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

The susceptibility of valley slopes and river beds to erosion and accretion under the impact of climatic change – Alpine examples

PETER ERGENZINGER
Berlin Environmental Research Group (BERG), Institut für Geographische Wissenschaften, Freie Universität Berlin, Grunewaldstrasse 35, D-12165 Berlin, Germany

Abstract Changes in the rates of erosion and accretion on slopes and river beds are expected in relation to climatic change. These changes are anticipated for the drainage basins of steep alpine torrents where a critical situation is being approached both on slopes subject to mass movements and the related river beds. The newly established EROSLOPE project confronts varying scenarios of climatic change by attempting to determine the probabilities of erosion on slopes and river beds in Alpine drainage basins. In order to define the susceptibility of the erosion of river beds, an ERC (Erosion Criteria) is established whereby the stress and resistance of specific shear planes is estimated. On the slopes the geometry of shear planes, determined by geophysical surveys, defines the amount of rock mass susceptible to movement. On the river bed the potential shear stress and the local roughness must be assessed by measurements of micro-topography. With such detailed surveys the potential amount of sediment that is available for transport into the fluvial system can be estimated for certain conditions, and the potential bed load volume transported out of the system can be assessed.

INTRODUCTION

Acceleration of erosion and accretion on slopes and river beds due to potential global hydrological change poses a hazard to a large proportion of the population especially in areas where present geomorphological processes are very active. This is true for many alpine catchments and forms the background for the newly established EROSLOPE project incorporated into the global change program of the European Union. The goals of this program are to determine the probabilities of erosion and solid material transport in alpine catchments under varying scenarios of climatic change. The program includes not only field observations and measurements, but also laboratory studies and the development of specific computer models.

The susceptibility of slopes and river beds to erosion is a well known scientific problem that has been tackled by earth scientists and engineers using varying approaches. In each case the main question deals with the conditions under which erosion will occur. Engineers as well as physicists are concerned with the forces in action at a critical moment, whereas earth scientists will visit the site, explore the "environmental" conditions and investigate the distribution of phenomena in order to define the boundary conditions causing the disequilibrium. As is apparent, both disciplines have their pros and cons and it therefore lies within the interests of the EROSLOPE project to combine different approaches.

River bed stability or, in other words, the critical conditions for erosion of bed load material can be investigated using a variety of different approaches. A host of criteria have been discussed using a wide range of parameters or properties both of boundary and hydraulic conditions. The most common approaches depend on "critical shear stress" (Shields, 1936), "critical stream power" (Bagnold, 1966), "critical discharge" (Schocklitsch, 1962), or "critical water velocity" (Hjulström, 1935). Lasting solutions for the problem have yet to be found (Carson & Griffith, 1987, p. 12) because boundary conditions vary greatly in time and space and the determination of representative parameters such as grain size remains a major problem. This is of particular relevance for mountain torrents where the grain sizes vary from sand to boulders and the related roughness can vary substantially both temporarily and spatially during a single flood event (Ergenzinger, 1992).

Aspects of slope stability are also becoming increasingly important under the menace of hydraulic change. Problems of slope stability are primarily studied under the category of "soil erosion" by soil scientists and geographers, and under the category "mass movements" by geotechnicians and geologists. The various approaches enable problems of erosion to be investigated in different ways. Empirical approaches, such as the well known Wischmeier & Smith (1965) formula exist in addition to the impulse approach for overland flow (Schmidt, 1991), not to mention the many models related to mass movements proposed by geotechnicians. As was demonstrated by Simon *et al.*, (1990), modern field techniques are of great importance in the determination of major material properties at the site. Since the greatest menace is created by mass movements in the alpine basins under consideration, even more diffuse erosion from surface runoff is here only of secondary importance. Studies on the susceptibility of erosion will therefore focus especially on phenomena associated with large and deep seated mass movements.

Using a probability approach for the relationship between resistance and shear stress, a safety factor or a factor of erosivity will be defined in a first attempt to outline a common criteria for the critical conditions on both slopes and river beds (Rocha, 1991). This approach will be exemplified by studies in the Schmiedlaine drainage basin at the northern border of the Alps in Upper Bavaria and in the Squaw Creek basin in Montana, USA.

