Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advances
(Proceedings of the Oslo Workshop, June 2002). IAHS Publ. 283, 2003.

Monitoring bed load transport using acoustic and magnetic devices

WOJCIECH FROEHLICH

Homerka Laboratory of Fluvial Processes, Institute of Geography and Spatial Organization, Polish Academy of Sciences, Frycowa 113, 33-335 Nawojowa, Poland

wfroehlich@pro.onet.pl

Abstract The work reported was undertaken in the Homerka instrumented catchment in the Polish Flysch Carpathians, where different techniques for monitoring coarse sediment transport have been applied over the past 30 years. The area is characterized by highly active erosion, sediment transport and fluvial sedimentation processes. Bed load transport has been measured using both acoustic and magnetic techniques. The acoustic (hydrophone) method permits continuous measurement and is able to provide a continuous record of coarse particle movement during flood events, which is a direct reflection of the magnitude of bed load movement. In general, bed load transport reaches a peak more rapidly than the water discharge. For a given flood discharge, the intensity of bed load transport varies between the rising and falling stages of a flood event. Coarse material bed load transport has also been measured in the Homerka catchment using magnetic tracers. In this case, magnets are cemented into holes drilled into gravel particles and an electromagnetic sensor is used to track their movement through a designated short reach. In addition, transport distances associated with individual gravel particles tagged with magnets during individual events have been documented by recovering the labelled gravel after the event using a metal detector. These magnetic tracing techniques permit the bed load transport rate associated with individual grain size fractions to be quantified.

Key words acoustic device; bed load transport; hydrophone; magnetic device; mountain streams; Polish Carpathians; sediment transport

INTRODUCTION

The high energy and active morphodynamic environment associated with mountain streams introduces important practical constraints in the application of standard techniques for measuring bed load transport. Direct classical methods for investigating bed load transport are for the most part expensive to apply, in terms of both equipment and manpower requirements. As a result, most studies applying such methods have addressed very limited objectives and have involved only short term measurements. It is difficult to use short term measurements in the interpretation of longer term sediment yields and contemporary channel system changes.

Most existing work has centred on comparisons of bed load and suspended load transport, since this is important for investigating the total sediment flux. Such studies have indicated that bed load commonly constitutes a substantial part of the total load of most mountain rivers and is generally much more important than suspended load in terms of channel development and change in such rivers (Froehlich, 1982; Pitlick & Thorne, 1987; Leopold, 1992).

THE STUDY AREA

The work reported in this contribution was undertaken in the Homerka instrumented catchment in the Polish Flysch Carpathians, where different techniques for monitoring sediment transport have been applied over the past 30 years (Froehlich, 1982, 1995). The Homerka stream drains a catchment area of 19.6 km^2 with a longitudinal slope of 53.3‰. The catchment has a mean discharge of 0.350 m^3 s^{-1}, a mean annual flood discharge of 9.15 m^3 s^{-1} and a mean annual rainfall of 909 mm. The area is characterized by highly active erosion, sediment transport and fluvial sedimentation processes. Fluvial processes are dominant, and the channel network is being actively deepened. Extreme floods exert an important control on the fluvial system and are highly significant as geomorphologically effective events (Froehlich, & Starkel, 1994).

Bed load transport along the Homerka stream is characterized by significant spatial variability, in response to variable sediment supply related to the occurrence of bedrock channels, bed armouring and hillslope mass movements. The armoured surface layer consists of grain sizes with a D_{50} of 55 mm.

PROBLEMS ASSOCIATED WITH BED LOAD TRANSPORT INVESTIGATIONS IN MOUNTAIN STREAMS

Geomorphologists and hydrologists are constantly seeking improved methods for measuring bed load transport, in order to quantify sediment yields from drainage basins more accurately. The results from individual field investigations are, however, difficult to compare, because of the considerable range of measurement techniques and sampling procedures employed (Wohl, 2000). There is a particular need to develop improved techniques for monitoring bed load transport in mountain streams.

