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Equal-mobility bed load transport in a small, step-pool channel in the Ouachita Mountains

Daniel A. Marion[a,*], Frank Weirich[b]

[a] Southern Research Station, USDA Forest Service, Oxford, MS 38655-4915, USA
[b] Geoscience Department, University of Iowa, Iowa City, IA 52242, USA

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Abstract

Equal-mobility transport (EMT) of bed load is more evident than size-selective transport during near-bankfull flow events in a small, step-pool channel in the Ouachita Mountains of central Arkansas. Bed load transport modes were studied by simulating five separate runoff events with peak discharges between 0.25 and 1.34 m^3/s (1.0- to 1.6-year recurrence intervals) in a natural channel using controlled releases from a storage tank. EMT occurrence was investigated using four different bed load relationships suggested by previous research. With each of these approaches, the relationship of a given bed load characteristic (D_{max}, distribution percentile, displacement distance and skewness) to some independent factor (τ_c^*, τ and grain size) was assessed to determine which transport mode was evident. Regression models derived using combinations of these four relationships with different datasets provide seven separate tests. Five of the seven tests indicate that EMT occurred or was predominant. Several reasons may explain the apparent contradictory results, but the confounding effects of changes in the structural arrangements of bed material prior to or during the events seem particularly important.
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Keywords: Bed load transport; Equal mobility; Size-selective; Step-pool channel; Bed material size; Bankfull streamflow

1. Introduction

The equal-mobility transport (EMT) theory has been advanced to explain how variability in bed material sizes and exposure of individual grains affects bed load entrainment and grain size (Parker et al., 1982). The theory states that for a channel bed composed of heterogeneous grain sizes, the larger grains are more easily entrained than smaller ones because they are relatively more exposed to lift and drag forces (Andrews, 1983). It challenges the traditional, size-selective transport (SST) theory (Shields, 1936) that holds that bed load size is directly proportional to displacement forces (e.g., shear stress, discharge, stream power).

Past field testing for the occurrence of EMT has largely been done in gravel-bed channels where the largest grains are cobble-sized or smaller (e.g., Andrews, 1983; Ashworth and Ferguson, 1989; Komar and Shih, 1992). Step-pool channels differ from these channels in that they exhibit a wider range of bed material sizes (typically sands and finer to small boulders and larger; Heede, 1972; Laronne and Carson, 1976; Best and Keller, 1986; Grant et al., 1990; Ergenzinger,

* Corresponding author. Tel.: +1-662-234-2744x248; fax: +1-662-234-8318.
E-mail address: dmarion@fs.fed.us (D.A. Marion).

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1992; Ryan, 1994) and a stepped longitudinal structure. Only Blizard and Wohl (1998) have considered whether EMT occurs in step-pool channels. While they concluded there was a general trend toward EMT in the step-pool channel they studied in the Colorado Rocky Mountains, they also found evidence suggesting that SST occurred.

The objective of this study is to assess whether EMT or SST occurs in a step-pool channel during near-bankfull streamflow events. Four different testing methods are used to evaluate which bed load transport mode occurs. The current study was undertaken as part of a larger investigation into how bed load and channel morphology interact in a typical step-pool channel in the Ouachita Mountains (Marion, 2001b).

2. Study site description and methods

We tested the bed load transport mode using data collected during five simulated flow events in a step-pool reach located within the Ouachita Mountains of central Arkansas.

2.1. Study site description

The study reach is located on an unnamed tributary of Little Bear Creek, hereafter referred to as Toots Creek (Figs. 1 and 2). Toots Creek has environmental characteristics typical of the region. Annual precipitation averages 130 cm, occurring almost entirely as rain; and streamflows are ephemeral to intermittent.

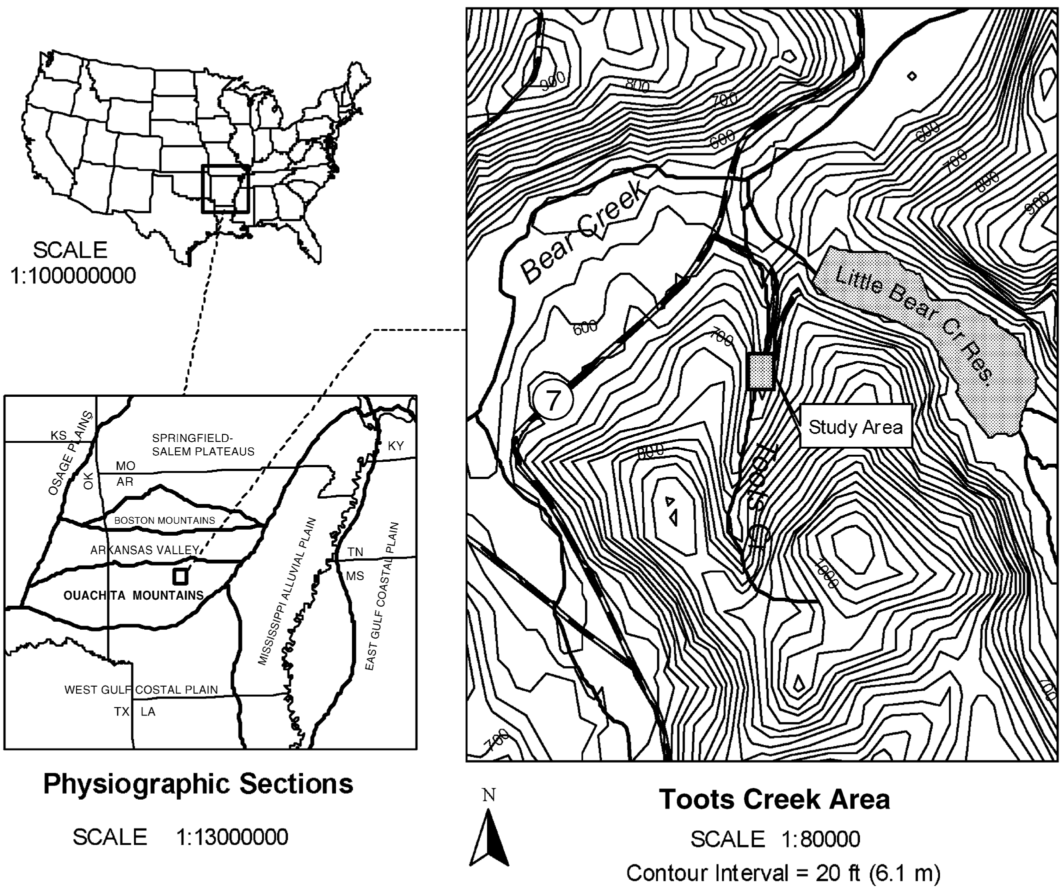

Fig. 1. Location of the Toots Creek study area in the Ouachita Mountains of Arkansas. Data sources: conterminous USA (Environmental Systems Research Institute, 1983); physiographic sections (Fenneman and Johnson, 1946); Toots Creek area contours, roads, streams and water bodies (Ouachita National Forest).

