Bed load measurements with a passive magnetic induction device

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Abstract The Bed load Movement Detector (BMD) is installed on the O'Ne-ell Creek, a gravel bed stream, with a forced pool-riffle morphology, in the upper Fraser River basin in northern British Columbia, Canada. The device records the passage of individual particles across the full width of the channel. At the peak of the 1999 nival flood sediment movement, approximately 3×10^5 particle passages per hour were detected. The transport rate increases as the stage and water discharge increase. Bed load movement in this flood involved nearly all of the stream bed, but the point of most intense transport varied across the channel throughout the flood. During one week of flood discharge, 14.41×10^6 particles were recorded passing the BMD. We estimate that this is approximately equivalent to 7.88 m^3. Pulses of sediment movement are apparent at a variety of time scales ranging from diurnal to seconds. While the spasmodic character of the sediment transport is most pronounced at scales of 5 min to 1 h, there is no stable periodicity in the record.

Key words bed load; bed load movement sensors; fluvial geomorphology; gravel bed streams; pool-riffle morphology

INTRODUCTION

In the last decade there has been an increase in interest in the measurement and visualization of bed load movement in streams. As a result, there have been a series of new developments in bed load movement sensing apparatus including: devices based on repeated measurements of the stream cross-section (Ergenzinger, 1992), repeated bed load sampling using Helly-Smith samplers or net samplers (Bunte, 1990, 1996), Birkbeck-type slot samplers with pressure pillows (Lewis, 1991; Harris & Richards, 1995; Garcia *et al.*, 2000; Sear *et al.*, 2000), magnetic induction devices (Bunte, 1996), acoustic Doppler velocity devices (Rennie *et al.*, 2002), and hydrophones and impact sensing devices (Bänzinger & Burch, 1990; Rickenmann *et al.*, 1997). These devices either sample the pattern of movement across the stream width, or the pattern and quantity of movement through time. We report on recent developments using a bed load movement detector that produces continuous records of clast movement across the channel width in a format which permits visualization of changing transport patterns through time.

METHODS

Bed load movement was monitored from 1993 to 1999 on a small stream in the headwaters of the Fraser River in northern British Columbia, Canada, as part of the Stuart-Takla Fish–Forestry Interaction Project (Macdonald *et al.*, 1992). The investigation entailed three components: (a) tracer studies, to obtain information on the distance of travel and depth of burial of clasts; (b) repeated topographic surveys, to develop volumetric estimates of nival and summer flood events; and (c) a passive magnetic bed load detection device spanning the channel to record the passage of coarse clastic material. This paper will discuss the results of the Bed load Movement Detector (BMD) from the 1999 nival flood event.

In 1997 the BMD device was installed in the riffle section of a small forest channel. The device consists of an array of 82 magnetic sensors set in an aluminium housing, mounted on an adjustable frame that may be raised or lowered to compensate for changes in stream bed elevation (Fig. 1). The sensing surface is set flush with the stream bed. The sensors (Fig. 2) are disc-shaped (4 cm high × 8 cm diameter) and spaced 10 cm apart along the 8.2 m length of the device. Ferromagnetic minerals in particles passing over the sensors induce small electrical currents. Sufficient magnetism is found in most igneous and metamorphic rocks that moving particles, of pebble and cobble size, can be detected. The apparent lower size limit of detectable particles, under laboratory conditions, is 1–2 mm. The signal duration is proportional to the size of the clast and the velocity of transport. The signals generated from passing particles are sampled at 100 Hz by a data acquisition system and stored on a computer hard drive.

The BMD is a significant improvement of earlier magnetic bed load detection devices. Ergenzinger & Conrady (1982) and Reid *et al.* (1984) employed single coil detectors to record the passage of tracers with embedded magnets. Ergenzinger & Custer (1983) built an instrument with two 1.25 m rods wound with copper wire

