Relationship between sediment supply and sediment transport for the Roaring River, Colorado, USA

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ABSTRACT A 1-km long gorge, cut into a glacial moraine by a dambreak flood wave, has provided the setting for a study of the relationship between supply of sediment from the gorge cliffs and the sediment transport along the Roaring River. Measurements during two snowmelt seasons have indicated two major supply systems. The initial snowmelt flows, peaking at about 5 $m^3 s^{-1}$ in May-June, carry relatively large bed and suspended loads, composed of material supplied to the channel bed and margins by winter erosion processes. Rapid depletion of these supplies, though, means that the sediment loads of later flows are reduced by an order of magnitude. This trend may be reversed in July and August when heavy rainstorms can dramatically increase cliff erosion and thence sediment transport. Relatively high transport rates may then persist for several days. External supply of sediment can thus cause two orders of magnitude variation in sediment transport for a given flow discharge. A full understanding of the relationship between supply and transport is obtained only by considering events in chronological order.

INTRODUCTION

Until recently, studies of fluvial sediment transport processes have concentrated on lowland rather than mountain rivers. However, development pressures throughout the world's mountain areas are increasingly altering the naturally sensitive balance between sediment supply and transport at the upper ends of river systems (e.g. Dickinson, 1982; Sundborg, 1983). This in turn has repercussions throughout the whole river system (e.g. Schumm, 1977, p.3; Newson, 1981). Research into the processes by which sediment is delivered from drainage basins is therefore required, so that the impacts of changes in supply can be minimized and drainage basins can be more satisfactorily managed. In particular, several recent reviews have indicated the need for research into the link between in-channel sediment transport, in-channel storage and sediment supply from outside the river (Wolman, 1977; Swanson et al., 1982; Sundborg, 1983).

This paper describes a study of the effect of supply events (principally from the immediate channel margins) on the sediment transport of a mountain stream with a snowmelt regime. Its aim is to illustrate the variation in sediment supply through the snowmelt season and the consequent variations of the sediment transport rate. The field work was carried out on the Roaring River in the Rocky Mountain National Park, Colorado, USA, in a joint programme of research between the British Institute of Hydrology and Colorado State University. Some further information, especially on the field measurements, is provided in Bathurst et al. (in press) and Pitlick & Thorne (in press). Full analysis of the data is likely to take some years and the results presented here are therefore preliminary.

DATA COLLECTION

The setting for the field measurements on the Roaring River was a 0.75-km long gorge, cut into a glacial moraine by the flood wave from the Lawn Lake Dam failure in July 1982 (Jarrett & Costa, 1985). Immediately downstream of the gorge lies an alluvial fan, also created during the flood, which straddles the confluence of the Roaring River with the Fall River (Fig. 1). The gorge cliffs were expected to form an important sediment source for the Roaring River and the aim of the field measurements was to relate the sediment supply from the gorge to the transport out of the gorge and across the fan. In order to provide a control variation, fluvial sediment transport into the gorge was monitored at the Ypsilon Lake Trail bridge (the upstream gauging site). The transport out of the gorge was monitored at the Fall River Road bridge on the fan (the downstream gauging site).

Between the bridges the river reach is about 1 km long and falls about 180 m, giving an average slope of 18%. Channel widths are about 5-10 m. Bed material sizes [obtained by Wolman (1954) samples] were found to vary in the range D_{16} = 10-60 mm, D_{50} = 70-140 mm and D_{84} = 160-270 mm, where D_n is the size of median axis for which n% of the sediment is finer. Fine scree from the cliff faces of the gorge, which in many places form the channel margins, was found to have a distribution of D_{16} = 0.5-2.8 mm, D_{50} = 3.2-6.3 mm and D_{84} = 8.0-13.5 mm. Whilst this scree material can be grab sampled, large boulders were also present; these prevent a complete numerical description of the supply material. The flow regime of the river is dominated by a spring and summer snowmelt with a contribution from summer rainstorms. Maximum water discharges are around 5 m^3s^{-1} and the upstream basin area is about 29 km^2.

