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Determining event bedload volumes for evaluation of potential degradation sites due to gravel extraction, N.S.W., Australia

JONATHAN B. LARONNE
Ben Gurion University of the Negev, Beer Sheva 84120, Israel
DAVID N. OUTHET & JOEL L. DUCKHAM
N.S.W. Dept. of Water Resources, P.O.B. 3720, Parramatta, N.S.W. 2150, Australia
TONY J. McCABE
N.S.W. Public Works Department, P.O.B. 546, Wollongong, N.S.W. 2520, Australia

ABSTRACT A novel technique to determine event bedload volumes has been used first ever to assist in evaluating the effect of gravel extraction on reach degradation. The technique is based on the continuity equation for bedload. It requires only pre and post flow measurements of river-bed scour and fill and tracer distances of movement. The proposed technique is relatively cheap, personell specialisation is not required, it may be applied to small and medium sized rivers and it can be used concomittantly at a number of sites. It is applicable to ephemeral and intermittent rivers as well as to perennial ones with shallow (< 0.2 m) baseflow.

THE DILLEMMA OF BEDLOAD DETERMINATION

Bedload transport rates are very difficult to determine with acceptable accuracy (Bathurst, 1987). Available methods involve the use of bedload equations or bedload measurements. Bedload equations are notoriously inaccurate for gravel bed streams (e.g., see Wiberg and Smith, 1989), unless a specialised data set is available on the hydraulic and sedimentological character of each flow event (Parker, 1990). Measurements involve bedload sampling (Hubbell, 1964) or else semi-automatic (e.g., Leopold and Emmett, 1976; Milhous, 1973) or totally automatic (Ashida et al., 1976; Reid et al., 1980) slot stations. The disadvantage of sampling is that it involves a large manpower expenditure, presence at the site during floods and the standard deviation of measured bedload dicharges is often larger than the average bedload discharge (McLean & Church , 1986). As for slot stations, they require a large capital investment unavailable except for specific research purposes, and they are prohibitively expensive to operate in medium sized rivers, let alone at several sites.

Throughout Eastern New South Wales, Australia, the extraction industry has been mining the scarce resource of gravel and sand to the extent that river bed degradation has occurred in some reaches and it may occur in others. This has endangered the stability of bridge piers, has lowered local ground water levels, has destroyed the scenic beauty of riverine landscapes and has caused upstream erosion in others (Erskine et al., 1985). Destructive effects have occurred elsewhere (e.g., Collins and Dunne, 1989). The extraction of sand and gravel is particularly problematic because bedload sources appear to be vey limited in N.S.W. rivers. Bedload deficit, caused by supply limitation, and indicated by the difficulty in using bedload equations, is evidenced by low denudation rates and extensive pavements in headwater reaches (Hean & Nanson, 1987). The need to evaluate bedload transport rates in degrading or potentially degrading rivers throughout Eastern New South Wales for permit purposes combined with the realistion that available bedload formulae, sampling and automatic installations are inappropriate has prompted the N.S.W. Department of Water Resources to adopt a nonconventional approach (Laronne, 1987a).

THEORY

Our technique is a first attempt to calculate bedload rates for an entire region based on measured bedload transport parameters without the need to sample bedload. Similar in concept to an original attempt at evaluating bedload transport rate in New Zealand (Mosley, 1978), the technique has since been refined (Laronne & Duncan, 1986). The results described herein have been initially analysed by McCabe (1989).

The method utilises the continuity equation for sediment. The average volumetric bedload transport discharge (Q_b) for an entire event is equal to the product of the cross sectional area of the moving mass of bedload (A_b) and the average velocity of the bedload particles during the flow event (u_b). A_b is determined from the total active cross sectional bed area, A:

$$A_b = (1-p)\,A \tag{1}$$

where p is porosity. Eq. 1 is applied to bedload, but it is identical in physical reasoning and in functional form to the common equation applied to water discharge. u_b may be calculated from the average distance of bedload transport (L_b) divided by the relevant duration of bedload transport, t_b:

$$Q_b = A_b\,u_b = A_b\,(L_b/t_b) \tag{2}$$

Because unavailable bedload measurements or equivocable assumptions regarding threshold conditions for initiation of bedload are required to determine t_b, and because the problem at hand is the calculation of the volume of bedload (V_b) rather than its rate, we have been using the following equation:

$$V_b = t_b\,Q_b = t_b\,A_b\,(L_b/t_b) = A_b\,L_b \tag{3}$$

We calculate A from known changes in bed levels determined by scour chain measurements. L_b is measured as the average distance of transport of tagged gravel tracers. We use the arithmetic average rather than the geometric average (Sayre and Hubbell, 1965; Crickmore, 1967) to avoid dealing separately with zero distances of transport.