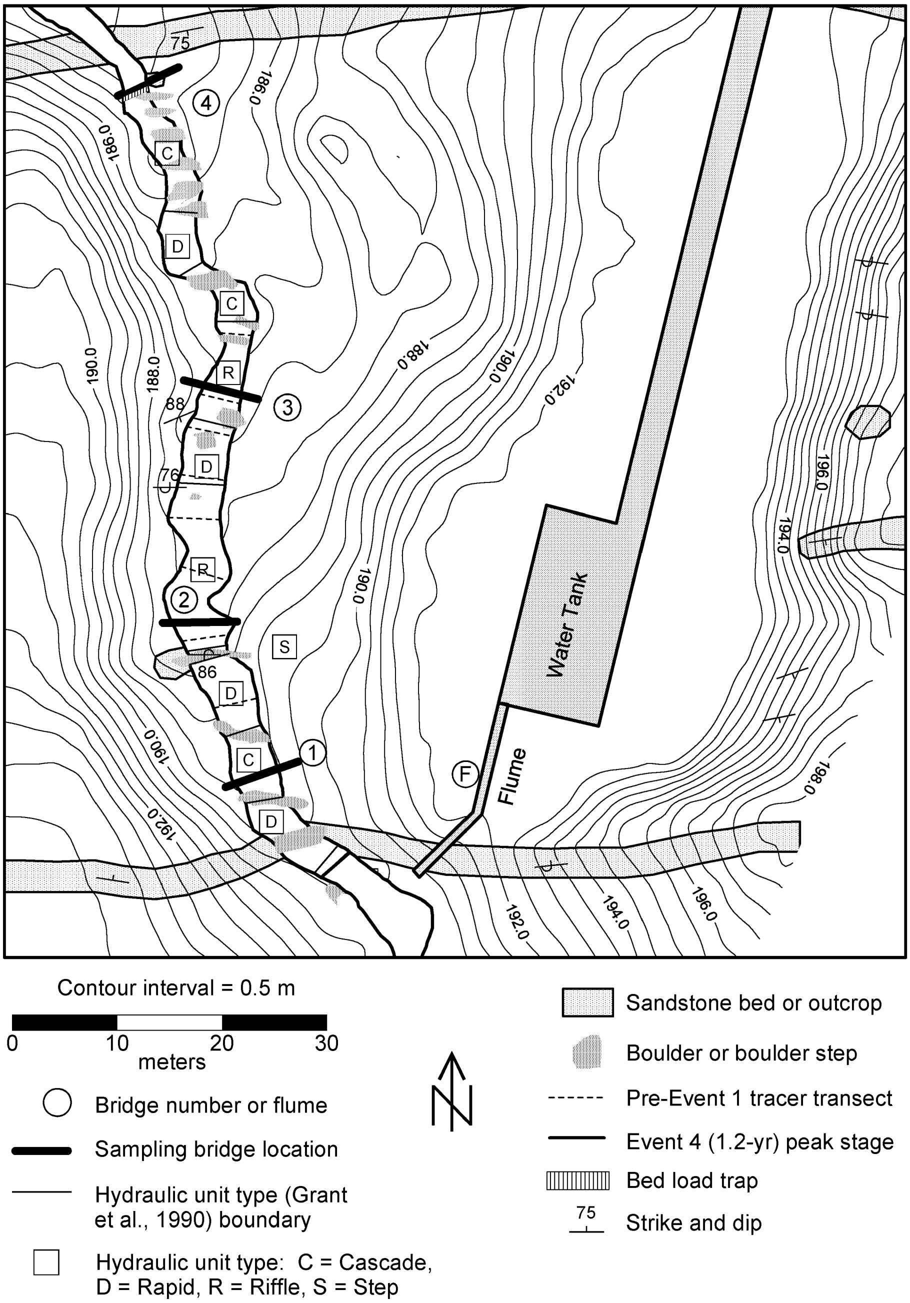

Fig. 2. Toots Creek study reach, local geology and water storage tank. Geology compiled from field mapping on 18 January 2001 by Daniel A. Marion and Charles G. Stone.

The catchment area above the study reach is 39 ha, overall relief is 140 m, and hillslopes range from 15 to 30%. Vegetation is predominantly composed of a shortleaf pine (*Pinus echinata* Mill.) overstory and a mixed hardwood understory including white oak (*Quercus alba* L.), red oak (*Quercus rubra* L.) and

Fig. 3. Toots Creek study reach looking upstream from just above Bridge 4.

various hickories (*Carya* spp.) (Marion and Malanson, in press).

The 96-m study reach has banks composed of mixed colluvial and alluvial deposits. Bankfull widths average 4.2 m and the channel has a weighted (by channel length) mean gradient of 8.8% (Fig. 3). The reach contains segments representing four different hydraulic unit types (Grant et al., 1990): step, cascade, rapid and riffle (Fig. 2). The reach-wide, grain-size distribution ranges from silts to large boulders. Grain sizes within hydraulic unit types display the same relative size relationships reported by Grant et al. (1990): cascades are coarser than rapids which are coarser than riffles (Fig. 4).

The channel bed is almost entirely composed of sandstone clasts with only very small amounts of shale and quartz. Grain sphericity is predominantly bladed to very elongate (after Sneed and Folk, 1958), while particle roundness is mostly subangular to subrounded. Across the bed surface, neighboring grains exhibit all three of the structural arrangements originally described by Laronne and Carson (1976). *Closed structures* occur over most of the study reach wherein grains are in close contact and voids between the large clasts are infilled by smaller grains. Most of the particles forming step risers exhibit *imbricate structures*, where cobble-sized and larger grains lean against one another, dipping upstream and strongly resisting individual grain entrainment. *Open structures*, where grains are loose and have minimal overlap, account for the smallest portion of the study reach. Here, grains are generally smaller, better sorted and occur in relatively small patches within step treads (Marion and Weirich, 1999).

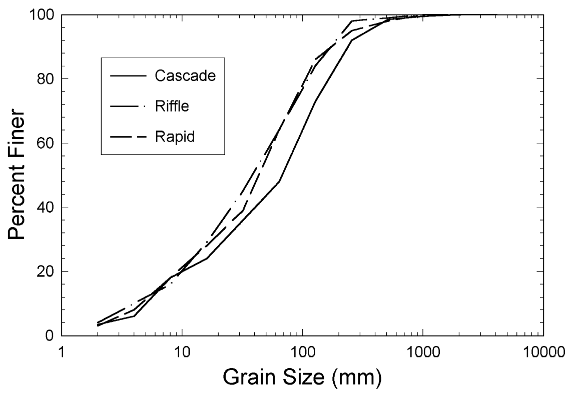

Fig. 4. Surface grain-size distributions for hydraulic unit types (Grant et al., 1990) within the Toots Creek study reach. Grain sizes determined by pebble count of grains >1.0 mm. The single-step segment is excluded due to the small number of clasts present.

Coarse (diameter>10 cm) woody debris loading was small within the study reach and appeared to have very little effect on bedload transport. The Toots Creek volume (2.45 m^3/100 m) is very similar to the mean of 2.2 m^3/100 m computed from data at 27 other sites in the Ouachita Mountains (Fowler, 1994), but differs markedly in both amount and influence on sediment routing from those reported for step-pool channels elsewhere (e.g., Heede, 1972; Megahan and Nowlin, 1976; Nakamura and Swanson, 1993).

2.2. Experimental methods

Five individual flow events with peak discharges ranging from 0.25 to 1.34 m^3/s (1.0- to 1.6-year recurrence intervals) were simulated. All flow events were created using controlled releases from a storage tank (Fig. 5) (see Marion and Weirich, 1997, for details on system operation). Events were produced on five consecutive days and sequenced so that Event 1 had the smallest peak flow while Event 5 had the largest (Fig. 6). Bankfull discharge was estimated to be 1.11 m^3/s (1.4-year recurrence interval) from channel features and computed hydraulic values.

Bed load was assessed in two ways. During each event, bed load transport rate was sampled at Bridge 2 (Fig. 2) using a 73-mm Helley–Smith sampler. Bridge 2 occurs within a riffle hydraulic unit type (Grant et al., 1990) that has a D_{50} of 104 and 51 mm for the bed surface and subsurface, respectively. Three 1-min samples were taken at three fixed locations across the bridge and were composited into one sample for analysis. Composite samples were generally taken at 4–5-min intervals, depending on the event duration. Discharge and other hydraulic characteristics associated with the bed load data were determined at Bridge 2 using methods described in Marion (2001b).