Water, bed load and suspended load discharges were measured according to the techniques described by Bathurst et al. (in press). Continuous recorders for these variables were not available and data were obtained from periods of continuous manual measurement varying from 2½ to 55 hours in length. Usually the measurements were made simultaneously at the two gauging sites.

The field work was carried out during the periods June-July 1984 and May-June 1985 which, fortuitously, when taken together, illustrate a range of flows and sediment discharge conditions considered typical of a complete snowmelt season. Between these two periods, though, a new measurement problem was introduced at the downstream gauging site by the construction of a foot bridge about 80 m upstream of the Fall River Road bridge (Fig. 1). The associated disturbance

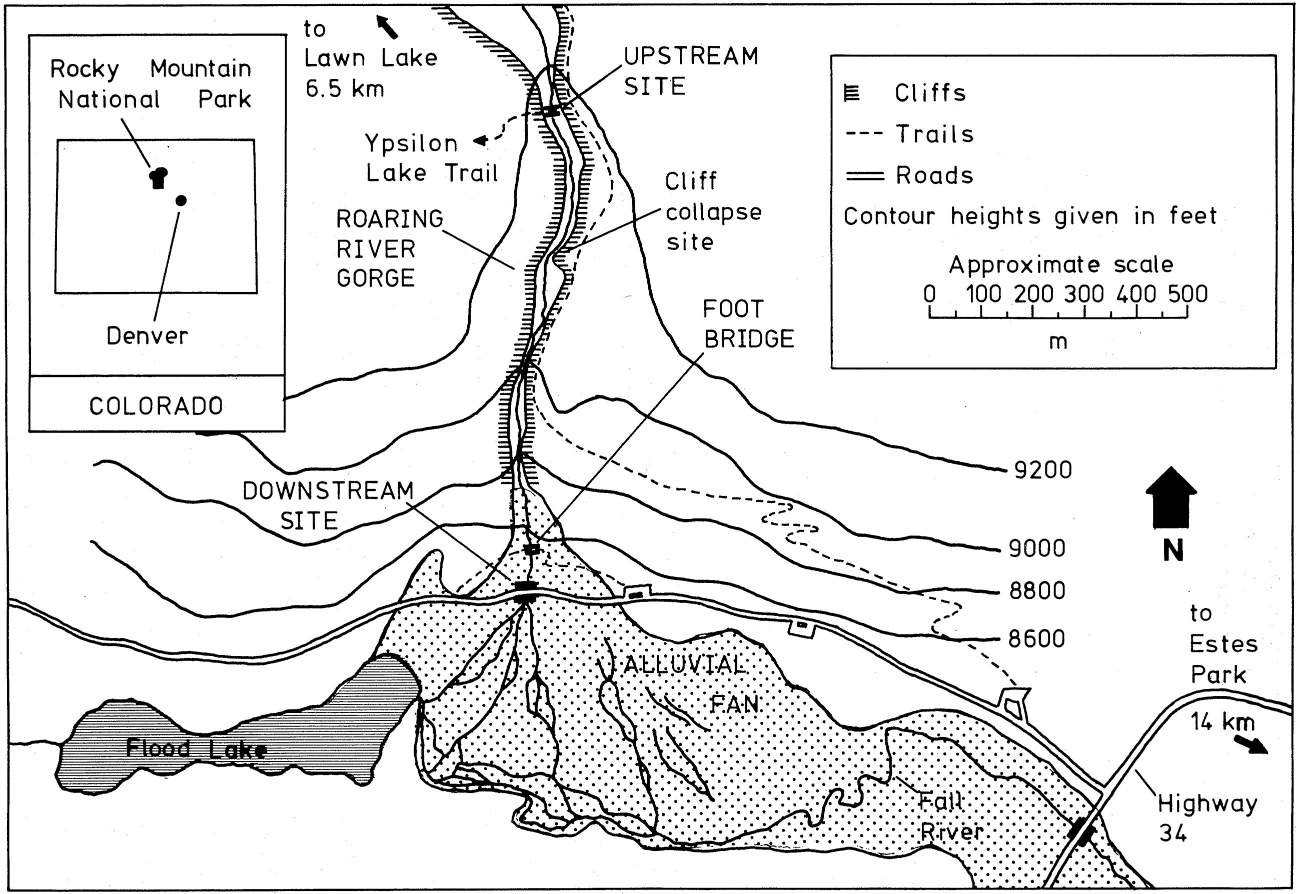

FIG. 1 Sketch map of the Roaring River study area, Rocky Mountain National Park, Colorado, USA.

