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The significance of extreme events in the development of mountain river beds

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Abstract The dynamics of an extreme flood/debris flow with a 150 year recurrence interval were reconstructed in the Schmiedlaine, a tributary of the Lainbach in Upper Bavaria. The extreme range in sediment size, bend curvature and local gradients allow flow dynamics and sediment transporting capacity to vary significantly along the reaches and thereby influence river bed development. Mean velocities for the flood were calculated from the angle of superelevation in the bends. Sedimentary sections were analysed in detail with the use of a new photo-sieving technique that allows the description of particle size whilst large-scale river bed roughness was analysed with a Tausendfüssler profiler. Gradients, as well as individual reach geometry, were obtained from a 2 km geodetic survey. Width to depth ratios were calculated for the 1990 event and compared to the active sections of the river bed in 1993. Surveys were repeated over a four year period after the extreme event in order to monitor the adjustment of the river bed. The hierarchy of bedforms in relation to bend curvature and gradient reveals different stages and scales of river bed development, of which most are unique to the extreme event.

INTRODUCTION

This study analyses how extreme events are essentially responsible for the formation of long-lasting effects in terms of channel geometry and roughness in high gradient mountain streams. The Schmiedlaine is taken as a case study for determining the effects of extreme flood magnitude on river bed formation. A four year measuring period in the Schmiedlaine typifies not only the effects of low flow and normal floods but also the influence of an extreme flood event with an estimated 150 year recurrence interval. It is postulated that extreme events have a significant effect on river bed formation at all spatial scales as long as there is little or no subsequent flow reworking.

Schumm *et al.* (1987) suggest that the episodic behaviour of extreme events has lasting effects on the river system. Evidence for the significance of episodic erosion and accretion has been cited by many other authors. Whenever extreme events supply large quantities of sediment to the river this results in an overloading of the drainage system. The extent to which the effects of this overloading perseveres on the river bed depends on discharge, bed load, grain size and sorting. In turn, velocity, slope, width and depth of the channel are dependent variables that are affected not only by the independent variables (produced by the flood itself) but also by one another (Rubey, 1952). Rivers with such adjustability and stability have been defined as "graded" (Davis, 1902) i.e. there exists a balance between erosion and deposition. This type of river is one where, over a period of years, slope is delicately adjusted to provide with available discharge and with prevailing channel characteristics just the velocity required for the transportation of the load supplied from the drainage basin (Mackin, 1948). The graded stream is a system in equilibrium; its diagnostic characteristic is that any change in any of the controlling factors will cause a displacement of the equilibrium in a direction to absorb the effect of change.

STUDY AREA

The Schmiedlaine consists of a high gradient, bedrock-confined mountain stream at the foot of the Northern limestone Alps, 60 km south of Munich. Average gradients lie around 5°. The stream is characterized by many differentiated local sedimentary inputs, both in the form of minor slumps and large debris flows (Fig. 1). The variety of geology allows the Schmiedlaine to change in character from a straight, highly incised bedrock reach to a meandering reach with a high width to depth ratio over a mere 2 km. Average annual precipitation consists of approximately 760 mm in snow and 730 mm in the form of rain. Flood flows have an average discharge of 14.6 m^3 s^{-1}. The D_{50} and D_{84} on the lower bar near the confluence of the Lainbach are 86 and 170 mm respectively. An extreme event with a 150 year recurrence interval and an estimated discharge of 75 m^3 s^{-1} occurred at the beginning of the study, on the 30 June 1990.

METHODOLOGY

Grain size was calculated with the photo-sieving technique (Diepenbroek & De Jong, 1994) at various test locations along the Schmiedlaine. Surveys were repeated annually. In regions with *b*-axes larger than 300 mm, grain size was calculated with the grid by number method, using *b*-axes. The photo-sieving technique was also utilized for reconstructing the sedimentary characteristics of vertical sections. As for the horizontal analyses, this technique allowed particle roundness and orientation as well as grain size to be determined. River bed roughness was determined at 2 m intervals using the K_3 roughness (Ergenzinger, 1992) coefficient for the situation both during after the extreme event. This interval is representative for system (unit) roughness under the given grain size distribution of the Schmiedlaine (De Jong, 1993). In this study, the K_3 parameter provides a new approach for describing the hydraulic geometry and large scale form roughness in river systems.

