Hydrology in Mountainous Regions. II - Artificial Reservoirs; Water and Slopes
(Proceedings of two Lausanne Symposia, August 1990). IAHS Publ. no. 194, 1990.

Debris flows 1987 in Switzerland: geomorphological and meteorological aspects

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ABSTRACT In the Swiss Alps three major regions with areas of 70 to 500 km^2 were heavily affected by numerous debris flows during two storm events in summer 1987. Based on a qualitative and quantitative interpretation of aerial photos and field investigations, the spatial distribution of the debris flow events was mapped and geomorphological properties were assessed. The analysis of rainfall amounts and intensities gave more or less similar behaviour in the three regions. The spatial distribution shows a distinct concentration of debris flows in the periglacial belt as well as several clusters of events in small tributary valleys. This distribution pattern could be only partly explained by the meteorological conditions.

INTRODUCTION

In the alpine and prealpine areas of Switzerland debris flows are a widespread geomorphological phenomenon. Within a single catchment however, the recurrence of such events is irregular and may take place after long intervals of inactivity. Therefore, systematic observation and investigation of debris flows is difficult. During the two major storm events in summer 1987 (17-19 July, 23-25 August 1987) a large number of debris flows occurred in several parts of the Alps (Switzerland, Italy, Austria; cf. Richter, 1987, Smiraglia, 1987, Zeller & Röthlisberger, 1988 or Naef et al., 1989). Damage to settlements, traffic routes and other infrastructures was severe. In the Swiss Alps the Puschlav, Lukmanier and Gotthard areas were badly hit. The simultaneous occurrence of many events provided the opportunity to investigate important aspects of alpine debris flows (Haeberli et al., 1990 a,b; Rickenmann 1990, Rösli & Schindler, 1990). In the present paper geomorphological characteristics and meteorological aspects are discussed.

DISTRIBUTION PATTERN OF 1987 DEBRIS FLOWS

About 600 debris flow events were systematically mapped in the three regions (see Table 1). This documentation is based on an interpretation of infrared and black-and-white airphotos and of oblique photos from helicopter flights. In order to confirm evidence of recent debris flow occurrence on slopes or in channels and to discern debris flows from other processes, such as rock slides or fluvial processes, several definite criteria were used (eg, Johnson & Rodine, 1984 or Costa, 1988): (1) u-shaped depth erosion with a width to depth ratio of less than about 5, (2) cleared gullies and polished rock, (3) marginal levees along the flow path built up with mainly coarse debris and boulders, and (4) unsorted debris lobes and debris cones with large boulders. The debris flow activity in the 3 investigated regions is summarized in Table 1 (all the figures are rough estimations):

TABLE 1 Areas affected by debris flows.

Date of occurrence	Area	Size km^2	Debris flows number	Eroded vol. 10^3 m^3	Unit erosion m^3/km^2
18/7/87	Puschlav	60	70	400	6700
18/7/87	Lukmanier	300	90	500	1700
24/8/87	Gotthard	500	300	750	1500
	Bedretto[1]	140	140	500	3600

[1] Centre of Gotthard area

The spatial distribution of debris flow activity in these regions is very heterogenous. A dense pattern of debris flows with high values of specific erosion was found in the Puschlav area and between Bedretto and Urseren Valleys (part of Gotthard area). One of the largest events of 1987 in Val Varuna (Puschlav area) is estimated to have eroded more than 200'000 m^3 of material. This explains the specific erosion of 6700 m^3/km^2. The distribution patterns have the following characteristics (Fig. 1 shows the pattern in the Gotthard and Lukmanier areas):

- All altitudinal belts were affected by debris flow activity. However, a striking concentration of starting zones was observed in the periglacial belt (above about 2200 - 2400 m a.s.l.), especially in the Puschlav area (Zimmermann & Haeberli, 1989). The starting zone of about 70% of mainly large scale events is above 2300 m a.s.l.

