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Debris-flow magnitude–frequency relationships for mountainous regions of Central and Northwest Europe

Henk van Steijn

The Netherlands Centre for Geo-ecological Research, Faculty of Geographical Sciences, Utrecht University, P.O. Box 80.115, 3508 TC Utrecht, The Netherlands

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Abstract

Debris-flow activity within a given area can be defined in terms of magnitude and frequency. When for such an area ranges of event magnitudes can be related to the corresponding frequencies, the regional characteristics of debris-flow activity will be obtained. From the viewpoint of hazard assessment this magnitude–frequency characteristic is an essential element of the debris-flow process. For larger areas, (supra)regional comparison may also be undertaken on this basis. However, the data available often specify magnitude insufficiently. For the present study, published data specifying both magnitude and frequency (a very limited amount) were used for the Alps, the Tatra Mountains, Scotland, Norway, and Swedish Lapland in addition to material for the French Alps from the author's research. Activity levels within Northwest European mountains were found to be lower than in the Alps or the Tatras. Possible explanations are discussed, in which precipitation patterns and debris availability play a prominent part. However, the general conclusion has to be that firm statements about the causes of observed differences in magnitude–frequency patterns cannot yet be given.

1. Introduction

1.1. General

Debris flows have been reported from a wide range of mountainous environments. Dimensions vary strongly, both within and between different regions. Beside this spatial variability, the temporal patterns also appear to be highly variable. The present article is an analysis of temporal patterns (in the sense of magnitude–frequency relationships) of debris-flow activity in parts of Central and Northwest Europe (Alps, Polish Tatras, Pyrenees, northern Scandinavia, Scotland). The material used is partly based on literature data (with additional information given by several researchers), and partly the result of the author's own research on debris flows in the French Alps. The study does not claim to be comprehensive. It merely tries to describe some trends for a number of "sample" areas in two parts of Europe, chosen only because of data availability.

At first sight, areas like the high-mountain parts of Lapland and of the Alps or the Tatra Mountains show a strong resemblance with regard to slope physiognomy. Generally, the upper parts of the slopes consist of steep rock walls separated by chute systems through which most transfer of sediment to lower parts of the slopes is taking place. Vegetation is largely lacking. Extensive systems of screeslopes and fans are present in the zone between the rock cliffs and the valley bottoms. Vegetation cover and type are very variable on the screes and fans, partly

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due to different levels of talus and fan process activity. Spatial distribution of debris-flow tracks, dimensions of flow deposits, or morphometric slope properties appear to be comparable. This is true at least for hillslope debris-flow sites (cf. Brunsden, 1979) but probably also for small torrent systems (up to a few square kilometres) ending with colluvial fans. However, when looking at the duration of debris-flow activity phases and at their temporal patterns, and comparing events of similar magnitude, it becomes clear that large differences exist between the mountains of Northwest Europe and the Alpine chain.

The purpose of the study is first, to detect for the regions indicated above possible systematic differences in debris-flow activity between the regions. Second, to analyse whether the differences found correspond to different general levels of process magnitude when comparing these regions. For this latter purpose, elements for explanation are analysed. All reports used were scanned on statements about the influence of precipitation (duration, intensity, return periods) and debris availability as well as other geomorphological factors.

This attempt is made because a better knowledge of the temporal patterns and their relation to process intensity may increase the quality of debris-flow frequency prediction and hence of hazard assessment. The sites of debris-flow hazard generally can be identified without much problem, so debris-flow probability and runout distances must be seen as the most difficult part of the hazard assessment. The problem of runout distances is out of the scope of this study.

1.2. Methodological aspects

In order to keep the analysis as simple as possible, it is limited to geomorphologically simple debris-flow systems. Therefore, only data on hillslope debris flows and related flows on small fans in front of short torrential systems (as noted above) were used in this study. One exception was however allowed for reasons of comparison: the same kind of magnitude-frequency analysis was carried out for a data set of (very) high-magnitude events that follow other lines of development after their initiation. Such high-magnitude events, in which large-scale landsliding contributes to the development of the flows, are reported for several large torrential systems, mainly in the Alps.

Debris flows are recognized by the morphology of their deposits: a pair of elongated lateral levees along a shallow central furrow, and frontal lobes at the terminus of the track. These elements can easily be detected in the field and often on aerial photographs as well. The deposits appear to be relatively stable forms which means that they may obtain relatively old ages. Rapp and Nyberg (1981) give estimated ages for debris-flow deposits of up to 2700 years.

The parameter most frequently used to represent "magnitude" of debris-flow activity is the volume of material deposited by an individual event. Individual events generally comprise several surges, coming down one after another within a short period of time (generally, the duration of one storm). Volume estimates are derived from morphometric properties of the deposits. Losses due to further transport or subsequent erosion are neglected, and as a whole, the estimates must be considered rather crude. In this way volumes were obtained for the "Scotland" case (Innes, 1983) and for the "Bachelard" case (both described below). The other studies used do not specify the method to estimate volumes. Innes (1983, 1985b) used volume classes (at a very detailed level) to summarise the large "Scotland" data set. This idea has been followed in the "Bachelard" case study.

As noticed by Innes (1985b), debris-flow frequency can be defined in two ways. One definition is the number of cases of a specified magnitude within the total range of magnitudes observed. This essentially is a spatial phenomenon. The other one is based on the temporal aspect: the frequency through time of events in their real sequence or expressed in terms of return periods.

Estimates of frequency (in the present article reciprocally expressed as return period) are obtained by dating debris-flow deposits. In most cases, datings are based on lichenometry (Lapland, Norway, Scotland, Spitsbergen, Tatras), because other dating techniques often cannot be applied. Lichenometry methods used are based on the detection of the "largest" thallus diameter on the substrate to be dated — either the mean of the five largest thalli found, or the absolute largest. This "largest" lichen size is a measure of the age of the phenomenon provided that an appropriate lichen-growth curve (defining the relationship between lichen size and age) is available. Recently developed lichenometrical techniques using frequency distributions of largest lichen size (Bickerton and Matthews, 1993; McCarroll, 1993; Bull et al., 1994) widen the applicability of the method. In the case of the Bachelard valley dendrochronology as well as lichenometry was used. Data for very high-magnitude events are based on written reports or other historical documents (Antoine, 1988, 1989; Eisbacher and Clague, 1984; Peiry, 1990).

