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An assessment of the accuracy of the Spatial Integration Method (SIM) for estimating coarse bedload transport in gravel-bedded streams using tracers

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Abstract The accurate estimation of coarse sediment transport rate remains one of the goals of geomorphological and engineering studies of river channels. This paper describes an experiment designed to assess the accuracy of the Spatial Integration Method (SIM) of determining sediment transport rate or yield, using passive tracers. Tracer dispersion results are presented from five events of different magnitude. The study concludes that the SIM is capable of producing estimates of sediment transport rate that correspond with trapped values. Sources of error are quantified and guidance is given on the appropriate methods for deploying passive tracers for the estimation of coarse sediment transport rates.

Key words sediment transport rate; spatial integration method; tracers

NOTATION

d_s	active layer thickness (m);
Q_b	bulk sediment transport (kg s^{-1});
v_b	virtual velocity of sediment particles (m s^{-1});
w_s	active layer width (m);
λ	porosity of sediment;
ρ_s	density of sediment (taken as 2650 kg m^{-3}).

INTRODUCTION

The evolution of morphology and physical habitat in river environments is linked intrinsically to the processes of sediment transport. In many cases, these environments are dominated by coarse sediments (here, defined as particles having a diameter of 8 mm and greater), (Leopold, 1992). Understanding coarse sediment transport processes has direct economic and ecological benefits, via improvements in the prediction of changes in physical habitat and the location and magnitude of erosion and deposition, the latter accounting for substantial costs in terms of land loss and disruption of infrastructure (Sear *et al.*, 2000).

The study of sediment transport processes has become increasingly sophisticated (McEwan *et al.*, 2001; Habersack, 2001) with progress in fluvial research converging on the prediction of sediment transport rates; this has taken place through improvements in the physically-based understanding of entrainment, transport and deposition. Sediment tracing provides a cost-effective approach to the determination of sediment transport rates (Laronne *et al.*, 1992; Haschenburger & Church, 1998; Sear *et al.*, 2000). Furthermore, the derivation of transport rate includes information on the processes of sediment movement (for example, active width and depth of moving sediment) that are usually absent from other methods. The principle behind tracer studies is to introduce material that is easily distinguishable from the natural sediment but behaves similarly, into an environment, and to monitor its behaviour. In practice, several types of tracer study exist (Madsen, 1989): the present study focuses upon the Spatial Integration Method (SIM). This approach is the most widely and simply deployed method in both littoral and fluvial tracing studies (Mosley, 1978; Kondolf & Mathews, 1986; Laronne *et al.*, 1992; Lee *et al.*, 2000; Sear *et al.*, 2000). Three quantities need to be measured during a SIM tracer study: (a) the distance travelled by the tracer's centre of mass or volume (centroid) during a given time period (allowing the virtual velocity of downstream or longshore movement to be determined); (b) the thickness of the active layer (de Vries, 2003); and (c) the width of the active layer (Ashiq, 1999). The relationship is represented mathematically as:

$$Q_b = v_b d_s w_s (1 - \lambda) \rho_s$$

An important assumption made in all tracer-based estimates of transport rate using SIM is that the active depth is well represented by the distribution of tracers. Laronne *et al.* (1992) argue that tracers in fact consistently underestimate the depth of active layer since they tend to be distributed exponentially with depth into the active bed, with highest concentrations at the surface (Hassan & Church, 1994). However, in practice several studies have indicated that for average values of active layer thickness, tracer and scour chain estimates are comparable (Hassan, 1990; Haschenburger & Church, 1999; de Vries, 2003). The latter have been criticised as being difficult to deploy and unrepresentative of the spatial variability in active layer thickness (Hassan, 1990; de Vries, 2003). The main problem with the assumptions made with the SIM is that the levels of uncertainty are difficult to quantify without deploying both forms of measurement. This paper utilises the benefit of contemporaneous trapping of bedload to evaluate a series of different assumptions used in the estimation of v_b, d_s and w_s.

METHODS & FIELD SITE

The field site chosen to test the SIM is a small gravel-bedded watercourse in southern England, the Highland Water (Table 1). Stream hydrology is flashy, and provides on average, 14 bedload transport events per year. These conditions optimized access to the bed after tracer dispersion, and ensured that a number of experiments were possible over the field season. Two passive tracer technologies were used; cast aluminium

Table 1 Field site characteristics used in SIM experiments.

Field Site	Basin Area (km^2)	$Q_{bankfull}$ ($m^3 s^{-1}$)	Bed Slope ($m\ km^{-1}$)	Bankfull width (m)	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)
Highland Water	11.5	2.90	0.0073	3.5	9.9	32.8	46.3

"forms", and aluminium foil covered natural clasts. The latter technology is low cast, offers three dimensional (3-D) detection to 0.25 m burial depth, and provides good representation of grain size and shape.

