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FIELD OBSERVATIONS ON HYPERCONCENTRATED FLOWS IN MOUNTAIN TORRENTS

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ABSTRACT

Field observations on hydraulics and sediment dynamics during extreme floods in two mountain torrents show the influence of man-made constructions such as bridges and check dams, in addition to the sediment supplied naturally by the basin and the channel network, on the formation of hyperconcentrated flows. In the Pyrenean Arás basin, hyperconcentrated flow occurred after collapse of a bridge, which in turn mobilized large volumes of sediment from the stream channel and, subsequently, destroyed a series of check dams. Boulders up to several metres in size were transported in a mixture of sand and fine material. A minimum of 100000 tonnes of sediment were deposited on the alluvial fan during the event. Prior to bridge destruction, mean bedload transport rates had reached 0·4 t m^{-1} s^{-1} upstream. In the alpine Lainbach basin, the flood was characterized by transportation of large amounts of slope material, including debris flows. Along its main tributary an intensive hyperconcentrated flow occurred during the rising stage, whereas in the main valley smaller flows occurred after failure of check dams. The depth of coarse material deposited reached 80 cm. The effectiveness of the Aràs and Lainbach floods was attained due to exceptional rates of energy expediture. Flood power ranged from 20000 W m^{-2} to 40000 W m^{-2} on average. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS mountain torrent; extreme flood; hyperconcentrated flow; flood power; bedload

INTRODUCTION

Floods are the extremes of the hydrological behaviour in river basins, events of high magnitude that occur rarely (Beven and Carling, 1989). They are of interest to water authorities, water supply bodies, emergency services, insurance agencies and planners. Scientific understanding of floods, including both water and sediment dynamics, are of use for planning and for dealing with the consequences of such events, especially in areas with strong environmental constraints related to the climate and to the geomorphology, such as those in mountain areas.

Floods in mountain regions may present a viscous flow consisting of a mixture of sand, silt and clay particles, in which big boulders can be transported. It has been found that these flows often show a non-Newtonian fluid behaviour, but rather a Bingham-type rheological behaviour (e.g. Costa, 1984). In addition, bedload transport rates have been found to increase with increasing fluid density, if the flow around the grains remains fully turbulent (Rickenmann, 1991). Hyperconcentrated flows are not uncommon in mountain regions, where significant amounts of sediment are either naturally supplied from tributaries, often as debris flows, or human-induced because of the failure of check dams and other constructions. Hyperconcentrated floods have also been reported for large rivers, such as the Yellow River (Li *et al.*, 1997), where annual maximum suspended sediment concentrations can reach more than 700 kg m^{-3} (Xu, 1997).

The purpose of this paper is to report on observations of flow and sediment dynamics in hyperconcentrated flows during two extremely high magnitude events in relation with man-made

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constructions: the Arás flood which occurred in 1996 in the Central Pyrenees, and the Lainbach flood which occurred in 1990 in the Bavarian Alps. No casualties occurred in Lainbach while 86 people died in Arás, during the so-called Biescas campground disaster.

CHARACTERISTICS OF THE EVENTS

The Arás flood

The Arás torrent is a tributary of the Gállego river, in turn one of the largest tributaries of the Ebro. It drains an area of 18 km^2 on Eocene flysch and Quaternary morainic deposits. The Aso (8 km^2) and the Betés (4 km^2) are its main tributaries. The Arás mean slope is 0·14 m m^{-1}, reaching 0·20 m m^{-1} on the lower stretches where 22 check dams were built during the 1940s to prevent flooding of the road to France. On 7 August 1996, a summer thunderstorm with mean intensity up to 250 mm h^{-1} caused a 60 min flash-flood. Maximum rainfall intensity probably reached 500 mm h^{-1} at the storm cell – a deposit of 500 litres was filled up in Betés town during the storm. The estimated peak discharge was 500 m^3 s^{-1}, equivalent to a 1000-year return period for the area. Specific discharges reached 20 m^3 s^{-1} km^{-2}, although the Betés basin contributed up to 75 m^3 s^{-1} km^{-2}. Two factors can be identified as responsible for the high magnitude of the event: (1) steep in-channel slopes which produced a high velocity flood-wave, and (ii) the high antecedent soil moisture caused by an unusual rainy season. Almost no debris flows or landslides were triggered within the catchment, reflecting the lack of soil infiltration during the vent. There were probably not many slopes which were unstable under these conditions. In contrast, mobilization of sediment from the stream bed and footslopes were extremely high. This resulted in the blocking and collapse of one bridge and the subsequent release of large amounts of sediment and the destruction of a series of check dams. That was a 'channel flood' rather than a 'slope flood', following Newson's (1989) categories.

