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PREDICTION OF BED LOAD TRANSPORT ON SMALL GRAVEL-BED STREAMS

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ABSTRACT

Rates and size distributions of bed load were calculated using 3 transport relations and compared to data collected on three streams with sand-gravel beds in the Goodwin Creek Experimental Watershed in north central Mississippi, USA. Bed load transport rates were greatly over predicted by two of the three relations with the third yielding values closer to the measured values. Predictions of the median size of the bed load as compared to measured values were within about 100 percent for all three relations. The effect of bed material size distributions on the predicted rates from the 3 relations was evaluated and it was found that bed material sizes substantially larger than those measured in the field were needed to yield predicted rates close to those measured in the field for two of the three relations. The third relation yielded transport rates within about 50 percent of the measured rates using the measured bed material surface size distribution as input.

1. INTRODUCTION

Accurate prediction of bed load transport on streams with bed material composed of sand-gravel mixtures is difficult. Yet knowledge of bed load transport is important for assessing the stability of channel bed and banks and necessary for determining total sediment load. Total sediment load is a critical component needed for effective channel and watershed management. Tools are needed to accurately estimate the rate of sand and gravel transport in agricultural and other watersheds. Bed load sediment transport relations generally relate the amount of sediment in transport to a function of flow strength and sediment size. In the past, some measure of the mean or median grain size was generally used to represent the size of the sediment available for transport. These have been replaced by relations that treat size fractions individually and determine the effect of the different grain sizes on one another by using hiding or exposure coefficients. In recent years, some researchers have identified the bed surface size distribution as the characteristic grain sizes to use in bed load transport relations. While this reasoning has merit, determination of the bed surface size distribution for a given flow in field channels is problematic. In this study, the effect of the bed surface size distribution on the prediction of the transport rate and size distribution of the bed load using the transport relations of Parker (1990 -PG), Wilcock and Crowe (2003 -WC), and Wu et al. (2000-WWJ) is explored. The PG relation deals only with gravel sizes (> 2mm), while the WC and

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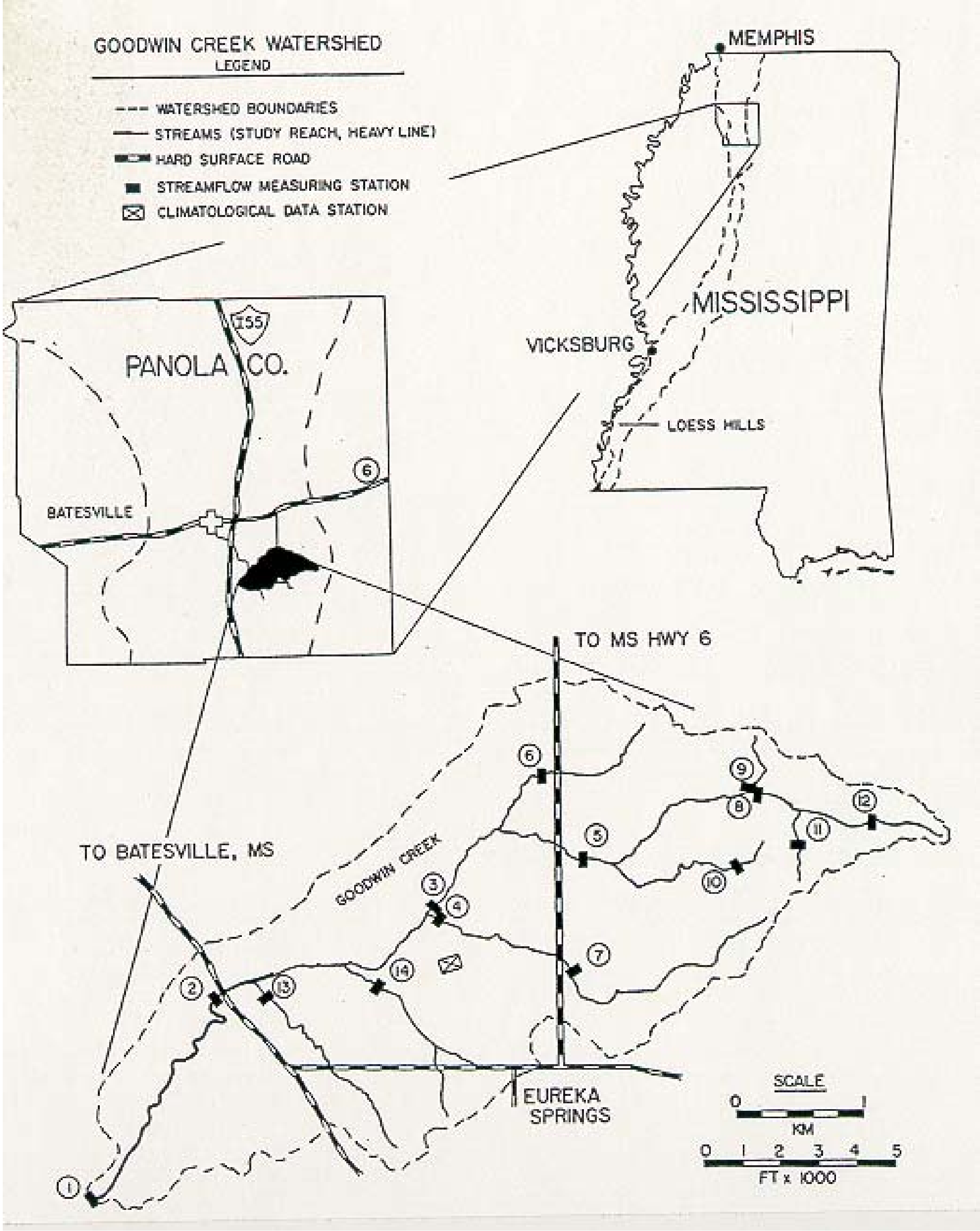