In total, data on tracer movement, hydrodynamics, and bedload transport were recovered from five events of contrasting magnitude and duration (Table 2). In each experiment, the tracers were deployed in three "patches", located at 25%, 50% and 75% across the channel width. Each "patch" contained the same number of tracer forms, of the same size and shape; a total of 90 in each bed. Each patch was 0.3 m^2, and tracers were buried down to the maximum expected active layer depth of $2 \times D_{90}$ (0.20 m), (de Vries, 2003). A line of pit traps was located across the full width of the stream some 25 m downstream of the injection section. These sampled over 90% of the bed width with minimal separation between each trap. Trap width was larger than any sampled clast within the study reach and trap length was greater than $100 \times D_{95}$. The traps provided an independent estimate of the event transport rate and yield. In practice, these traps overfilled during events three and five. Recovery of the tracers was by commercial submersible metal detector, with a detection range of up to 0.3 m burial depth. Burial depth was estimated as the distance from the bottom of the tracer to the bed surface, using a graduated rule (Haschenburger & Church, 1998). Tracer recovery rates were all over 90%. Water surface slope was measured using two calibrated Druck pressure transducers, situated 25 m upstream and downstream of the tracer injection site; logging averaged 10 s values every 10 min.

Theoretical issues in the study focused initially on manufacturing tracers that represented the indigenous material in terms of size and shape. The accurate measurement of bulk grain size was undertaken, for each study site, using the ISO lower precision curves published by Church *et al.* (1987). A set of nine "forms" were manufactured from cast aluminium. The nine forms were defined by a matrix that represented the sixteenth, fiftieth and eighty-fourth percentiles of the grain size distribution and 3 shapes that equated to the average, and ±1-standard deviation of the particle shape distribution (Oakey *et al.*, in review). An additional random sample of

Table 2 Event magnitudes associated with each tracer deployment.

Event	Q_{max} ($m^3 s^{-1}$)	Duration above Q_{crit} for 8 mm gravel (h)	Maximum event power ($W\ m^{-1}$)	Trap yield (kg)	Recovery (%)	No. mobile tracers
1	1.19	14.5	71.2	73.9	100	46
2	0.94	5.3	63.6	4.1	100	21
3	2.36	45.2	201.8	*206.2**	99	302
4	0.8	0.7	52.5	1.7	100	25
5	3.68	20.3	319.5	*212.6**	91	283

* Traps filled, minimum estimate.

120 particles was coated in aluminium foil, with 40 deployed in each "patch". The bulk porosity of the sediment was taken as 0.191 after Carling & Reader (1982).

RESULTS

Haschenburger & Church (1998) demonstrate a method for estimating the uncertainty in a SIM transport rate experiment. The method also estimates the contribution to the total error from v_b, d_s and w_s. This method was applied to the tracer data sets from the Highland Water. Table 3 shows that the contribution to the total error is largely derived from the estimation of burial depth (53%) and virtual velocity (39%), and shows no systematic trend with event magnitude. Active width accounts on average for only 8% of the total uncertainty, although this was higher for the two smallest events.

The second area of tracer theory explored the methodology for the SIM estimates of v_b, d_s and w_s. Different measures were used, and tested against measured transport yields recorded from traps installed in the Highland Water fluvial site. Unfortunately, for the larger events, the traps became over-filled. However, a log-linear relationship ($r^2 = 0.743$, $P < 0.001$) based on sediment transport data from 60 flood events for a reach 350 m downstream of the study site enabled a conservative estimate of the transport rates to be made.

Four methods for estimating the variables v_b, d_s and w_s were used in this study:

(a) Average Values Method (AVM) takes the average value for each variable—this is the most commonly adopted approach in SIM estimates.

(b) 95% Method (95%M) developed for littoral tracer experiments by Bray (1996). The method makes the assumption that the outliers in the estimation L are probably erroneous and deletes the largest 5% from each distribution.

(c) Maximum Depth Method (MDM)—is commonly deployed in littoral tracer studies (Bray, 1996) and assumes that the maximum burial depth recorded in each event most closely represents the depth of the active layer. Considerable variability in active layer depth is recorded in fluvial environments (de Vries, 2003), which casts doubt on the validity of this assumption.

(d) Area Method (AreaM)—is theoretically the most appropriate representation since transport rate is a product of the active cross-section area multiplied by the velocity of particles. Problems with the estimation of the active area from tracers occur as they become more dispersed with distance. In this study cross-sections were derived from 2 m downstream bins.

