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RELATIVE BED-MATERIAL DISCHARGES AT A MOUNTAIN STREAM CONFLUENCE USING A NATURAL SEDIMENT TRACER

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ABSTRACT

A locally occurring distinctive rock type is used as a tracer to estimate relative bedload sediment yields from tributary streams. Tracer concentration by mass is measured for samples of sub-surface gravel, which approximate bedload-sized material. Estimates of relative bed-material discharge from the Kowai and Foggy River catchments in the Torlesse Range, near Springfield, South Island, New Zealand, are obtained using a regression technique where possible. The calculated figure of 0.96 for the ratio of Foggy:Kowai bed sediment output compares with a value of 0.37 using an empirical sediment yield-basin area relationship. The natural tracer technique is of use where empirical relationships are unreliable, and direct estimates of sediment yield are unavailable.

INTRODUCTION

The study of sediment movement through drainage networks often uses estimates of relative sediment yield from different catchments, obtained using empirical relationships between sediment yield and basin area (ASCE, 1975). Where there is doubt as to the accuracy of such estimates an alternative method is to use naturally occurring tracers. Heavy minerals often have been used to document patterns of sediment redistribution, especially where their input is related to mining activity which provides temporal control (e.g. Graf, 1990; James, 1991; Macklin and Lewin, 1989; Wolfenden and Lewin, 1977,1978). Variations in tracer concentration can be used to evaluate the spatial and temporal patterns of sediment flux, and sediment yields can be estimated using a suitable mixing model (Marcus, 1987). Lithological tracers are useful for tracing coarse bedload material (>2mm), especially if different lithologies can be differentiated visually. Both naturally occurring and artificially introduced (e.g. Kondolf and Matthews, 1986; Mosley, 1978) tracers can be used.

The use of a lithological tracer for gravel sizes is described for the Kowai and Foggy Rivers, near Springfield, South Island, New Zealand.

THEORY AND ASSUMPTIONS

Consider the junction of two tributary catchments. Bed material inputs to the junction from the two tributaries are Q_1 and Q_2 m^3/ unit time. The output from A is Q_3 m^3/unit time. Subscripts 1 and 2 refer to the two tributary catchments, and 3 to the main stream downstream of the confluence. A perfectly mixed tracer is assumed, the concentrations of which are c_1, c_2 and c_3, respectively.

In the absence of aggradation or degradation, the continuity equation for bed material at the junction is

$$Q_3 = Q_1 + Q_2 \tag{1}$$

The volume of tracer material exported from catchment 1 is c_1Q_1 m^3/unit time. Continuity for the tracer material gives,

$$c_3Q_3 = c_1Q_1 + c_2Q_2 \tag{2}$$

Combining equations (1) and (2) yields,

$$\frac{Q_1}{Q_2} = \frac{c_3 - c_2}{c_1 - c_3} \tag{3}$$

Equation (3) enables calculation of the relative bed material discharges of the two input catchments from the concentrations of tracer material in the three reaches. These concentrations are easier to estimate than total bedload yields from the incoming catchments. If an estimate of absolute bed-material discharge is available for any one of the three catchments, the absolute values for the other two are readily calculated. Marcus (1987) used a re-arrangement of equation (3) to predict concentrations downstream of a confluence, assuming that Q_1 and Q_2 could be estimated from an empirical sediment yield equation.

Equation (3) is a direct analogy with mixing-model methods of estimating water discharge at tributary confluences. There are several differences between water and bedload discharges which constrain the application of this equation. Gravel bedload transport is episodic, occurring during high flows. Even with constant water discharge, rates vary between zero and about 4 times the mean (Hubbell, 1987). It also is spatially variable with peak rates not necessarily coincident with locations of peak shear stress (Davoren and Mosley, 1986). For these reasons, tracer mixing is unlikely to be perfect. The effects of variation can be reduced by increased sampling within each catchment, and by selecting hydraulically similar locations for sampling.

