Debris flows as a factor of hillslope evolution controlled by a continuous or a pulse process?

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Abstract: Flood effectiveness observations imply that two families of processes describe the formation of debris flow volume. One is related to the rainfall–erosion relationship, and can be seen as a gradual process, and one is related to additional geological/geotechnical events, those named hereafter extraordinary events. In order to discuss the hypothesis of coexistence of two modes of volume formation, some methodologies are applied. Firstly, classical approaches consisting in relating volume to catchments characteristics are considered. These approaches raise questions about the quality of the data rather than providing answers concerning the controlling processes. Secondly, we consider statistical approaches (cumulative number of events distribution and cluster analysis) and these suggest the possibility of having two distinct families of processes. However the quantitative evaluation of the threshold differs from the one that could be obtained from the first approach, but they all agree in the sense of the coexistence of two families of events. Thirdly, a conceptual model is built exploring how and why debris flow volume in alpine catchments changes with time. Depending on the initial condition (sediment production), the model shows that large debris flows (i.e. with important volume) are observed in the beginning period, before a steady-state is reached. During this second period debris flow volume such as is observed in the beginning period is not observed again. Integrating the results of the three approaches, two case studies are presented showing: (1) the possibility to observe in a catchment large volumes that will never happen again due to a drastic decrease in the sediment availability, supporting its difference from gradual erosion processes; (2) that following a rejuvenation of the sediment storage (by a rock avalanche) the magnitude–frequency relationship of a torrent can be differentiated into two phases, the beginning one with large and frequent debris flow and a later one with debris flow less intense and frequent, supporting the results of the conceptual model. Although the results obtained cannot identify a clear threshold between the two families of processes, they show that some debris flows can be seen as pulse of sediment differing from that expected from gradual erosion.

Observations of debris flow in small alpine catchments show at first sight the existence of two 'types' of events: ones that are frequently produced by sediment sources that are near and/or within the stream and that do not significantly change the morphology of the stream bed; and ones that incise the stream bed deeply, changing the catchment in the long term, which could be related to rare, but major, events. The flood effectiveness (in the sense of Wolman & Gerson 1978) resulting from these two 'types' of event differs strongly. Observations related to alpine debris flows made by other authors show the existence of extraordinary processes of erosion (at least at a local scale) very different from the gradual erosion behaviour on a short time scale (e.g. Haeberli *et al.* 1991; Tonanzi & Troisi 1996). Is this apparently unsteady behaviour of the system reflecting a continuous process, the existence of two kinds of processes separated by threshold crossing, or the existence of a gradual and an extraordinary behaviour of catchments?

The geomorphological systems we consider here range from dismantling cliffs to the alluvial fans, referred to hereafter as the alpine catchment system. The component on which this paper focuses is the volume of sediments exported out of the system or stored on the fans, mainly by debris flows. The relative magnitude of the events (e.g., 'normal' or 'catastrophic' events) will be defined according to whether the catchment exhibits steady or unsteady behaviour, a distinction which is made according to the effectiveness of the event (Newson 1980). A system in a steady-state is defined as one in which the evolution of the slope proceeds by erosion (in the broad sense) that is proportional to the intensity of the tectonic and climatic agents and consequently that can be correlated with them (Schumm 1977; Burbank & Anderson 2001). A system which is not in a steady-state is defined as one where disruptive erosive events occur, which strongly deviate from the erosion–climatic agent relationship. This could be induced by widespread erosion over the basin (Nouvelot 1990; Meunier

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1991; Cannon *et al.* 2001), delivery of sediment to the stream system by landslides (Ellen & Fleming 1987; Jakob *et al.* 1997), internal erosion of the stream bed (Koulinski 1993; Zimmermann *et al.* 1997) or a combination of these factors. When generalized to a major part of the catchment, these various erosive events can be viewed as differing from the 'normal operating' conditions of the catchment. This unsteady-state behaviour of erosion was recognized some time ago as a possible evolutive process of the geomorphological system and has recently been modelled in geomorphological studies (e.g. Tucker & Slingerland 1996; Pinter & Brandon 1997).

To study the sediment dynamics of the alpine catchment system, several approaches can be followed. In the first step, data analysis (at a regional scale and at a local scale) is performed to see if some classes could be defined, reflecting the existence of two 'types' of events. Then a simple conceptual model was built in order to look at the relationship between the components of the alpine catchment system. Finally, case studies analysis was used to verify and discuss the results obtained.

Data sources

In the Alps only a few catchments have been systematically surveyed and instrumented. Thus, available time series of sediment fluxes are generally incomplete and inhomogeneous for a given catchment. For this reason, analysis is often done at a regional scale, in order to increase the amount of data. The data used in this study comes from the Swiss Alps and was collected mainly during the last 25 years. Repeated rain storm events and intensification of land use during this period have highlighted the problems caused by sediment transfer. The data comes from Swiss official syntheses (OFEE 1991; Haeberli *et al.* 1992; Rickenmann & Zimmermann 1993; Zimmermann *et al.* 1997; OFEG 2000; BWG 2002; Petraschek & Hegg 2002), as well as unpublished operational reports and a survey carried out by the authors.

Exploratory data analysis

On the basis of the available data, a descriptive approach relating the event volume to the sole catchment area was performed in order to characterize the catchments and the associated events. This general approach gives a scattered result which is difficult to analyse. In a second step, it was interesting to relate the event volume to the specific difference of level, a property of the catchment that is more characteristic for sediment production.

Methods

Volume of one event v. catchment area. One of the basic relations used to study a debris flow is to relate its volume to the catchment area. This kind of representation has been used in past studies attempting to predict debris flow volume (Kronfellner-Kraus 1984; D'Agostino 1996; Rickenmann 1999). As the data sources were different, and because the reported volume possibly was only a fraction of the total volume (especially for small tributaries that reach the main river when it is in flood), we tried to estimate the potential error on the total volume of sediment.

Volume of one event v. specific difference of level. In order to take into account the morphometry of the catchment, which has a great influence on the sediment dynamics (Evans 1997), the specific difference of level, D_s (Melton 1965; Marchi & Brochot 2000), was used,

$$D_s = \frac{alt_{max} - alt_{min}}{\sqrt{A}}$$

where alt_{max} and alt_{min} are the minimum and the maximum altitudes of the catchment, expressed in masl, and A is the catchment area, expressed in square metres.

Based on the reports, we tried to define the causes of the magnitude of the events. If the events seemed to be influenced by other causes than the rainfall–erosion relationship, such as a lake outburst or deep erosion, we classed them under the appellation 'extraordinary geological causes evident' (cf. Fig. 2).

Results

Figure 1 plots the volumes of debris flows as a function of the catchment area in which they occurred. This graph shows a very large dispersal of the data, and it should be noted that these data only represent values from events sufficiently extraordinary to be listed by the Swiss cantonal and federal services. This scattering of volume data is observed all over the European Alps (Kronfellner-Kraus 1984; Franzi 2001), but the overall trend is to have bigger debris flows in wider catchments. Comparison of the data with formulas that infer event volume from the catchment area showed that they give results one or more orders of magnitude higher or lower than the reported data. As a consequence, the area of the catchment alone cannot explain the variability of the observed volumes: the sediment supply is a function of the area, but is also related to other parameters.