STUDY AREA

The Schmiedlaine forms part of the Lainbach drainage basin and is situated 60 km south of Munich. Despite its small size (Table 1), the Schmiedlaine basin exhibits very diverse slope and river bed situations between its maximum altitude at the Benediktenwand (1801 m) and its confluence with the Kotlaine at about 750 m a.s.l. This variety is due to the great diversity in the geological and the geomorphological setting (Ergenzinger, 1992). Whereas the highest and steepest parts of the basin consist of Wetterstein limestone eroded by former mountain glaciers, the lower Schmiedlaine flows in a narrow V-shaped valley incised into mighty glacial deposits down into the Lechtal nappe and finally drains through the Flysch. Of most importance for the lowermost 2.5 km are glacial deposits created by the Loisach glacier which invaded this secondary valley several times,

Table 1 Characteristics of Schmiedlaine and Squaw Creek.

Characteristics	Squaw Creek	Schmiedlaine
Drainage area	105.7 km^2	9.4 km^2
Drainage length	20.3 km	3.4 km
Maximum height	3 154 m	1801 m
Average gradient	0.025	0.05
Drainage density	0.99 km km^{-2}	1.6 km km^{-2}
Annual precip. snow	457 mm	761 mm
Annual precip. rain	356 mm	729 mm
Forest cover	50%	75%
Channel width (average)	8 m	3 m
Channel depth (average)	0.3 m	0.3 m
Average flood (study site)	6.8 $m^3 s^{-1}$	14.6 $m^3 s^{-1}$
Average Q (study site)	0.35 $m^3 s^{-1}$	0.54 $m^3 s^{-1}$
D_{50} (bar surf., study site)	34 mm	86 mm
D_{84} (bar.surf.,study site)	56 mm	1150 mm

accumulating more than 160 m of rather soft material (Geologische Karte von Bayern 1:25 000, Blatt Kochel Nr. 8334). These deposits are the main sources for solid material which is transported through the valley and down the Schmiedlaine and Lainbach into the Kochel basin, creating the large alluvial fan of Benediktbeuern. Of special importance for this study is an extreme event with a 150 year recurrence interval and an estimated discharge of 75 $m^3 s^{-1}$ which occurred in the summer of 1990 (De Jong, 1992a).

Squaw Creek is situated at the foot of the Rockies in south-western Montana, Gallatin County, 42 km south of Bozeman. The measuring site lies just above the confluence with the Gallatin river. Details on the drainage basin and its characteristics are shown in Table 1. Down to its middle reach Squaw Creek flows through a formerly glaciated valley, the lower reach is a narrow canyon cut into Palaeozoic and Mesozoic sedimentary rocks.

Squaw Creek drains an area which contains andesitic and intrusive rocks (55%), pre-Cambrian gneiss (25%), Palaeozoic limestone, sandstone and shale (20%). The high percentage of magnetite (7.4%) contained in the andesites were the main reason for the establishment of the measuring site because bed load transport monitoring is dependent on magnetically induced signals. In fact 76% of the coarse bed load is of volcanic origin.

METHODOLOGY

For the study on river bed stability the following parameters were measured:

(a) longitudinal profile and 50 representative cross sections (Schmiedlaine);

(b) precipitation and water discharge;

(c) micromorphology and grain size of selected sites;
(d) bed load transport rates (Squaw Creek).

The techniques applied were as follows:

