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The nature of coarse material bed load transport

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Abstract The principles governing the conditions for coarse bed load movement have often been questioned. Existing bed load formulae concentrate on the hydraulic conditions necessary to initiate pebble motion, but research carried out in the Buonamico basin in southern Italy and in Squaw Creek, Montana, USA, indicates that bed load transport is more complicated. The hydraulic conditions are of paramount importance, but other factors such as sediment supply and channel form changes have to be examined to comprehend the specific wave-like movement of bed load during a flood wave. These aspects are complicated further by apparent changes in the types of waves of bed load transport. Channel geometry has been studied in order to ascertain whether or not the passage of waves of bed load material can be directly measured. Changes in the channel form can be attributed to the passage of such waves through the channel systems and they also correspond well to the varying hydraulic conditions that influence the removal of storage of material within the reach. It is therefore important that bed load transport equations should be questioned by devising a continuous recording technique for bed load transport with simultaneous investigations of changes of channel geometry, sediment supply and types of bed load movement.

Nature du transport par charriage de fond des matériaux grossiers

Résumé Il y a une longue tradition de recherches sur les principes et les conditions de transport des matériaux grossiers charriés. Les fonctions disponibles décrivant le transport au fond des fleuves sont restreintes aux conditions hydrauliques nécessaires pour provoquer le mouvement de galets et ne sont valables que dans des cas particuliers. Toutefois, des recherches au bassin de Buonamico en Italie du sud ainsi que dans le bassin de Squaw Creek au Montana (Etats Unis) ont montré que le transport de matériaux charriés est beaucoup plus complexe. Pour comprendre le mouvement spécifique en onde, des matériaux grossiers pendant les crues il faut d'abord connaître les conditions hydrauliques mais aussi la source des matériaux et les conditions géomorphologiques des fonds de vallée. En outre, il faut tenir compte de complications concernant des changements de types de transport en onde des matériaux solides. Afin de connaître s'il y a une méthode directe de mésurer le mouvement en onde de matériaux grossiers au fond des fleuves nous avons étudié la géométrie des chénaux. Les changements de forme des chénaux sont liés au passage de dunes de matériaux grossiers et en même temps aux conditions hydrauliques variables qui commandent l'érosion ou l'accumulation dans la partie concernée du fleuve. Il en résulte qu'avant d'utiliser une fonction pour décrire le transport de matière solide il faut avoir une série d'observations des changements de la forme du lit et des investigations spéciales concernant les différents types de transport en onde de matériaux solides.

INTRODUCTION

Measurements of coarse grain bed load transport and the sediment budgets of basins with a high output of coarse bed load have always been hampered by several factors. First, transport is highly unsteady, and there is no direct relationship between hydraulics and sediment supply. Secondly, there is a lack of suitable measuring devices. Thirdly, the existing descriptions of the processes by bed load functions are inconsistent and work only for special cases of transport with sufficient material supply. Some of these problems have been reviewed by Klingeman & Emmett (1982). In order to deduce the principles of bed load transport, some results of investigations in the Buonamico basin in southern Italy and in Squaw Creek, Montana, USA, concerning the unsteady nature of transport and river bed adjustments and the importance of wavelike and carpetlike bed load transport conditions will be presented.

MEASURING TECHNIQUES FOR COARSE MATERIAL BED LOAD

The unsteady and unstable nature of the bed load transport of material coarser than sand requires measuring techniques which provide a continuous record of the movement. The vortex tube bed load sampler developed by Klingeman & Milhous (1970) and installed at Oak Creek in Oregon in 1970 was the first instrument with such a record. In Europe a similar system was installed by Tacconi & Billi (1987) at Virginio Creek in the Chianti hills south of Florence. Leopold & Emmett (1976) developed a conveyor-belt bed load sampler at the East Fork River in Wyoming. Klingeman *et al.* (1987) reported that there have been only four vortex type samplers operating worldwide. This accounts for the paucity of data on the variation of bed load transport. The reason for this situation is the expense involved in constructing these installations.

In 1981 the first continuous records of bed load transport were obtained by the magnetic tracer technique (Ergenzinger & Conrady, 1982). According to the Faraday principle, the naturally magnetic volcanic pebbles and cobbles of Squaw Creek create a low voltage whenever they cross a coil system with a certain velocity. These signals can be amplified and counted electronically and depict with great reliability the different transport situations. Since not all coarse material can create magnetic signals, the method is restricted to material with a high content of magnetite. Therefore it is a natural tracer technique. To calculate total transport, further assumptions (Ergenzinger & Custer, 1983a) must be made and more sampling undertaken. Similar measurements with artificial magnetic pebbles have been made by Reid *et al.* (1985) and by Hassan *et al.* (1984). In contrast to the vortex samplers, the installation costs of these systems are relatively low. The most suitable sites for this technique are basins with some naturally magnetic material.