The record of debris-flow activity obtained from datings and observation is always incomplete. Many flow deposits remain undated, simply because datable objects are absent. Furthermore, lichenometric dating is impossible for deposits younger than the age given by the "colonisation time" for the species used (i.e., the period since deposition during which no macroscopically visible lichen thalluses are present). Younger deposits may completely bury older ones, bringing the latter out of the scope for lichenometry. This latter fact may be a serious problem when trying to estimate the importance of earlier events, as was stated by Luckman (1992). The example given by Rapp and Nyberg (1981: pp. 191, 192) however is an indication that the possibilities for lichenometrical assessment of debris-flow activity in the past depends to a high degree on local circumstances: the higher the present-day activity, the higher the probability that important parts of the evidence are lost and that former activity is underestimated. Finally, Rapp and Nyberg (1988) suggest that a certain bias may exist with regard to debris-flow activity in recent times, especially for thinly populated regions: an increased population and a higher level of awareness may result in an increased number of debris-flow events observed.

Several practical problems arise when trying to interpret reports on debris-flow activity in terms of magnitude–frequency relationships. Often, only the total range of dimensions is given, specifying merely the smallest and the largest cases observed. The same is true for return periods, as generally again only a range is given. This means that on the base of such data it is not possible to find return periods for individual events of a given magnitude. Another problem is the inconsistent use of terms. For instance, sometimes a "large" or "catastrophic" event appears to be a single debris flow displacing an unusual amount of material, but sometimes it means a generalised activity affecting a large area, where it remains unclear whether the individual cases are large or small.

Ideally, the following data are needed to allow comparison between different regions:

- statistical frequency of events of specified magnitude within the local range of magnitudes (a "spatial" frequency distribution);
- temporal pattern of debris-flow events, taking into account their magnitude, showing the regional sequence of events in the past;
- magnitude-related frequencies (or, inversely, return periods);
- spatial concentration of events (density of tracks).

In this way, it will be possible for each region to define "modal" as well as "extreme" events and their frequencies. Only the data sets for Scotland and for the Bachelard valley (described below) approach these requirements.

The regional description of debris-flow activity starts with the Bachelard valley (French Alps), followed by additional information from other parts of the Alps, The Tatra Mountains, and the Pyrenees. For Northwest Europe, material from Swedish Lapland, northwest Norway, and Scotland is summarised, with a few additional remarks concerning south Norway and Spitsbergen.

The results of the inventory carried out in the present study are summarised in a series of diagrams (Figs. 1–3). The regression lines shown (power functions) should not be interpreted in a rigorous way, because in many cases the amount of data is insufficient to allow this. For the same reason the regression equations are not given here. The lines are merely intended to give an idea of trends as well as "average" values of activity levels. The scatter within the different data sets is indicated by means of envelopes. The results are described and analysed in the section on magnitude–frequency relationships.

2. Results

In this section the most important characteristics of debris-flow activity within the several regions mentioned are described. Background features such as geological, topographical and other factors are summarised in Table 1. Only for the Bachelard valley is a more detailed description given here. This region is thought to be representative for the type of landscape in which valley-side debris flows are an important geomorphological phenomenon.

2.1. Debris flows in the Alpine chain

For the French Alps, data were gathered especially for an area within the Bachelard valley near the Col de la Cayolle. This valley belongs to the easternmost part of the Durance drainage basin. Additional information came from other sites of the southern French Alps (cf. Van Steijn et al., 1988). 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 are near 2800 m. Debris-flow source areas (steep chute systems bordered by rock walls or by slopes covered with a relatively fine-grained regolith) are found at altitudes of about 2100–2800 m. The climate of the area is characterised by both Mediterranean and oceanic influences. High-intensity rainstorms occurring during summer and autumn appear to be responsible for the debris-flow activity in this region. Flows are triggered by rapidly initiated runoff, destabilising coarse debris accumulated in depressions within the source areas. The influence of melting snow is thought to be very limited, as most known activity occurred in the absence of snow. Within the source areas, debris availability appears to be no limiting factor. This is probably caused by a rapid production of weathering materials because no large stocks of sediment of (for instance) glacial

Table 1
Characteristics of main regions for which magnitude/return-period data were obtained (see text for further explanation)

	Bachelard (Fr. Alps)	Tatra	Arve	Tyrolian Alps [a]	Ariège	Swedish Lapland	Northwest Norway	Spitsbergen	Scotland
Latitude (°N)	44	49	46	47	43	66–69	69	78–79	56–58
Base level (m)	1600–1800	1600–1700	800–1200	530–700	500–650	600–1170	0	10–50	170–930
Relief (m)	500–1300	350–750	500–1800	1000–1700	1400–1800	340–600	500	600–1700	70–750
Slope-angle range (°)	> 30	> 35 (?)	?	?	27– > 45	26–41	35–40	> 30–35	> 30
Bedrock	sedim.	granite	sedim., metam.	sed., metam., + unconsol.	sedim., metam.	metam., granite	metam., granite	sedim., granite	volc., sed., granite
MAAT [b] (°C)	3.3	0	7.5 [d]	7–8 [d]	10 [d]	−1.7 to −0.9	4.4	−5.8	5–7 [d]
Jan., mean temp. (°C)	−6.2	−8.5	−2.5 [d]	−3 [d]	2.5 [d]	−12	0.9	−15.3	3.3
Jul., mean temp. (°C)	12.5	8.2	17.5 [d]	15 [d]	20 [d]	11.5	11.5	6.3	13.9
Annual precip. (mm)	977	1400–1800	1200– > 1600 [d]	1000–1500 [d]	> 1200 [d]	322–1750	808	208–385	1000–2500
Storm rainfall intensity (mm/h or mm/12h) [c]	20– > 50/h	20–55/h	?	> 40–60/h	?	> 30/h 107/12h	?	31/12h	> 40/12h
Oceanic (O)/ continental (C)	O/C	C	C	C	C/O	C	O	O	O
Vegetation	grass/bare open forest	grasses shrubs	?	?	?	birch forest shrubs, grasses	birch forest grasses	?	grasses mosses

[a] Generalised data for the regions of Zell am See and Zillertal (Austria).
[b] MAAT: Mean Annual Air Temperature.
[c] According to published data.
[d] Source: WMO/Unesco/Cartographia (1970).

origin were found at the level of the source areas. Rapid weathering is controlled by the periglacial conditions present at the level of the source areas together with a general absence of vegetation. The level of 0°C mean annual air temperature in this region is about 2400 m.