Fig. 5. Water storage tank and flume used to simulate near-bankfull events at Toots Creek.

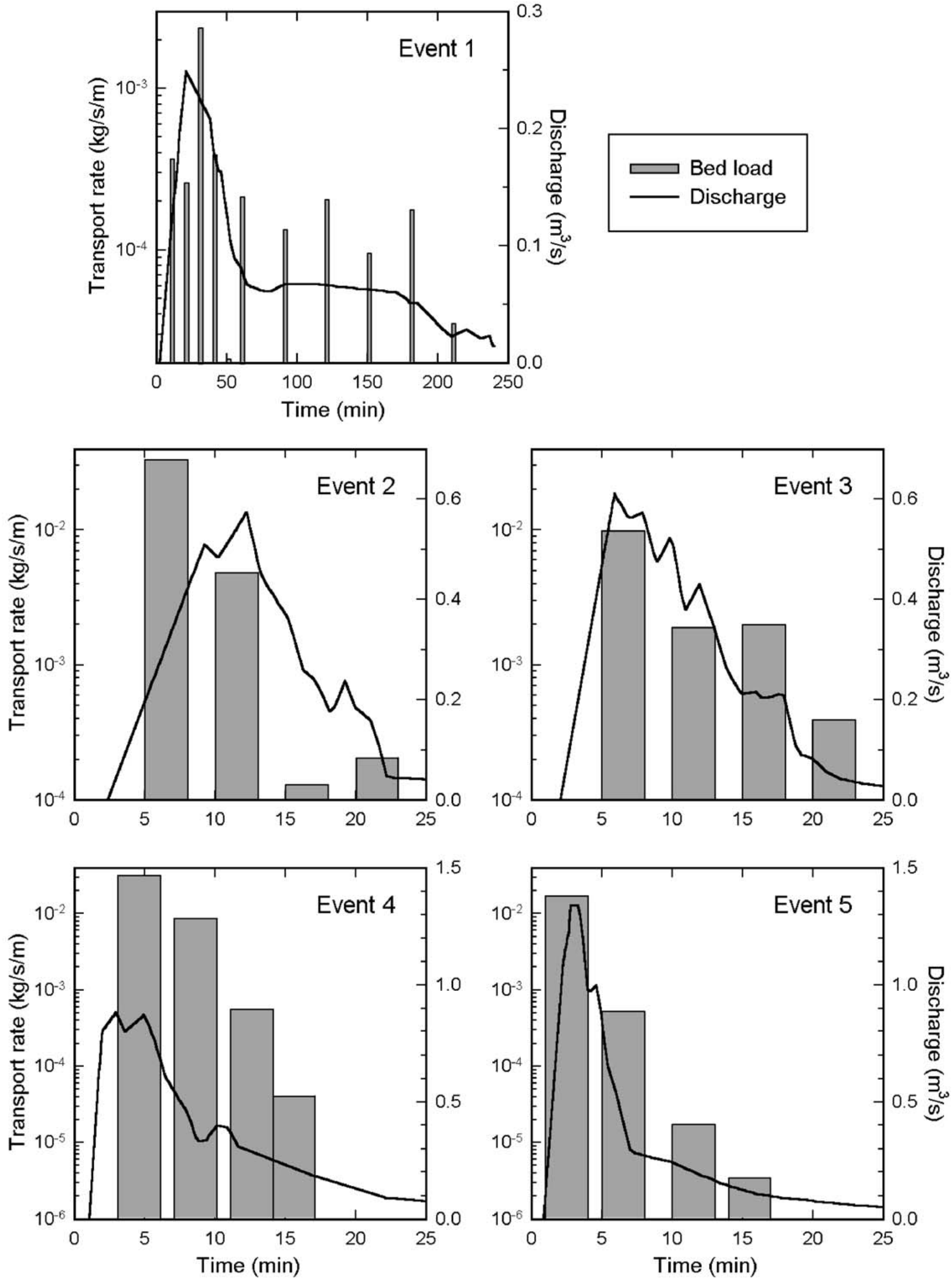

Fig. 6. Bed load transport rates and discharges used during the July 1995 experiments at Toots Creek. Bar widths indicate the 3.0-min time interval over which bed load was measured during Events 1–5.

Bed load displacement distance was determined using 79 bed particles between 34 and 380 mm (*b*-axis) in size. Tracers were initially installed along eight cross-sections evenly spaced within the central portion of the study reach (Fig. 2). At each section, 6–10 grains were randomly selected in proportion to the reach-wide, grain-size distribution, painted white and replaced to approximate their original orientation and packing. All tracers were sandstone and had the same shape characteristics as noted above. Their initial locations fell within a large variety of microsite situations (e.g., within pocket pools, adjacent to larger grains, in clusters of similar size grains or within finer grained bed patches). Tracer position was measured by tape after each event and used to compute displacement distances.

During the five events, bed load moved under Phase 1 or Phase 2 (after Warburton, 1992) conditions. D_{max} sizes ranged from 74 to 180 mm and unit bed load transport rates ranged from 3.5×10^{-6} to 3.3×10^{-2} kg/s/m (Fig. 6) (Marion, 2001a). Marion (2001a) showed that these rates span the lower to middle portion of the overall range defined by five previous studies of step-pool channels.

2.3. Testing methods

Four approaches have been previously advanced or suggested for determining whether EMT occurs.

2.3.1. Critical dimensionless shear stress vs. relative bed material grain size

According to Parker et al. (1982), an inverse relationship (i.e., regression slope coefficient $[b_1] = -1$) should exist between critical dimensionless shear stress (τ_c^*) and maximum bed load size (D_{max}) when EMT occurs. Andrews (1983) tested this using data from natural streams by regressing τ_c^* against D_{max}/D_{50sub}, where D_{50sub} is the median subsurface grain size. D_{50} is used to standardize D_{max} for bed material size differences between different locations. This ratio is assumed to reflect the relative exposure of a grain within the supporting matrix. Andrews found a highly significant inverse relationship between D_{max}/D_{50sub} and τ_c^*. This analysis assumes that the dimensionless shear stress computed when each bed load sample was taken is the critical value necessary to entrain the D_{max} measured. Andrews used the geometric mean of the half-φ size class containing the D_{max} as his measure of D_{max} size, whereas we used the bed load D_{95}. In addition, following Ashworth and Ferguson (1989), we used the bed surface D_{50} (D_{50b}) rather than the subsurface D_{50} as was done by Andrews (1983) because the lack of extensive pavement breakdown during the five events suggested that the bed surface was the primary bed load source and a more appropriate gauge of grain exposure. Thus, the relationship we examined was $\tau_c^* \alpha D_{95}/D_{50b}$.

2.3.2. Bed load displacement distance vs. grain size

A second approach is based upon the assumption that if SST occurs then bed load displacement distance decreases with increasing grain size; i.e., an inverse linear relationship should be evident (Ashworth and Ferguson, 1989). Thus, in a linear regression between distance and grain size, b_1 should be negative if SST occurs and near zero (i.e., no relationship) if EMT occurs. Using the tagged rock data for each event, linear regressions were computed for both grain weight and *b*-axis length (two measures of size) against displacement distance. In addition, both size metrics were regressed against cumulative displacement over all five events. Event 3 data were not considered because only two tracers moved during this event.

2.3.3. Grain size of selected bed load distribution percentiles vs. shear stress

In a third approach, if grain size increases with increasing shear stress (τ), as predicted by SST, then a positive relationship should be evident in the regression model (i.e., $b_1 > 0$) for any given bed load distribution percentile (e.g., D_{50}) as a function of τ (Komar and Shih, 1992). Conversely, if $b_1 = 0$, then equal-mobility is defined as occurring. We derived models for the D_{05}, D_{16}, D_{50}, D_{84} and D_{95} bed load percentiles against τ. All models were tested using a general linear model (GLM) to assess both the effect of τ and event magnitude in case the latter affected the $\tau - D_x$ relationship.