Discharge was determined from a stage recorder inserted below the confluence with the main Lainbach stream. For the extreme event, water velocity was reconstructed from the angle of superelevation of water in the curve (De Jong, 1992b). Repeated long profile surveys over the four year period allowed gradients and cross-channel geometries to be obtained both for the extreme event and for the year to year normal flow comparisons.

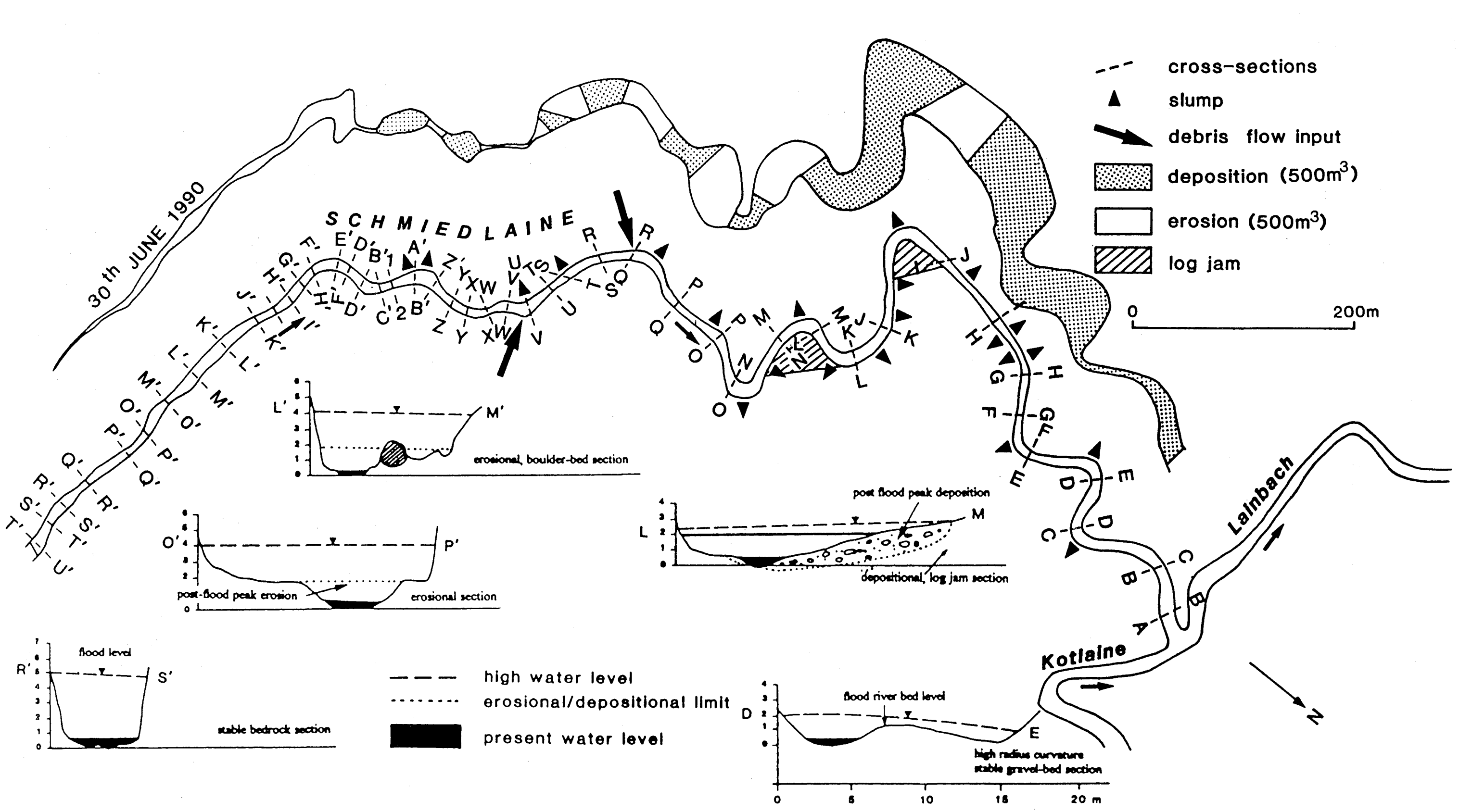

Fig. 1 Geomorphological map of study area. Note the distribution of bends, debris flow inputs and associated log jams.