At the Bachelard-valley study site of about 15 km^2, over 200 tracks were counted. Track length of the depositional part, used as a first approach to represent "magnitude" of the events, varies from about 100 to 1150 m. The next step was to make a (crude) estimate of volumes of debris-flow deposits per event. For this purpose, a mean cross-section value was estimated for each track, taking into account its variability along the track. Justification for this approach is found in the strong relationship reported by Innes (1985b) between planimetric flow dimensions and volumes. The volumes obtained are used for the comparisons that will be discussed subsequently.

For the analysis of frequency as a temporal phenomenon, dating of deposits by lichenometry and dendrochronology was undertaken (Braam et al., 1987; Van Asch and Van Steijn, 1991). The period over which flows could be detected is relatively short, for the oldest events presently known are from

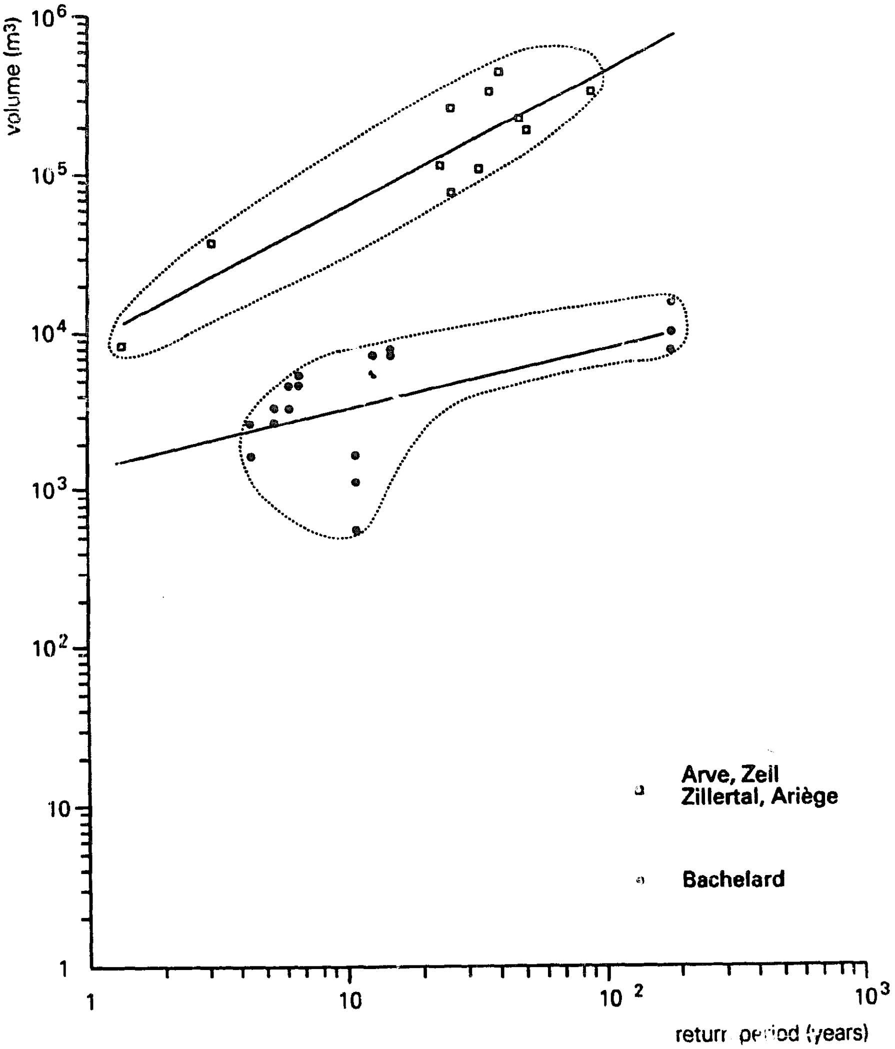

Fig. 1. Debris-flow magnitude–frequency patterns for the Bachelard-valley study area (lower part) and for "very high-magnitude" events (upper part). The regression lines are only meant to underline trends (as explained in text). Bachelard data: from present author's analysis; high-magnitude events: data from several sources (see text).

the first decades of the 19th century. Using all events that could be traced for the period 1810–1987, return periods between 4.0 years (for track-length class 300–400 m) and 45 years (for flows > 900 m) are found. For flows of 100–300 m the average return period is about 5.4 years.

During the interval 1900–1930 activity appeared to be high, and again after 1980. For the period 1940–1980 only very few flows could be dated (indeed 38% of all tracks remain undated). The low number of old deposits found will be due in part to the burying of old deposits by younger flows. Thus, a good image of temporal fluctuations of debris-flow activity is not yet possible. The year 1987 gave an abnormally high number of debris flows, as at many other places in the Alps.

Fig. 1 shows the relationship between return period and magnitude for the debris-flow events detected in the Bachelard-valley study area. The contents of the diagram will be discussed below, together with that of the other figures.

More or less detailed figures are available also for the Tatra Mountains (Kotarba, 1989, 1991, 1992; Kotarba et al., 1987; Krzemien, 1988). Activity in especially the High Tatra, known over some 200 years, appears to be comparable to that found for the French Alps. It was found to be relatively high between 1825 and 1870, the final phase of the Little