2.3.4. Bed load grain-size skewness vs. shear stress

Lastly, if SST occurs, then a progressive increase in D_{max} size with increasing τ must also occur (Komar and Shih, 1992). The latter would cause bed load grain-size skewness to increase in magnitude with increasing τ (i.e., $b_1 > 0$). EMT would be apparent if $b_1 \leq 0$. We derived a τ–skewness model and tested whether $b_1 > 0$. As with the previous test, we also used a GLM to assess whether the τ−skewness relationship was affected by event magnitude.

With each of these approaches, the relationship of a given bed load characteristic to some independent forcing factor was assessed to determine which transport mode was evident. The nature of each test determined whether the proposed hypothesis was testing for the presence of EMT or SST. The first method described above tested for EMT (H$_a$: $b_1 = -1$), while the other three tested for SST (H$_a$: $b_1 > 0$). Notably, all of these approaches were originally developed using data from gravel-bed channels that lacked the significant structural roughness features, such as boulder clusters and steps, that are common in step-pool channels.

3. Results

Results from the tests differed in which transport they indicated was operational during near-bankfull events.

3.1. τ_c^* vs. D_{max}/D_{50b}

This test indicated that EMT occurred when data from all events were considered together. However, confidence in this conclusion is not high. The τ_c^*–D_{max}/D_{50b} relationship does not vary with event magnitude ($P = 0.46$) so data from all five events were used together. Two models were tested: one based on all data and one excluding the one case where D_{95}>32 mm (Fig. 7). The case in question has a very large leverage value, thus, a large effect on the model slope, and falls within the size range in which Helley–Smith accuracy is most questionable.

In a similar analysis, Ashworth and Ferguson (1989) excluded all cases where τ_c^*>1.0 on the assumption that gravel-size grains could be suspended under such conditions and thus escape sampling. However, an analysis of suspended sediment data during all five events showed no evidence of significant gravel suspension (Marion, 2001b). Therefore, these cases were included in the present analysis.

The probability that $b_1 \neq -1$ is quite low (0.04) for both models, indicating that EMT occurred. However, while both model slopes are significant ($b_1 \neq 0$) at the 0.05 level, both models also have very low R^2 values (0.33 and 0.18) and relatively large standard errors for these slope coefficients. Thus, while the occurrence of EMT is more evident than SST (where $b_1 \neq -1$), it is not conclusively demonstrated by these models.

3.2. Tracer displacement distance vs. grain size

Initial results indicate that SST occurred in Event 1 but not in Events 2, 4 and 5 (see Table 1). Transport

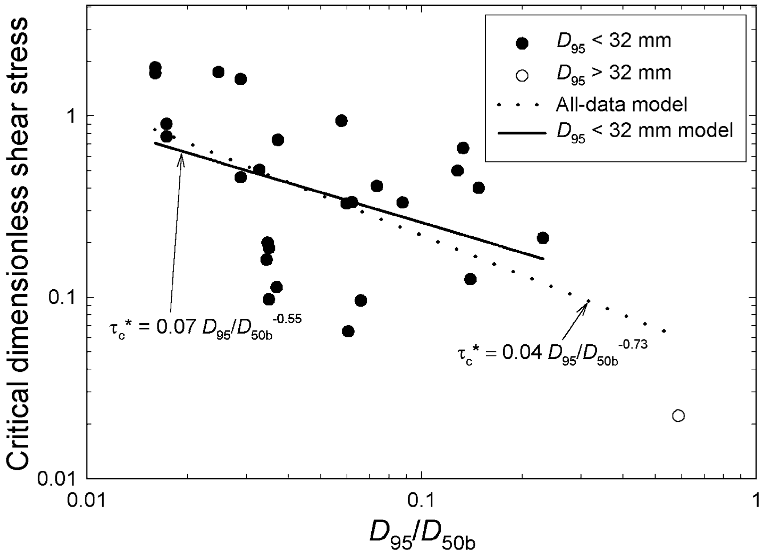

Fig. 7. Critical dimensionless shear stress as a function of relative bed load grain size during all five experimental events at Toots Creek.

Table 1
Tracer recovery rates and slopes for regression models of displacement distance vs. grain size at Toots Creek (data are for Events 1–5 and cumulative displacement)

Event	No. of tracers	Recovery rate (%)	No. tracers displaced	Slope coefficients			
				Using all data		Excluding outliers	
				b-axis	Weight	*b*-axis	Weight
1	79	100	16	– 0.66**	– 0.18**	N/A	N/A
2	79	100	7	– 0.01	– 0.06	– 0.68	– 0.40**
3	77	97	2	N/A	N/A	N/A	N/A
4	77	97	10	– 0.15	– 0.03	– 0.43	N/A
5	77	97	15	– 0.63	– 0.49	– 1.00*	– 0.46**
Cumulative	77	97	30	– 0.13	– 0.18	N/A	N/A

N/A = not applicable. Number of outliers excluded is 0, 1, 1 and 3 for Events 1, 2, 4 and 5, respectively.
* Probability of regression slope ≥ 0 is ≤ 0.10.
** Probability of regression slope ≥ 0 is ≤ 0.05.

distance is not related to bed load grain size for Events 2, 4 and 5 but is related for Event 1. All individual events and cumulative displacement do have models with $b_1 < 0$, but only for Event 1 is the coefficient significant at the 0.05 level. Results are very similar for both *b*-axis length and grain mass. Therefore, only the relationship with grain mass is discussed below.

Despite the initial results, the majority of the data for Events 2, 4 and 5 do appear to show a clear trend (see Fig. 8). Further analysis indicates that significant relationships can be derived for Events 2 and 5 if a limited number of samples are excluded. These possible outliers are identified in Fig. 8. For Event 2, exclusion of one possible outlier produces a significant model. The excluded case has both high leverage and a large residual value, thus, it has a large effect on both b_1 and its probability of not being less than zero. For Event 5, exclusion of three possible outliers also results in a substantially different model. The excluded cases all have very large residual values, causing the original mean square error term (0.50) to be twice that for Event 4 and over seven times those for Events 1 and 2. The revised model has a b_1 with a P value of 0.03 and mean square error of 0.14. No improvement is achieved for Event 4 by excluding the two possible outliers.

Thus, SST is not consistently evident, but is indicated in particular events. SST is most apparent for Event 1, but Events 2 and 5 may also exhibit such transport. In contrast, SST cannot be discerned for Event 4 or for cumulative distance over all five events. The difference between these two sets of results suggests that larger sample sizes may be needed for this test to produce a more certain answer.

Schmidt and Ergenzinger (1992) observed grain weight and transport distance relationships similar to those at Toots Creek in the Lainbach, a step-pool stream in southern Germany. They measured significant negative correlations between grain weight and travel distance in two of three separate events. However, they found that at best, they could only explain 33% of the travel distance variance even when including a factor for grain shape along with weight. Therefore, they concluded that there was only a weak tendency for travel distance to decrease as weight increased. These findings are similar to Toots Creek in that relationship strength varies significantly by event, that general trends are evident, but that these trends are only weakly expressed.

3.3. Bed load D_x vs. τ

This test produces differing results depending on how event data are combined. SST is not evident for any except perhaps the largest percentile when data from all events are considered together. Probabilities are >0.29 for all percentiles except D_{95} where P = 0.10. Such a dataset is similar to that used by Komar and Shih (1992) in that it is composed of observations from multiple events.

However, a GLM test indicates that the τ–D_x relationship varies between Events 1–3 and 4–5.