(a) **Geodetic surveys** (Schmiedlaine): After the event of 1990 a survey was conducted of the lower reaches of the Schmiedlaine. The longitudinal profile and 50 cross sections were measured and marked along the lowermost 2 km. In October 1993 this survey was repeated.
(b) **Geomorphological survey** (Schmiedlaine): The river bed changes during the years after the event were documented by mapping and oblique photos. The disturbances were mapped at a scale of 1:5000.
(c) **Micromorphology and grain size determination**: The grain size distribution and related roughness was studied in great detail at representative sites. The mini-Tausendfüssler (De Jong 1992b) was used for microprofiling of gravel bars and shallow river beds at 2 cm intervals. Grain sizes of the surfaces are determined by basket sieving as well as by the photo-sieving technique developed by Ibbeken & Schleyer (1986).
(d) **Bed load transport rates** (Squaw Creek): As described by Spieker & Ergenzinger (1990) and Ergenzinger *et al.* (1994) bed load measurements were monitored electronically during flood flows using two magnetically sensitive sills situated 30 m apart. The technique is based on the Faraday principal recording voltage pulses created by naturally magnetic particles passing over the sills. The lower size class detectable lies around 15 mm. Approximately 76% of the material is magnetic thus ensuring a large sample of the bed load was detected.

The studies on slope stability were undertaken in the Schmiedlaine basin with the help of the following techniques:

(a) **Geodetic surveys** with a theodolite in October 1993 and with a infrared laser theodolite in subsequent years in order to correct the existing topographic plan and as a basis for the geoelectric surveys of geophysicists.
(b) **Geomorphological mapping** including all slopes in the incised lower reach of the Schmiedlaine basin. A special map at 1:2500 was prepared for zones with active landslides.
(c) **Geophysical investigations** of parts of the basin were first accomplished by Bader (1985) in connection with the geological map. The fresh landslides of summer 1993 were explored by geoelectric surveys in order to determine shear planes and the distribution of humidity.

RESULTS

The susceptibility of river beds and valley slopes to erosion and accretion demands an understanding of the actual geomorphological dynamics of the area. Since these investigations are part of an impact study of climatic change, including the effects of potential hydrological change, the actual slope and river bed dynamics must be known in addition to the necessary projections for the near future. The scenario anticipated includes warmer summers and winters with less snow and more rainfall. Increased carrying capacity of warmer air will induce a related instability which will cause more thunderstorms, or at least a higher subsurface humidity due to increased summer rain. Changes in the vegetative cover are discussed by Ozenda & Borel (1991). In this study only two scenarios will be discussed in detail: summers with intensive thunderstorms (this situation is tackled from the experiences of summer 1990) and summers with a high number of rainy days and high subsurface humidity (this situation is treated according to the experiences of summer 1993). The following sections will first concentrate on studies of slope dynamics and slope stability, followed by studies on the related changes of the river bed in the lower reaches of the Schmiedlaine.

Susceptibility of slopes to erosion and accretion

The topic of slope stability or the susceptibility of slopes to erosion and accretion is becoming increasingly important under the menace of hydrological change. Amongst other factors, detailed studies are required on the mechanics of slope erosion and slope failures, the behaviour of mass movements, debris flows and weathering effects in threatened river basins. Fortunately, two quite extreme climatically induced situations occurred in the Schmiedlaine during the study period. Therefore two quite different examples can be presented.

During the night of 30 June to 1 July 1990 a thunderstorm originating directly above the Benediktenwand created 85 mm of rain and hail in only half an hour. Because the month of June was dry, the moisture content of the soils was low and the soil surface was cracked. Under these conditions the rainwater could only partly infiltrate and surface runoff occurred even in the hollows and swales under the forest. In hollows where both surface water and subsurface water flowed together, locally the grass sod was uplifted by the pore pressure of the subsurface water. All creeks of zero order that originated in such locations actively eroded and rejuvenated these lines of concentrated runoff. The material eroded in small rivulets on the slopes along the lowermost parts of the valley slopes adjacent to small slumps and landslides created an input of approximately 6000 to 15 000 m^3 into the torrent system. Even some small debris flows occurred in the lower parts of steep tributaries. Under these conditions the *Reissen*, nonetheless areas of maximum erosion, remained unaffected by high erosion rates (Becht, 1991). This situation emphasizes the importance of antecedent moisture conditions for erosion during extreme events.

Deep seated mass movements are very important for erosion on the slopes of the lower Schmiedlaine. The humid summer of 1993, with a precipitation amounting to double the normal for the month of June and July, was sufficient to rejuvenate an ancient landslide. Most of the mobilized material is still lying in the middle parts of the slope, but some mudslides have reached the river bed as forerunners.