Concentrations of tracer material are estimated, not from bedload when in transport, but from bed-material deposits at low flow. To allow for spatial variations in tracer concentration consequent upon bedload transport being a stochastic process (Einstein,1950), multiple samples must be taken and averaged for the individual reaches. This assumes that all samples are drawn from the same statistical population. This may be invalid where there are sources of sediment external to the river channels, unless these sources have tracer concentrations identical to those within the channels. For long reaches with external sediment sources, tracer concentrations may change systematically downstream. Martin (1972) describes a technique for dealing with this (Fig. 1). Regression lines are fitted through data for samples taken along reaches, plotted as concentration vs. distance downstream and projected to the confluence. Tracer concentrations predicted by the regressions at the confluence are used in equation (3). For heavy minerals, Wolfenden and Lewin (1978) used a log concentration vs. distance regression, and Marcus (1987) found a log-log relationship to be appropriate. The method of ordinary least squares is used as interest lies in prediction of tracer concentration at a particular location, rather than specification of a functional relationship (Mark and Church,1977).

The assumption that the bedload material is represented by the deposits requires that bed material be sampled in locations of bedload deposition. This implies sampling of sub-surface material, which has particle size distributions in close agreement with those of bedload (Parker et al.,1982; Parker,1990). The method further assumes that the proportions of tracer and host material are the same in events of different size. This is less relevant if the majority of bedload transport occurs during high magnitude events when all particle sizes are in transport and generally equally mobile i.e. all grain sizes are in transport in direct proportion to their abundance in the sub-surface bed material. Considering an individual size fraction of material, equation (1) becomes

$$P_{i1}Q_1 + P_{i2}Q_2 = P_{i3}Q_3 \tag{4}$$

where P_{ij} is the proportion of the bed material discharge in the ith size class in the jth catchment. Similarly, equation (2) becomes

$$c'_{i1}P_{i1}Q_1 + c'_{i1}P_{i2}Q_{i2} = c'_{i3}P_{i3}Q_3 \tag{5}$$

where c'_{ij} is the concentration of tracer in the bed material discharge of the ith fraction in the jth catchment. Equations (4) and (5) yield equation (6),

$$\frac{Q_1}{Q_2} = \frac{(c'_{i3} - c'_{i2})P_{i2}}{(c'_{i1} - c'_{i3})P_{i1}} \tag{6}$$

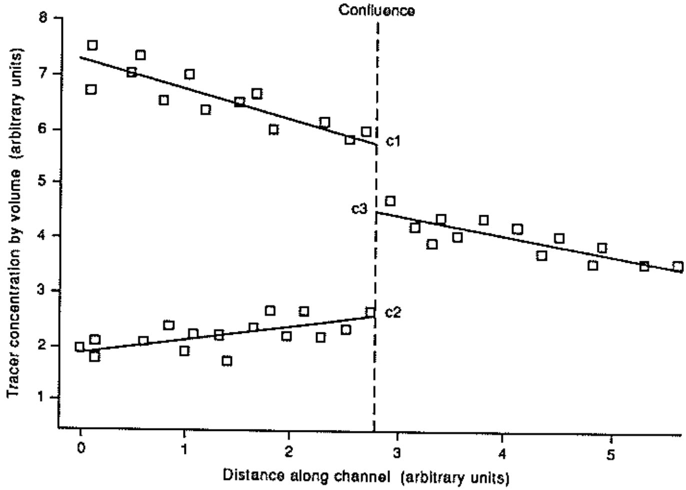

FIG. 1—Hypothetical example showing use of a regression method for estimating tracer concentration at a confluence. Solid lines are least-squares regression equations. Boxes show individual samples.

As samples of the bedload are not directly available, it is convenient to assume equal mobility, in which case equation (6) becomes

$$\frac{Q_1}{Q_2} = \frac{(c_{i3} - c_{i2})f_{i2}}{(c_{i1} - c_{i3})f_{i1}} \tag{7}$$

in which f_{ij} is the proportion of sub-surface bed sediment in the ith size class in the jth catchment, and c_{ij} is the tracer concentration in that class. By summing equations (4) and (5) over all size classes, equation (3) can be verified, whether c_{ij} is constant or variable for different i. Although subtle, departures from equal mobility are well recognised (Ashworth and Ferguson, 1989; Parker, 1990), and it should be noted that their presence affects measured tracer concentrations.