Figure 1. Goodwin Creek Experimental Watershed, Panola County, Mississippi, USA. The stream gauging station sites are labeled with circled numbers.

WWJ relations consider both sand and gravel sizes. Bed load transport data collected on three streams with bed material size distributions consisting of sand and gravel were used to test the predictions of the PG, WC, and WWJ relations. These streams are located in the Goodwin Creek Experimental Watershed (GCEW) in north central Mississippi, USA.

2. FIELD CONDITIONS

The GCEW is located in the bluff-hills region of north central Mississippi, USA, a region of relatively steep slopes and active erosion and sedimentation (Figure 1). Runoff at stream 2 consists of low base flows most of the time with streams 13 and 14 drying out completely during the summer months. Flow in the channels sufficient to move the coarsest bed material sediment occurs on average from 12 to 15 times per year, usually during runoff events caused by the intense rainfall of the convective storms common to this region. The watersheds of the three streams (streams 2, 13, 14) drain 17.9, 1.24, and 1.63 km^2 , respectively. Conditions at the three sampling sites are summarized in Table 1. The bed load samples on stream 2 were collected using modified Helly-Smith type samplers (Kuhnle , 1992a), while recording pit-type samplers were used at streams 13 and 14 (Kuhnle, 1991, 1992b). The number of individual measurements of bed load were 488, 2679, and 2011 on streams 2, 13, and 14, respectively. These measurements were binned by flow strength and mean transport rates and mean grain size distributions were calculated for each mean flow strength bin. Bed material surface size distributions were calculated from the mean of 12 to 20 samples collected between runoff events at base flow at the three sites.

Table 1. Summary of conditions at sampling sites.

stream	bed width (m)	bed slope	bed material size range (mm)	bed material surface median (mm)	percent sand in bed material
2	39.	0.003	0.15 - 64.0	11.73	25.2
13	3.0	0.010	0.09 - 64.0	5.53	38.9
14	3.4	0.008	0.13 - 64.0	8.51	34.4

3. TRANSPORT RELATIONS

The three transport relations were developed using different data sets. The PG relation was developed using only field data from gravel-bed streams in which the sand fraction (< 2 mm) was not utilized. The WC relation was developed with transport data collected in one laboratory flume using various mixtures of sand and gravel as bed material. The WWJ relation was developed from a combination of field and laboratory data and has the widest potential conditions of application of the three relations (van der Scheer et al., 2002). Excel-based programs made available by the authors over the internet were used to make calculations using the PG and WC transport relations. A Fortran program supplied by the senior author was used to make calculations of the WWJ relation. Rates and size distributions of the bed load were calculated using flow strength and bed surface size distribution as the inputs (forward calculation). The WC relation was also used to do reverse calculations in which bed surface size distributions and shear velocities were calculated with inputs of bed load transport rate and bed load grain size distribution (Wilcock and DeTemple, 2005).