To model the susceptibility of mass movements on the slopes of the lower Lainbach the proposal of Anderson & Richards (1987) is used. They combine geomorphological and geotechnical approaches and prove that a comprehensive procedure towards these problems quite promising. There are many constraints applying limit equilibrium methods for natural slopes (Maranha Neves, 1991), but to keep the approach simple and flexible, a recently proposed safety factor (SF) by Crozier (1986) is used for mass movements. This factor relates resistance of the shear plane to shear stress or of shear strength to shear stress:

$$\mathrm{SF} = (C + (W/A \cos \beta - u) \tan \theta)/(W/A \sin \beta) \qquad (1)$$

where: C = cohesion with respect to normal stress, W = weight of the material, A = area of shear plane, u = pore water pressure, β = angle of shear plane and θ = angle of internal friction with respect to effective normal stress.

The same author notes the three decisive factors for destabilization (Crozier, 1986, pp. 35-36):
(a) "Preparatory factors which dispose the slope to movement"
(b) "Triggering factors which initiate movement"
(c) "Controlling factors which dictate the condition of movement"
On the slopes of the lower Schmiedlaine, the main preparatory factor is shear planes of ancient landslides, the controlling factor is the specific local topographic conditions and the triggering event is the increased load due to a wet summer with an intensive rainfall event.

The determination of the shear plane geometry is fundamental for the calculation of the safety factor. Special geophysical surveys are necessary to gather the required information. At Schmiedlaine, geoelectric surveys were undertaken and the discontinuity of the water contents were interpreted as an effect of the shear plane. If the geometry of the shear plane and the properties of the material are known, the above mentioned function can be used to calculate the amount of water required to charge the slope material and to overcome shear strength or resistance.

Susceptibility of the river bed to erosion and accretion

The stability of the river bed must also be treated in a differentiated way. It is impossible to describe the stability of a coarse-grained river bed using average values of grains size, water depth or velocity. According to Carson & Griffith (1987, p. 12) a lasting solution of the problem will not be produced by the pursuit of correct values for critical shear stress, critical stream power or critical water velocity.

Even the determination of representative grain sizes for coarse-grained river beds is very demanding. At the Lainbach site the problem is partially solved by photo-sieving the surface material before and after the flood. Results can vary considerably, however, depending on whether boulders are included or not (Ergenzinger & Stüve, 1989). Since boulders can be considered as particles which normally create form roughness, but that become a special case of grain roughness during more extreme flood flows, it is difficult to decide how to deal with these extreme grain sizes (Bathurst, 1993). The decision must be taken according to the size of the flood under consideration. But what is the representative grain-size for a flood where the river bed is mobile and the surface material is renewed several times? To overcome this problem in the Lainbach and at Squaw Creek the bed dynamics and roughness were determined using the so-called "Tausendfüssler". This can be used to measure the microtopography of the bed both in cross profiles and longitudinal profiles (De Jong, 1992b). The device consists of a horizontal reference bar with vertical holes every 10 cm. The vertical distance between the river bed and the horizontal bar is measured with a rod as often as possible during the transit of a flood. This procedure has the advantage of measuring both the development of bed geometry with the necessary precision and simultaneously determining the K_3 value as a parameter of roughness. The K_3 parameter is defined as the maximum differences in depth between three neighbouring measurements (Fig.1). In order to obtain a good description of the roughness of a total section, maximum

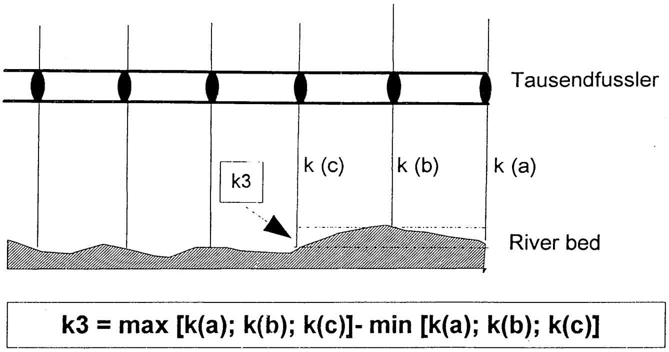

Fig. 1 Calculation of the K_3 roughness coefficient from the Tausendfüssler profiling device.

moving differences are calculated. The distribution of the K_3 values varies according to the part of the river bed and the flood situation. For example, the roughness of the bed will always decline with phases of intensive bed load transport. This is demonstrated with the help of measurements from Squaw Creek in Montana, USA, where both the number of magnetic particles transported and the related changes in geometry and roughness of different parts of the river bed (channel and bar) are known (Fig. 2).