The active cross sectional bed area is determined from scour and fill magnitudes measured throughout about a dozen cross sectional locations. The scour layer has an average cross sectional thickness d_s, and the bedload deposit has an average cross sectional thickness d_f. The active cross sectional scour area A_s may be calculated from

$$A_s = (1-p)\,w\,d_s \tag{4a}$$

and the active cross sectional fill area A_s may be calculated from

$$A_f = (1-p)\,w\,d_f \tag{4b}$$

where w is the width of active bed.

The volume of bedload that moves downstream from the cross section is represented by the scour from the reach. Similarly, the volume of bedload that moves from upstream to the cross section is represented by the fill at the reach. Hence, two values of bedload volume may be separately calculated: the volume of bedload moving downstream from a reach (V_{bd}) and the volume of bedload moving to the reach from upstream (V_{bu}):

$$V_{bd} = A_s L_b \tag{5a}$$

and, similarly,

$$V_{bu} = A_f L_b \tag{5b}$$

Self evidently, during steady sediment transport the channel bed is mobilised but varies around a constant elevation, such that

$$V_{bd} = V_{bu} \tag{6}$$

Conditions excluding perfect short term (i.e., event) bed stability imply that bedforms change their shape and location, i.e., $V_{bd} \neq V_{bu}$. Such instances are much more prevalent than a perfect short term equilibrium (eq. 6). Therefore, the general case defined by eq. 3 is used to calculate the *average bedload volume* passing a given cross section during an event according to

$$V_b = L_b (A_s + A_f)/2 \tag{7}$$

It is realised that L_b may not necessarily be identical in eq. 5a and 5b. Because tracer distances of transport have been measured for one rather than two cross sections, we assume that L_b is, indeed, identical upstream and downstream.

METHODOLOGY

Gravel particles were tagged by inserting magnets; they were located by a metal detector. Similar in principle to the original method (Hassan et al., 1984) , we inserted two rather than one somewhat stronger magnets into each particle. The tracers could be located to a burial depth approaching 1 m. Their intermediate diameters were in the 20-150 mm size range, typically representing D_{50} - D_{95} of the surface bed material. Searching the bed for tracers requires time, and it is particularly slow if the bed is not dry. The location of a tracer is noted and it is returned to its exact location even if buried at a considerable depth.

Scour chains with a link length of 25 mm similar to the bed roughness were used to minimise local scour near the chain. Chains were initially inserted by digging manually , mechanically or hydraulically, but these techniques changed the bed texture and structure. Hence, a technique was developed to insert chains with minor disturbance (McCabe, 1989; Laronne, 1992).

Fig. 1 demontrates the use of the scour chain to determine the depth of scour and fill. Chains are initially placed vertically in the bed (Fig. 1a). During a flow event the bed may scour (Fig. 1b), fill (Fig. 1c) or scour and then fill (Fig. 1d). The magnitude of scour is equal to the chain length above the elbow (E in Fig. 1). The magnitude of fill is equal to the thickness of the bed material deposited above the elbow. It has been assumed that scour precedes fill and that only one scour/fill cycle occurs between resurvey periods. This assumption is generally correct but we are aware that it is not universal (Laronne and Duncan, 1989). A typical post event search for tracers and chains may require 4 persons for 5 days.

