Extreme value analysis of design events

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ABSTRACT: Design events are used in avalanche engineering applications like hazard zone mapping, dimensioning of protection measures or the optimization and calibration of computational simulation software. A design event is defined by its return period that is related to a certain magnitude. It is often determined by the run out length of single historically documented avalanche events accompanied with subjective period estimates. Avalanche paths with detailed, continuous records are rare and therefore statistical analysis can hardly be realized for most avalanche paths.

In this work we perform design event estimates for the Arzler-Alm avalanche situated above the Tyrolean capital Innsbruck, Austria. Avalanches in urban areas raise special attention, due to of their constant threat to life. Consequently several historical avalanche records articles exist since the year 1859. Refinement of protection measures around the avalanche path led to continuous observations of the avalanche activity between 1945 and 1970. Due to the number of good quality observations extreme value statistics is an adequate method to combine the information of frequent and historical sources. Based on the methods of extreme value theory, employing observations of frequent avalanche run out distances, we discuss an approach to improve the estimation of (1) return periods of historical events and (2) the design event intensities. For avalanches of high return periods the analysis shows that extreme run outs can be limited to a specified range, while return period estimates are subject to high uncertainties.

Key words: snow, avalanche dynamics, extreme value analysis, run out, design event, extreme event

1. INTRODUCTION

Snow avalanches are categorized by their frequency and magnitude. In avalanche engineering extreme events correspond to events with low frequencies accompanied by catastrophic magnitudes. Extreme avalanches are often used as references for design event estimates and raise special attention of engineers and scientists (Ancey, 2012). Design events are characterized by their associated return periods and return levels. They provide fundamental information for applications like hazard mapping or mitigation planning as well as the optimization and calibration of computational simulation software (Johannesson et al., 2009). For snow avalanches return levels are often determined by the run out length. For most avalanche paths only few avalanche events accompanied with subjective or empirical return period estimates are historically documented. Sophisticated analysis, such as extreme value analysis, is based on long term observations and time series and thus its applicability is often limited.

Extreme value analysis is commonly used in the field of hydrology and has previously been applied to snow avalanches, e.g. to estimate avalanche return periods or extreme snow accumulations (Burkard and Salm, 1992; Fohn and Meister, 1981). In addition McClung et al. (1989) and McClung (2000) used extreme value statistics on run out data for different mountain ranges. Eckert et al. (2007) used a Bayesian approach to get predictive run out distributions and Eckert et al. (2008) performed return period estimates based on annual avalanche frequency.

Here, an extreme value analysis taking into account the generalized extreme value (GEV) distribution of run out lengths related to their return periods is applied to a well documented avalanche path. The two basic questions are (i) what run out is expected for a certain return period and (ii) what return period can be assigned to a historically documented event. To answer these questions we adapt principles of flood return period estimates (DWA, 2012) to the field of snow avalanches.
2. AVALANCHE PATH AND DATA

In this work we perform design event estimates for the Arzler-Alm avalanche situated above the Tyrolean capital Innsbruck, Austria. Avalanches in urban areas raise special attention, because of their constant threat to life and property. Consequently, several historical avalanche records by photographs and newspaper articles exist. Figure 1 shows a local newspaper article of an event in the year 1859, the oldest documented avalanche. Since then all avalanches that reached the township of Innsbruck-Arzl and led to loss of lives or damage to property have been recorded. This allows the definition of a run out threshold indicating the maximum run out for avalanches in the years between historically documented avalanches. In addition to these sources of documentation observations, continuously documenting every avalanche event, were performed in certain time periods. Between 1945 and 1970 and 2000-2010 refinement of protection measures around the avalanche path led to systematic observations by contemporary witnesses of the avalanche activity. The full time series of run out lengths, measured in projected run length $s$ is shown in figure 2. The shown data represents block maxima, corresponding to the maximum run out in each winter from 1859 up to now. As outlined above the total time series of return levels is not continuous. It is split into three parts: the historical, systematic and unknown series. The historical series includes events above the run out threshold. Events below the threshold are split into the systematic series, where continuous observations were performed over certain years and the unknown series, where no further knowledge about the return level is available.

3. EXTREME VALUE ANALYSIS

Extreme value analysis based on the generalized extreme value (GEV) distribution are often applied in hydrology in order to estimate flood return period (DWA, 2012). In the field of snow avalanches these methods have also been used, mostly to estimate return periods of new snow accumulations.

Generally we have to distinguish between empirical and statistical investigations by means of extreme value analysis.

Empirical investigations allow to directly relate run out lengths (return levels) of observed events to return periods. Empirical return periods are directly related to the total length of the time series and the data rank of the event magnitude.

The statistical extreme value analysis of the data includes a maximum likelihood estimate (mle) to fit the three parameter (location $\mu$, scale $\sigma$ and shape $\xi$) GEV distribution to the recorded data. A custom likelihood function is defined as a combination of the probability distribution function values of the historical and the systematic run out positions $f(R_i)$ as well as the cumulative distribution function values of the thresholds $F(R_{lim})$:

$$L = \prod_{i} f(R_i|\theta) F(R_{lim}|\theta)^{n-h-s} \prod_{j} f(R_j|\theta),$$ (1)

with $n$, the total length of the investigated series, the run out threshold $R_{lim}$, $R_i$ the run out values of the systematic series of length $s$ and $R_j$, the run out values of the historical series of length $h$, respectively. The GEV distribution links exceedance probabilities to return levels. Exceedance probabilities are directly related to return periods. With this a direct return level - return period relation is established and empirical results can be compared with the GEV distributed ones. Figure 3 shows the empirically determined plotting positions of the time series as well as the mle-GEV fit, including confidence intervals.
3.1. RESULTS AND DISCUSSION

The fitted GEV distribution allows to statistically relate return periods to return levels and vice versa. Generally the statistical estimates of the GEV distribution and empirical data are in good agreement, i.e. almost all observed events are in the 95% confidence intervals. To highlight the main results of the presented analysis the largest event (1859) of the time series is investigated in more detail. It has a return level of 3735 m (run out length s) accompanied with an empirical return period of 187 years, which is in the range of typically applied return periods for design events (Johannesson et al., 2009).

The observed event return level with its empirical return period can be compared to the statistical estimate in two ways:

- taking into account the empirical return period of 187 years, the GEV distribution estimates a return level of 3657 m. This is slightly lower, but in good agreement with the observed return level, also considering the 95% confidence intervals ranging from 3486 m to 3840 m, compare green dashed line in figure 3.

- taking into account the observed return level of 3735 m a return period of 4313 years is statistically assigned. This is considerably higher than the empirical one, but still in the 95% confidence intervals ranging from 52 years to infinity, compare pink dashed line in figure 3.

This example highlights the challenges in assigning return periods to events of a certain return level. Limitations that have to be considered interpreting the presented results are the choice of the threshold value, fitting method, definition of run out and changes of the avalanche path (topography and vegetation).

The analysis shows that for avalanches with high return periods the range of possible run outs can be accurately specified, while return period estimates for certain events are subject to high uncertainties.

References


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