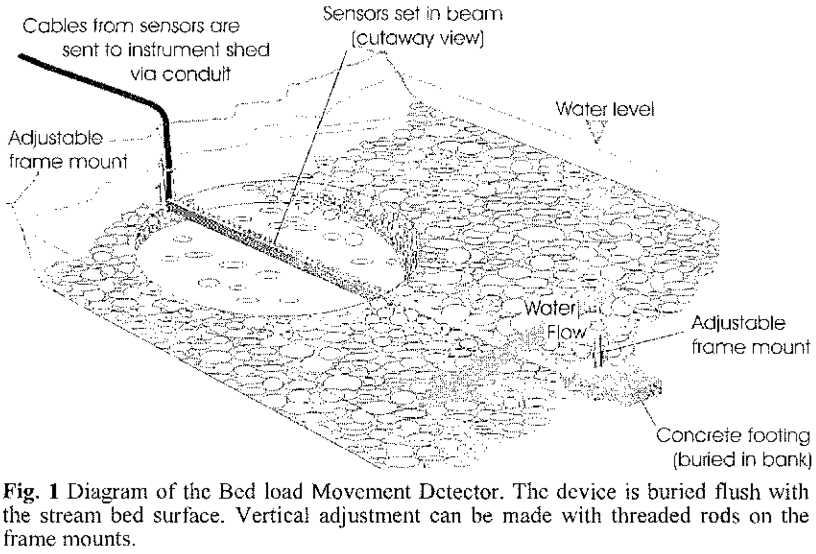

Fig. 1 Diagram of the Bed load Movement Detector. The device is buried flush with the stream bed surface. Vertical adjustment can be made with threaded rods on the frame mounts.

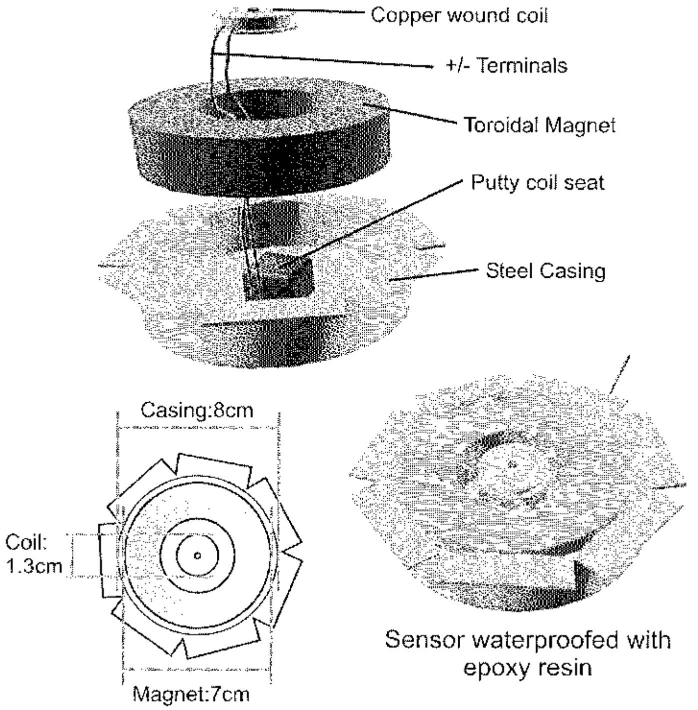

Fig. 2 The Bed load Movement Detector sensor shown in exploded view, sensor dimensions, and the assembled product.

placed horizontally within the stream bed, that could detect the passage of naturally magnetic andesite clasts >32 mm. In 1986 a more sensitive device was developed which used 1.55 m units of micro-coil assemblies extending across Squaw Creek, Montana (Custer *et al.*, 1986; Bunte, 1996).

All of these devices used strip chart recorders, which can record no more than several signals per second and a few sensor channels. The practical limit of resolution of the strip recorder system at Squaw Creek may be 200 h^{-1} (Bunte, 1996).

The BMD has a sensor that is several orders of magnitude more sensitive than earlier devices. The spacing of sensors at 10-cm intervals permits recognition of lateral variation at a scale comparable to the largest clasts transported. The sampling rate of 100 Hz permits recognition of about 10 particle passages per second on each sensor. The theoretical maximum number of passages discernable with the BMD is about $3 \times 10^6 h^{-1}$. Actual maximum rates measured are about four-fold less due to a variety of factors including: low rates of transport at the stream margins, and to some extent, saturation of the sensors when more than one particle passes simultaneously across the sensor, a situation that is likely during intensive transport, since most recorded particles are smaller than 1 cm. Finally, the use of a data acquisition system allows data to be recorded and analysed on computers, which permit sophisticated signal detection algorithms to be employed. Further details of the construction and calibration of the BMD can be found in Tunnicliffe *et al.* (2000) and Tunnicliffe (2000).

