FREQUENCY OF HILLSLOPE DEBRIS FLOWS IN THE BACHELARD VALLEY (FRENCH ALPS)

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Abstract

Debris flows of moderate dimensions in the Bachelard Valley (French Alps) appear to be triggered by surface runoff generated within the source areas of the flows during high-intensity rainstorms. This runoff will destabilise the coarse material accumulated along the drainage lines of source areas if discharge of overland flow surpasses a certain level. The frequency of debris-flow events thus should be related to precipitation patterns. The actual frequency of debris flows within a test area is discussed with regard to its meaning as a validation tool for models forecasting debris-flow frequency. Over the period 1810-1987, return periods between 4 years (for track lengths between 300 and 400 m) and 45 years (for tracks >900 m) were initially found, while most recent information points to still shorter return intervals (on average 2 to 2,5 years for the Bachelard Valley as a whole).

Key words: debris flows, French Alps, magnitude-frequency analysis.

Riassunto

Frequenza dei debris flow nella valle di Bachelard (Alpi francesi). Debris flow di dimensioni ridotte sono innescati da ruscellamento superficiale che avviene nella zona sorgente delle colate durante precipitazioni di elevata intensità. Il ruscellamento rende instabile il materiale grossolano accumulato lungo le linee di drenaggio nelle aree sorgente se l'entità del deflusso dell'acqua supera una certa soglia. La frequenza degli eventi di *debris flow* dovrebbe essere pertanto connessa con le caratteristiche delle precipitazioni. Viene discussa la frequenza attuale dei *debris flow* in un'area campione con riferimento al suo significato come elemento di validazione per modelli di previsione della frequenza di *debris flow.* Per quanto riguarda il periodo 1810-1987 inizialmente sono stati individuati periodi di ritorno compresi tra 4 anni (per lunghezze di trasporto tra 300 e 400 m) e 45 anni (per trasporti >900 m), mentre recenti informazioni mostrano tempi di ritorno più brevi (in media da 2 a 2,5 anni per l'intervallo di Bachelard).

Parole chiave: *debris flow*, Alpi francesi, analisi intensità-frequenza.

1. INTRODUCTION

Debris flows of relatively modest dimensions are a common - though episodic - feature of many parts of the French Alps. They may be harmless when they occur in remote places, but sometimes they cause damage to pass roads, other infrastructural works, or houses. Debris flows are defined in a general way as rapid mass movements of granular solids, water and air. Because this definition does not give information about scale or geomorphological properties, these phenomena require some more specification. The debris flows dealt with in this text have volumes in the order of 1000 to 10.000 m^3. They start within steep source areas situated within the upper cliff zones of the mountains and connected by chutes or channels to talus slopes or colluvial fans. For the French Alps debris-flow like events have been described by the term *crue* or *lave torrentielle.*

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Debris flows occur in connection with high intensity storms. Basic requirements seem to be steep slopes, heterogeneous regolith material, high pore water pressures and high shearing force of runoff. The vertical zonation of these debris flows and especially the fact that their source areas are restricted to the alpine zone (*sensu stricto*) is an indication that at least in the French Alps they should be seen as periglacial features, though generally not connected with permafrost environments. Snowmelt appeared to be unimportant in triggering debris flows: in this region all known events occurred during heavy precipitation in summer or autumn.

The frequency and spatial density of such debris flows may be high enough to make them a natural hazard which increases with increasing human pressure on the higher alpine zones. For an accurate understanding of the concept, it is important to realise that frequency can be defined in two ways: (1) as the number of cases of a specified magnitude within the total magnitude range observed, and (2) with regard to the temporal aspect: the frequency through time of events of a given magnitude (*Innes*, 1985). The present article discusses the reconstruction of debris-flow activity, seen as one step within the framework of hazard assessment. The hazard analysis of debris-flow activity comprises the following questions:

A. where do debris flows occur within the region of interest? This requires a specification of the morphological subsystem of source area and track, followed by mapping the spatial distribution of the several components.

