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TOWARDS A FREQUENCY-MAGNITUDE RELATIONSHIP FOR TORRENT EVENTS IN AUSTRIA

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ABSTRACT

Hazard assessment and the design of mitigation measures against mountain hazards are usually based on statistically derived magnitude-frequency relationships of process parameters such as discharge, flow velocity, or the volume of debris deposits. However, with respect to debris flows there is a particular lack of such data, as these processes are rare phenomena, the systematic measurements of relevant parameters have only been carried out in selected watersheds within the last decades. In some areas, geomorphic and stratigraphic assessments and dendrochronology studies have been used for estimating magnitudes and frequencies of debris flow events. However, there is still an information gap for quantitative debris flow hazard assessment based on recurrence intervals and associated magnitudes. Our study aims to close this gap by an analysis of an Austrian database of historic events. Information on a local and regional scale has been gathered from records of the Austrian Torrent and Avalanche Control Service and the transcription of the so-called "Brixner Chronicle" (Strele, 1893). The earliest events of our database date back to the 6th century, while in-depth information on the events is available since the 18th century. In total, more than 20,100 torrent events were recorded, and around 5,700 have been identified as debris flow-like events. We report how to best identify different process types and to derive quantitative information from historic texts. Our results may improve the evaluation of frequency-magnitude relationships to be used in hazard and risk assessment and might also be used for estimates of possible consequences of climate change in the Eastern Alps.

Key words: *historic database, torrent events, debris flow, frequency-magnitude relationship, process characterisation*

INTRODUCTION

Mountain hazards pose a continuous threat in areas such as the Austrian Alps, including snow avalanches, landslides and floods. In an alpine context, flooding processes occur mostly in relatively small torrent catchments. Torrents are defined as constantly or temporarily flowing watercourses with strongly changing perennial or intermittent discharge and flow conditions, originating within small catchment areas (Aulitzky, 1980; Slaymaker, 1988; ONR, 2009). Apart from debris flows, torrent events show a variety of different flow characteristics including pure water runoff, fluvial sediment transport and debris floods[1] (Aulitzky, 1980; Costa, 1984; Hungr *et alii,* 2001; ONR, 2009). In order to mitigate such hazards, knowledge on the general predisposition of a catchment to a certain torrent process, referred to hereafter as *dominant process*, has to be gained. Moreover, information on the frequency (Jakob & Bovis, 1996) and magni-

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[1] Torrential debris floods are characterised by considerable transport of coarse sediment (Scheidl & Rickenmann, 2010). Hyperconcentrated flows are used as a synonym for debris floods (Costa, 1984; 1988) but in general transport larger amounts of fine sediment in suspension (Scheidl & Rickenmann, 2010)

tude (Marchi & D'Agostino, 2004) of an event is a compulsory prerequisite for any mitigation concept, as well as hazard and risk assessment. Especially with respect to vulnerability assessment of elements at risk, generally seen as a central part in the framework of risk assessment, information on the type of process and the process magnitude and frequency is indispensable. From an Austrian perspective, systematic measurements of such parameters have been carried out only in selected watersheds over the last decades. Only approximately 100 out of 10,000 torrent catchments are equipped with monitoring devices. Such devices provide information on discharge used in the deduction of frequency and magnitude. As measurement data from smaller catchments is virtually not available at present, alternative procedures to estimate frequency and magnitude are necessary, e.g., stratigraphic methods (Coe *et alii*, 2003), dendrogeomorphic methods (Jakob & Bovis, 1996; Mayer *i*., 2010) and lichenometric methods (Helsen *et alii*, 2002). These methods are traditionally conducted by earth scientists to assess landslide occurrence, while in contrast, historical databases are used by local administrative bodies to estimate the impact of natural hazards (Carrara *et alii,* 2003).

This study is based on a dataset of historic events that was compiled at the Institute of Mountain Risk Engineering (Hübl *et alii*, 2010) on behalf of the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management. First results concerning the assignment of dominant process types in torrent catchments and the estimation of mean frequencies for selected catchments are presented.

