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Use of radio-tracking techniques in bed load transport investigations

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Abstract This paper aims to analyse the use of radio-tracking techniques in bed load transport investigations. The Lagrangian technique of radio-tracking offers the opportunity to investigate the stochastic elements of transport, from erosion to final deposition after a flood. It consists of a swinging quartz in transmitters, antennae and receivers, and computer/software for storing data and controlling the measurements. The technique is shown to be useful for analysing the interaction between flow turbulence and initiation of motion, bed particle dispersion, distribution of step lengths and rest periods, as well as the interaction between morphology and transport paths.

Key words bed load transport; gravel bed rivers; river morphology

INTRODUCTION

In principle there are two main possibilities for observing and mathematically describing bed load transport: Eulerian concept; Langrangian concept. Most measurement techniques like basket sampling (Habersack & Laronne, 2002) and trap measurements (Habersack *et al.*, 2001; Laronne *et al.*, 2003) belong to the first category, allowing one to answer e.g. questions concerning the quantitative and qualitative transport of material through a defined cross section. In order to examine particle motion along a river course, other methodologies like passive and active tracer techniques have been developed. Painted particles were used intensively in laboratory investigations for determining the transport paths of bed particles (e.g. Einstein, 1937) and later also in the field by Leopold in the USA and Takayama in Japan (Hassan *et al.*, 1984). Luminofluorescent-coloured pebbles improved detection via ultra-violet light (DVWK 127, 1992). Whereas typically only about 30% of the particle input could be recovered, iron or magnetic cores, implanted either in natural or artificial stones, increased the recovery rate to over 90% (Hassan *et al.*, 1991; Schmidt & Ergenzinger, 1992; Laronne & Duncan, 1992). Among the results derived by passive tracer techniques, were the cumulative travel lengths of individual pebbles, the effect of weight, grain size and shape on travel length, as well as transport probability, dispersion of particles, the influence of different hydraulic conditions, initiation of motion and vertical mixing of coarse particles in gravel bed rivers (McEwan *et al.*, 2001).

Besides radioactive tracers, described by Hubbell & Sayre (1964) and Stelczer (1981), especially the radio-tracing technique has been applied with success for monitoring the stochastic nature of bed load transport.

In this paper the active radio-tracer technique is discussed and results of radio tracking gravel particles in the large braided gravel bed river Waimakariri, New Zealand, are presented.

RADIO-TRACER MEASUREMENT TECHNIQUE

In 1989 Ergenzinger *et al.* and Chacho *et al.* independently developed radio tracers of similar size and frequency (150 MHz, Ergenzinger *et al.*, 1989; Chacho *et al.*, 1989; Ergenzinger & Schmidt, 1995). The further developed Austrian radio-tracer equipment consists of eight main parts (Fig. 1).

The radio-transmitter consists of several parts. First, a swinging quartz emits a radio-signal at a frequency of about 150 MHz with an impulse interval of 450 to 600 ms. The transmitter is mounted in a water-proof, shock-resistant cover. Whenever the pebble is turned through 180° about a given axis a mercury switch is triggered (with an accuracy of 11 ms, Fig. 2). For the measurement of an individual pebble with this system a maximum theoretical temporal resolution of about 650 ms can be assumed. Combined with a pulsing time of 13 ms and depending on the battery capacity the life-time of one transmitter lies between 3 and 10 months. Regular transmitters are between 4.5 and 8.0 cm long (related to the battery lengths), which implies a preferred use for coarse gravel material. Newly developed mini-transmitters of cylindrical shape (length and diameter both 1 cm) are available, but have a life of only a few weeks. In general it can be stated that the smaller the transmitter, the shorter the life time and transmission power.