B. how are debris-flow events triggered? Initiation models are treated elsewhere (for instance *Blijenberg*, 1998).

C. when (or: how often) do debris flows of a given magnitude occur?

Because the recognition of debris-flow endangered sites is relatively easy, the probability of events of a given magnitude is the main problem in hazard assessment. This probability is a function of debris availability and hydrometeorological conditions controlling the stability of the slope materials. Thus, frequency is related to the occurrence of critical situations, especially of precipitation intensity-duration combinations. The latter statement implies that elements to answer this question are found within the initiation models which combine hydrological and slope stability models. However, an important contribution both to our knowledge of the actual frequency of debris flows and to the validation of the initiation/frequency models can be obtained by field inventories of debris flows with regard to magnitude and age. Therefore, one step towards the prediction of debris-flow activity is the recognition of its activity pattern in the past (cf. *Blijenberg*, 1998). The present article deals with the results of a frequency study from an area of some 15 km² situated near Barcelonnette, Alpes de Haute-Provence.

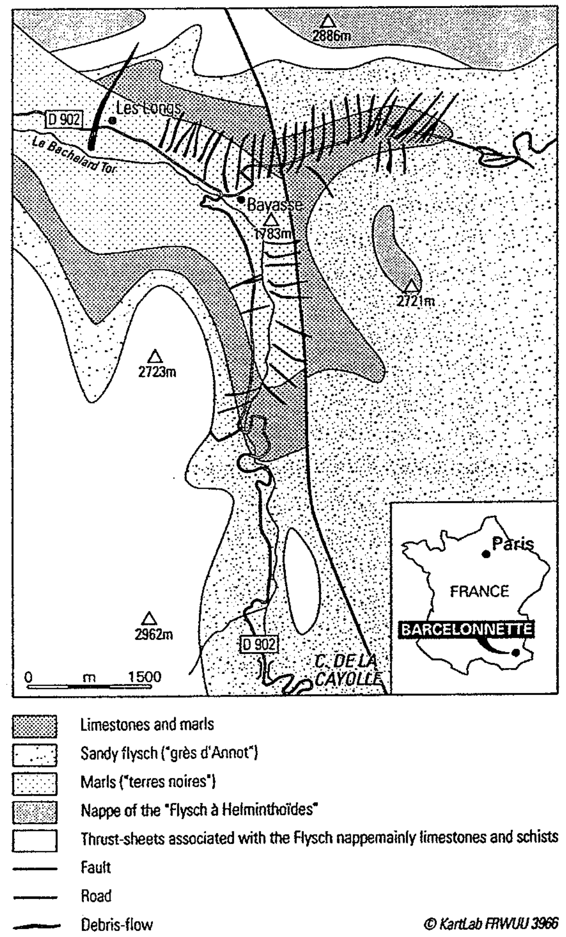

Fig. 1 - The study area.

2. CHARACTERISTICS OF THE STUDY AREA

Data were obtained for a part of the Bachelard valley near the Col de la Cayolle (Fig. 1). This valley belongs to the easternmost part of the Durance drainage basin. The part of the Bachelard valley studied is situated within an area of sedimentary rocks of different resistance. The valley bottom is near 1700 m and summits reach 2800 m. Debris flow deposits are found at altitudes from 1700 m to about 2400 m. Their tracks are mainly situated on talus slopes below high and very steep rock walls and generally in connection with narrow chutes dissecting the cliffs. In some cases the debris flows built fans having mean slope angles of about 12-14° situated in front of steep torrential catchments.

The climate of the area is characterised by mediterranean and oceanic influences. High-intensity rainstorms occurring during summer and autumn are responsible for the debris flows in this region. Eye-witness accounts of some debris-flow events in the Bachelard valley in 1986 and 1987 indicate that debris flows occurred near their houses within 15 minutes after the beginning of the rain at the source area. Because the distance between houses and source area is about 1200 m, one could estimate that the flow was triggered between some 5 and 8 minutes after the beginning of the rain. This estimate is based on velocity values of 2 to 3 m/s, as found by *Van Steijn et al.*, 1988. Peak intensity values of the rainstorms involved are not available, but intensities required are estimated in the order of 40-50 mm/h during about 10 minutes or about 100 mm/h during some 5 minutes (cf. *Blijenberg*, 1998).

