Variability in Stream Erosion and Sediment Transport (Proceedings of the Canberra Symposium, December 1994). IAHS Publ. no. 224, 1994.

Interpreting the temporal and spatial dynamics of bed load transport phases according to FAST (Fluid and Sediment Transfer Model)

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Abstract High resolution measurements on the temporal and spatial variability of bed load transport reveal that phases with intermittent bed load transport are characteristic of bed load waves, whereas phases with intensive bed load transport occur as a more or less continuous carpet-like layer of particles. According to our measurements of snow-melt floods at Squaw Creek in Montana these differences in bed load transport correspond with quite distinctive hydraulic phases. A magnetic bed load sensing system with two magnetically sensitive sills enables the detection of naturally magnetic material down to hecto-second intervals. When bed load transport is of a pulsed, wave-like nature there is a strong tendency for the development of vortex flow, whereas intensive bed load transfer corresponds with a far more turbulent chaotic two-layered flow. This situation is of major importance not only for sediment erosion and transfer but also for the dynamics of the river bed geometry. Bed load and river bed measurements form the conceptual basis for a new model approach (FAST) that interrelates the dynamics of particle transport with the dynamics of flow and river bed adjustment.

INTRODUCTION

This study examines bed load transport interactions with flow hydraulics and river bed adjustment at the smallest temporal and spatial scales possible. It focuses on different phases of sediment transport based on the dynamics of single particle transport over a short, carefully monitored measuring reach using a recently developed electronic measuring system. An understanding of the irregular nature of bed load transport can only be obtained if water surface gradients, river bed adjustment and roughness conditions are to be interrelated (Ergenzinger *et al.*, 1994). Therefore, the aims are to interpret the spatial and temporal dynamics of bed load transport according to the conceptual FAST (Fluid and Sediment Transport) model.

Documentation of the unsteady nature of bed load transport at 5-10 minute measurement intervals has existed for a long time (Ehrenberger, 1931; Nesper, 1937; Schoklitsch, 1938). The wave-like fluctuations of these transport phenomena have been attributed to the migration of bedforms (see also Church, 1985; Gomez *et al.*, 1989; Hubbell, 1987). As in studies by de Vries (1965) and Hamamori (1962) the investigations are confined to sand beds and document dune migration. In contrast, the investigations at Squaw Creek encompass a coarse-grained, high gradient environment and suggest different interpretations.

STUDY AREA

Squaw Creek basin has an area of 105.7 km^2. It is situated at the foot of the Rockies just above the confluence of the Gallatin River in Montana (Ergenzinger & Custer, 1983). Annual precipitation is 457 mm in rain and 356 mm in snow. Average flood flows at the study site have a magnitude of approximately 6.8 m^3 s^{-1} and are the result of predictable snow-melt, usually occurring between May to early July. The D_{50} of the surface and subsurface of the main bar at the study site is 34 and 56 mm respectively (Ergenzinger & Custer, 1983). The straight study reach has a gradient of 0.02.

METHODOLOGY

Bed load was measured electronically down to sub-second frequency during flood flows. Two magnetically sensitive sills were inserted across the entire width of the river bed and situated 30 m apart from each other. Detailed descriptions of the method can be obtained from Ergenzinger *et al.* (1993). Pulses created by naturally magnetic particles passing over the sills were transferred and recorded on computer. The lower size class detected lies around 15 mm and approximately 70% of the material at the site is magnetic. Incoming and outgoing particles could be monitored over the 30 m and divided precisely into channel, interface and bar.

Temporal and spatial changes of roughness and geometry were measured using the macro-Tausendfüssler device (Ergenzinger, 1992; De Jong, 1992). It probes the river bed at 10 cm intervals from a fixed horizontal reference level. Roughness was determined according to the K_3 roughness parameter (Ergenzinger & Stüve, 1989; De Jong, 1993).

The nature of the water surface topography and development of surface waves was determined by probing the water surface from the Tausendfüssler device at 50 cm intervals (De Jong, 1993). Average water velocity measurements were also obtained. Water surface gradients were monitored manually at 1-2 h intervals over the 30 m reach from water hoses inserted along the right and left channel edges (Bunte, 1992).