of the channel bed and banks was such that sediment yields at the road bridge in 1985 were significantly influenced by the adjustment of the affected channel during periods of high flow. However, by surveying the subsequent changes in channel shape and, when the bed was stable, making check measurements from the new foot bridge itself, allowance could be made for the contribution of the construction site to the sediment discharge at the road bridge.

RESULTS

Østrem et al. (1971) have indicated that the most meaningful relationship between water and sediment discharges with time in mountain rivers is achieved when day to day changes are studied in chronological order. The field data are therefore presented as if in order through a snowmelt season. This means that the 1985 data are considered first since they deal with a typical pre-snowmelt to peak snowmelt period. The 1984 data then cover typical post-peak and declining snowmelt periods, together with rainstorm events. The range of data values recorded at various stages of the snowmelt season are shown in Table 1 and Fig. 2. In Fig. 2, the hatched columns represent mean values for the periods of continuous measurement from which were calculated the percentages of the total load transported as bed and suspended loads (Table 1). The open columns represent the maximum measured values.

Pre-snowmelt period (20-24 May 1985)

Water discharges were relatively low and generally incompetent to transport the coarse bed material. Also, the water levels were too low to reach the supplies of sediment which had built up along the margins of the channel during the winter. The main source of mobile sediment was therefore the lenses of sand lying in the wake of the larger boulders. [These features are described by, for example, Brayshaw (1984) and Martini & Ostler (1973).] Thus the bed load consisted of sediment generally finer than 15 mm in diameter and both bed load and suspended load transport rates were in the same range above and below the gorge.

Mid-snowmelt period (27-30 May 1985)

During the first major snowmelt hydrograph of the season (peaking at 2.5 m^3s^{-1}), bed load discharge at the upstream site was relatively low (up to 0.02 kg s^{-1}). Consisting mainly of sand, it was probably responding to the flushing of the sand lenses from behind boulders. By contrast, bed load discharge at the downstream site, augmented by the erosion of material from the gorge, and from around the new foot bridge, exceeded 1 kg s^{-1}. Even without the contribution from the bridge site, the transport was still an order of magnitude higher than that at the upstream site. Suspended load discharges, too, were generally higher (up to two times) at the downstream site than at the upstream site.

This imbalance demonstrates the influence of supply from within the gorge, derived from the finer scree material (sand and fine gravel) which had collected at the bottom of the cliff faces during the winter. However, the supply was rapidly depleted since water levels were not sufficiently high to promote slumping and continuity of supply. During the two subsequent snowmelt events, which were

TABLE 1 Range in measured values of water discharge, sediment discharge and maximum particle size caught at the upstream and downstream gauging sites in 1984 and 1985

Period of flow	Water discharge ($m^3 s^{-1}$)		Bed load discharge ($kg\ s^{-1}$)		Suspended load discharge ($kg\ s^{-1}$)		Percentage of total load as bed and suspended loads		Maximum particle size caught (mm)	
	Up-stream	Down-stream	Up-stream	Down-stream	Up-stream	Down-stream	Up-stream	Down-stream	Up-stream	Down-stream
Pre-snowmelt	0.5-1.0	0.5-1.0	0.001-0.01	0.0005-0.02	<0.001-[c] 0.03	<0.001-0.04	48:52	37:63	16	16
Mid-snowmelt	1.4-2.6	1.4-2.9	0.003-0.06	0.004-1.1[a]	<0.001-0.7	<0.001-0.81	33:67	46:54	49	150
Peak snowmelt	3.5-5.0	3.6-5.0	0.05-0.12	0.12-4.3[a]	0.5-1.8	0.2-13.0	9:91	5:95	30	79
Post-peak snowmelt	1.8-3.2	1.9-3.0	0.002-0.03	0.003-0.13	<0.001-0.4	<0.001-0.23	27:73	47:53	67	82
Artificial cliff collapse	1.8-2.3	2.0-2.7	0.002-0.03	0.005-0.05	-	<0.001-1.5	-	30:70	55	75
Declining snowmelt + storms	2.3-3.4	0.2-4.0	0-0.03	0.002-2.7	-	<0.001-19.0	-	30:70[b]	86	145