The Lainbach flood

The Lainbach is an alpine torrent tributary of the Loisach river. It drains an area of 15·5 km^2, the Schmiedlaine (9·4 km^2) and the Kotlaine (5·1 km^2) being its main tributaries. The lithology consists of folded marls, limestones and sandstones, Tertiary flysch and Quaternary morainic deposits. The stream has a peaky discharge, with floods of 10 m^3 s^{-1} occurring four times annually. The Lainbach gradient lies around 0·2 m m^{-1}. The flood which occurred on 30 June 1990 was triggered by a heavy thunderstorm of 85 mm in 30 min, and involved transportation of large volumes of slope material, including some debris flows. The flood had an estimated peak of 170 m^3 s^{-1}, a 150-year return period for the area. Specific discharges reached 9 m^3 s^{-1} km^{-2}. High velocities in the main valley led to a highly destructive flood. Consequently, more than 40 per cent of check dams failed, delivering high amounts of bedload which blocked the Schmiedlaine bridge and destroyed the Lainbach road. In the Schmiedlaine basin hyperconcentrated flows on the rising limb of the flood were modified by the occurrence of two closely spaced debris flows in the boulder–gravel reach just before the confluence with the Lainbach.

Mean flow velocities ranged between 3·5 m s^{-1} and 7·5 m s^{-1} in both events. These values fall well within the range of velocities for hyperconcentrated flows recorded by a number of other workers (see summaries in Costa, 1984), although tend towards the lower part of the range due to their relatively low gradients.

RESULTS AND DISCUSSION

Hydraulics and sediment transport in Arás

At the first phase of the flood a bridge in the Aso valley upstream from the junction with the Betés torrent was blocked by rocks and organic debris. From field observations on hydraulic channel geometry, the old bridge was destroyed once it was overflowed by 2·5 m ($\pm$0·5 m) of water (d'),

Table I. At-a-section estimation of flood parameters during Arás and Lainbach events

	Flood peak (m^3 s^{-1})	Mean depth (m)	Mean width (m)	Mean velocity (m s^{-1})	Stream power (10^3 W m^{-2})	Bedload rates (t m^{-1} s^{-1})
Aso	130	2·5	11·0	5·0	20–25	0.41*
Betés	300	5·0	8·0	7·5	80–85	–
Arás	500	–	–	–	–	–
Schmiedlaine (braided)†	75	2·0	16·0	2·3	10–15	–
Schmiedlaine	75	1·5	23·0	2·1	12–18	–
Schimedlaine (bedrock)†	75	3·0	8·5	3·0	30–40	–
Lainbach	170	3·5	15.0	3·7	32–35	

*Estimated from upstream accumulation prior to the destruction of the Aso bridge
†From de Jong (1992)

approximately 15 min after the flood began. Orders of magnitude of volumes of water and sediment at the bridge collapse can be estimated from bridge geometry – 11 m width (w), 9 m depth (d), 60 m retention lengh (m) and 0·14 m m^{-1} upstream slope (s) – resulting in a bulk volume of sediment (v) of 2970 m^3 ($wdm/2$). Estimated errors in field observations of channel hydraulic geometry could attain ± 25 per cent. An order of magnitude of bedload transport rates (i_b) prior to the bridge destruction can be obtained from the stored volume of sediment as follows:

Bed-material density	$\rho_s = 2650$ kg m^{-3}
Submerged density	$\rho_s' = 1650$ kg m^{-3}
Storage porosity (Shen and Julien, 1992)	$h = 0{\cdot}17$
Submerged storage density	$\rho_b' = \rho_s'(1-h) = 1370$ kg m^{-3}
Time prior to bridge destruction	$t = 15$ m $\times$ 60 s m^{-1} = 900 s
Volume of storage	$v = 2970$ m^3
Mean bedload rate	$i_b = \rho_b'\ v/tw = 0{\cdot}4$ t m^{-1} s^{-1}

