Comparison of bed load yield estimates for a glacial meltwater stream

J. WARBURTON
Department of Natural Resources Engineering, Lincoln University, Canterbury, New Zealand

ABSTRACT Estimates of bed load yield in mountain streams can be made using three principal methods: sediment traps, sediment rating curves and sediment transport formulae. This paper compares these three techniques for estimating the bed load yield in the Bas Glacier d’Arolla proglacial stream (Valais, Switzerland) for May-September 1987. This stream is a steep (0.07 m m⁻¹), coarse-bed, boulder and cobble channel. Bed load yield estimates are provided by a self-purging sediment trap; a bed load rating curve constructed from a program of Helley-Smith bed load sampling; and loads calculated using the Schoklitsch sediment transport formula. The sediment trap estimate is taken as a reference for the evaluation of the site-specific bed load rating curve and the Schoklitsch formula. Results for 1987 show that both methods over-predict yields; the bed load rating curve by 36% and the Schoklitsch formula by 111%. These discrepancies arise due to temporal and spatial variation in transport rates, problems in defining "active bed" width and difficulty in characterising a representative particle size for the critical threshold of bed material movement.

INTRODUCTION

Bed load transport rates in mountain rivers tend to be high when compared with their lowland counterparts (Bathurst et al. 1985). Engineering projects involved with mountain rivers are therefore required to manage a large flux of coarse bed material. This is especially true of projects involved with run-of-the-river water extraction, sediment control structures built to protect dwellings, cultivated land and communications, and reservoir and dam storage schemes. Such projects usually involve excluding sediment from intakes, minimising changes in local bed topography, planning to avoid downstream aggradation problems and predicting the functional life of the structure. Therefore, an estimate of bed load yield is essential. Understanding bed load transport in mountain rivers is also important in fluvial hazard prediction and estimating rates of denudation in mountain catchments.

However, estimation of bed load yield in mountain rivers is difficult due to temporal and spatial variability in transport processes and the wide range of sediment sizes involved. Although no standard estimation technique is agreed upon, three general methods are used (Fig. 1). Bed load yield can be estimated from sediment traps (e.g. Lauffer & Sommer 1982), bed load rating curves (e.g. Hollingshead 1971) and computations involving sediment transport formulae (e.g. Hean & Nanson 1987). Fig. 1 shows the general relationship between these three estimation techniques and the data requirements of each. Sediment trap estimates are the simplest and involve the collection of the total amount of bed load moved in a given period. Survey of the trap volume together with an estimate of the trapped sediment packing density provide a gross bed load yield (Fig. 1). Rating curve estimates are based on the assumption that a quantifiable relationship exists between bed load discharge and
water discharge.

**FIELD MEASUREMENTS**

- Slope
- Channel form
- Bed Material Size
- Define critical conditions
- Sediment Transport Equation
- Discharge Series
- Bed load Sampling
- Sediment Trap
- Trap Volume
- Packing Density
- Rating Curve
- Sediment Trap
- BED LOAD YIELD ESTIMATE

**FIG. 1** Interrelationships amongst field variables involved in the estimation of bed load yields.

Such a relationship when combined with continuous discharge data can be used to estimate bed loads (Fig. 1). The rating curve is usually constructed from pairs of intermittent observations of bed load transport and water discharge, measured simultaneously. Alternatively, bed load yields can be estimated using bed load transport formulae based on the assumption of a relationship between fluvial hydraulics, sediment characteristics and bed load transport rate. Bed load yield is computed using the transport formula together with the flow series (discharge or a derivative of that). Application of bed load transport formulae usually involves a limited amount of field data used to define critical conditions for initial motion of the bed material (Fig. 1).

The aim of this paper is to compare estimates of bed load yield derived from these three methods for the Bas Glacier d'Arolla proglacial stream (May 29 - September 4 1987), and to discuss the limitations of these methods in relation to field evidence of bed load transport at this site.