Process group	Process
Avalanches	Powder snow avalanche
	Dense snow avalanche
	Mixed avalanche
Slides	Rotational
	Translational
	Debris slide
	Erdstrom
Falls	Rockfall [of different magnitudes]
	Bergsturz
Floods	Pure water runoff – flood
	Fluvial sediment transport
	Debris flood
	Debris flow[3]

Tab. 1 - Classification of processes (modified after DIS-ALP, 2007)

METHODOLOGY

The database was derived from an analysis of written reports which were compiled during the implementation of hazard maps by the Austrian Torrent and Avalanche Control Service (WLV)[2]. This data source was completed by the transcription and analysis of the "Brixner Chronicle" (Strele, 1893). Table 1 summarises the hazard process groups and their subcategories (referred to as processes) that were included in the database. As the sources of this database are primarily focused on mountain hazards, flood events related to lowland rivers are mostly excluded.

DATA ACQUISITION

Following the axiom of the "3W-Standard", the process group and the process, the name of the watershed and the corresponding geographical location, as well as the date of the event were initially extracted from the raw data and entered in the first form. Keywords were used to define the allocation of the event to a certain process type. The names of the watershed and the affected villages were given in the event description for most datasets. Using a GIS environment, a so-called information point including geographic coordinates was assigned to each data record. The structure of the database took the inhomogeneous format of the event dates into account (recent events often included information on the year, month and day, and sometimes the time of day, while only the year was recorded for mediaeval events).

Furthermore, where available, information on both event magnitude and triggering factors were gathered and stored in the database. If such information was not available, qualitative indicators recorded in the run-out area, e.g., spatial extent, number of plots affected, or deposition heights were used as a proxy to determine the event magnitude (Fig. 1). If no corresponding information was provided in the event description, a magnitude was not assigned in the individual dataset ("magnitude not assessed").

If available, additional information regarding the meteorological triggering factors such as type and amount of precipitation was included in the individual datasets.

A quality code was attached to the quantitative

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[2] *The Austrian Torrent and Avalanche Control Service is a federal institution operating throughout Austria to protect the population from torrent hazards and other mountain hazards (Republik Österreich, 1975).*

information entered in the database to define the uncertainty inherent to this information. The following codes were used: measurement, estimation, unclear information, not determinable.

Applying the second form of the data acquisition tool, existing information on damage and losses was entered into the database. As far as quantitative information was available, the entry form provided five categories of losses, as shown in Tab. 2. For damages related to the built environment, different damage levels, i.e. destroyed, damaged, and/or (in case of linear infrastructures) interrupted, were selectable.

DATA ANALYSES

The datasets were analysed in order to achieve spatial and temporal process patterns on a catchment scale. As the main focus of this paper was debris flow-like processes, fluvial-like datasets were, apart from comparative purposes, not included in the subsequently described analyses. Debris flow-like process include an aggregation of debris flows and debris floods due to the general understanding of debris floods as a transition between fluvial sediment transport processes and debris flows (Costa, 1988). Events characterised by pure water runoff or fluvial sediment transport were aggregated as fluvial-like events. Within the category of debris flow-like processes approximately 5,700 datasets were available for further analysis, i.e., a spatial distribution analysis and a time series analysis.

SPATIAL DISTRIBUTION ANALYSIS

Using the geographic coordinates of the information points, the spatial distribution of torrent events in Austria was visualised. Firstly, the number of fluvial and debris flow-like events per individual catchment was summed up, and the relative share of process categories was calculated. If, during the set of calculation, more than 60% of the entire number of events within an individual catchment was characterised by being either fluvial-like or debris flow-like, a corresponding dominant process was assigned to the respective catchment. If the proportion was between 40% and 60%, no dominant process was derived and the corresponding catchment was classified as intermediate. Secondly, the resulting dominant processes were assigned to the area of individual catchments, resulting in a threshold size for the occurrence of debris flow-like events.

In a further step, the catchment layer was intersected with the geologic map of bedrock (Egger *et alii*, 1999) to obtain a relation between lithology and the occurrence of dominant torrent processes. Thereby, a lower threshold of 60% by area of a specific type of bedrock was defined for the assignment of a dominant geological unit to a catchment otherwise a catchment was classified as intermediate. Combining the information regarding dominant processes and dominant geological units on a catchment basis, the specific occurrence of processes in relation to a specific type of bedrock was assessed.

