Natural Hazards
and Earth System
Sciences

Open Access

Statistical correlation between meteorological and rockfall databases

A. Delonca, Y. Gunzburger, and T. Verdel

GeoRessources, Université de Lorraine, CNRS – CREGU, Ecole des Mines de Nancy, Campus Artem, CS14234, 54042 Nancy CEDEX, France

Correspondence to: A. Delonca (adeline.delonca@univ-lorraine.fr)

Abstract. Rockfalls are a major and essentially unpredictable sources of danger, particularly along transportation routes (roads and railways). Thus, the assessment of their probability of occurrence is a major challenge for risk management. From a qualitative perspective, it is known that rockfalls occur mainly during periods of rain, snowmelt, or freeze–thaw. Nevertheless, from a quantitative perspective, these generally assumed correlations between rockfalls and their possible meteorological triggering events are often difficult to identify because (i) rockfalls are too rare for the use of classical statistical analysis techniques and (ii) not all intensities of triggering factors have the same probability. In this study, we propose a new approach for investigating the correlation of rockfalls with rain, freezing periods, and strong temperature variations. This approach is tested on three French rockfall databases, the first of which exhibits a high frequency of rockfalls (approximately 950 events over 11 years), whereas the other two databases are more typical (approximately 140 events over 11 years). These databases come from (1) national highway RN1 on Réunion, (2) a railway in Burgundy, and (3) a railway in Auvergne. Whereas a basic correlation analysis is only able to highlight an already obvious correlation in the case of the "rich" database, the newly suggested method appears to detect correlations even in the "poor" databases. Indeed, the use of this method confirms the positive correlation between rainfall and rockfalls in the Réunion database. This method highlights a correlation between cumulative rainfall and rockfalls in Burgundy, and it detects a correlation between the daily minimum temperature and rockfalls in the Auvergne database. This new approach is easy to use and also serves to determine the conditional probability of rockfall according to a given meteorological factor. The approach will help to optimize risk management in the studied areas based on their meteorological conditions.

1 Introduction

Rockfall hazard is defined as the probability that a rockfall of a given volume occurs in a given area within a specified time interval (Varnes, 1984). This definition considers three different components of hazard: space, time (rockfall frequency), and the intensity (volume) of the event. Numerous studies on hazard mapping (e.g. Baillifard et al., 2003; Jaboyedoff et al., 2005) and rockfall frequency (e.g. Brunetti et al., 2009; Dussauge et al., 2003) are available in the literature, but little work has been conducted to quantify the influence of meteorological factors on rockfall frequency.

Temporal probability can be estimated through the study of triggering factors, which are external causes that are principally climatic in origin. These factors, which appear only at discrete times, induce changes in the forces acting on rock blocks (Hoek, 2007) and cause the blocks to fall. The most common triggering factors are intense rainfall episodes (André, 1997; Berti et al., 2012; Ilinca, 2008; Rapp, 1960), the freeze and thaw of water-filled fractures (Ilinca, 2008; Matsuoka and Sakai, 1999), and repeated rock surface temperature variations (Frayssines and Hantz, 2006; Gunzburger et al., 2005; Luckman, 1976). Furthermore, seismic activity has been shown to influence rockfall events (Bull et al., 1994; Vidrih et al., 2001; Zellmer, 1987).

Table 1. Principal characteristics of the three databases.

	RN1 on Réunion	Burgundy	Auvergne
Number of events	949	135	142
Number of days with events	529	126	122
Average number of events per day with events	3.51	1.07	1.16
Number of days in the database	4008	4739	4008
Daily rockfall hazard	0.13	0.03	0.03

Rockfall inventories can be used to quantify the statistical correlation between rockfall events and their triggering factors (Chau et al., 2003; Helmstetter and Garambois, 2010). However, it is generally difficult to identify such a correlation because (i) rockfalls are too rare for the use of classical statistical analysis techniques and (ii) all intensities of triggering factors do not have the same probability. More precisely, as the occurrence or action of a triggering factor does not necessarily result in a rockfall, it is necessary to distinguish the rockfall probability itself from the frequency of its potential triggering factors.

