Published online in 2010 as part of U.S. Geological Survey Scientific Investigations Report 2010-5091.

Monitoring of Bed Load Transport Within a Small Drainage Basin in the Polish Flysch Carpathians

Wojciech Froehlich

HOMERKA Laboratory of Fluvial Processes Institute of Geography and Spatial Organization, Polish Academy of Sciences, Nawojowa, Poland.

Abstract

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 35 years. Bedload transport has been measured using both acoustic and magnetic techniques. The detection and measuring/registration units were made by the author and developed step-by-step and improved over the years. They are still experimental and have inherent advantages and limitations. The passive acoustic method permits continuous measurement and is able to provide a continuous record of coarse particle movement during flood events. Coarse material bedload transport has also been measured using magnetic tracers technique and electromagnetic sensors were used to track their movement through a designated short reach. Transport distances associated with individual gravel particles tagged with magnets during individual events have been documented by recovering after the event using a metal detector. The measuring techniques used at the Homerka instrumented catchment provided detailed and long-term records of temporal and spatial distribution of gravel transport during floods.

Key words: gravel bedload, acoustic geophone, magnetic tracer, Homerka catchment

1.0 Introduction

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 35 years (see Froehlich, 1982, 2003). The Homerka stream drains a catchment area of 19.6 km^2 with a longitudinal slope of 53.3 percent. 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. High energy floods exert an important control on the fluvial system and are highly significant as geomorphologically effective events (Fig. 1 and 2).