[a] Upper values are influenced by sediment released from around the new foot bridge on the alluvial fan

[b] These values refer to the rainstorm of 24 July 1984

[c] A concentration of 0.001 $g\ l^{-1}$ is the minimum which could be detected

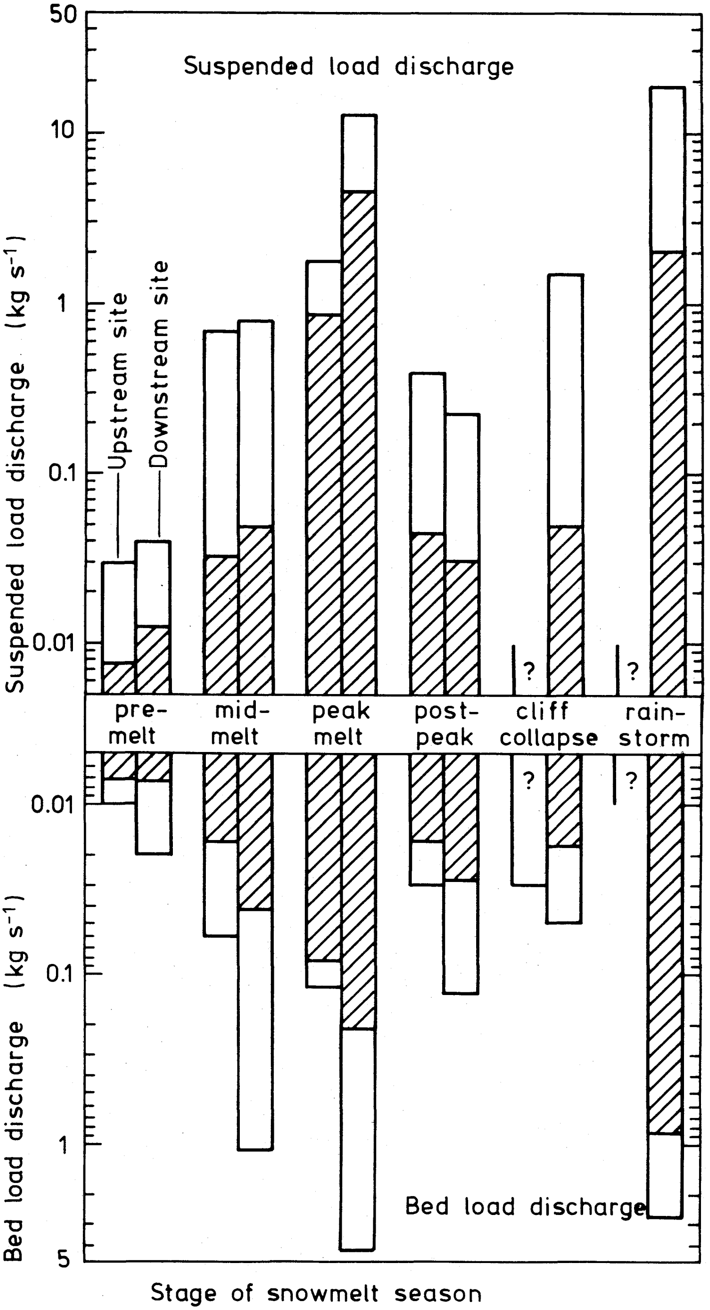

FIG. 2 Variation of suspended and bed load discharges at various stages of the snowmelt season. Hatched columns represent mean levels for periods selected as described in the text and open columns represent maximum measured values. In each pair the upstream site value is on the left and the downstream site value is on the right.

of similar water discharge, both bed load and suspended load discharges fell to levels comparable with those at the upstream site.

