity as those from Goodwin Creek, and the bed form height was approximately 1/10th of the flow depth in both the flume and the field channel (Table 2).

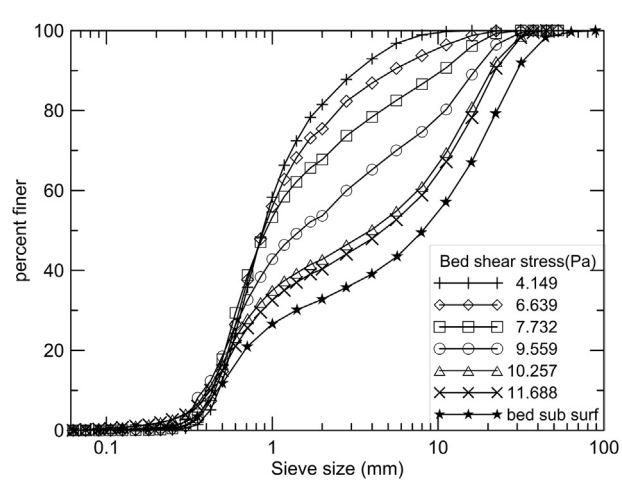

Fig. 6. Grain size distribution of the bed load for the flume experiments.

6. Comparison of field and laboratory bed load transport rates

The ratios of maximum to mean unit rates and sizes of bed load sediment were very similar for Goodwin Creek and the laboratory flume (Fig. 7). This indicated that the fluctuations of the transport in the two systems were similar; however, the values of the shear stresses were clearly larger for Goodwin Creek (Fig. 8). The relatively small transport rates, given the large shear stresses in the channel of Goodwin Creek, likely resulted from sources of drag that were not present in the

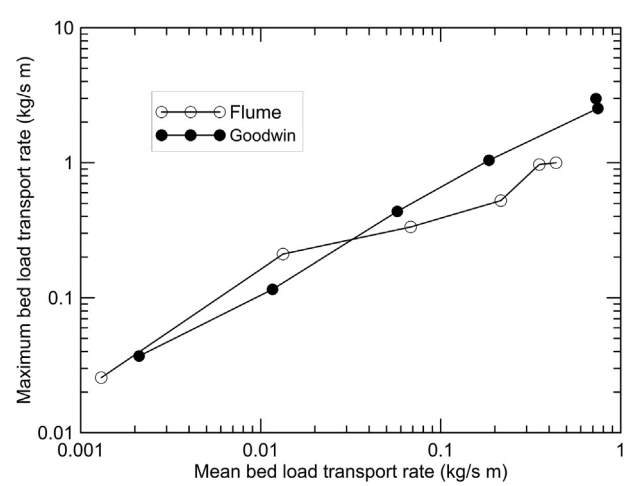

Fig. 7. The relation between maximum and mean bed load transport rates for individual flume experiments and each bin of the Goodwin Creek station 2 data.

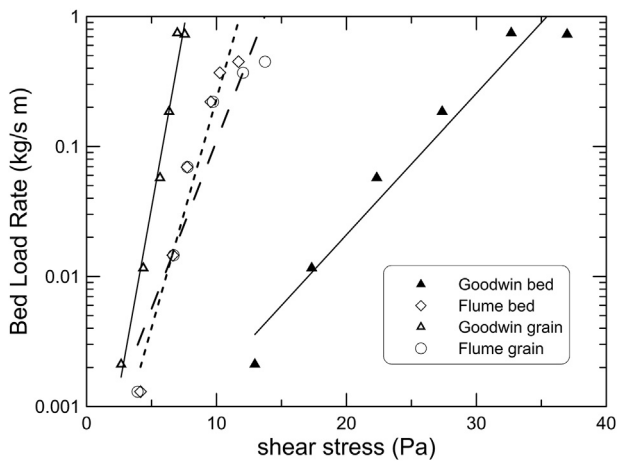

Fig. 8. Bed load transport versus bed shear stress and grain shear stress for laboratory and field data. In the legend the symbols labeled "bed" refer to bed shear stress and those labeled "grain" refer to grain shear stress.