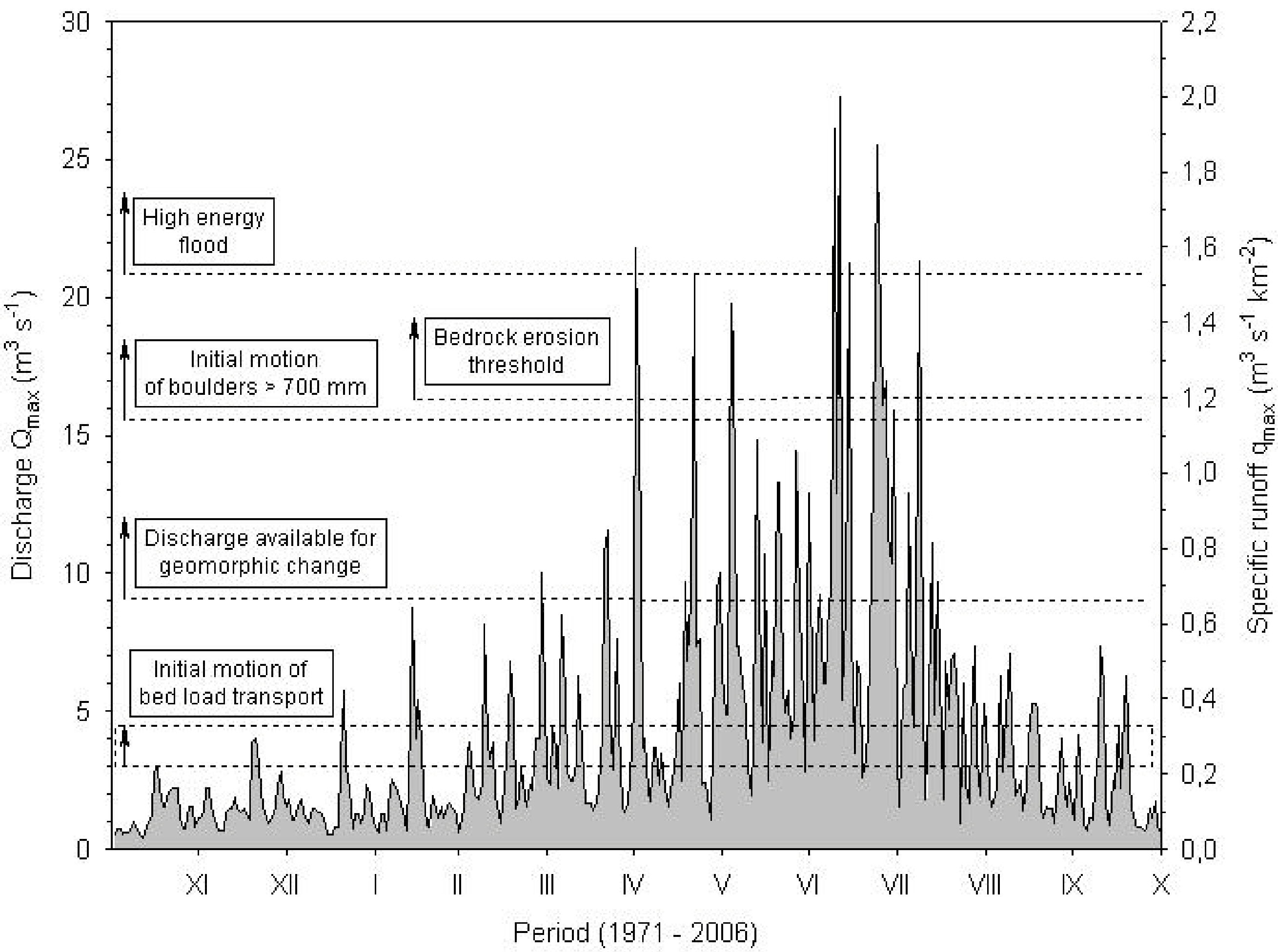

Figure 1. Variation of maximum daily discharge at a gauging station on the Homerka stream (14.04 km^2) during the period 1971-2006 and thresholds of bedload transport and effectiveness of fluvial processes.

