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DEFINING PHASES OF BEDLOAD TRANSPORT USING PIECEWISE REGRESSION

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ABSTRACT

Differences in the transport rate and size of bedload exist for varying levels of flow in coarse-grained channels. For gravel-bed rivers, at least two phases of bedload transport, with notably differing qualities, have been described in the literature. Phase I consists primarily of sand and small gravel moving at relatively low rates over a stable channel surface. Transport rates during Phase II are considerably greater than Phase I and more coarse grains are moved, including material from both the channel surface and subsurface. Transition from Phase I to Phase II indicates initiation and transport of grains comprising the coarse surface layer common in steep mountain channels. While the existence of different phases of transport is generally acknowledged, the threshold between them is often poorly defined. We present the results of the application of a piecewise regression analysis to data on bedload transport collected at 12 gravel-bed channels in Colorado and Wyoming, USA. The piecewise regression recognizes the existence of different linear relationships over different ranges of discharge. The inflection, where the fitted functions intersect, is interpreted as the point of transition from Phase I to Phase II transport; this is termed *breakpoint*. A comparison of grain sizes moved during the two phases shows that coarse gravel is rarely trapped in the samplers during Phase I transport, indicating negligible movement of grains in this size range. Gravel larger than about D_{16} of the channel surface is more consistently trapped during Phase II transport. The persistence of coarse gravel in bedload samples provides good evidence that conditions suitable for coarse grain transport have been reached, even though the size of the sediment approaches the size limits of the sampler (76 mm in all cases). A relative breakpoint (R_{br}) was defined by the ratio between the discharge at the breakpoint and the 1·5-year flow (a surrogate for bankfull discharge) expressed as a percentage. The median value of R_{br} was about 80 percent, suggesting that Phase II begins at about 80 percent of the bankfull discharge, though the observed values of R_{br} ranged from about 60 to 100 percent. Variation in this value appears to be independent of drainage area, median grain size, sorting of bed materials, and channel gradient, at least for the range of parameters measured in 12 gravel-bed channels. Published in 2002 by John Wiley & Sons, Ltd.

KEY WORDS: bedload transport; gravel-bed channels; Phase I and Phase II transport; piecewise regression; breakpoint

INTRODUCTION

Bedload transport in coarse-grained channels has been described as occurring in phases (e.g. Jackson and Beschta, 1982; Carling, 1988; Ashworth and Ferguson, 1989; Warburton, 1992), whereby transport rates are relatively low until a certain flow level is reached (Phase I). Transport rates increase substantially once this flow is exceeded, typically accompanied by an increase in the size of material moved (Phase II). Phase I transport consists primarily of sand moving over stable bed particles while Phase II consists of both sand and gravel movement over a stable or semi-mobile bed. Phase I likely represents remobilization of finer materials deposited from a previous transport event in pools and tranquil areas of the bed (Paola and Seal, 1995; Lisle, 1995), whereas Phase II transport represents initiation and transport of grains from the coarse surface layer common in steep mountain channels. The larger surface grains, dislodged at higher flows, release finer grains from the subsurface layer, producing a rapid increase in the bedload transport rate that is significantly different from Phase I (Milhous, 1973; Jackson and Beschta, 1982; Emmett, 1976; Beschta, 1987; Ashworth

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and Ferguson, 1989). The point at which this shift in phase occurs is important for defining the magnitude of flows needed to move the wide range of sediment sizes in and delivered to coarse-grained channels. The beginning of Phase II is thought to occur at or near the 'bankfull' discharge (Parker, 1979; Parker *et al*., 1982; Jackson and Beschta, 1982; Andrews, 1984; Andrews and Nankervis, 1995), but the threshold may be poorly defined. While a substantial amount of sediment is moved during Phase II, the duration is relatively short and so a considerable amount of the total sediment load may be moved during Phase I transport prior to general mobilization of the channel surface (Andrews and Smith, 1992; Wilcock and McArdell, 1993; Lisle, 1995).

Speculatively, the relative discharge at which there is a change in phase may vary with the character of the channel and the nature of sediment supply (Laronne and Carson, 1976; Andrews and Nankervis, 1995; Lisle, 1995; Dietrich *et al*., 1989). Here, we define relative discharge as the flow at which Phase II begins relative to the discharge with a 1·5-year return frequency, a surrogate that commonly corresponds to bankfull flow. There are a number of factors particular to coarse-grained channels that control the initiation of transport and may influence the discharge at which a change in phase occurs; these include differences in relative roughness (Church, 1978; Bathurst, *et al*., 1983), clustering of individual grains (Reid and Frostick, 1984; Laronne and Carson, 1976; Reid, *et al*., 1985), geometry of bed particles (Kirchner *et al*., 1990; Buffington, *et al*., 1992), imbrication (Mantz, 1980), and compaction or packing of surface grains (Church, 1978; Reid *et al*., 1985; Hassan and Reid, 1990). For instance, the change in phase may occur at a lower relative discharge in more distal, flatter, finer-grained channels where, observationally, the grain size of the bedload is closer to that of the channel bed (e.g., Lisle, 1995). However, we are unable to test this hypothesis without clear definition of the flows at which the change in phase occurs.

In this paper, we evaluate phases of bedload transport in coarse-grained channels and present an objective statistical procedure for determining the discharge at which the transition from Phase I to Phase II transport occurs. Specifically, we use a piecewise regression model, where two or more continuous functions are fitted to measured bedload transport rates, to identify the inflection (or *breakpoint*) formed where the fitted functions intersect. The breakpoint is interpreted as the discharge at which the change in phase takes place. The hypothesis is that distinctly different statistical characteristics and sedimentological factors are associated with flows that are less than or greater than the breakpoint discharge. The fitted line for flows that are less than the breakpoint discharge (Phase I transport) is expected to have a lower slope and less variability due to the fact that bedload at these discharges consists primarily of small quantities of sand-sized materials. In contrast, the fitted line for flows greater than the breakpoint is expected to have a significantly steeper slope and more variability in transport rates due to the physical breakup of the armour layer, the availability of subsurface material, and subsequent changes in both the sizes and volumes of material in transport.

Generating a breakpoint with piecewise regression requires a large number of measurements of bedload transport collected over a wide range of flows, including the 1·5-year (bankfull) and greater discharges. Ideally, there should be no substantial gaps in the distribution of samples, particularly at higher flows. There are, however, few sets of bedload data that meet these stringent criteria. We present and demonstrate the application of the piecewise regression procedure for transport rates measured at eight sites on the Fraser Experimental Forest near Fraser, Colorado, where 100 to 200 samples per site were collected between 1992 and 1997. Flow measurements range from 0·1 to nearly two times the bankfull discharge. The piecewise regression model is evaluated further using data from four streams in Colorado and Wyoming with comparable ranges of flow and numbers of observations.

OBJECTIVES

The objective of this paper is to demonstrate the best-fit functions between measured bedload and discharge and provide support for the selection of a two-piece linear regression model with a distinct breakpoint that can be bounded with confidence limits by applying bootstrapping techniques. Though piecewise linear regression is applied only to total rates of transport, we also evaluate differences in the grain sizes captured at discharges greater than and less than the breakpoint to demonstrate distinctions in the sizes of particles moved under different phases. Finally, the breakpoint estimates for several coarse-grained sites are compared to determine

whether differences in basin and channel characteristics explain variation in the relative discharge associated with the onset of Phase II transport.

SITE DESCRIPTION

St Louis Creek is a single-thread, fourth-order, perennial stream located within the subalpine environment of the Fraser Experimental Forest (Figure 1). East St Louis and Fool Creeks are second-order tributaries to