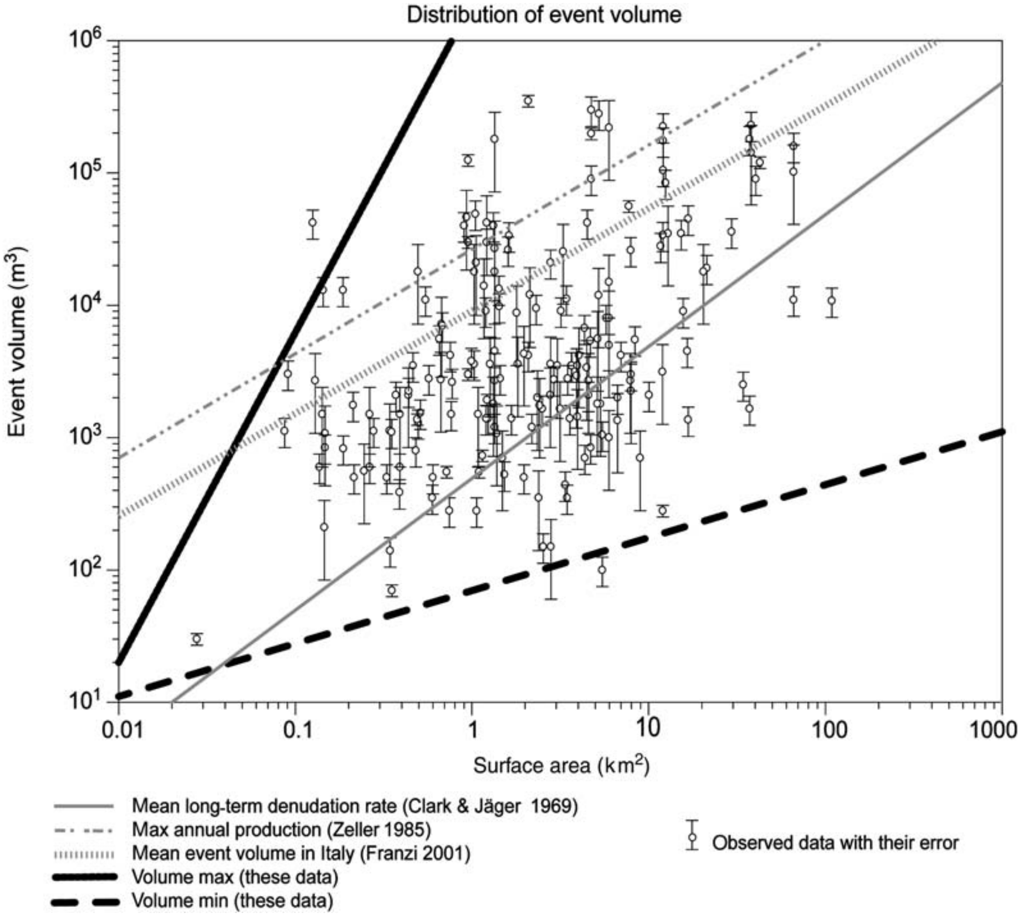

Fig. 1. Diagram showing the volume as a function of the catchment area and displaying other volume–area relations found in the literature.

However, it is interesting to consider the formula of Zeller (1985) depicting the maximal annual volume (in the Swiss Alps) and that of Franzi (2001) representing the mean volume of an event (in the Italian Alps). The two formulas have the same increasing trends that differ from the trend obtained with the long-term denudation rate (e.g. Clark & Jäger 1969).

In spite of this difference between the theoretical long term denudation rate and real event volume, the data seems to present – at least on a regional basis – a continuum. However, a closer look at the data base showed that, for the same catchment, the volume ranged over two orders of magnitude. Some of the reported events showed that catchments already known for the debris flow production (i.e. with data concerning 'normal' events) could be hit by intense mass wasting or extraordinary erosion processes resulting in debris flow volume significantly higher than that observed before. Table 1 shows that the operating of the catchment could differ from the classical rainfall–event relationship that gradually erodes the storage of sediments. These causes may then be viewed in terms of disequilibrium. The main causes of disequilibrium of the system reported in the Alps were glacial lake outbursts, blockage by rock fall and extreme erosion (cf. Table 1). Erosion could be seen as extreme when, for example, a moraine bastion was entrenched (a value of 250 m^3/m on a short reach was reported by Tonanzi & Troisi 1996) or when the torrent bed was deeply eroded, that is, by several metres – 5–7 m are reported from operational surveys. This represents two to three times the height of the former cross-section of the torrent (Petraschek, pers. comm., Chambon *et al.* 2005, and authors' observation). Such erosion led to an average sediment production of 50–70 m^3/m

Table 1. *Causes of some events with high magnitude that occurred during the nineteenth century in the Canton of Valais*

Name	Area (km^2)	Date	Volume (m^3)	Causes
Baltschiederbach	42.64	14 October 2000	120,000	Very heavy rainfall over a long period + no previous event for a long period
Saxé	0.95	10 November 1939	125,000	Hydrogeological enhancement in conjunction with very mobile material deposited upstream
St Barthélémy	12.05	20 July 1930	125,000	Rock avalanche
Täschbach	37.23	15 June 2001	150,000	Lake outburst
St Barthélémy	12.05	11August 1927	160,000	Rock avalanche
Illgraben	4.73	3 October 1995	180,000	Unknown (but possible effect of a rockfall dam)
Saasbach	5.22	24 July 1987	200,000	Very heavy rainfall over a long period leading to important mass wasting all over the catchment[a]
Saltina	66.01	24 September 1993	250,000	Very heavy rainfall over a long period leading to important mass wasting all over the catchment[a]
Illgraben	4.73	6 June 1961	300,000	Lake outburst (lake dammed by a Rock avalanche)
Bossay	2.08	15 October 2000	350,000	Man-made debris flow due to ruin of a pipe

[a]During these events, many other catchments were hit by mass wasting and no detailed survey was done at the time of the event.

on the whole range of the torrent, which is a very high value. These very high values were comparable with the maximum values of bank erosion (15–30 m^3/m), before considering sediment input as point source (landslide), as proposed by Hungr *et al.* (1984).

In a sense, the catchment area integrated too many variables, some of which were not linked to the sediment production, hindering refinement of the analysis. The specific difference of level depicted the potential energy of the catchment. Figure 2 shows that the data could be separated in two major groups: one with high density of small events (i.e. a relative high frequency of occurrence) and one with events of high magnitude apparently more influenced by geological/geotechnical causes (when they are known). If there was overlapping of the events influenced by geological causes other than the rainfall–erosion relationship, and if there were uncertain causes for some events, it seems that at least two zones could be differentiated at the 7.5×10^4 m^3 level. Moreover, in Figure 2 the population of small and frequent events without additional geological cause represents a non-exhaustive population, whereas the data for events of high magnitude, mainly influenced by geological causes, came from an exhaustive dataset. It follows that, below 2×10^4 m^3, the real density of small events is greater and thus the separation between the two zones becomes more evident.