4. COMPARISON OF MEASURED AND CALCULATED VALUES

Comparisons between measured and calculated rates of bed load transport and the median grain size of the bed load were made using data from the three streams and the calculations from the three transport relations. Shear velocities (u*) for the three streams were calculated as

$$u^* = \sqrt{gRS_0} \tag{1}$$

where g is the acceleration of gravity, R is the hydraulic radius, and S_0 is the slope of the water surface. These values were calculated using data from measured cross-sections and USGS bubble gauges to measure the height of the water surface at each field site. Flow strength was calculated in the WWJ relation using measured values of hydraulic variables at each field site. The measured size distribution of the bed material surface at the three sites was used as input for the three transport relations in the following comparisons.

4.1 Median Grain Sizes

The comparisons between median sizes of the calculated and measured bed load are shown for the three streams in Figure 2. The differences between measured and calculated values were quantified using the percent absolute difference (D_{fa}):

$$D_{fa} = \frac{100 * |D_{50m} - D_{50c}|}{D_{50m}} \tag{2}$$

where D_{50m} and D_{50c} are the measured and calculated median grain size of the bed load sediment, respectively. The percent differences for the PG relation were found to be the lowest of the three relations (Table 2). This is likely due to the fact that the PG relation does not deal with the complicating effects of the sand contained in the bed material and bed load. Of the WC and WWJ relations, the percent differences predicted with the WWJ are substantially less than those of the WC (Figure 2, Table 2).

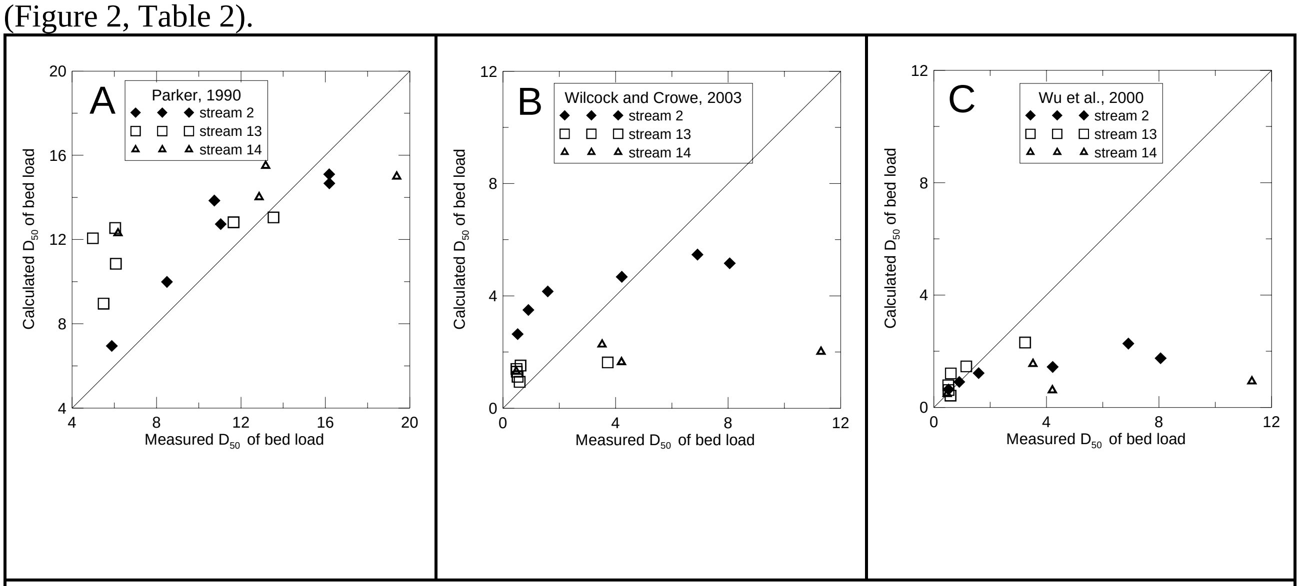

Figure 2. Comparison between measured median sizes of bed load to calculated values from (A) PG relation, (B) WC relation, and (C) WWJ relation. Line represents perfect agreement.