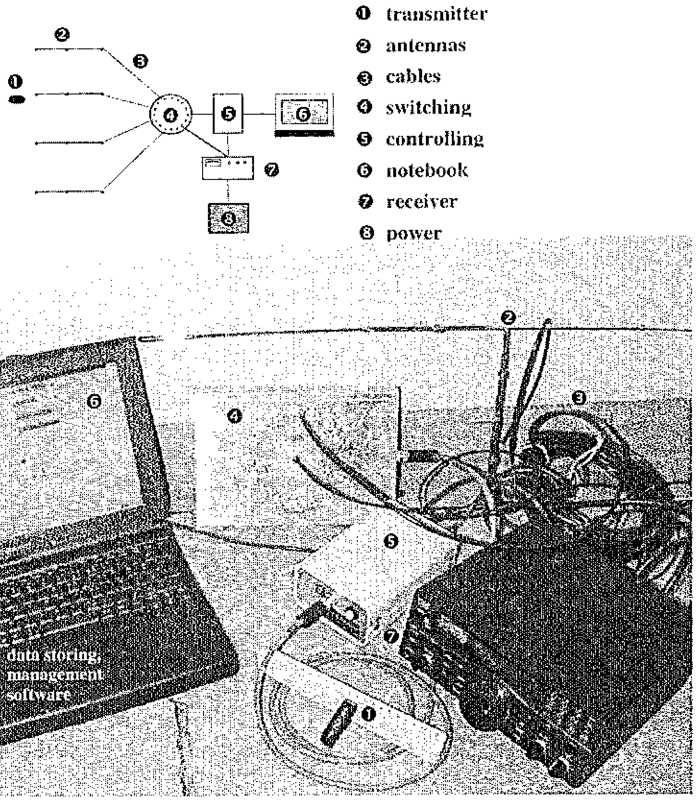


Fig. 1 Radio-tracer equipment, used at the IWHW/Austria.

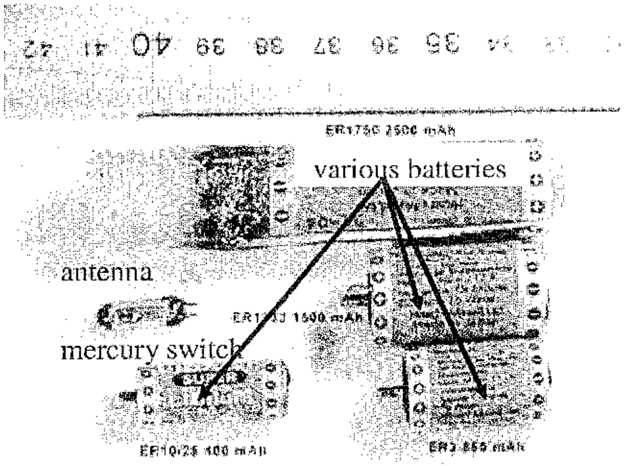


Fig. 2 Components of a radio-transmitter.

Table 1 Data of used transmitters.

Transmitter name	Length (cm)	Mass (g)	Battery capacity (mA h)	Life duration (months)
ER1750	8.0	30.9	2500	10
ER1733	5.6	21.8	1500	6
ER 3S	4.5	14.2	750	3

Table 1 shows the data of typical transmitters being used for field measurements. Life duration represents a permanent use of the transmitter at 13 ms pulse and 450 600 ms pause.

The radio signal emitted by the transmitters, is received first by the antennae, which transfer the signal via cables and the switching box (clockwise scanning of frequencies) to the controlling computer and receiver (the signal from the transmitters has about 1 mW). The Austrian system can use a maximum of 16 antennas, which are sequentially interrogated for the frequencies of the transmitters by a computer controlled switching box.

If several transmitters are used simultaneously the frequencies differ by at least 20 MHz. The system is connected with a notebook PC, whereby the help of special software individual measuring procedures can be defined and the management of the measurements is enabled.

Controlling computer

The controlling computer (Fig. 1) steers the receiver according to the measuring procedure, defined by the software. At this stage the receiver is locked for direct manipulation. Furthermore, the controlling computer transfers the data from the receiver to the notebook for data storage.

Receiver

A generally available radio set, which was constructed for high frequency signals, is employed for the receiver. The signals are visible and audible. A 12 V-battery is used for power supply. All components of the system have to be set in such a way, that the tracer signals are received significantly. Therefore the emitted signal must lie in a defined frequency range as well as show a certain minimum intensity.