From the regional analysis of the volume v. the catchment area, as well as from its refinement with the specific difference of level, it was difficult to see if the events of higher magnitude were catastrophic events or if they were the tail of the distribution of gradual erosion of watersheds. Site-specific analysis supported the separation of the events into two families on the basis of the processes of erosion.

Analysis with statistical tools

Even if the data were incomplete, it was interesting to see if they could really be separated into two groups and where the threshold lay between the two groups. Two statistical methods were used to look at this hypothesis.

Methods

Cumulative number of events. The goal of this analysis was to see if the event volume came from a single population or more. This analysis was based on the distribution of the cumulative number of events exceeding a given volume. It had already been successfully used to analyse rockfalls (Wieczorek *et al.* 1998; Hungr *et al.* 1999) as

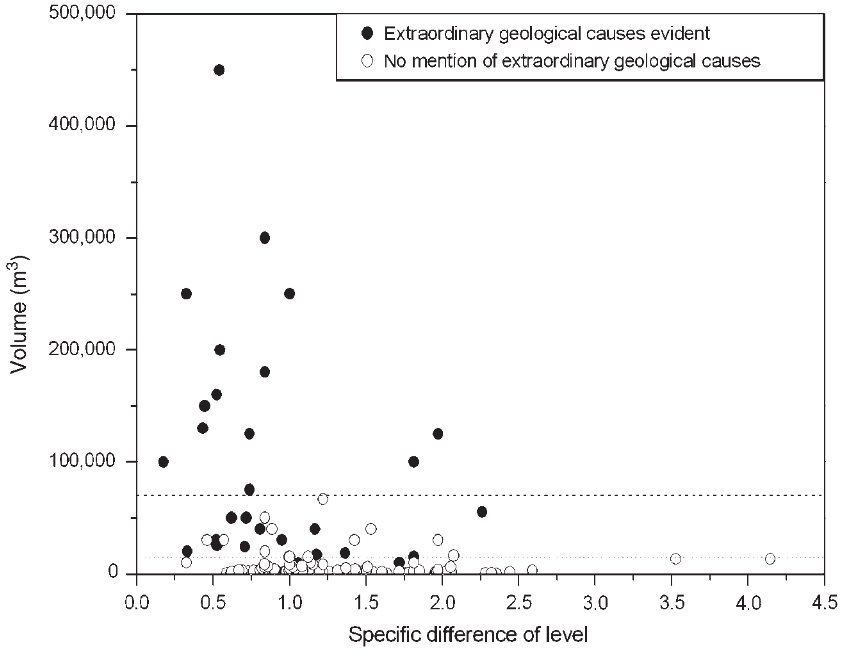

Fig. 2. Volume distribution according to the specific difference of level.

well as other kinds of mass wasting processes (Guzzetti *et al.* 2002; Brardinoni *et al.* 2003). As these authors have shown, part of the distribution can be described by a power law:

$$N(V) \approx V^{-b}$$

where V is the volume of the events, $N(V)$ the number of events that have a volume exceeding V and the exponent b is a constant parameter.

Wards' cluster analysis. The goal of the cluster analysis was to extract groups of data (Davis 1986). Here the idea was to look for the level of volume at which two families (one with a small and frequent debris flow and the other with a large and rare debris flow) could be distinguished. The difference between the sample elements was measured by an iterative procedure. The elements were aggregated and put into clusters. The higher the level of aggregation, the less similar were the members in the respective cluster. Among the various possibilities to compute aggregation rules (i.e. if the neighbouring cluster could be aggregated together in the next step), the following procedures were retained:

- The measuring of the 'distance' between data (here the volume) was done using the most common type of procedure: the Euclidean distance. It refers to the geometric distance in the multidimensional space and is computed as:

$$\text{distance}(x,y) = [\Sigma_i (x_i - y_i)^2]^{1/2}$$

where x and y are the coordinates of the object.
- As the aggregation rule, Ward's method (Ward 1963) was applied. To evaluate the distances between the clusters, the variance was analysed. This method attempted to minimize the sum of squares (SS) of any two (hypothetical) clusters that could be formed at each step.

Results

From the cumulative number of events analysis (cf. Fig. 3), it appeared that the data distribution was separated into two parts. For the high volume (on the right of the graph) the data could be fitted to a power law. The exponent b was 0.423 ± 0.007, which is surprisingly near the value of *c.* 0.4 found by Dussauge *et al.* (2003) for rockfalls. For this type of approach, the incompleteness of the data, especially for small volumes, can be put forward as an explanation for the presence of two families. Nevertheless, as already proposed by other authors, the observed knick point on the curve was much higher than if it was caused by the incompleteness of the data (Hovius *et al.* 2000; Guzzetti *et al.* 2002; Guthrie

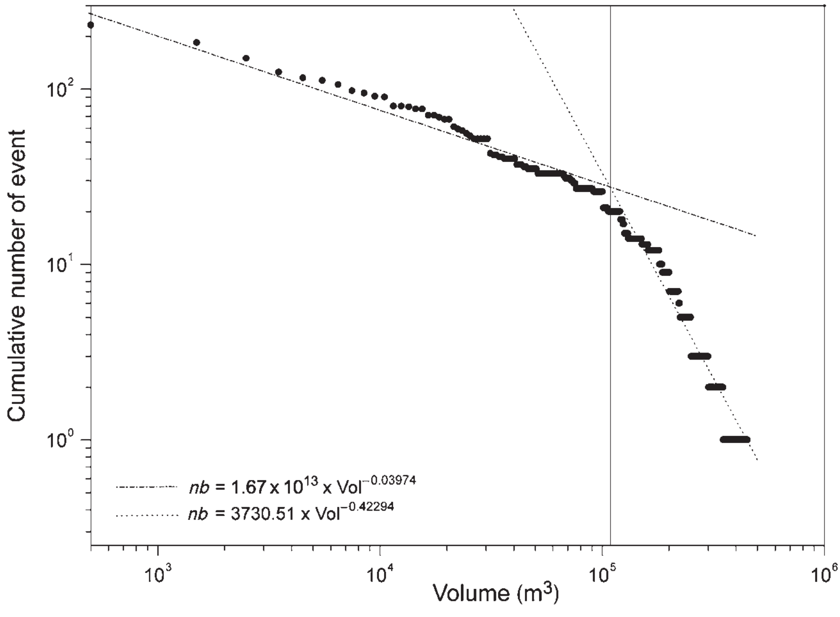

Fig. 3. Cumulative distribution of volume values.

& Evans 2004). This approach makes it possible to set a limit between two classes of volumes at approximately 1×10^5 m^3.

Another way of looking at the limit between the small and frequent events resulting from gradual erosion and catastrophic events of high magnitude was the cluster analysis. It was performed until two clusters were built. Once the two groups were constituted, the limiting branch of the hierarchical tree was reported. The data could be drawn as two box-and-whisker plots representing the distribution of the event within the two families. Again the limit appeared towards 10^5 m^3, as it can be seen from Figure 4.