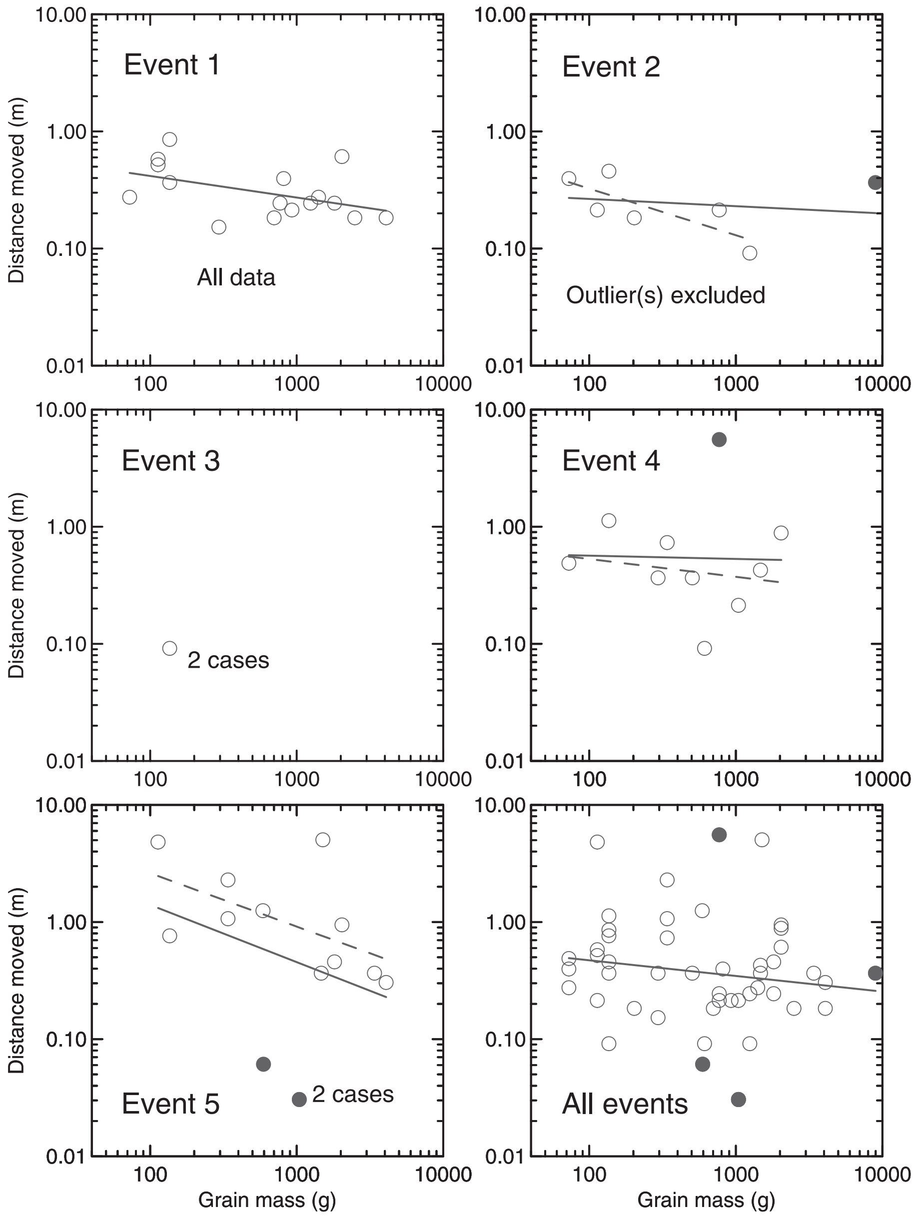

Fig. 8. Tracer travel distance vs. grain mass for individual events and total distance over all events. Possible outliers denoted with dot symbol. Regression models are based on all data (solid line) and with possible outliers excluded (dashed).

SST is evident during Events 4–5, but not during Events 1–3. The plot in Fig. 9 shows the difference between event groupings for bed load D_{50} and is typical of the relationships exhibited between τ and the other percentiles. For Events 4–5, all but one of the b_1 values are greater than zero for the five size percentiles at the 0.05 level, but R^2 values are not very high (see Table 2).

Shear stress appears to have no effect on bed load size during Events 1–3, thus, EMT is indicated. All model slopes test equal to zero. Large variability across the observed τ range causes this lack of any

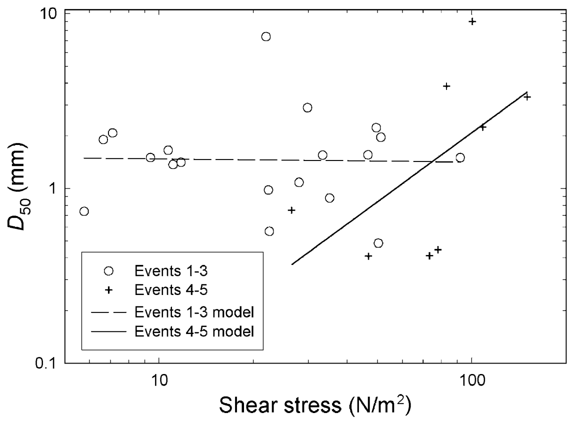

Fig. 9. Bed load D_{50} size variation with shear stress. Model for data taken from Events 1–3 is statistically different than that for Events 4–5.

relationship. Fig. 9 illustrates this for Events 1–3 and is typical of the variability in all other grain-size percentiles with shear stress.

Blizard and Wohl (1998) found τ was very effective in explaining bed load size variation at East St. Louis Creek. They derived significant ($\alpha = 0.05$) regressions using both at-a-point and cross-sectional mean values. Using the latter (same as used for Toots Creek), they obtained significant regressions between τ and three of the four size metrics they tested: D_{max}, D_{84} and D_{16} (no coefficients or R^2 values are reported). They found significant models only at particular sites: one site for the D_{max} and D_{84} sizes, and another for the D_{16} size. Interestingly, they found no significant relationship for D_{50}, the percentile showing the weakest relationship for Events 4–5 at Toots Creek. They found that at-a-point data produced significant regressions at more sites and for more size percentiles at any given site than did mean values. Their data were taken throughout one entire spring runoff season, not individual events like at Toots Creek.

The relationship between τ and bed load grain size evident at Toots Creek is different from that documented by Shih and Komar (1990). Toots Creek models are shown in Fig. 10 along with the models determined by Shih and Komar for bed load D_{50} and D_{90} from the gravel-bed stream they studied. The models indicate that much smaller grain sizes moved at Toots Creek than at Oak Creek for a given τ. For example, when τ equals 30 N/m^2, the expected D_{50} at Oak Creek is 3.0 mm while that at Toots Creek is 0.45 mm, roughly a tenfold decrease in size. Toots Creek models also have lower increase rates for grain size in comparison to comparable Oak Creek percentiles (see Fig. 10). Bed material size is finer at Oak Creek with a D_{50} of 60 and 20 mm for the surface and subsurface, respectively. At Bridge 2, the corresponding values are 104 and 51 mm. Thus, one possible explanation for the different responses might be that larger bed

Table 2
Regression statistics for models of bed load size (mm) at given percentiles as a function of bed shear stress (N/m^2) during Events 4 and 5 at Toots Creek Bridge 2[a]

Bed load percentile	b_0 ($\times 10^{-3}$)	b_1	Standard error of b_1	95% confidence limits on b_1		R^2
				Lower	Upper	
D_{05}	8.67	0.72**	0.36	− 0.16	1.60	0.40
D_{16}	9.89	0.86**	0.40	− 0.11	1.83	0.44
D_{50}	5.01	1.31*	0.74	− 0.51	3.13	0.34
D_{84}	3.70	1.51**	0.67	− 0.12	3.14	0.46
D_{95}	7.28	1.56**	0.54	0.24	2.88	0.58

[a] Data are from Helley–Smith samples taken at Toots Creek Bridge 2. Regressions were computed using log-transformed data for both variables. However, values listed below have been transformed back to the original units. Thus, all models are of the form $D_x = b_0 \tau b_1$, where D_x = bed load percentile, b_0 and b_1 = regression coefficients and τ = shear stress (N/m^2). *Probability of $b_1 \leq 0$ is ≤ 0.10. **Probability of $b_1 \leq 0$ is ≤ 0.05. For all models, sample size = 8 and df = 6.