Any sampler placed in the flow will perturb local hydraulic conditions. Direct bed load transport measurements, particularly during floods, are also extremely difficult, because of a number of problems, including high flow velocities, the large quantities of sediment being transported, the wide range of grain sizes involved, and dangerous field conditions. Furthermore, the thresholds for the initiation and cessation of bed load transport are highly variable in high-energy mountain streams (Wohl, 2000).

Bed load transport in mountain streams is also often characterized by waves of different frequency and amplitude, which again pose great problems for measurement programmes (Ergenzinger *et al.*, 1994; Bunte, 1990). Furthermore, grain sizes that normally move as bed load, may be transported as suspended load during extreme flood events. Macroturbulence may be responsible for the suspension of large blocks and cobbles (e.g. Leighly, 1934; Matthes, 1947; Froehlich, 1982). Large boulders are frequently moved by catastrophic floods, but there is evidence that they also move in floods lying within the normal flood range (Vaughn, 1990). During low and intermediate magnitude flood events, when a stream is not competent to transport the coarser bed material fractions, the finer, mobile fractions are selectively removed from the active layer. When the tractive force exceeds the critical value for the maximum grain size, all fractions are transported.

ACOUSTIC (HYDROPHONE) BED LOAD TRANSPORT MEASUREMENT

Numerous studies have attempted to use acoustic devices to measure bed load transport (e.g. Bedeus & Ivicsics, 1964; Tywoniuk & Warnock, 1973; Richards & Milne, 1979; Froehlich, 1982; Bänzinger & Burch, 1990; Rickenmann, 1994). The author has successfully used the acoustic method to provide a continuous record of bed load transport in the Homerka instrumented catchment, and an acoustic device was designed and constructed and successfully deployed at the gauging station on the Bacza stream, a tributary of the main Homerka stream (Froehlich, 1982). The device permits the continuous detection of coarse particle movement during flood events and the resulting record can be used to derive information on the magnitude of bed load transport. Early experimental investigations commenced in 1972 and an upgraded recording system has been in operation since 1975. In the past 29 years, 75 events have been documented.

The acoustic device comprises three steel pipes containing the microphones placed horizontally on the channel bed, a signal processing unit, an oscilloscope, an analogue recorder and a computer (Fig. 1). The system has been installed within a straight reach in the lower part of the Bacza stream. Field tests have demonstrated that the sensor does not interfere with the natural hydraulic conditions. Each steel pipe is 6 m in length and 42 mm in diameter, and these pipes have been installed on the channel bed at a distance of 10 m from each other. The small capacitive microphones have a flat frequency response over the range 20–35 kHz and, in order to determine the optimum configuration and specification, the author tested both different microphones and also steel and plastic pipes of different diameter.

The microphones detect sound (acoustic waves) transferred through the pipes after its generation due to collisions with the moving gravel. The acoustic noise has a frequency in the range 20–60 Hz. The signal-processing unit has a low frequency amplifier and six noise filters. The data logging system is based on recording of the signal output current. Power is supplied from external high-capacity lead-acid batteries connected to the power supply. The device described above is still experimental and has its own particular advantages and limitations.