Ideally all size classes should be sampled, obtaining statistically significant volumes of sediment from each one. Where relative sediment discharge may vary systematically for different size fractions, this is important. However, for coarse gravel deposits, large samples are required. Using the criteria of Church et al. (1987) the largest clast in a sample should comprise <1% of the sample mass to reliably estimate the parameters of the size distribution. In this study this applies to the tracer sample. With an ellipsoidal largest clast of 180mm b-axis and a tracer concentration of 20% this implies that each sample should weigh 4000kg. As this is impractical, the problem can be circumvented by concentrating on a particular size fraction of material. If grain breakdown is negligible, the particle size distributions of sediment change downstream only as a result of selective transport, and tracer concentration can be examined for one size fraction. The modal size fraction is the most appropriate for this, and equation (7) is used. Generalising this result to all sizes requires the further assumption that Q_1/Q_2 is constant for all grain sizes, which should be tested using a reduced number of samples.

METHOD

The study site is the Kowai River, near Springfield, New Zealand. The source of the Kowai is close to Mount Torlesse (1960m) in the Torlesse Range (Fig. 2). Approximately 4km below the source the Foggy River is a right bank tributary to the Kowai. Within the Torlesse Range the predominant lithology is greywacke sandstone of Upper Triassic age. Local intrusive veins produce small amounts of other lithologies, which usually can be differentiated from greywacke on the basis of colour. Two red-coloured materials are present, jasper and a ferruginous mudstone (Martin, 1972). The jasper is less friable than the mudstone, and often has veins of green metavolcanic minerals and mica. Jasper and mudstone particles larger than 4mm diameter can be easily differentiated, and in this study jasper is used as the tracer.

Bar heads were sampled to avoid the effects of local depositional variability (Church and Kellerhals, 1978; Dawson, 1988). The locations of the sampling sites are shown in Figure 2. A particle size distribution of sub-surface material downstream of the confluence (Fig. 3) shows a mode spanning the 8-16mm and 16-32mm size classes. Making the assumption that the ratio Q_1/Q_2 for the modal class adequately represents that for the entire grain size distribution, the 8-16mm class was selected for calculation of tracer concentrations, as it is more convenient to work with smaller particles.

TABLE 1— Bulk particle size data for sediment from the Kowai and Foggy Rivers. Sample locations are shown in Figure 2. All samples truncated at 2mm. Samples 5-7 taken from Blakely et al. (1981; Fig. 8) include both surface and sub-surface sediment. The bulk sample includes only sub-surface material.

Particle size		% in size class retained by sieve			
		SAMPLE			
(phi units)	(mm)	5	6	7	Bulk
-1	2	10.2	13.2	8.4	10.8
-2	4	8.2	15.9	7.6	14.6
-3	8	10.4	24.1	11.2	20.0
-4	16	14.0	20.9	16.0	20.2
-5	32	16.2	14.3	18.6	16.5
-6	64	16.8	11.6	13.2	8.5
-7	128	10.0		18.0	
-8	256	14.4		6.8	2.5

At each sampling site the surface sediment was removed down to the base of the coarsest material present at the surface. A sample of sub-surface sediment was taken and wet sieved on site to remove sizes <8mm and >16mm. The 8-16mm fraction was dry sieved in the laboratory to ensure no finer or coarser particles remained, and separated into jasper and 'all other' classes. These were weighed to determine tracer concentration by mass. Densities were measured as 2729 kg m^{-3} (standard deviation=245; n=10) for greywacke, and 2809 kg m^{-3} (s.d.=282; n=10) for jasper. There is no significant difference between these estimates (t-test), so tracer concentrations by mass can be considered equivalent to concentrations by volume.

Abrasion rates were estimated from data presented by Adams (1978). The mean abrasion rate for Torlesse sandstone is 0.0014 km^{-1}, ignoring data from pebbles classified by Adams as unsound. The only available jasper data gives a mean value of 0.00051 km^{-1}, which is 36% of the sandstone rate. Over the 6km distance between the furthest upstream and furthest downstream samples in this study the diameter of a sandstone clast would decline to 99.2% of its initial value, and that of a jasper clast to 99.7%. Neither of these is significant for the present study, but abrasion should not be ignored where much greater distances or higher abrasion rates are involved.