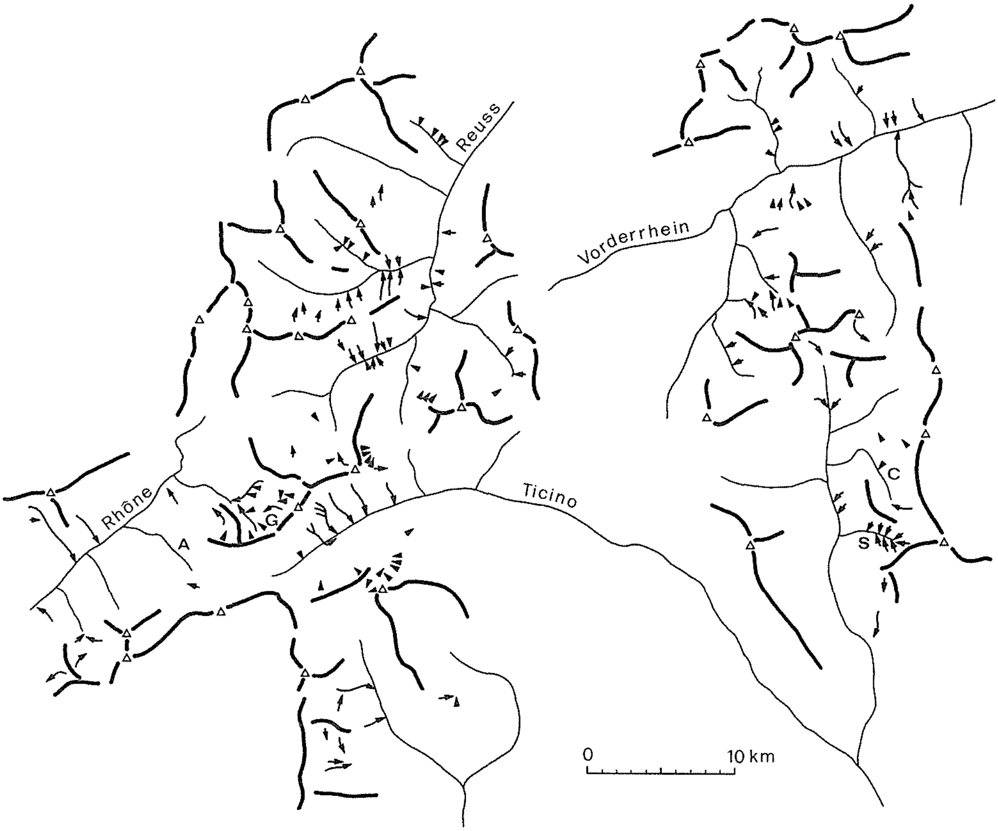

FIG. 1 Distribution pattern of debris flow events in the Lukmanier and Gotthard areas. S: Val Soi, C: Val Carassina, G: Geren Valley, A: Aegenental. Each arrow indicates a large or a group of smaller debris flows.

- Some valleys have clusters of events (Val Soi; Geren Valley) whereas neighbouring catchments with similar conditions for debris flow initiation show only a small number of debris flows (Val Carassina; Aegenental).
- In many cases the boundary between heavily affected and unaffected areas is striking: For instance in the north face of Vorderrhein Valley the starting zones are at an altitude between 1600 m and 1900 m a.s.l.; steep talus slopes and moraines at higher altitudes are absolutely untouched.

Only in two cases (Val da Plaunca, Vorderrhein Valley and Spitzigrat near the village of Andermatt, Gotthard area) was the occurrence of debris flows not to be expected either on the basis of the geomorphological setting (silent witnesses, mainly on the cone) or the historical records. In most other cases there was clear evidence of events having occurred in the past. In all regions a large potential for future debris flows still exists.

GEOMORPHOLOGICAL CHARACTERISTICS

About 80 debris flows with an eroded volume of more than 1000 m^3 per event could be analysed on aerial photos and partly also by field reconnaissance. According to a classification by Takahashi (1981), the starting zones of the debris flows could be devided into two main categories:

Slope type starting zones

The starting mechanism consists of an oversaturation of loose debris with subsequent slide. Surface runoff is either not evident or is concentrated only in shallow channels:

1) The starting zone is on a steep and deep-seated slope of slightly consolidated debris (mainly holocene moraines). Slope angles are between 25° and 38°. In many cases the scars were enlarged by retrogressive erosion (eg, Witenwassern or Cristallina, both in the Gotthard area). In a few cases only (Geren Valley, Gotthard area), shallow slides occurred in the active layer of permafrost areas, similar to events in northern Sweden reported by Larsson (1982).
2) The starting zone is in the contact zone of a steep rock cliff with an adjacent talus slope. Slope angles varies in the same range as type 1). The water is concentrated in gullies on the rockcliff and seeps in to the scree (Palü or Varuna Valley, Puschlav area)

Valley type starting zones

The starting mechanism is a liquefaction of the torrent bed or the sudden outburst of a clogg mass of water and debris:

3) Moraine filled steep rock couloirs were eroded down to the bedrock basis (Minstiger Valley, Gotthard area or Cambrena, Puschlav area). Slope gradient was found to be 45% and about 70% (24° and 35°).
4) Parts of the debris-bed in a steep channel get suddenly mobilized and a debris flow forms (Val Zavragia or Val Luven, Lukmanier area). Slope gradient varies between 23% and 65% (13° and 33°).