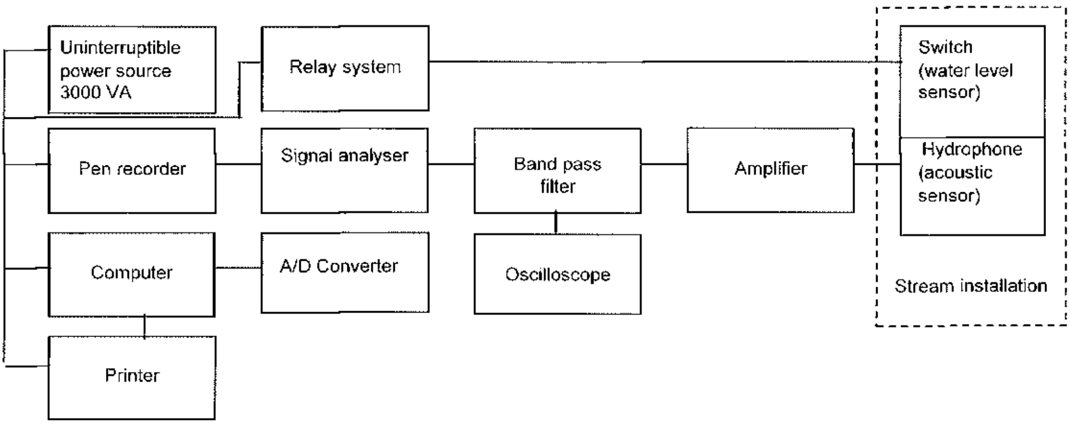

Fig. 1 The primary elements of the acoustic (hydrophone) system.

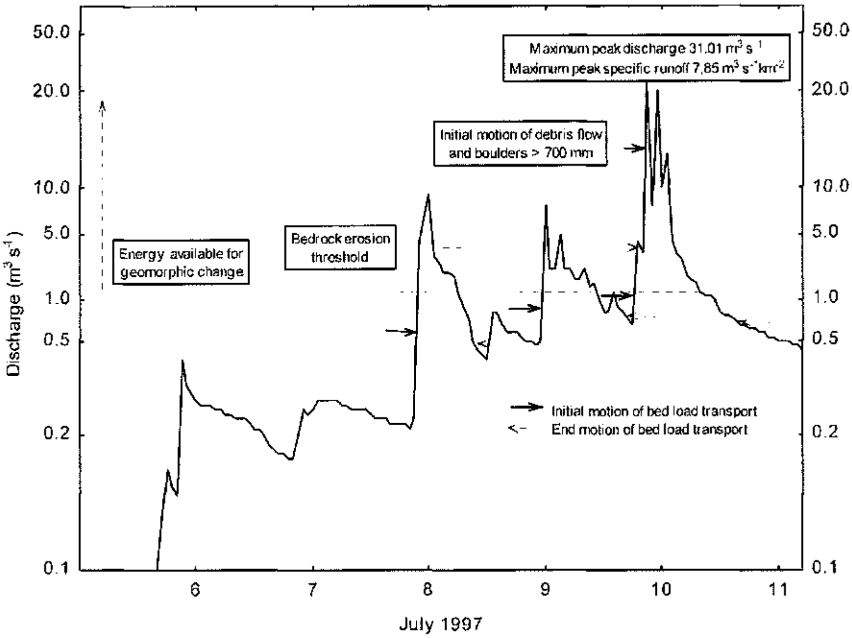

Fig. 2 Thresholds for the initiation and cessation of bed load transport during a series of flood events in early July 1997.

The initiation of particle movement represents a key component of the bed load transport process. However, Froehlich (1998) has reported that the threshold discharge, above which transport commences, may vary through time and the investigations undertaken in the Homerka catchment, using both acoustic and magnetic tracer techniques, have emphasized that the threshold discharge for initiation of bed load transport cannot be treated as a single definitive value (cf. Fig. 2).

The relationship between water discharge and the rate of bed load transport can be analysed using continuous measurements of water discharge and the continuous record of the acoustic signal provided by the coarse sediment. In general, sound intensity increases with transport rate and the frequency of the acoustic signal is inversely proportional to the diameter of the moving particles. The signal pattern is a complex hierarchic system reflecting both the pulsed nature of bed load transport and the noise generated by moving bed load. The transport rate increases rapidly and reaches its maximum value very soon after an increase in the magnitude of the flow renders the bed unstable. The threshold discharge for initiation of bed load transport varies between flood events. It is possible to recognise the discharge threshold for both initiation of bed load transport during the rising limb of a flood and for the cessation of transport during the falling limb (Fig. 2).