Peak snowmelt period (6-8 June 1985)

As water discharges rose to their maximum values, the bulk of the sediment transport was in the form of suspended load (Table 1). This was generally comparable at the two gauging sites (around 0.2-3 kg s^{-1}), except when slumps of scree deposits in the gorge provoked sharp but temporary increases (up to 13 kg s^{-1}) at the downstream site (Fig. 3). Bed load discharges reached their highest levels for snowmelt flows, with the discharge out of the gorge generally about two times that entering it.

The prominence of suspended load could be related to several factors. Firstly, the snowmelt runoff from the upper catchment presumably entrained much fine material. Secondly, sediment from the channel margins became more abundant as the high water levels promoted slumping of fine screes. In both cases the material would have contributed more towards suspended rather than bed load. Thirdly, the greater turbulence of the higher flows may have transported, as suspended load, sand particles which could be carried only as bed load at lower flows. A fourth possible reason is technical. During this stage of the field work the periods of measurement were more limited than at earlier stages. Thus, while covering the periods of high suspended loads in the late afternoon, they may have missed the periods of high bed loads, which tended to occur in the evening. If so, the proportions indicated in Table 1 would not be characteristic of a complete diurnal cycle of snowmelt.

Post-peak snowmelt period (14-27 June 1984)

During this period of moderate flows, the bed and suspended loads at the upstream site were slightly less than those measured at similar water discharges during the period of rising snowmelt flows. At the downstream site, on the other hand, the bed load discharges were about an order of magnitude lower than those of the rising snowmelt period. Suspended load discharge, too, showed a decrease although not such a marked one. On average the sediment discharge at the downstream site was slightly higher than that at the upstream site. Evidently the supply of sediment from the gorge was much reduced since the flow could no longer tap fresh supplies from the channel margin (a hypothesis tested by creating an artificial cliff collapse). This reduced supply of fine material may also have been partly responsible for the relative coarseness of the bed load.

Artificial cliff collapse (20-21 June 1984)

In order to study the effect of an individual supply event, an artificial cliff collapse was engineered by blowing up a small section of cliff, halfway along the gorge (Fig. 1). This dislodged about 10 m^3 (about 20 000 kg) of sediment but rather less than this actually fell into the river.

Measurements at the downstream site showed a rapid response by the suspended load discharge. Eleven minutes after the