4.2 Bed Load Transport Rates

Measured bed load transport rates were compared to calculated values from the three transport relations (Figure 3). The percent absolute differences were calculated using eq. 2, but with measured and calculated values of bed load transport instead of median grain diameter (Table 3).

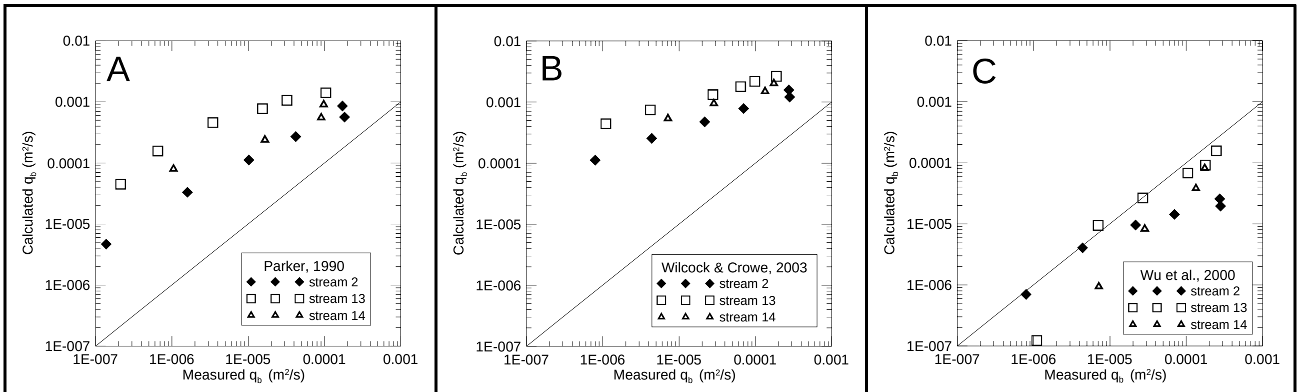

Figure 3. Comparison between measured and calculated bed load transport rates (q_b) from (A) PG relation, (B) WC relation, and (C) WWJ relation. Lines represent perfect agreement.

Table 2. Percent differences between measured and calculated D50 of bed load

stream#	PG relation			WC relation			WWJ relation		
	min.	max.	mean	min.	max.	mean	min.	max.	mean
2	6.7	29.0	16.0	10.9	407.7	154.3	1.1	78.3	43.1
13	3.6	142.2	67.6	37.4	191.7	115.0	19.2	101.7	43.4
14	4.4	31.6	19.0	35.3	206.8	84.5	2.1	91.8	58.8

Table 3. Percent differences between measured and calculated bed load transport rates

stream#	PG relation			WC relation			WWJ relation		
	min.	max.	mean	min.	max.	mean	min.	max.	mean
2	208.	3291.	1235.	329.	13970.	3930.	7.5	93.1	56.4
13	1252.	23906.	11244.	1006.	39991.	8432.	1.5	88.8	41.0
14	304.	3074.	1429.	858.	8900.	3289.	53.4	86.9	70.7

It is clear the PG and WC relations over estimate the transport rate by a large margin. The WWJ relation, however, provides estimates of the transport rates that are closer to the measured values but still with mean percent differences up to 71 percent.

Table 4. Results from reverse calculations using WC relation

meas shear velocity (m/s)	meas D50 of bed load (mm)	calc D50 of bed material surface (mm)	calc shear velocity (m/s)	ratio calc to meas shear velocity
stream 2				
0.114	0.52	27.94	0.076	0.67
0.132	0.90	26.75	0.091	0.69
0.149	1.59	31.41	0.114	0.76
0.165	4.22	17.17	0.115	0.70
0.181	8.06	20.97	0.151	0.84
0.192	6.91	21.62	0.149	0.77
stream 13				
0.129	0.59	37.85	0.083	0.64
0.148	0.52	30.74	0.083	0.56
0.160	0.52	28.78	0.082	0.51
0.169	0.49	5.14	0.076	0.45
0.175	0.51	17.84	0.089	0.51
0.182	0.58	5.99	0.088	0.49
0.188	0.60	15.46	0.111	0.59
0.191	0.62	17.85	0.112	0.59
0.196	1.15	12.17	0.120	0.61
0.200	3.72	19.90	0.137	0.69
0.202	3.24	17.66	0.138	0.69
stream 14				
0.144	0.47	27.34	0.084	0.58
0.163	4.21	24.74	0.115	0.71
0.181	11.3	25.70	0.145	0.80
0.194	3.52	17.78	0.132	0.68