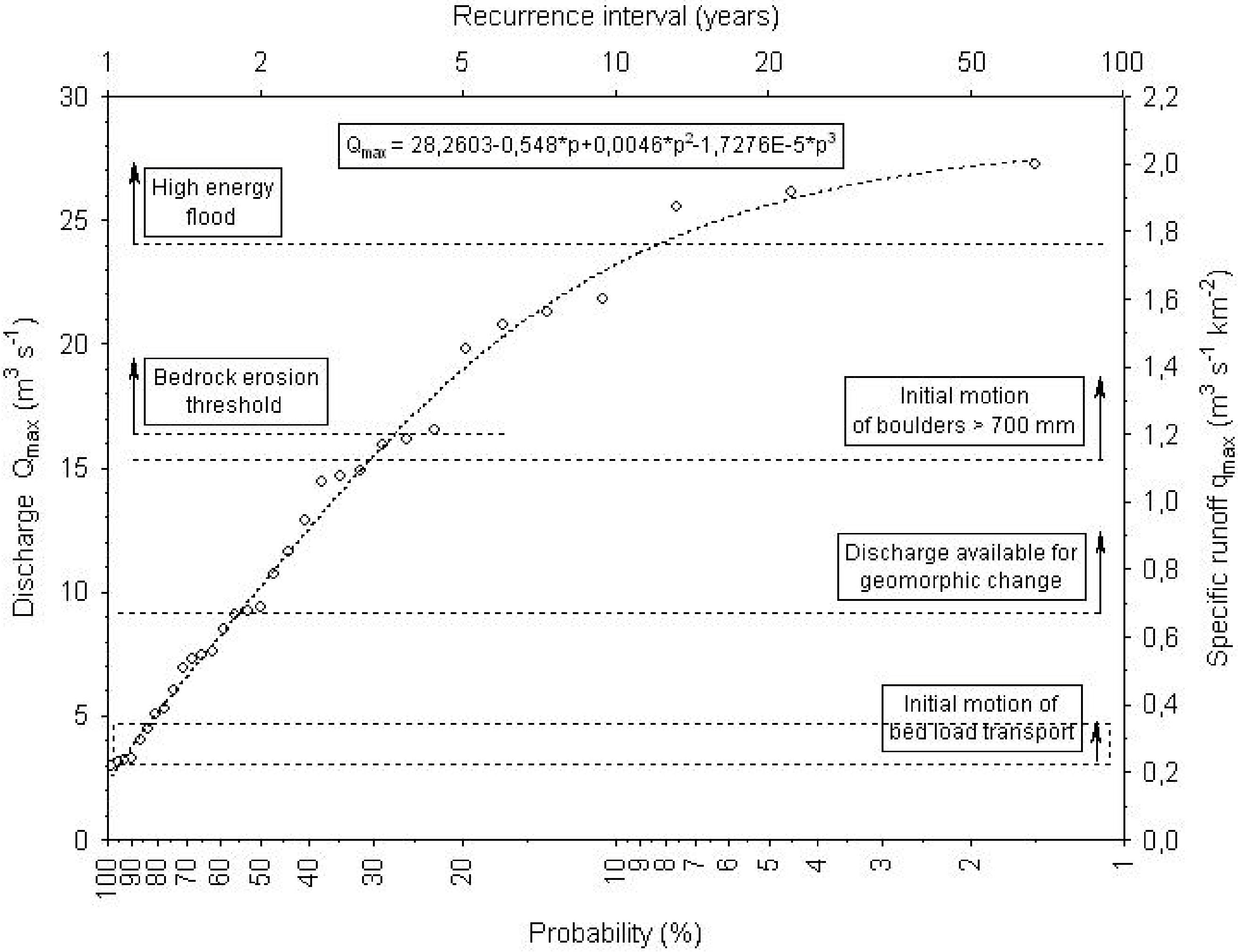

Figure 2. Probability and recurrence interval of maximum annual discharge at a gauging station on the Homerka stream (14.04 km^2) during the period 1971-2006 and thresholds of bedload transport and effectiveness of fluvial processes.

Bed load transport has been measured using both acoustic and magnetic techniques. The passive acoustic 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. Coarse material bed load transport has also been measured 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 (e.g. Reid, et. al., 1984; Froehlich, 2003). In addition, transport distances associated with individual gravel particles tagged with magnets during individual events have been documented by recovering the tagged gravel after the event using a metal detector (e.g. Ergenzinger and Conrady, 1982; Hassan et al., 1984; Froehlich 2003). These magnetic tracing techniques permit the bed load transport rate associated with individual grain size fractions to be quantified.

2.0 The use of passive acoustic method for continuous monitoring of bed load transport