As mentioned before, the influence of melting snow apparently is very small, because by far most known flow activity occurred after the snow cover had disappeared. Only under conditions of abundant rain falling on late-lying snow debris flows may be triggered. However, the altitudinal position of the source areas (2100 - 2800 m) suggests that an attenuated periglacial environment is important for the debris-flow activity, but probably mainly with regard to debris production. The isotherm of 0°C (mean annual temperature) is situated near 2400 m in this region (*Evin & Assier*, 1983). Geomorphologically, the valley-side debris-flow systems that are most frequently found within the Bachelard valley (and indeed in many alpine valleys elsewhere) typically consist of the following parts (Fig. 2):

1) a funnel-shaped debris source area consisting of a ravine (or a series of deep gullies) below steep rocky slopes. This is followed by a transitional part where the prolongation of the ravine is cut into a talus slope. At some distance downslope of the entrance of this gully on the talus the development of lateral levees becomes visible as an interrupted boulder line at the maximum height of the debris flow that has passed.
2) a zone where debris levees are found on both sides of the flow track. A meandering pattern is possible, especially in sections were slope angles are relatively low, generally in the lower parts of the track. The dimensions of the levees are influenced both by flow properties and channel morphology.
3) a terminal part where the levees join to form a frontal lobe. Often this part is

complicated by the presence of several lobes arranged across and beside each other.

The characteristics of the debris-flow source areas in this part of the Alps can be summarised as follows. Source areas are situated within the alpine zone (*sensu stricto*) in places where an alternation of resistant bedrock and layers of weaker material exists. Both types of bedrock produce large quantities of debris by rapid weathering. Slopes are very steep (minimum value 33°, mean value 38°).

They consist of rock surfaces that alternate with parts where a thin cover of relatively fine debris is present. Vegetation cover is less than 10%. Drainage lines below the slopes have gradients of at least 30°. Along the gully-like drainage lines coarse, cohesionless debris is accumulating due to rock fall and dry grain flow. The parts of the slopes covered with fine material often show surface sealing. Traces of erosion by running water are abundant (especially rills and miniature earth pillars), whereas slide scars or other mass movement traces are rare, apart from rock fall and dry grain flow. The latter process contributes to the redistribution over short distances (in the order of meters) of mainly coarse material within the steeper parts of the source areas.

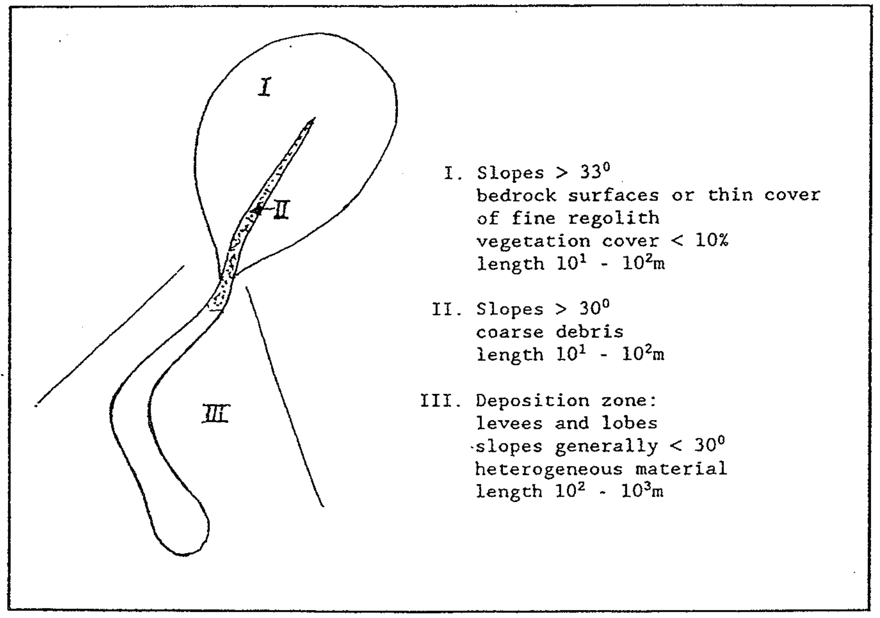

Fig. 2 - Debris flows in the French Alps: morphological subsystem.