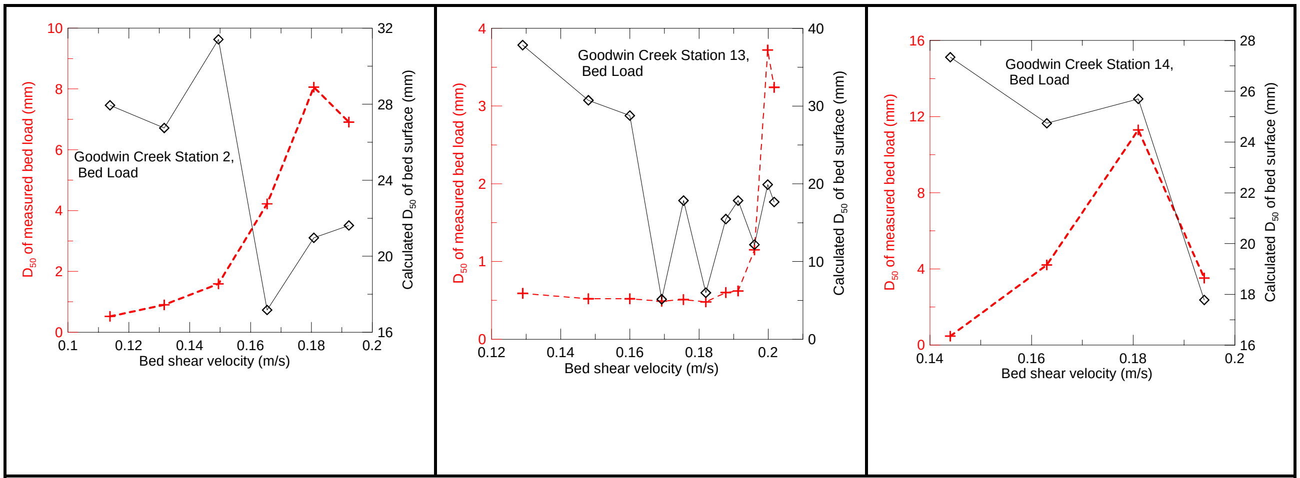

Figure 4. Median sizes of measured bed load and calculated bed material surface grain sizes from reverse calculation of WG relation.

4.3 Reverse Calculations of Bed Material Surface Size Distributions and Shear Velocities Using WC Relation

Reverse calculations in which the bed surface size distribution and bed shear velocity necessary to transport the measured rate and size distribution of bed load sediment at the three sites were conducted using the WC relation (Wilcock and DeTemple, 2005). An Excel-based program provided by the author of the WC relation was used for these calculations. The median sizes of the bed material predicted by the reverse calculation of the WC relation (Table 4, Figure 4) ranged from 17-31, 5-38, and 18-27 mm for streams 2, 13, and 14, respectively. For all three streams the predicted bed material surface size distribution generally decreased with increasing shear velocity. Shear velocities predicted with the reverse calculation of the WC relation were on average 0.74, 0.57, and 0.69 those of the measured values for streams 2, 13, and 14, respectively (Table 4). The bed material surface size distributions predicted by the WC relation for the lower flows (Figure 4) are substantially greater than those measured on the bed of the three streams on Goodwin Creek.