In this paper, we present a new approach for investigating the correlation of rockfalls with rain, freezing periods, and strong temperature variations. This approach is tested on three French rockfall databases, the first of which exhibits a high rockfall frequency (approximately 950 events over 11 years). The two other databases contain approximately 140 events over 11 years. The three databases came from the following sources: (1) national highway RN1 on Réunion (Indian Ocean), (2) a railway in Burgundy, and (3) a railway in Auvergne, France (Fig. 1 and Table 1). The spatial location and intensity of the events are not studied in this paper; only the number of rockfalls during the period of monitoring is considered. However, the volume range and the mean height of the source rock walls are given for each sector (cf. Part 2).

The standard time series approach (Helmstetter and Garambois, 2010) is able to highlight an already obvious correlation only in the case of the "rich" database. The newly suggested method also appears to detect correlations in the "poor" databases. This approach will help to optimize risk management in the areas considered in terms of the meteorological conditions.

2 Rockfall databases

There is a significant difference between the three databases: for Réunion, 13 % of the days have at least one rockfall (529 days out of 4008 days in the entire database), compared with 3 % for the Auvergne and Burgundy databases. The high frequency of events makes the first database particularly unique. Rockfall databases typically have an event frequency of approximately 3 % (Hungr et al., 1999; Jeannin, 2001; RTM Isère, 1996; Wieczorek et al., 1992).

Figure 1. Location of the three sites, corresponding to **(a)** Auvergne, **(b)** Burgundy, and **(c)** Highway RN1 on Réunion.

The daily rockfall hazard, which is the probability of a fall on a given day, regardless of the meteorological factors, is similar to these frequencies under the assumption of spatial and temporal homogeneity.

2.1 Highway RN1 on Réunion

National Road #1 (RN1) on Réunion (Indian Ocean, latitude: 21°10′ S, longitude: 55°30′ E) runs along the coast at the base of a 10 km long and up to 200 m high cliff composed of basaltic lava strata alternating with pyroclastic layers. This region has a tropical climate. In the studied area, precipitation can reach 372 mm a day, and temperatures typically vary from 16 to 35 °C over the year, with an average amplitude of 9.2 °C in a day.

Daily rockfall data are available due to the regular patrols conducted by the local public works authorities (DDE). A total of 949 rockfalls were recorded within the 11 year span between 1998 and 2009. The volumes of the rockfalls range between 2 and 27×10^3 m^3. Previous studies (Durville, 2004; Rat, 2006) that considered only a portion of the database (352 rockfalls recorded between 1998 and 2002) have shown that rockfalls are mainly correlated with intense rainfall episodes. We repeated this study with a more exhaustive database and also evaluated the influence of temperature on rockfalls.

2.2 Railway in Burgundy, France

The altitude of the study area is between 300 and 400 m. It consists of limestone–marl alternations. Its climate is oceanic to semi-continental. The oceanic influence is responsible for

frequent rainfall in every season, with a maximum in autumn (up to 89 mm daily). The semi-continental influence produces cold winters (minimum temperatures down to $-20\,^{\circ}$C) and hot summers (maximum temperatures up to 36 $^{\circ}$C). The daily temperature amplitude may be up to 24 $^{\circ}$C.

Technicians from the French National Railway Company (SNCF), who ensure railroad safety, are in charge of the rockfall inventory. Daily data are available, and 135 rockfalls were recorded within a 13 year span (1999–2012) along 100 km of the railroad studied. The average height of the rock walls is 20 m in the cut areas and more than 20 m in the areas of natural slopes. The volumes of the rockfalls range between 8 and 80×10^3 m^3.