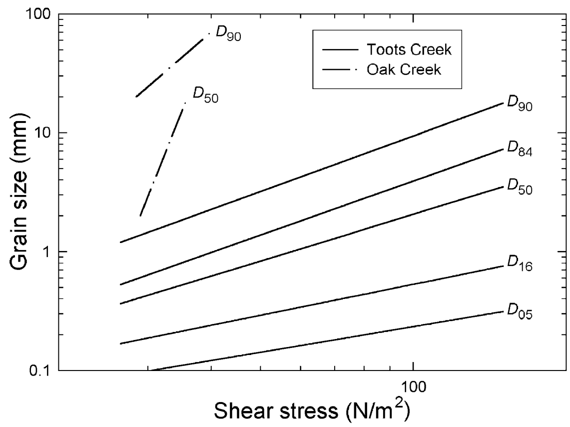

Fig. 10. Comparison of bed load grain size–shear stress relationship between Toots Creek and Oak Creek. Plot shows models of grain-size changes with shear stress for given grain-size distribution percentiles.

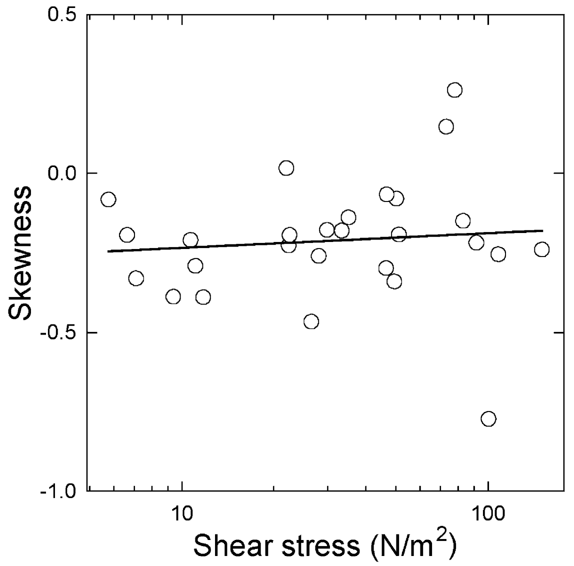

Fig. 11. Bed load skewness variation with shear stress during all five Toots Creek events. Line shows the regression model of the trend.

grains are relatively more exposed at Oak Creek because the surrounding bed matrix contains smaller sizes (Andrews, 1983).

3.4. Bed load grain-size skewness vs. τ

According to the skewness vs. τ test, EMT occurs. The probability is 0.32 that $b_1 \leq 0$ using data from all events. During the five experimental events, skewness remains essentially constant over the τ range observed (no differences between events) (see Fig. 11).

4. Discussion

Results are summarized in Table 3 for all of the tests discussed above. Five of the seven tests support the conclusion that EMT occurred or was predominant. Interestingly, EMT is indicated in all four tests when data from all events are used together (cumulative displacement for tracers).

4.1. Explanation of results

Several explanations may account for the seemingly contradictory results between different tests. First, the tests are based upon different assumptions. They fall into three types: those utilizing a representation of D_{max} (τ_c^* test), those utilizing just the larger particles (tracer displacement test) and those utilizing the entire bed load size distribution (percentile size and skewness tests). Komar and Shih (1992) showed that τ_c^* and

Table 3
Summary of hypothesis tests to determine whether size-selective or equal-mobility bed load transport is exhibited at Toots Creek during the five experimental events

Model and slope condition tested[a]	Result (probability [P] under H_0)	Conclusion
Model: tracer travel distance vs. grain weight. H_a: $b_1 < 0$ (i.e., SST occurs). Event 3 not tested due to insufficient data.	Using all data, $P < 0.03$ for Event 1; $P > 0.28$ for Events 2, 4, 5 and cumulative for all events.	Cannot reject H_0; EMT indicated in most events.
	Excluding outliers, $P < 0.03$ for Events 1, 2 and 5; $P > 0.45$ for Event 4 and cumulative for all events.	Reject H_0; SST indicated in most events.
Model: bed load percentile grain size vs. shear stress for D_{05}, D_{16}, D_{50}, D_{84}, D_{95}. H_a: $b_1 > 0$ (i.e., SST occurs).	Using combined data from all events, $P > 0.29$ for all size percentiles except D_{95} where $P = 0.10$.	Cannot reject H_0; EMT indicated.
	Using data for Events 1–3, $P > 0.32$ for all size percentiles.	Cannot reject H_0; EMT indicated.
	Using data for Events 4–5, $P < 0.05$ for all size percentiles except D_{50} where $P = 0.06$.	Reject H_0; SST indicated.
Model: bed load grain-size skewness vs. shear stress magnitude. H_a: $b_1 > 0$ (i.e., SST occurs).	Using combined data from all events, $P = 0.32$.	Cannot reject H_0; EMT indicated.
Model: relative bed load D_{95} grain size vs. dimensionless shear stress. H_a: $b_1 = -1$ (i.e., EMT occurs).	Using combined data where $D_{95} \leq 32$ mm from all events, $P = 0.04$.	Reject H_0; EMT indicated.

[a] b_1 = slope of regression model. D_x = x-percentile of bed load grain-size distribution.

percentile size tests can produce contradictory results using the same data. Komar and Shih offered a compelling argument that the theoretical basis of the τ_c^* test leads to the contradictory predictions that D_{max} changes rapidly with small changes in τ_c^* and that bed load grain-size distributions do not change. However, the τ_c^*–D_{max} relationship has been widely reported for gravel bed (see Komar and Shih, 1992 for a recent citation list) and recently for step-pool channels (Ryan, 1994), so it is included here.

Second, the tracer displacement tests supporting SST are somewhat suspect. Event 1 results might be questioned because Event 1 was the first event after tracer replacement. Despite efforts to reestablish their original position, tracer exposure may have been somewhat higher than under natural conditions or in subsequent events. Increased exposure, especially of smaller tracers, would increase the likelihood of SST. In addition, results implying SST for Events 2 and 5 are uncertain because they are only significant when possible outliers are excluded.

Third, bed load transport modes may be stage dependent. Komar and Shih (1992) proposed that modes shift from "apparent" equal-mobility at low stages to size-selective at higher stages then back to equal-mobility at still higher stages. Based on their analysis of data from a gravel-bed channel, Komar and Shih concluded that at stages where tractive forces were sufficient to mobilize the bed (i.e., when most of the grain sizes within the bed are present in the bed load) that SST occurred. This would correspond with Phase 2 transport in a step-pool channel (Warburton, 1992). At lower stages, the bed pavement would not be fully mobilized (Phase 1 transport) and Komar and Shih reasoned that random fluctuations in bedload size rather than bed material size variability would cause EMT to be evident. Komar and Shih further predicted that the transport mode switches back to EMT at some high stage when bed load size distribution matches that of the bed material (Phase 3). A shift is indicated at Toots Creek where Events 1–3, with relatively low stresses, exhibited equal-mobility in the D_x vs. τ test, while Events 4–5, with generally higher stresses, exhibited SST. Fig. 8 provides an example of this difference for bed load D_{50} grains. However, if a mode change did occur, then why similar differences between events are not evident in the bed load skewness vs. τ results is unclear.