THE NEVER NEVER RIVER

The Never Never River site is located immediately above the confluence with the

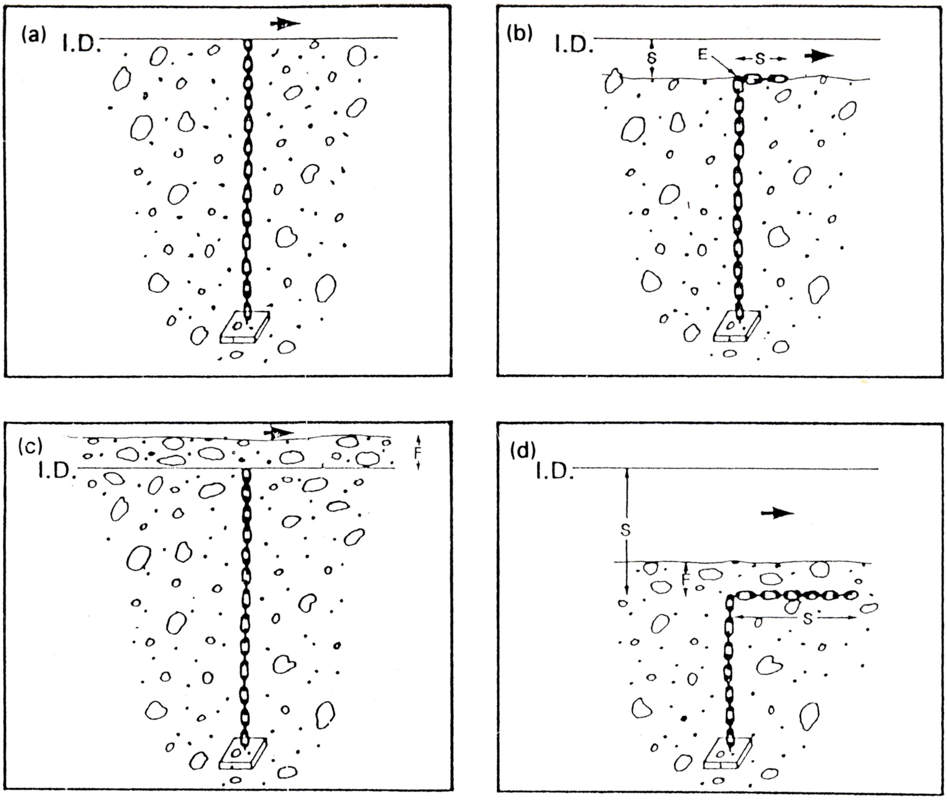

FIG. 1 Scour chain after initial insertion to I.D., the initial datum (a), after scour to e, the elbow (b), after fill only (c) and after scour with subsequent fill (d).

Bellinger River at 'Neverend' in north eastern N.S.W. At the site the drainage basin area is 95 km^2 and it is 51 km^2 at a nearby gauging station (no. 205014)) close to 'The Promised Land.' The average flow during 1982-1988 was 5.6 $m^3\ s^{-1}$, and it was 2.5 $m^3\ s^{-1}$ during the three months from its establishment in February 1988 to the first search. At the site the width of the channel bed is 42 m with a right bank bar protruding as much as 2 m above the thalweg.

Four stage rises occurred during 1-6.4.1988; peak flow was registered at 150 $m^3\ s^{-1}$. The site was revisited on 23.5.1988. Average scour was 0.14 m whereas average fill was 0.27 m. One scour chain was lost and 54 percent of the tracers were recovered (50 and 68 percent in the inner channel and the bar, respectively). The respective average distances of tracer transport were 125 and 58 m.

The following variables have been calculated for this event: $L_b = 106$ m; $A_s = 4.1\ m^2$; $A_f = 8.0\ m^2$. Assuming $p \approx 0.3$, $V_b = 641\ m^3$ based on eq. 7. The density of the Never Never River bed material is 2.63 T m^{-3} ; hence, the weight of the transported bedload was 1690 T.

DISCUSSION AND CONCLUSIONS

Our approach to determine event bedload transport volumes is not entirely novel. Mosley

