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Short-time relations between runoff and bed load transport in a steep mountain torrent

CHRISTOPH HEGG & DIETER RICKENMANN
Swiss Federal Institute for Forest, Snow and Landscape Research, Zürcherstrasse 111, CH-8903 Birmensdorf, Switzerland

Abstract In the Erlenbach experimental basin in central Switzerland the actual sediment transport has been measured for more than 10 years with so-called hydrophones. These measurements show that the relation between runoff and sediment transport is nonlinear and that its complexity cannot be described by simple sediment transport models. Therefore a new concept, the concept PROBLOAD is proposed. The probable sediment transport is described by a Monte-Carlo simulation based on assumptions on the driving and retaining forces acting on a grain on the bed surface. The concept seems to be able to describe the behaviour of sediment transport in a steep mountain torrent.

INTRODUCTION

Flood events in steep mountain torrents are often accompanied by very high sediment loads. In many cases the damage caused by such events is related to the sediment and mainly its bed load fraction. Therefore it is of great importance to know which processes determine the frequency and magnitude of events with significant bed load transport. To learn more about flood events in mountain torrents and the sediment transport during such events, the Swiss Federal Institute for Forest, Snow and Landscape Research has been operating three experimental basins in the Alptal area in central Switzerland for many years (Burch, 1994). In one of these basins, the Erlenbach catchment, the instrumentation has been designed in such a way as to obtain detailed information on bed load transport.

THE ERLENBACH MOUNTAIN TORRENT

The drainage basin of the Erlenbach stream covers an area of 0.74 km^2, its lowest point is 1110 m a.s.l. and its highest point 1655 m a.s.l. Forty percent of the catchment area is covered with forest and 60% consist of wetlands without forest. The annual precipitation totals are usually around 2300 mm. About 30–40% falls as snow during the period from November to April. During the summer season rainstorms of high intensity occur, which produce the highest runoff events.

The channel of the Erlenbach shows a pronounced step–pool–rifle morphology as described by Hayward (1980). In many steps wooden debris is found. The average grain-size distribution of the surface bed material can be characterized with a d_{90} of 35 cm, a d_{50} of 7.5 cm and a d_{30} of 1.8 cm. Locally important deviations from the average grain-size distribution can be observed.

In 1982 a sediment retention basin and a streamgauge were constructed at the outlet of the Erlenbach catchment (see Fig. 1). The basin allows for the measurement of the accumulated sediment at regular intervals as well as after extreme flood events. In order to measure not only sediment volumes but also transport rates and their relation to stream discharge, a new measuring technique was developed. In 1986 a number of so-called hydrophones was installed in the bottom of the inlet channel to the sediment retention basin (Bänziger & Burch, 1990).

THE HYDROPHONE SENSOR

The core of this sensor is a piezoelectric crystal. This crystal generates a small electrical potential whenever it is deformed. It is fixed to the underside of a steel plate, which is flush-mounted on a transverse structure above the sediment retention basin. In the case of sediment transport, moving gravel particles bump against the steel plate. The plate transmits the shocks to the crystal, which becomes deformed and thus produces an electrical potential. The magnitude of this potential is

Fig. 1 Sediment retention basin in the Erlenbach stream with a streamgauge. The hydrophone sensors to measure bed load transport are installed at the check dam above the retention basin.

measured. Whenever it exceeds a pre-selected value, the shock is recorded as an impulse. Whenever more than six impulses are registered in a minute, the sum of impulses per minute is registered together with the actual water runoff.

Overall nine hydrophone sensors are installed in the cross-section above the sediment retention basin. Experience shows that the sum of impulses registered with hydrophone number 3 (H3), a hydrophone mounted in the middle of the cross-section, can be used as a reliable indicator for total bed load transport (Rickenmann, 1997). 1000 impulses registered correspond approximately to 1 m^3 of sediment. According to field and laboratory tests, the measuring error is of the order of a factor of 1.5–2 when converting the number of impulses into sediment transport rates (Rickenmann *et al.*, 1997). This error is much smaller than the variations of transport rates described in the next chapter.

MEASUREMENT OF INSTANTANEOUS BED LOAD TRANSPORT

A number of bed load transport formulae has been proposed which relate the transport rate to the flow rate and the slope. Some of them are based on hydraulic laboratory tests performed in steep flumes with slopes up to 20% (Rickenmann, 1997). They generally indicate a power law relationship between bed load transport rate (Q_b) and flow rate (Q) above a threshold discharge (Q_a) of the type $Q_b = C\,(Q - Q_a)^b$, where C is a constant and the exponent b may vary form around 1 to 1.5 depending on the study.