RESULTS

Nature of flood events and slope movements

The passage of a normal flood event usually only lasts for 4-8 h with a rapidly rising ascending discharge limb and a longer lasting descending limb. Tracing of bed load suggests that transport usually occurs at a threshold discharge of 4 $m^3 s^{-1}$, which is about four times the normal discharge. The extreme flood event observed on the 30 June 1991 could not be monitored, but it was estimated from other sources that peak discharge was approximately 75 $m^3 s^{-1}$. The event occurred very rapidly as a result of 85 mm rainfall within half an hour with a descending limb that lasted for 3 days under very subdued discharge. It was very different in character to the normal flood events since it consisted of a combination of an extreme flood event and two minor debris flows which occurred during peak flow (De Jong, 1992b).

No major landslide occurred during the extreme event in 1990. However in 1993 after a season of prolonged rainfall, two mega-landslides occurred, mobilizing an estimated 3 ha of land each, of which one occurred at cross section UV, the other in the debris flow channel at cross section QR (Fig. 1).

River bed geometry and roughness

The Schmiedlaine has a hierarchy of characteristic bedforms associated with the steep gradients, variation in grain size and high curvature bends (De Jong & Ergenzinger, in press). Because river bed development is dependent on geometry and roughness, the grain size, water depth, angle of bend curvature, flood velocity and flow viscosity take on very important roles in the highly differentiated reaches. Streams that are seldom in a static state are therefore subject to transitory adjustment accomplished by the storage of sediment and water (Schumm *et al.*, 1987).

Normal flows Normal flows do not carry with them sufficient sediment to cause major depositional forms to develop. Nevertheless, these types of flows are very important in terms of their erosive work i.e. for channel reworking after extreme flood events. Taking an example from the top of the bedform hierarchy, step-pool systems (such as at CD, FG, HI and JK in Fig. 1) are destroyed by extreme events in the Schmiedlaine and may only reform on the basis of sediment starvation caused by the continued winnowing of finer sediments. Deep channel incision, causing decreased width to depth values for the active channel will also result from the persistent reworking of normal flows. The threshold cross section has banks of movable material which maintain erosion and deposition in equilibrium (Henderson, 1961; Leopold *et al.*, 1964). Even though the form of the cross section will remain stable, or constant during low flows, the position of the channel will remain free to wander.

Normal flood flows Normal flood flows are very important in shaping the smaller-scale features of the river bed. These types of flows are insufficient to determine the entire river system but they may exhume or totally remove flood deposits from extreme events. River bed structures that can ensue from such events include small bar forms, cobble berms, transverse ribs and different types of clusters (De Jong & Ergenzinger, in press). The bar forms that can result from such events are basically dependent on the water depth and geometry of the river stretch in question. In high curvature bends, new bars can form more readily due to cross-sectional water superelevation and increased gradients in the bend. Straight reaches will usually remain unaffected. In the outer bends, small series of cobble berms will form as a result of the deposition of sediment-laden flows in response to the centrifugal forces concentrating within the bends (De Jong & Ergenzinger, in press). Straight, high gradient reaches will respond to such events by the deposition of transverse ribs. These transverse rows of cobbles are deposited as a result of standing waves forming over stranded obstacles (De Jong, 1993). The smallest scale features take shape as different clusters and cluster systems. These bedforms consist of the coarsest fraction of the river bed and are usually deposited as a result of sediment becoming trapped behind an obstacle during the descending limb of floods on shallow, low gradient bars.

Extreme flood events Extreme events are responsible for reorganizing the river system and depositing the largest scale features (Fig. 2). Thus megaclusters (which may reach 3 m in length) and step-pool systems are dependent on the passage of deep flows and the mobilization of large boulders, cobbles and tree trunks. The extent to which these features become preserved as part of the river bed is nevertheless dependent on their location relative to the bend curvature as well as the hydraulic geometry. At reach PQ (Fig. 2), megaclusters initiated redirected flow channels on the bar top. These features have remained stable over the years due to their inaccessibility to normal flows.