Assuming a submerged density of the stored sediment of 1370 kg m^{-3} and estimating an instantaneous volume of water overflowing the bridge accumulation of 825 m^3 (*c*. 825 tonnes from ($wmd/2$), the average density of the flow after bridge destruction can be estimated at around 1300 t m^{-3} (ρ'). This value is calculated from an instantaneous weight of water and sediment of 4895 tonnes (4070 tonnes of sediment plus 825 tonnes of water), corresponding to a volume of 3795 m^3 (2970 m^3 of sediment plus 825 m^3 of water). The calculation takes into account the interstitial water held within the stored sediment (h). Either in terms of concentration percentage by weight or by volume, these values fit well within the category of hyperconcentrated flows (Bradley, 1986).

In-channel stream power was very high, especially in the final reaches of the torrent, where the flow is constrained in a narrow funnel on glacial drift before it enters in the alluvial fan. Froude numbers remained around critical values at the flood peak in all sections. Flood power (ω) downstream of the bridge was of the order of 20000 W m^{-2} (Table I), from the stream power formula per unit of width, that is per unit of bed area (Leopold *et al.*, 1964):

$$\omega = \mathrm{g}\ Q\ \rho'\ s/w$$

where g is the acceleration due to gravity (9·8 m s^{-2}), Q is the discharge (m^3 s^{-1}), ρ' is the fluid density (kg m^{-3}), s is the slope and w is the channel width (m). For comparison calculations for similar extreme floods vary from 1000 W m^{-2} to 100 000 W m^{-2} in the Missoula flood, USA (Benito, 1997), to 6256 W m^{-2} in the Herbert Gorge, Australia (Wohl, 1992) and 12800 W m^{-2} in the Narmada River, India (Rajaguru *et al.*, 1995). The estimated unit upstream power for the largest floods on the alluvial Amazon and Mississippi Rivers is approximately 12 W m^{-2} (Baker and Costa, 1987). Data are reported from Benito (1997).