A marked change in bed material size composition prior to Events 4 and 5 could also explain their apparent SST. Kuhnle (1992) showed that EMT from the two separate components of a bimodal bed distribution could produce an overall SST relationship. He found this to occur in a gravel-bed, pool-riffle channel during relatively low-energy peak flows like those used in this study. However, this explanation does not seem relevant for Toots Creek. While the subsurface layer in the study reach does have a bimodal size distribution, the surface does not. Because extensive pavement breakup was not indicated for most of the bed load samples, then the surface should have been the primary bed load source. While either accelerated bank erosion or sediment release from the breakdown of a step might cause transient changes in bed material size distribution, post-event observations and measurements showed that neither occurred.

The occurrence of "bed waves" could affect the variability observed in all of the relationships tested. A bed wave is an increase in sediment storage at a given location over time or relative to adjacent upstream and downstream channel areas (after Hoey, 1992). Their occurrence and downstream movement in step-pool channels have been directly observed in the field (Hayward, 1980), indicated by intra- and interevent surveys (Ashida et al., 1981; Ergenzinger, 1992; Warburton, 1992; Gintz et al., 1996; Blizard and Wohl, 1998) and demonstrated in flume studies (Whittaker and Davies, 1982; Whittaker, 1987). Periodic oscillations in bed load transport rates at a particular site ("bed load pulses"; Hoey, 1992) have been attributed to the presence of bed waves (Hayward, 1980; Whittaker and Davies, 1982; Whittaker, 1987; Blizard and Wohl, 1998).

The passage of bed waves through the study reach could have affected the bed load relationships derived for this study in a variety of ways. The sampled D_{max} could have been larger due to increased protrusion of the largest clasts within a matrix of smaller clasts in a bed wave. Conversely, D_{max} could have been smaller through burial of the largest clasts by smaller ones. Tracer displacements could have been similarly affected if tracer grains were caught up in a bed wave. The preferential entrainment or hiding of larger grains could also affect bed load size distributions, thereby altering either percentile sizes or skewness. Additional effects can also be imagined. Clearly, the influence of bed waves could introduce increased variability to the observed bed load relationships and possibly affect the test results.

Bed waves were not directly observed within Toots Creek during any of the five events. However, bed load pulses did occur during the Event 1 recession flow (Fig. 6), suggesting bed waves may have been present during that time. During the period between 50 and 200 min, discharge was fairly constant, yet bed load transport rates oscillated between 2.1×10^{-5} and 2.1×10^{-4} kg/s/m. The sample numbers during Events 2–5 are insufficient to judge whether bed load pulses occurred. If bed waves did occur, they could only have resulted from in-channel sources as no out-channel sediment inputs occurred during the experiments. We assessed whether bed waves may have affected the test results by excluding the suspect samples, reanalyzing the data and repeating those tests which previously utilized the suspect samples.

With one possible exception, the interpretations of the test results remain the same even when possible bed wave samples are excluded. The one exception is for the $\tau_c^* - D_{95}/D_{50b}$ relationship where $P = 0.08$ for the test statistic in the new model. Therefore, the rejection of the H_0 (i.e., SST occurs) is less certain than for the original analysis ($P = 0.04$), but still plausible. Test statistic probabilities increase somewhat in magnitude in all of the other tests, too, but this acts to increase confidence in the original test interpretations. The tracer displacement data could not be reassessed as there is no way to determine which tracers might have been affected by possible bed waves during Event 1. Interestingly, Event 1 is the only event in which tracer data clearly exhibit SST (Table 3). We conclude from these additional tests that bed waves did not confound the original test results.

Changes in sediment availability prior to or during a given event could either promote or inhibit SST. EMT can be thought of as the result when factors other than an individual grain's size influence its entrainment potential. Past EMT work has focused on the size of neighboring bed material relative to a given particle's size as the primary factor influencing entrainment potential (Andrews, 1983; Wiberg and Smith, 1987). Neighboring clast size affects both the exposure of a grain to tractive forces and the force necessary to roll it over the adjacent downstream clast (Andrews, 1983). Both of these relate to how available a grain is for entrainment.

Tracer studies have determined that other factors also influence sediment availability in step-pool channels. The structural arrangement of bed grains has also been shown to affect how available they are for entrainment. Laronne and Carson (1976) found grains within open or infilled structures to be more mobile than grains in tight (vertically infilled and imbricate) structures. Within the latter, not only hiding but also the packing of the interlocked grains further restricts their mobility. The disruption of tight bed structures would be expected to increase sediment availability and increase particle mobility. This response was observed by Gintz et al. (1996) after a large event obliterated an existing step-pool pattern.

Thus, the disruption of structural arrangements within the bed during certain events might explain the inconsistent expression of EMT. As noted earlier, the removal and reinstallation of tracers prior to Event 1 could have disturbed the local bed organization and thereby increased tracer mobility. Tractive forces during the higher flows in Events 4 and 5 may have been sufficient to dislodge some larger pavement clasts, expose previously hidden grains and generally increase sediment availability to the point that SST was manifested.

Grain shape is another factor that has been shown to affect particle mobility in step-pool channels. Schmidt and Ergenzinger (1992) found that rod-shaped grains had the greatest mobility while disc-shaped ones had the least. Laronne and Carson (1976) observed that disc-shaped grains were more prone to being incorporated in tight structural arrangements that limited their movement. Differences in grain shape between sites might explain variations in the degree to which EMT is apparent, with EMT being more evident at sites where grain shapes are predominantly disc-shaped. However, grain shape does not explain differences between events at a single site like Toots Creek where the grain-shape distribution remains constant.

4.2. Comparison to past work

Blizard and Wohl (1998) also found a general trend towards EMT for a step-pool channel of similar size and under similar flow conditions as those at Toots

Creek. While they found several instances of significant positive relationships between some bed load percentile sizes and τ (indicative of SST), they concluded based on bed load size skewness and the lack of overall coarsening of bed load size distributions with increased τ that equal-mobility was evident. Thus, their results are very similar to this study in that different relationships indicated different transport modes, but equal-mobility seemed most apparent.

5. Conclusions

Altogether, the results, while not unequivocal, lend greater support to the conclusion that equal-mobility was the predominant transport mode during the near-bankfull flow events used in this study. Five of the seven tests support the conclusion that EMT occurred or was predominant. Some of the tests indicating SST are suspect because they require excluding possible outliers from the analysis. The remaining tests indicating SST can be explained by plausible changes in sediment availability (through changes in the structural arrangements of bed grains) that promote SST occurrence. In general, our results strongly indicate that bed size heterogeneity significantly affects bed load entrainment and size in step-pool channels. They also suggest that changes in the structural arrangements of bed material prior to or during events may confound this effect.

Our results seem to fit within the conceptual model of bed load transport proposed by Komar and Shih (1992) for gravel-bed channels. The apparent transport mode appears to shift depending upon the level of pavement mobility present. These shifts in transport mode correspond to the three different phases of bed load transport identified by Warburton (1992) for step-pool channels. In the case of Toots Creek, the shifts are only evident in the $\tau - D_x$ relationship, and additional data will be required to confirm these shifts.

When our work is combined with previous efforts, certain consistent patterns in bed load transport begin to emerge for step-pool channels. Entrainment does appear to be significantly affected by neighboring clast size as well as other structural characteristics of the bed. The mutual interactions of these factors may well change at certain force thresholds, producing shifts between EMT and SST as proposed by Komar and Shih (1992). If so, then finding ways to predict when the mode shifts occur should greatly improve our ability to predict bed load transport in step-pool as well as gravel-bed channels. Clearly, additional work is needed to confirm these patterns and, if real, predict their operation.

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References

Andrews, E.D., 1983. Entrainment of gravel from naturally sorted riverbed material. Geological Society of America Bulletin 94, 1225–1231.

Ashida, K., Takahashi, T., Sawada, T., 1981. Sediment yield and transport on a mountainous small watershed. Bulletin of the Disaster Prevention Research Institute 26, 119–144.