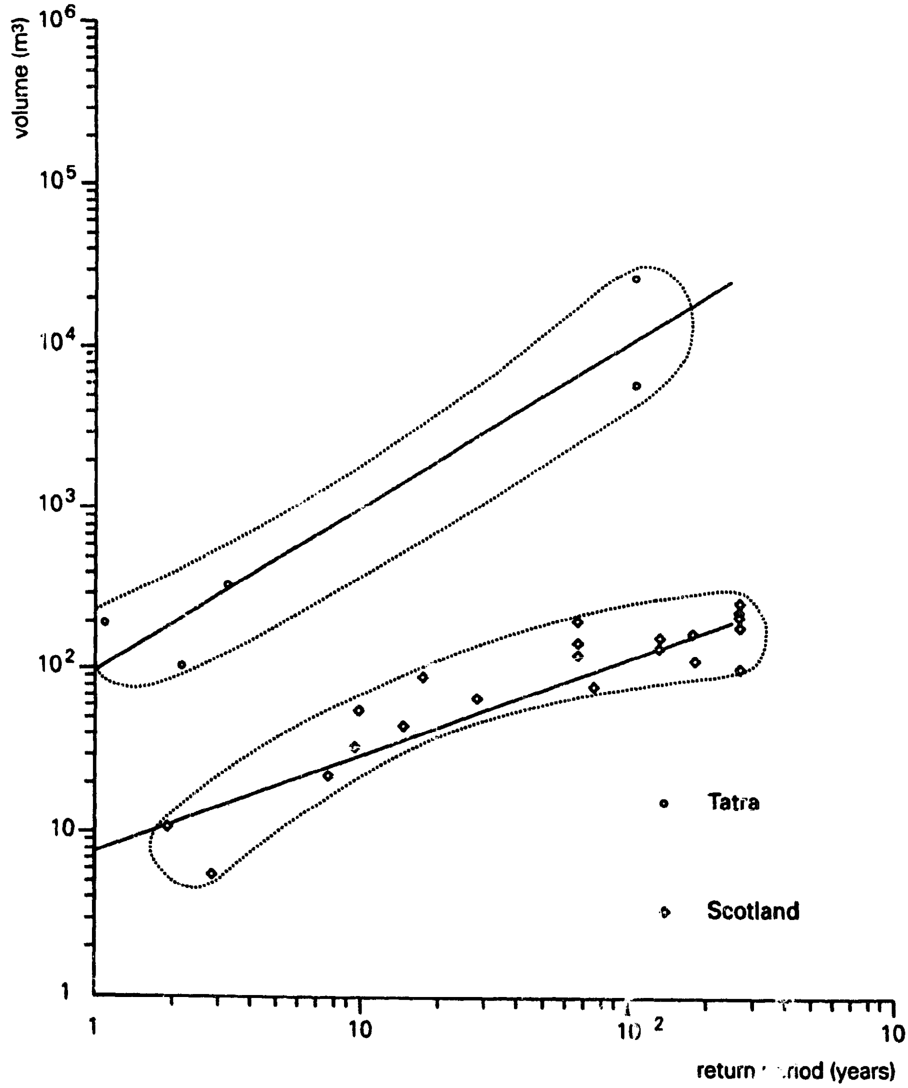

Fig. 2. Magnitude–frequency patterns for the Tatra Mountains (upper part) and for Scotland (lower part). Source: Tatra data: Kotarba, 1989; Scotland: Innes, 1983. See also Fig. 1.

Ice Age. During this period the largest debris flows occurred that were found in the study area. Deposit volumes of these flows are up to 25,000 m^3 (Kotarba, 1989). Many smaller events are known (100–300 m^3), for which Kotarba estimates return periods of about 1–4 years. For the largest flows, return periods of about 100 years are given by A. Kotarba (pers. commun.). Debris availability is mentioned to be relatively important, but again precipitation is seen as the dominant factor. Precipitation thresholds for debris flows of different magnitudes are also estimated by the same author (pers. commun. — see below). Fig. 2 shows a tentative magnitude–frequency relationship for the Tatras debris flows.

For other parts of the Alps, data on debris-flow frequency are more scanty. Interesting material is published by Strunk (1988, 1991, 1992) about a part of the Dolomites. Data cover a period of 370 years. Episodes of higher and lower activity again alternate, and generalised return periods of some 11–30 years can be deduced. No such indicators are given, but the magnitude seems to be in the order of 1000's of cubic metres.

Very different, extremely large debris flows are described by Peiry (1990) and Eisbacher and Clague (1984) for other parts of the Alps. The morphological systems in which this debris-flow activity has been observed are more complicated than those of the cases described so far. They are much larger, and, more important, they each consist of a series of subsystems that may all contribute to the developing debris flows after their triggering in the uppermost parts. As stated in the introduction, the data are given here in order to compare the data for small-scale debris flows with such for systems that are thought to function in a different way.

Peiry (1990) discusses eight torrential tributaries (1.6–11.4 km^2) of the Arve river near Chamonix, between the Mont Blanc and Lake Geneva. The catchments are developed in weak bedrock types that are covered by important masses of Quaternary deposits (moraines and screes). Within the eight torrent systems as a whole, 5 flows of over 100,000 m^3 of deposits each are reported over the period 1895–1988, the last one occurring in 1964. Three flows of 34,000–70,000 m^3 occurred since 1953, and six others (of about 7500 m^3) were noted in the period 1983–1988. These figures apparently mean a return period of ca. 6.5 years for flows of > 70,000 m^3. The behaviour of the individual torrent systems analysed showed large differences, but large-scale landsliding occurring along the middle course of these torrent systems and triggered by the passing debris flow seems to be involved in most cases. In Fig. 1 data for these flows are shown, together with that of other very large events, summarised by Eisbacher and Clague (1984) for Zell am See and for the Ziller Valley, both in the Austrian Alps. The role of landsliding remains unclear in these latter cases, but the presence of very large stocks of unconsolidated material within the source areas is believed to be an important factor in the occurrence of these debris-flow events. Nevertheless, Eisbacher and Clague (1984: pp. 218, 195) mention high-intensity rain storms triggering the flows. Antoine (1988, 1989) analysed debris-flow activity within the Ariège Valley, in the eastern Pyrenees. Here, large debris flows reached the main valley from several torrent tributaries during the last 250 years. Volumes of 30,000 to 70,000 m^3 are mentioned (Antoine, 1989: p. 532). Data are included in the data set "very high-magnitude events" that is shown in Fig. 1. Unfortunately, these publications lack information about triggering mechanisms or precipitation amounts.

Much has also been published about the devastating events in Switzerland during the summer of 1987 (cf. Rickenmann, 1990; Rösli and Schindler, 1990; Zimmermann, 1990; Haeberli et al., 1990), but no magnitude values for individual cases are given. Zimmermann (1990), in his Table 1, suggests mean values of about 2500 to 6000 m^3. Corresponding return periods are unknown.