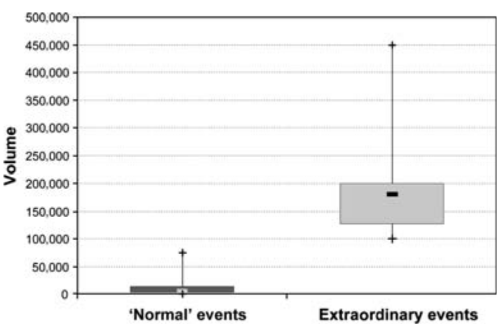

Fig. 4. Box-and-whiskers plot of the distribution of the population of the two families formed by the cluster analysis.

Conceptual modelling

Given the environment of alpine catchment and the data available, it was interesting to investigate the sediments dynamic resulting from different mechanisms of volume formation. As differentiation between gradual and catastrophic events can appear to be possible only for a short time scale (the one used for natural hazard assessment), a longer time scale was envisaged. If one takes a geological scale of time into account, it is possible for a sufficient number of events to exist on a site to build a steady statistical population. At a shorter time-scale, the evolution of the landscape fluctuates, partly due to the variability of the sediment fluxes (Pratt-Sitaula *et al.* 2004). To avoid analyses biased by the smoothing of these diverse and complex phenomena, a simple conceptual stochastic model was built.

Methods

For this study a model was developed to estimate the behaviour of catchments suffering debris flow, balancing the volume available. This made it possible to describe the sedimentary budget dynamics of an alpine catchment system on time scales under 10,000 years. If landscape evolution models already exist, the integration of a physical difference in the sediment response according to the magnitude and to the temporal evolution of the sediment availability is new (Tucker & Slingerland 1996).

The model is made up of two modules that stochastically generate: (1) the volume of sediment available at a given time according to erosion and landslide sediment production; and (2) the triggering conditions – if they are met, the whole available sediments are supposed to form a debris flow.

The components of the model are described in Figure 5. The model assumes a catchment area (S) from which only a part (S_A) could deliver sediments to the torrent by erosion (E) during one event (as observed in many cases e.g. Haeberli *et al.* 1992). The catchment contains an initial stock of sediment having a volume (V_i) such as moraine and others sediments. On average, V_i is assumed on the entire surface S. Only part of the store of sediment is easily available (R), and presents a random variable (D) with time. This random variability reflects the complexity of the processes that deliver sediments to the gully.

The debris flows are assumed to be triggered by precipitation above a given intensity threshold Th_p (expressed in mm/h), following a normal distribution (m_p, σ_p). The time frequency of precipitations follows a Poisson distribution with a mean frequency (t_p). Landslides, including rockfalls, are assumed to be an important potential sediment supply (Iverson *et al.* 1997; Sandersen *et al.* 2001). An average volume V_l and a return period T_l, both following Poisson distributions as indicated on Figure 5, control the alimentation of the gullies by landslides. This variability in the initiating conditions of sediment supply induces a threshold in erosion, which is an important issue in landscape erosion modelling (Tucker & Whipple 2003).

Some other factors that influence the sediment yield, like vegetation (Cerdan *et al.* 2002; Istanbulluoglu & Luce 2004), tectonic (Tucker & Slingerland 1996; Hovius *et al.* 1997) and thermal

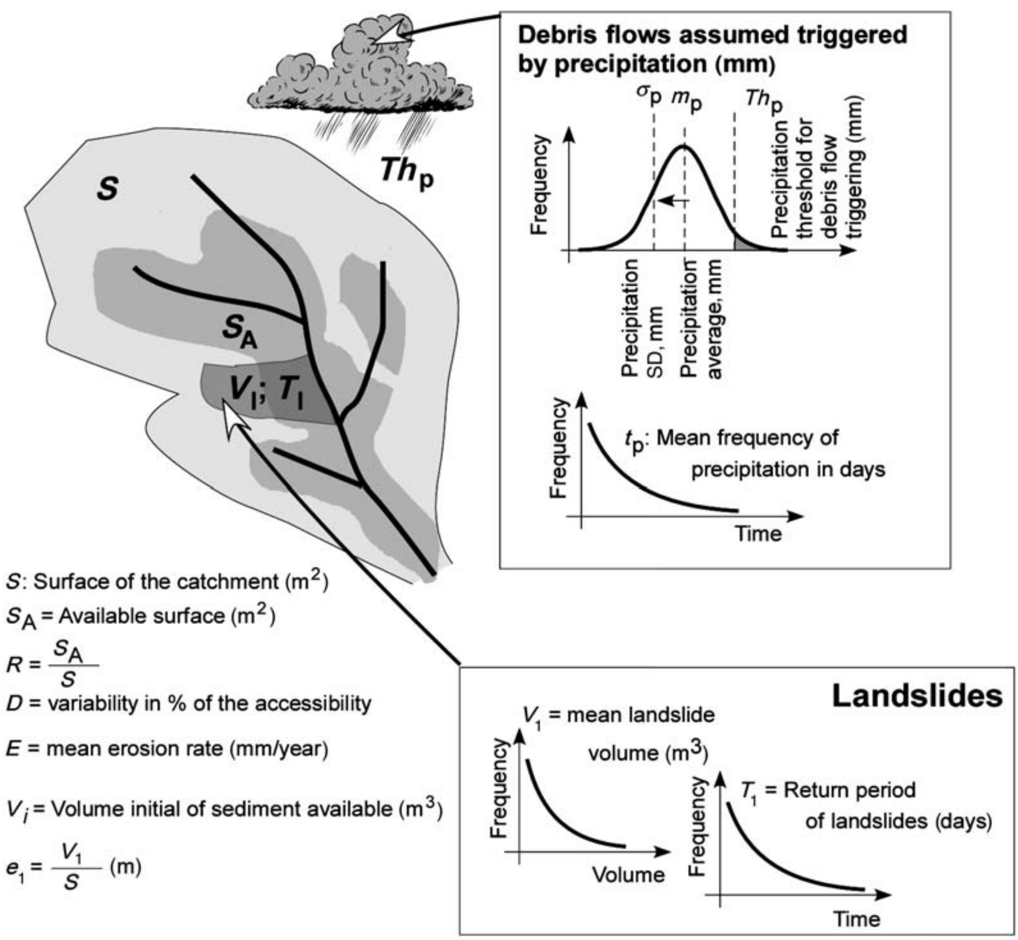

Fig. 5. Description of the conceptual model and its components.

Table 2. *Parameters of the long-term simulations*

Variable	Units	Simulation 1	Simulation 2	Simulation 3
S	m^2	10,000,000	10,000,000	10,000,000
V_i	m^3	30,000,000	30,000,000	—
e_i	m	3	3	—
E	mm/a	0.5	—	0.5
V_1	m^3	10,000	—	10,000
T_1	years	3	—	—
m_p	mm	5	5	5
σ_p	mm	3	3	3
t_p	days	10	10	10
Th_p	mm	13	13	13
R	%	15	15	15
D	%	20	20	20

effects (i.e. passage through the freezing point, Bogaart *et al.* 2003; Bardou & Delaloye 2004), are not modelled here. As this model is a first attempt to conceptualize the variation of the sediment dynamics at the event scale, simplicity was preferred. Nevertheless, if quantification of the sediment volume is researched, a more complex model should be built.