An attempt to define the stability conditions of the river bed or vice versa, the susceptibility for erosion, is based on an suggestion by Grass (1982). In a description of the critical flow conditions for initial particle movement he defined the overlap area

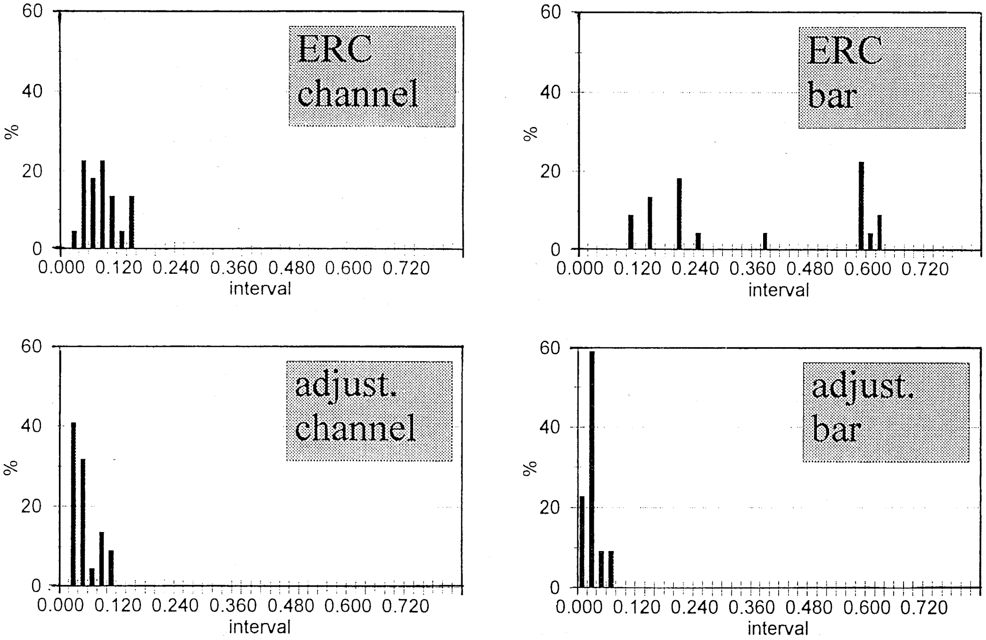

Fig. 2 Distribution of bed adjustment at 6 June between 3.45 and 6.00 and the ERC parameter for 6.00 a.m. for channel and bar (phase with moderate bed load transport).

between "the distribution of bed shear stress and the critical shear stress for the movement of individual "grains in the surface layer". Under natural conditions the critical shear stress for erosion of single particles cannot be measured. Therefore this parameter will be replaced by the distribution of the K_3 roughness factor. Using this approach the resulting Erosion Criteria (ERC) is very similar to the entrainment function of Shields: ERC = distribution of shear/distribution of resistance:

$$\mathrm{ERC} = \frac{\delta D_n S}{C(\delta_s - \delta) K_{3n}} \tag{2}$$

where δ = specific weight of water, δ_s = specific weight of particles, D_n = distribution of water depths, S = bed slope, K_{3n} = distribution of maximum differences and C = form parameter.