laboratory experiments. These sources of drag could result from larger bed forms, vegetation and debris on the bed and banks, or large scale bars on the bed of the channel. To explore the possibility of sources of form drag that would not be available for the transport of bed load, the drag partition procedure of Einstein (1950) as recast by Garcia (2008) was used:

$$H_s = \frac{U^2}{gS}\left[\frac{1}{\kappa}\ln\left(11\frac{H_s}{k_s}\right)\right]^{-2} \tag{6a}$$

$$\tau_{bg} = \rho g H_s S \tag{6b}$$

where H_s is the portion of the hydraulic radius due to grain roughness, τ_{bg} is the fraction of the shear stress acting on the sediment grains, κ is Von Karman's constant and assumed equal to 0.4, and k_s is the roughness length for sediment grains. The variables needed to solve Equation (6a,b) for H_s by iteration were readily available in this study, with the exception of k_s. One of the principal difficulties of using a drag-partitioning technique is the determination of the k_s parameter. A wide range of grain sizes and multipliers based on the bed material have been used in previous studies to calculate k_s (Garcia, 2008). To determine a reasonable value of k_s, it was assumed that the shear stress in the laboratory channel resulted entirely from the drag on the grains. Equation (6a,b) was used to iteratively determine that a grain size of 25 mm ($\sim D_{84}$ of bed material subsurface) yielded nearly the same shear stresses for the six experimental runs of this study, thus the drag partition applied to the bed load data from Goodwin Creek used this length for the value of k_s. The use of grain shear stress dramatically reduces the separation between the data sets of bed load transport rates (Fig. 8); however, the shear stress values from Goodwin Creek have apparently been over-corrected, since they are less than those measured in the laboratory channel for similar unit sediment transport rates. The degree of over-correction is apparently greatest for the highest transport rates. The lack of correspondence between the field and flume shear stresses will be discussed further below.

Another difference between the conditions in the field and laboratory is the concentration of fine (<62 microns) sediment in the water column of Goodwin Creek. For flows which transported bed material on Goodwin Creek, concentrations of fine sediment generally ranged from 500 to 5000 mg/l, while essentially no fine sediment was present in the flows of the flume experiments. According to the equations of Yang et al. (1996), the effects of fine suspended sediment on variables related to the fluid and flow are minimal for concentrations below 10,000 mg/l. Another study (Wren and Kuhnle, 2012) has found that changes to sand transport rates for silt concentrations below 9000 mg/l were inconsistent and small. The concentrations of fine sediment commonly found on Goodwin Creek were therefore assumed to not have an effect on the transport of bed load.

7. Implications for the prediction of bed load

Improvements in the prediction of bed load transport rates for a stream with a bed material composed of sand and gravel was one of the primary goals of this work. As related above, for similar bed load transport rates, the calculated bed shear stresses were three times greater for the Goodwin Creek data than for the laboratory data. When total shear stress was partitioned using the technique of Einstein, grain shear stress calculated for Goodwin Creek was on average 0.64 of the grain shear in the flume for similar bed load rates. Yet, the bed load transport rate, in most bed load transport relations, is related to excess shear stress raised to a power from 1.5 to 7.5 and thus yields large changes in transport rate for small changes in excess shear stress (Scheer et al., 2002). To evaluate the prediction of bed load transport on this stream, several bed load transport rate predictors were applied and compared to the bed load transport data collected in this study.