The initial parameters of the model were as follows. An erosion rate of 0.5 mm/a and a three-year return period for a landslide with an average volume of 10,000 m^3 were used, which are relevant for an alpine region subject to debris flows. This represents the sedimentary input (cf. Table 2). On the other hand, a stock of sediment of 30 Mm^3 was considered (roughly evaluated in analogy with typical alpine catchments). Precipitations were supposed to fall on average every 10 days. Around 1% of these precipitations was supposed to lead to debris flows. The time step adopted thus was 1000 days and the total duration of the simulation was approximately 10,000 years.

Results

Initially, three catchment behaviours were modelled (cf. Fig. 6), each one having a different origin for the sediment: (1) a basin with a mixed origin (storage + weathering, column A); (2) another with only a primary storage of sediments (column B); and (3) a third with supply only by weathering (column C). For each of these simulations, the climatic factors were considered to be identical (cf. Fig. 6). Only the availability of the sediments varied.

Starting the simulation for a catchment with storage (e.g. moraines) and sediment supply (erosion and landslides), the debris flow volumes and frequency were higher at the beginning of the period, before reaching steady-state behaviour after 5000 years, that is to say half of the reference period (cf. Fig. 6, column A). For a catchment that possessed only a limited input of fresh sediments (i.e. the supply by weathering is equal to zero, column B), large debris flows occurred during the first 2000 years, that is to say one-fifth of the reference period. After that period, a progressive decrease of the debris-flows volumes to zero after 4000 years could be seen. On the other hand, a catchment without pre-existing sediment storage (i.e. the storage was zero, column C), but possessing a constant input of fresh sediments, reached a steady-state behaviour after 2000 years, that is to say one-fifth of the reference period.

Following the type of formation of the debris flow volume, there could be a great difference between sediment volumes available at the beginning and the end of the period. After 20–50% of the time of the reference period, the volume never reached the high value simulated in the first part of the period again. This reflects the tendency of the catchment to reach its equilibrium.

However, this simulation could not simply be extrapolated to real data, due to the limitations of the various assumptions made, i.e. the climatic scheme was considered to be identical for the whole period. In order to reach a more 'realistic' modelling, the model was run over a 150 year period. This time horizon corresponded to the last important generation of sediment storage in the European Alps (the Little Ice Age). Over this 150 year period, the assumption of stationarity of the parameters was less strong. At this time-scale, the existence of different classes of events volumes still appeared. The same trend (i.e. proportion of high magnitude events at the beginning of the series) can be seen (Fig. 7). The events were due to the presence of easily mobilized sediments, which could, for example, correspond to the deglaciation phases (Evans 1997) or the alteration of moraine bastion (Tonanzi & Troisi 1996; Delaloye pers. comm.).

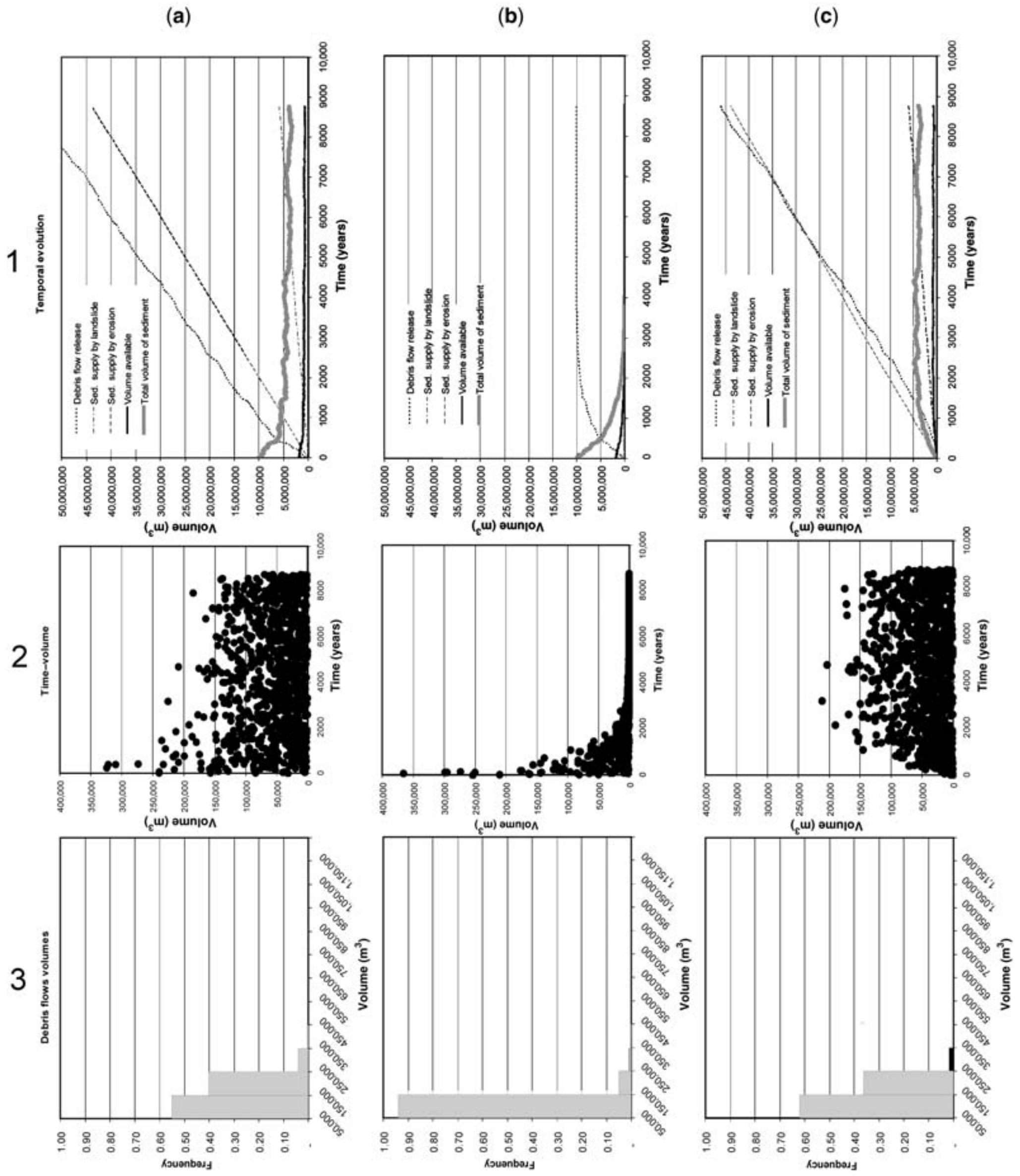

Fig. 6. Results of the simulation for three different origins of sediments.

Discussion

Distinction between gradual erosion and catastrophic events

The results obtained from the data analysis led to the differentiation between small and frequent events resulting from gradual erosion and larger but rarer events resulting from catastrophic geological causes in the catchment. Although the separating range between the events judged as catastrophic and normal events was computed using several methods, it should be noticed that the values fall in a wide range. This is not only due to the quality of the data and to the different shortcomings inherent to each method, but probably also to the variability of nature (e.g. there is surely an overlap between the higher volume supposed to come from gradual behaviour and the lower volume produced by noticeable geological processes).