In the Schmiedlaine, the highly variable reaches can be subdivided into stable sections according to their position in the bend apex, or unstable sections at the entrance and exit to the bends. The deposition of log jams in stable sections, i.e. exclusively in the bend apex of highly curved reaches is unique to extreme events such as the one recorded in 1990 (Fig. 1). The spatial and temporal preservability of log jams remains dependent on the significance of stream power or channel change. In other locations, features formed under deep flows will only remain dominant if they lie fully above the present water levels. Thus the braided channel system that formed downstream of GH as a result of the extreme event could not be preserved for longer than 2 weeks due to the effective role that subsequent normal flows played in reshaping the river system into its former step-pools. Unless there is a local input of sediment, the predestined dimensions of the channel cross section resulting from meander confinement in the valley will remain the same and repeatedly force the river channel and bed to develop in accordance.

The significance of extreme events is dependent on the viscosity of the flow. Thus the ability of the flood to reshape and reorganize the structure of the river bed depends on whether flows are Newtonian or non-Newtonian. In the case of the non-Newtonian flow which formed around peak flow as a result of the two debris flows (Fig. 1), very large boulder "walls" were mobilized and bulldozed the river bed. During the flood, this resulted in a temporary lowering of roughness. Highly concentrated boulder transport results in the hyperconcentrated flow end-lobes (such as at EF) which cannot be created under any normal flood circumstances. The most acute effects of the flood were created during the flood recession when the extreme flood was still of high density. Flows reworked the sediment layers, which had been deposited to a height of 2 m in some locations, and deeply incised the channel, forming a series of terraces in adjustment to the new level of the river bed.