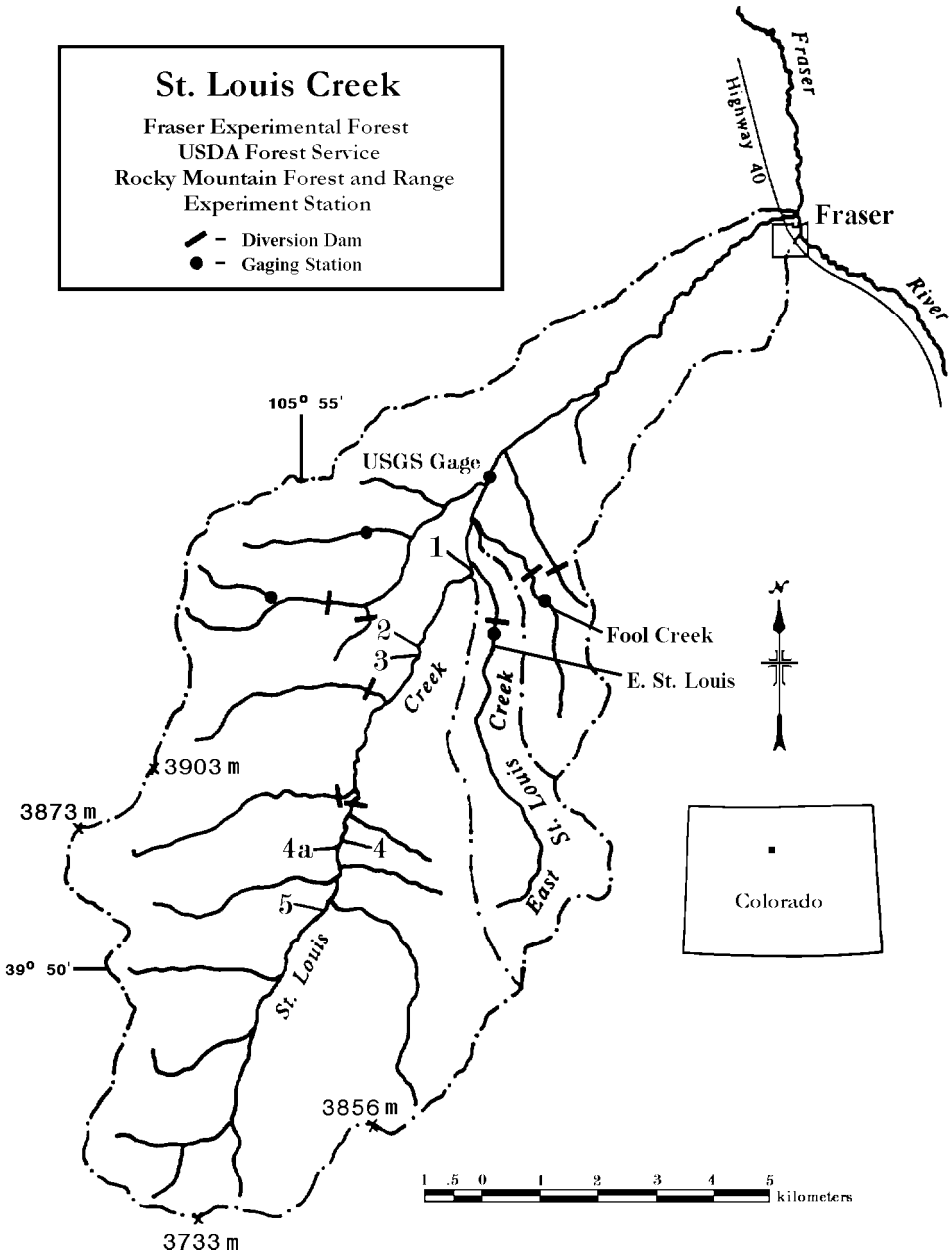

Figure 1. Map of study sites at Fraser Experimental Forest near Fraser, Colorado. Numbers on the main stem of St Louis Creek correspond to those in Table I. Lines with labels 'E. St. Louis' and 'Fool Creek' indicate location of sampling sites relative to gauges and diversions

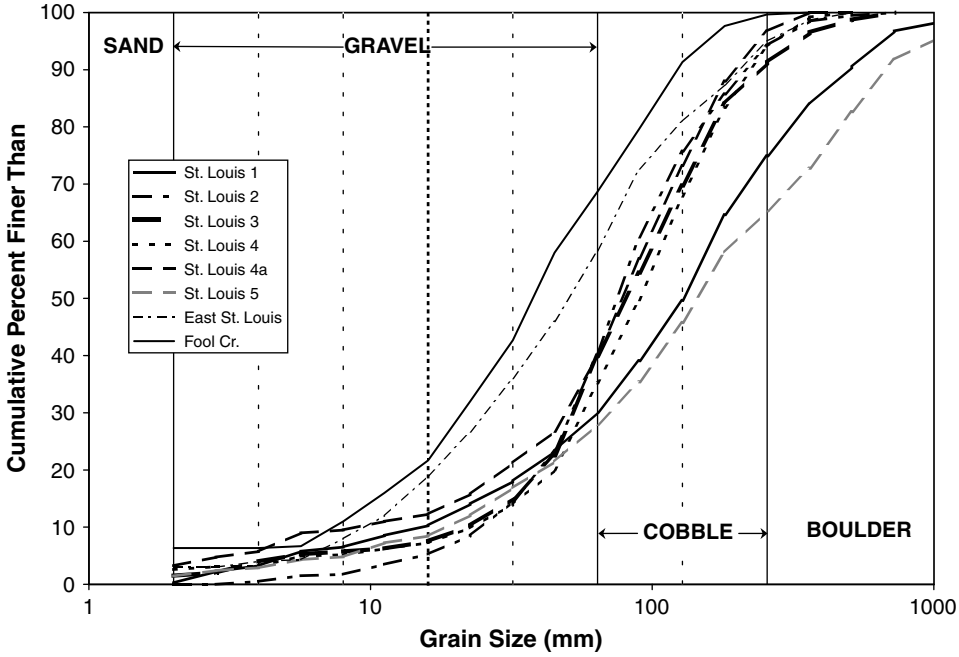

Figure 2. Distribution of particle sizes from the bed surfaces of the eight study sites at the Fraser Experimental Forest. Distribution of the surface sampled using Wolman (1954) pebble counts between 1996 and 1998. Classification of sand, gravel, cobble, and boulder based on Guy (1969)

St Louis Creek. Channels are characterized by moderate to steep slopes (0·02 to 0·05), with beds composed largely of gravels, cobbles, and boulders (Figure 2) derived from Quaternary glacial outwash and tills. The median grain size (D_{50}) of the channel surface ranges from 38 to 146 mm (Table I). The D_{50} of the surface is between 3 and 11 times that of the subsurface (Table I) indicating the channels are strongly to very strongly armoured. The basin is underlain by granite, gneiss, and schist bedrock. Mass wasting processes in the region are relatively limited and bedload in subalpine streams, in general, is derived primarily from bank erosion and channel scour (Caine, 1986). Channel banks are stable over a wide range of flows and have dense to moderately dense vegetative cover composed of: (1) subalpine tree species Engleman spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and, to a lesser extent, lodgepole pine (*Pinus contorta*); (2) willows (*Salix* species); and (3) numerous herbaceous species (i.e. *Carex* species and grasses).

The average yearly temperature recorded at the Fraser Experimental Forest is 2 °C, with a mean January temperature of −9 °C and a mean July temperature of 13 °C. The average annual precipitation is 610 mm, ranging from 380 to 760 mm; two-thirds falls as snow. Ninety-five per cent of the total annual runoff occurs during snowmelt in spring (Gartska *et al*., 1958). Water is diverted from the St Louis system at several points (Figure 1); three of the studied sites are located in channels from which an average of 40 per cent of the total annual flow is diverted (Ryan, 1994). However, water was rarely diverted at high flow during bedload sampling periods.

METHODS

Collection and analysis of field data

Data on water and bedload discharges were collected at eight sites at the Fraser Experimental Forest, including three boulder-bed (step–pool) and five cobble-bed (pool–riffle or plane bed) channels (Figure 1, Table I). Sites were selected using slope, particle size, channel topography, and valley floor constraint criteria and are typical of channels in a subalpine riparian forest environment (Ryan, 1994). Cross-sections in

Table I. Selected characteristics for eight sites in St Louis Creek catchment

Site	Channel topography	Flow management	Bankfull width (m)	Water surface slope* ($m\ m^{-1}$)	Mean bankfull depth (m)	Mean bankfull velocity ($m\ s^{-1}$)	Median bed particle size (mm)	Ratio surface D_{50} to subsurface D_{50}	Drainage area (km^2)	Number of years sampled
St Louis 1	Step–pool	Diversion	6·8	0·040	0·47	1·38	129	7·8	55·6	5
St Louis 2	Plane bed	Diversion	7·6	0·020	0·43	1·46	76	5·4	54·2	5
St Louis 3	Riffle	Diversion	9·3	0·019	0·36	1·36	82	5·0	54·0	5
St Louis 4	Plane bed	Free-flowing	7·0	0·024	0·38	1·35	91	7·3	33·8	5
St Louis 4a	Riffle	Free-flowing	8·2	0·020	0·34	1·21	79	6·2	33·5	4
St Louis 5	Step–pool	Free-flowing	5·3	0·050	0·38	1·34	146	11	21·3	5
E St Louis Creek	Step–pool	Free-flowing	3·0	0·055	0·30	0·96	51	3·9	8·03	4
Fool Creek	Plane bed	Free-flowing	2·0	0·054	0·17	0·90	38	2·7	2·89	4

* Water surface slope measured over a channel reach (approximately 20 channel widths) reported here may differ from local water surface slope measured at lengths on the order of one to two channel widths at the cross-section that are published in reports elsewhere.

step–pool channels were located at the downstream end of a pool in an area largely free of large boulders. Cross-sections in pool–riffle and plane bed channels were located in straight or meander cross-over locations.

Bedload transport was sampled on a near-daily basis during several weeks between May and July in 1992, 1993, and 1995. Samples were collected less frequently in 1996 and 1997, except at sites 4 and 4a when bedload was sampled on the order of once every 4 hours in 1996 (Ryan, 1999). Bedload was collected using a hand-held Helley–Smith sampler (Helley and Smith, 1971) while wading in 1992 and from platforms suspended above the channel in later years (Martinez and Ryan, 2000). The sampler is constructed of 16 gauge sheetmetal, has a 76 × 76 mm orifice, 3·22 expansion ratio, and a 0·25 mm mesh catch bag. The upper size limit of the samples is therefore restricted to grains smaller than about 76 mm. We and others (e.g. Leopold, 1992; Lisle, 1995; Whiting *et al.*, 1999) have observed that a substantial portion of the material moved as bedload in coarse-grained channels is sand and small gravel, the majority of which will pass through the 76 mm orifice. Moreover, an analysis of sediment taken from settling ponds at sites on the Fraser Experimental Forest and Medicine Bow National Forest indicates that 85–95 per cent of the total load would pass through the Helley–Smith opening (Wilcox *et al.*, 1996; Ryan and Porth, 1999). Hence, while there are limitations on the grain sizes capable of entering the Helley–Smith sampler, cobbles (>64 mm) generally constitute a relatively small proportion of the total bedload transported in these systems.

Cross-channel measurements from nine to 14 equally spaced verticals were combined to determine the mean rate of bedload transport through the cross-section. Spacing between verticals ranged from 0·3 to 0·7 m, and the sampler was held in place for either 1 or 2 minutes at each position; importantly, sampling time per vertical was the same on any given traverse. Each composite sample, therefore, represents a spatially and temporally averaged rate measured over 20 to 30 minutes. Transport rate was calculated using the total weight of the sample (in kg) divided by the total sampling time and width of the sampler to obtain the unit bedload transport rate (in kg m^{-1} s^{-1}). This value is multiplied by the width of the channel to obtain the mean transport rate (in kg s^{-1}) through the cross-section. Flow was estimated for each sample using the mean discharge during the sampling period from the stage–discharge relationship, or by discharge measurement immediately following the bedload measurement. Mean velocity was measured at each vertical with Price AA or pygmy current meters. Discharge was calculated from the average velocity, interval width, and total depth measurements for channel subsections, using standard methods (Buchanan and Somers, 1969; Nolan and Shields, 2000).