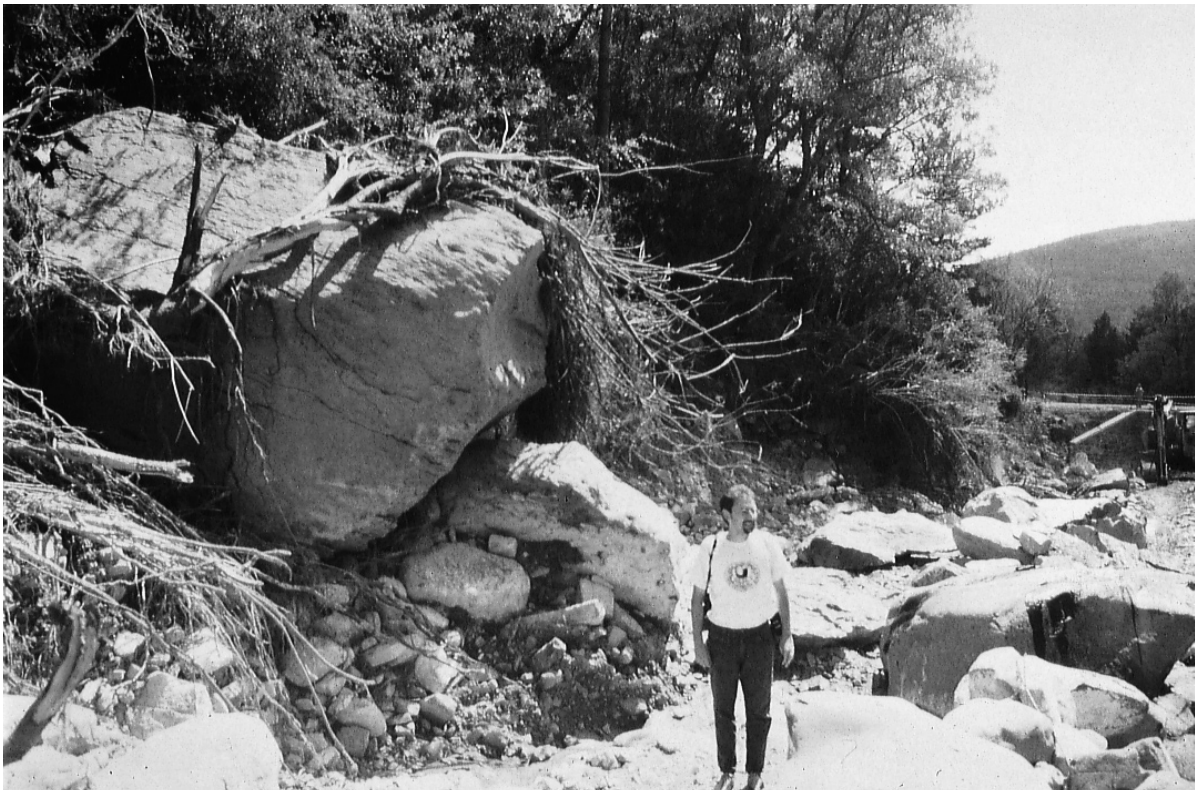

Figure 1. Mobilization of coarse material and channel incision in the Betés torrent, upstream from the confluence with the Aso

Power associated with the high-density floodwave was the main cause of the destruction of the check dams. Most of them had decametric dimensions but were supported only on metric blocks transported in the past by a glacier (García-Ruiz *et al.*, 1996). Even under the assumption of Newtonian flow, competence based upon the Baker and Ritter (1975) function for palaeofloods would have produced enough shear stress to entrain boulders of up to 10m (Batalla and Sala, 1996) (Figure 1).

The sedimentology of deposits at the torrent outlet and the geomorphologic effects of the flood have been described by White *et al.* (1997). River-bed degradation was especially acute in some reaches causing severe channel incision and erosion: lateral channels 20m wide and 10m deep were reworked in some sections. Therefore, in spite of the rarity of the event (a 1000-year return period flood), it achieved high effectiveness in terms of erosion and sediment transport capacity: (a) before the bridge destruction, bedload reached $0{\cdot}4\,\mathrm{t\,m^{-1}\,s^{-1}}$, and (b) when the bridge collapsed and the flow become non-Newtonian, it reached higher potential to transport even coarser material. The sources of fines supporting the hypothesis of hyperconcentrated flow were small-scale landslides on the valley footslopes, accumulation up stream from the bridge and the channel network itself.

The floodwave from the Aso torrent plus water and sediment flowing out from the Betés basin was powerful enough to entrain most of the sediment accumulated behind the check dams, destroying some of their retaining walls, weakening others and seriously damaging most of them. Once the barrier of boulders and all-size debris began to be deposited on the apex of the alluvial fan, very active upstream erosion would have excavated and demolished the remainder of the lower check dams, releasing all the sediment accumulated over years, while opening lateral water paths within the morainic tills. As a result of this process, a minimum of 100 000 tonnes of sediment, more than 1m of aggradation, was deposited on the fan.

Flood dynamics and sedimentation in Lainbach

The extreme thumderstorm in the Lainbach basin caused a very steep hydrograph, but sediment transport followed a different pattern. Along the Schmiedlaine an intensive hyperconcentrated flow occurred during the rising stage, whereas in the Lainbach several smaller ones occurred during the first half of the flood after failure of check dams. In the Schmiedlaine metre-sized boulders were moved in the upper bedrock reach; many were trapped in several log jams in the lower reach of incised meanders.

The observations of the collaborators working at the confluence of the Schmiedlaine and the Kotlaine were remarkable. At the start of the event they passed the bridge at the Schmiedlaine to reach the parking lot and only a quarter of an hour later the steep artificial channel of the Schmiedlaine below the bridge filled rapidly with boulders, closing the section and forcing the flood to flow around and over the bridge. During this phase the confluence was submerged with coarse sediment. On top of the coarse sediments the river created a uniform new river bed only shortly afterwards. Nearly all artificial bedload tracers deposited before the event were buried under a layer of 80cm of coarse material in an open framework without fine-grained interstitial fill. Only eight out of 400 bedload tracers were found after the extreme flood in the Lainbach between the site and the Benediktbeuern alluvial fan (de Jong, 1992). Once 85 particles were relocated at the zone of confluence of the Schmiedlaine and the Kotlaine, the search for tracers was terminated.