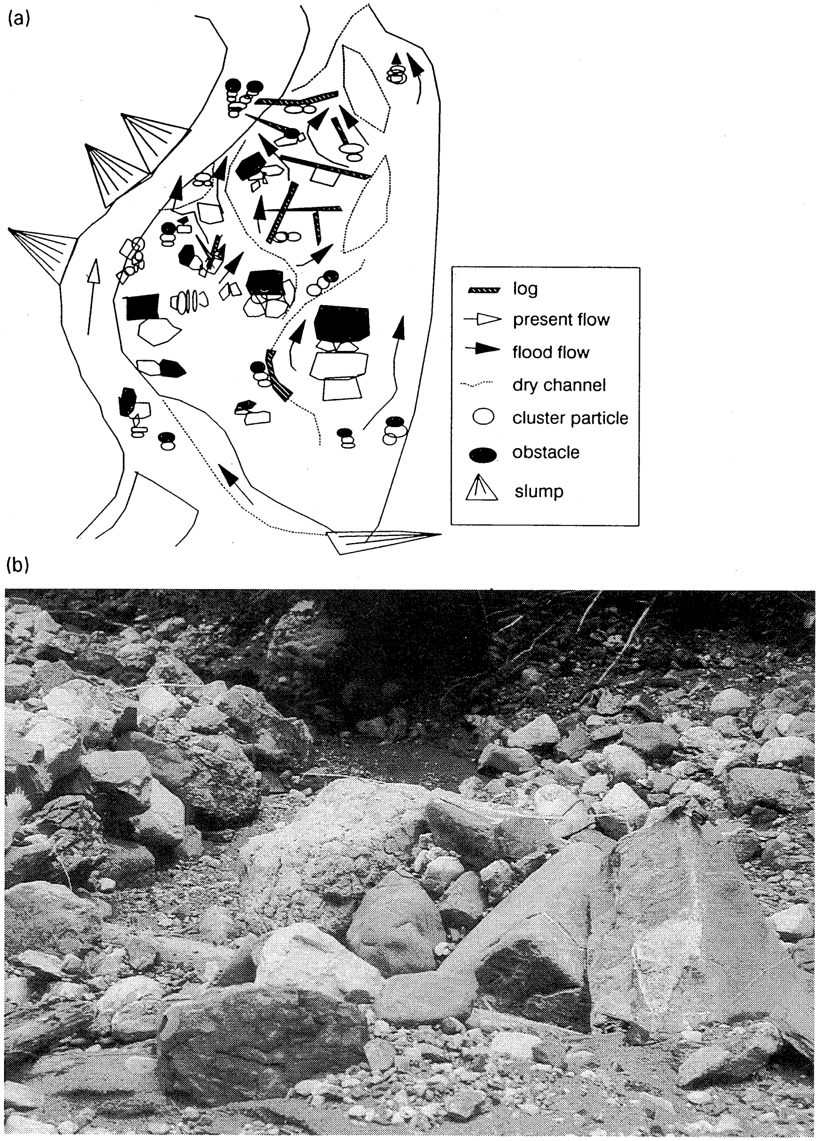

Fig. 2 (a) Geomorphological sketch of high curvature reach PQ (reach below debris flow) with megacluster. (b) Photo of megacluster at section PQ.

The photo-sieving sections showed the difference between the grain size distribution of the freshly deposited hyperconcentrated flow layers and those further downstream subject to normal flood reworking. The simple model (Fig. 3) describes the spatial distribution of the relationship between the surface and subsurface layers. At QR, the subsurface hyperconcentrated flow layer and the surface layer reworked by the descending limb of the extreme flood are mutually independent from each other (Fig. 3(a)), whereas further downstream (Fig. 3(b) near NO) the grain size distributions start overlapping and encompass a wider grain size range (Fig. 3(c) near BC). Over the next three years, the spatial distribution of the two layers along most of the sites along

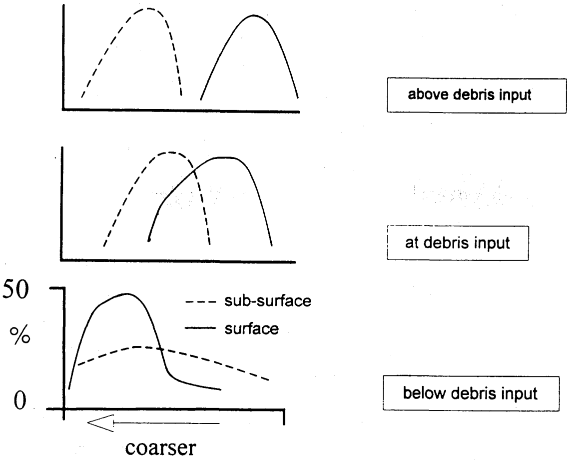

Fig. 3 Model of grain size distribution of surface (deposited by the extreme flood) and subsurface layers (deposited by the debris flows) at selected sites along a 1.5 km course of the Schmiedlaine from (a) QR, (b) NO to (c) BC.

the 2 km reach merged to produce a grain layer relationship similar to that in Fig. 3(c). The spatial variability of the river bed at the time of the flood was reproduced at each location in the temporal dimensions, so that the result was an equalization of the two layers. Thus over the 3 years, as the river reaches became reworked, all the sections began resembling those furthest downstream in the depositional reach. There are exceptions to this rule at sites where the sections were completely protected from erosion.

The preservability of the different roughness components on the river bed depends on their location, gradient and surrounding grain sizes, and to a lesser extend on the thickness of the deposit. In steep mountain environments with active bed load transport, the geomorphological effects of such extreme events are barely in existence after a few years. The only important lasting effects depend on the availability of non-fluvial sediment reworked from the valley-side deposits and redistributed throughout the river reaches. This includes organic debris such as logs as well as the large single grain roughness such as boulders.

In order to quantify the changes in large scale system roughness with a single, descriptive parameter, the K_3 roughness coefficient was calculated at 2 m intervals. This type of roughness description depends on cross-sectional gradients between the channel and bar and on grain size. Figure 4 indicates the average roughness coefficients at each cross section in 1990 and 1993, compared to the conventional Darcy-Weissbach coefficient reconstructed for the flood. Comparisons of the K_3 coefficient reconstructed for the flood sections of the extreme flood in 1990 with the reworked sections in 1993 indicate that system roughness was generally lower during the extreme flood in 1990 with the exception of the lower braided reaches (downstream of GH). These reaches were subject to major erosion after the extreme event up to 1993. The Darcy-Weissbach coefficient for 1990 matches the K_3 roughness in 1990 but does not reproduce the variability in roughness in as much detail. The greater precision of the K_3 coefficient is due to it being a direct indicator of the hydraulic geometry.