2.2. Northwest Europe

Debris-flow activity patterns within mountain areas of Northwest Europe were analysed by several authors, but only some of the more recent investigations can be used here, because only these contain information about both return periods and magnitudes. Available data concentrate on Swedish Lapland, Norway, Spitsbergen, and Scotland. Morphologically, the descriptions given in the introduction apply to all these regions. According to the authors cited below, soil slips related to episodes of high-intensity rainfall often play an important role here in debris-flow initiation. Characteristics of the landscapes involved are given in Table 1.

The oldest events, dated by lichenometry, are reported from Lapland, where several phases of activity of hillslope debris flows were found over 2700 years (Rapp and Nyberg, 1981). Return periods of 50–400 years are deduced, but precise data about magnitude–frequency relationships are not given. Moreover, in a later article, shorter return periods for "major recent events of large debris flows" are suggested (Rapp and Nyberg, 1988). For the Tarfala area, the largest debris-flow deposits of the 1972 event measured 4000–10,000 m^3 (Rapp and Strömquist, 1976). Elsewhere, the "magnitude" range is stated to be some 10 to 10,000 m^3 (Nyberg, 1985).

Old events of hillslope debris flows are also reported from Spitsbergen (André, 1990): 4 episodes over nearly 2000 years. The author mentions return periods of 80–500 years, but no differentiation is made based on magnitude. She nevertheless indicates these events as "catastrophic", being different from "minor" episodes, like one in Longyear valley, 1981. The 1972 event at the same location (described by Larsson, 1982) would represent a "major" episode. A volume range of 1–600 m^3 is given, and Larsson (1982) estimated the volumes of the flows at Longyear valley as 50–500 m^3, although there the

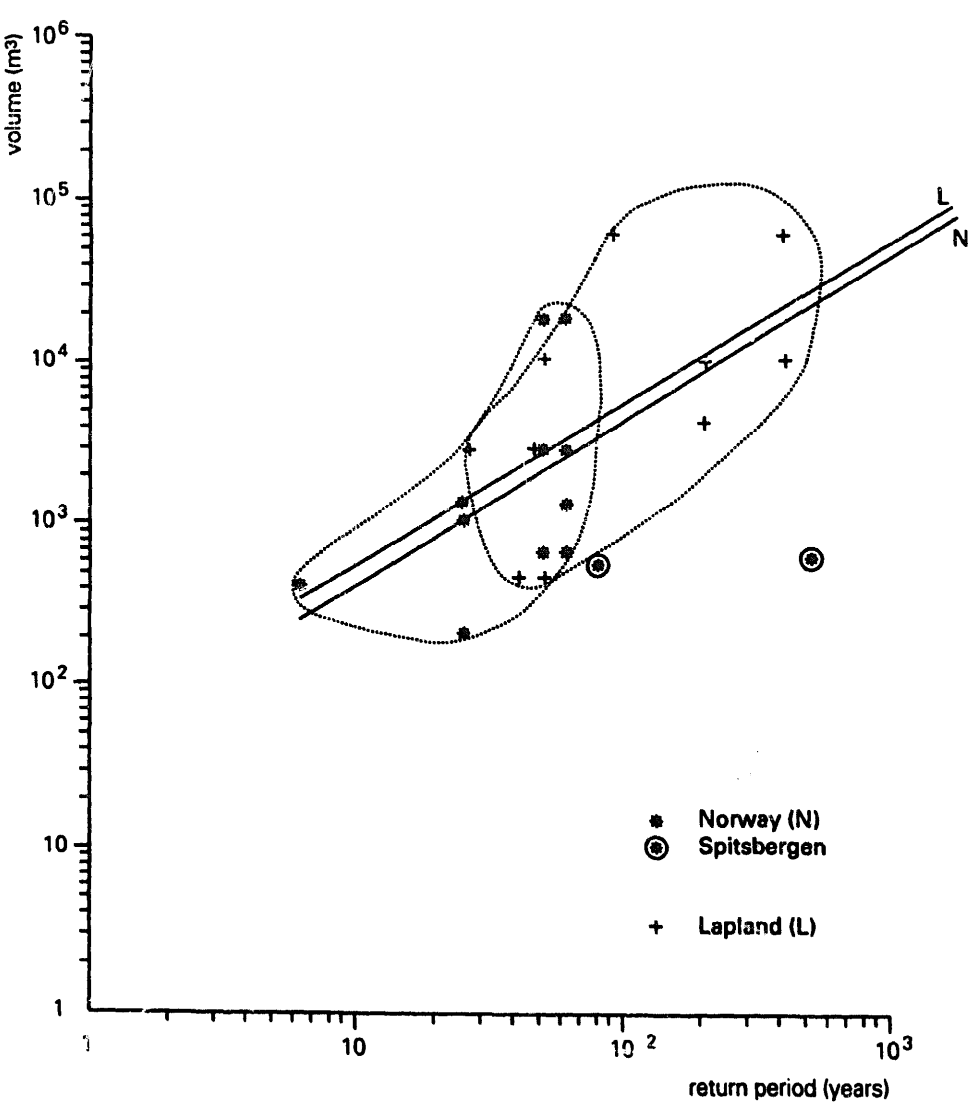

Fig. 3. Magnitude-frequency patterns for Scandinavia (Swedish Lapland and northwest Norway). From different sources, as explained in text. See also Fig. 1.

class of < 100 m^3 was by far most important. The presence of permafrost on the slopes is mentioned as a favourable condition for debris-flow triggering by shallow landsliding. For Spitsbergen, the role of aspect was emphasised, debris flows occurring especially on east-exposed slopes (Åkerman, 1984: p. 283).

On a shorter timescale (about 100 years), debris-flow activity is known in north Norway. Flows displacing some 2800 to 19,000 m^3 of debris appear to have return periods of 25–60 years (Strömquist, 1976). Higher frequencies are suggested for a range of smaller flows (50–500 m^3) by Rapp (1987). Fig. 3 is a compilation of data about return periods and debris-flow magnitudes from several of the publications mentioned above. Innes (1985a) analysed debris-flow deposits on colluvial fans in southwest Norway. The oldest events dated from about 1560 AD. The activity was reported to be "highly episodic". The range of deposits of individual flows is about 10–2200 m^3, but flows > 1,000 m^3 appeared to be rare. The available data did not allow an entry in Fig. 3.