RESULTS

Nature of flood event

The flood of 5-6 June 1991 shows that the transfer of bed load does not occur continuously at Squaw Creek. Instead, bed load pulses both in the spatial and temporal dimension (Ergenzinger *et al.*, 1993; Ergenzinger *et al.*, 1994; De Jong, 1993). Phases with intensive bed load transport do not correspond with the equivalent magnitude in discharge, such as between 4:00 and 7:00 (Fig. 1). In addition, phases with low intensity bed load transport often occur during higher discharges (as at 24:00). At the beginning

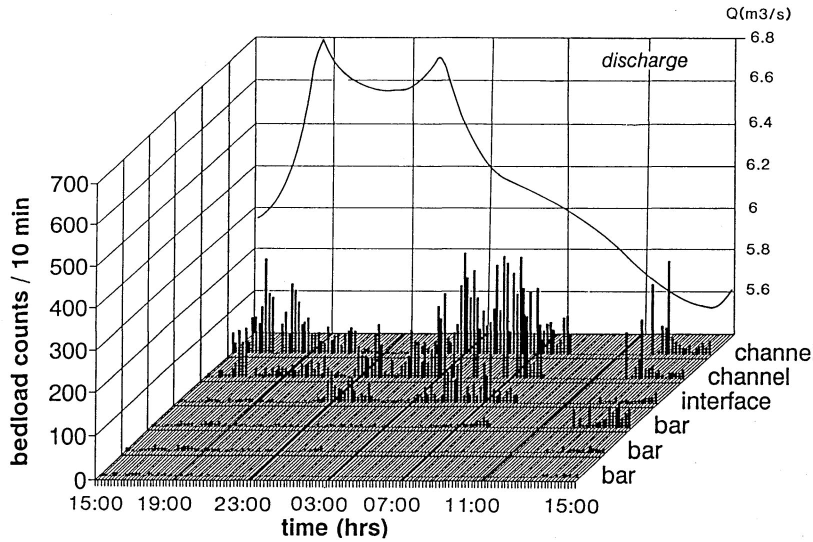

Fig. 1 Bed load transport over upper sill at Squaw Creek, 5-6 June 1991. The sill was spatially subdivided into channel, interface and bar. Notice that the largest pulses occurred both during the ascending and descending flood limbs.

of the flood, bed load transport occurs most intensively in the channel. From approximately 23:00 to 09:00 there is a shift in intensity towards the bar and interface.

Interactions of bed load transport with roughness and flow hydraulics

Bed load transport relates closely with the dynamics of the river bed and flow hydraulics, reconstructed from the water surface topography. Thus in Fig. 2, the total balance in bed load, calculated from the input and output of particles from the upper and lower sills respectively, serves as a guide to phases of erosion and deposition. The K_3 roughness coefficient reflects the state of the river bed during different phases of the flood in relation to the gradient of the right and left water surface gradients. The diagram illustrates that during phases with intensive bed load transfer, causing major erosion during the ascending flood limb, roughness values are lowered and both the right and left water level gradients rise parallel to each other. During the phase with negligible bed load, roughness is high but the gradients of the water levels begin to rise steeply. In response, another major pulse of bed load material that is transferred over the upper sill becomes deposited in the region between the detector sills, most of which does not exit over the lower sill. As deposition starts during the bed load transfer, roughness values drop but water levels become stable again. After maximum deposition, roughness begins to rise to high levels. Water level gradients drop sharply and cross each other, accompanied by a transfer into a phase with erosion and major river bed adjustment. Immediately after the onset of erosion, water level gradients again increase to their former levels and roughness adjusts to its former state. Similar observations of deposition occurring between bed load pulses and during the descending flood limb have been observed by Jackson & Beshta (1982).

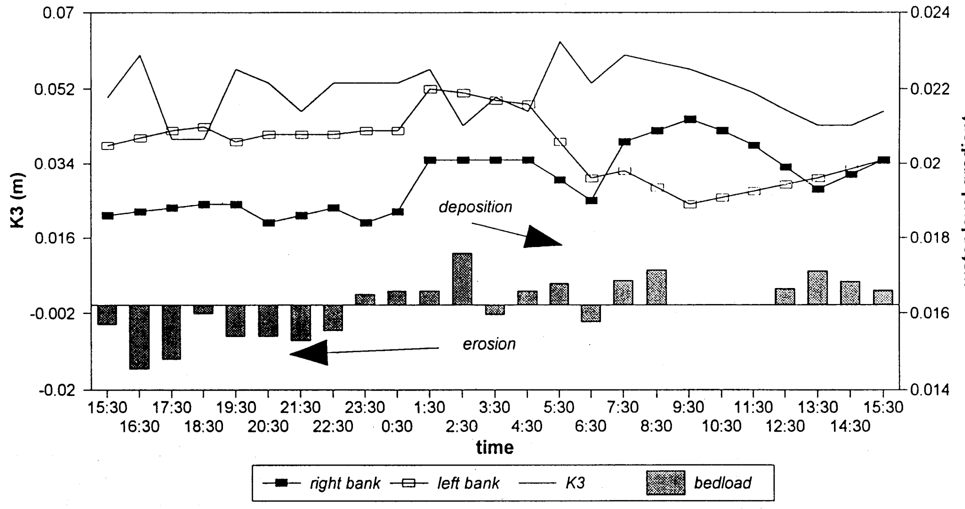

Fig. 2 K_3 roughness coefficient plotted against right and left water surface gradients and bed load balance (difference between total input and output of particle counts) at Squaw Creek for flood of 5-6 June 1991.