Roughness is heavily dependant on the hydraulic geometry in streams with an extreme range in sediment size, flow depth and gradients. For normal floods, roughness

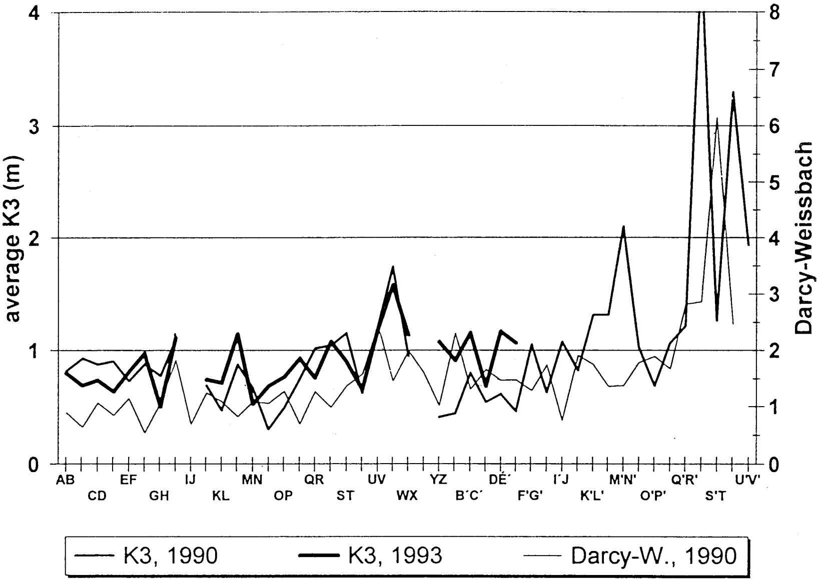

Fig. 4 Average K_3 system roughness coefficient for each cross section in a comparison for the extreme flood in 1990 and the reworked sections in 1993, together with the related Darcy-Weissbach coefficient for 1990. In order to avoid duplication in the bedrock reach upstream from E′F′ where roughness changes were minimal, roughness values were omitted for 1993.

tends to adjust to a similar state both before and after the event (De Jong, 1992a) and roughness hardly changes at all. However, extreme flood events cause roughness to change extensively (Fig. 4). Roughness is very high in those reaches that provide the opportunity for sediment deposition e.g. in the bend apices and in the narrow, high gradient reaches. Wide, low gradient reaches characteristic of bar formation tend to produce the same bar dimensions as for normal flows. At sites such as at LM (Fig. 5) in the bend apex where a major log jam developed during the extreme flood, extensive deposition in mid-channel location during the three years has added irregularities to the cross section and caused substantial increases in the K_3 system roughness. At other sites, landslides cause major infills of material. This smooths the section profile and decreases the K_3 values such as at QR (Fig. 6).

The hydraulic geometry is in balance with flow velocity both for normal flows and for extreme events. Thus during the flood peak, bed load reworks the river bed in such a manner that the velocity remains in equilibrium with flow depth. This means that erosion has to occur in straighter, deeper locations and deposition in the highly curved, shallower areas. The ribbon above the channel (in Fig. 1) emphasizes the alternation and volumes of erosion and deposition according to curvature. In energy terms, the Schmiedlaine can adjust its hydraulic geometry over time in order to provide optimum flow and sediment transport efficiency.

Thus during the extreme event, width to depth ratios were high (Fig. 7) and flows capable of working the entire channel dimensions. The width to depth ratios were lowest in the deeply incised bedrock reach, which was capable of transporting boulders, whereas they increased in the highly meandering reaches with greater channel and bar