In general, bed load transport reaches a peak more rapidly than the water discharge, and for a given flood discharge, the intensity of bed load transport will vary between the rising and falling stages. This is reflected in the shape of the hysteretic loop characterizing the relationship between bed load transport and discharge (e.g. Froehlich, 1982; Bathurst, 1987; Schöberl, 1991; Rickenmann, 1994; Moog & Whiting, 1998). Each flood is characterized by a loop with a different shape, in a

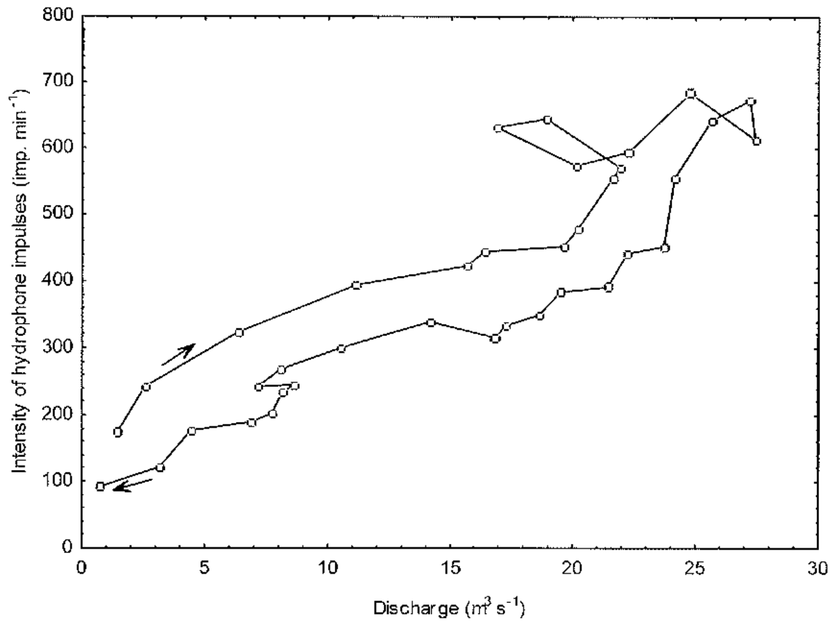

Fig. 3 The relationship between the intensity of hydrophone impulses generated by transported particles and water discharge.

similar way to the hysteresis curves reported for suspended sediment transport (Fig. 3). It is therefore impossible to establish a single rating relationship between bed load transport rate and water discharge that can be applied to all events (Froehlich, 1982). Bed load transport is non-uniform and unsteady and can fluctuate over an order of magnitude, for given flow conditions. In general, more bed load is transported by discharges associated with the first exceedance of the threshold for initial motion in a particular year and the sequence of floods and their associated inter-arrival times play an important role in controlling the pattern of bed load transport in subsequent events (Froehlich, 1982, 1998). The role of the relaxation time is still poorly understood.

The acoustic device can also be used to estimate the magnitude of the bed load discharge, if it can be calibrated. Independent measurements of bed load discharge were obtained using periodic surveys or emptying of the sedimentation basins upstream of concrete weirs and drop structures and these were used to establish the calibration relationship between the cumulative impulse count and the total amount of sediment moved, presented in Fig. 4. The particle size distributions of the sediment trapped in the sedimentation basins was determined using large sieves.

THE USE OF MAGNETIC TRACERS FOR MEASURING BED LOAD TRANSPORT

The use of magnetic tracers affords a means of establishing the bed load transport rate during flood events associated with individual size fractions (e.g. Ergenzinger & Conrady, 1982; Ergenzinger & Custer, 1983; Hassan *et al.*, 1984; Reid *et al.*, 1984;