Bedload samples were dried and sieved using standard sedimentological methods (Folk, 1968). Large organic matter was picked from the sample during processing and excluded from the total sample weight. Samples were separated into grain size classes using full phi sieves ranging from 0·25 to 64 mm. Rates of transport for particles finer than 4 mm are not discussed separately.

Determining breakpoints using piecewise regression

In exploring a relationship between an independent variable (x) and a dependent variable (y) (in this case, discharge and bedload transport, respectively) it is often apparent that a linear model is not appropriate for the entire range of values, but a non-linear function may not fit best either. One possibility is that different linear relationships occur over different ranges of x. *Breakpoints* (c) are values on the x-axis where a change in the slope of the different linear relationships can be defined; these breaks may or may not be known before the analysis. While the regression functions so determined may be discontinuous, the model can be written in such a way that the function is continuous at all points, including the breakpoint. We assume that, given what is understood about the nature of bedload movement in natural channels, the function should be continuous.

When there is only one breakpoint (at $x = c$) the model can be written as:

$$E[y] = a_1 + b_1 x \qquad \text{for } x \leq c$$
$$E[y] = a_2 + b_2 x \qquad \text{for } x > c$$

In order for the function to be continuous, the two equations for $E[y]$ need to be equal when $x = c$:

$$a_1 + b_1 c = a_2 + b_2 c \Rightarrow a_2 = a_1 + c(b_1 - b_2)$$

The function can be rewritten as follows, substituting for a_2:

$$E[y] = a_1 + b_1 x \qquad \text{for } x \leq c$$
$$E[y] = \{a_1 + c(b_1 - b_2)\} + b_2 x \qquad \text{for } x > c$$

This can be extended to cases where there appears to be more than one breakpoint. The functions for the combination of 2 breakpoints and 3 linear segments would be:

$$E[y] = a_1 + b_1 x \qquad \text{for } x \leq c_1$$
$$E[y] = \{a_1 + c_1(b_1 - b_2)\} + b_2 x \qquad \text{for } c_1 < x \leq c_2$$
$$E[y] = \{a_1 + c_1(b_1 - b_2) + c_2(b_2 - b_3)\} + b_3 x \qquad \text{for } x > c_2$$

The actual number of breakpoints may vary, and both physical and statistical criteria should be considered in determining the number of breaks in slope. An exploratory view of the data using a smooth regression curve can be used to provide insight into the number of breakpoints needed. Models using 1, 2, or more breakpoints are then compared to see if the goodness-of-fit improves by increasing the number of inflections.

RESULTS

Hydrograph

Bedload was collected over a wide range of conditions during several relatively wet years (recurrence intervals up to five years). Sustained high flow, defined as the period of time when flow was at or exceeded bankfull stage, lasted between one and two weeks in years 1993, 1995, 1996, and 1997, providing ample opportunity to collect bedload under conditions of relatively high flow and transport (Figure 3). Runoff was below average in 1992, the year this study was initiated; peak flow was about 60–80 per cent of the bankfull discharge (Ryan, 1994; Ryan and Troendle, 1996). Only five sites on the main stem of St Louis Creek were sampled that year.

Data suitability

Bedload data from sites on St Louis Creek and its tributaries represent a compilation of samples collected over several years. One might suspect, however, that estimates of transport rates for individual years could be different due to factors such as changes in annual or seasonal accumulation of sediment (e.g., Sidle, 1988; Hassan and Church, 2001) or, to a lesser extent, collection by different persons (Ryan and Porth, 1999). The similarity between samples collected in different years is assessed to determine whether the data measured over a similar range of flows appear to have been drawn from the same population. Bedload data collected at all sites exhibit linearity, normality, and heterogeneous variance problems, requiring transformation of the data that would permit testing with the commonly used ANOVA model. However, there was no one transformation which corrected all of the problems, so a generalized additive model (GAM) was used to test for differences between different years. The GAM uses a smooth, non-parametric fit to the data and tests for differences between the smoothed fits to determine whether they are significant (Hastie and Tibshirani, 1990). We used a Lowess (a locally weighted, least squares regression using the k nearest neighbours) smoothing procedure because it most closely approximates trends in the data for all sites (Figure 4).

Discharge and year were included as predictors in the GAM because we are interested in evaluating both flow and annual difference in the data. Year or the year × flow interaction was significant at six sites indicating that there was at least one year that differed from the others. No significant differences were detected at sites 4a and 5 (Table II). Subsequent tests to determine specifically which years differed were conducted in chronological order, starting with data from 1993 and 1995. If there were no significant differences in the first two years, the data were pooled and tested for similarity against successive years. In this manner, similarity between earlier and supplementary sets of data is tested in the order in which they were collected. Bonferroni

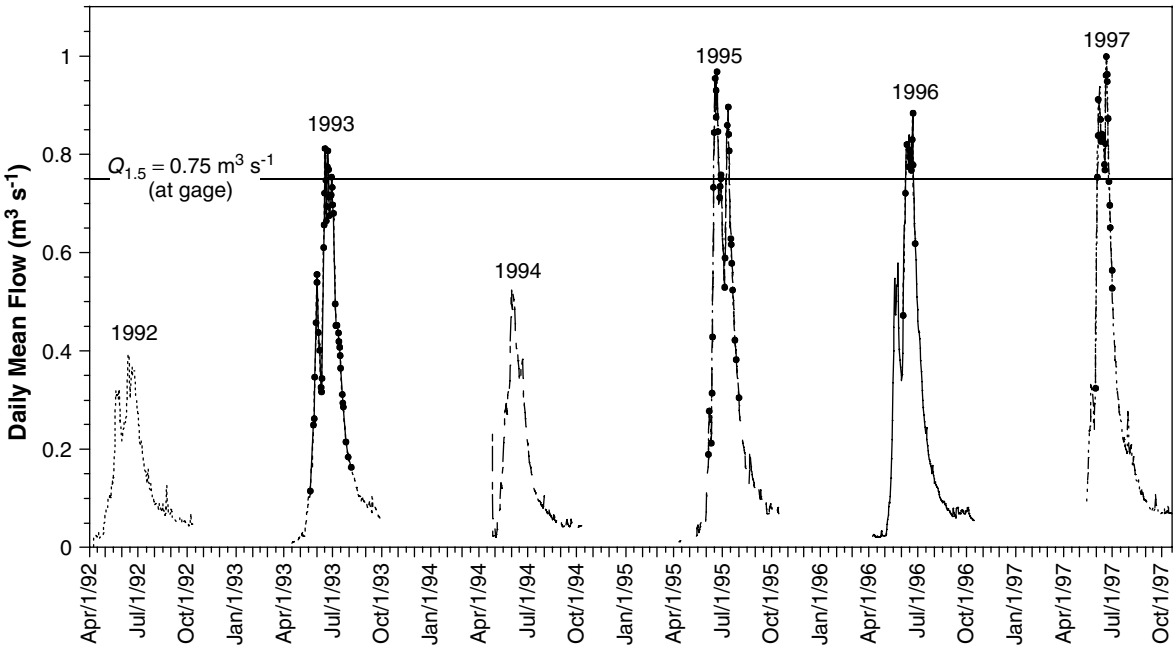

Figure 3. Mean daily discharge recorded at East St Louis Creek gauge for years during which bedload was collected. The gauge is started on approximately 1 April each year and discontinued on 30 September, producing a seasonal record of flow. Black circles represent days on which bedload was sampled. Periods of sustained high flow were observed in 1993, 1995, 1996, and 1997. No samples were collected at this site in 1992 and 1994

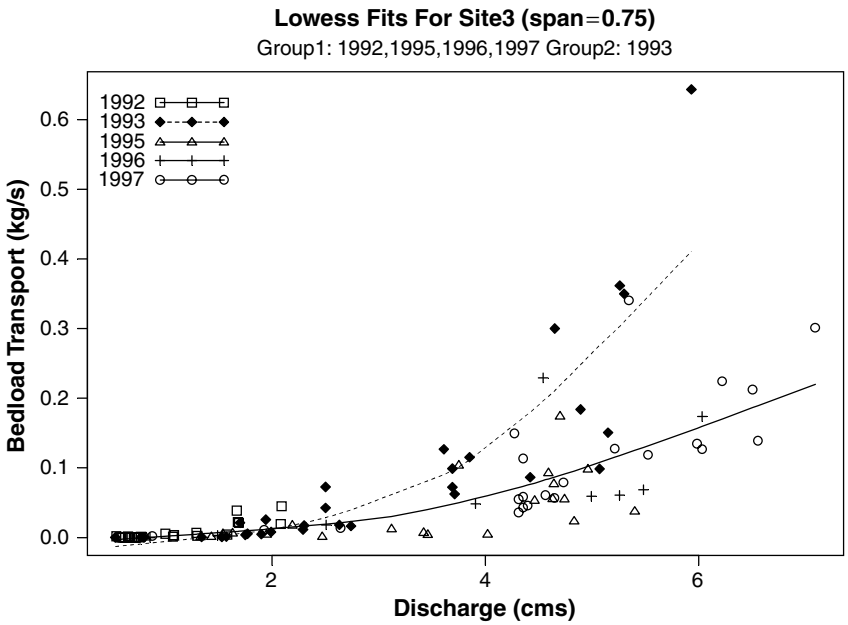

Figure 4. An example of a Lowess fit to annual bedload data at site 3 on St Louis Creek. The span is the proportion of the total number of points close to a given datapoint that are used to direct the position of the line in that graphic space. Spans range from 0 to 1·0, with larger spans including more points, producing a smoother fit. A span of 0·75 was used for all sites in our analyses. In this example, the data from 1993 were statistically different from other years, due primarily to a few high measured rates of transport at about 5 m^3 s^{-1}. However, because we cannot ascribe a specific cause to the discrepancies, all data are used in fitting the piecewise regression model shown in Figure 5

Table II. Results of a generalized additive model (GAM) indicating years with similar bedload data

	1993	1995	1996	1997
St Louis Creek, Site 1	1	1	2	2
St Louis Creek, Site 2	1	2	1	2
St Louis Creek, Site 3	2	1	1	1
St Louis Creek, Site 4	2	1	1	1
St Louis Creek, Site 4a	1	1	1	1
St Louis Creek, Site 5	1	1	1	1
East St Louis Creek	1	1	1	2
Fool Creek	1	2	1	1

Number indicates groups with similar data at individual sites.

corrections, reflecting the number of tests in a set, were applied to p-values to determine significance level for each comparison. If there were significant differences in the first test, we concluded that there were at least two groups and subsequent tests were performed on both groups. Data from five sites measured in 1992 were not included in these comparisons because the range was restricted to low flows. However, it was apparent from plots that the values are comparable to those collected in other years, so we include data from 1992 in the piecewise regression, described later.