Ashworth, P.J., Ferguson, R.I., 1989. Size-selective entrainment of bed load in gravel bed streams. Water Resources Research 25, 627–634.

Best, D.W., Keller, E.A., 1986. Sediment storage and routing in a steep boulder-bed, rock-controlled channel. In: DeVries, J. (Ed.), Proceedings of the Chaparral Ecosystems Research Conference. California Water Resources Center Report, vol. 62. University of California at Davis, Davis, CA, pp. 45–55.

Blizard, C.R., Wohl, E.E., 1998. Relationships between hydraulic variables and bed load transport in a subalpine channel, Colorado Rocky Mountains, U.S.A. Geomorphology 22, 359–371.

Environmental Systems Research Institute, 1983. States (digital coverage). Spheroid Projection. Environmental Systems Research Institute, Redlands, CA.

Ergenzinger, P., 1992. Riverbed adjustments in a step-pool system: Lainbach, Upper Bavaria. In: Billi, P., Hey, R.D., Thorne, C.R., Tacconi, P. (Eds.), Dynamics of Gravel-Bed Rivers. Wiley, Chichester, UK, pp. 415–429.

Fenneman, N.M., Johnson, D.W., 1946. Physical divisions of the United States (Physiography). U.S. Geological Survey, Washington, DC, 1:7,000,000 scale. Original map in polyconic projection and digital coverage available on-line from U.S. Geological Survey in Albers Equal Area Projection at http://water.usgs.gov/lookup/getspatial?physio.

Fowler, W.P., 1994. Woody debris dynamics in zero order streams of the Ouachita National Forest: preliminary findings. In: Baker, J.B. (Compiler), Proceedings of the Symposium on Ecosystem Management Research in the Ouachita Mountains: Pretreatment Conditions and Preliminary Findings, Hot Springs, AR. General Technical Report SO-112. USDA. Forest Service, Southern Forest Research Station, New Orleans, LA, pp. 182–185.

Gintz, D., Hassan, M., Schmidt, K., 1996. Frequency and magnitude of bedload transport in a mountain river. Earth Surface Processes and Landforms 21, 433–445.

Grant, G.E., Swanson, F.J., Wolman, M.G., 1990. Pattern and origin of stepped-bed morphology in high-gradient streams, Western Cascades, Oregon. Geological Society of America Bulletin 102, 340–352.

Hayward, J.A., 1980. Hydrology and stream sediments in a mountain catchment. Tussock Grasslands and Mountain Lands Institute. Special Publication, vol. 17. Lincoln College, Canterbury, New Zealand. 236 pp.

Heede, B.H., 1972. Flow and channel characteristics of two high mountain streams. Research Paper RM-96. US Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO. 12 pp.

Hoey, T., 1992. Temporal variations in bedload transport rates and sediment storage in gravel-bed rivers. Progress in Physical Geography 16 (3), 319–338.

Komar, P.D., Shih, S., 1992. Equal mobility versus changing bed load grain sizes in gravel-bed stream. In: Billi, P., Hey, R.D., Thorne, C.R., Tacconi, P. (Eds.), Dynamics of Gravel-Bed Rivers. Wiley, Chichester, UK, pp. 73–93.

Kuhnle, R.A., 1992. Fractional transport rates of bed load on Goodwin Creek. In: Billi, P., Hey, R.D., Thorne, C.R., Tacconi, P. (Eds.), Dynamics of Gravel-Bed Rivers. Wiley, Chichester, UK, pp. 141–155.

Laronne, J.B., Carson, M.A., 1976. Interrelationships between bed morphology and bed-material transport for a small, gravel-bed channel. Sedimentology 23, 67–85.

Marion, D.A., 2001a. Bed load transport rates at near-bankfull flows in a step-pool channel. Proceedings of the Seventh Federal Interagency Sedimentation Conference, Reno, NV. U.S. Subcommittee on Sedimentation, Washington, D.C., USA, pp. III-32–III-39.

Marion, D.A., 2001b. Field experiments on channel morphology and bedload interactions at near-bankfull flows in a small, step-pool stream in the Ouachita Mountains of Arkansas. PhD dissertation, University of Iowa, Iowa City.

Marion, D., Malanson, G., in press. Ordination of wood vegetation in a Ouachita National Forest watershed. In: Guldin, J.M. (Ed.), Proceedings of the Symposium on Ecosystem Management Research in the Ouachita and Ozark Mountains, Hot Springs, AR. US Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC.

Marion, D.A., Weirich, F., 1997. Simulating storm events. Environmental Testing and Analysis 6 (4), 15–16.

Marion, D.A., Weirich, F., 1999. Fine-grained bed patch response to near-bankfull flows in a step-pool channel. In: Olsen, D.S., Potyondy, J.P. (Eds.), Wildland Hydrology, Proceedings of the Specialty Conference, Bozeman, MT. American Water Resources Association, Herndon, VA, pp. 93–100.

Megahan, W.F., Nowlin, R.A., 1976. Sediment storage in channels draining small forested watersheds in the mountains of central Idaho. Proceedings of the Third Federal Inter-Agency Sedimentation Conference, Denver, CO, pp. 4-115–4-126. Water Resource Council, Sedimentation Committee, place of publication unknown.

Nakamura, F., Swanson, F.J., 1993. Effects of coarse woody debris on morphology and sediment storage of a mountain stream system in Western Oregon. Earth Surface Processes and Landforms 18, 43–61.

Ouachita National Forest. Contours, roads, streams, and water (digital coverages). Stateplane projection. Ouachita National Forest, Hot Springs, AR.

Parker, G., Klingeman, P.C., McLean, D.G., 1982. Bedload and size distribution in paved gravel-bed streams. American Society of Civil Engineers, Proceedings, Journal of the Hydraulics Division 108 (HY4), 544–571.

Ryan, S.E., 1994. Effects of transbasin diversion on flow regime, bed load transport, and channel morphology in Colorado mountain streams. PhD dissertation, University of Colorado, Boulder, CO.

Schmidt, K.H., Ergenzinger, P., 1992. Bedload entrainment, travel lengths, step lengths, rest periods-studied with passive (iron, magnetic) and active (radio) tracer techniques. Earth Surface Processes and Landforms 17, 147–165.

Shields, I.A., 1936. Application of similarity principles and turbulence research to bed-load movement. Berlin. Translated by Ott, W.P. and van Uchelen, J.C. Publication no. 167. California Institute of Technology, Hydraulics Laboratory, Pasedena, CA, 36 pp. In German.

Shih, S., Komar, P.D., 1990. Differential bedload transport rates in a gravel-bed stream: a grain-size distribution approach. Earth Surface Processes and Landforms 15, 539–552.

Sneed, E.D., Folk, R.L., 1958. Pebbles in the lower Colorado River, Texas, a study in particle morphogenesis. Journal of Geology 66, 114–150.

Warburton, J., 1992. Observations of bed load transport and channel bed changes in a proglacial mountain stream. Arctic and Alpine Research 24 (3), 195–203.

Whittaker, J.G., 1987. Sediment transport in step-pool streams. In: Thorne, C.R., Bathurst, J.C., Hey, R.D. (Eds.), Sediment Transport in Gravel-Bed Rivers. Wiley, Chichester, pp. 545–570.

Whittaker, J.G., Davies, T.R.H., 1982. Erosion an sediment transport processes in step-pool torrents. In: Walling, D.E. (Ed.), Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield: Proceedings of the Exeter symposium. IAHS Publication, vol. 137. International Association of Hydrological Sciences, Wallingford, UK, pp. 99–104.

Wiberg, P.L., Smith, J.D., 1987. Calculations of the critical shear stress for motion of uniform and heterogeneous sediments. Water Resources Research 23 (8), 1471–1480.