Stochastic nature of bedload transport – results from radio-tracking gravel particles

HELMUT M. HABERSACK
Department of Water Management, Hydrology and Hydraulic Engineering
Universitaet fuer Bodenkultur Vienna,
Muthgasse 18, 1190 Vienna, Austria
email: haber@edv2.boku.ac.at

ABSTRACT This paper aims to analyse the stochastic nature of bedload transport on the basis of radio-tracking gravel particles in the field. The Lagrangian technique of radio-tracking offers the opportunity to investigate the stochastic elements of transport from erosion to final deposition after a flood. These results demonstrate 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. Following Einstein´s pioneering work on a probabilistic view of bedload transport field data are analysed and discussed in relation to theoretical considerations and concepts.

Keywords bedload transport, gravel bed rivers, river morphology

INTRODUCTION

In general two different approaches exist concerning bedload transport modelling:

- determinisitic concepts
- 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.

Researchers and practitioners are familiar with the difficulties in making reliable estimates of bed-load transport rates. Since 1873, when Du Boys introduced his bed-load equation, there have been a large number of bed-load equations put forward in the technical literature.

Einstein, 1937, was the first to introduce a probabilistic view with respect to sediment transport, obtaining a compound Poisson distribution. The following processes of bedload transport reveal a stochastic nature:

- initiation of motion
- transport path
- transport rates
- river morphology
- sediment budgets and catchment-wide aspects

Our lack of understanding of some of the basic interactions between flow and moving sediment is, in a large part, due to the difficulty we have had in making reliable observations of the underlying physics. Einstein (1937) assumed that the mean step length of the particles with average sphericity in a uniformly-sized sediment is about 100 grain diameters. At the time few data were available to justify this assumption or provide insight into how it might be improved. Over the succeeding decades numerous investigators have questioned it but even today we have not reached a consensus about how the mean step length depends upon the flow velocity. This uncertainty presents a major obstacle to the development of a bed-load transport equation securely based on the physics of the processes (McEwan et al., 2001).

The uncertainty concerning the parameterisation of the bed-load transport rate equation faced by Einstein can be resolved by employing new technologies to the sediment transport research. In this paper one field technique, active tracers, is discussed. Here the results of radio tracking gravel particles in the large braided gravel bed river Waimakariri in NZ are presented.

TRACER MEASUREMENT TECHNIQUE

The most commonly used bed-load transport measurement techniques (e.g. basket samplers, traps or acoustic methods) are based on the Eulerian measuring concept, where the measurement takes place at a stationary point. In contrast tracer particles are a Lagrangian technique as they examine particle motion along the river course. Einstein (1937) used a Lagrangian concept as a basis for his transport rate formula when he described the motion of individual particles in terms of step lengths (length between consecutive points of deposition made by rolling, sliding or saltation) and rest periods (particles stay deposited until the instantaneous lift force overcomes the particle weight).

Passive tracer techniques have given insight into the cumulative travel lengths of individual particles, the effect of grain size, weight and shape on travel length (e.g. Hassan *et al.*, 1984) and transport probability, the dispersion of particles, the influence of varying hydraulic conditions, the initiation of motion (Ashiq & Bathurst, 1999) and vertical mixing of coarse particles in gravel bed rivers (Hassan & Church, 1993). The first active-tracer technique was the radioactive tracing method (e.g. Hubbell & Sayre, 1964, Stelczer, 1981) but mainly due to environmental concerns and high costs this method is not applied anymore in the field.

Chacho *et al*. (1989) and Ergenzinger *et al*. (1989) independently undertook the first experiments with radio tracers with similar size and frequency (150 MHz, Ergenzinger and Schmidt, 1995). A development of this system has recently been used by an Austrian research group to collect data in Austria and New Zealand.