Although, there have been a number of sediment transport relations published over the years, most do not yield reasonable predictions for streams with bed materials which consist of bimodal mixtures of sand and gravel. Initially, the Meyer-Peter and Müeller (1948) relation was applied to the bed load rates measured in this study. The Meyer-Peter and Müeller (1948) relation predicted zero transport rates for low shear stresses and values greater than the measured bed load rates for the highest shear stresses for the flume data while all of the predicted rates for Goodwin were zero. This same problem with the formula for low to moderate shear stresses was found by Scheer et al. (2002). The transport relation developed by Recking (2010), which has been developed using a large amount of field and laboratory data from gravel-bed streams, was applied to the bed load data collected in this study. This relation was formulated to calculate transport rates using two grain sizes in a two-part relation that takes into account the mobility of the bed armor (Eqs. (1), (12)–(14) of Recking, 2010). The relation of Recking (2010) under-predicted rates for Goodwin Creek, while for the laboratory data, it moderately over-predicted for low transport rates and

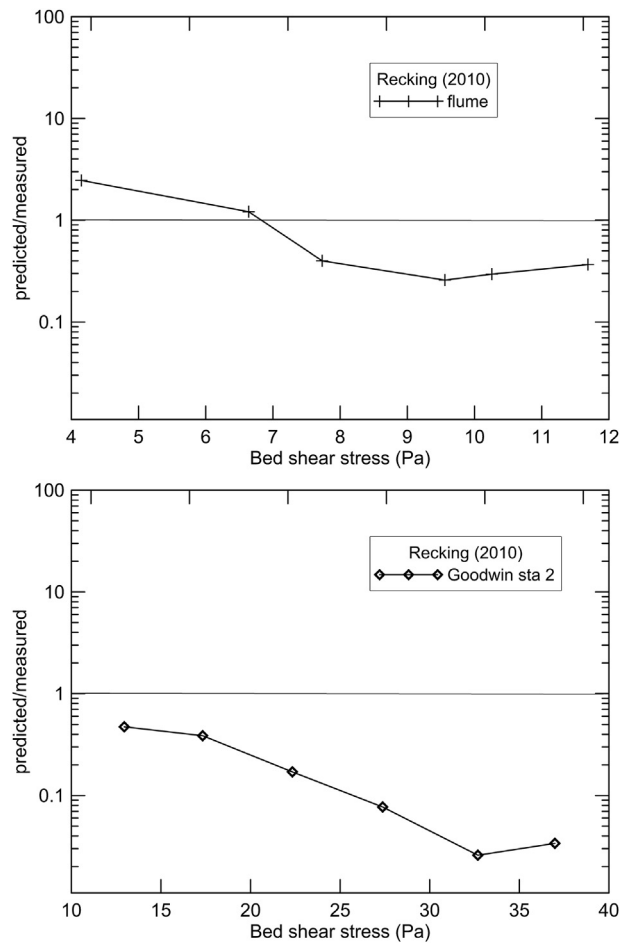

Fig. 9. Comparison between Recking (2010) bed load transport relation and measured bed load data from laboratory flume and Goodwin Creek.

under-predicted for higher transport rates (Fig. 9). The predictions from the Recking relation were reasonably close to the data from the laboratory but were from about 0.5 to 0.03 times the transport data from Goodwin Creek. Because of the poor performance of the Meyer-Peter and Müeller (1948) relation and moderate performance of the Recking (2010) relation, transport relations which predict the size distribution as well as the rate were explored. The transport relations of Wilcock and Crowe (2003) and Wu et al. (2000) were chosen to compare to the data of this study because they have been recommended as the best to use with widely graded mixtures of sand and gravel to predict both the bed load size distribution and the transport rate (Scheer et al., 2002). Both of these relations predict the transport of individual sediment size fractions which are summed to yield the total bed load transport rate and size distribution.

The Wilcock and Crowe (2003) relation (W&C) references transport rates to the size distribution of the bed surface and has a hiding function that relates the reference shear stress (a surrogate for critical shear stress for initiation of motion of a sediment particle) of the individual size fractions (D_i) to the relative location of that size compared to the mean size (D_m) of the distribution (D_i/D_m). The reference shear stress of the mean size of the distribution in the W&C relation is represented as a function of the magnitude of its grain size and the fraction of sand in the sediment mixture. The W&C relation was developed and calibrated from flow and transport data collected from a series of laboratory experiments with bed material mixtures composed of gravel up to 64 mm in diameter and five different amounts of sand.