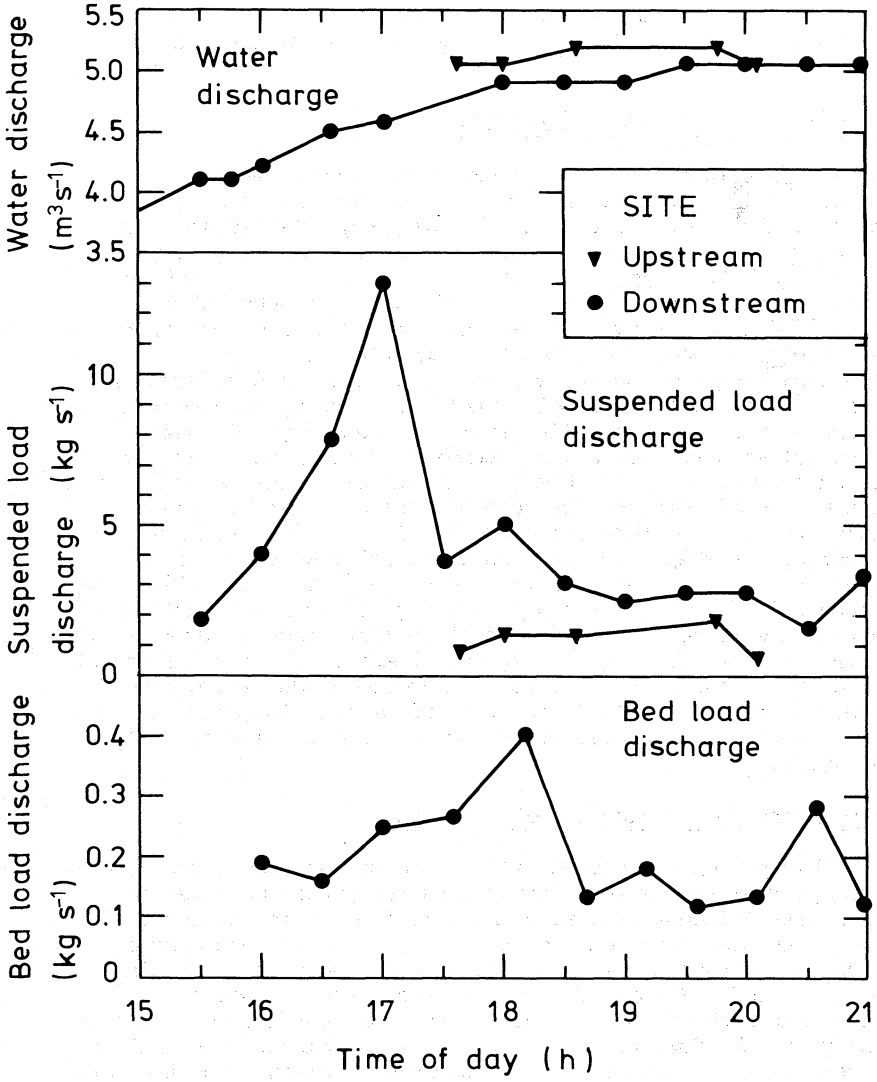

FIG. 3 Sediment discharge at the downstream site following slumps of scree deposits during a rising snowmelt flow on 7 June 1985. For comparison, the suspended load discharge for the upstream site is shown but no bed load discharge measurements were made at that site.

collapse, this peaked at 1.48 kg s^{-1} and, within half an hour, levels were back to their pre-collapse values. It is estimated that the peak concentration moved at about 0.5 m s^{-1} through the gorge.

Passage of the extra bed load is thought to have occurred during the following diurnal cycle of snowmelt. Bed load transport rates at the downstream site were then twice as high as those observed at similar water discharges in flows unaffected by the collapse. It is estimated that about 1425 kg of extra material passed the downstream site as a result of the collapse, composed 70% of suspended load and 30% of bed load.

Declining snowmelt period with rainstorms (July 1984)

Heavy rainstorms occurred in the neighbourhood of the field site on 30 June, 9-10 July and 24 July 1984. Observations during some of these indicated severe rill erosion by runoff on the cliff faces of the gorge and this considerably increased the sediment transport rates at the downstream site. During the storm of 24 July, suspended load discharge again reacted quickly at the downstream site and peaked at 19 kg s^{-1} on the rising limb of the hydrograph (Fig. 4). Bed load discharge also increased sharply and peaked at a value in excess of 2.7 kg s^{-1} on the falling limb of the hydrograph. These rates exceeded all values for the peak snowmelt period, except when the artificially disturbed sediment was released from beneath the new foot bridge. It is estimated, from an incomplete record, that the total load carried past the downstream site by the storm flow consisted 70% of suspended load and 30% of bed load.

At the downstream site, relatively high bed load discharges persisted for several days after a storm. Two days after the storm of 30 June, for example, transport rates (averaging 0.09 kg s^{-1}) were three or four times higher than for a comparable flow (2.6-2.7 m^3s^{-1}) before the storm (averaging 0.024 kg s^{-1}). Similar persistence was not recorded at the upstream site (although rather fewer measurements were made at that site). This suggests that the erosion of the cliff faces by runoff recharged the bed of the channel with a fresh supply of fine material, perhaps eventually reforming the sand lenses observed in the pre-snowmelt season as flows dropped to late summer levels. Some support for this interpretation is provided by the observation that, during the interstorm period, the bed load at the downstream site was composed mainly of sand and fine gravel.