Since 1972, the author used the passive acoustic method to provide a continuous record of bed load transport. An acoustic device was designed, constructed, and successfully deployed at the gauging station on the Bacza stream, with a drainage area of 3.95 km^2. The Bacza stream is a tributary of the main Homerka stream (Froehlich, 1982, 2003). The acoustic 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.

The acoustic device comprises three steel pipes containing the geophones placed horizontally on the channel bed, a signal processing unit, an oscilloscope, an analogue recorder and a computer (Fig. 3). The system has been installed within a straight reach in the lower part of the Bacza stream. Field tests have demonstrated that the passive 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 geophones 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 geophones and also steel and plastic pipes of different diameter.

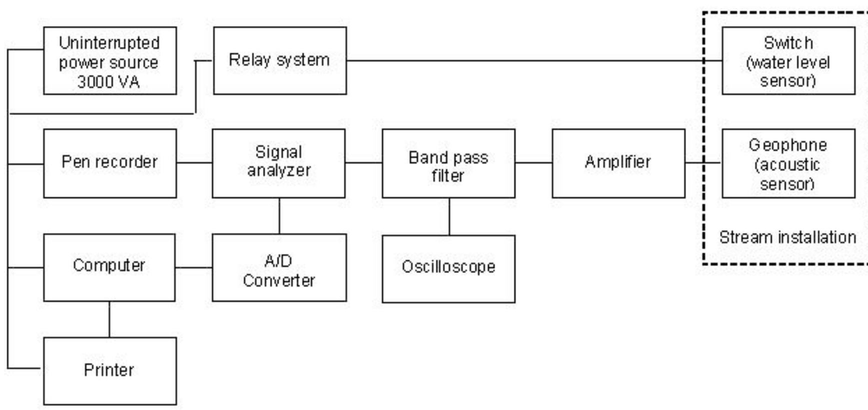

Figure 3. The primary elements of the passive acoustic system used for monitoring bed load transport.