**STUDY SITE AND METHODS**

The Bas Glacier d'Arolla proglacial stream (Valais, Switzerland) extends 300m downstream of the snout of the Bas Glacier d'Arolla to a meltwater intake/gauging structure. The stream is part of a multiple glacier basin, which is managed by the Grande Dixence S.A. hydro-electric company. The catchment has an area of 21.5 km$^2$, of which 55% is glacierized. Bedrock is dominantly gneiss and schist. The proglacial stream has a steep (0.07 m m$^{-1}$), coarse, boulder and cobble bed channel. The stream is confined by bluffs to a valley train which is approximately 30-40 m
wide. Channel widths vary between 4-7 m but can be as great as 12 m. Channel pattern is generally low sinuosity single-thread with nodes of braiding. In steep single-thread sections a step-pool morphology is developed. Median sediment sizes for the channel bed surface were 60-80 mm, and 128-430 mm for bed material clusters and steps.

**Gravel trap**

The intake structure, located at the outlet from the catchment, incorporates two "self-purging" sediment traps (one for gravel and one for sand). These traps have been field calibrated and can be used to estimate bed load and suspended load yield (Gurnell et al. 1988). Streamflow is diverted through the gravel trap and then through an underground sand trap. Discharge is gauged continuously at the outlet from the sand trap by means of a weir and stage recorder. A sensor in the trap automatically purges the sediment at a pre-determined level of accumulation. Periodic automatic purging of the two sediment traps is registered, on the stage record, as a fall to two different levels depending on which trap is purged. Bed load transport was monitored by surveying the accumulation of sediment in the gravel trap and estimating packing density of the accumulating sediment using cartons suspended in the trap. Given the frequency of gravel trap purging, determined by a characteristic "purge signature" on the stage record, these data can be used to estimate bed load yield. Suspended sediment monitoring at the inlet and outlet of the gravel trap showed that no appreciable amounts of suspended sediment were deposited in the gravel trap and therefore the material trapped was exclusively bed load. This estimate is a minimum because at the end of August 1987 a large flow event caused prolonged intermittent purging of the intake over a 24 h period. To ensure comparability of all the bed load yield estimates this period was omitted from the analysis.

**Rating curve**

Field measurements of instantaneous bed load transport were obtained using a 152mm orifice Helley-Smith bed load sampler. These measurements were made at a stable cross section approximately 100m upstream of the gravel trap between May 25 and July 30 1987. Instantaneous bed load transport measurements were used to construct a rating relationship and illustrate the variability of the bed load transport process. Between 3-10 measurements were taken in each traverse of the stream to determine the composite bed load transport rate through the cross section. Based on 64 determinations a rating relationship was constructed from a least squares log-log regression of instantaneous bed load transport rate on discharge. The relationship had the form:

\[
\log \text{BLT} = -1.36 + 3.86 \log Q
\]

(1)

where BLT is the instantaneous bed load transport rate (kg s\(^{-1}\)), Q is the water discharge (m\(^3\) s\(^{-1}\)), \(r^2 = 0.75\) and standard error = 0.72. The simple correction factor proposed by Ferguson (1986) is used to remove the bias associated with the log-transformation regression used to derive the rating relationship. This simple correction factor has recently been criticised (Walling & Webb, 1988) on the basis that bias correction procedures do not provide accurate estimates of sediment yield alone and other sources of error are more important in producing inaccurate estimates. Nevertheless bias correction is still necessary before other sources of error in the rating relationship can be considered.

**Schoklitsch bed load transport formula**

Sediment transport formulae give the rate of discharge of sediment in terms of sediment properties and the hydraulic properties of the flow. Several formulae are
available for predicting sediment transport in steep mountain rivers (Bathurst et al. 1987; Jaeggi & Rickenmann 1987). The choice of formula is somewhat arbitrary as long as the formula chosen has been developed for flow conditions and sediments typical of mountain streams. Of the available formulae, that of Schoklitsch (1962) is attractive since it is suitable for steep, coarse-bed mountain streams where sediment supply is high (Bathurst et al. 1985). Also it is based on discharge rather than shear stress or stream power, which from a practical point of view is important, as discharge is frequently measured at hydro-electric sites.

The Schoklitsch (1962) form of the transport formula is:

\[ g_b = 2500 S^{3/2} (q - q_{cr}) \]  

(2)

where \( g_b \) = specific bed load discharge kg m\(^{-1}\) s\(^{-1}\); \( S \) = channel slope; \( q \) = specific water discharge m\(^2\) s\(^{-1}\); and \( q_{cr} \) = critical specific water discharge for initial movement m\(^2\) s\(^{-1}\). Critical conditions for the initiation of bed load movement (qcr) are given using the following expression (Schoklitsch, 1962):

\[ q_{cr} = 0.26 (ps/\rho -1)^{5/3} d_{40}^{3/2} S^{1/6} \]  

(3)

where: \( ps \) = sediment density; \( \rho \) = water density; and \( d_{40} \) = size of particle median axis for which 40% of the sediment is finer. Alternatively, where data exist, the critical threshold discharge can be determined from a scatter-plot of the relationship between discharge and measured instantaneous bed load transport rate as shown in Fig. 2.