Figure 2 shows the data of all sediment transport events registered at the Erlenbach measuring site from 1986 to 1996. The sum of impulses counted per minute by hydrophone H3 is plotted against the corresponding actual runoff. It can be seen that the sediment transport tends to increase with higher runoff. But the relation is nonlinear and the scatter is very high tending to become smaller with increasing runoff.

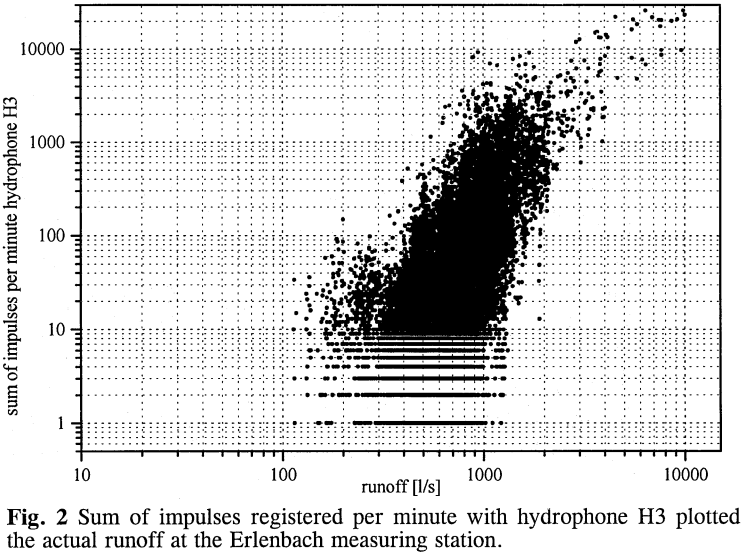

Fig. 2 Sum of impulses registered per minute with hydrophone H3 plotted against the actual runoff at the Erlenbach measuring station.

The relation between runoff and bed load transport in Fig. 2 can be divided into three different ranges. In the first range with a runoff below about 100–200 l s^{-1} there is no bed load transport at all. In the next range from 200 to about 2000 l s^{-1} average bed load transport increases dramatically. The slope of the regression line on a log-log scale is around 4 or 5. Furthermore, the number of runoff events with no bed load transport at all decreases from 95% for a runoff of around 200 l s^{-1} to less than 5% for a runoff between 1000 and 2000 l s^{-1}. The scatter in this second range is very high. For a runoff of 1 m^3 s^{-1}, for example, any bed load transport rate between zero and 10 m^3 min^{-1} has been measured.

Above a runoff of 2000 l s^{-1} the regression line between runoff and bed load transport has a slope around 1 or 1.5 (on a log-log scale), which is much smaller than in the second sector. This slope lies in the same order of magnitude as is known from different experiments in laboratories. The scatter also tends to be much smaller (around one order of magnitude). Nevertheless it must also be kept in mind that compared to the second range only a few data points exist.

In steep mountain torrents the threshold discharge is replaced by a wide transition range (range two in Fig. 2), which links the range of no bed load transport with the range of a power law relationship between runoff and bed load transport. This rather complex behaviour cannot be explained with simple bed load transport models. Different approaches have been proposed to take into account this complexity of bed load transport, e.g. the probabilistic approach of Einstein or proposals to use different critical discharges for different grain sizes (e.g. Julien, 1995). To take into account the extremely high variations in steep mountain torrents, Hegg (1997) proposed the concept PROBLOAD which is briefly explained in the next section.

THE CONCEPT PROBLOAD

With the concept PROBLOAD (PROBLOAD is an abbreviation of probable sediment load) the sediment transport is described based on assumptions about the distributions of the driving and the retaining forces acting on grains on the bed of a mountain torrent. These distributions are described as probability functions and are combined with a Monte-Carlo simulation to calculate actual bed load transport. As a first step, a short uniform channel reach with no sediment input is considered. Thus, the sediment output out of this reach is primarily a result of erosion and deposition processes in the reach.

Schematic examples of assumed probability functions for erosion processes in such a reach are shown in Fig. 3. By comparing stochastic realizations of the function of the retaining forces with realizations of the function of the driving forces, the probability of a grain to be mobilized on the channel bed, can be determined. This factor is called the probability of mobilization. For the two examples shown in Fig. 3 this probability of mobilization is 0.03 for the low and 0.5 for the high runoff event.