The unsteady nature of bed load transport was emphasized by the results from all installations with continuous records. Reid *et al.* (1985) report pulses with a period of 1.7 h from Turkey brook, Tacconi & Billi (1987) obtained pulses with a period of about 30 minutes. During experiments in a special flume Hubbell *et al.* (1987) observed similar short period pulses and related them to the movement of bedforms. To increase understanding and to improve theories of bed load transport, more reliable reports of different transport situations are urgently required.

UNSTEADY AND UNSTABLE BED LOAD TRANSPORT

There has been a remarkable change in the perception of unsteady and unstable transport conditions of bed load transport. Ehrenberger (1931) and Mühlhofer (1933) observed the unsteadiness of transport over time and the unstable spatial pattern and presented them in convincing diagrams. But during the following decades these empirical observations of natural bed load movement were replaced by the deduction of bed load functions based on flume experiments. Due to the impact of the work of Meyer-Peter & Müller (1948) and Einstein (1950) the unsteadiness of transport phenomena received very little attention (except by de Vries (1962) and Hamamori (1962)). As long as there was the conviction that bed load transport could be deduced from a suitable combination of hydraulic parameters alone, all factors which put this assumption in question were disregarded. Under these circumstances the valuable three-dimensional diagram of Mühlhofer's measurements of bed load transport in the River Inn has never been published in a textbook.

Observations of the unsteadiness of transport phenomena have multiplied during the last decade. At first this has had only some impact on the definition of good sampling procedures for bed load trapping (Emmett, 1980). In the case of sand transport, the phenomena of unsteady transport were linked to the transport of dunes. Since no comparable bedforms were observed in coarse material, the interpretation of the related fluctuations during transport is difficult. Hubbell *et al.* (1987) observed these fluctuations with a period of about 10 minutes in flume experiments, where they were caused by the transit of dune-like pebble concentrations. Both Jackson & Beschta (1982) and Reid & Frostick (1984) report variations of bed load transport during flood waves. In each case there were two peaks of transport. The first peak occurred during the rise of the hydrograph, and the secondary peak during the recession of the flood. In between there were several hours of low transport. Jackson & Beschta (1982) interpet this phenomenon as due to special conditions of transport through a riffle and pool system.