The well established differentiation between slopes, covered with fines or consisting of rock surfaces, and drainage lines where coarse material is concentrated in a potentially unstable position is setting the stage for a process of debris-flow initiation in which surface runoff is the main factor. During high-intensity rainstorms, flows are triggered by rapidly initiated runoff on the steepest slopes, destabilising the coarse debris accumulated along the drainage lines within the source areas. These coarse accumulations fail due to either saturation (infiltrating runoff) or loading (small-scale debris flow already formed on the slopes). A comprehensive discussion of debris-flow initiation processes is given by *Blijenberg* (1998).

The depositional environment is characterised by the presence of vegetation in highly variable amounts. On the higher parts lichens develop if the surfaces involved are sufficiently stable. Under favourable conditions (mainly concerning the state of available nutrients), lichen species can be found that are suitable for dating purposes. The relative abundance of the more or less quartzitic *Grès d'Annot* within the debris-flow deposits is such a favourable condition. In other places either individual trees or fairly open Larch forests are present. When trees are present along debris-flow tracks they are potentially useful for dendrochronological dating of flow events.

3. MAGNITUDE-FREQUENCY ANALYSIS

Although no exact data are available on the volumes of sediment deposited by individual debris-flow events, estimates can be made based on geometric properties of the deposits. *Innes* (1983, 1985) found a good correlation between track length and volume of deposits. Therefore, track length (of morphologically recognisable deposits) is used as a surrogate to represent "magnitude" of events.

In a first attempt, over 200 tracks were counted within the study area of about 15 km². Track length varies from about 100 to > 1300 m. First, a classification of tracks was made, using length intervals of 100 m. Looking at the total population, it was found that a clear mode exists for the length class of 300-400 m (21%), and about 68% of all tracks are within the range of 300-700 m. Larger events are very rare (less than 2% for tracks >900 m), and tracks of <300 m cover 17%.

As stated above, temporal frequency analysis is based on dating of debris-flow deposits by lichenometry and dendrochronology. Lichenometric datings were based on the growth curve for *Rhizocarpon geographicum (s.l.)* published by *Orombelli & Porter* (1983), which was checked for the Southern French Alps by *Miltenburg* (1986). Another check was the comparison of data obtained by lichenometry and dendrochronology for a series of deposits on which both techniques could be applied. The period over which flows could be detected is relatively short, for the oldest events presently known are from the first decades of the 19th century. Datings older than 1900 AD were all obtained by lichenometry. For the period 1986-1990 flow deposits were observed shortly after the events that produced them. Some of the results obtained by dendrochronology are shown in Fig. 3.

Recently, more detailed analyses were carried out on a few debris-flow systems

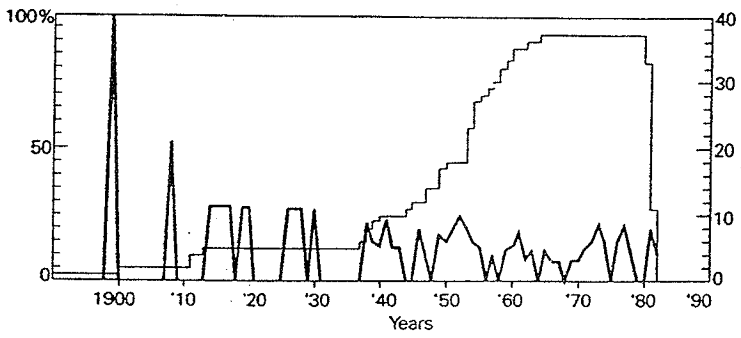

Fig. 3 - Dendrochronological analysis of debris-flow events, Bachelard Valley (after *Van Asch & Van Steijn*, 1991).

by *Blijenberg* (1998). In his study the emphasis was on frequency, without estimating the event magnitudes. *Blijenberg* (1998) also reports on numbers of debris-flow events that occurred during the period 1991-1994.