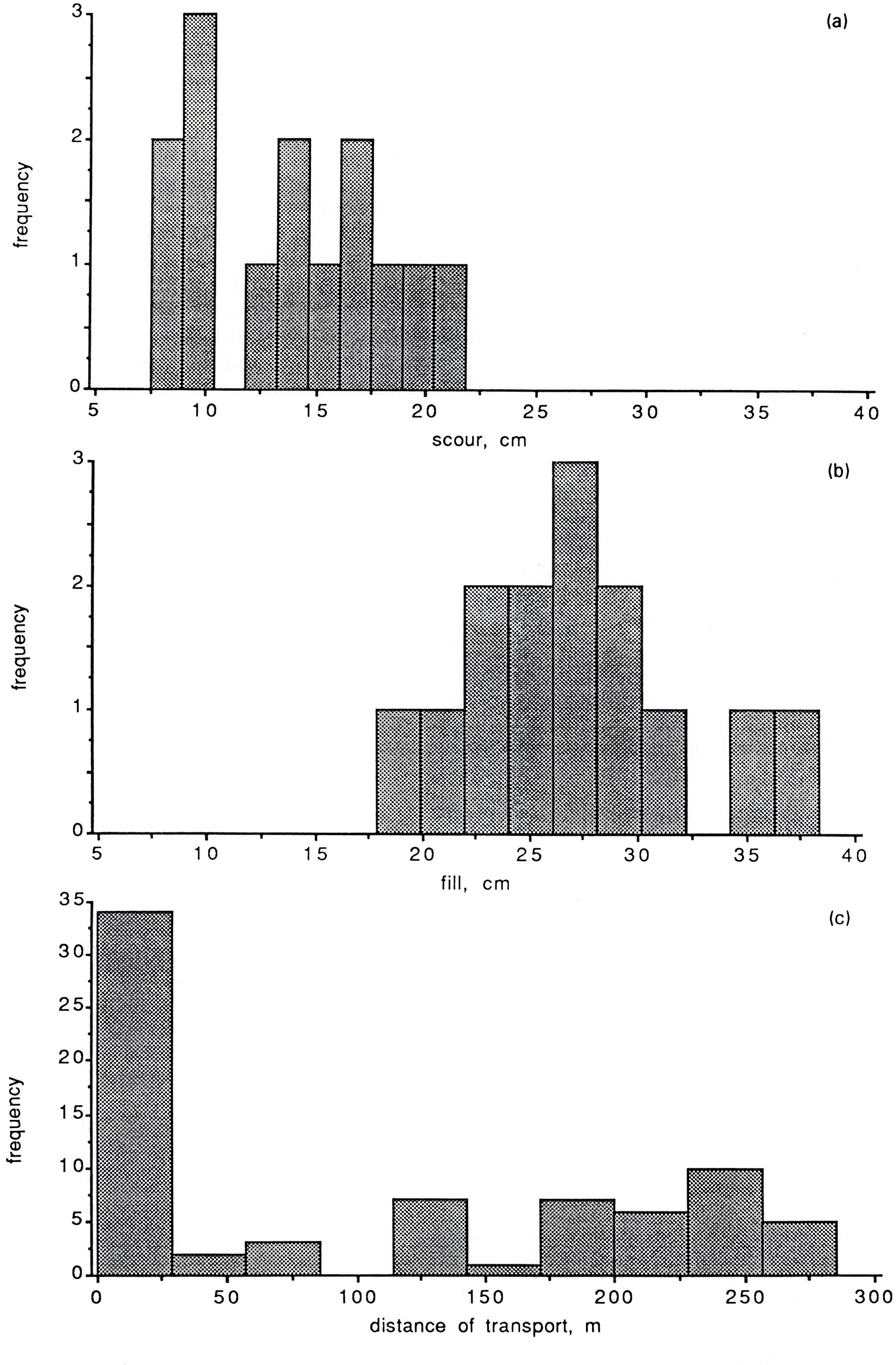

FIG. 2 Histograms of the magnitude of scour (a), fill (b) and distance of tracer transport (c) for the April 1988 event, Never Never River.

(1978) and Kondolf & Mathews (1986) forwarded a similar suggestion to ours; they assumed rather than measured the depth of bed activity. Carling (1987) measured the depth of scour and fill but assumed, rather than measured the bedload velocitiy (or, in our case, the transport distance). Hence, our technique is distinct because all the relevant variables are measured. Additionally, the distinction between scour and fill allows an average rate to be calculated for a reach.

The technique is based on pre and post flow measurement of scour and fill as well as tracer distances of transport. Apart from a variety of technical improvements that can be applied in order to facilitate the use of the proposed technique, there are a number of statistical characteristics of scour, fill and tracer transport that must be addressed.

Statistical characteristics of scour, fill and transport distances are shown in Table 1. Whereas the variation in magnitude of scour and fill is small, that of transport distance is large, typically about as large as the average. Still smaller variations in scour/fill magnitudes may be achieved by dividing the bed to areas of distinct activity (Laronne & Duncan, 1989). Tracer distances of transport are known to be very variable (Laronne & Carson, 1976; Hassan & Church, 1991). This variability can be decreased by dividing the bed area accordingly, somewhat increasing search times for missing particles, increasing the strength of the magnetic field, and excluding tracers that were initially placed in unstable positions on the bed surface prior to 'small' events (Laronne, 1991).

The distribution of scour, fill and tracer transport distances are depicted in histograms (Fig. 2a-2c). It is evident that fill is larger than scour, that there is a high variability in transport distance and that the mode of the transport distance is zero.

The technique has been applied to the Murrumbidgee, Numeralla, Pages, Cockburn, Bellinger and Never Never East Coast Rivers since 1987 (Laronne, 1987b). It's marked disadvantages are that tracer preparation and relocation are time consuming, and that tracer transport distances may be as variable as bedload sample catch. Once a few tracer batches have been prepared and relocated, the time required for further tracer preparation is reduced. The advantages of this approach is that it does not require presence during flow events, personell specialisation is not required and a number of sites may be instrumented and studied simultaneously.

TABLE 1 Scour / fill magnitudes and tracer transport distances, Never Never River, April 1988.

	scour (cm)	fill (cm)	transport distance (m)
average	13.8	27.1	106
standard deviation	4.3	5.2	103
coeff. of var. (%)	31.5	19.3	97
stdandard error	1.2	1.4	12
minimum	7.5	17.9	0
maximum	20.8	37.4	275
skewness	0.1	0.5	0.3
kurtosis	-1.2	0.0	-1.6

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