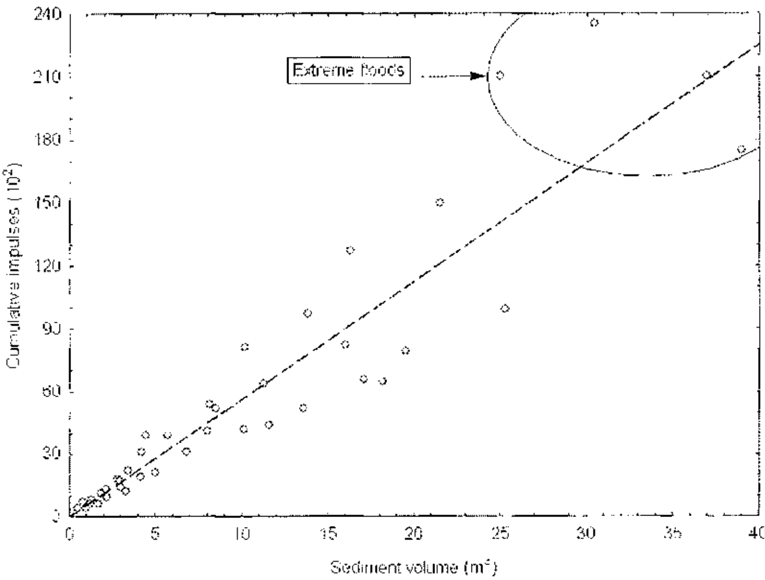

Fig. 4 A calibration relationship between cumulative hydrophone impulses and the volume of bed load transported during an event.

Ergenzinger *et al.*, 1994). Two approaches to the use of magnetic tracers can be distinguished. In the first, the more conventional passive approach, individual gravel clasts of varying size are tagged with magnets and placed at known positions within a river reach. By relocating the tagged clasts after individual events, it is possible to establish the distance of travel. This approach permits the effects of grain size and particle density and shape on transport distance to be explored (e.g. Hassan *et al.*, 1984). In the second, or active, approach, the actual timing and speed of movement of the tagged particles within a study reach is recorded as they cross magnetically sensitive coils installed across the river channel (cf. Reid *et al.*, 1984). Although the individual gravel particles are usually tagged by implanting magnets into the clasts, Ergenzinger & Custer (1983) also reported the successful application of the approach to a stream where the coarse bed load was naturally magnetic.

Coarse material bed load transport has been investigated within the Homerka catchment using both magnetic approaches. In each case, small magnets were cemented into holes drilled into gravel clasts of different sizes using an epoxy resin. Early experimental work with an active bed load transport sensor commenced in 1982, when a measuring system designed and constructed by the author, was installed at a gauging station on the Homerka stream (Fig. 5). The device consists of two magnetically sensitive coils (copper windings on an iron core), each 4 m in length. These coils were installed across the channel bed, separated by a spacing of 30 m (cf. Reid *et al.*, 1984). The movement of the tagged gravels during a flood is registered by their passage over the coil, which affects the magnetic field, causing a change in the inductance of the coils. According to the Faraday principle, a voltage peak is induced and the signal is detected, amplified and transmitted to a receiver and then to recorder. The median diameter of the bed material in the experimental reach is 64 mm. Magnets

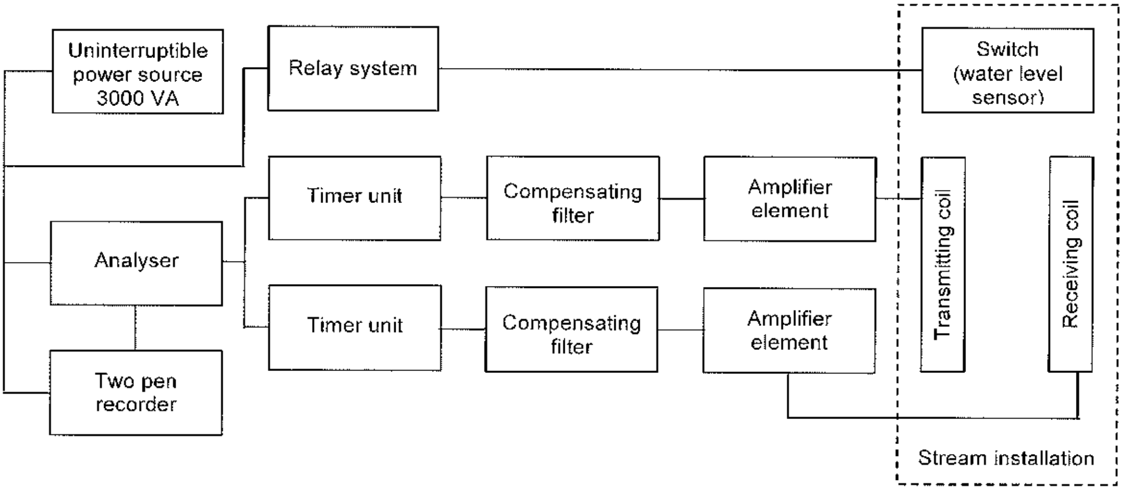

Fig. 5 The primary elements of the electromagnetic system used for monitoring bed load transport.