We found the GAM procedure to be sensitive to small differences between annual sets of data. Often only a few points changed the fit of the curve, making the whole year appear significantly different, while the majority of the datapoints overlapped with the existing data. The results from the GAM (Table II) indicate which years were similar and different for each site. The results are varied and there was no one year that differed at all sites. In six cases, there were no differences or only one year that differed from the main group. Two years differed at sites 1 and 2, but the differing years were themselves similar, indicating that there were only two, not three, groups. There was, however, no obvious cause for the differences between years (such as a pulse of sediment from hillslope failure). There was also no consistency in the years that are different that would suggest an operator effect. We therefore decided that the full dataset expresses the natural range of variability inherent in bedload transport at any one site and until we understand better the nature of this variability, it would be imprudent to exclude data at this point in time. With this in mind, the piecewise regression model was applied to both the full and the censored data to determine whether they gave different results. We found that while the value of the generated breakpoint was not substantially different, the width of the confidence limits on the breakpoint estimate was greater using the uncensored dataset. We report only the results of the fits to the full datasets, with the exception of site 1 where the model results were greatly improved by excluding data measured in 1996.

Breakpoint analysis

The piecewise regression model was fitted using several approaches, including generalized least squares (GLS), iteratively reweighted least squares (IRLS), and least absolute deviation (LAD) (Neter *et al.*, 1989). The latter two methods are less sensitive to outliers, which are common in bedload data. However, the estimated equations were nearly identical using the three approaches. Because the methods produced similar results, only those from the analysis using GLS are presented.

Data were fitted using a single linear function, a power function, and a third or fourth order polynomial to determine if any of these worked better than the piecewise linear regression. The linear model was typically poorer than the non-linear models, as may be expected. However, the model standard errors (MSE) using the power, polynomial, and piecewise regression functions were quite similar, indicating the models are comparable for estimating the mean rate of transport for a given discharge. However, the breakpoint generated by the piecewise regression function identifies a threshold at which there is a substantial change in the rate of transport, and therefore provides an objective means for detecting changes in phase. When accompanied by

grain size data (described later), the breakpoint analysis provides compelling evidence distinguishing between at least two phases of bedload transport. Hence, we choose the breakpoint model for further examination based on 'scientific reasons' rather than exclusively on goodness-of-fit comparisons (Bates and Watts, 1988).

One of the difficulties encountered in using the piecewise regression procedure on bedload data is that typically the residuals are not homogeneous and so the standard error of the estimates for each of the parameters (a_1, b_1, b_2, and c) is suspect. In order to correct for these problems, we applied a bootstrapping procedure to calculate non-parametric estimates of standard errors of the parameters and confidence intervals (Efron and Tibshirani, 1993). Bootstrapping involves resampling from the original dataset with replacement, meaning a datapoint may be selected more than once in order to obtain a secondary dataset. The piecewise regression model is then fitted to this secondary dataset and the parameters from this equation are retained. The procedure is repeated a specified number of times (in our case, we used 1000 iterations, meaning 1000 secondary datasets were generated) and the standard deviation of the parameters for the bootstrap estimates are used to determine the 95 per cent confidence limits on each of the parameter estimates (Efron and Tibshirani, 1993). The confidence limits generated by the bootstrapping procedure help characterize the reliability of the breakpoint estimate (Table III).

One breakpoint and two linear, continuous functions were generated for each site (Figure 5, Table III); the intercept (a_1) was negative in all cases. This makes physical sense because bedload movement becomes undetectable (or goes to near zero) before flow becomes zero. While the piecewise regression model will usually converge to produce a breakpoint, one needs to evaluate the confidence limits of the parameters and the variance accounted for by the model to determine if it is an appropriate fit. In some cases, the breakpoint was well-defined with relatively narrow confidence limits (Figure 5e). In other cases, the breakpoint was less distinct and the confidence bands were relatively wide (Figure 5c). Occasionally, the piecewise regression procedure produced a lower breakpoint than might be picked visually. This is likely due to the scatter of the data observed during the second phase of transport (e.g. Figure 5d). Here, one linear model fitted the data nearly as well as two linear models with a breakpoint, indicating that the breakpoint determined by the analysis may be suspect for this particular site. More generally though, the piecewise regression fit appeared to properly identify the approximate discharge at which substantial increases in bedload transport rates manifest themselves.

Rates of fractional transport at varying flow levels

The primary constituent of all the bedload samples was sand and fine gravel (<4 mm) that ranged from 40 to 100 per cent of the total sample weight (crosses on Figure 6); the predominance of sand in bedload is typical for channels with very coarse beds (Leopold, 1992; Lisle, 1995). Transport rates for grains sizes between 4 mm and 64 mm were calculated by proportioning the total transport rate by standard classes (full phi). Rates of fractional transport were then plotted against discharge to determine whether there were differences in grain sizes transported at flows greater than or less than the value of the breakpoint discharge (Figure 6).

Coarse gravel (defined below for individual sites) was rarely trapped at flows less than the breakpoint. Fewer than 3 per cent of the samples contained large grains, indicating their movement over this range of flows is essentially negligible. Instead, bedload consisted primarily of sand with minor contributions of fine to medium-sized gravel. Fine gravel frequently behaves similarly to sand for streams in the St Louis Creek catchment and together they are the principal constituents of Phase I transport. The source of material trapped at less-than-breakpoint flow is most likely from more mobile patches and interstitial areas and does not represent widespread entrainment of the channel surface.

Samples collected at greater-than-breakpoint flows are notably more coarse than those measured at less-than-breakpoint discharges (Figure 6). While the majority of even high flow samples consist of sand and fine gravel, coarser gravel that is largely absent from samples at low flows becomes common in samples collected at high flows. Grain sizes larger than 32 mm appear in samples at St Louis sites 1, 2, 3, 4, 4a, and 5; grain sizes 16 mm and larger appear in samples from Fool Creek and East St Louis Creek at the same relative level of flow. Notably, the D-values of grains 32 mm in diameter represent approximately D_{16} of the surface at the St Louis sites (ranging from D_{11} to D_{22}); the D-values of 16 mm grains at Fool Creek and East St Louis Creek are D_{22} and D_{19}, respectfully. Hence, the surface D_{16} (or an approximation thereof)

Table III. Calculated ratios between the breakpoint and estimated bankfull discharges

Site	Channel type	Q_{br} Discharge at breakpoint ($m^3\ s^{-1}$)	Standard error breakpoint estimate	95% lower CL ($m^3\ s^{-1}$)	95% upper CL ($m^3\ s^{-1}$)	$Q_{1\cdot5}$ 1·5-year RI discharge ($m^3\ s^{-1}$)	($Q_{br}/Q_{1\cdot5}$) Relative breakpoint (%)	95% lower CL ($Q_{br}/Q_{1\cdot5}$) (%)	95% Upper CI ($Q_{br}/Q_{1\cdot5}$) (%)
St Louis 1	Step–pool	3·41	0·56	2·31	4·52	4·41	77·4	52·4	102·5
St Louis 2	Plane	4·50	0·33	3·86	5·13	4·75	94·7	81·3	108·0
St Louis 3	Riffle	3·17	0·50	2·19	4·14	4·59	69·1	47·6	90·2
St Louis 4	Plane	2·07	0·29	1·49	2·64	3·61	57·3	41·4	73·1
St Louis 4a	Riffle	2·84	0·18	2·49	3·19	3·37	84·3	73·9	94·6
St Louis 5	Step–pool	2·35	0·13	2·10	2·61	2·63	89·4	79·7	99·4
E St Louis Creek	Step–pool	0·76	0·06	0·63	0·88	0·86	88·4	73·4	102·7
Fool Creek	Plane	0·22	0·02	0·18	0·26	0·30	73·3	61·3	85·7
Little Granite Cr.	Plane	4·86	0·97	2·95	6·76	5·95	81·7	49·6	113·6
S. Fork Poudre R.	Riffle	8·57	0·43	7·72	9·41	9·71	88·2	79·5	96·9
Coon Creek	Plane	2·62	0·15	2·32	2·93	2·77	94·6	83·8	105·8
E. Fork Encampment	Plane	1·50	0·14	1·24	1·77	1·45	103·4	85·5	122·1
Median FEF							80·8	67·4	97·0
Median other sites							91·4	81·6	109·7

CL, confidence limit; FEF, Fraser Experimental Forest; RI, return interval.