Bed-material grain size distributions measured by Blakely et al. (1981; their Figures 7 and 8) were used to provide values of f_{ij}. These samples included surface material and so do not strictly represent bedload particle sizes. Table 1 gives these data together with the sub-surface sample shown in Figure 3, modified so as to truncate the samples at 2mm, an arbitrary division between suspended load and bedload-sized material. Using samples B5 and B6 from Blakely et al. (Fig. 2) suggests that f_K/f_F= 10.4/24.1 = 0.43 for the 8-16mm size class.

A pilot study was made to estimate tracer concentration directly from surface material using grid-by-number surface samples. These are equivalent to bulk sieve

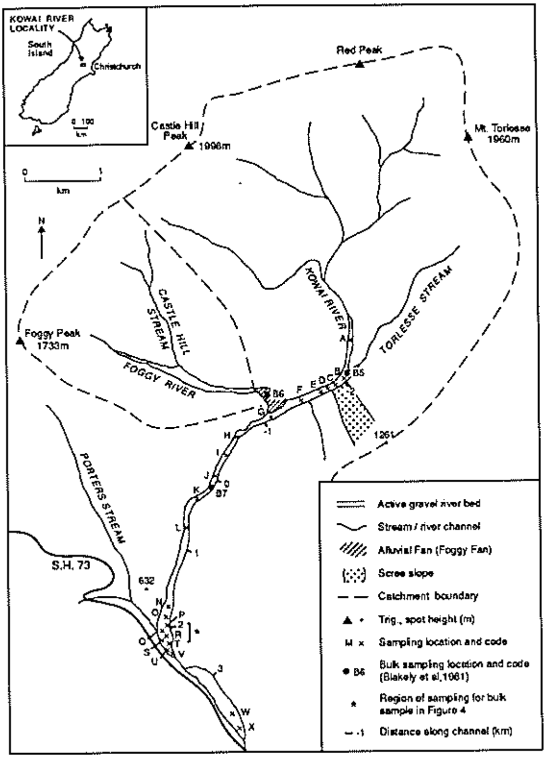

FIG. 2—Location of sampling sites within the Kowai and Foggy River catchments.

samples of the surface sediment by weight (Kellerhals and Bray, 1971; Church et al., 1987). The test results were inconsistent with sub-surface samples, due to the small number of jasper clasts in each sample. To obtain adequate numbers of jasper clasts (at least 50) would involve large samples. The pilot study of 12 sites suggested that between 630 and 4600 clasts would need to be sampled in order to obtain 50 tracer clasts. This method may be useful where tracer concentrations are greater (> 10% in all samples), and the problem could be circumvented by using photography and image analysis, covering a large area of the bed.

RESULTS

Samples from the Foggy River contained no jasper, and no jasper clasts were found during reconnaissance of the catchment. Using subscripts K,F and C to denote the Kowai, Foggy and combined catchments, respectively, equation (7) becomes,

$$\frac{Q_F}{Q_K} = \left(\frac{c_K}{c_C} - 1\right)\frac{f_{iK}}{f_{iF}} \tag{8}$$

TABLE 2—Summary data for 8-16mm size fraction. Figure in brackets after mean Q_F/Q_K is the fractional standard deviation of the estimate. Corrected estimates have been adjusted for the relative abundance of material within the two tributary catchments.

	SITE	
	Kowai	Combined
Sample size	6	17
Mean tracer concentration	0.084	0.024
Standard deviation	0.041	0.009
Coefficient of variation (=s.d./mean)	0.49	0.40
Regression significance level	0.05	0.05
Regression r^2	0.63	0.49
Mean Corrected Q_F/Q_K	1.11 (0.48)	
Regression Corrected Q_F/Q_K	0.81	

where i in this case refers to the 8-16mm class. In the pilot study of surface material, surface tracer concentrations were measured in each of 12 half-phi size classes starting at 8mm, at four sites – two upstream and two downstream of the confluence. The ratio Q_F/Q_K (equation 8) for the 8-16mm class is 6.11. The values of this ratio for the other size classes lie in the range 0-8.09. Those that are within the 95% confidence limits of the estimate for the 8-16mm size class account for 75% of the surface grain size distribution. Data from only two size classes, representing 11% of the size distribution, gave ratios less than 1, which imply that $Q_F<Q_K$. Although the number of samples and sample sizes in this pilot study are too small, these results provide some support for using the 8-16mm size class as representative of the entire grain size distribution.