of different size were inserted into different sized gravel clasts, permitting the movements of clasts of different size to be distinguished (Fig 6). The tagged gravels were also painted to facilitate their recovery after an event. After every flood, the gravels were relocated using a portable metal detector. Recovery rates ranged from 12 to 85%. Some typical results generated by this measurement system are depicted in Fig. 7.

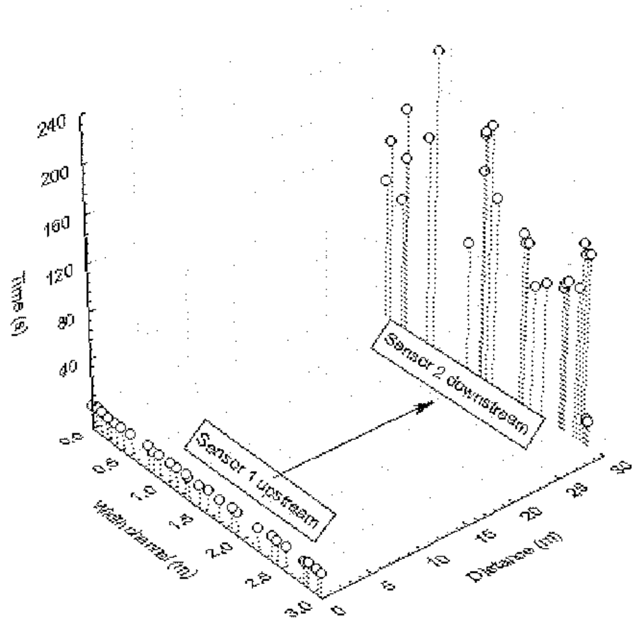

Fig. 6 Results obtained from the electromagnetic system used for measuring bed load transport during a flood occurring on 20 July, 2001.

Recording of the locations of the tagged clasts within the Homerka channel system after successive events also provided a means of documenting the transport distances of tagged clasts of different size during individual events. However, the results obtained for the first event after the emplacement of the labelled gravel were not considered to be representative, since it is almost impossible to relocate a tagged gravel clast in exactly the same position as it occupied prior to removal for labelling. The transfer of gravel particles through the Homerka channel system was shown to be influenced by both flood magnitude and duration. Transport distances for single gravel clasts during an event with a magnitude equivalent to the mean annual flood ranged from 5–140 m. The smaller clasts were found to have significantly lower transport distances than the larger particles. The coarsest fractions (>600 mm) of the bed material only become mobile during extreme floods and the results are presented in Fig. 7 show that under similar flow conditions individual clasts moved varying distances in successive steps. These results clearly demonstrate the stochastic nature of the entrainment and movement of individual particles in a step-pool mountain stream. This stochastic behaviour assumes increasing importance during extreme flood events. The consequent lack of a clear relationship between distance of movement and particle size has been reported in many field experiments. Little is currently known about the movement of large particles through the channel systems of catchments at different scales.