The power of this approach is demonstrated with the help of data and experience obtained during the flood of 5-6 June 1992 at Squaw Creek in Montana. This flood is selected for bed load transport, changes in geometry and roughness, discharge and the slope of water surface all of which were measured quite frequently during a 24 h period. The data set is part of the thesis of De Jong (1993) and was partly published by Ergenzinger *et al.* (1994). For testing purposes, measurements were selected during the passage of a secondary wave of bed load in the early morning. The first series of measurements was finished at 6.00 a.m., just before the onset of the bed load wave, the second measurement was terminated at 6.45 a.m. typical for the onset of a bed load wave, whereas the third measurements were undertaken during the times of maximum transport and maximum changes both in roughness and geometry.

Figure 2 shows the distribution of the ERC numbers and the rates of channel adjustment (compared to the cross section measured at 3.00 a.m.) for the channel and the bar segment of the cross section. If the C parameter of ERC is uniform, the high ERC values for the bar correspond with a situation of very little adjustment which indicates high stability in contrast to the lower ERC values for the channel which are indicative for changes on the bed. This situation is shown in cumulative frequency curves of Fig. 3. The closer the distribution of the values for ERC and adjustment, the

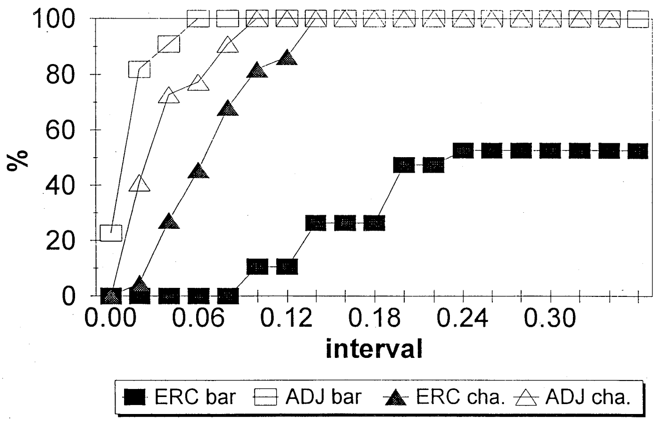

Fig. 3 Cumulative frequency of bed adjustment and ERC parameter for the same data as in Fig. 2.

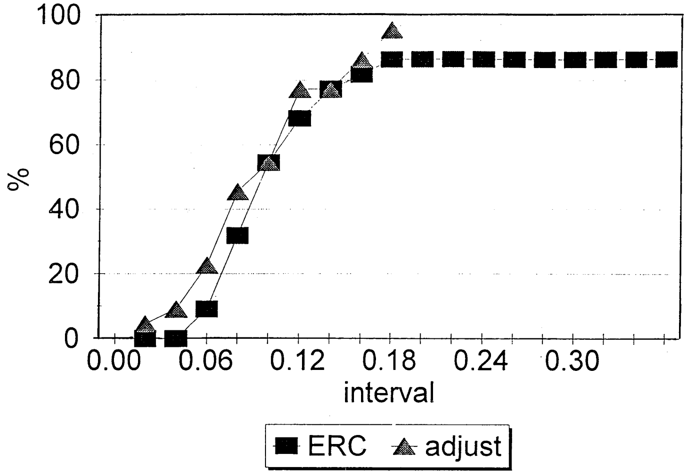

Fig. 4 Cumulative frequency of bed adjustment at 6 June between 6.45 and 7.10 and the ERC parameter for 7.10 for the channel (phase with intensive bed load transport).

more change occurs. It is notable that the distribution of these values went more or less parallel during the transit of the bed load wave (Fig. 4).

According to experience, these observations are quite typical for the behaviour of natural river beds and demonstrate that the stability of the bed of a natural river depends intensively on the rate of bed load transport. According to Ergenzinger (1988) the transport situation and the stability of the river bed can be divided into three different phases:

- In phases of random transport, as at 6 p.m., particles will be transported for hours and the ERC values in the channel will be similar to the bar (Figs 2 and 3). The related changes of the bed are minimal but not zero.
- At 6.00 a.m. the passage of some "families" of coarse particles created a typical situation of "wavy transport". Under these conditions pronounced vortex flow occurs even in straight reaches (Ergenzinger *et al.*, 1994) erosion and accretion occurs in small distinct areas.
- The most unstable situations occurs during intensive carpet like bed load transport. During such phases ERC values will not change intensively, but at least 15% of the distribution reflects high roughness values and the configuration of the river bed changes dramatically within a rather short time. This situation happened during the extreme event in the summer of 1990 when the entire river bed changed from a step-pool system to a system with a strong tendency towards braiding (Ergenzinger, 1992).