To determine the amount of mobilized material per time unit, it is assumed that the volume of a mobilized stone has the same value as the force that retains it on the channel bed. The volume of the mobilized material is then calculated as the sum of

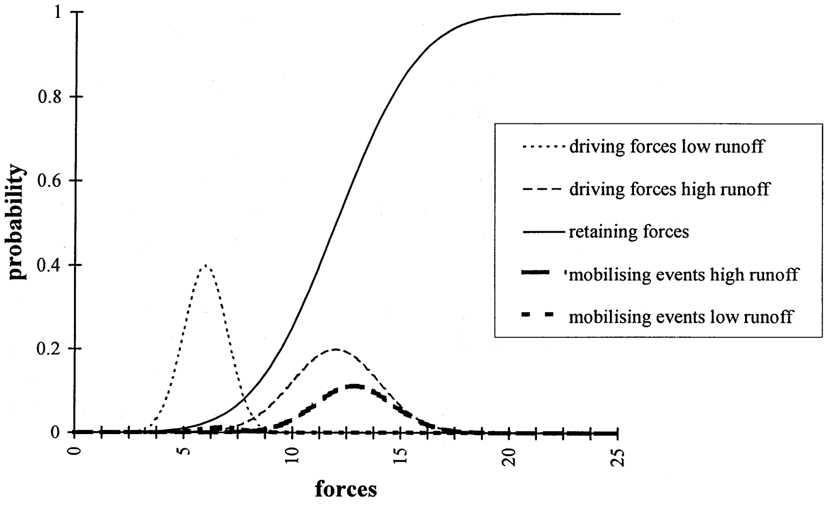

Fig. 3 Assumed distributions of the driving and retaining forces acting on the bed of a short uniform reach of a mountain torrent.

the volumes of the mobilized stones. Because periods of constant runoff are very short during flood events in mountain torrents, short time units are used that contain only 10 mobilizing events.

The amount of mobilized material varies from time unit to time unit even if the runoff stays constant. Therefore the simulated amount of material mobilized in one time unit is called a probable erosion rates (PER). In Fig. 4 histograms of 1000 probable erosion rates are shown which have been determined using the forces described by the probability functions in Fig. 3. For the left histogram the driving forces for low runoff and for the right histogram those for high runoff events have been used. It can clearly be seen that considerable variations in the probable erosion rates can occur with certain combinations of driving and retaining forces.

As mentioned above the probable sediment transport out of the assumed channel reach can be described as the eroded volume minus the volume that is deposited again in the same reach. Therefore probable deposition rates have been determined in a similar way as probable erosion rates. This procedure is described in Hegg (1997). Probable rates of sediment transport (PQ_s) can then be determined as the difference of probable erosions rates minus probable deposition rates.

In Fig. 5 the assumed driving forces for eight different runoff levels are shown. For each of these eight runoff levels 1000 probable rates of sediment transport have been determined in the same way as described above. The result is shown in Fig. 6. In this figure the same three ranges can be identified as has been done for Fig. 2. Range one includes the runoff level 1. There is no sediment transport at all. Range two starts with runoff level 2 and ends between level 5 and 6. In this range a sharp increase in the simulated probable rates of sediment transport accompanied by a very high variation can be observed. Range three includes levels 6 to 8. Increases and variations of the simulated probable rates of sediment transport are much smaller than in range two.

The behaviour of bed load transport with increasing runoff observed in the

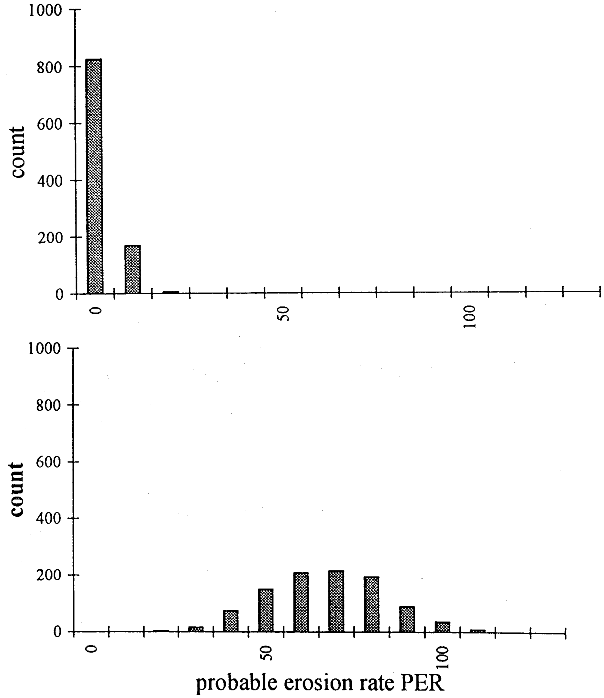

Fig. 4 Histograms for 1000 probable erosion rates (PER) determined using the probability functions for driving and retaining forces shown in Fig. 3 (*top* image low runoff, *bottom* image high runoff)

Erlenbach stream is similar to the one simulated with the concept PROBLOAD. This suggests that an approach similar to this concept can be used to describe the behaviour of sediment transport in a steep mountain torrent.