Table 3 Total error and the contribution to the total error from determination of virtual velocity (v_b), burial depth (d_s) and active width (w_s). Events are arranged in order of increasing stream power from left–right.

	Ev.4	Ev.2	Ev.1	Ev.3	Ev.5	H&C (98)	Average
Total Error (%)	20.6	14.7	28.8	8.8	9.5	7.0–124.6	N/A
Contribution from v_b	49.7	20.1	37.9	57.4	30.7	65*	38.7
Contribution from d_s	32.7	46.0	59.7	38.0	56.2	24*	53.4
Contribution from w_s	17.6	33.9	2.4	4.6	13.1	11*	7.9

* Estimates are mean values for all events, H&C is Haschenburger & Church (1998).

Figure 1 demonstrates the variability in calculated transport rates arising from the different methods used to estimate v_b, d_s and w_s. Three points emerge from this analysis. First, there is up to three orders of magnitude variability in transport rate, depending on the assumptions made in the Spatial Integration methods used. Second, assuming the trapped data is the real value, then the 95%M (Bray, 1996) provides the most consistent, and accurate prediction of 'observed' transport rates; attaining on average ±84% of the measured rate. The AVM also consistently performs better than other methods, with an average accuracy of ±130%. The MDM over-predicts in all cases, demonstrating that the active layer thickness is typically smaller in each event than the maximum scour depth. The AreaM has an uncertainty in transport rate estimation of the order of ±190%. This arises from the difficulty in quantifying the boundary of the cross-sections, particularly when defined by a relatively few tracers. In subsequent analysis of data, the 95%M was applied. Thirdly, the values predicted by the 95%M, and AVM are close to the measured values, demonstrating that the SIM method, when applied carefully, is a valid method for estimating sediment transport rates across a range of stream powers in this study stream. Furthermore, the average value for burial depth appears to be a reasonable approximation of the active layer thickness. Encouragingly, application of the AVM (the only one permitting comparison with published data sets), to existing published literature collapses transport rates onto a single relationship with stream power (Fig. 2) with exponent values similar to those from other gravel transport studies (Reid & Laronne, 1995). Given the variability in hydrograph shape recorded from these streams it is to be expected that the

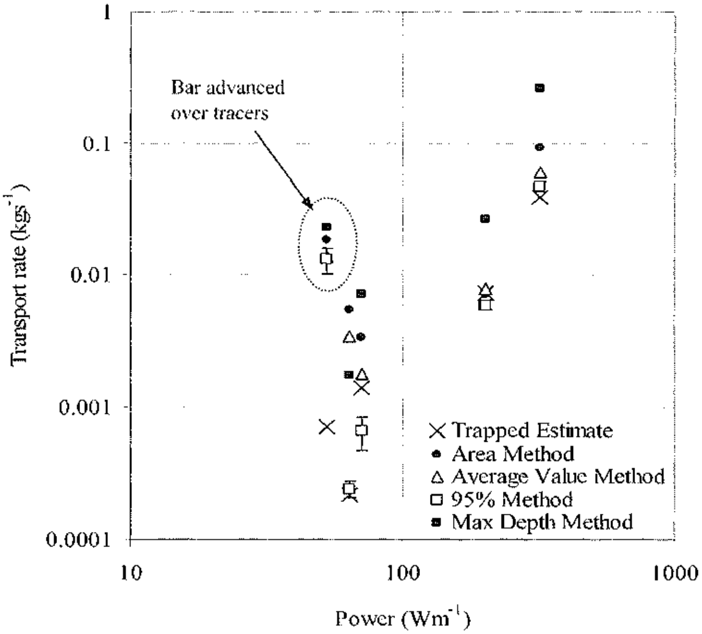

Fig. 1 Variation in transport rates estimated using different methods of spatial integration.