In a very detailed study, Innes (1983) described debris-flow activity for Scotland. He counted several hundreds of flows of small dimensions. Within the valleys analysed by Innes, the vegetation cover seems to be more important than in all other areas described. Dating was obtained by lichenometry. This data set was used by Innes (1983, 1985b) to trace the

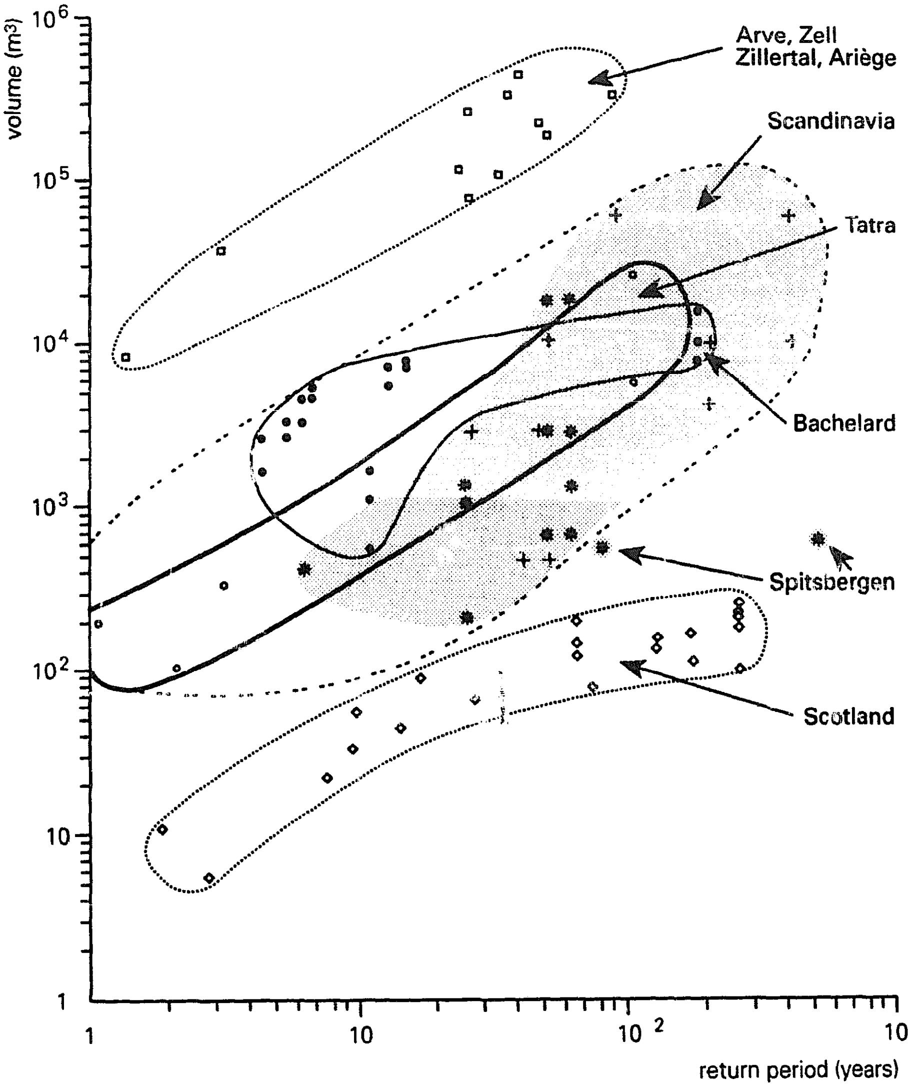

Fig. 4. Diagram combining the contents of Figs. 1–3, to visualise different fields and overlaps.

temporal pattern of events during the last 500 years. He found an increase in debris-flow activity in relation to landuse changes during the 19th and early 20th centuries. Rearranging Innes' data, return periods for the different magnitude classes were estimated. The result of this treatment is shown in Fig. 2.

2.3. *Magnitude–frequency relationships*

As will be clear from the foregoing statements, there generally is no detailed information about the frequency distribution of flows of different magnitude classes. Exceptions are the "Scotland" and "Bachelard valley" case studies. Only generalised ranges of debris-flow volumes could be derived from the published material. The analysis of return periods also reveals many uncertainties, despite a well-dated series of events in some cases (Rapp and Nyberg, 1981; Nyberg, 1985).

Not surprisingly, a large spread is found as well in volumes as in return periods. This means that interpretation of the diagrams (Figs. 1–3) in terms of either causes or prediction will be difficult. This spread cannot be explained by referring only to the vastness of the region for which data were collected. For example, separation of the Scandinavian data into an oceanic (Norway) and a continental (Swedish Lapland) part does not yield significantly narrower envelopes (see Fig. 3).

The tentative envelopes shown in Figs. 1–3 partly support the trend indicated by the regression lines, but partly suggest another type of correlation. For all data series a trend of increasing return periods with increasing magnitude is recognisable. The relatively large data set for the Bachelard valley indicates that there seems to exist a maximum magnitude for debris flows in this region: for the longest return periods the corresponding magnitude values seem to become constant. The same trend toward a maximum magnitude is shown by the Scottish data, in other words: for the only other larger data set. In the other cases such a tendency cannot be found, although morphologically all of them are well comparable, with the exception of the large torrent systems for which the activity is summarised in the upper part of Fig. 1. It appears that in the Scandinavian case for a given return period a very wide range of magnitudes is observed, and conversely, debris flows of a given magnitude may occur with very different recurrence intervals. This variability is also present within the subregions involved, for instance when looking only at the data for Swedish Lapland. The scatter is less pronounced in the Scotland and the Bachelard valley data.

Debris-flow activity in northern Scandinavia, especially in Lapland, can be traced over relatively long time spans (Rapp and Nyberg, 1981) when compared to the Central European mountains. This means that returns periods for "modal" debris flows (of some 500–5000 m^3) are much larger for Scandinavia than for the Alps (Fig. 4).

The Tatra and Bachelard valley envelopes are overlapping to a high degree. The trend toward a maximum magnitude that might not be surpassed however is not found in the Tatra data. It is possible that the limited number of flows for which both magnitude and frequency are known in the case of the Tatras explains this difference. Perhaps surprisingly, an important overlap also exists between the Tatra and Bachelard sets at one hand, and the Scandinavia data at the other.