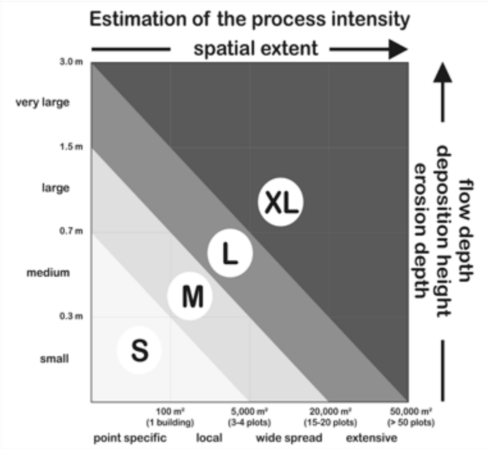


Fig. 1 - Classification of process magnitudes, applicable for torrent events in European mountain regions

Category	Subcategory
Casualties	Fatalities, persons injured, persons affected
Buildings	Private, public, agricultural, industrial, commercial and buildings for tourism
Forested and agricultural land	Forests, grassland, cropland, livestock
Infrastructure	Traffic facilities, supply facilities (e.g., electricity, gas, telephone), wastewater disposal facilities
Technical protection measures	Check dams, bedded rockfills, snow bridges

Tab. 2 - Categories and subcategories for recording losses

TIME SERIES ANALYSIS

Apart from an overall time series for all events highlighting the number of events per year and decade, times series for two individual torrents were derived for a more detailed analysis with respect to event magnitude. The torrent Bretterwandbach and the torrent Farstrinne were chosen due to their long series of well-documented events. The location of these torrents is illustrated in Fig. 2. The torrent Bretterwandbach is located in Western Austria close to the village of Matrei in Osttirol. The west-exposed basin is part of the Granatspitzgruppe mountain range with an elevation difference between 938 m and 3,085 m a.s.l. The catchment covers an area of 18.2 km^2. Lithologically, the basin comprises mainly the Penninic unit and crystalline rock. The Farstrinne is located in Western Austria close to the village of Umhausen. The basin is south-west exposed and extends over an area of about 5.8 km^2 between 944 m and 3,010 m a.s.l. Crystalline rock is the predominating lithological unit in this catchment.

Using the two time series, the mean frequency (return period) of both ordinary and extraordinary events was calculated. Ordinary events were defined as those events with either a small or a medium magnitude, whereas extraordinary events were aggregated from large and very large events (compare Fig. 1). The mean recurrence interval was calculated as a ratio between the period of records (time period between the first recorded event and the present) and the number of events of a certain magnitude that occurred during this period of record (Coe *et alii*, 2003).

RESULTS

In total the database consists of 27,912 individual datasets of different hazard type that occurred between the 6th century and 2009. Table 3 summarises the distribution of datasets across different process groups and the dominance of flooding processes (including torrent events) is evident.

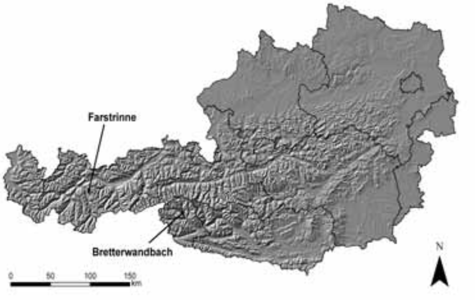


Fig. 2 - Location of the test sites in the Austrian Alps, indicated by arrows

In Figure 3 the relative distribution of hydrologic processes is presented. Focusing on these hydrologic processes, 14,400 or 71% of the datasets can be attributed to fluvial-like events (pure water runoff and fluvial sediment transport) and 5,700 or 29% of the datasets can be attributed to debris flow-like events (debris flood and debris flow).

In Figure 4 a time series of debris flow-like events is shown for the period between 1880 and 2010. The time is plotted on the abscissa and the number of events is plotted on the ordinate. The number of events per year is shown by black bars and the number of events per decade is presented by grey bars. The annual mean is equal to 37 events. The data shows a slightly increasing trend for debris flow-like processes over the entire period, whereas the number of events seems to decrease sharply from the 1960s onward.