The potential of the ERC parameter is restricted for phases with low bed load transport and cannot match events of excessive bed changes due to a surcharge of bed load material.

CONCLUSION

In many alpine catchments mass movements are the most common local sources of solid material. Deep seated slope failures are very effective in locally producing high amounts of material during certain events. This will change the river bed dramatically (Ergenzinger, 1988) and the effects can be quite long lasting. The calculation of a safety factor, especially for slopes with scars of ancient mass movements, urgently requires investigations with geophysical techniques. A knowledge of the changing subsurface water condition scenarios for different hydrological impacts can be established.

If the river bed is known precisely from closely-spaced measured cross sections, the K_3 roughness coefficient and the distribution of ERC values can be computed for certain water depths and slopes. This procedure will produce some ideas on the stability of the river bed for phases with low bed load transport. However, during intensive carpet-like bed load transport, the instability of the river bed will increase considerably. These phases cannot be covered by the ERC procedure. The results and discussions on climatic and hydraulic change have shown that the most important approaches towards river bed adjustment should not primarily consider changes in the amount of flood runoff, but should consider the change in the amount of solid material transport connected with these floods. This fact stresses the importance of interrelated studies on the potential erosion of slopes and river beds.

Acknowledgements The Scientific Counsel of the European Union financed most of the investigations. The Deutsche Forschungsgemeinschaft (German Research Council) and the Research and Development Branch of the US Army is thanked for its additional support. Most of the data for this paper was provided from the PhD thesis of Carmen De Jong. Velocity data was provided by Paul Carling and his group. Help in the field was greatly appreciated by the research groups of Georg Christaller and Stephan Custer, and especially by Kristin Bunte, Carmen De Jong, Margarita Cruz Almanza, Albrecht Berner and other students. I am very grateful to Carmen De Jong for reviewing this article and revising the English.

REFERENCES

Anderson, M. G. & Richards, K. S. (1987) *Slope Stability, Geotechnical Engineering and Geomorphology*. Wiley, Chichester, UK.

Bader, K. (1985) Geophysikalische Untersuchungen, in: Geologische Karte von Bayern 1:25 000. *Erläuterungen zum Blatt Nr. 8334*. Kochel am See, München.

Bagnold, R. A. (1966) An approach to the sediment transport problem from general physics. *US Geol. Survey Prof. Pap. 422*, I, p. 37.

Bathurst, J. G. (1993) Flow resistance through the channel network. In: *Channel Network Hydrology* (ed. by K. Beven & M. J. Kirkby), 69-98. Wiley, Chichester, UK.

Becht, M. (1991) Auswirkungen und Ursachen von Katastrophenhochwassern in kleinen, alpinen Einzugsgebieten. *Z. Geomorphol.* NF, Suppl. **89**, 49-61.

Carson, M. A. & Griffiths, G. A. (1987) Bedload transport in gravel channels. *J. Hydrol. (NZ)* **26**(1), 1-151.

Crozier, M. J. (1986) *Landslides: Causes, Consequences and Environment*. Croom Helm, London.

De Jong, C. (1992a) The dynamics of a catastrophic flood/multiple debris flow in a confined mountain stream: an example from the Schmiedlaine, Southern Germany. In: *Erosion, Debris Flows and Environment in Mountain Regions* (ed. by D. E. Walling, T. R. Davies & B. Hasholt) (Proc. Chengdu Symp., July 1992), 237-245. IAHS Publ. no. 209.

De Jong, C. (1992b) Measuring changes in micro and macro roughness on mobile gravel beds. In: *Erosion and Sediment, Transport Monitoring Programmes in River Basins* (ed. by J. Bogen, D. E. Walling & T. J. Day) (Proc. Oslo Symp., August 1992), 31-40. IAHS Publ. no. 210.