This supports the fact that bed load transport and the associated adjustment of the river bed and flow hydraulics occurs as a complex interactive process which can be subdivided into discrete phases. Thus during phases of intensive bed load transport, roughness decreases, mainly to enable efficient bed load transfer (Ergenzinger *et al.*, 1993) and the water surface topography is in a "chaotic" turbulent state. During the phases with negligible bed load transport, roughness becomes very pronounced and the water surface becomes organized into regularly structured secondary flow cells (Ergenzinger *et al.*, 1994). Phases of regulated three-dimensional flow cell development have been documented elsewhere in association with high roughness values (Nezu & Nakagawa, 1993). Even though the higher roughness areas reported consist of sand ridges and not of coarse cobbles, as at Squaw Creek, the inferred direction of flow cell circulation is similar to that observed and measured in nature. This relates to the phases with low bed load transport or restricted local bed load transport streets.

Flow cell development

Figure 3 illustrates a theoretical explanation for flow cell development (Ergenzinger *et al.*, 1994; De Jong, 1993). Einstein & Li (1958), Leopold (1982) and Bhowmik (1982), amongst others, also support the evidence that secondary currents can develop in straight reaches. As in Nezu & Nakagawa (1993), flow cells at Squaw Creek are attributed to a divergence of flow over large roughness areas on the river bed and convergence at the water surface. In contrast, the adjacent low roughness areas will experience a convergence of flow and a divergence at the water surface. An explanation for the formation of flow cells in relation to bed load transport is still lacking in the literature. As envisaged in nature, flume experiments show that bed load transport is concentrated into intermittent streets of high bed load transport between the high roughness areas. To

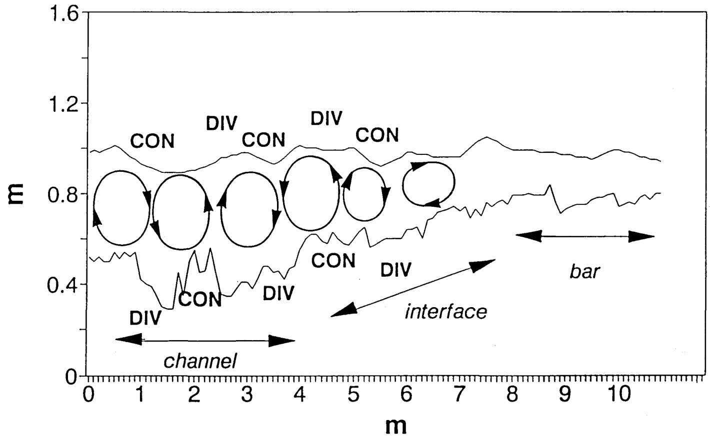

Fig. 3 Development of flow cells. Water converges over large roughness areas on the river bed, resulting in divergence at the surface. The opposite is true for the adjacent low roughness areas. Alternating areas of convergence and divergence enable the localized transport of bed load in "streets".

understand the temporal interactions of flow and bed load, interpretations cannot be limited to one lateral transect but must take into account detailed spatial variations of bed load. At Squaw Creek the sophisticated measuring device allows the precise monitoring of the erratic and discontinuous process of incoming and outgoing bed load transport, so that flow cell development can be followed closely.

Flow cells are not fixed in space but fluctuate three-dimensionally according to the given flow depth and the local development of roughness. Over the shallow bars, flow cells can only develop when flow depths are higher than 30 cm, thus during peak discharge and during the phases with low bed load transport intensity. In turn, flow cells