The number of events per year as well as per decade reaches a maximum in the 1950s, 1960s and 1970s. A considerable above-average number of events was observed in 1959, 1965, 1966 and 1975.

In Figure 5 the results of the assignment of dominant process types to individual torrent catchments is shown. The individual catchments were assigned to either debris flow-like, flood-like or intermediate process types. A concentration of torrent catchments prone to debris flow-like processes is visible for the Western part of Austria (Provinces of Tyrol and Vorarlberg) and for the district of Bruck an der Mur (Province of Styria). Based on the assignment of dominant process types to catchment areas, a certain threshold of catchment area size was found for the distinction between catchments prone to debris flow-like processes and those catchments that do not show specific process proneness. Debris flow-like processes were observed only in catchments < 80 km^2, whereas 95 % of all catchments showing a dominance of debris flow-like process are smaller than 15 km^2 (Tab. 4).

In addition to the dominant process, the prevailing geological unit within individual catchments, dis-

Process group	Avalanches	Slides	Falls	Floods
Datasets	6,750	765	216	20,181

Tab. 3 - Distribution of datasets

regarding the quaternary deposits, was determined. In Table 5 the number of catchments showing a specific type of bedrock is summarised with respect to fluvial-like and debris flow-like processes. Whereas the overall dominance of fluvial-like processes is obvious for all types of lithology, the relative share of debris flow-like processes in Chrystalline and Penninic areas and regions characterised by Palaeozoic bedrock is larger than in areas characterised by other geological units.

With respect to the large-scale analysis of individual catchments, a continuous time series of debris flow-like events of two individual torrents, Bretterwandbach and Farstrinne, is shown in Figures 6a and 6b. The time is plotted on the abscissa and the magnitude of the events is plotted on the ordinate. The process magnitude is classified into five classes: XL = very large, L = large, M = medium, S = small, and na = magnitude not assessed. The same period of time (1700 – 2010) is visualised in Figures 6a and 6b to improve the comparability of the two time series, although the first recorded event in the torrent Bretterwandbach already occurred in the year 1445 and four events occurred before 1700. In general, the majority of events are characterised by small to medium process intensity. A concentration of events can be observed in both figures around the second half of the 19th century.

The calculated return periods based on these time series are given in Table 6, combining events of the XL- and L-type to a class of extraordinary events and events of the M- and S-type to a class of ordinary events. Within the period of records, the average probability of occurrence of M- and S-type events equals 1 in 26 years (Bretterwandbach) and 1 in 10 years (Farstrinne), while the average probability of occurrence of XL- and L-type events equals to 1 in 56 years and 1 in 26 years, respectively.