As shown in Tab. 1, debris-flow tracks of different sizes are found. These are seen as an expression of the magnitude of the individual events. On this base, an idea was obtained of the relationship for the Bachelard valley between frequency and magnitude of debris-flow activity. Over the period 1810-1987, return periods between 4 years (for track lengths between 300 and 400 m) and 45 years (for tracks > 900 m) are found. Track length has been used as a first "surrogate" for debris flow magnitude. Afterwards, crude estimates of volumes of material displaced by individual events were derived from geometrical properties of debris-flow deposits (cf. Fig. 4).

Table 1 furthermore shows that the distribution of flows over the "magnitude" classes is fairly constant over the whole period for which data were obtained. The low number of old deposits found (i.e. older than ca 1890) will be due in part to the burying of old deposits by younger flows. A problem is the absence of dated flows for the period 1950-1980. For a number of reasons it is not yet possible to conclude that debris-flow activity was really low during this period. First, lichens need a relatively long period before their thallus becomes macroscopically visible. For *Rhizocarpon geographicum* (s.l.) this colonisation time appears to be some 25 years at the south side of the Alps (*Orombelli & Porter*, 1983). Second, when two or more debris flows occur at one location, only the youngest can be dated (if already lichens have developed). Third, many debris flows came down unnoticed. Moreover, only a low number of debris-flow deposits are sufficiently in contact with trees to allow dating by dendrochronology. All together, 38% of all tracks within the first test remain undated. Nevertheless, it might be no coincidence that both dating techniques give the same blank period. During the period 1900-1930 activity appeared to be high, and again after 1980. Especially the year 1987 gave an abnormal high number of debris flows, as at many other places in the Alps. In that year, 29 tracks were counted within the study area, most of them in the range of 300-700 m (16 cases, with a mode of 10 for the class 600-700 m). The number of short tracks was relatively high, although much smaller than that of the modal class (5 and 10, respectively). Table 1 also suggests an alternation of periods of higher and lower debris-flow activity in a more generalised way. Peaks occur around 1820, 1860, 1910, and after 1985, the spacing between the subsequent high-activity periods apparently becoming larger. As stated before, the number of events found for recent times is much higher than that for the older periods. This does not necessarily point to a recently increased debris-flow activity. In a system with a high degree of activity, younger deposits will easily cover or sometimes erode the older flows, which means that only the younger events can be dated by lichenometry, unless deposits are juxtaposed, and not superposed. On the contrary, the increase in time between subsequent periods of higher activity might as well point to a general decrease of debris-flow activity. There also is a spatial differentiation of activity at a local scale: a limited number of debris flow source areas and tracks showed a high degree of activity (average recurrence interval about 5 years) over longer periods, whereas others revealed only one debris flow deposit. In the latter case the difference in age between neighbouring tracks may be large. Using all events that occurred during the period 1810-1987, return periods between 4 years (for the track-length class of 300-400 m) and 45 years (for flows > 900 m) are found. For flows of 100-300 m the return period is about 5,4 years.