The basic part of the technique is a radio-transmitter, that is either implanted in a natural or artificial pebble (Fig 1). A swinging quartz, which is mounted in a water-proof, shock-resistant cover, sends a signal of a frequency of about 150 MHz at an impulse interval of 450 to 600 ms. A mercury switch is triggered whenever the pebble is turned through 180° about a given axis (with an accuracy of 11 ms). This means that a maximum theoretical temporal resolution of about 650 ms can be assumed for the measurement of an individual pebble. Based on the described impulse interval and a pulsing time of 13 ms the life-time of one transmitter is between 3 and 10 months, depending on the battery capacity. The length of the regular transmitters varies between 4.5 and 8.0 cm, so that the long lasting transmitters can only be used 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.

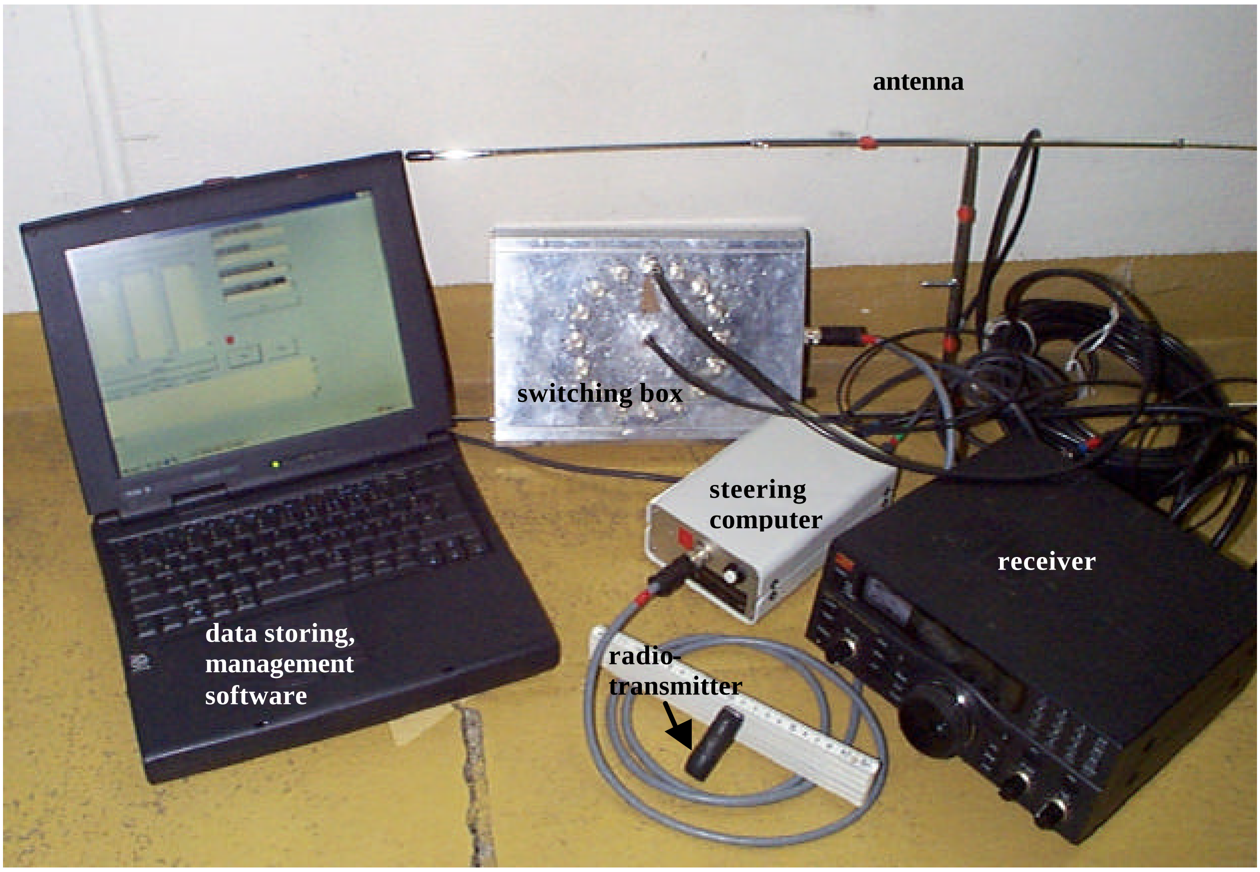

Fig 1. Radio-tracer equipment, used at the IWHW / Austria

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. The signal from the transmitters (~ 1 milliwatt) reaches a receiver (Fig. 1) via the antennae that are positioned along the measuring reach. If several transmitters are used simultaneously the frequencies differ by at least 20 MHz. Software on the computer stores the data and enables management of the measurements.