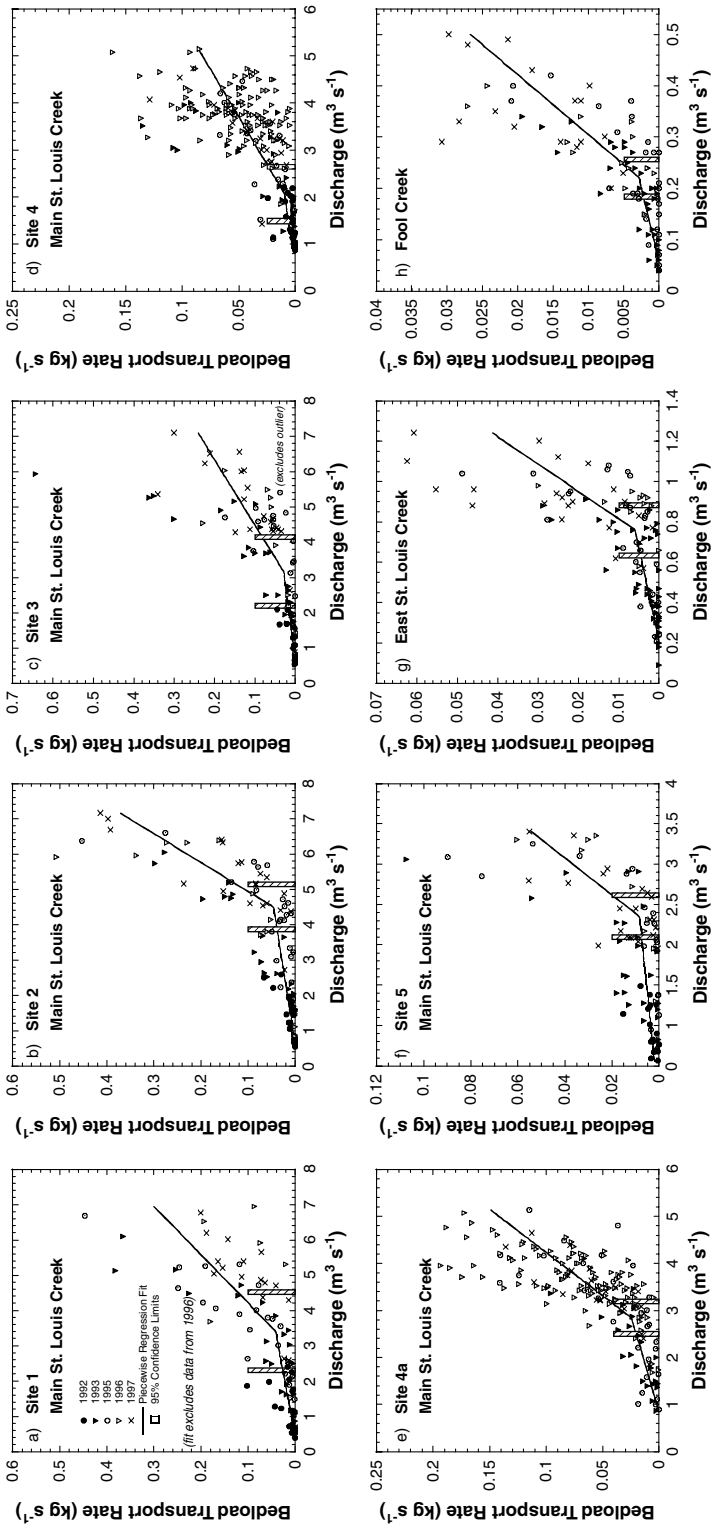

Figure 5. Plots of bedload and discharge data from at eight sites at Fraser Experimental Forest collected between 1992 and 1997. Best-fit lines and breakpoints are shown. Bars indicate the confidence limits on the estimate of the breakpoint. The height of the bar is arbitrary

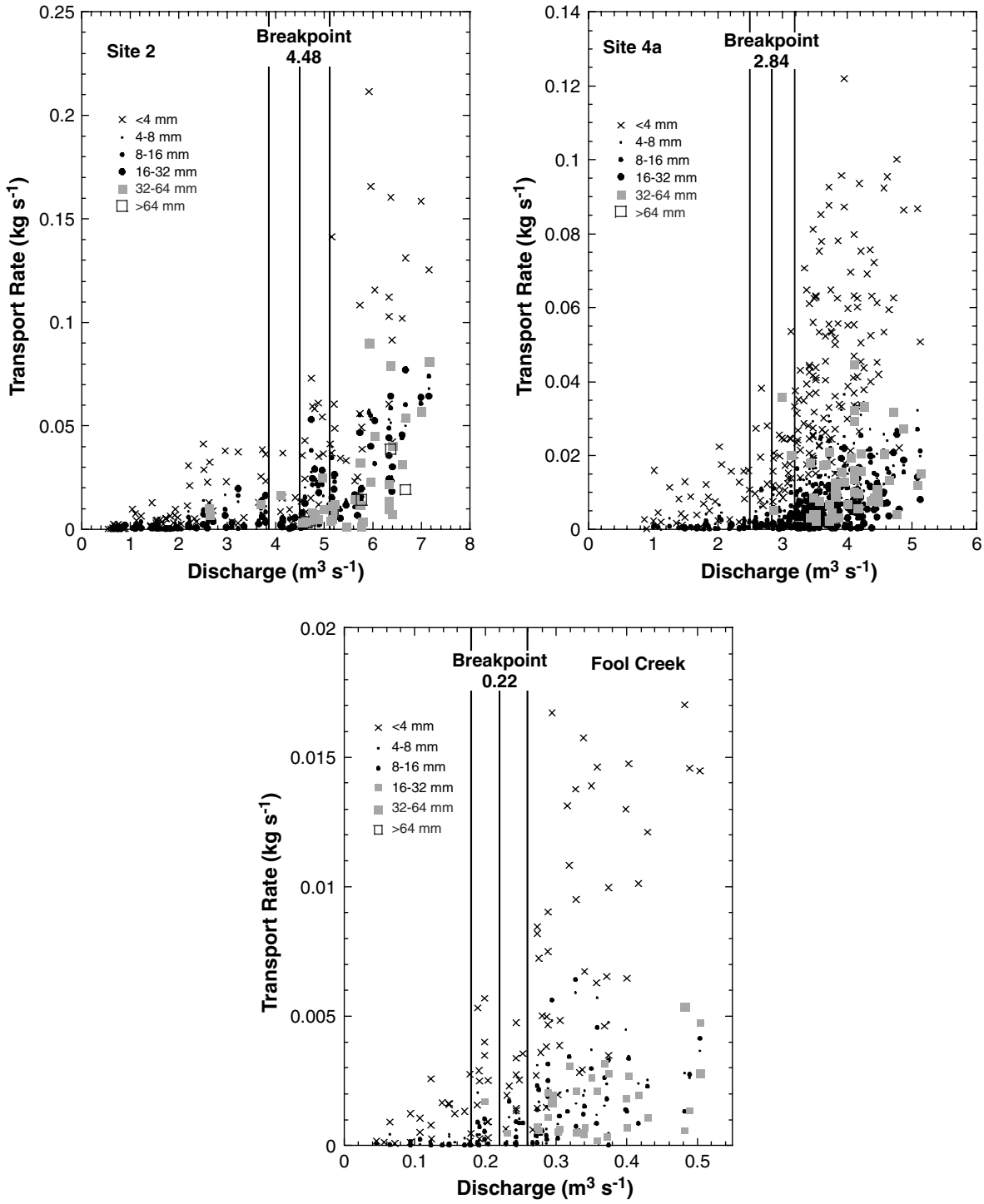

Figure 6. Fractional transport rates observed at three sites at the Fraser Experimental Forest. Grey square symbols indicate gravel that is 'coarse' at a particular site (>32 mm on the main stem and >16 mm for Fool Creek). Value of the discharge at the breakpoint is shown by the short solid line while longer lines indicate the confidence limits on this estimate. The discharge at which coarse gravel begins to appear in the samples more or less coincides with the value of the breakpoint

appears to be an important grain size whose capture in samplers represents mobilization of grains from the coarse surface layer. In addition, D_{16} of the surface layer in natural sediments is roughly equivalent to the D_{50} of the subsurface grain size distribution (e.g. Bathurst *et al.*, 1987; Thorne and Hey, 1983) and so the increasing presence of this grain size in bedload samples is likewise a useful indicator of mobilization of the subsurface once the coarse surface layer is disrupted. There is typically an order of magnitude difference between the rate of transport for sand and small gravel at greater-than-breakpoint flows relative to lower flow which supports the notion that once the coarser surface layer is disturbed, there is an accompanying increase in the availability of fines from the subsurface.

As a caveat, reliance upon the presence of coarse gravel in bedload samples could conceivably produce estimates for the onset of transport that are greater than 'actual' conditions. This is because gravel transport is irregular (e.g. Parker and Klingeman, 1982), consisting of only a few particles moving at a point in time, characterized by brief periods of motion followed by longer periods of rest. Hence, the likelihood of entrapping coarser gravel is relatively low, particularly at conditions near onset (e.g. Emmett, 1980; Dietrich and Whiting, 1989). However, in light of low probability of capture, the presence and persistence of some coarse gravel in bedload samples at high flows provides good evidence that conditions suitable for gravel transport have been reached, though the estimate of the rate of transport may be a conservative one. The fact that coarse gravel appears in samples beginning at about the breakpoint reinforces the concept that the rapid increase in transport at the onset of Phase II transport can be attributed to the break-up and transport of coarse grains from the channel surface, accompanied by an increase in fines availability from the subsurface.