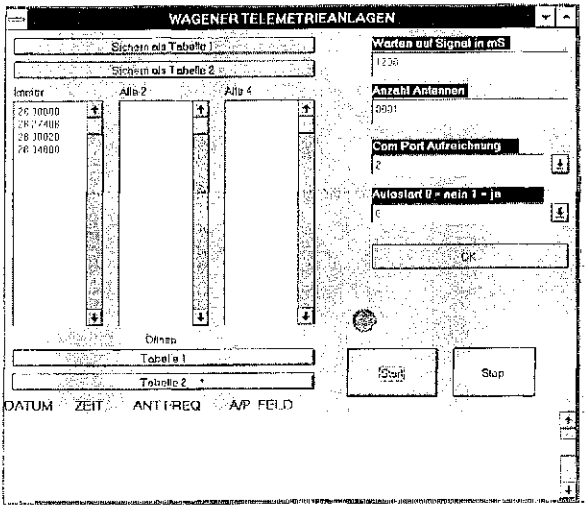
Hand receiver

A hand receiver is necessary in order to locate the transmitter and thereby the tracer pebbles after final deposition at the end of a flood. Special antennas for radio location have to be used together with the hand receiver, allowing an exact definition of the deposition point. Practical tests in New Zealand demonstrated that the tracers can be located already at distances of up to 300 m and at burial depths of over 1.5 m.

Software

The "stone"-controlling software is used for transmitting parameters to the controlling computer and storing the data on the notebook, where the following window is shown after starting the program (Fig. 3).

The user can select the frequencies of the individual transmitters, the number of antennas and the length of pauses between individual pulses (in ms). The data date, time, antenna, frequency, motion or rest = A/P, intensity = FELD, are shown in the lower part of the window.



Warten auf Signal in mS: 1206

Anzahl Antennen: 0001

Com Port Aufzeichnung: 2

Autostart 0 = nein 1 = ja: 0

Fig. 3 Controlling software.

Preparation of natural or artificial radio-pebbles

Basically there are two options for preparing radio-pebbles with respect to the insertion of the transmitter: drilling holes into natural stones; production of artificial pebbles.

Depending on the geology and thus quality of the material, drilling of holes is mostly impossible. The alternative means is to produce artificial pebbles. One way is to use a wooden or plastic model of a natural stone (with a representative diameter and shape factor), fill the model with a synthetic resin and compensate for the lower specific weight of resin as well as that of the transmitter by adding lead spheres (Fig. 4).

After hardening of the recin the stick is removed and replaced by the radio transmitter. Tests in the laboratory and the field demonstrated that the behaviour of the artificial pebbles is similar to natural ones.

Implementation in the field

Along the river course the antennas are mounted at defined positions (known orientation) in order to allow calculation of the path of pebbles during a flood. As the

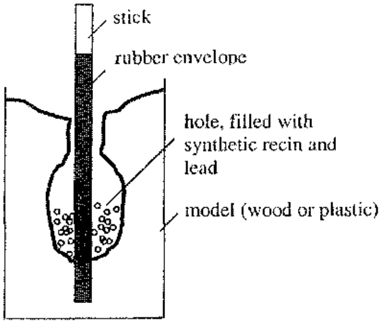


Fig. 4 Scheme of the production of artificial radio-pebbles.

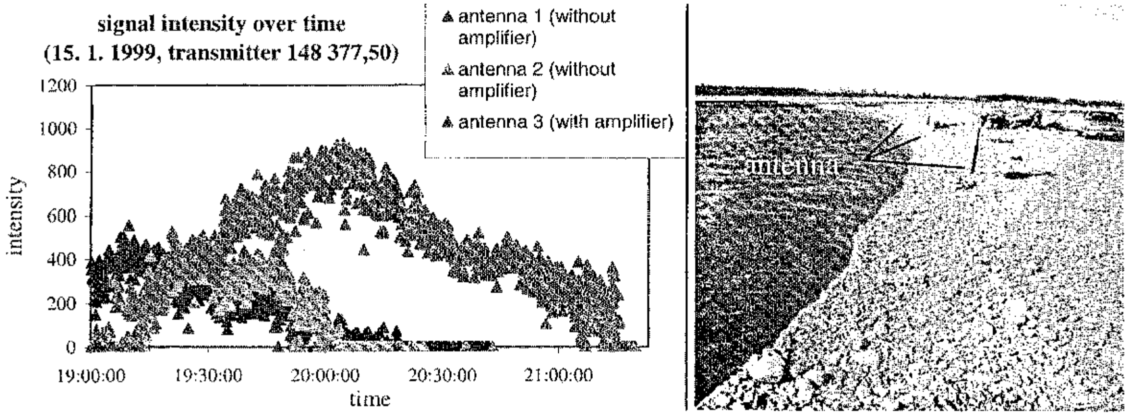


Fig. 5 Raw data of intensity measurements at 15. 1. 1999 for one radio-pebble.

radio transmitter is approaching one antenna the intensity increases until it reaches a maximum value at the closest distance to the antenna. Further transport away from the antenna leads to a reduction of the intensity again until the stone is finally deposited (Fig. 5).