DISCUSSION AND CONCLUSIONS

Through the snowmelt season there was an order of magnitude variation in water discharge (0.5-5 m^3s^{-1}). At the same time, at the control or upstream site, a two orders of magnitude variation in bed load discharge was recorded (0.001-0.1 kg s^{-1}), while suspended load discharge varied from <0.001 to 1.8 kg s^{-1}. At the downstream site, a three orders of magnitude variation in bed load discharge was recorded (0.001-4 kg s^{-1}), while suspended load discharge varied from <0.001 to 19 kg s^{-1}. Also at the downstream site, two orders of magnitude variation in sediment transport was observed for a given flow discharge, e.g. a mean bed load discharge of 0.024 kg s^{-1} at a water discharge of 2.7 m^3s^{-1} during the post-peak snowmelt period and respective figures of 2.7 kg s^{-1} at 2.4 m^3s^{-1} during a rainstorm. The role of sediment supply from the gorge in boosting the sediment transport is clear. However, the supply process is not uniform and its importance varies through the snowmelt season and even from day to day. The effect of each supply event also depends on the persisting results of preceding events. Thus, only by considering events in chronological order can the relationship between sediment transport, sediment supply and water discharge be understood.

Two major supply systems, based on the initial snowmelt flows

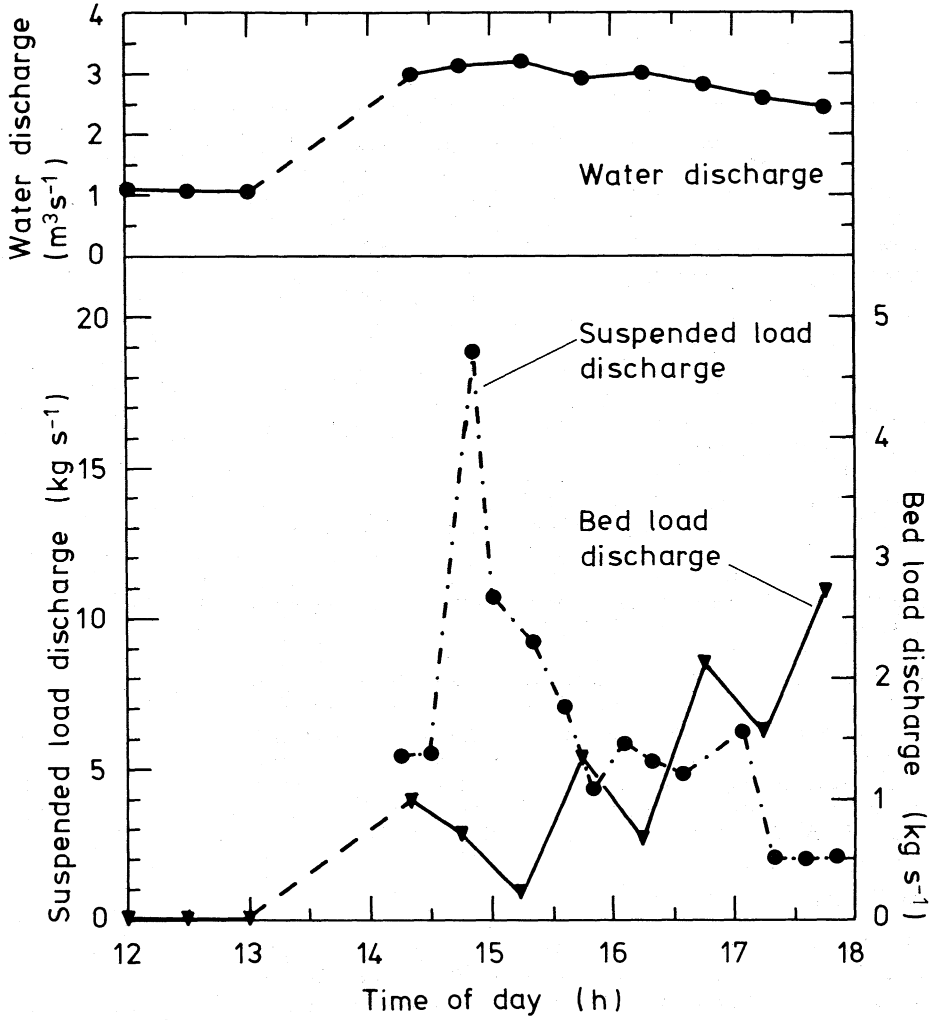

FIG. 4 Sediment discharge at the downstream site during a rainstorm flow on 24 July 1984. Measurements are not available for the rising limb of the hydrograph and the water and bed load discharge variations are therefore interpolated with dashed lines.

and on rainstorm runoff, are illustrated by the field data. During the period of increasing snowmelt activity, large quantities of sediment can be flushed from the channel bed and margins and transported rapidly along the channel. However, this level of transport is maintained only as long as peak snowmelt discharges show significant increases from day to day. Decreases, or even small increases, mean that the flow is unable either to promote (by slumping) or to reach fresh supplies and that sediment transport may be reduced by an order of magnitude. Thus the store of material along the immediate channel margins is quickly depleted, suggesting that for only a few of the snowmelt flows is sediment transport greatly enhanced by supply. The results show in particular the importance of the first major snowmelt flow in removing sediment supplies.

Once the period of peak snowmelt activity has passed, the only source of sediment available to the continuing snowmelt flows is the bed of the channel. Results from the Roaring River suggest also that the sand lenses observed in the pre-snowmelt period are no longer present. Consequently, sediment transport as a result of snowmelt activity declines for the rest of the season.