Relative breakpoint

In order to compare breakpoints in channels with differing conveyance capacities, a relative breakpoint (R_{br}) was generated by dividing the breakpoint from the piecewise regression model (Q_{br}) by the 1·5-year return interval flow ($Q_{1\cdot5}$) and expressing as a percentage:

$$R_{br} = 100(Q_{br}/Q_{1\cdot5})$$

Return frequency was estimated for flows at sites 1, 2, and 3 through regression analysis with discharge data from the United States Geological Survey (USGS) gauge on St Louis Creek (no. 09026500). A strong linear correspondence exists between discharge measured at the site and that recorded at the gauge for the same time period; R^2 values were 0·96, 0·96, and 0·94, respectively. Return frequency was calculated on data from the St Louis gauge using the Log Pearson type III method (US Interagency Advisory Committee on Water Data, 1982) on annual maximum discharge between 1935 and 1955, a period when flow at this gauge was unaffected by trans-basin diversion. Similar computations were made for sites 4, 4a, and 5 using the gauge record from East St Louis Creek for the period 1943–1996 (United States Forest Service (USFS), unpublished gauge records). Here, good, though less strong, linear correspondence exists between gauged discharge and that measured at the sampling sites (R^2 values were 0·94, 0·86, and 0·84, respectively). Discrepancies are due to the studied sites being in a different watershed from the gauge resulting in slightly mismatched runoff regimes. Estimates of the 1·5-year instantaneous flow are less than that estimated by the 'bankfull' discharge in the field at sites 4 and 4a (4·00 $m^3\ s^{-1}$); the latter is more comparable to the two-year return interval flow (Ryan and Troendle, 1996). The 1·5-year flows for Fool Creek and East St Louis Creek were determined using Log Pearson type III analysis on flow records from nearby gauges. Because there were differences in discharges measured at the sampling cross-section and that estimated by the gauges for a given stage, the 1·5-year flow calculated for the gauged record was adjusted to flows measured at the cross-section; this was done using regression analysis with the two flow records. Estimates of the 1·5-year return interval of flows at the sampling locations and their relative breakpoints are listed in Table III.

The R_{br} for the Fraser sites ranged from 57 per cent at site 4 to 95 per cent at site 2. The median value of the breakpoint was 80·8 per cent, indicating a tendency for the change in the flow/sediment relationship at about 80 per cent of the 1·5-year discharge. The median values of the 95 per cent confidence limits for the relative breakpoint were between 68 and 97 per cent (Table III).

For comparative purposes, the piecewise regression model was applied to data from four additional gravel-bed streams in the Rocky Mountain region. Three of the sites (Coon Creek, Upper East Fork Encampment, and Little Granite Creek) are in Wyoming, USA, and one site (South Fork Cache la Poudre) is in north-central Colorado, USA. The datasets were collected for a variety of purposes, including monitoring (Little Granite; Nelson *et al*., 1991; Leopold, 1994; Emmett, 1999; Ryan and Emmett, 2002), support for instream flow claims (South Fork Cache la Poudre; Leopold, 1992), and for detecting changes in sediment yield following timber harvesting (Coon Creek and Upper East Fork Encampment; Troendle *et al*., 1996, 2000; Wilcox, *et al*., 1996). All sites are located near presently or historically operating gauging stations monitored by either the USGS or the USFS. Flow frequencies were calculated using Log Pearson type III on the annual maximum series for the periods of record. The value of the 1·5-year flows at Coon Creek and East Fork Encampment were adjusted using regression analysis to reflect differences in flows measured at the cross-section where bedload was measured and that gauged at the long-term station. All of the datasets contain previously published data that have been augmented with additional samples since original publication (USDA Forest Service, unpublished data). Each consists of approximately 90 datapoints with the exception of Little Granite Creek where there are in excess of 250 data points (Ryan and Emmett, 2002). Both sediment samples and discharge measurements were collected from relatively low flows to flows in excess of bankfull. Hence, all meet the criteria needed for generating a breakpoint using the piecewise regression model.

The results of the piecewise regression analysis at the supplementary sites show that the relationship between the 1·5-year flow and the breakpoint is similar to that observed at the St Louis Creek sites (Table III). While the R_{br} is typically greater than the median of 80·8 per cent at the supplementary sites, the range of values for these four sites generally falls within the range of observations at sites on the Fraser Experimental Forest, with the exception of the East Fork Encampment River, which is slightly higher. Overall, the range of observed values of R_{br} at all sites is between about 60 and 100 per cent of $Q_{1\cdot5}$. The variation in R_{br} may be due to several factors, including: (1) intrinsic differences in the systems; (2) the difficulties of optimizing the breakpoint on data with high variance; or (3) reliability of the estimate of the 1·5-year flow.

Channel characteristics and differences in relative breakpoints

The hypothesis that variation in the relative breakpoint is due to differences in the nature of the channel from which the data were measured was tested by regressing the relative breakpoint (y) against a number of basin and channel parameters, including: slope; median grain size of the channel bed; dimensionless grain size (D_{50}/w) where w is the channel width; drainage area; relative roughness ($D_{84}/H_{1\cdot5}$) where $H_{1\cdot5}$ is the mean depth at bankfull; and a sorting index (σ) for the channel surface (Andrews, 1983), defined by:

$$\sigma = \frac{1}{2}\left(\frac{D_{84}}{D_{50}}\right) + \left(\frac{D_{50}}{D_{16}}\right)$$

A linear fit to the data from 12 sites was used in this series of comparisons. There was, however, no significant trend between the relative breakpoint and any of the channel parameters; R^2 values and p-values are shown in Figure 7a–f. All fits are essentially flat lines with y-intercepts near 80. From this we conclude that the variation in relative breakpoints cannot be attributed to differences in the characteristics of the channels, but is more likely due to the variation in procedures used to calculate R_{br}, such as the reliability of the breakpoint or the 1·5-year flow estimates. The initial motion of the streambed and the onset of Phase II transport at the study sites occurs at about 80 per cent of the 1·5-year flow, the range being between 60 and 100 per cent.

Presence of a second breakpoint

Theoretically, a second breakpoint may exist at some point above the bankfull discharge. As flow increases and moves out of the channel, forces acting on the particles (specifically, shear stress) level off because the water surface slope remains about the same while the rate of increase in depth flattens as flow moves onto the floodplain. The presence of a second breakpoint and third linear function would suggest a levelling of transport rates, coincident with the levelling off of shear stress. However, no second breakpoint could be

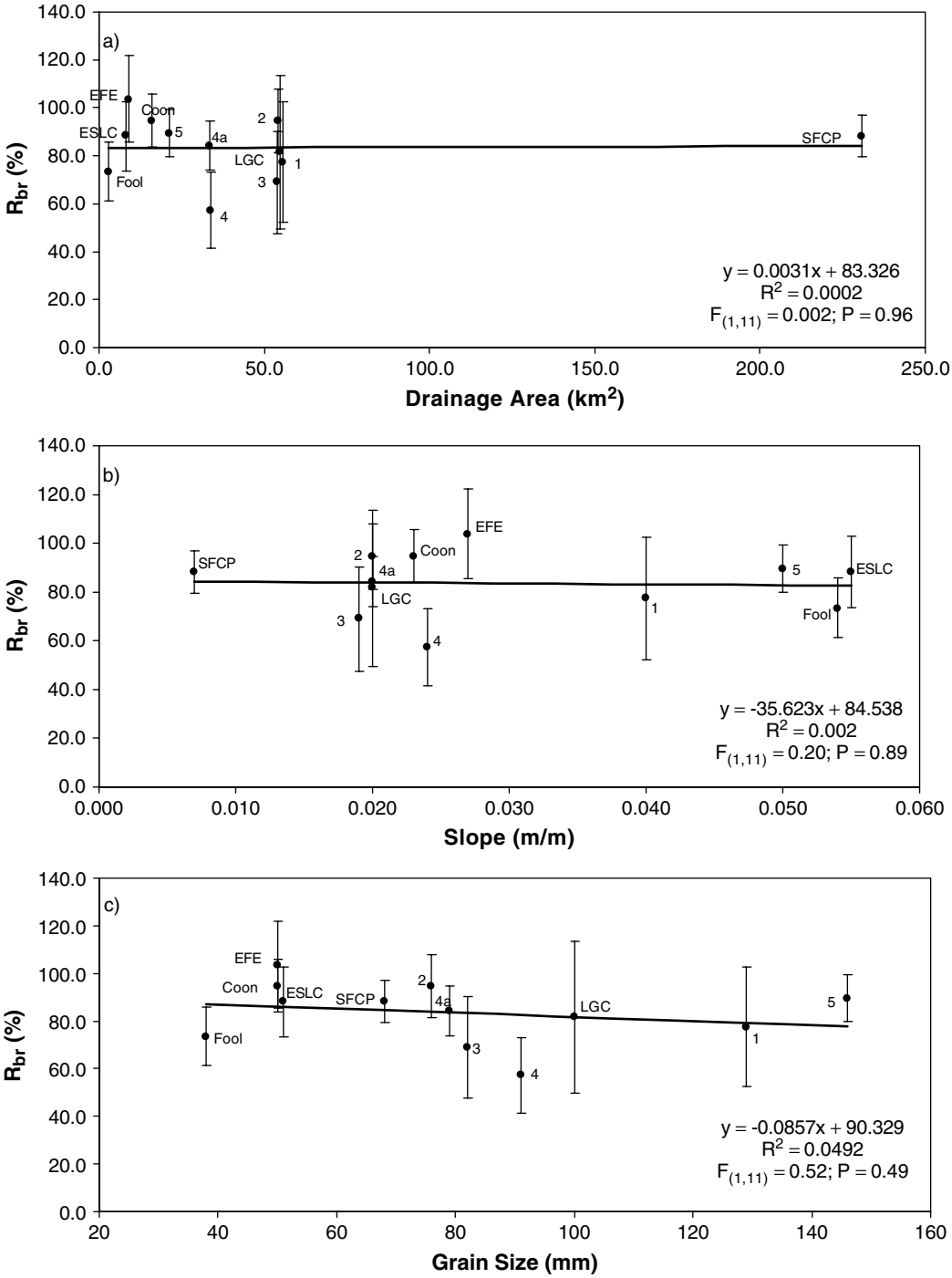

Figure 7. Relationship between the relative breakpoint (R_{br}) and an number of channel parameters, specifically: (a) drainage area; (b) slope of the water surface; (c) median grain size (D_{50}); (d) dimensionless grain size; (e) sorting index; (f) relative roughness. Error bars are the confidence limits on the relative breakpoint. No statistically significant trends exist between the relative breakpoint and any of the aforementioned parameters. Abbreviations are as follows. On St Louis Creek: 1, Site 1; 2, Site 2; 3, Site 3; 4, Site 4; 4a, Site 4a; 5, Site 5. ESLC, East St Louis Creek; Fool, Fool Creek; LGC, Little Granite Creek; SFCP, South Fork Cache la Poudre; EFE, East Fork Encampment River; Coon; Coon Creek