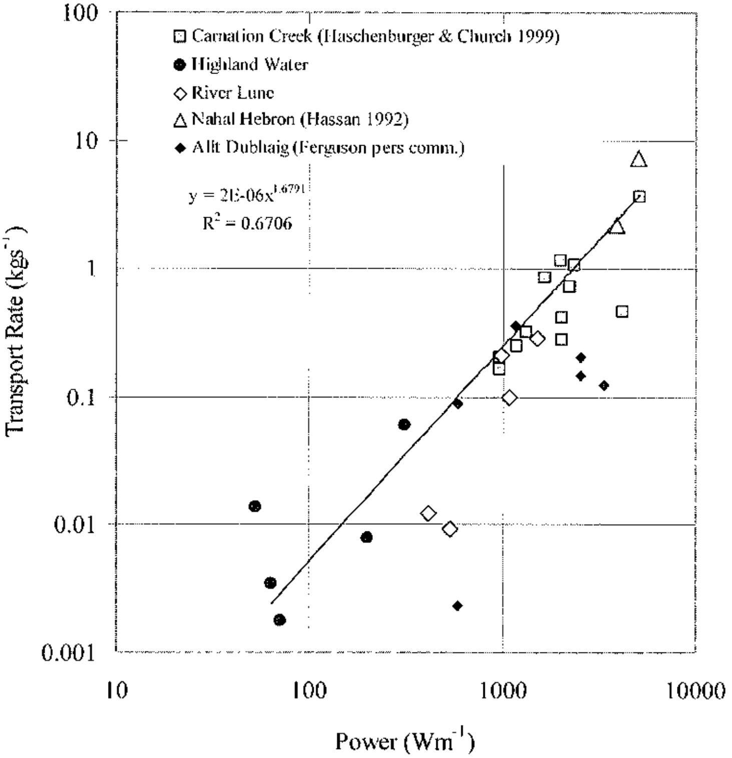

Fig. 2 Consistency in SIM estimates of bulk transport rate derived from published sources.

relationship between peak stream power used here and average event transport rate (or event volume) is not strong. Alternative hydraulic variables such as total event power may be preferable, depending on hydrograph shape (Inbar & Schick, 1979; Sear, 2003).

The influence of local filling of the river bed is illustrated by the erroneously high transport rates reported for Event 4. During this low energy event, migration of an upstream bar front over the tracers, after they had moved less than 1 m, resulted in relatively large values of burial depth. These accurately reflect the highly localized transport of sediment into the upper reach, but fail to represent the comparatively limited scour associated with the bedload traps. This implies that for events where there are strong local variations in scour and fill that are not represented by the tracer dispersal, the SIM method is likely to produce less accurate information. Figure 1 indeed shows that as transport rate increases, the overall accuracy of the SIM estimates increases for this reach.

The influence of tracer form (size and shape) and injection bed location was tested in a 2-way ANOVA for significant effect on the two dominant determinants of transport rate L and d_s. The results in Table 4 reveal that the position of the tracer injection is a significant control on both travel distance and burial depth in the river studied and is independent of event magnitude. Tracer form (size and shape) is a significant control on both travel distance and burial depth in the study river and

Table 4 Results of a 2-way ANOVA test to determine the effects of tracer form (size and shape) and injection position on travel distance and burial depth during each event. Events are arranged in order of increasing stream power from left–right.

Hypothesis	HW4	HW2	HW1	HW3	HW5
Distance (L)					
No difference between Injection sites	Reject (0.008)	Reject (0.002)	Reject (<0.001)	Reject (<0.001)	Reject (<0.001)
No difference between forms	Accept (0.879)	Cannot test	Cannot test	Reject (<0.001)	Reject (<0.001)
Burial depth (d_s)					
No difference between Injection sites	Reject (0.031)	Cannot test	Cannot test	Reject (0.032)	Reject (<0.001)
No difference between forms	Accept (0.032)	Cannot test	Cannot test	Reject (0.807)	Reject (<0.001)

appears less significant at near threshold conditions. This latter finding is unexpected, but is explained by the limited number of similar tracer forms that moved in Event 4. The behaviour of forms was not significantly different between injection beds. These results are directly comparable with previous tracer theory studies undertaken on shingle beaches (Lee *et al.*, 2000; Bray, 1996) and confirm earlier observations on the influence of size and tracer shape (Stott & Sawyer, 2000; Warburton & Demir, 2000) on travel distance.

CONCLUSIONS

The Spatial Integration Method for determining transport rate or yield determination can provide values that approach those measured using simple pit traps. The advantages of the tracer based approach, is that data can be obtained for high magnitude events, where other methods of monitoring typically fail. The method also provides information on other important transport parameters, such as active width and depth and the influence of size and shape. However, the SIM results are sensitive to the method of estimating v_b, d_s or w_s. In this assessment, 95% and Average Values methods both performed consistently across the different magnitude events. The use of Maximum Depth methods over-estimate transport rates in the study stream. The method for determining uncertainty in SIM transport rates utilized by Haschenburger & Church (1998) suggests that values are encouragingly low, and that most of the error is derived from estimating virtual velocity (dependant on L and duration of transport) and in this stream, active layer thickness from tracer burial depth.

The size, shape and location sensitivity of travel distance (L) reported in this study, confirms that the use of tracers for estimating sediment transport rates must replicate not only the size, but also the shape and spatial controls on transport distance and burial depths, regardless of event magnitude. Deployment of tracers in patches across the channel represents a balance between the ideal representation of the full cross-section, and pragmatic limitations of working in large rivers. Deployment of tracers should also seek to represent the active layer depth, in order to provide an accurate estimation of L.

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