The largest sediment transport rates recorded were the result of the rainstorms. Supply of sediment to the channel was not then limited to the channel margin but, through the agency of overland flow, extended over the glacial deposits forming the gorge cliffs. The resulting spectacular erosion considerably increased the sediment transport. Successive storms also had successively more impact. Thus, during the storm of 9-10 July, water discharge peaked at 4 m^3s^{-1} and bed load discharge reached 0.7 kg s^{-1}. During the storm of 24 July, though, the water discharge peaked at only 3.2 m^3s^{-1} yet bed load discharge exceeded 2.7 kg s^{-1}. These differences may have arisen from, for example, a different intensity or pattern of rainfall on the gorge cliffs. However, it is also possible that successive storms had a cumulative effect in reworking the channel bed, eroding the cliffs and generally increasing the availability of sediment. A number of other studies have found similarly that the effects of a given storm on sediment transport cannot be isolated from the effects of preceding storms (e.g. Hayward, 1980; Newson, 1980; Bergstrom, 1980).

The variations in sediment transport rate and their dependence on sediment supply carry a number of implications for the development of transport relationships and mathematical models. Firstly, the choice of sampling site in a mountain river system may well have an important influence on the results obtained. Secondly, there is no single-valued relationship between water discharge and sediment discharge at a site. If rating curves can be defined at all, several different versions are needed for the different stages of a snowmelt season and possibly even for the rising and falling limbs of a single hydrograph. Thirdly, the rapid fluctuations in sediment transport at short time intervals show that accurate determination of mean sediment discharge at a site requires a programme of very frequent sampling, at least at critical periods. The latter two points are also highlighted in other studies (e.g. Østrem et al.; Gurnell, 1982; Ferguson, 1984).

Fourthly, the data confirm the importance of mathematical models such as those of VanSickle & Beschta (1983) and Moore (1984), which allow for the build up and depletion of sediment supplies and the effect on sediment transport. The data also show, for the field area, that suspended load discharge reacts rapidly to supply events and typically peaks on the rising limb of a hydrograph. Bed load discharge responds more slowly and typically peaks after the water discharge. The different response times and changing relative proportions (Table 1) of these two components of sediment transport mean that they must be modelled separately for mountain rivers. Also, the relatively large contribution of the bed load to the total load means that it cannot be neglected relative to that of the suspended load. Finally, the variations in bed load particle size distribution show that allowance must be made for the varying mobility and rate of transport of the different particle sizes as water discharge varies.

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