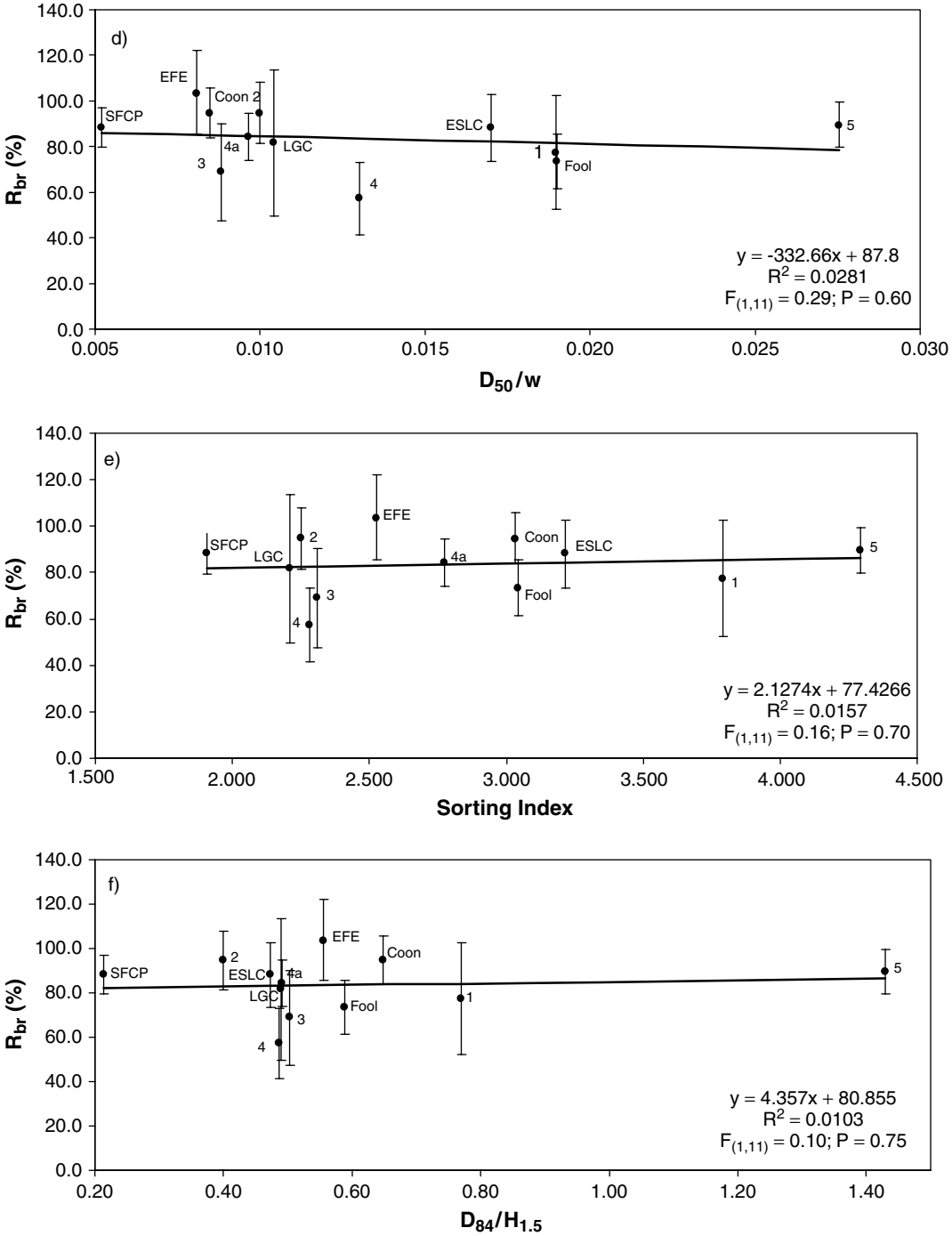

Figure 7. (*Continued*)

defined using the piecewise regression model as described. This could be due to the irregularity of the pattern of transport rates at flows greater than bankfull that make it difficult for the fitting procedure to detect the presence of a third linear segment and second breakpoint. Generally, transport rates increase rapidly between 80 and 100 per cent of bankfull and that portion of the line is fairly well defined. Then as flow increases

to discharges with five- to ten-year return frequencies, transport rates remain high (and variable) but they do not necessarily continue to increase at the same rate as that observed at close-to-bankfull flow. Because transport rates at high flows exhibit exceptional variability, additional data at still higher discharges are needed in order to define the flattening of the line somewhere above bankfull, if transport rates in the channel do indeed 'level off' during overbank flows. Transport rates may remain within the range of values observed at bankfull (assuming no new sources of sediment are introduced) until about twice the critical discharge when presumably stable banks begin to erode (Parker, 1979). Transport was measured at flows only up to about 1·5 times the critical discharge at the sites described herein.

DISCUSSION AND CONCLUSIONS

In this paper, we present the application of piecewise linear regression to rates of sediment transport and discharge measured at eight stream sites on the Fraser Experimental Forest where between 100 and 200 samples of bedload have been collected at each site. Measurements cover a wide range of flows, including many exceeding bankfull. The piecewise regression model was also successfully applied to data from additional sites in Colorado and Wyoming, indicating broader application of the procedure to sites outside of the Experimental Forest. We found that the breakpoint generated by the piecewise regression procedure objectively defines a discharge at which there is an apparent shift from low to moderate transport of sand and fine gravel atop a stable streambed (Phase I) to a disruption of the streambed and higher rates of transport that include larger particles (Phase II). When the level of flow at the breakpoint is tied to the bankfull discharge, one finds that the shift occurs typically at about 80 per cent of bankfull. This appears to be surprisingly consistent, even though the studied channels have varied slope, size, roughness, and bed topography; the confidence limits on the breakpoint estimates are also largely comparable. This suggests that these gravel-bed channels are adjusted so that the onset of transport of grains (about D_{16}) from the channel surface begins at a flow that occurs relatively frequently (nearly annually) and almost fills the banks. In this respect, there is a fundamental link between process and form whereby the channel reflects a roughness configuration or morphology for the type of sediment supplied to the system and the predominant flow regime. A shift in either supply may result in change to the form of the channel as it adjusts to a new regime.

One might argue, however, that strict thresholds for gravel initiation do not exist and that the transition between phases is more gradual. Granted, there may be a few coarse grains in motion at relatively low discharges and this process might not be detectable using the described methods for sampling bedload. The fact that a few coarse grains were trapped at relatively low flows in this study suggests this possibility. However, this motion likely reflects grains that occupy ideal locations such that they are moved relatively easily. In terms of maintaining the channel, these exceedingly low rates of gravel motion are likely to be of minor consequence. The identification of a breakpoint in the studied channels indicates that there is a flow above which there is a substantial change in the nature of sediment moved in gravel-bed channels. From a land management perspective, knowledge of the discrete flows needed to move different sized particles in streams is useful for determining discharges required to maintain the form and function of the channel and aquatic habitat.

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REFERENCES

Andrews ED. 1983. Entrainment of gravel from naturally sorted riverbed material. *Geological Society of America Bulletin* **94**: 1225–1231.

Andrews ED. 1984. Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado. *Geological Society of America Bulletin* **95**: 371–378.

Andrews ED, Nankervis JM. 1995. Effective discharge and the design of channel maintenance flows for gravel-bed rivers. In *Natural and Anthropogenic Influences in Fluvial Geomorphology: The Wolman Volume*, Costa JE, Miller AJ, Potter KW, Wilcock PR (eds). Geophysical Monograph 89. American Geophysical Union: Washington, DC; 151–164.

Andrews ED, Smith JD. 1992. A theoretical model for calculating marginal bedload transport rates of gravel. In *Dynamics of Gravel-bed Rivers*, Billi P, Hey RD, Thorne CR, Tacconi P (eds). John Wiley: Chichester; 41–48.

Ashworth PJ, Ferguson RI. 1989. Size-selective entrainment of bed load in gravel bed streams. *Water Resources Research* **25**(4): 627–634.

Bates DM, Watts DG. 1988. *Nonlinear Regression Analysis and Its Applications*. John Wiley: New York.

Bathurst JC, Graf WH, Cao HH. 1983. Initiation of sediment transport in steep channels with coarse bed material. In *Mechanics of Sediment Transport*, Sumer BM, Muller A (eds). Balkema: Rotterdam; 207–213.

Bathurst JC, Graf WH, Cao HH. 1987. Bed load discharge equations for steep mountain rivers. In *Sediment Transport in Gravel-bed Rivers*, Thorne CR, Bathurst JC, Hey RD (eds). John Wiley: Chichester; 453–477.

Beschta RL. 1987. Conceptual models of sediment transport in streams. In *Sediment Transport in Gravel-bed Rivers*, Thorne CR, Bathurst JC, Hey RD (eds). John Wiley: Chichester; 387–408.