The transport relation of Wu et al. (2000) (WWJ) was calibrated and tested by the developers using a wide range of flow and transport data collected from both laboratory flumes and field channels. Grain sizes of the bed material in the data sets used to develop the WWJ relation ranged from fine sand to 128 mm in diameter. The uniqueness of the WWJ relation is in the development of a hiding and exposure factor for each grain size in the bed material. This factor is based on the probabilities of particles hidden and exposed on the bed by particles in other size groups. This leads to a factor that adjusts the critical shear stress of each grain size fraction by the ratio of the exposure probability to the hiding probability for that grain size. In this way, the entire size distribution affects the calculation of the hiding and exposure factor. The WWJ relation includes a routine to calculate the grain stress while the W&C relation requires the user to calculate the grain stress before using the relation.

The bulk bed material size distribution was used as the input for both transport relations for laboratory and field conditions. The bulk size distribution was chosen because surface size distributions in the field are extremely difficult to measure during bed load transport events, whereas bulk size distributions of bed material are generally available from samples collected during low flows. Also, the distributions of the bed material surface and sub-surface size collected during low flow periods after runoff events from Goodwin Creek were quite similar. The calculations made with the W&C relation for this study were corroborated with results from using the W&C relation within the BAGS: Bed load Assessment in Gravel-Bed Streams version 2008.11 from the U.S. Forest Service Stream Systems Technology Center. Calculations made using the WWJ relation were corroborated with a Fortran program provided by Weiming Wu. The bed load transport predictions of the two relations were generally within a factor of 2 of the flume data for experiments with moderate and high shear stresses (Fig. 10). Both relations over-predicted by about an order of magnitude for the lowest flow rate (experiment number 1). Median grain diameters were closely predicted by both relations, except at the two highest shear stresses, where the W&C relation under-predicted by about a factor of five.

When applied to Goodwin Creek, both transport relations predicted bed load transport close to the measured values at low shear stresses (data seq. # 1–3), but under-predicted by up to an order of magnitude at higher shear stresses (Fig. 11). The grain shear stress calculated using Equation (6a,b) was used with the W&C relation in Fig. 11, since the total bed shear stress yielded bed load transport rates that were from one to more than two orders of magnitude higher than the measured

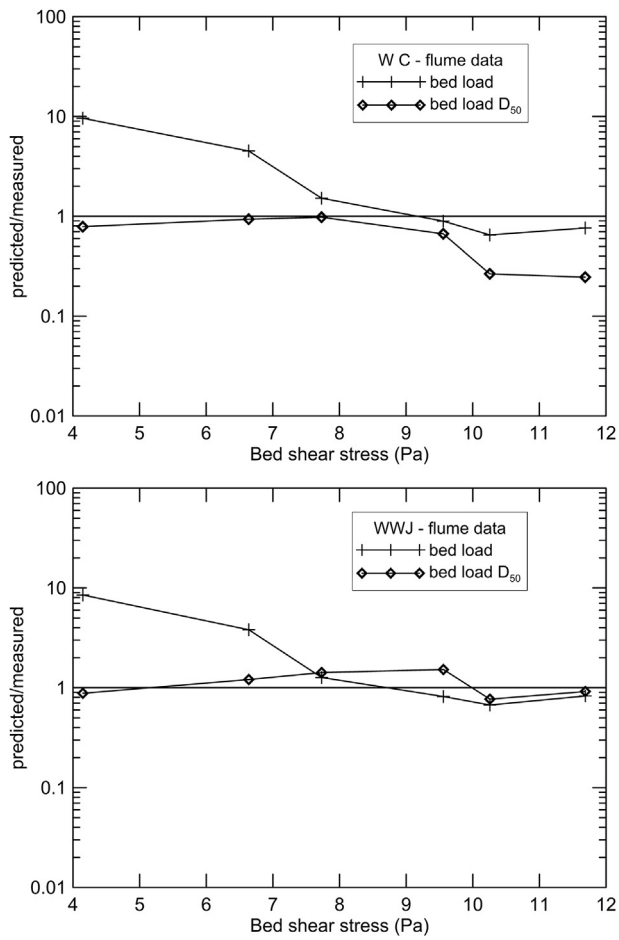

Fig. 10. Comparison between Wilcock and Crowe (2003) and Wu et al. (2000) transport relations and bed load data from the laboratory flume.