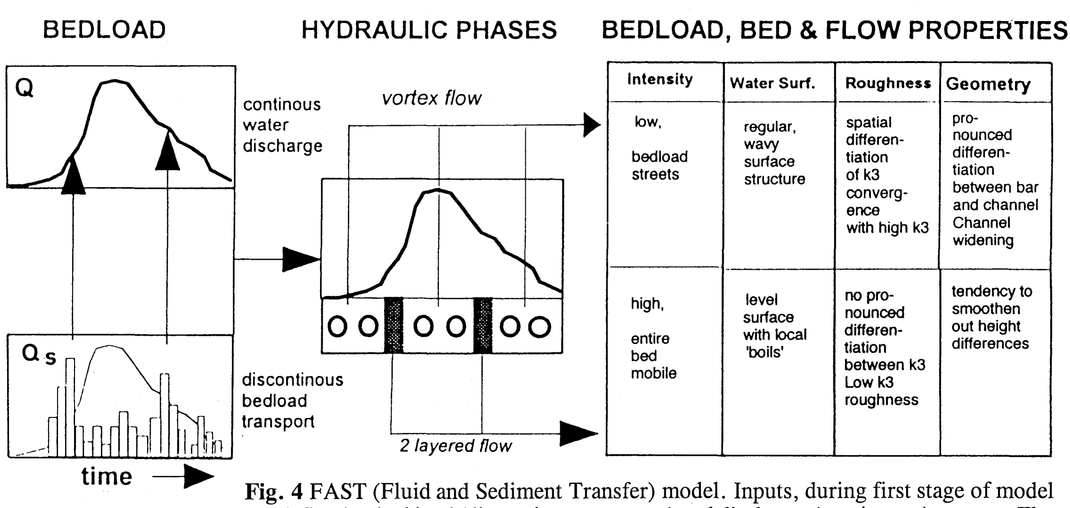

Fig. 4 FAST (Fluid and Sediment Transfer) model. Inputs, during first stage of model are defined as bed load (discontinuous process) and discharge (continuous) process. The effects of discontinuous bed load transport are characterized by the hydraulic phases in the second stage of the model i.e. whether two layered or subdivided into flow cells. Outputs are bed roughness and flow properties.

fluctuate through the channel and over the interface according to the bed load intensity and roughness characteristics. It is these subtle variations in flow cell location that are the most probable cause for bed load pulsing under the coarse-grained conditions at Squaw Creek.

Vice versa, on the basis of the various factors measured under natural floods, it can be speculated that the spatial and temporal distribution of bed load is the steering mechanism for the formation of high and low roughness areas or phases in time and the related development or destruction of flow cells. Thus during low transport intensities, such as are common during the very beginning and end of floods and during peak flow (Fig. 2), flow cells can come into existence, given that large roughness elements are temporarily stranded. In turn, flow cell development concentrates flow and energy into local streets that encourage the transport of bed load in the areas of local convergence and erosion. During high bed load transport intensities, flow cells are destroyed by the continuous spread of moving particles or "sheet" transport and flow becomes turbulent. Roughness values are very low during this phase in order to enable maximum particle transfer (Fig. 2). This phase is equivalent to the "two-layered flow" consisting of a lower, entirely mobile bed layer and covered by a turbulent, chaotic upper layer.

The FAST model

The ideas outlined above concerning the characterization of flood flows in coarse-grained rivers with high width to depth ratios and different phases of bed load transport, flow hydraulics and roughness has been qualitatively summarized in the FAST model in Fig. 4 (Ergenzinger *et al.*, 1994; De Jong, 1993). The FAST model basically interprets very distinct phases of river bed adjustment and differences in flow and water surface characteristics according to bed load transport. Intensive and non-intensive phases of bed load transport are related to the development or destruction of flow cells. These characteristics are dependent on the state that roughness is in and determine the process of river bed erosion or deposition.

CONCLUSION

The bed load, river bed and flow hydraulics measurements during flood flows form a conceptual basis for the new FAST model. When bed load transport is erratic and pulsed, there is a strong tendency for flow cells to develop, yet during phases of intensive bed load transport, flow cells are destroyed. These phases are important for determining whether roughness values are dominant or smooth and whether the river bed is adjusting in terms of erosion or deposition. The model demonstrates the importance of flow and river bed adjustment in controlling the nature of bed load transport and visa versa. Because bed load does not relate directly to the flood discharge, river bed adjustment and flow hydraulics form a delicate interactive process in determining whether the next phase of bed load transport is non-intensive or intensive, whether the formation of flow cells is due or not and whether the river bed will respond in terms of erosion, deposition or nor at all.

Acknowledgements This work was carried out as part of the first author's PhD whilst in receipt of a Studienstiftung Scholarship (National Science Foundation Scholarship). The Deutsche Forschungsgemeinschaft (German Research Council) is thanked for its support. We are also grateful to the extensive help we obtained from Prof. Georg Christaller and his group for electronics and from Prof. Steve Custer of Montana State University and his students in the field.

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