The largest starting volumes were found in the type 1) starting zones. Maximum erosional cross sections were about 450 m^2 and maximum erosion depth about 15 m. These maximum values agree with values found for debris flows from small Alpine glacier floods (Haeberli, 1983). The contributing catchments above the starting point were in general very small: 90% smaller than 1 km^2, 40% smaller than 0.1 km^2. The correlation between the catchment area above the starting point and the slope gradient in the starting zone is shown in Fig. 2. Median catchment area of valley type starting zone (types 3 and 4) is about 60 ha, of slope type starting zone (types 1 and 2) only 9 ha. The steeper the slope the less important is the channelised surface flow. A clear trend have the valley type debris flows (open signs), whereas the slope type debris flows show only a weak correlation. This corresponds with data published by Takahashi (1981).

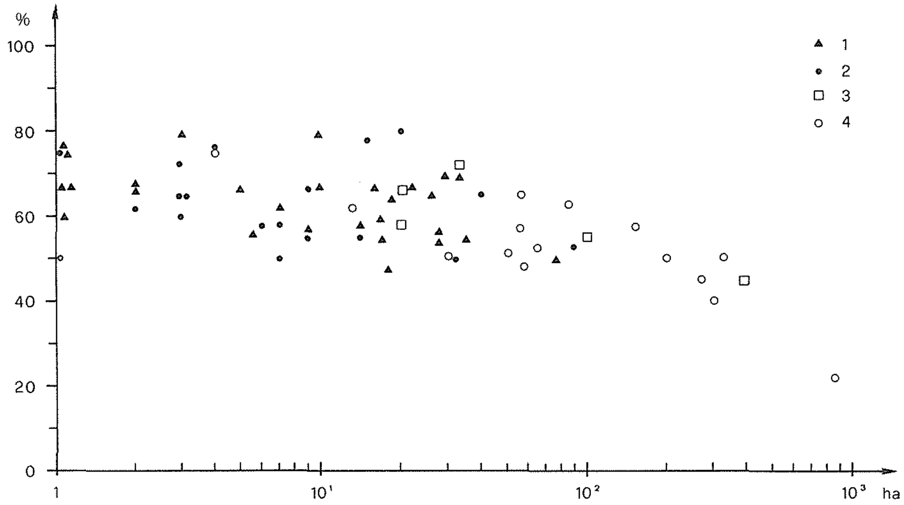

FIG. 2 Slope gradient of the starting zone as a function of the catchment area above the starting point.
1-4: Types of starting zones.

The runout distance (expressed by the mean slope) plotted as function of the catchment area at the cone and of the total volume is given in Fig. 3 a and b. In a large catchment there is, under equal rainfall conditions, in general a high runoff. This additional water influences the viscosity of the flowing mass and therefore the runout distance. In addition, a distinct channel from a large basin prevents the debris flow from spreading out and losing flow depth. Larger debris flows or pulses of debris flows have a longer travelling distance than smaller ones. Similar correlations are found for

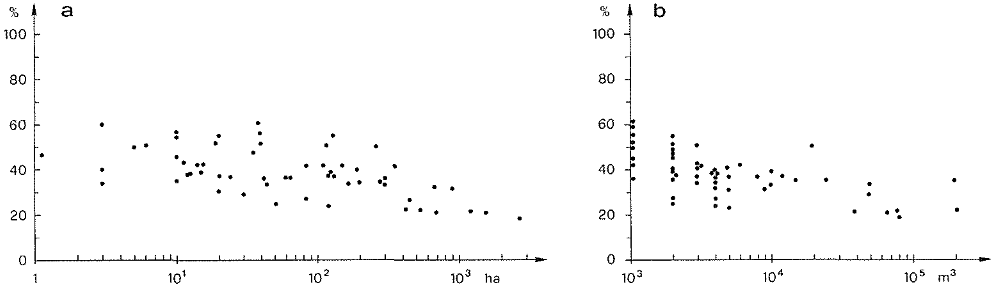

FIG. 3 Relation between mean slope of debris flows and catchment area at the cone (a) and total volume of debris flows (b).

ice avalanches (Alean 1984) or for rockfall events (Scheidegger 1973, Körner 1983). However, the deviation is much larger than from rockfalls, for example, and the mean slope is in no case less than 19% (11°). Losses along the flow path due to the building of levees were estimated to be 5 to 10 m^3/m. This loss is of great importance for small scale debris flows.