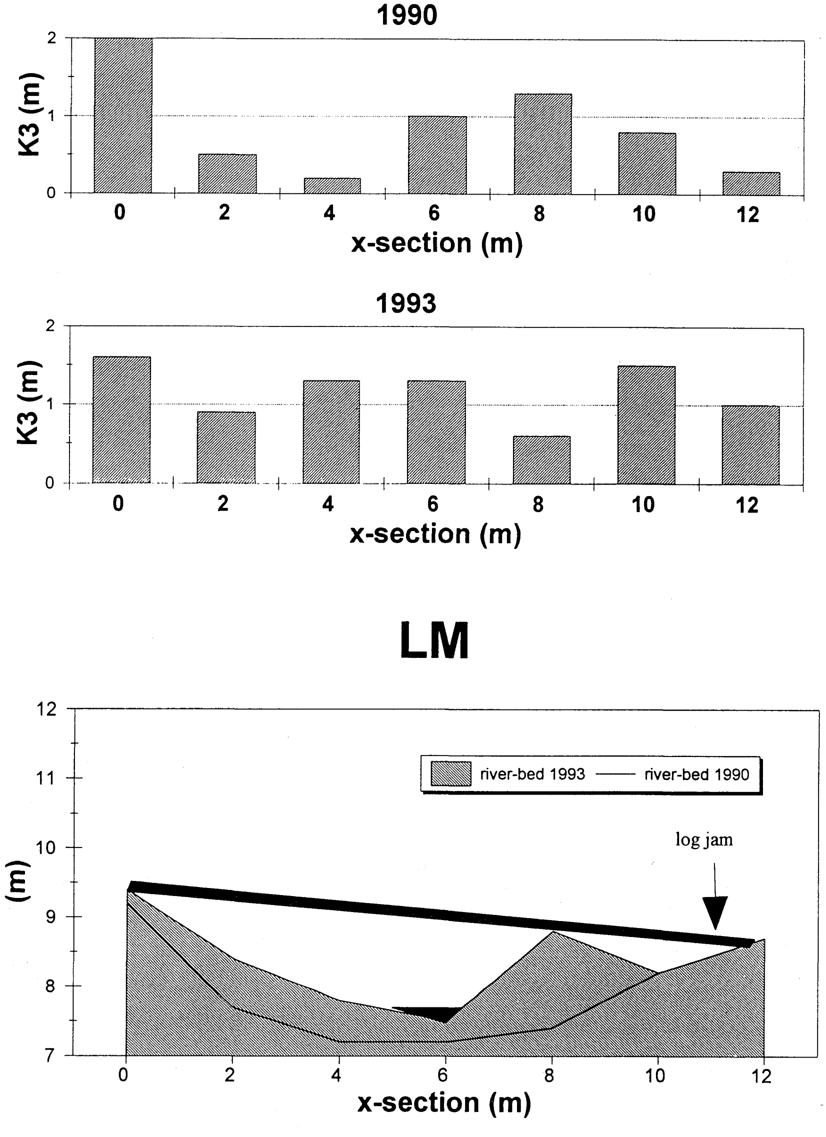

Fig. 5 River bed profile at reach LM with log jam for 1990 and 1993 with cross-channel distribution of K_3 roughness distribution at cross section LM. View is looking downstream.

widths. In the lower reaches, where the channel becomes more confined because of geological constraints, the ratios are lower again. The 1993 data show that for the reworked sections within the channel, width to depth ratios are generally higher. Ratios are highest in cross sections subject to fewest change e.g. in the bedrock confined reaches. Ratios are lowest where the cross sections are subject to the impact of landslides and mass movements. In these cases extensive deposition has decreased the channel width in the section itself and those downstream of it.