Table 3. *Summary of the limits found with the various approaches*

Method	Volume threshold
Geomorphologic (according to specific difference of level)	75,000 m^3
Cumulative number of event	100,000 m^3
Cluster analysis	100,000 m^3

Table 3 summarizes the different thresholds of volumes separating the two possible behaviours of a catchment. For the Central European Alps, depending in part on the predisposition of the catchment, this threshold is around 5×10^4 m^3. This distinction into two families of events is based on differences in physical processes related to volume formation of debris flow (linked with peaks of sediments supply, e.g. the one given in Table 1).

The defined thresholds have to be taken as indicative, and not as well-determined values. They are merely order of magnitude estimates. They could be moderated by the predisposition of the catchment and/or by human changes in the watershed (e.g. building of safety works that reduce the sediment supply, at least for a certain time).

Availability of sediments as a cause of the two distinct behaviours

A simple stochastic model suggests that the distribution of debris flow volumes depends strongly on both the supply of fresh sediment and the initial storage of sediment. For catchments only supplied by weathering, the events show a quite regular distribution. The presence of sediment storage (e.g. Quaternary deposits) can induce large debris flows at the beginning of the period, with volume significantly higher than can be restored by the rate of fresh sediment supply. As a consequence, the storage will be progressively emptied. Thus, debris flows decrease in volume and in frequency. The present distribution of large debris flows is therefore incomplete, because it has to be correlated with the early period of the catchment history. At present, most of the catchments contain Quaternary deposits. Large debris flows are still available, but they will not represent the standard volume. Owing to the gradual erosion processes acting on the catchment, smaller events will be more frequent. In other words, the highest volumes belong to same statistical distribution. The law of large numbers is not applicable, and thus extraordinary events can appear discontinuous with the background activity of the catchment. This transient behaviour at the beginning of the activity in the catchment that appears for each mode of sediment supply is consistent with other models (Tucker & Slingerland 1996) and field measurement in comparable environments (Evans 1997).

At least two process types of debris-flow formation coexist within a given stream: one implying a gradual erosion (steady-state process) and the other a pulse of erosion (process in disequilibrium with its environment). The pulse events, producing large volumes, are due to peaks in sediment supply and/or change in triggering factors. They can be followed by periods of slight activity in the gully. Therefore, the sediment fluxes can be described by a variable pattern. This variability has been the rule during Holocene (Martin 2000; Hinderer 2001).

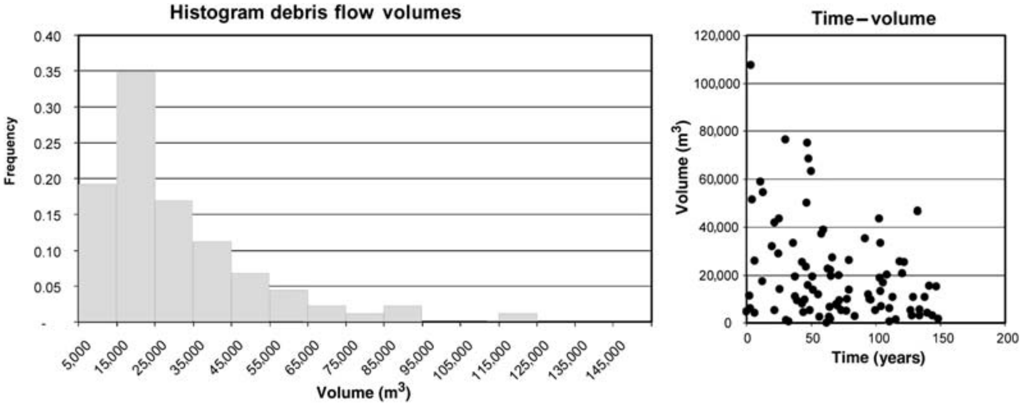

Fig. 7. Simulation for a catchment with stock and recharge by weathering over a period of 150 years (i.e. approximately from the end of the Little Ice Age to the present).

Thus the generation of a sediment volume forming the debris flow is a complex function of various phenomena having neither the same time scale nor the same magnitude. The output of this function (i.e. the description of the behaviour of the catchment) is not continuous, but shows thresholds. The level of these thresholds may vary with time (Baker 2002). In the case of the alpine catchment system, the magnitude of an event results from at least two different behaviours of the catchment: the gradual one is related to the generalized erosion (Meunier 1991), and the catastrophic one is influenced by the extent of the geological and the hydrogeological phenomena occurring in the upper part of the drainage system.

Case studies

Two case studies are presented in order to illustrate how and why the sediment supply can change with time. This enables us to consider how the results presented above (although descriptive and linked to strong hypotheses) are relevant to field observations.

The Illgraben catchment

The active area of the Illgraben catchment reaches 4.4 km^2 and elevations range from 900 to 2720 masl. The study conducted in the Illgraben torrent since 1997 have shown that it is prone to sudden floods. Several texts dating from the end of the Middle Ages mention these floods. In the analysis of the severe floods which struck Switzerland during the end of the nineteenth century, the Illgraben appears to be a torrent prone to causing problems to human infrastructures (Culmann 1864). In the scope of the present study, the distribution of debris flow linked with a rock avalanche event will be looked at in detail.

In 1961, a 5 Mm^3 large rock avalanche occurred in the upper part of the catchment (Lichtenhahn 1971; Eisbacher & Clague 1984). This event produced important deposits along the axis of the valley, which became a new storage of easily available sediments. This deposit dammed a lateral channel of the Illgraben's torrent, resulting in the creation of a lake. The failure of this dam triggered the most extreme debris flow recorded in a century. It was triggered by low-magnitude rainfall. Figure 8 shows that, after this geological event, an increase in debris flow frequency was observed on the main fan (approximately 3–4 a year up to 1963), followed by a long period of relatively low debris flow activity (Zimmermann 2000; Bardou *et al.* 2003).

This case study agrees with the results of the conceptual modelling. The increase of debris flows after 1961 can be linked to the high availability of sediment provided by the rock avalanche deposit (i.e. a new sediment storage). The frequency of the debris flows increased over some years, until the rock avalanche deposit talus reached equilibrium. Afterwards the frequency decreased over some years, probably due to the protection work built in reaction of the 1961 event. Then the torrent recovered a dynamic that corresponded to its new equilibrium, until a new geological event happens and changed the sedimentary predisposition of the catchment. The first event, the one that occurred when the dam was breached, could be considered as a catastrophic (it is the largest event listed in the 'history'). The subsequent events were readjustment of the bed cross-section to the new storage of sediment. It could be considered that these events differed from the gradual dynamic of erosion of the torrent.

The Saxé and Métin catchments

The areas of the Saxé and Métin catchments are respectively 0.93 and 1.01 km^2. The two torrents are an average of 275 m apart (cf. Fig. 9). Both catchments are made from Granodiorites, which are surmounted by Limestones belonging to the Nappe of Morcles (cf. Fig. 10). In the middle part of the Saxé catchment, an important mass of deposited sediments (from not clearly identified palaeo processes) provides a mass of loose sediments. This is not the case in the Métin catchment, where availability of sediments is low.