Other approaches for using radio tracers are related to storing the travel information inside the tracer pebble itself (Sear, this volume).

RESULTS OF MEASUREMENTS IN NEW ZEALAND

Between November 1998 and July 1999 the braided Waimakariri River in New Zealand was studied by means of radio-tracking gravel particles during floods, as well as aerial surveys of the planform development. At the study reach the Waimakariri River is about 1000 m wide, has a slope of 0.0038 m m^{-1}, an average discharge of 116 m^3 s^{-1}, a 100-years flood of 4300 m^3 s^{-1} and a subsurface mean grain-diameter of 24 mm. Before we further discuss the results of radio-tracking measurements in New Zealand, a few general comments concerning modelling of bed load transport are made.

In general two different bed load transport modelling approaches exist: deterministic concepts and stochastic concepts.

The first concepts describe processes by using a deterministic approach to investigate the responses of hydraulic systems in terms of various parameters. A system is said to be deterministic if its response at any time due to a given input is uniquely determined. Stochastic concepts describe and analyse processes and phenomena by the methods of probability theory (Habersack, 2000).

The following processes of bed load transport reveal a stochastic nature: initiation of motion; transport path; transport rates; river morphology; sediment budgets and catchment-wide aspects.

The difficulties in making reliable estimates of bed-load transport rates are well known in science and practice. Einstein (1937), was the first to introduce a probabilistic view with respect to sediment transport, obtaining a compound Poisson distribution. Einstein (1937) used a Lagrangian concept as a basis for his transport formula. Step lengths (motion lengths between rests) and rest periods (particles stay deposited until the instantaneous lift force overcomes the particle weight) describe the transport of individual particles.

The mean step length of a bed particle (with average sphericity in a uniformly-sized sediment) should be about 100 grain diameters (Einstein, 1937). This assumption was mainly based on laboratory investigations and field data with high quality were missing. For two test particles sizes in the Waimakariri River in New Zealand, values of 6.7 m or 150 grain-diameters and 6.1 m or 120 grain diameters, were observed. Together with other available large-scale field data a dependence of the mean step length on particle diameter relative to the D_{50} of the bed surface was found (Habersack, 2001). Even minor events lead to a total time of about 2.7 percent of the total duration from erosion to deposition, which cannot be neglected in stochastic transport models. Knowledge of the flow path of pebbles between erosion and deposition sites is essential for the interpretation of morphological changes in relation to bed load transport.

According to Einstein an exponential distribution can be used for modelling rest periods, which has been proven in the laboratory and nature (Stelczer, 1981; Chacho *et al.*, 1989; Ergenzinger *et al.*, 1989; Nakagawa & Tsujimoto, 1980; Shen & Cheong, 1980). The density distribution for rest periods, $f_T(t)$ has the form:

$$f_T(t) = \lambda_2 e^{-\lambda_2 t} \qquad t \geq 0 \tag{1}$$

where t is the time interval, and λ_2, which acts as a scale parameter, is the number of rest periods per time unit [1/minute].

For the Waimakariri River the rest periods are modelled with this exponential distribution with a λ_2 of 0.115, which is the inverse value of the mean rest period (Fig. 5, Habersack, 2001). In this case the assumption of Einstein is valid also for a braided river.

The step periods could not be modelled with an exponential distribution (Stelczer, 1981; Chacho *et al.*, 1989; Ergenzinger *et al.*, 1989) as suggested by Einstein. Instead, a gamma distribution (Fig. 6) had to be applied for modelling the step periods of the Waimakariri River (Habersack, 2001; McEwan *et al.*, 2001). The density distribution for step lengths, $f_X(x)$ is:

$$f_X(x) = \frac{\lambda_1}{\Gamma(r)} (\lambda_1 x)^{r-1} e^{-\lambda_1 x} \tag{2}$$