The geophones 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.

The initiation of particle movement represents a key component of the bed load transport process. However, Froehlich (1982, 2003) has reported that the threshold discharge, above which transport commences, may vary through time. 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. 1 and 2).

The relationship between water discharge and the rate of bed load transport can be analyzed using continuous measurements of water discharge and the continuous record of the acoustic signal provided by the coarse sediment. The acoustic signals generated by the water turbulences were analyzed with the oscilloscope and the calibrated noise meter. The author still did not solve a problem of interference of acoustic signals during high energy floods.

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 recognize 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. 4).

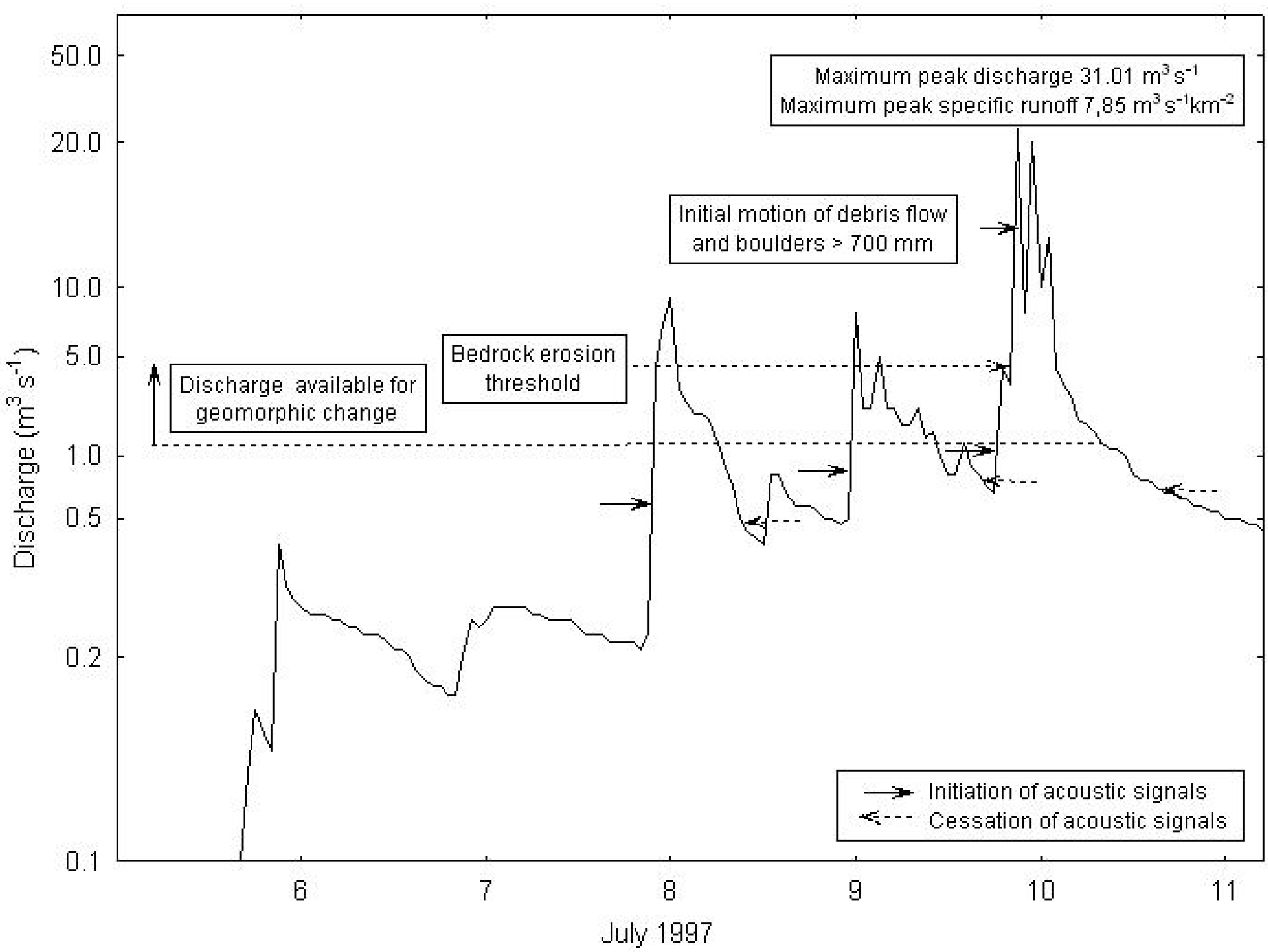

Figure 4. Thresholds for the initiation and cessation of bed load transport during a series of flood events in early July 1997.

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, 2003; Bathurst, 1987; Schöberl, 1991; Rickenmann, 1994; Moog and Whiting, 1998; Bogen and Møen, 2003) Each flood is characterized by a loop with a different shape, in a similar way to the hysteresis curves reported for dissolved and suspended sediment transport.

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 (see Fig. 1; 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. 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, 2003). 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. 5. The particle size distributions of the sediment trapped in the sedimentation basins was determined using large sieves.