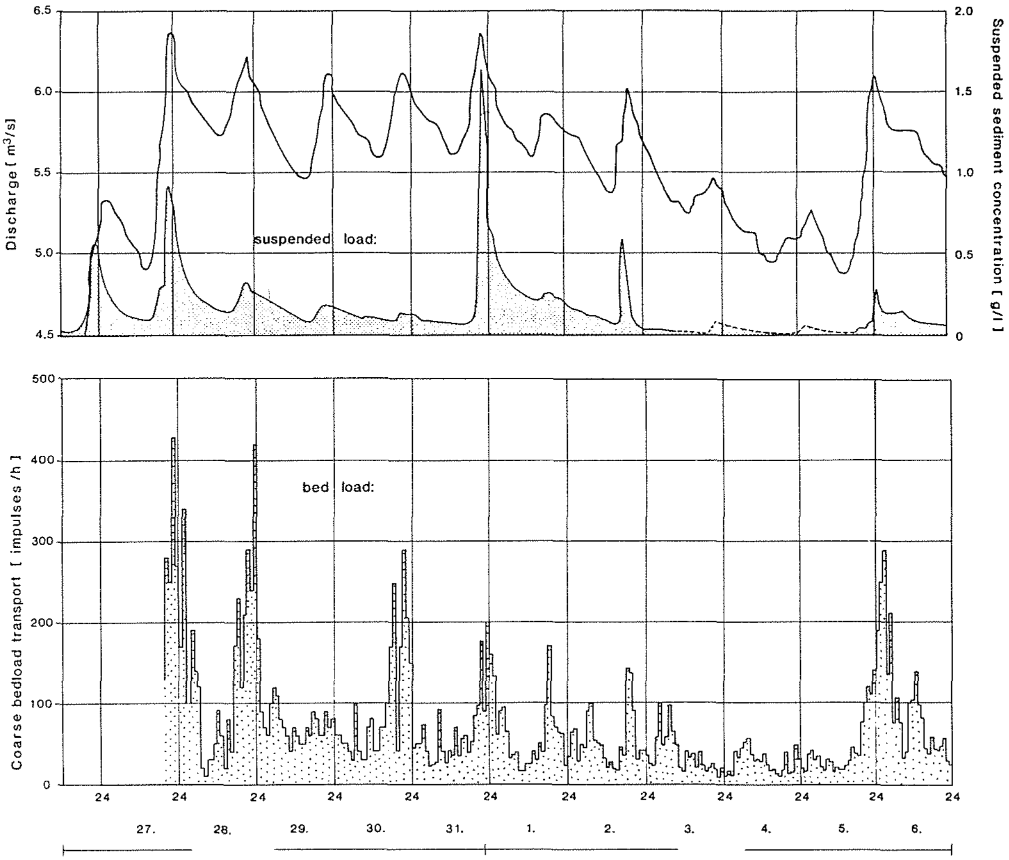

Fig. 1 Squaw Creek: discharge, suspended sediment concentration and coarse bed load transport in May/June 1986.

At Squaw Creek in Montana waves of bed load transport were measured during several periods with snowmelt runoff. The dataset for May–June 1986 (Fig. 1) was discussed in Bunte *et al.* (1987). The runoff conditions remained very similar over several days. Snowmelt created small daily floodwaves which passed the observation point during the hours before midnight. During the rise of the hydrograph the amount of transported pebbles and cobbles also increased. Close to peak discharge the amount of transported material diminished. The time of low transport could last several hours, but during the fall of water stage there were always secondary waves of transport (e.g.

the situation on 2–3 June in Fig. 1). The time interval between these waves of transport is about 6 to 7 h. The unsteady transport conditions are due either to the hydraulic conditions or to insufficient sediment supply. To rule out the impact of macroturbulence, in May 1988 during similar floods, the short period changes in velocity were measured continuously in two dimensions at two points in the cross section by two electromagnetic velocity meters. During all the days with small floodwaves no macroturbulence with sudden changes of velocity occurred. During the floods, the velocity increased appreciably, especially during the first phases of rise, but close to peak runoff there were only minor changes in velocity, due to small thalweg changes. These measurements and the related observations of changes in the surface waves of the water underpin the supposition that the supply and availability of material exert an important impact on bed load transport during minor floodwaves.

In May 1981 a flood with a recurrence interval of about 16 years occurred at Squaw Creek. The resulting bed load transport was reported by Ergenzinger & Custer (1983b). As shown in Fig. 2, except for a small drop in transport just after the major peak the transport situation was more similar to the situation predicted according to the Meyer-Peter & Müller formula. This flood eroded the channel bottom and the carpet transport across the whole channel bottom by far exceeded the amount of bed load transported in the following years. Afterwards it took more than three months to re-establish an armoured channel bottom and during the whole time there was always a

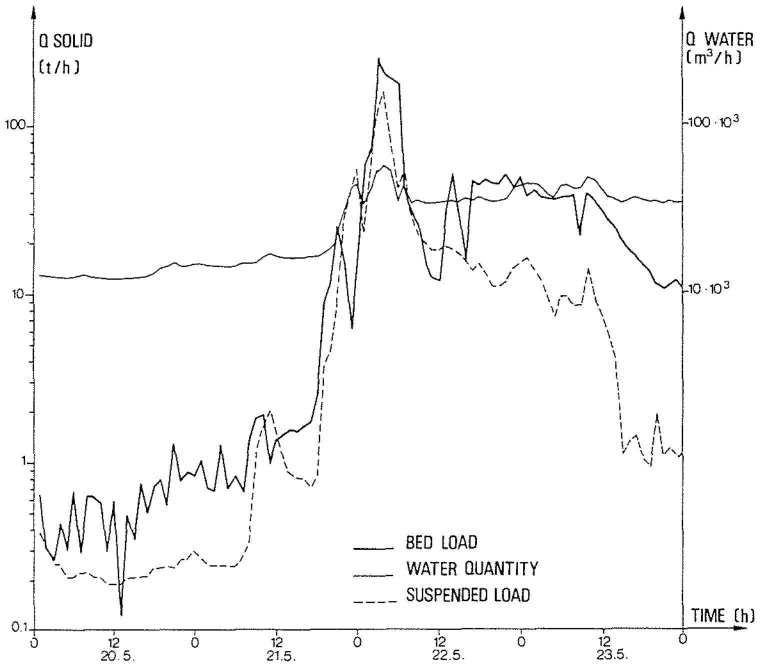

Fig. 2 The hourly solid material load of Squaw Creek, 20–23 May 1981.

certain amount of bed load transport, even during summer periods with very low discharge. As during the minor floodwaves there was again a close relationship between bed load transport and channel adjustment.