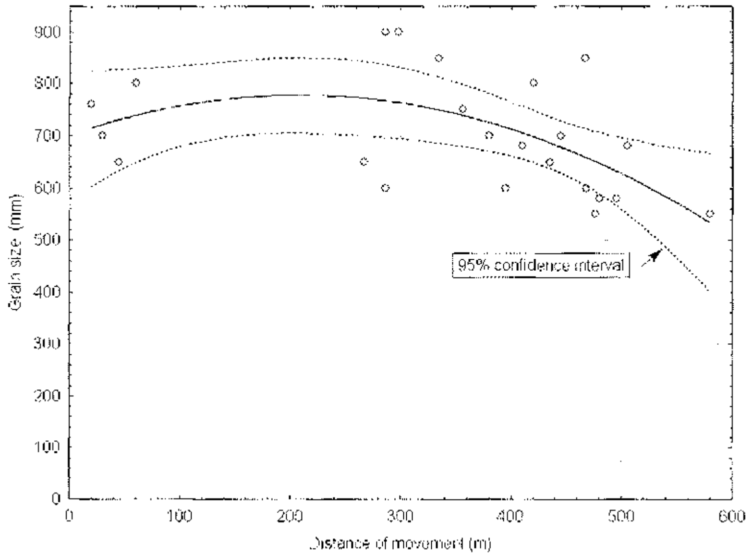

Fig. 7 The relationship between transport distance and the grain size of magnetically tagged coarse bed load particles for a flood occurring during the period 9–11 July 1997.

CONCLUSIONS

The results from the investigations described in this contribution demonstrate that acoustic and magnetic approaches to investigating bed load transport both provide valuable and complementary results. These results emphasise the complexity of bed load transport in mountain streams. Both the threshold discharges for initiation and cessation of bed load transport and the volume of bed load transported can vary significantly between individual flood events. Equally, the lack of a clear relationship between transport rate and discharge emphasises the stochastic nature of bed load transport and the importance of pulse transfer.

REFERENCES

Bedeus, K. & Ivicsics, L. (1964) Observation of the noise of bedload. In: *Land Erosion, Precipitations, Hydrometry, Soil Moisture*, 384–390. IAHS Publ. 65.

Bathurst, J. C. (1987) Measuring and modelling bedload transport in channels with coarse bed materials. In: *River Channel: Environment and Process* (ed. by K. Richards), 272–294. Blackwells, Oxford, UK.

Bänzinger, R. & Burch, H. (1990) Acoustic sensors (hydrophones) as indicators for bed load transport in a mountain torrent. In: *Hydrology in Mountain Regions I. Hydrological Measurements; The Water Cycle* (ed. by H. Lang & A. Musy), 207–214. IAHS Publ. 193.

Bunte, K. (1990) Experiences and results from using a big-frame bed load sampler for coarse material bed load. In: *Hydrology in Mountain Regions I. Hydrological Measurements: The Water Cycle* (ed. by H. Lang & A. Musy), 223–230. IAHS Publ. 193.

Ergenzinger, P., De Jong, C. Laronne J. & Reid, I. (1994) Short term temporal variations in bed load transport rates: Squaw Creek, Montana, USA and Nahal Yatir and Nahal Estemoa, Israel. In: *Dynamics and Geomorphology of Mountain Rivers* (ed. by P. Ergenzinger & K. -H. Schmidt), 251–263. Springer-Verlag, Berlin, Germany.

Ergenzinger, P. & Conrady, J. (1982) A new tracer technique for measuring bedload in natural channels. *Catena*. **9**, 77–80.

Ergenzinger, P. & Custer, S. G. (1983) Determination of bedload transport using naturally magnetic tracers: First experiences at Squaw Creek, Gallatin County, Montana. *Water Resour. Res*. **19**, 187–193.

Froehlich, W. (1982) Mechanizm transportu fluwialnego i dostawy zwietrzelin do koryta w górskiej zlewni fliszowej (The mechanisms of fluvial transport and waste supply into the stream channel in a mountainous flysch catchment). *Prace Geogr. IG i PZ PAN*. **143**, 1–144.

Froehlich, W. (1995) Sediment dynamics in the Polish Flysch Carpathians. In: *Sediment and Water Quality in River Catchments* (ed. by I. Foster, A. Gurnell & B. Webb), 453–461. John Wiley & Sons, Chichester, UK.

Froehlich, W. (1998) Transport rumowiska i erozja koryt potoków beskidzkich podczas powodzi w lipcu 1997 roku. In: *Powódź w dorzeczu górnej Wisly w lipcu 1997 roku* (ed. by L. Starkel & J. Grela). 133–144. Wydawnictwo Oddziału PAN, Kraków, Poland.