De Jong, C. (1993) Temporal and spatial interactions between river bed roughness, geometry, bedload transport and flow hydraulics in mountain streams – examples from Squaw Creek, Montana (USA) and Lainbach/Schmiedlaine, Upper Bavaria (Germany). PhD thesis, Freie Universität Berlin.

Ergenzinger, P. (1988) The nature of coarse material bed load transport. In: *Sediment Budgets* (ed. by M. P. Bordas & D. E. Walling) (Proc. Porto Alegre Symp., December 1988), 207-216. IAHS Publ. no. 174.

Ergenzinger, P. & Stüve, P. (1989) Räumliche und zeitliche Variabilität der Fließwiderstände in einem Wildbach: der Lainbach bei Benediktbeuern in Oberbayern. *Göttinger Geographische Abh.* **86**, 61-79.

Ergenzinger, P. (1992) River bed adjustments in a step-pool system: Lainbach, Upper Bavaria. In: *Dynamics of Gravel Bed Rivers* (ed. by P. Billi, R. D. Hey, C. R. Thorne & P. Tacconi), 415-430. Wiley, Chichester, UK.

Ergenzinger, P., De Jong, C. & Christaller, G. (1994) Interrelationships between bed load transfer and river bed adjustment in mountain rivers: an example from Squaw Creek, Montana. In: *Series in Geomorphology: Process Models* (ed. by M. Kirkby), 141-158. Wiley, Chichester, UK.

Grass, A. J. (1982) The influence of boundary layer turbulence on the mechanics of sediment transport. *Euromech* **156**: *Mechanics of Sediment Transport*, 3-17.

Hjulström, F. (1935) Studies on the morphological activity of rivers (as illustrated by the River Fyris). *Bull. Geol. Inst. Univ. Uppsala* **25**, 221-452.

Ibbeken, H. & Schleyer, R. (1986) Photo-sieving, a method for grain-size analysis of coarse grained, unconsolidated bedding surfaces. *Earth Surf. Processes and Landforms* **11**, 59-77.

Maranha Neves, E. (1991) Methods of soil slope stability. Constraints of the limit equilibrium methods for natural slopes. In: *Prevention and Control of Landslides and Other Mass Movements* (ed. by M. E. Almeida-Texeira, R. Fantechi, R. Oliveira & A. Gomes Coelho). Report EUR 12918 EN. Comm. of the European Communities.

Ozenda, P. & Borel, J.-F. (1991) *Mögliche ökologische Auswirkungen von Klimaveränderungen in den Alpen. Vaduz.* Internationale Alpenschutz-Kommission.

Rocha, J. (1991) Erosion and sedimentation processes and evaluation. In: *Prevention and Control of Landslides and Other Mass Movements* (ed. by M. E. Almeida-Texeira, R. Fantechi, R. Oliveira & A. Gomes Coelho). Report EUR 12918 EN, Comm. of the European Communities.

Schocklitsch, A. (1962) *Handbuch des Wasserbaus.* Springer, Vienna.

Schmidt, J. (1991) A mathematical model to simulate rainfall erosion. *Catena Suppl.* **19**, 101-109.

Shields, A. (1936) Anwendung der Ähnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung. *Mitteilungen der Preußischen Versuchsanstalt für Wasser-, Erd- und Schiffbau* **26**, Berlin.

Simon, A., Larsen, M. C. & Hupp, C. R. (1990) The role of soil processes in determining mechanisms of slope failure and hillslope development in a humid-tropical forest, eastern Puerto Rico. *Geomorphology* **3**, 263-286.

Spieker, R. & Ergenzinger, P. (1990) New developments in measuring bed load by the magnetic tracer technique. In: *Erosion, Transport and Deposition Processes* (ed. by D. E. Walling, A. Yair & E. Berkovicz) (Proc. Jerusalem Workshop, March-April 1987), 169-178. IAHS Publ. no. 189.

Wischmeier, W. H. & Smith, D. D. (1965) Predicting rainfall erosion losses from cropland east of the Rocky Mountains. *Agric. Handbook*, 282.