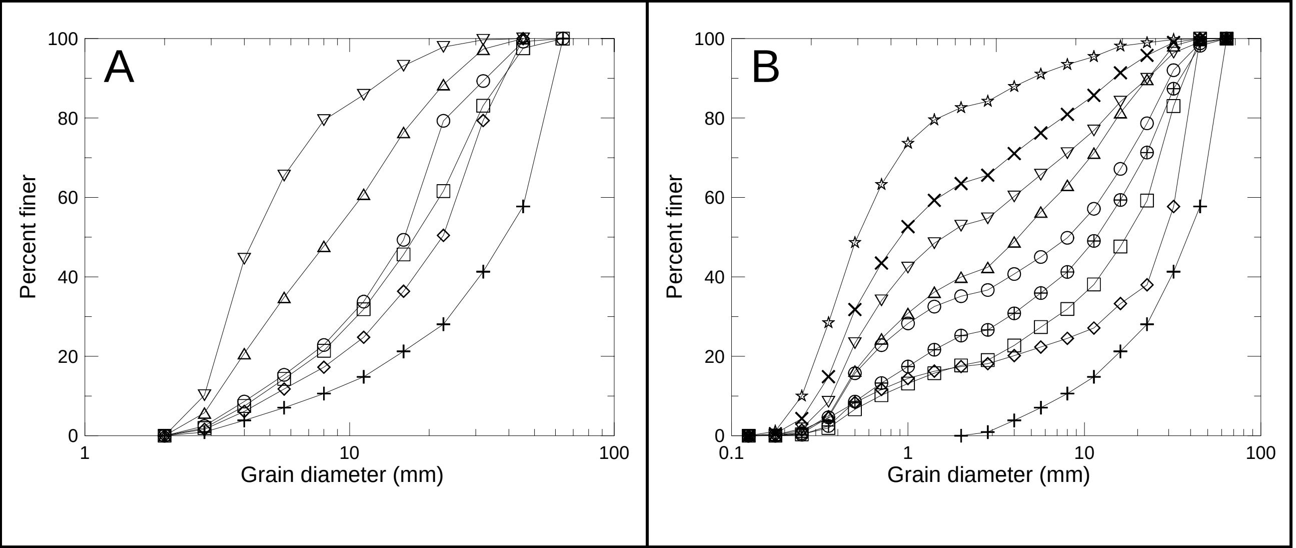

Figure 5. Bed material surface size distributions used with (A) PG relation and, (B) with WC and WWJ relations.

4.4 Sensitivity of Relations to Bed Material Surface Size Distribution

One of the difficulties of applying surface-based transport relations is accurate knowledge of the bed material surface size distribution for a given flow condition. There is evidence from laboratory flumes that bed surface grain distributions change with flow strength during active transport (Dietrich et al., 1989; Kuhnle, 1989; Lisle et al., 1993; Parker et al., 1982). This change in bed material surface size distribution with flow strength has been attributed to an artifact of the experiments that is not necessarily representative of field channels by Wilcock and DeTemple (2005). To shed light on this problem, a range of bed material size distributions (Figure 5) and flow strengths were used as inputs to the three transport relations and the results compared with the measured data from stream 2 (Figures. 6 and 7). Bed material size distributions with median grain diameters from 4.38 to 38.44 mm for the PG relation and 0.52 to 38.44 for the WC and WWJ relations were used for the comparisons (Figure 5). For median grain sizes of the bed load, the predictions of the PG relation bracketed the measured medians from stream 2 (Figure 6). The median grain sizes of bed load predicted by the WC relation were within the range of the measured data, however the change with increase of shear stress of the predicted values was less than that of the measured data. Except for the values predicted using the coarsest bed material size distribution, the median grain sizes predicted by the WWJ relation were generally finer than those of the measured data.