The Bed load Movement Detector is installed on O'Ne-ell Creek at a site 8 m wide with a slope of 0.013, and a peak discharge about 15 $m^3 s^{-1}$. The channel has a forced pool-riffle morphology with abundant large woody debris. The reach is in an approximate equilibrium, with no marked tendency for aggradation or degradation over the past 10 years. The sampled reach has a coarse gravel bed with a mean grain size of 42 mm. The largest clasts are approximately 300 mm. Clast lithologies and thus magnetic properties are extremely variable. This work and similar field experiments suggests that approximately 30% of the rocks in O'Ne-ell Creek yield sufficient ferrous material to obtain a voltage response greater than 1.7×10^{-4} V (noise threshold of the data acquisition system) from a sensor. This proportion of detectable lithologies can be increased substantially using more sensitive voltmeter instrumentation.

Bed load movement occurs annually during the peak of the snowmelt flood in May or June and during short floods following intense summer storms. O'Ne-ell Creek has relatively little suspended sediment transport. At the study site, the stream bed could be visually observed from a catwalk over the stream for much of the 1999 flood. Particles in motion could be observed and captured with a basket sampler. At the peak of the 1999 nival flood sediment movement, approximately 3×10^5 particle passages were detected per hour (Fig. 3).

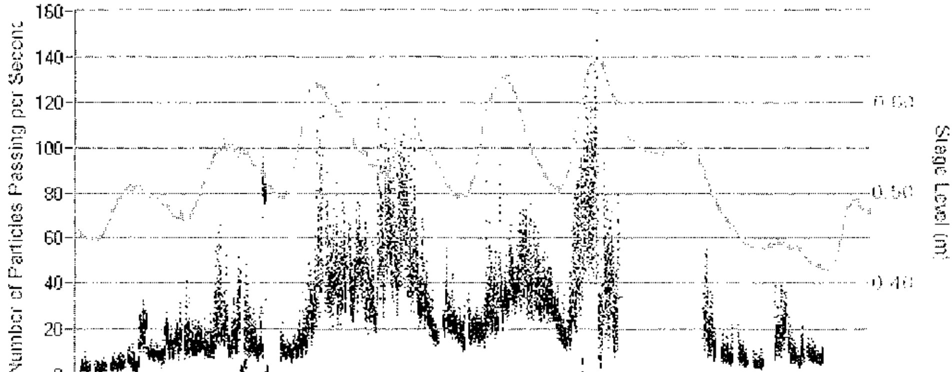

Fig. 3 Rates of particle transport (number of particles s^{-1}) over the course of the flood.

OBSERVATIONS

The 1999 flood was unusual. A cool cloudy spring and high snow accumulations resulted in the snowmelt period being prolonged over about six weeks. Peak discharge was relatively low. Stream flows were just below that sufficient to initiate bed load movement from 25 May to 9 June. During this time sporadic movement of only single particles and bursts of finer material was observed. Between 10 June and 12 June the rate of entrainment increased, and the sensors detected "batches" of larger-sized material crossing the device. Sampling with a small basket net yielded maximum particle sizes of 20–30 mm. Particle counts ranged from 0 to 35 s^{-1}. As the stage rose during the afternoon and evening of 12 June, increasingly intense pulses of sediment passed