COARSE SEDIMENT SUPPLY AND CHANNEL ADJUSTMENT

At Squaw Creek the main sources of coarse material are:

- talus material,
- coarse material transported by snow avalanches,
- the fans of tributary streams,
- terrace material mobilized by bank erosion,
- mobilized channel bottom material.

These sources are not evenly distributed within the basin. Most talus material is situated in the canyon along the lowermost part of the basin and the avalanches are typical only in the uppermost part and at two spots in the lowermost area of Squaw Creek. The impact of fan material is also only of minor importance. Most of the coarse fluvial sediment is supplied by bank erosion in the middle part of the basin. This is the reason for the widespread occurrence of braided channels in the middle basin just above the canyon. Most of the eroded material is deposited in the middle part of the river system and in the lowermost part of the canyon above the measuring site.

During minor flood waves the entire river bottom is never eroded. At these stages the bottom adjustment to runoff is restricted to a narrow zone close to the thalweg and to small areas where there is either erosion or accretion of bars. The major waves of material transport during the small snowmelt floodwaves are created by the adjustment of the river bottom to the fluctuations of discharge. Each change in the bottom geometry induces a response in bed load transport. These changes are rather rapid events. Often it took only about 20 minutes to enlarge the main channel to a suitable size and afterwards there were only minor refinements of channel size. During the erosion of the channel the main waves of bed load were monitored. Afterwards there was just random transport interrupted by some minor waves. As regards transport conditions during small flood waves at Squaw Creek, it is obvious that the material transport must be described in terms of its relationship with channel bottom adjustment and not in terms of the bed load functions which are suitable only for periods with erosion and transport over the whole channel bottom.

SOME PRINCIPLES OF BED LOAD TRANSPORT

Coarse material bed load transport is unsteady in time and unstable in pattern. As is shown by the scattering of the dots in Fig. 3, there is no distinct threshold for the onset of transport, and the variability of transport during times with high discharges is remarkable. If the scale of observation time is as short as five minutes there are waves of transported material with very different amplitudes and durations (Fig. 4).