Froehlich, W. & Starkel, L. (1994) The response of slope and channel systems to various types of extreme rainfalls: A comparison between the temperate zone and humid tropics. *Geomorphology* **11**, 337–345.

Hassan, M. A., Schick, A. P. & Laronne, J. B. (1984) The recovery of flood dispersed coarse sediment particles – a three-dimensional magnetic tracing method. In: *Channel Processes: Water, Sediment, Catchment Controls* (ed. by A. P. Schick). *Catena Suppl. Bd*. **5**, 153–162.

Itakura, Y., Taniguchi, S., Miyamoto, K. & Shimokawa, E. (1994) Acoustic sensor for detecting the occurrence of debris flows. In: *Variability in Stream Erosion and Sediment Transport* (ed. by L. J. Olive & J. A. Kesby) (Poster Contributions Canberra Symp., December 1994), 34–38. Special Publication no. 5, Department of Geography & Oceanography, Australian Defence Force Academy, Canberra, Australia.

Johnson, P. & Muir, T. C. (1969). Acoustic detection of sediment movement. *J. Hydrol*. **7**, 519–540.

Leighly, J. B. (1934) Turbulence and the transportation of rock debris by streams. *Geogr. Rev*. **24**, 453–464.

Leopold, L. B. (1992) Sediment size that determines channel morphology. In: *Dynamics of Gravel-Bed Rivers* (ed. by P. Billi, R. D. Hey, C. R. Thorne & P. Tacconi), 297–311. John Wiley and Sons, Chichester, UK.

Matthes, G. H. (1947) Macroturbulence in natural stream flows. *EOS Trans. AGU*. **28**, 255–265.

Moog, D. B. & Whiting, P. J. (1998) Annual hysteresis in bed load rating curves. *Water Resour. Res*. **34**, 2393–2399.

Pitlick, J. C. & Thorne, C. R. (1987) Sediment supply, movement and storage in an unstable gravel-bed river. In: *Sediment Transport in Gravel-Bed Rivers* (ed. by C. R. Thorne, J. C. Bathurst & R. D. Hey), 151–183. John Wiley & Sons, Chichester, UK.

Richards, K. S. & Milne, L. M. (1979) Problems in the calibration of an acoustic device for the observation of bedload transport. *Earth Surf. Processes Landf*. **4**, 307–317.

Reid, I., Brayshaw, A. C. & Frostick, L. E. (1984) An electromagnetic device for automatic detection of bedload motion and its field applications. *Sedimentology* **31**, 269–276.

Rickenmann, D. (1994) Bedload transport and discharge in the Erlenbach stream. In: *Dynamics and Geomorphology of Mountain rivers* (ed. by P. Ergenzinger & K. -H. Schmidt), 53–66. Springer-Verlag, Berlin, Germany.

Ryan, S. E. & Troendle, C. A. (1997) Measuring bedload in coarse-grained mountain channels: procedures, problems, and recommendations. In: *Water Resources Education, Training, and Practice: Opportunities for the Next Century*, 949–958. American Water Resources Association, Littleton, Colorado, USA.

Schöberl, F. (1991) Continuous simulation of sediment transport in the case of glacierized watershed. In: *Fluvial Hydraulics of Mountain Regions* (ed. by A. Armanini and G. DiSilvio), 71–81. Springer-Verlag, Berlin, Germany.

Tywoniuk, N. & Warnock, R. G. (1973) Acoustic detection of bedload transport. *Proceedings of Hydrologic Symposium at University of Alberta, Edmonton* (May 8 and 9, 1973), 728–743. Department of Environment Natural Resource Council, Canada.

Vaughn, D. M. (1990) Flood dynamics of a concrete-lined, urban stream in Kansas City, Missouri. *Earth Surf. Processes Landf.* **15**, 525–537.

Wohl, E. (2000) *Mountain Rivers*. Water Res. Monograph Series AGU, 14.