**BED LOAD YIELDS**

Table 1 shows the bed load yield estimates based on the gravel trap, rating curve and Schoklitsch formula.

**TABLE 1 Bed load yield estimates Bas Glacier d’Arolla proglacial stream, May 29 - September 4 1987.**

<table>
<thead>
<tr>
<th>Estimation method</th>
<th>Yield in tonnes</th>
<th>Discrepancy*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel trap</td>
<td>31210</td>
<td></td>
</tr>
<tr>
<td>Schoklitsch formula</td>
<td>65898</td>
<td>+ 111%</td>
</tr>
<tr>
<td>Rating curve (bias corrected)</td>
<td>42636</td>
<td>+ 36%</td>
</tr>
<tr>
<td>Rating curve (no bias correction)</td>
<td>10794</td>
<td>- 65%</td>
</tr>
</tbody>
</table>

* Discrepancy is the departure of the bed load yield estimate from the bed load yield measured in the gravel trap. This is expressed as a % underestimation (-) or overestimation (+).

The bias corrected rating curve is superior to the Schoklitsch formula in predicting the bed load yield and produces an estimate within 36% of the gravel trap yield. However, a rating relationship without bias correction under-predicts the load by 65%
Bed load yield estimates for a glacial meltwater stream

(Table 1), a result which is expected given log transformation of the data and the relative high standard error of the relationship (Ferguson, 1986). At first sight, the Schoklitsch estimate appears to be tolerable given the rapid and inexpensive nature of the technique. However, application of this formula, to date, has met with only limited success. For example, during a period of snow melt flooding on the Roaring River, Colorado, Bathurst et al. (1985) predicted transport rates 3 orders of magnitude greater than actual measured transport rates. But this is not true only of the Schoklitsch formula; Lauffer & Sommer (1982) used the Meyer-Peter formula to estimate bed load transport on the Pitzbach (Austria) and found that calculated transport rates exceeded average measured transport rates by 10-fold. Hean & Nanson (1987) in a test of 8 bed load transport formulae, including that of Schoklitsch, at gauging sites on 11 eastern Australian rivers found the formulae inherently unreliable under field conditions, concluding that using formulae to determine absolute bed load yields was a futile exercise. In these cases, where sediment availability is supply-limited, formulae (including Schoklitsch 1962) which predict bed load transport capacity are unlikely to produce bed load transport estimates of the correct order of magnitude (Bathurst et al., 1987). However, before these results can be fully accepted further testing is required: namely consideration of bed load transport rate variations and testing the sensitivity of the Schoklitsch formula to input data.

Table 2 shows bed load yields estimated by the Schoklitsch formula for various combinations of input data.

**TABLE 2 Bed load yield estimates based on the Schoklitsch formula showing the sensitivity to input data.**

<table>
<thead>
<tr>
<th>Values used in the formula</th>
<th>Yield in tonnes</th>
<th>Discrepancy*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge series</td>
<td>Slope m m⁻¹</td>
<td>Critical discharge m³ s⁻¹</td>
</tr>
<tr>
<td>A Hourly</td>
<td>0.07</td>
<td>2.4</td>
</tr>
<tr>
<td>B Hourly</td>
<td>0.088</td>
<td>2.4</td>
</tr>
<tr>
<td>C Hourly</td>
<td>0.052</td>
<td>2.4</td>
</tr>
<tr>
<td>D Hourly</td>
<td>0.07</td>
<td>0.85</td>
</tr>
<tr>
<td>E Hourly</td>
<td>0.07</td>
<td>0.65</td>
</tr>
<tr>
<td>F Mean daily</td>
<td>0.07</td>
<td>2.4</td>
</tr>
</tbody>
</table>

* Discrepancy as defined in Table 1.