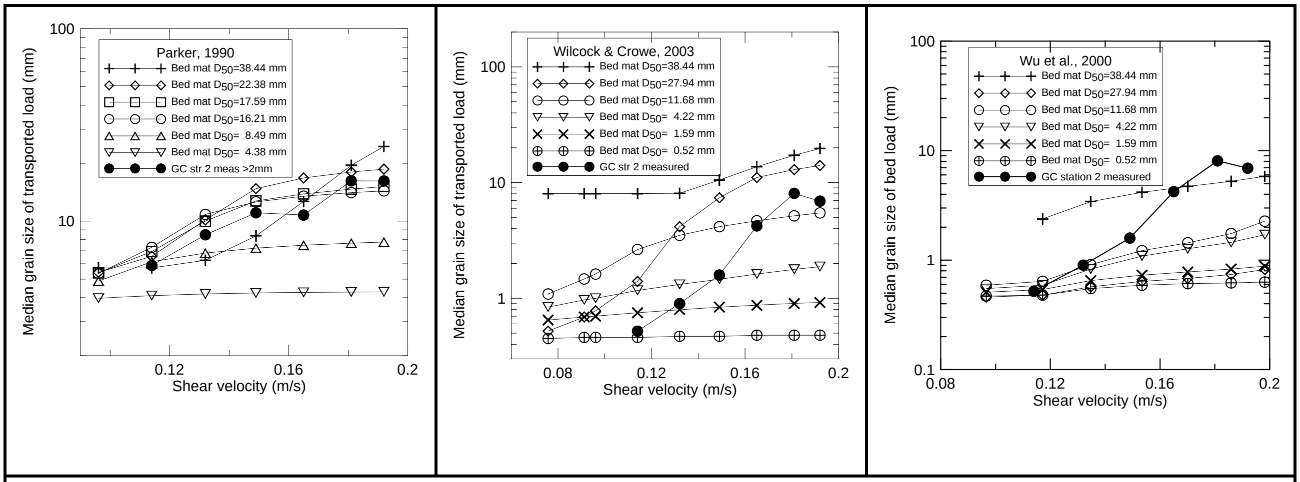

Figure 6. Median grain size of calculated bed load for a range of bed material surface size distributions. For clarity, not all results were plotted.

Bed load transport rates predicted by the PG and WC relations were substantially greater than the measured rates for all bed material size distributions except for the coarsest one (Figure 7). The range of bed load rates predicted by the WWJ relation bracketed the measured rates for low to medium values of shear stress, while for higher values of shear stress, the predicted values were somewhat less than the measured bed load rates (Figure 7).

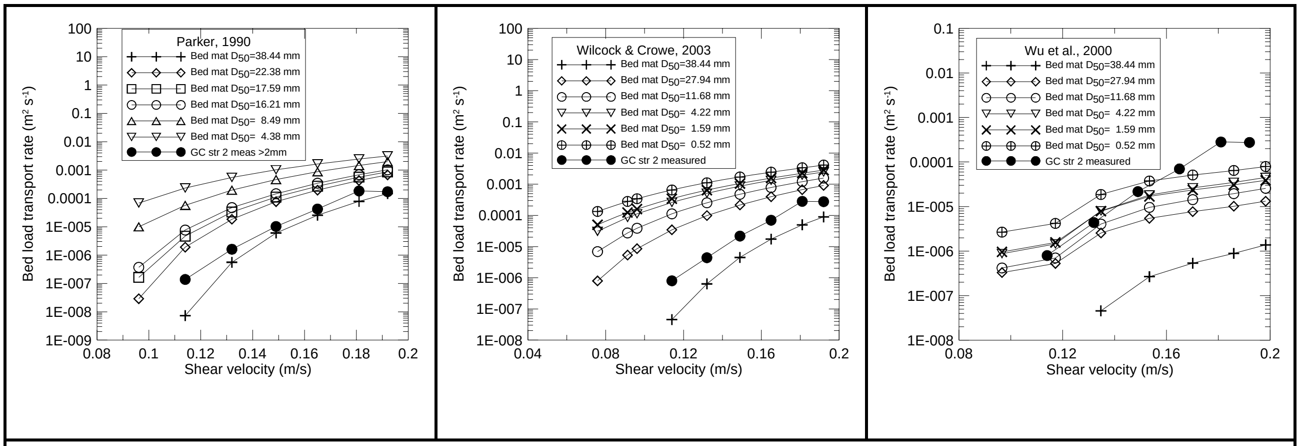

Figure 7. Calculated bed load rates for a range of bed material surface size distributions. For clarity, not all results were plotted.

The sensitivity of the three transport relations to bed material size distributions is a key element to their effective use for predicting bed load transport rates on streams and rivers. Bed surface size distributions in channels in which the bed material is composed of mixtures of sand and gravel are difficult to measure or predict accurately and may change appreciably over the expected range of sediment-transporting flows. Therefore, the usefulness of bed load transport relations, in which the bed material surface size distribution is a primary input parameter, on streams and rivers is necessarily dependent on the accuracy of the tools available to measure or predict the size distribution of the bed material surface.

5. CONCLUSIONS

The comparison of three bed load transport relations to measured data from three channels on the Goodwin Creek Experimental Watershed yielded mixed results. The predictions of median grain size of bed load as compared to the measured values were within about 100 percent for the three relations. Two of the relations yielded bed load transport rate predictions greatly above those measured, while one yielded rates within about 50 percent of the measured rates. An analysis of the sensitivity of the bed load transport relations to bed material surface size distributions demonstrated the difficulties involved with using bed material surface size distributions to predict transport rates on field channels. Improved methods to accurately predict bed material surface size distributions are needed if reliable prediction of sand and gravel transport in the field is to be accomplished.

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