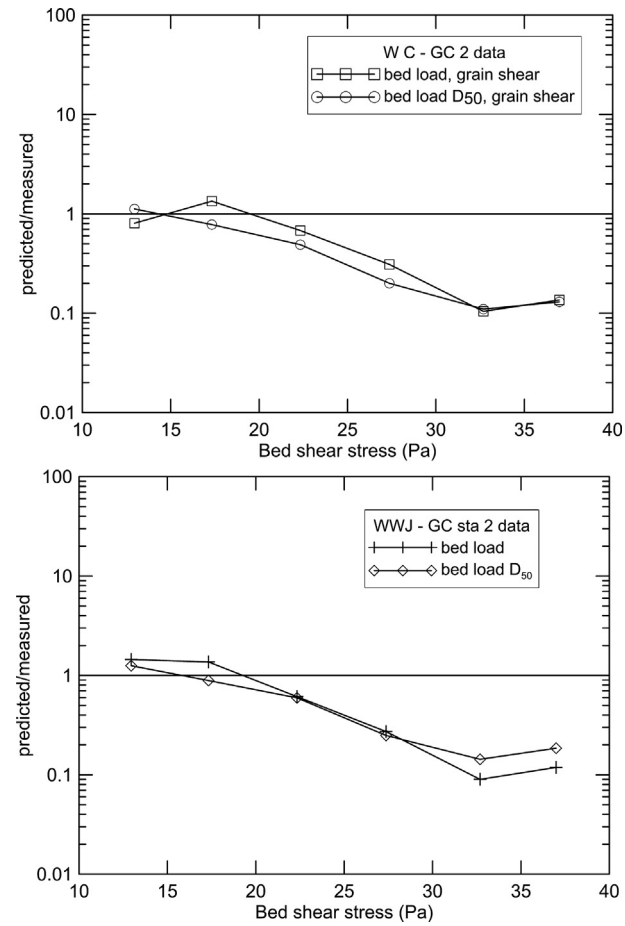

Fig. 11. Comparison between Wilcock and Crowe (2003) and Wu et al. (2000) transport relations and Goodwin Creek bed load data.

rates for all cases. The shape and magnitude of the discrepancies in Fig. 11 are similar for both relations.

8. Discussion

The comparisons conducted above illuminate the difficulties of accurate predictions of bed load transport using simple relations. This is especially the case when there are two distinct modes in the bed material size distribution. Transport relations that use only one size tend to underestimate the rates of transport for low shear stresses when the bed load is composed of predominantly sand and overestimate rates of transport for high shear stresses when the coarser material of the bed are in motion. This trend was found for the predictions of the Meyer-Peter and Müeller (1948) relation in this study. The relation developed by Recking (2010), which takes into account the spread of the size distribution and the fact that the sand and coarser sizes require separate relations, yielded reasonable results for the laboratory data, but yielded rates substantially less than the measured for the field data (Fig. 9).

With the exception of the transport rate at lower bed shear stresses, it is clear that the W&C and the WWJ transport relations did an excellent job of predicting the bed load transport rates for the flume experiments. For predictions of the median grain size of the bed load, the WWJ relation yielded a much better prediction for the highest shear stresses in the experiments. If the flume transport conditions were representative of a field situation, either relation would be expected to predict the mass of bed load transported over a runoff season with a high degree of accuracy. Since, the largest discrepancies occurred at the lowest shear stresses and lowest transport rates, the cumulative error over a runoff season would be small, assuming that the largest fraction of bed load sediment was not moved at relatively low bed shear stresses.