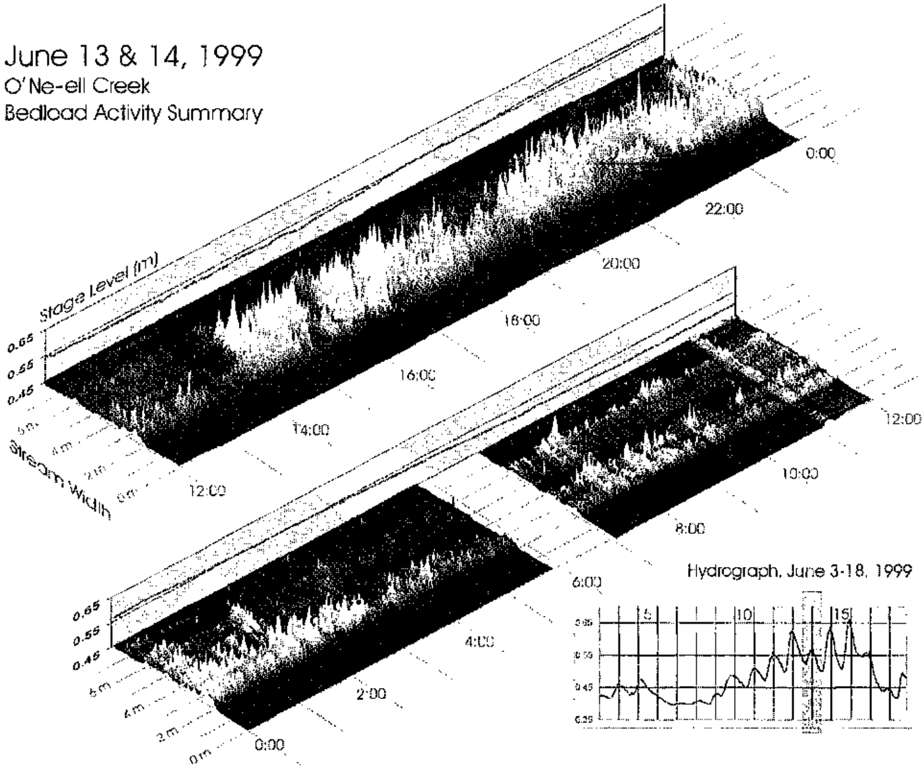

Fig. 4 Summary of bed load movement 13–14 June 1999. Bed load movement commences abruptly with increase in stage at about 14:00 h on 13 June. Pulses of sediment movement of variable intensity and duration continue to 00:30 on 14 June. As the overall sediment flux declines in the early morning, bed load movement is confined to one to three streets. One hour of data were missed at 06:00 h while hard drive files were transferred.

over the device. Inter-granular collisions, and the sheer volume of material in motion, often blurred the distinction of passing particles. Rates exceeding 60 particles s^{-1} were recorded during about 10% of the total event. Maximum counts of up to 150 particles s^{-1} were attained at the peak of transport activity. At times, the material seemed to pass in steady sheets. The activity continued until about mid-day on 13 June, when the amount of material in transit subsided for a few hours and then resumed and reached a maximum on the evening of 13 June. There was clearly an abundant supply of material entrained by the high flows, and the bed load discharge continued even as the stage level dropped during the mid-day period of 13 June.

With the ample availability of material for transport, the "batch" effect became less conspicuous as more intense pulses of sediment passed over the BMD. In the intervals between pulses, the transport rate dropped substantially. A condensed record of 24 h at this peak stage is shown in Fig. 4.

The final portion of the bed load transport event, 14–17 June, featured one or two narrow transport zones, 1–2 m wide, which migrated laterally by about 1 m. Material in transport, observed and sampled non-quantitatively, was sand to small pebble size.

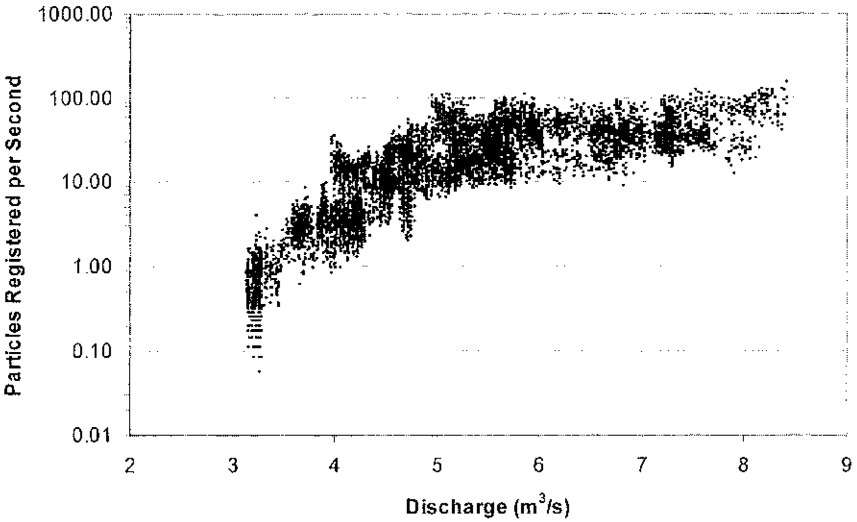

Fig. 5 The number of particle counts per second counted by the BMD as a function of stream discharge.

The bed load streets seen at the end of the nival flood were active while a sandy gravel bank was being eroded about 75 m upstream (about 9 stream widths).