A massive layer of clast-supported material was deposited along the lower Schmiedlaine in many sections, which was created as the river reformed itself after the flood. These coarse sediments are typical of hyperconcentrated flows (Costa, 1986). De Jong (1992) suggested that they were moving in the Schmiedlaine as a high-density traction carpet (Todd, 1989). On deposition the layer was drained of the wet fluid matrix, causing the clasts to settle. The reduction of turbulence and of secondary flows by hyperconcentrated flows (Costa, 1986) caused the deposition of a series of levels at the edge of sharp channel curves. The bends and the decline in valley slope locally gave rise to the build-up of tongue-like accumulations of coarse cobbles and boulders. Separated by an abrupt discontinuity, the coarse sediments are covered by a thick matrix layer of stratified material although, locally, this material is interspersed with cobbles. This corresponds with debris flow inputs from several steep mountain creeks. They occurred mostly during and shortly after peak flow and were therefore deposited on top of the clasts. A similar deposition pattern has been described by White *et al.* (1997) during the high-density phases of the Arás flood.

Flow velocities in the Schmiedlaine decelerated from the deep flows in the upper bedrock reaches to the shallower flows in the distal reaches. Bedrock and narrow reachers were subject to the highest stresses during the flood, decreasing in the lower and meandering gravel-bed reaches. Stream power ranged from 30000W m^{-2} down to 10000W m^{-2} respectively, reaching 40000W m^{-2} in some bedrock areas (Table I).

Volumes of erosion and accretion did not always correspond with stream power locally; values below 12000W m^{-2} generally caused high amounts of deposition whereas those above 14000W m^{-2} eroded normally. Average Froude numbers did not fluctuate greatly along the river and even remain subcritical. Pierson (1980) describes this behaviour as representing the result of increased viscosity and the flow being characteristically laminar.

CONCLUSIONS

Data on the Arás and the Lainbach catastrophic flood events throw light on the role of construction failure in the formation and development of hyperconcentrated flows, their power and carrying capacity, and the magnitude of the associated sediment transport. They showed clear evidence of a non-Newtonian flow behaviour, both in sediment concentrations and in depositional features. During the first event, flow reached a sediment concentration of the order of 300kg m^{-3} and this was produced after the collapse of a bridge. More sediment was supplied downstream by the subsequent release of sediment from a series of check dams. In the second event, check dams were mostly destroyed by a hyperconcentrated flow formed out of slope materials and debris flows. Both events show similar values of flood power (20000 to 40000 W m^{-2} on average) as well as similar sedimentological patterns and thickness of the downstream deposits (> 1 m). Bedload rates during the Arás flood reached 0·4 t m^{-1} s^{-1}, similar to those obtained experimentally on hyperconcentrated flows by Smart and Jäggi, Meyer-Peter and Müller and Rickenmann (all in Rickenmann, 1991), using both uniform grain size and mixtures.

The significance of a given discharge capable of doing geomorphic work over a period of time is determined by two main factors: event magnitude and frequency. The concepts of magnitude and frequency of geomorphic processes were developed by Wolman and Miller (1960). One of the principles they presented is that, especially in rivers of humid temperate environments, the effective geomorphic force is a relatively frequent event. Results from the Arás and from the Lainbach floods point out that highly effective geomorphic work is accomplished, at least in very energetic mountain environments, by extreme events of high magnitude and high rate of energy expenditure, as stated by Baker (1977) generally. Both floods developed erosional landforms, especially severe degradation of the channel network, and depositional landforms, such as sedimentation in the alluvial fan in the case of the Arás and in the valley floor in the case of the Lainbach.

In addition, catchments of approximately 10 km^2 seem to have valley and hydraulic characteristics that optimize flow depth, energy slope and velocity to maximize flood power (Baker and Costa, 1987, in Newson, 1989). Costa (1987, in Newson, 1989) added that maximum flood peaks originate from an optimal combination of basin morphology, physiography and storm intensity. Observations reported here reinforce this hypothesis, although the role of man-made constructions, such as bridges and check dams in mountain torrents, and the antecedent soil moisture conditions should be added to broaden Costa's description. Such catchments also provide maximum likelihood of non-cohesive sediment gravity flows, debris flows and other forms of hyperconcentrated sediment transport mechanisms (Newson, 1989), as has been reported for the two events described in this paper.

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