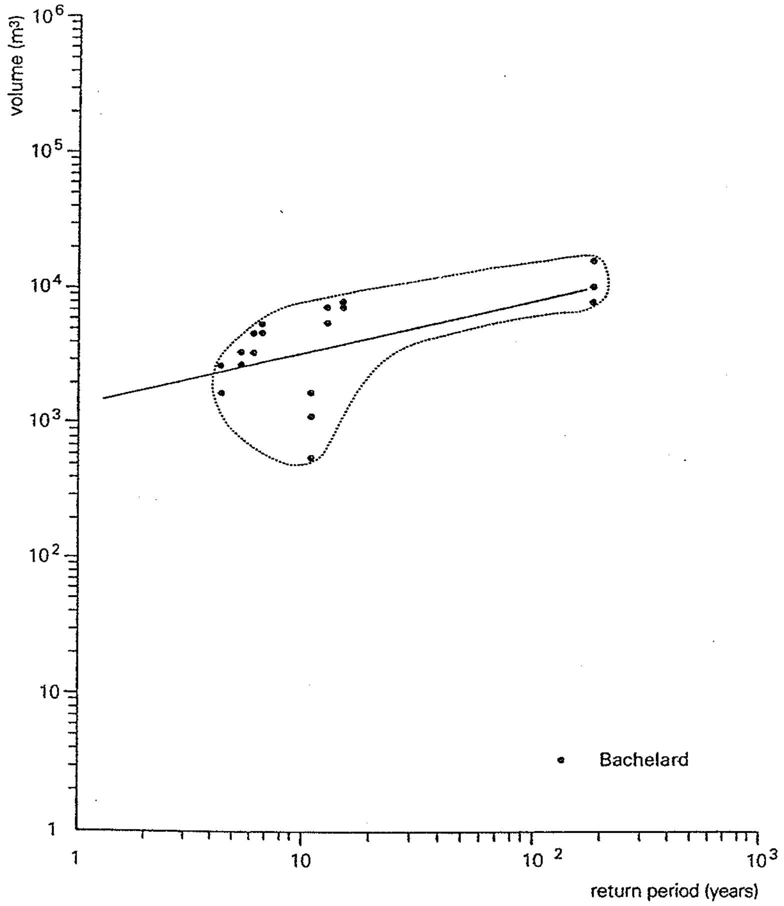

Fig. 4 - Debris-flow magnitude-frequency pattern for the Bachelard-valley study area. The regression line is only meant to underline the trend within the relationship (after *Van Steijn*, 1996).

Blijenberg (1998) on the base of his observations concludes that debris-flow frequency is higher than previously thought, giving return periods of 1 year or even less for some debris-flow trigger zones, and an overall average value for the Bachelard valley of 2-2,5 years. Much of this discrepancy might be due to the intensity of observation on the one hand, and to a bias towards larger (less frequent) events for dated cases on the other hand.

Dendrochronological dating was based on tree ring eccentricity patterns for *Larix decidua*, using the approach described by *Braam et al.* (1987). Along a large part of the flow tracks trees are however lacking, in which case lichenometry is the only dating technique available provided suitable species can be found. Fig. 3 shows debris-flow events in the same part of the Bachelard valley dated by dendrochronology. The continuous line in the figure shows the number of trees ("cases") analysed. Activity is indicated by the peaks that show the percentage of trees having significant ring eccentricity in the year indicated.

When comparing both series of datings, it is clear that there exists a concentration of debris flow activity in clusters of years. The number of events found for recent times is much higher than for the beginning of this century. This does not necessarily means an increased debris-flow activity. In a system with a high degree of activity, younger deposits will easily cover the older flows, which means that the lichenometric dating allows the discovery of only the younger events, unless older deposits stay exposed.

The relationship between magnitude and frequency for the test area within the Bachelard valley in a more statistical sense is shown in Fig. 4. It can be seen from this figure that a relationship exists between magnitude and frequency, larger events showing longer return intervals. The most striking aspect is that there seems to exist a maximum magnitude for debris flow in this region: for the longest return periods the corresponding magnitude values seem to become constant.

Research on initiation and frequency of debris flows concentrated on the easternmost part of the Bachelard valley. However, a comprehensive inventory of debris-flow source areas was carried out for the total catchment, and for certain moments the actual activity was surveyed (*Blijenberg*, 1998). Finally, a map showing debris-flow activity within the valley over the period July 1992 until October 1994 based on "direct" observation was also prepared by *Blijenberg* (Fig. 5).