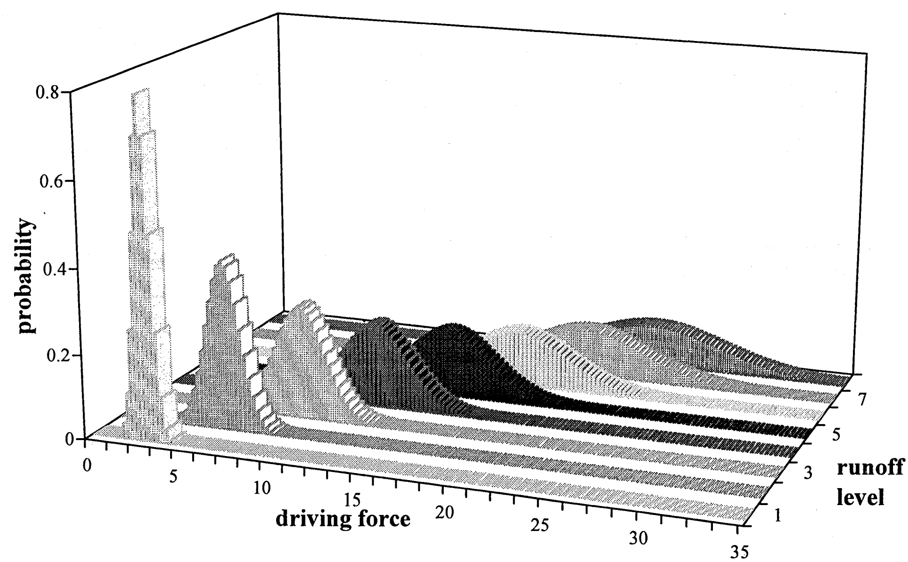

Fig. 5 Probability functions of the driving forces for the eight runoff levels used in Fig. 6.

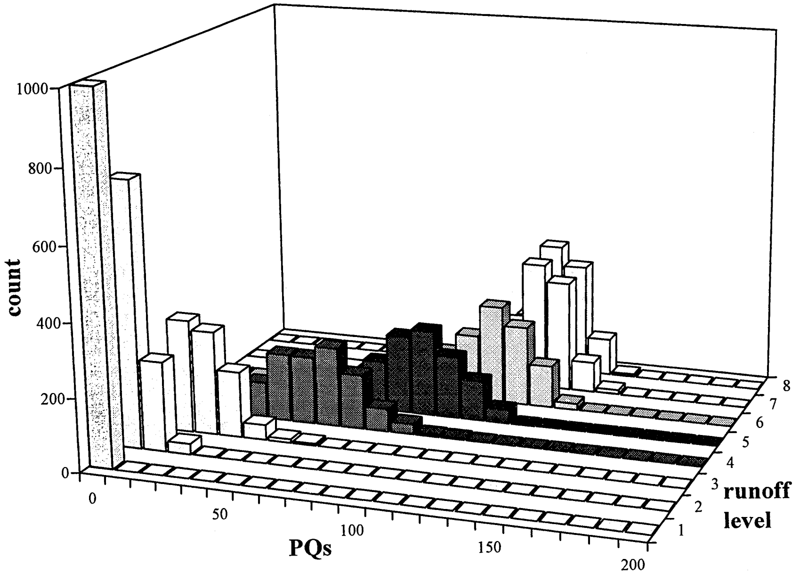

Fig. 6 Histograms of the probable rates of sediment transport (PQ_s)determined for the eight runoff levels in Fig. 5 using the concept PROBLOAD explained in the text.

CONCLUDING REMARKS

In many lab experiments it has been shown, that there is a power law relationship between discharge and sediment transport above a threshold discharge. These experiments are normally carried out in flumes with more or less uniform grain-size distribution. In steep mountain torrents these variations are much higher and therefore the threshold discharge is replaced by a wide range of transition as can be seen in Fig. 2. Such a range of transition can only be reproduced by a model which takes into account the probability of mobilization. This parameter describes the fact that not all grain sizes can be mobilized with the same runoff. One possible approach to do this is the concept PROBLOAD briefly presented in this paper.

Nevertheless up to now PROBLOAD is a theoretical concept which is far from being transferred to practical use. For this purpose a much better insight into the processes of mobilization, transportation and deposition of sediment in a mountain torrent is needed. This can only be done with field observations and laboratory experiments which include the wide variation found under natural conditions.

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