RESULTS

At the 1 km wide braided section of the Waimakariri river at Crossbanks, New Zealand, the transport path of individual, artificially produced gravel particles, was monitored during various floods of different magnitude. It was found that the rest periods followed an exponential distribution whereas the step lengths were modelled by the use of a gamma distribution with the density function.

In general the results of the work at the Waimakariri River suggest that combining the exponential and gamma-distributions should give an appropriate model for the migration process of bed load particles in a large braided river as well (Habersack, 2001).

Einstein assumed an average travel distance of 100 grain-diameters for any bed-load particle between consecutive points of deposition, but larger values of 6.7 m or 150 grain-diameters and 6.1 m or 120 grain diameters were measured for two test particles sizes. 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). During small floods the time used for movement represents only 2.7 percent of the total time from erosion to deposition. The increase of the percentage of time being used for transport means that it then has to be regarded in stochastic transport models. Tracing the flow path of bed load particles between erosion and deposition sites is a step towards explaining the interactions between sediment transport and river morphology.

Both theoretical and experimental studies in mechanics have not produced data which verify the complete movement of particles in the system. The radio-tracked particle was naturally eroded and transported towards the thalweg (deepest point in a cross section) of the channel. The final location marked the position of the stone after the flood, where it was deposited in an aggraded, extended bar. Similar flow paths were observed from other particles used in the same flood.

The flow path of gravel particles is a composition of invididual steps, interrupted by rest periods. On their way through the fluvial environment particle dispersion takes place.

The *local range* corresponds to ballistic particle trajectories between two successive collisions with the bed (Fig 2). The *intermediate range* corresponds to particle trajectories between two successive rests or periods of repose. The (intermediate) trajectories from this range consist of many local trajectories and may include tens or hundreds of collisions with the bed. The stream-wise component of the straight line connecting the ends of the intermediate particle trajectory is equivalent to the “quick length step” in the Einstein’s (1937, 1942) theory of bedload. The *global range* of scales corresponds to particle trajectories consisting of many intermediate trajectories just as intermediate trajectories consist of many local trajectories. This three-range conceptual model was verified by the analysis of video camera observations in an irrigation canal in NZ (Nikora et al., 2002). In this paper large scale data from the radio tracking of gravel particles in the Waimakariri river will be analysed.