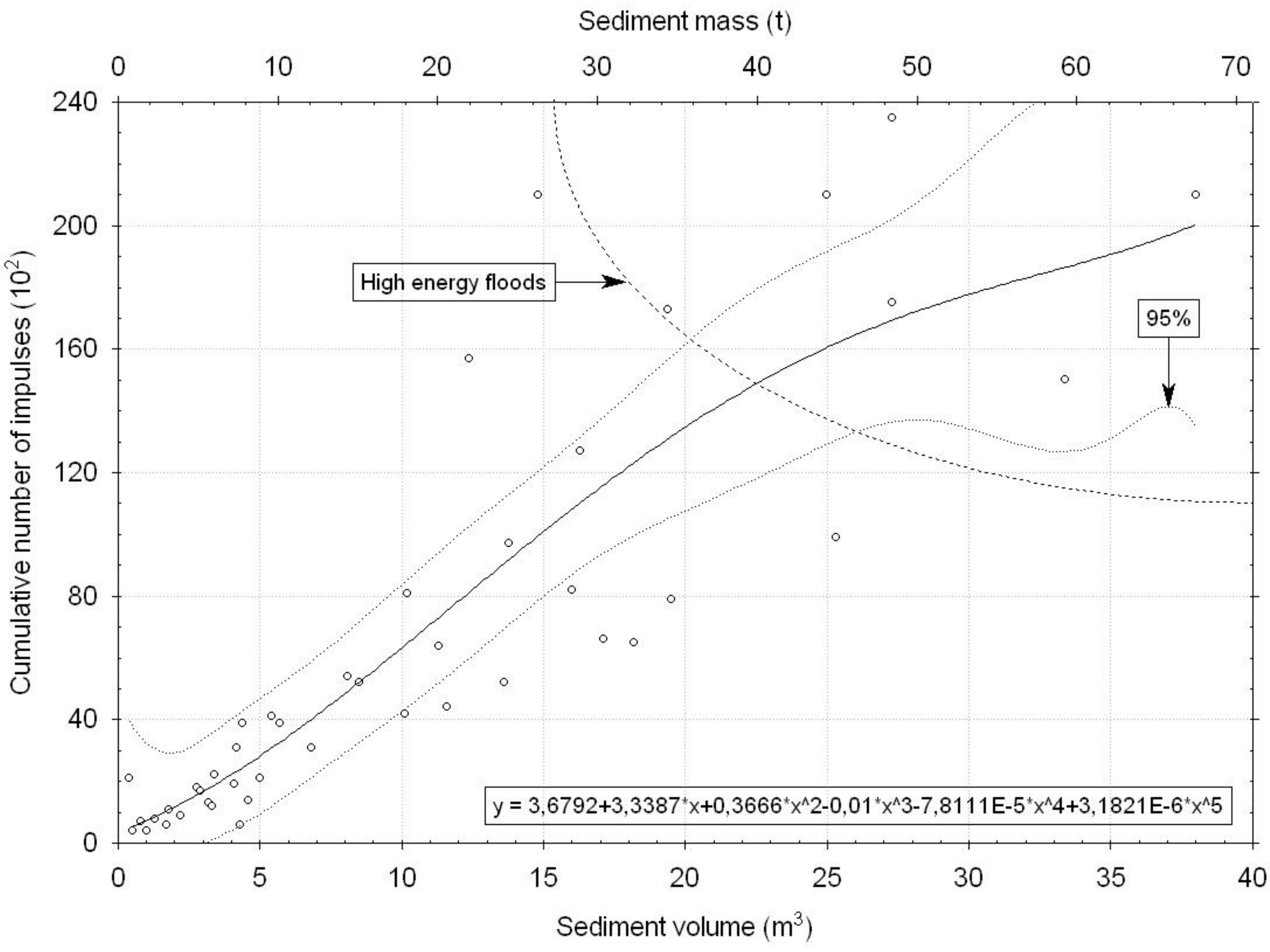

Figure 5. A calibration relationship between cumulative geophone impulses and the bed load transported during an event.

3.0 The use of magnetic tracers for measuring of bed load transport

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. 6). 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, Froehlich 2003).

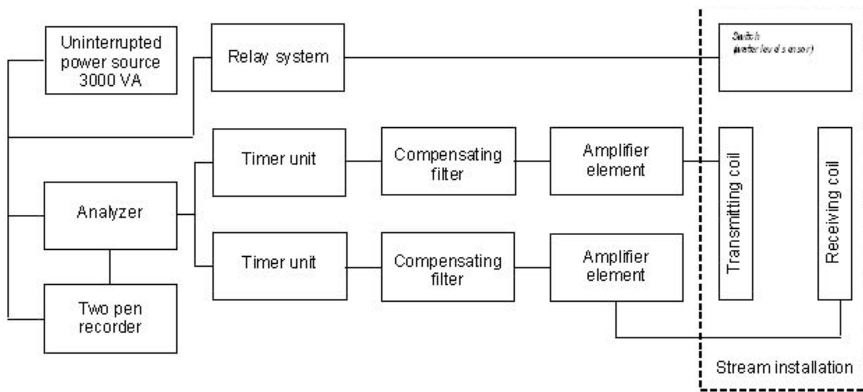

Figure 6. The primary elements of the electromagnetic system used for monitoring bed load transport.

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 of different size were inserted into different sized gravel clasts, permitting the movements of clasts of different size to be distinguished. 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.