The very large events shown in Fig. 1 still show the same trend of a relatively regular increase of magnitude with increasing return period. Bringing all data together, three fields finally emerge as shown in Fig. 4:

- low magnitudes at all observed return periods: Scotland;
- wide magnitude range at all observed return periods: Bachelard, Tatra, Scandinavia;
- very high magnitudes at all observed return periods: Arve, Ariège, Austrian valleys.

The diagrams of Figs. 1–4 show differences in terms of *y*-axis intercept, regression coefficient (slope of the regression lines), and ranges of return periods and debris-flow volumes. Fundamentally, these differences will be related to differences in the way in which the regional geomorphological systems involved are functioning, although methodological inaccuracies (caused by dating problems, difficulties in estimating volumes, or choice of statistical methods) may be depicted as well. An attempt can be made to interpret the differences mentioned.

The *y*-axis intercept indicates the general level of activity within a certain area, with only small debris flows as in the Scotland case on the one hand, and only large to very large flows on the other, like in the case of the Arve tributaries. Factors involved are the components of the geomorphological system, producing debris flows, as a whole. For Scotland, the presence of vegetation explains the occurrence of mainly small debris flows (Innes, 1983), although Luckman (1992) points to the absence of large amounts of recent rockfall material from the cliffs as an other important factor in this case. The high-magnitude flows shown in the upper part of Fig. 1 clearly are related to a fundamentally different geomorphological system, as was explained in Section 2.1. Return periods do not play a role in the explanation of intercept differences.

The regression-line slope points to the way in which "magnitude" increases with return period. Gentle inclinations mean that the intensity level does not increase much when looking at longer return periods. This indicates that either the precipitation regime involved is not very variable at the relevant time scale (intensity/duration combinations stay within fairly narrow ranges of return periods) or that the morphological characteristics of the region do not allow the production of larger flows, even under extreme conditions of precipitation. Limiting factors in the latter sense may be the dimensions of the debris-flow source areas.

The range of return periods observed for one region is related to differences of precipitation conditions under the present-day climate or to local differences between the morphological debris-flow systems involved. The different ranges of return periods visible in Fig. 3 for the "Norway" and the "Lapland" data may point to differences in precipitation regimes between these regions (cf. Table 1). For larger time intervals (centuries or more), fluctuations of climate may be involved. An example of the effect of climatic fluctuation is given by Kotarba (1989): a higher debris-flow activity was found for the final part of the Little Ice Age.

The scatter of debris-flow volumes ("magnitude") within one region is controlled by several factors: debris availability, concentration time of runoff, morphographical differences between the several source areas, magnitude of individual precipitation events, and fluctuations of return periods for precipitation as far as they influence the time needed for debris production. Debris availability may be expected to be influenced by lithology. A comparison of bedrock types mentioned in Table 1 and the patterns shown in Figs. 1–3 however did not reveal any clear trend. This is partly due to the high degree of generalisation of bedrock types in Table 1, but local conditions like the degree of tectonic weakening of bedrock or microclimate are equally important factors as lithology in producing non-cohesive debris. The degree of vegetation cover may be an other factor influencing debris-flow magnitude. For most of the regions discussed vegetation cover is very limited within the source areas. Only Scotland seems to be an exception to this statement (Innes, 1983). The types given in Table 1 generally give only an impression of the regional character of the vegetation. The Scotland case illustrates the possible limiting role of a denser vegetation cover with regard to debris-flow volumes.

3. Discussion

The overlapping fields for the Scandinavia, Tatra Mountains, and Bachelard data shown in Fig. 4 might be interpreted in terms of similarity of the geomorphic systems involved. Indeed, when looking at the description of morphometric and lithologic characteristics of valley sides and source areas for all these regions, they appear to be well comparable. This means that in these regions for the systems of valley-side debris flows comparable ranges of flow dimensions are highly probable. Differences between the Central-European regions and Scandinavia are mainly differences in frequency: higher frequencies are more characteristic for the mountain ranges of Central Europe, while for Scandinavia lower frequencies prevail. As discussed at the end of Section 2.3, these differences in process activity may have several causes, climatic as well as geomorphological.

With the present state of knowledge the interpretation of the diagrams with regard to causes is a very difficult matter. There are several sources of uncertainty that may play a role, apart from possible inaccuracies within the datings obtained. First, present-day activity may be different from that in the past. The example given by Kotarba (1989), who found that the Tatras had a period of high debris-flow activity during the final phase of the Little Ice Age, was mentioned already. It is however not known, whether this higher activity was caused by differences in the precipitation regime or in the availability of debris (thawing of formerly frozen soil?), or by a combination of both. Second, in most of the regions mentioned, the real state of activity is not well known. As stated, Rapp and Nyberg (1988) point to the possibility that in thinly populated regions a seemingly increasing debris-flow activity during this century can be partly explained by improved observation after a somewhat denser settlement had developed. This may lead to incorrect estimates of return periods when sufficient dating of older events cannot be obtained. Third, in all of the regions treated, there is insufficient information about precipitation in terms of threshold values for short-term rainfall intensities (i.e., within rain storms) and for intensity–duration frequency patterns. The values shown in Table 1 are only very crude estimates made for areas generally much larger than the study sites. Fourth, as is shown by the Arve and related examples, the type of debris flow has to be known, because the large events in which large-scale landsliding is involved in the triggering and/or in the further development of the event differ strongly from the "valley-side" events caused by overland flow. The latter type may be able to reach high magnitudes as well (see Fig. 3), but only in exceptional cases as is shown by their very long return periods. It is probable that for the Arve-type high-magnitude events other precipitation types (longer duration and lower peak intensities) are required than for the "valley-side" debris flows. Finally, in some cases human influence appeared to be important, as is illustrated by Innes (1983).

In almost all studies mentioned so far, precipitation patterns are mentioned as a very important factor, but actual return periods can be explained only when combining precipitation thresholds and debris availability.

Present-day differences in climate between Scandinavia and Central Europe are thought to be the main controlling element in the explanation of the different magnitude–frequency patterns shown. Precipitation regimes and weathering conditions (for instance, number of freeze–thaw cycles) will have most influence.