In November 1939, the settlement of Saxé was inudated by a 125,000 m^3 large debris flow, flowing through the village over 5 h, when the Métin's torrent produced only several hundred cubic metres (Montandon 1940). An important part of the deposited volume was eroded from the sediments located in the middle part of the hillslope, as no other scars are visible. From the mapped inundated area and from the estimation done in 1939, we attempted to assess the potential volume of in-place sediment that was removed (accounting for water content, 10%, and bulking, 30%). This estimation gave 86,000 m^3. The present estimation of the missing volume in the current gully gave a value of 88,000 m^3. That is a variation of only 2000 m^3 on the best estimate of volume in place potentially mobilized during the event of 1939. The magnitudes of the values of the missing volume (surprisingly similar, considering that some events implying a few thousand cubic meters have been recorded since 1939) and the current morphology (allowing a reconstitution of that of 1939) show that the gully was only notched slightly to have

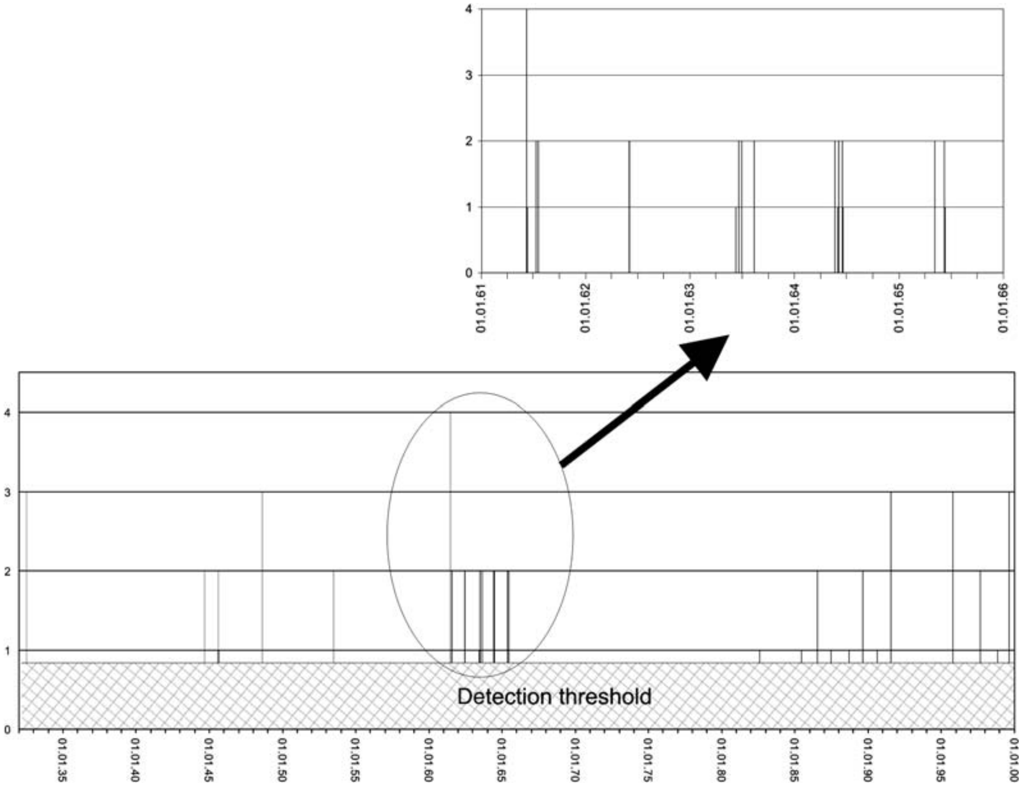

Fig. 8. Distribution of debris flow exceeding a survey threshold and classified according to their magnitude (assessed from the damages and flooded area) in the Illgraben torrent.

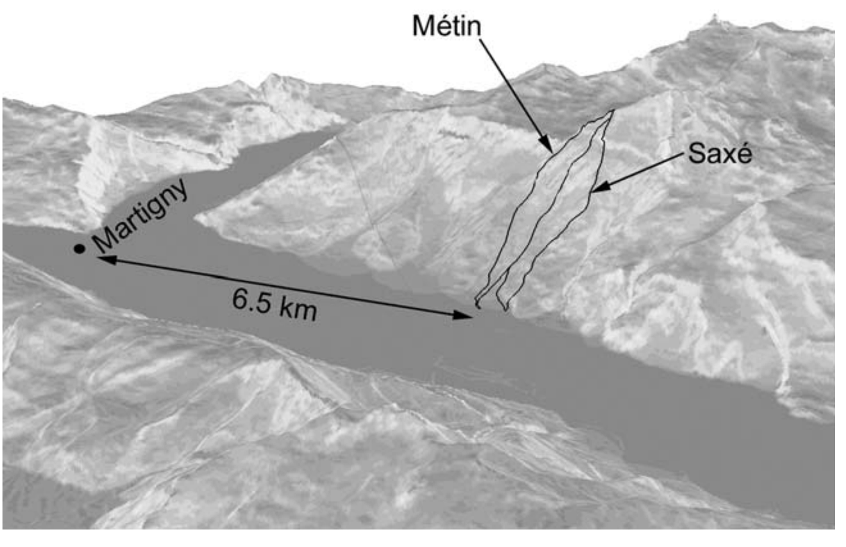

Fig. 9. Perspective of the catchments of Saxé and Métin.