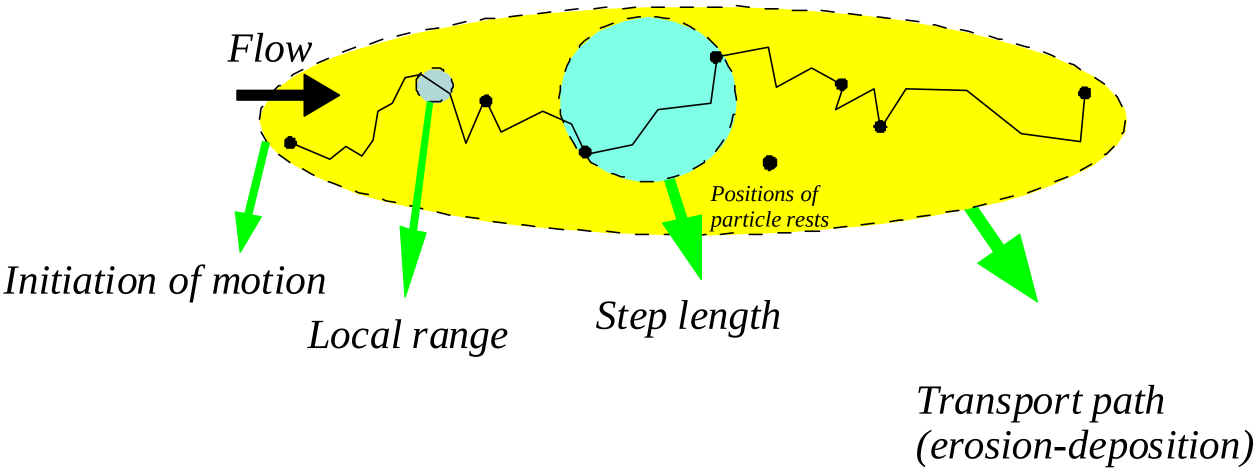

Fig 2. Stochastic elements of bedload transport at various scales (modified after Nikora et al., 2002)

Knowledge of the actual transport path of gravel particles helps us to understand important processes in river morphology at several scales, extending the analysis of stochastic transport components, which was introduced by Einstein. At a point scale we have the interaction between turbulence and initiation of motion. The use of a modified Pitot tube and radio tracers allowed the analysis of the interrelation between turbulence and bed particle erosion for the Waimakariri and demonstrated a significant correlation, which will be analysed in future research. At a local scale we have the stochastic nature of bed load transport. At larger scales, we have the development of bars and other bed forms and the relation between erosion and deposition zones.

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.

REFERENCES

Ashiq, M. & Bathurst, J.C. (1999) Comparison of bed load sampler and tracer data on initiation of motion, *J. of Hydr. Eng.*, 125, 661-664.

Chacho E.F., Burrows R.L. & Emmett W.W. (1989) Detection of Coarse Sediment movement using radiotransmitters, in: *Proceedings XXIII IAHR congress*; 367-373.

Einstein H. A. (1937) The bedload transport as probability problem. *Mitteilung der Versuchsanstalt fuer Wasserbau an der Eidgenössischen Technischen Hochschule.* Zürich; 110.

Ergenzinger P., Schmidt K.H. & Busskamp R. (1989) The Pebble Transmitter System (PETS): First Results of a Technique for Studying coarse Material Erosion, Transport and Deposition. *Zeitschrift für Geomorphologie N.F.* **33**: 503-508.

Ergenzinger P. & Schmidt KH. (1995) Single particle bed load transport: first results from new approaches. *Zeitschrift für Geomorphologie. N.F.*, Suppl. Bd. **100**: 193-203.

Habersack, H.M. (2001) Radio-tracking gravel particles in a large braided river in New Zealand: a field test of the stochastic theory of bed load transport proposed by Einstein, *J. Hydrol. Processes*, 15, 3, 377-391.

Habersack, H.M. & Laronne, J.B. (2001) Bedload texture in an Alpine gravel bed river. *Wat. Resour. Res.*, 37, 12, 3359-3370.

Hassan M. A. & Church M. (1993) Vertical mixing of coarse particles in gravel bed rivers: a kinematic model. *Wat. Resour. Res.* 30(4), 1173-1185.

Hassan, M. A. Schick, A. P. and Laronne, J. B. (1984) The recovery of flood-dispersed coarse sediment particles, in: *Channel Processes – Water, Sediment, Catchment Controls* (ed. by A. P. Schick (Ed.), *Catena supplement* 5, 153-161.

Hubbell D.W. & Sayre W.W. (1964) Sand transport studies with radioactive tracers. *J. of the Hydraulic Division* **90**: 39-68.

McEwan, I.K., Habersack, H.M. & Heald, J.G.C. (2001) Discrete particle modelling and active tracers: new techniques for studying sediment transport as Lagrangian phenomenon. in: *Gravel Bed Rivers V* (ed. by P. Mosley, New Zealand Hydrological Society, Wellington, NZ) 339-360.

Nikora, V., Habersack, H.M., Th. Huber & McEwan, I. (2002) On bed particle diffusion in gravel-bed flows under weak bed-load transport., *Wat. Resour. Res.* (in print).

Stelczer, K. 1981. Bed load transport: theory and practice. *Water Resources Publications*, Littleton, Colorado.