Estimate A is considered the "best estimate" using the Schoklitsch formula. The input data for estimate A include channel slope surveyed in the field and critical discharge determined from the water discharge bed load transport plot (Fig. 2). Loads are calculated using the mean hourly discharge series gauged at the meltwater intake structure. In order to test the sensitivity of the formula to slope, 1° was added to and subtracted from the actual channel slope (estimates B and C respectively). The yield estimates, B and C, are altered by between 76 and 87% of the actual bed load yield. Calculating critical discharge using formula (3) rather than determining the value from Fig. 2 causes an even worse discrepancy. Critical discharge calculated using the mean d₃₀ from grid samples of bed material produces
an over-estimate (D) of 952% using the $d_{16}$ (as recommended by Bathurst et al. 1987) is even worse over-estimating by 1235% (estimate E). Given these large discrepancies the critical discharge formula (3) cannot be used in this type of channel. Finally the estimate will also vary with the nature of the flow series used to calculate loads. Estimate F based on a mean daily discharge series produces an improved bed load yield estimate by reducing the influence of the more extreme discharges in the load calculations. Based on the results in Table 2 it appears the Schoklitsch formula is difficult to apply to field conditions in a physically meaningful manner.

VARIATIONS IN BED LOAD TRANSPORT

Bed Load - Water Discharge Relationship

Bed load transport measurements collected from the field site (Fig. 2) with a Helley-Smith bed load sampler do not show a clear linear relationship with discharge.

\[
\begin{align*}
\text{BED LOAD TRANSPORT (kg s}^{-1}) & \\
\text{UNIT DISCHARGE (m}^2\text{s}^{-1}) & \\
\end{align*}
\]

No transport

PHASE 1

PHASE 2

Schoklitsch critical water discharge

FIG. 2 Variation of bed load transport rate with unit water discharge for the Bas Glacier d'Arolla proglacial stream. Sampling period June-July 1987.

Below 0.26 m$^2$ s$^{-1}$ bed load transport is negligible but above 0.26 m$^2$ s$^{-1}$ there is a very rapid increase in transport rate. This applies up to 0.36 m$^2$ s$^{-1}$. There is thus a critical threshold discharge of approximately 0.26 m$^2$ s$^{-1}$ (2.4 m$^3$ s$^{-1}$) for the initiation of bed load transport at this site. The theoretical critical discharge for the bed material at the measurement site, based on the Schoklitsch formula (Schoklitsch, 1962) Wolman grid surface sampling, was 0.142 m$^2$ s$^{-1}$. The lack of correspondence between the predicted threshold of motion and the observed bed load movements suggests that the Schoklitsch critical water discharge formulae is of limited value in this case.

The lack of correspondence between observed and calculated thresholds may also be partly caused by the problems of determining a representative grain size. Bed materials vary considerably in mountain streams so the threshold of motion would
be better represented by an envelope of curves. Furthermore, calculations based on a single representative grain size are unrealistic since both the conditions for the initiation of motion and transport itself will be affected by other sizes in the mixture. For example, the threshold water discharge calculated for the boulder and cobble cluster bed forms (for a representative grain size of 263 mm), which form the channel bed steps, was 1.7 m$^2$ s$^{-1}$. This corresponds to a critical discharge of approximately 10 m$^3$ s$^{-1}$ for the Bas Glacier d’Arolla proglacial stream. Discharges of this magnitude only occur during extreme floods. Whittaker (1987) suggests that bed steps (clustered bed forms) of step pool streams are relatively stable over the usual flow conditions. This is certainly true of the Bas Glacier d’Arolla proglacial stream since it is only after large floods that the channel pattern is substantially altered.

For gravel bed rivers Jackson & Beschta (1982) divide bed load transport into two phases. Phase 1 movement involves the flushing out of sands deposited in the channel during low discharges. The bed structure is unaltered and thus initial transport rates are low. This condition is probably similar to bed conditions under which the "running bed load" described by Lauffer & Sommer (1982) is transported. With increased flow, bottom velocities and associated shear stresses increase; the armour layer is disrupted as gravels are entrained and erosion of bed sediments proceeds rapidly as smaller relative particle sizes are exposed. This disruption of the armour layer is phase 2 transport. In mountain streams, and the example studied here, the bed structure alternates between reaches of armoured bed and step pool sequences of clustered boulders. This will have the effect of producing a third threshold for bed load movement which involves the break up of clustered bed forms. This hierarchy of bed material motion thresholds suggests extreme discontinuity of transport in phase 1 to almost continuous transport in phase 3. Therefore, bed load transport formulae will be less reliable at lower discharges when a greater proportion of the bed is stable and transport is supply-limited. Although each phase may become supply-limited as armouring occurs. Recognition of various thresholds of motion in mountain streams is essential. Application of bed load transport formulae, such as Schoklitsch, must be made for each size fraction in turn since it cannot be assumed that when the stream discharge exceeds the critical discharge, all the bed is in motion.