The sub-surface sample data are presented in Figure 4 and summarised in Table 2. Only the results of linear regression are presented as the semi-log and log-log methods yielded no improvement over the linear model. Estimates of the ratio Q_F/Q_K are 1.11 and 0.81 for the mean and regression methods, respectively. There is considerable scatter in the data from the Kowai River upstream of the confluence (Fig. 4), and the 95% confidence limits on the regression relationship reflects this. The data from this reach are poorly suited to regression analysis being composed of 2 groups of 3 samples, each with similar concentrations. This illustrates a problem with the regression method where sample sizes are small, which is common in studies of this type. The nature of the data also makes the mean method unreliable. While it is clear that jasper concentrations should be reduced downstream of the confluence compared to upstream, the magnitude of this reduction is difficult to evaluate.

Below the confluence, jasper concentrations increase with distance downstream. The regression relationship, the slope of which (0.034) is significant at

α=0.05, has narrower confidence intervals than upstream of the confluence. Sample S (Fig. 2) had a concentration of 0.0024, and was excluded from the regression analysis, as its close proximity to an eroding fluviglacial terrace and the Porters Stream confluence, both of which contain little jasper, makes it likely that this sample was imperfectly mixed.

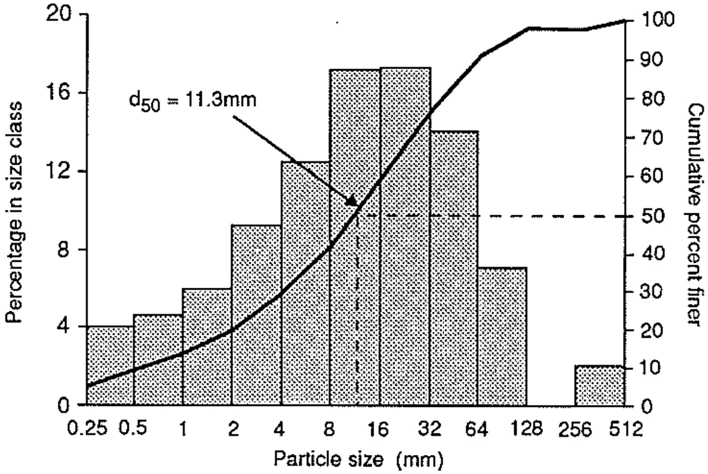

FIG. 3—Sub-surface particle size distribution from the Kowai River. See Figure 2 for sampling location. Total sample mass is 136kg.

DISCUSSION

Statistical considerations

The need to stratify sampling locations, which is a consequence of sediment sorting, restricted the number of potential sampling sites upstream of the confluence of the Foggy and Kowai Rivers. High coefficients of variation (Table 2) are partly a sampling problem, but also result from local sediment supply to the river. Obtaining a large enough number of samples may be difficult in many cases. The overall mean method for determining dilution is difficult to justify where there is a downstream change in tracer concentration, since it is conditions at the confluence that are of interest. The regression method is preferred for this reason, but is unreliable when sample sizes are small and variance is high. Within the 95% confidence intervals the regression method yields values of Q_{t}/Q_{K} in the range 0 to 6.5.

Where statistically significant regression relationships with sufficiently narrow confidence limits can be defined both upstream and downstream of the confluence, this method is recommended. Where one or both regressions fail to meet this criterion, due to widely scattered data, the absence of a downstream trend in tracer concentration, or small sample sizes, the total mean method is preferred. However, which samples are included when calculating this mean can be varied according to local conditions, since it is concentrations at the confluence itself that are of primary interest. For example, the mean of the three samples collected immediately upstream of the confluence should give a more reliable indication of tracer concentration at the confluence than the regression model in Figure 4 which uses all 6 upstream samples. When compared with the apparently reliable regression model from downstream of the confluence, a value of 0.96 (the 95% confidence interval is 0.67 - 1.39; note that this is asymmetric due to the result being expressed as a ratio) is suggested for Q_F/Q_K. Within the constraints of the present data this is the best available estimate. Such an abstraction is justifiable on subjective grounds only, and is dependent on what is known of local conditions.