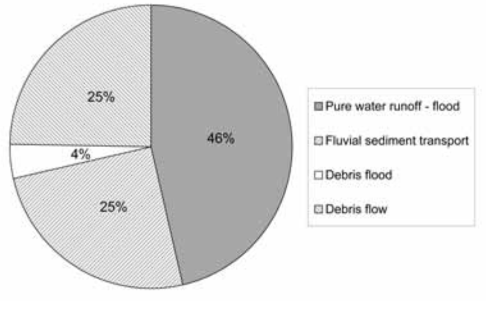


Fig. 3 - Distribution of datasets

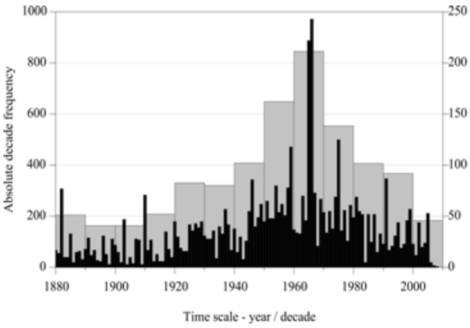


Fig. 4 - Time series of debris flow-like events

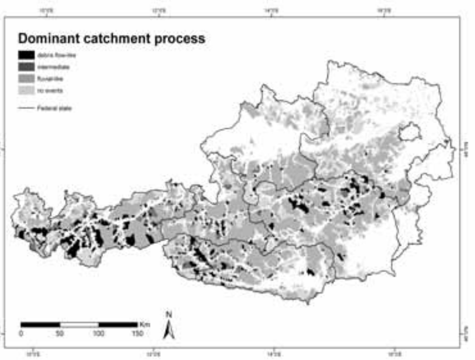


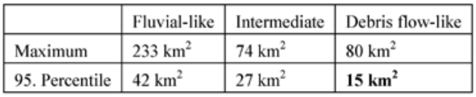
Fig. 5 - Dominant process fortorrentc catchmens in austria

DISCUSSION AND CONCLUSION

A database of historic events, which included different hazards such as avalanches, slides, falls and floods, was compiled for the Republic of Austria. Information on a local and regional scale had been gathered from records of the Austrian Torrent and Avalanche Control Service and the transcription of the so-called “Brixner Chronicle” (Strele, 1893). Approximately 28,000 events, distributed over the entire country, were entered into the database and subsequently analysed with respect to magnitude and frequency. The earliest events of this database date back to the 6th century, while in-depth information on the events is available since the 18th century. More than 20,100 torrent events, including around 5,700 events identified as debris flow-like, and 5,045 as debris flows, represent the majority of the datasets. Three data entries, defining the type of process, the date of occurrence and the geographic location, were mandatory for each dataset and referred to as “3W-Standard” (DIS-ALP, 2007). If available, additional information regarding event magnitude, triggering factors and losses was included. Focusing on debris flow-like events, a spatial distribution analysis and a time series analysis was conducted to show the applicability of such a database for an evaluation of frequency-magnitude relationships, and in particular with respect to the framework of hazard and risk assessment.

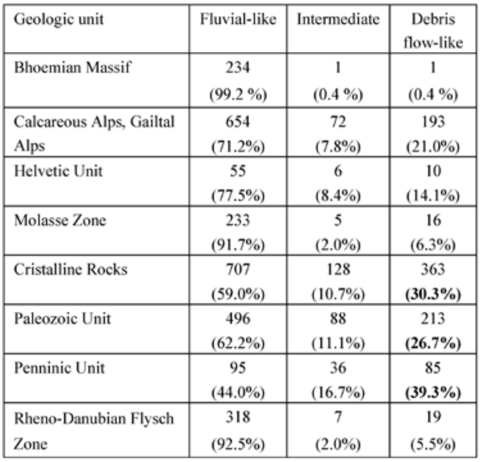
The time series analysis showed that a maximum of events occurred during the decades of 1950-1970, while for individual years (particularly 1965 and 1966) a prominent peak in the number of events was observed.

The spatial distribution analysis resulted in considerable insights into the geographical distribution of torrent events in the Austrian Alps. An above-average concentration of debris flow-like processes is traceable for the Western part of the Republic of Austria. These processes are the evident and documented dominant processes in the central part of the (populated) torrent fans, assigned to the individual datasets and now summed up for this analysis. This method is in line with the understanding that the dominant process in the central part of the deposition zone is used to define the entire event characteristics (Hungr *et alii*, 2001).



	Fluvial-like	Intermediate	Debris flow-like
Maximum	233 km^2	74 km^2	80 km^2
95. Percentile	42 km^2	27 km^2	**15 km^2**

Tab. 4 - Threshold of catchment area for different processes



Geologic unit	Fluvial-like	Intermediate	Debris flow-like
Bhoemian Massif	234 (99.2 %)	1 (0.4 %)	1 (0.4 %)
Calcareous Alps, Gailtal Alps	654 (71.2%)	72 (7.8%)	193 (21.0%)
Helvetic Unit	55 (77.5%)	6 (8.4%)	10 (14.1%)
Molasse Zone	233 (91.7%)	5 (2.0%)	16 (6.3%)
Cristalline Rocks	707 (59.0%)	128 (10.7%)	363 **(30.3%)**
Paleozoic Unit	496 (62.2%)	88 (11.1%)	213 **(26.7%)**
Penninic Unit	95 (44.0%)	36 (16.7%)	85 **(39.3%)**
Rheno-Danubian Flysch Zone	318 (92.5%)	7 (2.0%)	19 (5.5%)