Short-term temporal variations in bed load transport

Variations in transport rates occur over relatively short timescales. Measurement of bed load transport at hourly intervals on July 6 1987, between 0920 h and 2010 h, reveal marked fluctuations in the maximum transport rate even though the minimum transport rate is relatively stable. Peak transport rates (>0.27 kg s$^{-1}$) do not correspond directly to discharge peaks, rather variations in bed load transport correspond to variations in discharge whether increasing or decreasing. This suggests that flow variability is more important than discharge magnitude in regulating bed load discharge (although this needs further investigation). Indeed, over very short timescales (seconds), fluctuations in bed load transport can be related to turbulent velocity bursts. Alternatively, supply factors such as bank erosion along the channel margins or sporadic inputs of sediment from outside the channel can produce variability. In fact during this period of observation the local bed elevation at the measurement site changed little, which suggests that supply was not from the immediate channel bed but from upstream.

Intensive bed load sampling at 10 min intervals on July 8 1987 showed even more pronounced variations in transport rates during a period of almost constant discharge (0.3-3.1 kg s$^{-1}$). During the two-hour sampling period both minimum and maximum transport rates increased although fluctuations were very marked. Survey of the channel bed before, during and after the sequence of measurements showed the bed elevation to increase between 1020 h - 1120 h and decrease from 1120 h -
1200 h which suggests the possible passage of a bed sediment wave or load pulse because by 1150 h bed load transport was declining.

Cross section variations in bed load transport
Substantial variations in transport also exist in the cross-channel dimension with bed load moving as threads along the channel bed (Bathurst et al., 1985). This bed load "streaming" effect varies markedly between days. Generally peak bed load peak transport rate roughly corresponds to the central thread of flow. Transport rates can vary by as much as 10 times in the space of 1 m. Pitlick (1988) also found considerable variation in bed load transport rates; cross-section mean values were found to be of the same order of magnitude as the standard deviation of the measurements.

These observations have implications for sampling and for the calculation of mean transport rates and bed load yields (Hubbell, 1987). Given the high variance of observed transport rates, estimation of mean bed load transport rates from cross section traverses, based on a few cross-channel samples, are likely to have large errors associated with them. Surveys of cross-section variation in transport rate are also useful in determining the "active" bed width over which bed material movement takes place. In the Bas Glacier d'Arolla channel the active width is fairly stable and can be approximated by 0.6-0.7 channel width (for within channel flow).

CONCLUSIONS
Where estimates of bed load yield are required for management of glacial meltwater streams the indiscriminate use of the Schoklitsch sediment transport formula is not recommended, and bias corrected rating curves should only be used where a clear relationship exists between sediment transport and discharge at a particular site. Predictions of bed load yield will be even more unreliable in mountain streams where permanent stream flow gauging structures do not exist. Sediments traps, whether man-made or natural, provide the "best" estimate of bed load yield.

The Schoklitsch bed load transport formula does not realistically model bed load transport in mountain streams. If used at all it is recommended that the critical threshold discharge \( q_u \) be determined from field measurements, where possible.

Variability in bed load transport is very marked in short-term bed load transport series, cross section surveys and in the relationship between bed load transport and discharge (Fig. 2). Bed load moves in "threads" with transport rates varying by a factor of 10 in the space of a metre. Sediment supply and storage are important factors in determining the strength of the bed load transport relationship. Sediment storage related to a hierarchy of bed elements within the channel appears to be an important control on the release of bed sediment. A 3 phase model of bed load transport may be appropriate to mountain streams but this needs to be verified.

Finally, bed load transport processes in the Bas Glacier d'Arolla proglacial stream, although generally characteristic of steep, coarse bed mountain streams should be considered site specific. Each mountain stream will require a specific solution in estimating bed load yield.

ACKNOWLEDGEMENTS Financial support was provided by a research studentship provided by the U.K. Natural Environment Research Council. Grande Dixence S.A. kindly provided the discharge data and access to field installations. Tim Davies and Bill Young reviewed the manuscript.
REFERENCES