For the Goodwin Creek data, the predictions of both relations matched well with the measured data for low bed shear stresses but under-estimated the rate and size of the bed load for high bed shear stresses by about a factor of ten. This would be expected to cause large errors in the calculation of coarse sediment budgets over a runoff season, as in most cases the largest part of the coarse sediment transport occurs during infrequent large events. The under-predictions calculated for high shear stresses would cause bed load transport rates to be under-predicted by up to a factor of ten. Inaccuracy in the prediction of transport rates at high shear stresses has the potential to produce much greater errors than inaccuracy for predictions at low shear stresses. The large deviations between

predicted and measured transport rates for high bed shear stresses indicates that it is likely that the stress responsible for sediment transport was underestimated for these conditions. The drag partitioning technique used in this study implicitly assumes that the roughness elements are not in motion. It has been shown by several researchers that once the bed material of a stream begins to move the characteristic grain diameter of the bed is not the correct length scale to use to characterize the roughness experienced by the flow (Garcia, 2008). There have been several equations proposed to calculate the increased roughness of the moving bed without the effect of bed forms (Smith and McLean, 1977; Dietrich and Whiting, 1989; Wiberg and Rubin, 1989). These equations use a combination of the bed material grain size and the ratio of bed shear stress to critical shear stress to estimate the extra roughness caused by the moving bed material on the flow. The data used to develop these relations was mostly limited, to cases in which the bed material consisted of sand and were found to be not applicable to the conditions considered in this study. Further research is needed to broaden the application of these roughness prediction techniques.

While both transport relations yielded similar results in comparison to the bed load data collected in the laboratory and field, the relation of WWJ is preferred because the W&C relation does not include a method to partition the shear stress to yield the grain stress responsible for sediment transport. The qualified success of using the Einstein drag partitioning technique is predicated on accurate information for the roughness length or grain size that is representative of the grain shear stress. A laboratory study of bed load transport to compare to the field is seldom available for use in finding the H_s term in Equation (6a,b). The problem of calculating a representative grain shear stress before applying the relation does not arise with the use of the WWJ relation since it has its own drag-partitioning scheme.

9. Conclusions

Experiments were conducted in a laboratory flume to aid in modeling the transport of gravel and sand mixtures in streams. The rates and size distributions of the bed load transport in the laboratory flume were very similar to those present in the field and were a good representation of the conditions found in the field. The experiments at high shear stresses were apparently less representative of the conditions in the field, possibly due to differences in flow depth, bed forms, bank roughness or poorly known bed material size distributions. Thus, it is concluded that the laboratory experiments were a good predictor of the flow and transport conditions in the field for low to moderate flows.

Comparisons of the measured bed load transport rates from this study to the Meyer-Peter and Müeller (1948) relation were generally poor, likely due to the complexity of the entrainment and transport of bed materials composed of mixtures of sand and gravel. The Recking (2010) transport relation, which accounted for mixture effects, yielded reasonable predictions for the laboratory data but under predicted for the field bed load data. Transport relations which calculated transport rates of individual fractions separately and accounted more fully for the interactions between the sizes (Wilcock and Crowe, 2003; Wu et al., 2000) yielded excellent agreement with the laboratory bed load rate data except at low shear stresses when rates were over-predicted by an order of magnitude. Predictions of the median grain size of the bed load were very close to the measured sizes for low shear stresses for the W&C and WWJ transport relations. At high bed shear stresses, the WWJ relation yielded good estimates of median grain size, while the W&C relation under-predicted by about a factor of four to five. For the field data, both the WWJ and W&C relations predicted rates and median grain sizes that compared closely to the measured values for low shear stresses. Predictions began to diverge from the measured data at medium shear stresses and were an order of magnitude less than the measured data at the higher flow strengths. The divergence of the predictions from the measured values may be attributed to the difficulty of accurately characterizing the grain shear stresses and possibly bed material size distributions at high shear stresses and high rates of sediment transport. Improved methods to calculate grain stresses which take into account more fully the interactions of the moving grains with the flow are needed.

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