Figure 5 shows that for any given flow, the transport rate (it must be emphasized that this is measured as particles detected per minute, not mass) varies within roughly an order of magnitude. The transport rate increases with discharge, up to roughly 5 m^3 s^{-1}, at which point the slope in the relation seems to flatten. This may be due to depletion of the material available for transport during the 1999 flood, or saturation of the sensors due to multiple clasts crossing the 10 cm sensors simultaneously. But, in part, the decline in the rate of increase of the number of particles in transport is counteracted by an increase in the maximum size of particle transported, so that the volume in transport increases faster than the count of particles.

Temporal variation in transport rates

Pulses of sediment movement occurred during the flood at a variety of scales. Snowmelt flows in O'Ne-ell Creek show a clear diurnal discharge cycle. As the stream power increased each evening, from 12 June to 17 June, high rates of coarse bed load movement commenced. The transport commences abruptly (Fig. 5), presumably as clusters and patches of the stream bed disassemble and are entrained (Kuhnle & Southard, 1988; Brayshaw *et al.*, 1983).

Within the frame of this daily cycle, the transport rate considerably vacillates on a time scale measured in minutes, independent of channel flows. We examined the pulsation of the sediment transport record with Fourier analysis to identify periodicity in the pulsation record. Fisher's test of significance in harmonic analysis (Fisher, 1929; Nowroozi, 1967; Kuhnle & Southard, 1988) showed that the amplitude of most peaks in the range of interest (minutes to hours) on the Fourier spectra were not significantly

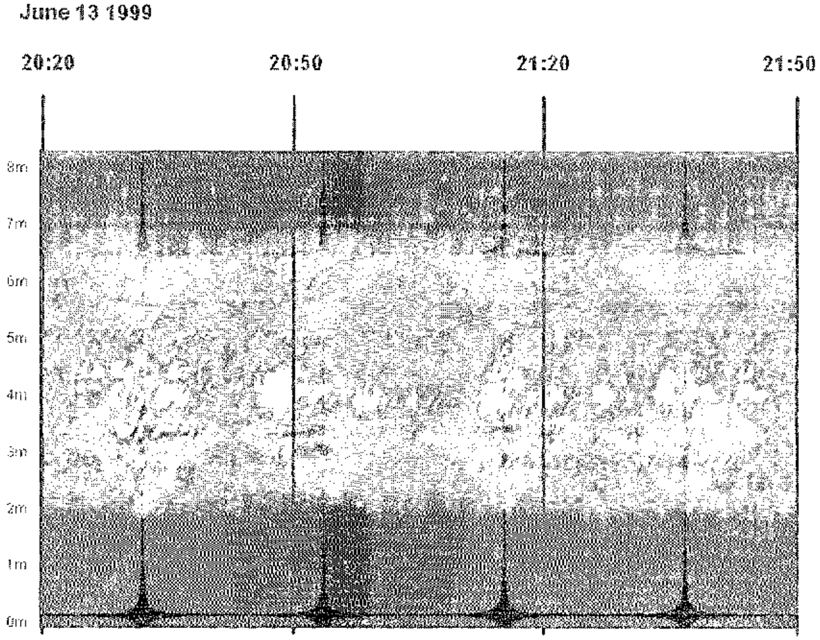

Fig. 6 Transport of pulses of sediment past the Bed load Movement Detector during 90 minutes of high transport rates.

different from random noise at the α = 0.05 level. Although previous authors (Gomez *et al.*, 1989; Kuhnle & Southard, 1988; Whiting *et al.*, 1988) have attributed this kind of variation to the migration of bed form elements such as bed load sheets, bars or ripples, it is not clear from our limited observations of upstream conditions that this is the operating mechanism in the forced pool-riffle morphology of O'Ne-ell Creek. Figure 6 shows a summary of an hour and a half of bed load activity, with at least 10 distinct surges in bed load activity.

At the finest scale, that of seconds, particle movement is concentrated into "batches". Batches are present during intervals of both low and high transport rates, although at the highest transport rates, size and number of individual particles becomes difficult to determine because a mixture of sand and gravel particles are moving across each sensor simultaneously.