Cones, shaped by debris flows mainly have a very rugged surface. Large boulders are spread over the whole cone. The longitudinal profile compared to fluvial cones is steeper. These characteristics represent the distinct sedimentation processes. 80 to 90% of the total sediment load from 1987 events was deposited on the well developped debris flow cones. The sediment delivery to the river systems was relatively low. In the Urseren Valley, for example, total sediment transfer from 15 debris flows was about 50'000 m^3, the sediment input into the River Reuss was negligible. Control works on a cone, like deflection dams or river channelisation prevent the sedimentation. It is, therefore, important to enable the debris flow to spread out on the cone. This characteristic of natural sedimentation has to be taken into account for future land use or for technical measurments.

METEOROLOGICAL CONDITIONS

The hydrometeorological conditions for debris flow initiation may vary widely. Rainfall intensity, accumulated rain during the storm event as well as antecedent precipitation are important factors for triggering debris flows (Campell, 1975). Very small rainfall amounts are required, for exemple, in polar areas. Larsson (1982) describes a storm event in Spitsbergen of about 30 mm within 12 hours with heavy debris flow activity on slopes. The meteorological situation of summer 1987 was investigated by Grebner and Richter (1989). They produced maps with 3-h-isohyetes for the two rain storms in the Swiss Alps. These maps were used to estimate rainfall amount and intensity in the three mainly affected regions. In the Lukmanier area (17-19 July) the main part of the storm event lasted 30 to 40 hours. The time of occurrence of debris flows (reported by witnesses) was between 12 and 30 hours after the onset of the main storm. In this period the accumulated precipitation varied, therefore, from 90 to 170 mm. Medium rainfall intenisity was about 15 to 45 mm/3 h, not to mention the normal variability. Due to the synoptic weather situation no short time peaks were to be expected. The antecedent rainfall amount 20 days prior to the events was about 30 to 100 mm.

In the Gotthard area (23-25 August), after a 40-hour rainfall with medium intensities between 15 and 50 mm/3 h, an intense downpour of 40 mm/h followed at midnight of 24 August. A raingauge in Bedretto, in the centre of the intense rain cell, recorded this peak. Nearly all of the debris flows that reached the valley bottom with its settlements and roads, occurred around midnight. The accumulated rainfall reached between 150 and 200 mm in the north and upto 260 mm in the south of the Gotthard area. The conditions prior to the events were much drier than for the July storm: only 15 to 30 mm fell within the 20 days before.

A special case is the debris flow in the Minstiger Valley (Goms) which damaged Münster at noon, ie, about 12 hours before the extreme rainfall event. A water pocket rupture in Minstiger Glacier is assumed as the triggering mechanism of the debris flow originating in a rocky couloir filled with morainic material.

SPATIAL DISTRIBUTION AND RAINFALL

The spatial pattern of heavy debris flow occurrence in the Gotthard area coincides approximately with the 50 mm isohyete of the 3 hours around midnight, even if the accumulated precipitation varies by a factor of 2 within the whole region. In contrast, the debris flow events in the Lukmanier area lie not in the centre of the storm with high intensities (up to 150 mm/3 h) and very high total rainfall amounts (more than 400 mm in 36 hours). It is assumed that strong snowmelt in the first days of July had contributed a continuous input of moisture into the scree in the Lukmanier area. On the other hand, it is probable that earlier events (mainly in 1978) had emptied many channels in catchments susceptible to debris flows in the central areas of the July 1987 storm. It is assumed that the occurrence in clusters within all of these 3 regions is a result of local meteorological effects in narrow and deep-cut tributary valleys.

In both cases the striking concentration of debris flow activity in the periglacial area may be explained by the high air temperature during the events. Precipitation fell as rain in the highest catchments (over 3000 m a.s.l.) even at the end of the storm.

CONCLUSIONS

Most debris flows of the 1987 storm events occurred in gullies or on slopes where debris flow activity had to be expected on the basis of geomorphological signs and/or of past documented events. The extraordinary situation in 1987 is given by the simultaneous occurrence of numerous events in 3 large areas. For the triggering of debris flows, precipitation is an important but not the only critical factor. Hydrological conditions days and probably weeks before the event, as well as the chronology of events in the catchment, are essential for debris flow initiation. The events in 1987 made clear that debris flows are a great hazard and that they will be more important in future due to intesified use of alpine regions. The determination of areas susceptible to debris flow initiation is possible with the knowledge of the type and characteristics of the starting zone. The time of occurrence, however, can hardly be predicted. On the cone the sedimentation characteristics have to be taken into account: Large volumes of boulders, gravel and sand are trapped under natural sedimentation conditions. A massive channelisation may force a debris flow to travel over the whole cone and to cause greater damage in the main river.

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