Geomorphological considerations

The data in Figure 4 demonstrate a dilution of tracer concentration downstream of the Foggy River confluence, and the value of 0.96 for Q_F/Q_K is reasonable. The omission of the three samples from farthest upstream to obtain this value can be justified on geomorphological grounds. Between these three samples and the three lower ones a scree slope is being directly eroded by the Kowai River (Fig. 2), and no jasper clasts were observed in this scree material. The small left bank tributary downstream of this scree adds further dilution. Given the short distance from these sediment sources to the sampling sites, the new material may not have mixed perfectly before the sampling sites, which would further lower the calculated Q_F/Q_K ratio. The degree of mixing cannot be evaluated and no improvement for the estimate of Q_F/Q_K is possible.

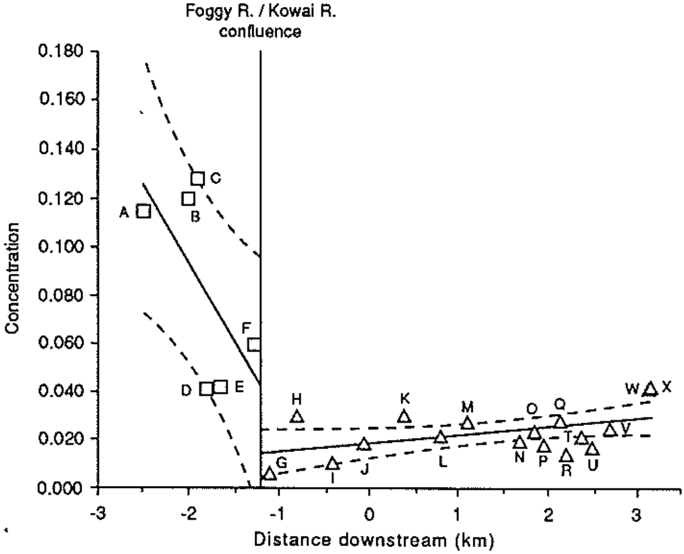

FIG. 4—Concentration of jasper along the Kowai River. Letters correspond to site locations on Figure 2.

The catchment areas upstream of the confluence are approximately 17 km^2 for the Kowai River, and 5.5 km^2 for the Foggy River. The relationship between the sediment delivery ratio (SDR= sediment output from basin/ sediment production within basin= Y/E) and basin area (A) is can be approximated in the form (ASCE, 1975)

$$SDR \;\alpha\; A^{-0.125} \tag{9}$$

Assuming that sediment production (E) varies linearly with basin area, and that the SDR relationship holds for bedload material, this can be re-arranged to give

$$Y \;\alpha\; A^{0.875} \tag{10}$$

Measurements have shown that the coefficient 0.875 lies in a wide range, but over long time periods is generally below 1 (Walling, 1983). Using equation (10) as a first approximation of bed material supply from catchments of different size, the ratio Q_F/Q_K is 4.44/11.9, or 1/2.7. This is 1/2.6 of the ratio calculated using the tracer method. Two reasons can be advanced for this discrepancy. Firstly, because of bedrock differences, the sediments in the Foggy catchment are finer grained than in the Kowai, immediately above the confluence (Fig. 5). This may offset the effect of greater water flow in the Kowai River. Secondly, the Foggy basin contains extensive fine grained flood deposits dating from an event of 125-160