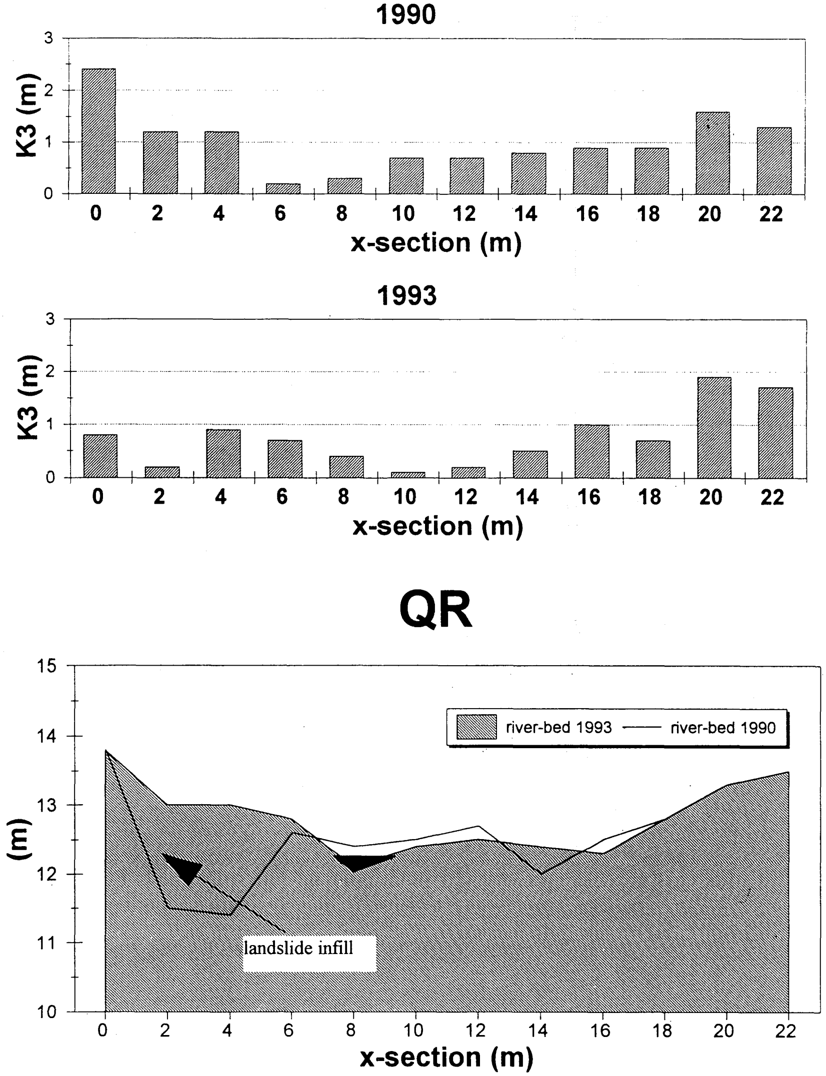

Fig. 6 River bed profile at reach QR with major landslide infill in 1993 with cross-channel distribution of K_3 roughness distribution at cross section QR. View is looking downstream.

CONCLUSION

The effects of extreme events depend not only on channel parameters, roughness, flow hydraulics and sediment transport but also on the antecedent conditions. In 1990, 85 mm of rainfall were sufficient to trigger a mega-flood with some permanent features such as log jams and end-lobes and to mobilize two debris flows along concentrated flow routes. The event was not sufficient to trigger a major landslide. Repeated saturation triggered two large landslides in 1993 that significantly restructured a few very localized sections of the river bed by major channel infill and flow routing in the absence of a major flood.

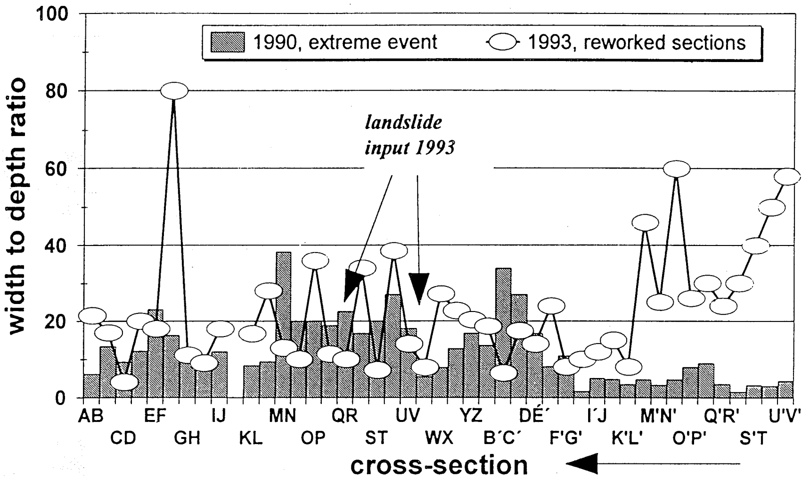

Fig. 7 Width to depth ratios for all sections reconstructed for the extreme flood in 1990 and for the reworked areas of the cross sections in 1993.

As for the debris flows, hyperconcentrated flow was important for the mobilization of large particles and bedforms developed in association with the transport of larger particles than would have been mobilized during normal flood flow. Extreme floods and slope movement cause decreases in roughness values and decreases in width to depth values that significantly restructure the river bed according to bend curvature.

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