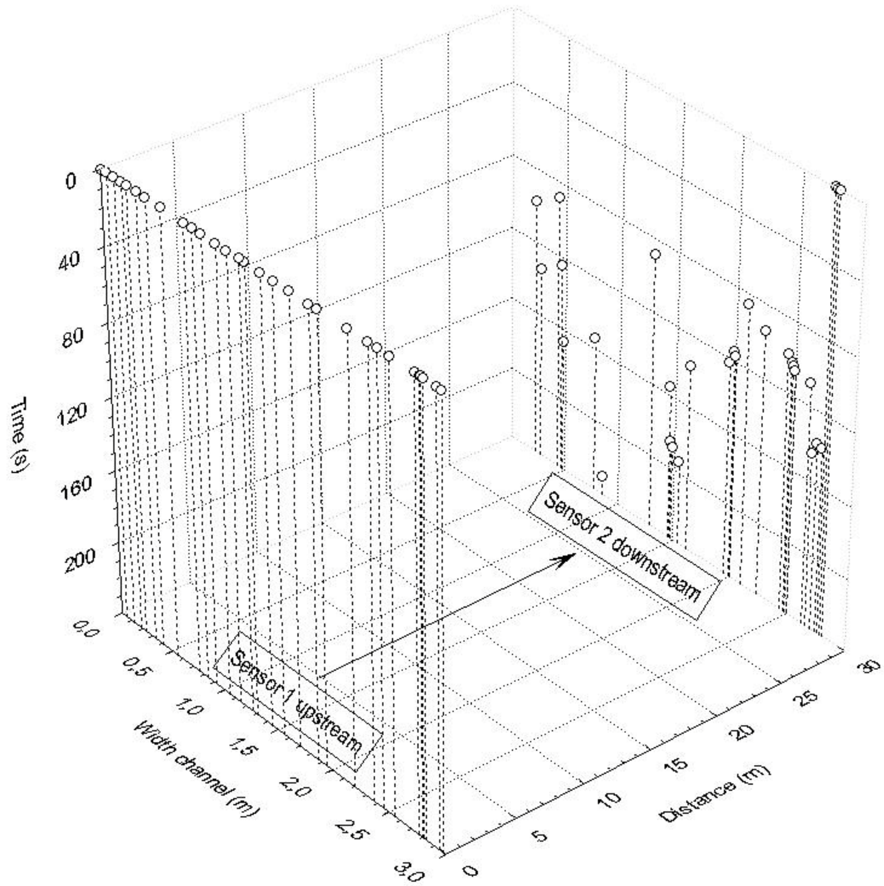

Figure 7. Results obtained from the electromagnetic system used for measuring bed load transport during a flood occurring on 20 July, 2001.

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 tagged 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 tagging. 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 5–140 m. The smaller clasts were found to have significantly higher transport distances than the larger particles (Fig. 8). The coarsest fractions of the bed material only become mobile during extreme floods. The results show that, under similar flow conditions, individual clasts moved varying distances in successive steps.