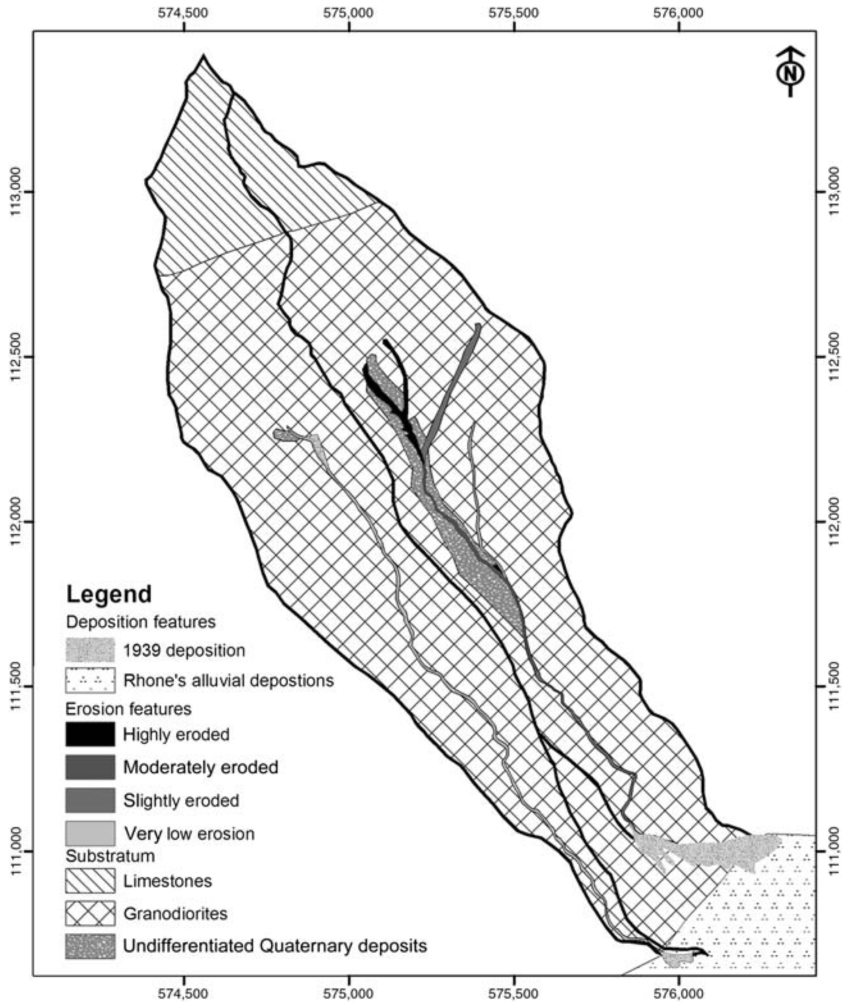

Fig. 10. Geological disposition and geomorphology of the present gullies in the Saxé and Métin's catchment. The reference is the Swiss coordinate given in metres.

sufficient sediments at disposal (cf. Fig. 11). According to the traces currently mapped, the storage of the necessary sediments had to be in the gully (the proximity of the old torrent-bed and the easily movable sediments, which corresponds to the parameter S_A in the model). As a result, the quantity of available sediments decreased. The estimation of probable maximum volumes today made according to the method of Hungr *et al.* (1984) shows that, with the observed predisposition, an event like that of 1939 is unlikely to occur. Figure 11 indicates that the catchment tends to pass from a transport-limited condition to a supply-limited one. This kind of change would influence the magnitude–frequency relationship. This has already been observed in other areas with significant relief (Newson 1980). The conclusions of Montandon, although careful, show that the event already appeared extraordinary at the time when the traces were still fresh: 'As far as we know, localities situated on these fans have not suffered ... serious damage due to debris flow ... Otherwise, it seems that we would have been informed by local historians ... It is certain that in Saxé, going back for four generations – to 100 or 120 years – one has no memory of a similar misfortune to that of November 1939 – which does not say ... that nothing serious did happen there 200, 500 or 1000 years ago' (translated from French, Montandon 1940).

Analysis of the rainfall compared with the average water necessary to the mobilization of

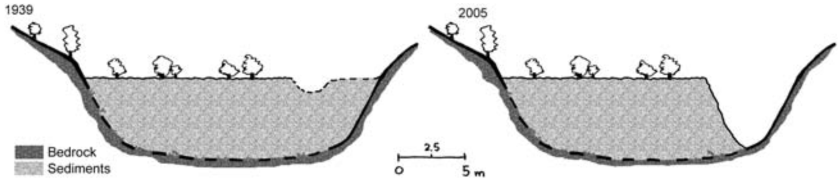

Fig. 11. Cross-section of the torrents at an altitude of 1200 masl, where reconstitution of the probable morphology of the event of 1939 is the most precise (the linear production of 17 m^3/m at this place). The estimate of the current potential delivery of sediments is of 6.5 m^3/m. If the ratio (approximately 1 to 2) is supposed to be similar throughout the channel and with an estimate of current probable maximum volume around 70,000 m^3, i.e. a little more than half of the event of 1939 (estimated by other sources, Marquis pers. comm.) one can admit that the reconstitution is coherent.

such a large debris flow (evaluated from rheologic measurements, Bardou, 2002) shows that the one-day rainfall with a 100-year return period applied for 3 consecutive days would have been necessary. The rainfall recorded at the raingauge at Martigny, situated 6.5 km southeastwards, and the witness reports did not indicate this kind of exceptional precipitation (cf. Fig. 9). Furthermore, old pictures show that, at the end of the event, snow replaced rainfall (Kunz 1939). This inconsistency between the rainfall, the runoff transport capacity and the effective volume led us to consider an additional contribution of water. This contribution has to be sought among hydrogeological effects (e.g. the temporary outbreak of a local spring, a fact observed in this area by the authors during field work in 2001), as is often the case in such an environment (Hungr *et al.* 1984).

This case study shows that the conditions leading to a trigger could change and in some case perhaps could not be put together. From a physical point of view, the events that occurred in Saxé's torrent come from two distinct geomorphological families. In this case, the emptying of the sediment storage after the 1939 event was so drastic that, without other changes, the present torrent seems to be unable to produce a volume similar to that of 1939. Furthermore, the unknown origin of the water that produces the debris flow changes the possibility to assist, or not, such an event.

What the case studies illustrate

Detailed surveys of historical events make it possible to link the statistical and conceptual models to reality. The two case studies presented support the hypothesis of coexistence of continuous and catastrophic erosion processes on a catchment already observed by others authors (e.g. Jakob *et al.* 1997). The behaviour of the Saxé catchment was related to the change in triggering factors, drastic emptying of the sediment storage and/or the temporary apparition of a local spring, that no longer enables events with a magnitude similar to that one of 1939. In the case of the Illgraben torrent, complex geological processes formed the sediment supply. These can evolve rapidly or in a discrete way. When one of these processes unbalances the catchment operating (here the rock avalanche), other processes can take place in turn (e.g. natural dam failure), causing a series of large and frequent debris flows differing from the gradual erosion expected in such a catchment. After that crisis, the catchment tends to reach its equilibrium-production again.

Conclusions

Different approaches, made at different spatial and temporal scales, indicate that at least two different families of events can be distinguished. Depending on the processes involved in the catchment, an event in either steady-state (gradual erosion) or in non-steady-state (extraordinary behaviour) can take place. However, it is difficult, and in a certain way of little importance, to set a limit between the families. Nevertheless, the different methods used made it possible to set a threshold at around $7.5-10 \times 10^4$ m^3 for the western Swiss Alps. This threshold is only valid for the environmental settings and there is probably an overlap between the two families. The study of the frequency distribution of debris flow volumes, including an event that took place in volcanic settings, Jakob (2005), show that there is a knick point in the distribution at 1×10^6 m^3 (linked with a change in the process of available sediment production).

This coexistence of two different behaviours has to be integrated into hazard assessment procedures. This could be done by a comprehensive analysis of the relevant catchment. The new conceptual model, developed for analysing the variability of the sediment fluxes in a given catchment, made it possible to clarify the time scale necessary for statistically representative distribution. This model also gave new insights into the causes of catastrophic events. The predisposition of the catchment can be enhanced by geological events that change the magnitude of triggering factors. As a consequence, the identification of the possible supply of sediments, their dynamic of renewal and possible triggering factors, is of great importance to asses the general sedimentary behaviour of the catchment. Each catchment should be conceptualized as a system yielding complex interactions. In particular, distinctions should be made between the different geomorphological processes that participate either in the gradual erosion of the catchment or in catastrophic events.

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