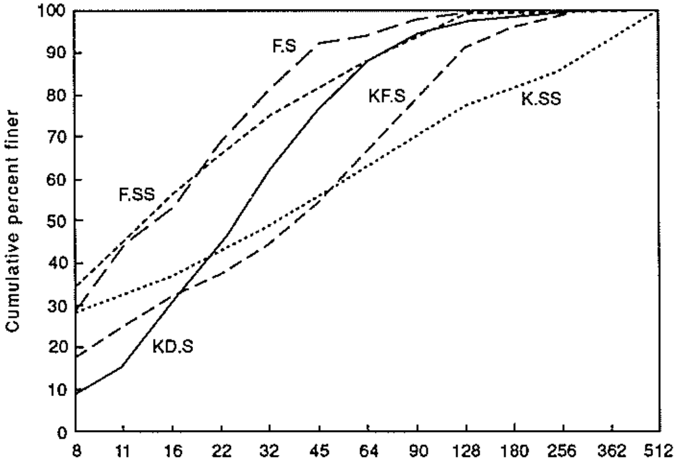

FIG. 5—Comparison of particle size data from within the two catchments. S refers to surface samples obtained by grid-by-number sampling. SS refers to bulk samples including both surface and sub-surface sediment, as sieved by Blakely et al. (1981). Samples F are from the Foggy River, K is from site B5, KD from site D and KF from site F in the Kowai River. Both surface and sub-surface sediment in the Foggy River is finer than that in the Kowai River.

year recurrence interval in 1951 (Beschta,1983). Beschta (1983) estimated that at least 200 000 m^3 of this material remained within the upper part of the Foggy basin in 1979. These sediments are stored in terraces up to 5m high which have not been stabilised by vegetation and are vulnerable to undercutting by the stream. Remaining 1951 flood deposits in the Kowai catchment (at least within 2km of the confluence) have less relief (<1m) and have been partially vegetated. These deposits are probably the source of the higher sediment yield from the smaller catchment, and this situation may persist for some time. The most conservative estimate from Beschta's (1983) data suggests that 60% of the accumulated sediment had been removed from the Foggy catchment in the 28 years after the event. If the recurrence interval is 150 years there is adequate sediment within the Foggy catchment to exceed Kowai catchment sediment delivery for about 30% of the recurrence interval. After erosion of the remaining sediment from within the Foggy River catchment, the relative bed material discharges of the two catchments will depend on the timing and magnitude of future sediment supply events. This result is consistent with those from several studies in which sediment yield per unit area has been found to increase with basin area due to localised episodes of erosion and remobilisation of temporarily stored sediment (Owens and Slaymaker, 1992).

The mechanism of transfer of sediment from the Foggy River to the Kowai will influence patterns of tracer concentration downstream of the confluence. Immediately upstream of the confluence, the Foggy River has an active, unvegetated alluvial fan (approximately 700m long and 250m wide at its downstream end; Fig. 2). This forces the Kowai River against the true left bank of its valley in this region. During 'normal' conditions, aggradation of the fan means that little bedload is transferred directly into the Kowai River. On occasions the Kowai erodes the toe of the fan adding sediment to the Kowai, and initiating degradation within the fan channels. A period of accelerated sediment delivery to the Kowai is thus postulated when this erosion occurs. This may be a recurrent process (Harvey, 1992; Richards, 1993), and is suggested to be a mechanism by which sediment waves enter the Kowai River system (Blakely et al., 1981; Beschta, 1983). Smaller waves may be introduced under 'normal' conditions. Any such wave of Foggy River material would initially contain no jasper. As this material and the Kowai material mixed the jasper concentration would increase downstream, which concurs with observation (Fig. 4). However, other reasons, such as additional jasper sources within the Kowai catchment downstream of the confluence, could also be responsible, so the evidence is inconclusive.

CONCLUSION

A number of simplifying assumptions were made in adapting a mixing model to bedload sediment. These constrain the precision of results, but provide a valuable estimate of relative sediment yield in areas where equation (10), or a variant containing additional independent variables, is not applicable. The scatter about such relationships is such that determination of relative bed material discharge will often be impossible using such a method, which is subject to both spatial and temporal aggregation (Walling, 1983). Tracer dilution enables the disaggregation of these effects if changes in sediment storage are known for the period of interest. The Kowai River / Foggy River example illustrates the utility of the tracer technique for determining relative bed material discharge in small catchments, suggesting that the proportion of bed material contributed by the Foggy is larger than would have been predicted using empirical equations based on catchment area. The tracer concentration data used herein is scattered, but no more so than in many studies of sediment yield. This estimate of relative bed material discharge makes several assumptions, and adequate supporting field evidence is required for the successful use of this technique.

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