Precipitation thresholds appear to be different for the different regions. This of course is not surprising: Larsson (1982) already remarked that in Spitsbergen debris-flow events that occurred in 1972 were triggered by rain intensity–duration combinations well below the threshold line proposed by Caine (1980). The presence of permafrost explains this situation because the topsoil is easily saturated under this condition, and debris flows can be triggered, starting as soil slips. For the Alps and for the Tatra Mountains, threshold values around 40–50 mm/h for a duration of 60 minutes are proposed by Blijenberg (1993) and Kotarba (1989), respectively, for debris flows of "moderate" magnitude (i.e., in the order of 10^3 m^3 deposit per event). Blijenberg (1993) stresses, that the same result may be obtained by storms in which a peak intensity of 100–150 mm/h during some 5 minutes is obtained, followed by rainfall of lower intensity. For flows < 100 m^3 of material deposited per event, Kotarba (personal communication) gives an estimate of 25 mm/h during 60 minutes. Luckman (1992), for Scotland, mentions intensities of about 25 mm/h and 24-h precipitation of 86 mm which caused a "large" number of debris flows. Such values underline the necessity of having not only threshold intensity data, but also intensity–duration frequency curves available for the assessment of debris-flow frequencies. As can be seen from Table 1, the actual knowledge about precipitation thresholds still is very incomplete.

Permafrost degradation in Alpine areas since the Little Ice Age is reported to be important with regard to debris-flow frequency in the higher regions (> 2700 m), where large stocks of glacial deposits become available for transport once the interstitial ice has disappeared (Haeberli et al., 1991). Nevertheless, Zimmermann (1990: p. 392) states that for the catastrophe of 1987 in Switzerland the concentration of debris-flow activity in the periglacial area may be explained by the high air temperature during the events. He notes that precipitation fell as rain in catchments over 3000 m altitude.

Precipitation patterns may be influenced by the spatial character of the rainfall. As suggested by Rapp and Nyberg (1981), the spatial distribution (or the areal extent) of a debris-flow occurrence may reflect the spatial distribution of the rain. Thus, rainfall impact regions (frontal rain), rainfall impact cells (of more limited extent), and rainfall impact spots (very locally developed storms) were distinguished (Rapp and Nyberg, 1981: p. 186). The relative abundance of these rainfall types might have some relation to the general climate of a region, but perhaps may not be recognisable within available intensity–duration frequency curves. It certainly will influence the spatial distribution of debris flows.

Temporal precipitation patterns will cause temporal differences in debris-flow activity. Therefore, it is interesting to look for trends of changing debris-flow frequencies, for instance an increase in recent times — as suggested by Zimmermann and Haeberli (1990). The image obtained from the data sets discussed in the present article is diffuse. For Scotland, an increase in frequency was reported for the 19th and early 20th centuries. The different sources for Scandinavia do not allow a clear trend to be recognised, and the same is true for the Bachelard valley where a period (about 1900–1930) of high debris-flow frequency was found with an activity level similar to that since about 1980. For the large systems described by Peiry (1990), Eisbacher and Clague (1984), and Antoine (1988, 1989) again no clear trend is detectable. In the Tatras, larger events were particularly frequent during the final part of the Little Ice Age (about 1825–1870). Strunk (1991: p. 80) also reports a relatively high frequency in a part of the Dolomites during the Little Ice Age. Strunk (1992) suggests that no important change of debris-flow frequency occurred in the period 1884–1989 in this region. The balance of this short review therefore must be that no general trend of changing debris-flow activity (in any sense) can be established on the base of the data available for this study. As stated by Strunk (1991), who analysed a series of debris-flow cones, local factors greatly influence frequency: each cone revealed a frequency of its own.

Human influence sometimes is a very important factor, as was shown for Scotland by Innes (1983), but the real extent of this influence is not well understood in all regions discussed. For Scotland, Innes (1983) argues that landuse changes during the 18th and 19th centuries caused an increase of debris-flow activity, apart from the effect of the natural factors mentioned before, such as the absence of large amounts of recent rockfall material within the system, as mentioned by Luckman (1992).

A lack of sufficiently precise knowledge about the circumstances under which debris flows are triggered, especially in the Scandinavian case, means that firmer conclusions about the backgrounds of the patterns found still are impossible.

4. Conclusions

The available data do not allow an accurate image to be developed of similarities and differences between the European regions involved. Nevertheless, some indications are obtained. There appear to be different general levels of debris-flow activity that are related to differences in characteristics of the landscape systems involved. In this way, three fields were observed within the magnitude/return-period diagrams, two of which representing morphologically similar debris flows while the third one represents the independent series of "very high-magnitude" events (Fig. 4). This latter series concerns events that had a development completely different from all others. In all fields a trend of increasing return period with increasing magnitude is present. Large overlaps were found in the data sets for the Central European regions on the one hand and for Scandinavia on the other. However, frequency of events of a given magnitude can said to be higher for the Central European mountains than for northern Scandinavia.

Understanding debris-flow frequencies is strongly related to understanding triggering conditions. In this regard important differences exist between the Alpine chain and Northwest Europe. Debris availability is a limiting factor for the latter domain, but much less so for the former. In both cases, precipitation thresholds have been mentioned to be the major control, but the levels required are very different, and the direct effects of the precipitation are different too. In Northwest Europe, triggering of shallow landslides (soil slips) and subsequent transformation into debris flows is reported to be the general case, whereas in the Alps threshold quantities of surface runoff, generated within the source areas and destabilizing coarse debris accumulations initiates most of the valleyside debris flows. Integration of landslides with passing debris flows is important in larger torrent systems of the Alps. In this case, very large flows develop.

In terms of applied geomorphology, an improved knowledge of temporal patterns of debris-flow activity is important with regard to hazard assessment. Especially the detection of frequencies of large single events as well as of events occurring simultaneously in larger areas during one precipitation episode will improve the prediction of the risks involved. For this purpose, intensity–duration frequency curves for precipitation on a regional basis are urgently needed. Beside that, morphological properties of debris-flow source areas and tracks must be known in detail.

If at a regional scale sufficiently accurate data on magnitudes and frequencies for debris flows are obtained, then order-of-magnitude estimates for 10-year or 100-year events can be given on the base of the magnitude–frequency diagrams. For the data sets presently available this application can hardly be achieved — with the possible exception of those for the Scottish Highlands or the Bachelard valley.

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