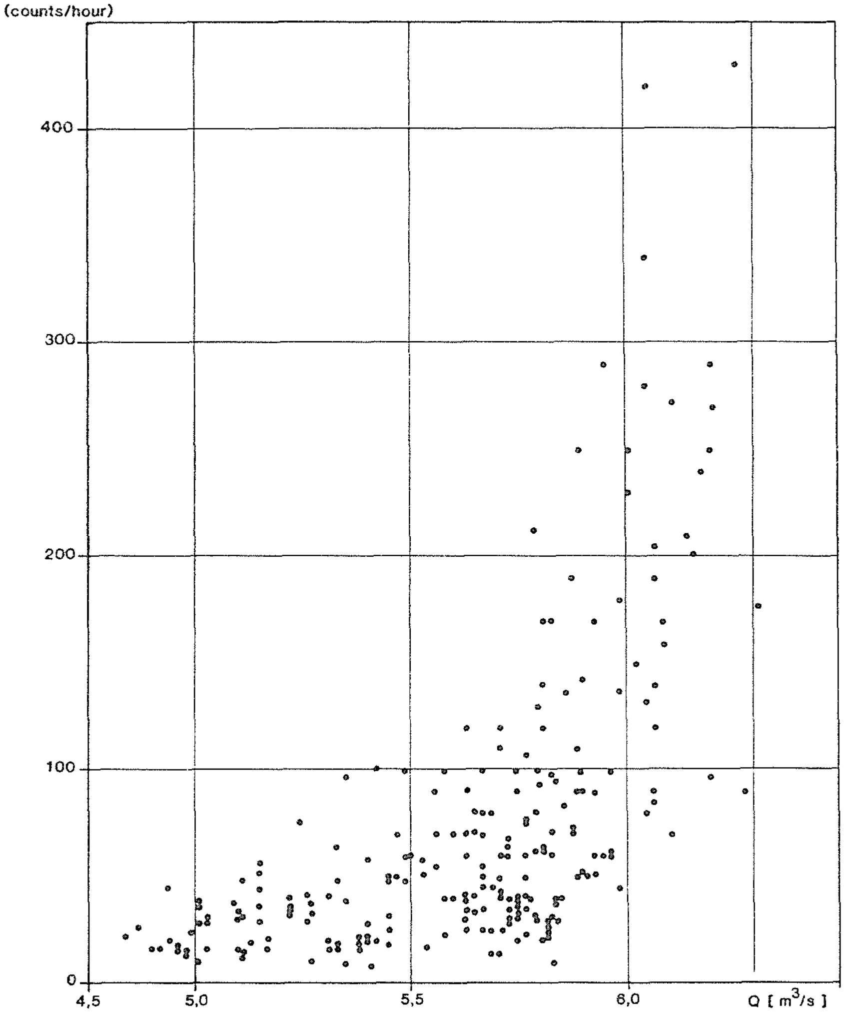

Fig. 3 Squaw Creek, 31 May–7 June 1986. Discharge and hourly counts of bed load.

The changes of bed load transport during time intervals of 10 or 20 minutes are related to the transit of bedforms. As was emphasized by Hubbell *et al.* (1987), the minor forms of dunes in coarse material channels must be investigated. This form of material transport is especially important during the initial phase of bed load transport. As long as there is no bottomwide transport, the bed load transport is often restricted to these small waves. The travel velocity of these waves depends on dune geometry, coarseness of material and water velocity.

Related to the transit of small flood waves, there are often waves of material transport with time intervals of several hours (Fig. 2). In most cases these waves are related to the rise of the hydrograph. At Squaw Creek, this phase often has not only one, but several waves of material transport

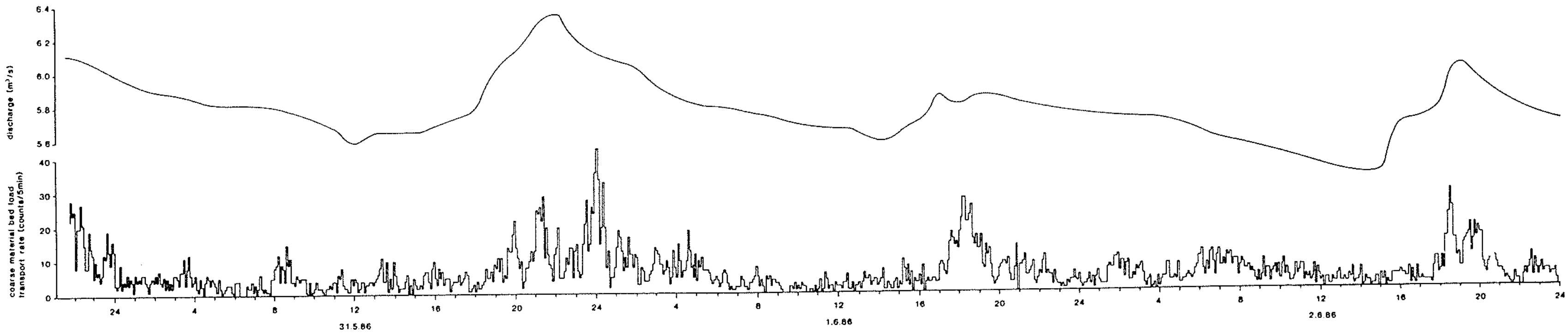

Fig. 4 Short-term fluctuations (5 minute interval) of coarse material bed load transport in Squaw Creek.

(compare 30 to 31 May and 31 May to 1 June in Fig. 1). As the detailed observations in 1988 show, these fluctuations are caused by the adjustment of the channel to the changes in discharge. This is the reason why similar waves of material transport can also occur during the recession of water discharge (compare the situation during the night from 2 to 3 June). From investigations of river channel adjustment of braided systems in Calabria, Ergenzinger (1988) deduced that there is a strong tendency to obtain critical channel dimensions and critical runoff conditions even during the discharge of floodwaves. By this rule, channel bottom changes depending on changes in discharge can be predicted. When these changes are known, the related amount of material to be transported can be estimated. Since there is a paucity of material available to be transported under these low flood conditions, the figures derived from bed load transport functions suitable for coarse material are often too high.

High transport rates during major flood events are related to the erosion of the channel bottom, the destruction of the armoured layer and a related sheet- or carpet-like bed load transport. For this condition the availability of bed load material is irrelevant, and existing bed load transport functions, such as the Meyer-Peter equation may be applied.

Coarse material transport is complicated. The exclusive importance of the relationship between hydraulic conditions and the rate of material transport must be questioned. The supply of suitable material and the influence of river channel adjustment can be equally important. A greater number of continuous observations of bed load transport are necessary.

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