Lateral instability in the transport record

Over the course of the 1999 flood, bed load movement involved nearly all of the stream bed. The channel cross-section at the BMD site is relatively flat, since the device was sited midway along a riffle section. To characterize the locus of transport (the point of maximum bed load transport activity), total signal intensity for each sensor channel was summed for each sampling session, generally about 3 h (Fig. 7). Over the course of the flood, the locus of greatest transport migrated widely across the channel and back. Early and late in the flood, when small volumes of bed load were in

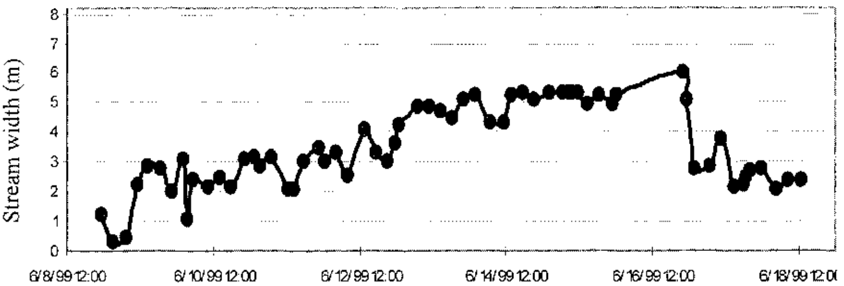

Fig. 7 The wandering locus of transport in the 1999 nival flood. The locus of transport moved substantially throughout the event, starting within roughly 1 m of the right bank (9 June) and drifting to within 2 m of the left bank (15–16 June).

motion, the lateral field of transport tended to be narrow and located in the deeper part of the channel; during the peak of the nival flood, most of the channel was simultaneously active.

Not only does the locus of transport wander across the stream bed, and the width of the transport zone change, but the intensity of transport varies as well. The continuous record of transport can be conceptually divided into portions of intensive transport, active transport and marginal transport (Fig. 8). Contours in the lower part of Fig. 8 show the number of particles per second passing each of the 82 sensors for the duration of the flood. During this flood, most of the stream cross-section experienced marginal bed load transport rates of <1 particle s^{-1}. Intensive transport (≥4 particles s^{-1}) did not occur in more than 25% of the stream width at any time.

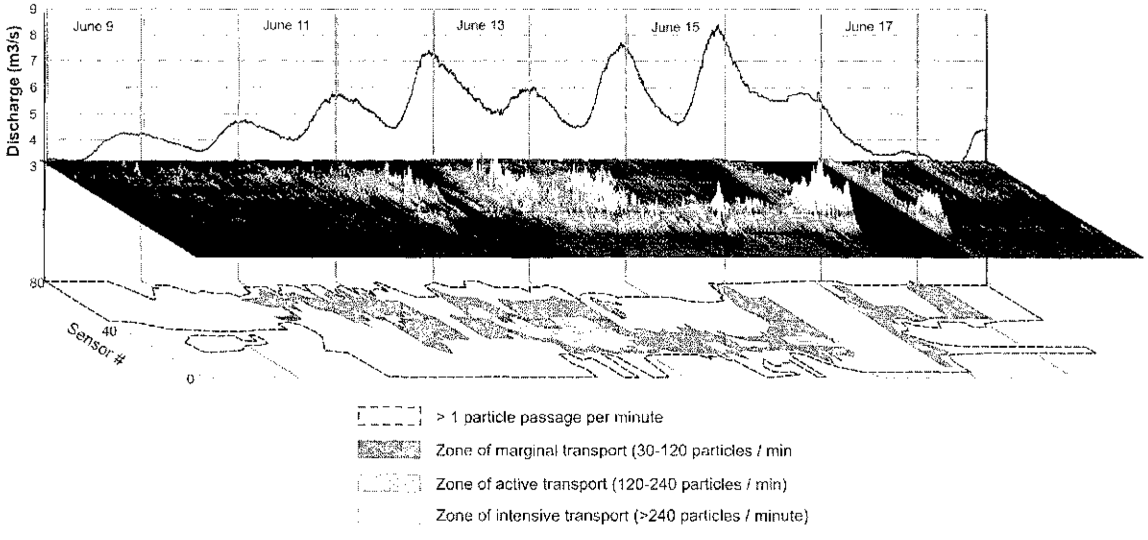

Fig. 8 Bed load transport activity during the 1999 nival flood. The upper half of the diagram is a hydrograph of flood discharge. The lower half of the diagram shows intensity of transport during 10 days of the nival flood. Transport is represented by the cumulative voltage during 30-s intervals. Three intensities of transport are contoured: marginal transport (<1 event s^{-1}), active transport (1–4 events s^{-1}), and intensive transport (>4 events s^{-1}).