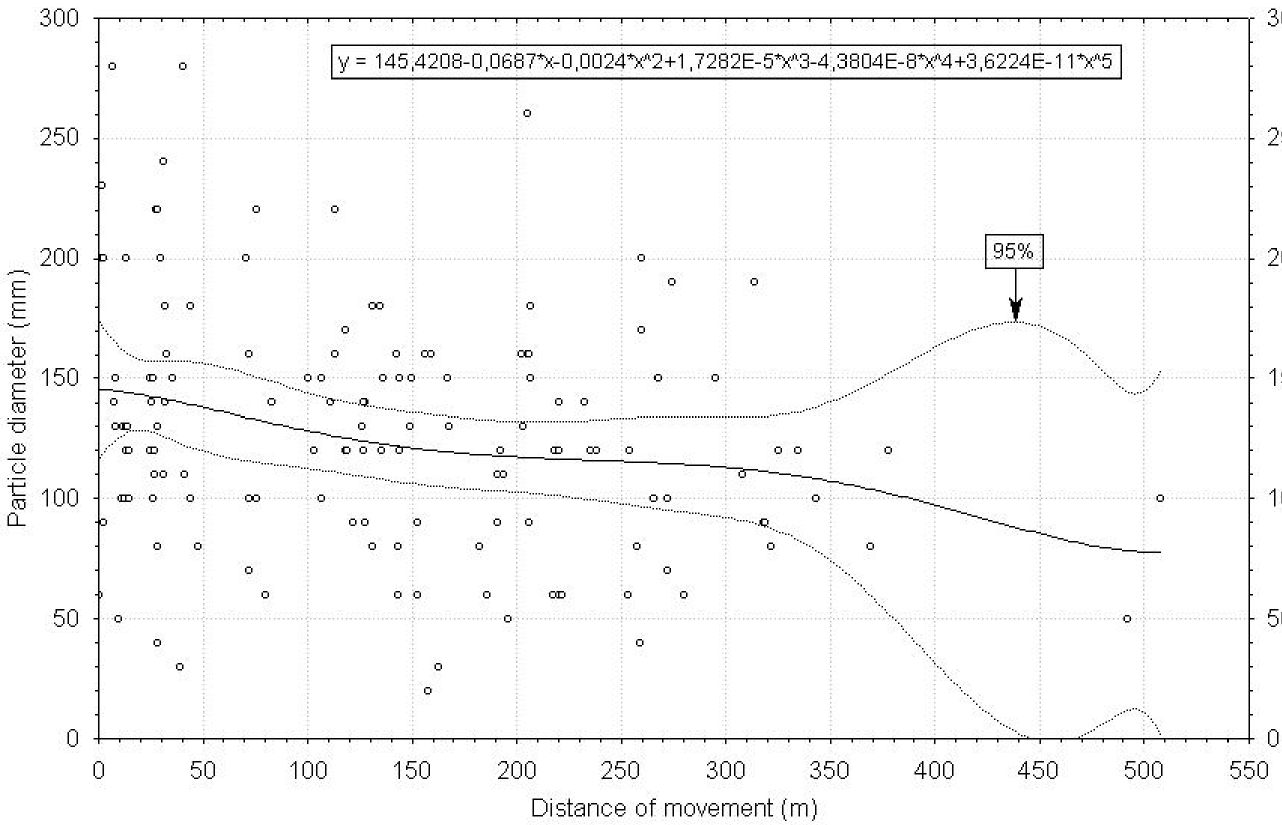

Figure 8. The relationship between transport distance and the particle diameter of magnetically tagged coarse bed load particles for a flood occurring during the period 20 June 2001.

These results clearly demonstrate the stochastic nature of the entrainment and movement of individual particles in a step-pool mountain stream. This stochastic behavior 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.

4.0 Conclusions

The results from the investigations described in this contribution demonstrate that acoustic and magnetic tracer technique approaches to investigating bed load transport both provide valuable and complementary results. These results emphasize the complexity of bed load transport in mountain streams. The pulsating and discontinuous nature of bed load transport introduces problems with the calibration of apparatus and estimation of the magnitude errors of measurements. 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 emphasizes the stochastic nature of bed load transport and the importance of pulse transfer. 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 armoring and hillslope mass movements.

Acknowledgements

The presentation of the present work at the International Bedload Surrogate Monitoring Workshop at St. Anthony Falls Laboratory, University of Minnesota was made possible through financial support by the University of Minnesota and help of Jonathan Laronne, John R. Gray and Jeff Marr are greatly thanked. I would like to thank Jonathan Laronne provided useful comments on the manuscript and also reviewers Timothy J. Randle and Andreas Krein.

References cited

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

Bogen, J. and Møen, K., 2003, Bed load measurements with a new passive acoustic sensor In: Erosion and Sediment Transport Measurement in Rivers. Technological and Methodological Advances. Proceedings of the Oslo Workshop (19-21 June 2002) (eds. Jim Bogen and Des E. Walling). IAHS Publication no. 283, pp. 201-210.

Ergenzinger, P. and Conrady, J., 1982, A new tracer technique for measuring bedload in natural channels. Catena. 9, pp. 77–80.

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. no. 143, pp. 1-144.

Froehlich, W., 2003 Monitoring bed load transport using acoustic and magnetic devices. In: Erosion and Sediment Transport Measurement in Rivers. Technological and Methodological Advances. Proceedings of the Oslo Workshop (19-21 June 2002) (eds. Jim Bogen and Des E. Walling). IAHS Publication no. 283, pp. 201-210.

Hassan, M. A., Schick, A. P. and 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, pp. 153–162.

Moog, D. B. and Whiting, P. J., 1998, Annual hysteresis in bed load rating curves. Water Resour. Res. 34, pp. 2393–2399.

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

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

Schõberl, 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), Springer-Verlag, Berlin, Germany, pp. 71–81.