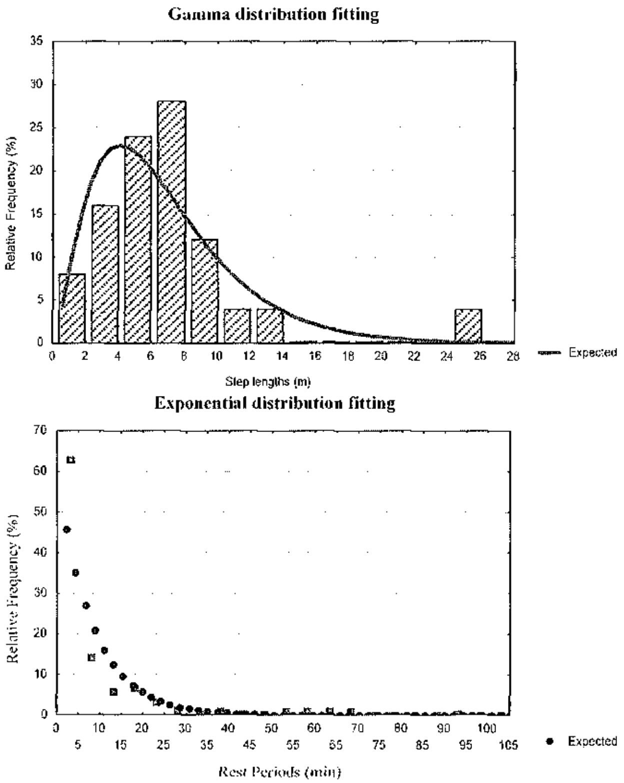


Fig. 6 Modelling of step lengths and rest periods based on measured transport of radio-tracers in the Waimakariri River in New Zealand (modified after Habersack, 2001).

where x is the distance that a particle moves from the origin, λ_1 (the inverse of the mean step length) is a scale parameter [1/metre], Γ is a gamma function, and r is the shape parameter.

Furthermore, Einstein assumed that the probability of a given sediment particle being moved is independent of its previous history, suggesting no relation between step lengths and rest periods. No relation was found between step lengths and rest periods for the Waimakariri River, demonstrating that at least the past rest period does not influence the following step. Based on the work done at the Waimakariri River in New Zealand, the combination of an exponential and gamma-distribution (equation 2) is an improved modelling concept for bed load particles transport in a large braided river as well (Hubbell & Sayre, 1964, Yang & Sayre, 1971), which gives:

$$f_t(x) = \lambda_1 e^{-(\lambda_1 x + \lambda_2 t)} \sum_{n=1}^{\infty} \frac{(\lambda_1 x)^{nr-1}}{\Gamma(nr)} \frac{(\lambda_2 t)^n}{n!} \tag{3}$$

where x is the displacement of the particle from the origin, t is the time taken during this displacement, and n is the number of single step lengths and rest periods. Being able to monitor the detailed way of tracer pebbles from erosion to deposition, the stochastic nature of the interaction between river morphology and bed load transport can be analysed.

CONCLUSIONS AND FUTURE PERSPECTIVES

Over the last decade the radio-tracer technique has been developed in a way that the stochastic behaviour of bed particle transport can be analysed under field conditions even in large braided rivers. This allows the study of transport processes in relation to hydraulic conditions and the interaction with complex morphological developments. Already available data will be used e.g. for the improvement of bed load transport formulae, the analysis of the role of turbulence and pressure differences for initiation of motion as well as the verification of recently developed new concepts for describing bed particle dispersion (Nikora *et al.*, 2002). In future, combining field studies of "Einstein-parameters" and hydraulic as well as morphological boundary conditions will allow the stochastic behaviour of bed load transport to be further investigated.

Concerning the measurement technique itself it has to be mentioned that the use of radio tracers gives mainly additional data (especially due to the Langrangian monitoring approach) to other methods (e.g. basket samplers, traps). So, the transport paths from erosion to deposition are observed. At the moment the transmitters are relatively expensive and only a restricted number of pebbles can be used during one flood in order to get the necessary temporal and spatial resolution. According to recent technological developments significant improvements will be made towards increasing the statistically important higher number of stones and also reducing spatial uncertainties.

In order to derive and verify improved model concepts many more tracer measurements in various environments (different geologies, channel slopes, discharges, shear stresses, etc.) will be necessary. In combination with other techniques like traps or basket samplers, the quality of field data will be improved significantly.

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