The 1999 nival flood produced modest changes in the stream bed. Previous studies of nearby reaches, using repeated total station surveys (Poirier, 2003), show modest alteration of nearly all of the stream bed during nival floods, with complex patterns of scour and fill averaging one to two clasts thick.

Estimate of transport volumes

During the flood, 14.41 × 10^6 particle signals were recorded by the BMD at O'Ne-ell Creek. We attempted to estimate the volume of transport making a number of simplifying assumptions, including: (a) that the variation in magnetic intensity is uniform for various size clasts, and is similar in character to the bed material; (b) that the material in transport has the same composition and size distribution as the stream bed; (c) that 30% of the moving particles are detected; (d) that only particles >4 mm are detected; and (e) that intervals of peak sensor response represent single sediment particles. With these assumptions the estimated volume is 7.88 m^3. Independent estimates for transport rates on this stream and in similar reaches in a stream in the adjacent watershed were determined in previous years by repeated detailed mapping of the stream bed and by magnetic tracer studies (Gottesfeld, 1998; Poirier, 2003). These estimated transport volumes agree within a factor of two (Table 1).

Table 1 Transport volume estimates for O'Ne-ell and Forfar Creek Nival Floods. Forfar Creek is a similar watershed immediately north of O'Ne-ell Creek with about 60% of the peak flow.

Transport volume estimates for O'Ne-ell and Forfar Creeks (m^3)			
Stream reach	Tracer study 1992–1996[1]	Morphologic method 1996–1997[2]	BMD 1999
Forfar 1050	2.88	3.06	
Forfar 1545	12.70	3.82	
O'Ne-ell 925		6.76	
O'Ne-ell 1550	16.86	8.99	
O'Ne-ell BMD Site			7.88

[1] Gottesfeld (1998), Gottesfeld, unpublished data.

[2] Poirier (2003).

DISCUSSION

The bed load transport patterns shown in Figs 3, 5 and 6 have a number of interesting features. We see a clear threshold effect as competent flow is reached at about 3 $m^3 s^{-1}$. There is diurnal forcing in the bed load discharge record with high transport rates attained near midnight as the peak of the previous day's snowmelt passes.

The large quantity of data recorded at 100 Hz permit analysis of the timing of pulses of sediment moving past the instrumented stream cross section. Although the pattern of bed load transport shows pulses lasting several minutes throughout, and pulses are often spaced 5 min to an hour apart, there is no stable, coherent periodicity in the 1 min to 1 h range. Instead movement is chaotic, and is perhaps best thought of as jams in the congested flow of material (Langbein & Leopold, 1968) Pulsing at the finest scale (batches) may result from the disaggregation of clusters.

Much of the diversity of response in bed load discharge is probably related to supply, i.e. upstream stochastic phenomena. This is to be expected since pulses of sediment are derived from varying distances upstream, they disperse during transport both laterally and along the path of transport and, on a finer scale, there are innumerable complex interactions among particles in movement and the irregular stream bed. The width of the transport zone varies greatly during the flood. Lateral dispersion of sediment pulses as they move downstream is inevitable, so that intervals where much of the channel width is active likely reflect periods of augmented supply from further upstream. Periods of narrow transport reflect nearby sources. With exhaustion of supply late in the flood, gravel streets which derive from small areas of supply not far upstream, become conspicuous. The width of passing pulses is also related to the size of bed forms which disassembled upstream. Small clusters would be expected to have narrow signatures that widen during downstream translocation.

Thus, while the BMD shows a number of important improvements over previous bed load detection systems, it faces a number of similar challenges. Noise from a number of external sources (such as an on-site generator) is problematic. However, the difficulties attributed to vibration, reported by Custer *et al.* (1987), appear to be minimal. The signals generated by the instrument contain limited information on the particles passing, and thus particle counts remain only a coarse approximation of rates of bed load flux. At present we are unable to separate the velocity and size components in the sediment passage record. In a stream with simpler bed load lithology the amplitude of the voltage response of the sensor would provide a scale for clast volume and permit calculation of apparent velocity. Problems related to simultaneous passage of several particles across each sensor would be alleviated by decreasing the size of the sensors. The additional data acquisition burden and need for a generator on site can be met using the more powerful laptop PCs currently available.

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