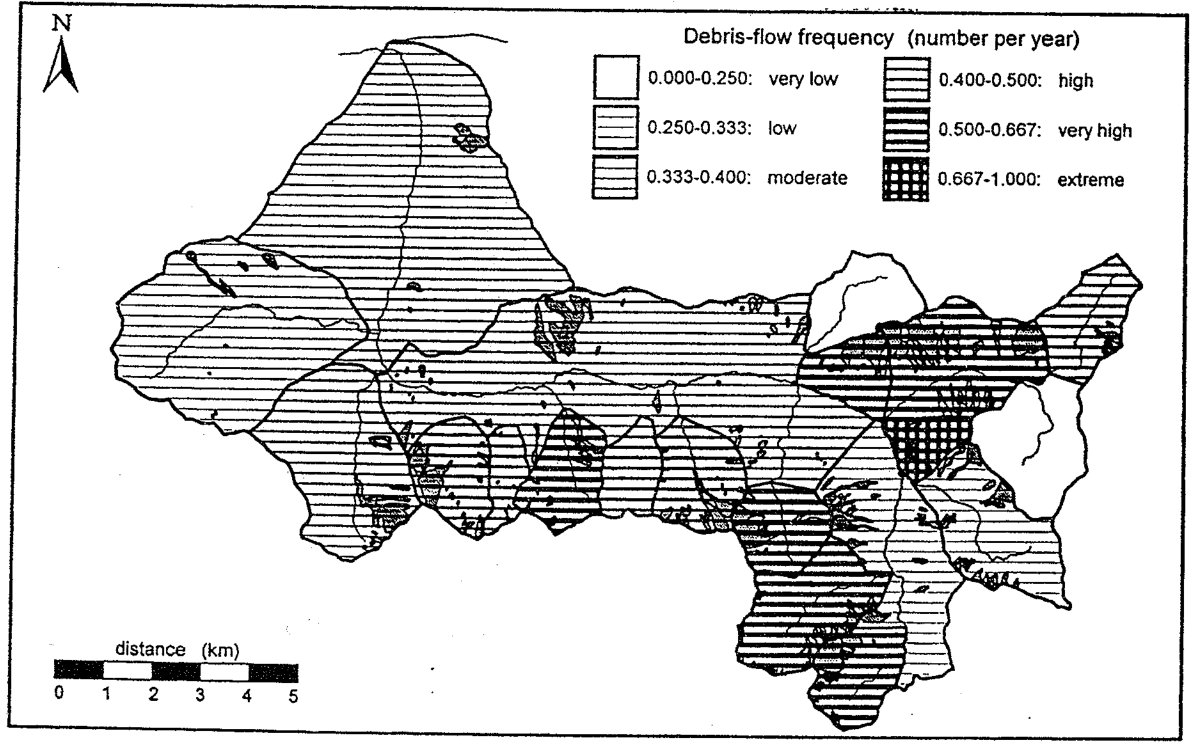

Fig. 5 - Bachelard valley: debris-flow activity from late July 1992 until mid-October 1994. Figures indicate number of events per source area per year (after *Blijenberg*, 1998).

4. CONCLUSION

Within the magnitude range of debris flows observed in the study area, events of moderate intensity occur most frequently. Nearly 70% of all deposit track lengths (used to indicate event "magnitude") are in the range of 300-700 m. The dimensions probably reflect properties of the

morphological system formed by the source area and the flow track, debris availability included.

Using all events that occurred during the period 1810-1987, return periods between 4 years (for the track-length class of 300-400 m) and 45 years (for flows > 900 m) are found. For flows of 100-300 m the return period is about 5,4 years. More recent observations, probably including many small flows that are missed by (delayed) dating of debris-flow deposits, indicate an overall average value for the Bachelard valley of 2-2,5 years.

The frequency pattern found for the study area in the Bachelard valley shows an alternation of periods with higher activity and low-activity periods. The intervals between these periods have irregular lengths. It is not yet possible to correlate this pattern with patterns of precipitation, partly because sufficiently accurate rainfall data are not available, while knowledge of precipitation intensity thresholds required to trigger the debris flows still is limited. The magnitude-frequency relationship for the debris flows in the study area indicates an increase of return periods for increasing magnitude of events. However, a maximum seems to exist as for the longest return periods the corresponding magnitudes tend to become constant.

A problem is the recognition of the older periods of high activity because the evidence for these (in the form of datable deposits) generally is difficult to obtain.

Tab. 1 - Bachelard valley. Debris flow activity 1800-1987 specified for "magnitude" classes as indicated by track length of deposits (see text). 1-13: track-length classes; 1: 100-200 m; 13: 1300-1400 m.