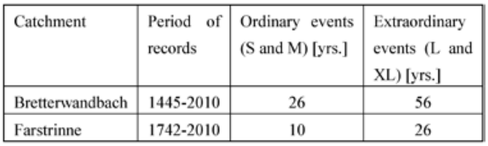
Tab. 5 - Number of catchments with dominant processes in geological units; the number gives the absolute value for individual process types while the percentage indicates the relative share between process types

Based on this assignment of dominant process types to catchment areas, a certain threshold of catchment area size was found for catchments prone to debris flow-like processes. This threshold of catchment area was 15 km^2, and is in the same order of magnitude as reported for European Alps in other studies (e.g., 20 km^2, Marchi & D'Agostino (2004), 20-30 km^2, Marchi & Brochot (2000) and 22 km^2, Rickenmann & Zimmermann (1993)).

An assessment of process type with respect to the underlying geologic conditions was undertaken, and resulted in a distinct relationship between different geological units and the dominance of certain process types. Whereas certain geologic units such as the Bhoemian Massif, the Molasse Zone and the Rheno-Danubian Flysch Zone show only a small number of catchments prone to debris flow-like processes, the relative share of debris flow-like processes in Chrystalline and Penninic areas and regions characterised by Palaeozoic bedrock is clearly above average.

An in-depth assessment of magnitude and frequency of debris flow-like events was carried out for two study sites in Western Austria. Due to the data quality, a semi-quantitative assessment of magnitude-frequency relationships was established. The results showed that the probability of occurrence of events of smaller magnitude (ordinary events) is between 1 in 10 and 1 in 26 years, while events of larger magnitude (extraordinary events) occur rarer with a frequency of up to 1 in 56 years.

In general the analysis of the database provided valuable insights with respect to process patterns in mountain environments. However, the analysis also showed some limitations due to an incomplete or missing documentation of events. Thereby, an increase in data reliability was traceable for more recent events, while older entries in general were more qualitative in terms of event magnitude. The documentation of events was mainly fragmentary in areas where human structures were missing, a phenomena also observed



Catchment	Period of records	Ordinary events (S and M) [yrs.]	Extraordinary events (L and XL) [yrs.]
Bretterwandbach	1445-2010	26	56
Farstrinne	1742-2010	10	26

Tab. 6. - Return periods for the torrents Bretterwandbach and Farstrinne

in other studies (Jaedicke *et alii*, 2009). However, this implies that the dataset is relatively reliable in areas of anthropogenic activity, such as settlements or transportation corridors.

Despite these limitations, the analysis of process magnitude and frequency as well as the assignment of dominant process types to individual torrent catchments is of high value for the assessment of hazard and risk, i.e., for the implementation of technical protection measures and the assessment of vulnerability (Fuchs, 2009). In order to allow for a comparison of risk reduction as a result of the implementation of different protection alternatives (Holub & Hübl, 2008; Holub & Fuchs, 2009), and the resulting shift in vulnerability of elements at risk and the society, information on the magnitude and frequency of events is indispensable. Dealing with physical vulnerability, also the type of process affects the vulnerability of elements at risk and, hence information about it is a compulsory prerequisite for vulnerability assessment. In this context various vulnerability functions were developed for different torrent processes (e.g., Fuchs *et alii,* 2007 and Akbas *et alii*, 2009; for debris flows and Totschnig *et alii* (in press) for fluvial sediment transport).

Especially with respect to alpine torrent processes (but principally also with respect to other mountain hazards such as snow avalanches) the major problem related to the establishment of frequency-magnitude relationships is the inherent complexity of the system. Moreover, the relationship between magnitude and frequency of an event in a certain (monitored) catchment is not necessarily transferable to an adjacent catchment that is not monitored due to possible changes in initial and boundary conditions. However, even if individual catchment properties may be responsible for individual process characteristics, general conclusions on process characteristics can be drawn. Nonetheless, the established relationship between process magnitude and frequency is only an approximation, and has to be evaluated carefully with respect to possible sources of (aleatory and epistemic) uncertainty.

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