Buchanan TJ, Somers WP. 1969. *Discharge measurements at gaging stations*. US Geological Survey, Techniques of Water Resources Investigations, Book 3.

Buffington JM, Dietrich WE, Kirchner JW. 1992. Friction angle measurements on a naturally formed gravel streambed: implications for critical boundary shear stress. *Water Resources Research* **28**(2): 411–425.

Caine TN. 1986. Sediment movement and storage on alpine slopes in the Colorado Rocky Mountains. In *Hillslope Processes*, Abrahams AD (ed.). Allen and Unwin: Boston; 115–137.

Carling PA. 1988. The concept of dominant discharge applied to two gravel-bed streams in relation to channel stability thresholds. *Earth Surface Processes and Landforms* **13**: 355–367.

Church MA. 1978. Palaeohydrological reconstruction from a Holocene valley fill. In *Fluvial Sedimentology*, Miall AD (ed.). Canadian Society of Petroleum Geologists: Calgary; 743–772.

Dietrich WE, Whiting P. 1989. Boundary shear stress and sediment transport in river meanders of sand and gravels. In *River Meandering*, Ikeda S, Parker G (eds). Water Resources Monograph 12. American Geophysical Union: Washington, DC; 1–50.

Dietrich WE, Kirchner JW, Ikeda H, Iseya F. 1989. Sediment supply and the development of the coarse surface layer in gravel-bedded rivers. *Nature* **340**: 215–217.

Efron B, Tibshirani RJ. 1993. *An Introduction to the Bootstrap*. Chapman and Hall: New York.

Emmett WW. 1976. Bedload transport in two large, gravel-bed rivers, Idaho and Washington. *Proceedings, Third Federal Inter-agency Sedimentation Conference* **4**: 101–114.

Emmett WW. 1980. *A field calibration of the sediment-trapping characteristics of the Helley-Smith bedload sampler*. US Geological Survey, Professional Paper 1139.

Emmett WW. 1999. Quantification of channel-maintenance flows for gravel-bed rivers. In *Wildland Hydrology*, Olsen DS, Potyondy JP (eds). American Water Resources Association: Herndon, VA; 77–84.

Folk RL. 1968. *Petrology of Sedimentary Rocks*. Hemphill: Austin, TX.

Garstka WU, Love LD, Goodell BC, Bertle FA. 1958. *Factors affecting snowmelt and streamflow: a report on the 1946–53 Cooperative Snow Investigations at the Fraser Experimental Forest, Fraser, Colorado*. US Department of the Interior, Bureau of Reclamation and the US Department of Agriculture, Forest Service: Denver, CO.

Guy HP. 1969. *Laboratory theory and methods for sediment analysis*. US Geological Survey, Techniques of Water Resources Investigations. Book 5.

Hassan MA, Church M. 2001. Sensitivity of bed load transport in Harris Creek: Seasonal and spatial variation over a cobble-gravel bar. *Water Resources Research* **37**(3): 813–825.

Hassan MA, Reid I. 1990. The influence of microform bed roughness elements on flow and sediment transport in gravel bed rivers. *Earth Surface Processes and Landforms* **15**: 739–750.

Hastie T, Tibshirani R. 1990. *Generalized Additive Models*. Chapman and Hall: New York.

Hayward JA. 1980. *Hydrology and stream sediments in a mountain catchment*. Tussock Grasslands and Mountain Lands Institute, Special Publication 17. Lincoln College: New Zealand.

Helley EJ, Smith W. 1971. *Development and calibration of a pressure difference bedload sampler*. US Geological Survey, Water Resources Division Open-file Report.

Jackson WL, Beschta RL. 1982. A model of two-phase bedload transport in an Oregon Coast Range stream. *Earth Surface Processes and Landforms* **7**: 517–527.

Kirchner JW, Dietrich WE, Iseya F, Ikeda H. 1990. The variability of critical shear stress, friction angle, and grain protrusion in water worked sediments. *Sedimentology* **37**: 647–672.

Laronne JB, Carson MA. 1976. Interrelationships between bed morphology and bed material transport for a small gravel-bed channel. *Sedimentology* **23**: 67–85.

Leopold LB. 1992. The sediment size that determines channel morphology. In *Dynamics of Gravel Bed Rivers*, Billi P, Hey RD, Thorne CR, Tacconi P (eds). John Wiley: New York; 297–311.

Leopold LB. 1994. *A View of the River*. Harvard University Press: Cambridge, MA; 204–206.

Lisle TE. 1995. Particle size variations between bed load and bed material in natural gravel bed channels. *Water Resources Research* **31**(4): 1107–1118.

Mantz PA. 1980. Low sediment transport rates over flat beds. *Journal of the Hydraulics Division, American Society of Civil Engineers* **106**(HY7): 1173–1190.

Martinez MH, Ryan SE. 2000. *Constructing temporary sampling platforms for hydrologic studies*. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-64.

Milhous RT. 1973. *Sediment transport in a gravel-bottomed stream*. PhD Dissertation, Oregon State University, Corvallis, OR.

Nelson JM, Emmett WW, Smith JD. 1991. Flow and sediment transport in rough channels. In *Proceedings of the Fifth Interagency Sedimentation Conference, March 12–21, Las Vegas, NV*. US Government Printing Office, Washington, DC; **2**(4): 55–62.

Neter J, Wasserman W, Kutner MH. 1989. *Applied Linear Regression Models* (2nd edn) Irwin: Homewood, IL.

Nolan KM, Shields RR. 2000. *Measurement of stream discharge by wading*. US Geological Survey, Water Resources Investigation Report 00-4036 (CD-ROM).

Paola C, Seal R. 1995. Grain size patchiness as a cause of selective deposition and downstream fining. *Water Resources Research* **31**(5): 1395–1407.

Parker G. 1979. Hydraulic geometry of active gravel rivers. *Journal of the Hydraulics Division, American Society of Civil Engineers* **105**(HY9): 1185–1201.

Parker G, Klingeman PC. 1982. On why gravel bed streams are paved. *Water Resources Research* **18**: 1409–1423.

Parker G, Klingeman PC, McLean DG. 1982. Bedload size and distribution in paved gravel-bed stream. *Journal of the Hydraulics Division, American Society of Civil Engineers* **108**(HY4): 544–571.

Reid I, Frostick LE. 1984. Particle interaction and its effect on the thresholds of initial and final bedload motion in coarse alluvial channels. In *Sedimentology of Gravels and Conglomerates*, Koster EH, Steel RJ (eds). Canadian Society of Petroleum Geologists, Memoir 10: 61–68.

Reid I, Frostick LE, Layman JT. 1985. The incidence and nature of bedload transport during flood flows in coarse-grained alluvial channels. *Earth Surface Processes and Landforms* **10**: 33–44.

Ryan SE. 1994. *Effects of Transbasin Diversion on Flow Regime, Bedload Transport, and Channel Morphology in Colorado Mountain Streams*. PhD Dissertation, University of Colorado, Boulder, CO.

Ryan SE. 1999. Diel variation in discharge and bedload transport processes in a subalpine stream during snowmelt runoff. In *Wildland Hydrology*, Olsen DS, Potyondy JP (eds). American Water Resources Association: Herndon, VA; 85–92.

Ryan SE, Emmett WW. 2002. *The nature of flow and sediment movement in Little Granite Creek near Bondurant, WY*. General Technical Report RMRS-GTR-90, Ogden, UT. US Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Ryan SE, Porth LS. 1999. A field comparison of three pressure-difference bedload samplers. *Geomorphology* **30**: 307–322.

Ryan SE, Troendle CA. 1996. Bedload transport patterns in coarse-grained channels under varying conditions of flow. In *Sedimentation Technologies for Management of Natural Resources in the 21st Century*. Sixth Federal Interagency Sedimentation Conference, March 10–14, 1996, Las Vegas, NV: VI-22–VI-27b.

Sidle RC. 1988. Bedload transport regime of a small forest stream. *Water Resources Research* **24**: 207–218.

Thorne CR, Hey RD. 1983. Discussion of "Bedload and size distribution in paved gravel-bed streams" by G Parker *et al*. *Journal of Hydraulic Engineering, Proceedings of the American Society of Civil Engineers* **109**(5): 791–793.

Troendle CA, Nankervis JM, Ryan SE. 1996. Sediment transport from small, steep-gradient watersheds in Colorado and Wyoming. In *Sedimentation Technologies for Management of Natural Resources in the 21st Century*. Sixth Federal Interagency Sedimentation Conference, March 10–14, 1996, Las Vegas, NV: IX-39–IX-45.

Troendle CA, Wilcox MS, Bevenger GS, Porth LS. 2000. The Coon Creek Water Yield Augmentation Project: implementation of timber harvesting technology to increase streamflow. *Forest Ecology and Management* **5268**: 1–9.

U.S. Interagency Advisory Committee on Water Data. 1982. *Guidelines for determining flood flow frequency*. Bulletin 17B of the Hydrology Subcommittee. US Geological Survey, Office of Water Data Coordination: Reston, Virginia.

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.

Whiting PJ, Stamm JF, Moog DB, Orndorff RL. 1999. Sediment-transporting flows in headwater streams. *Geological Society of America Bulletin* **111**(3): 450–466.

Wilcock PR, McArdell BW. 1993. Surface-based fractional transport rates: mobilization thresholds and partial transport of sand-gravel sediment. *Water Resources Research* **29**(4): 1297–1312.

Wilcox MS, Troendle CA, Nankervis JM. 1996. Bedload transport in gravel bed streams in Wyoming. In *Sedimentation Technologies for Management of Natural Resources in the 21st Century*. Sixth Federal Interagency Sedimentation Conference. March 10–14, Las Vegas, NV: VI-28–VI-33.

Wolman MG. 1954. A method of sampling coarse river-bed material. *Transactions of the American Geophysical Union* **35**(6): 951–956.