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*Tot.*
1800-09	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10-19	-	-	-	-	-	-	1	-	-	-	-	-	-	1
20-29	-	-	-	-	-	-	1	-	-	-	-	-	-	1
30-39	-	-	-	-	-	1	-	-	-	-	-	-	-	1
40-49	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1850-59	-	1	-	1	-	1	1	1	-	-	-	-	-	5
60-69	-		-	-	2	1	-	1	-	-	-	-	-	4
70-79	-	1	-	1	1	-	-	-	-	-	-	-	-	3
80-89	-	1	-	1	-	-	-	1	-	-	-	-	-	3
90-99	1	-	1	1	2	-	1	1	-	-	-	-	-	7
1900-09	-	-	5	4	5	-	2	2	-	-	-	-	-	18
10-19	-	3	10	5	2	-	-	1	-	-	-	-	-	21
20-29	2	2	5	3	3	-	2	-	-	-	-	-	-	17
30-39	-	1	2	2	1	1	-	-	-	-	-	-	-	7
40-49	-	-	1	-	-	2	-	1	-	-	-	-	-	4
1950-59	1	-	-	-	-	-	-	-	-	-	-	-	-	2
60-69	-	-	-	-	-	-	-	-	-	-	-	-	-	-
70-79	-	-	-	-	-	-	-	-	-	-	-	-	-	-
80-87	5	2	2	2	2	10	2	1	-	-	1	1	1	29
unknown	8	6	16	12	13	13	4	3	1	-	-	-	-	76
TOTAL	**17**	**17**	**42**	**33**	**31**	**29**	**14**	**12**	**1**		**1**	**1**	**1**	**199**
%	**9**	**9**	**21**	**17**	**16**	**15**	**7**	**6**	**-**	**-**	**-**	**-**	**-**	**100**

Furthermore, there is the difficulty to obtain figures for debris-flow activity in the period 1950-1980, because the dating techniques available are not suitable. As shown by Table 1, many debris-flow deposits still are undated, part of which might fill the gap between 1950 and 1980. Finally, the recent observation of still shorter return intervals, indicating a still higher activity of the debris flow process is another factor limiting the use of the reconstructed debris flow activity as a tool for validation of models predicting the probability of debris flow events.

References

BLIJENBERG H.M. (1998) - *Rolling Stones? Triggering and frequency of hillslope debris flows in the Bachelard Valley, southern French Alps.* Thesis, Utrecht University, 223 pp.

BRAAM R.R., WEISS, E.E.J. & BURROUGH P.A. (1987) - *Spatial and temporal analysis of mass movement using dendrochronology.* Catena, 14, 573-584.

EVIN M. & ASSIER A. (1983) - *Mise en évidence de mouvements sur la moraine et le glacier rocheux de Sainte-Anne (Quéyras, Alpes du Sud, France). Le role du pergélisol alpin.* Revue de Géographie Alpine, 71, 165-178.

INNES J.L. (1983) - *Lichenometric dating of debris-flow deposits in the Scottish Highlands.* Earth Surface Processes and Landforms, **8**, 579-588.

INNES J.L. (1985) - *Magnitude-frequency relations of debris flows in Northwest Europe.* Geografiska Annaler, 67A, 23-32.

MILTENBURG J. (1986) - *Verkenning naar de toepasbaarheid van lichenometrie in de Franse Alpen.* Unpublished report, Department of Physical Geography, University of Utrecht, 30 pp.

OROMBELLI G. & PORTER S.C. (1983) - *Lichen growth curves for the southern flank of the Mont Blanc Massif, Western Italian Alps.* Arctic and Alpine Research, 15, 193-200.

VAN ASCH TH.W.J. & VAN STEIJN H. (1991) - *Temporal patterns of mass movements in the French Alps.* Catena, 18, 515-527.

VAN STEIJN H. (1996) - *Debris-flow magnitude-frequency relationships for mountainous regions of Central and Northwest Europe.* Geomorphology, 15, 259-273.

VAN STEIJN H., DE RUIG, J. &D HOOZEMANS F. (1988) - *Morphological and mechanical aspects of debris flows in parts of the French Alps.* Zeitschrift für Geomorphologie, Neue Folge, 32, 143-161.