2.3 Railway in Auvergne, France

The altitude of the study area is between 700 and 900 m. It consists of volcanic (basalt) and plutonic (granite) magmatic rocks. Its climate is similar to that of Burgundy. Rainfall can reach 125,mm a day. Temperatures range between -18 and 36 $^{\circ}$C, with a daily temperature amplitude of up to 23 $^{\circ}$C.

The Auvergne database provides daily data based on a rockfall inventory maintained by technicians from SNCF. Overall, 40 km of railroads are included in this database, and the mean height of the cliffs is 15 m in the cut areas and more than 15 m in the areas of natural slopes. The database includes 142 rockfalls, which were recorded over an 11 year span (2001–2012). The volumes of the rockfalls range between 2 and 6×10^3 m^3.

The following analyses were conducted for the three study sites taken separately.

3 Preliminary analysis using a standard time series approach

3.1 Possible triggering factors considered in this study

Possible triggering factors include the following:

- P_{DN}, the amount of precipitation (or rainfall) of the considered day (D_0), or N days before (D_N), with N varying from 1 to 10;

- P_{cN}, the amount of precipitation (or rainfall) accumulated over N days (up to 10 days): $P_{cN} = P_{D0} + P_{D1} + \ldots + P_{DN}$;

- the day's temperature range, indicated by the minimum temperature ($T_{\min}$), maximum temperature ($T_{\max}$), and temperature amplitude ($T_{\mathrm{amp}} = T_{\max} - T_{\min}$);

- the daily duration of freezing. This factor was considered only for Burgundy and Auvergne because the temperatures on Réunion are never below 0 $^{\circ}$C.

These meteorological parameters were provided by Météo France (the French national weather service) for each sector

on a daily basis. The weather stations selected for this purpose were located no more than 30 km away from the studied area. The stations used in the study of the highway on Réunion have a mean altitude of 100 m. Those used for Burgundy have a mean altitude of 310 m, and those used for Auvergne have a mean altitude of 700 m.

3.2 Results

First, a qualitative analysis of the three databases was performed. Figure 2 shows the visual correlation between the rockfalls and meteorological factors over a 3-year period. The graphs were obtained by calculating a 30-day moving average to smooth the data and to focus on the trend. From a purely qualitative perspective, the graphs shed light on the following:

- a good correlation between rockfalls and rainfall and between rockfalls and minimum temperatures for Réunion;

- no noticeable correlation between rockfalls and meteorological factors in Burgundy;

- a low correlation between rainfall and rockfalls in Auvergne but no noticeable correlation between temperatures and rockfalls.

Table 2 presents the distribution of the total number of rockfalls per day as a function of the daily amount of rain for the three studied areas. The maximum frequency of rockfalls occurs for the lowest daily amount of rainfall. This lowest rainfall interval is also the most frequent. Low levels of rain are more frequent than high levels. This difference in frequency tends to conceal the effect of rain on triggering rockfall events.

The cross-correlation between the daily number of rockfalls (R) and the amount of precipitation (P), both expressed as time series, was investigated by calculating

$$C_k(X, Y) = \frac{\sum \left(X_t - \overline{X} \right) \left(Y_{t-k} - \overline{Y} \right)}{\sqrt{\sum \left(X_t, -\overline{X} \right)^2} \sqrt{\sum \left(Y_t - \overline{Y} \right)^2}}, \quad (1)$$

with k corresponding to the time delay between the rain episode and the rockfalls that it may have triggered (Hipel and McLeod, 2005).

Figure 3 presents the cross-correlation function of Eq. (1) for Réunion by considering various delays. A maximum value of 0.563 is reached for a delay of 1 day; this value is statistically significant in terms of the significance threshold applied to the data. If the cross-correlations are larger than $1.96/\sqrt{n}$ in magnitude, with n as the number of pairs of (R_t, P_t) available (equal to the number of days in the databases), then they are deemed significant. Similar cross-correlation analyses were performed for the other two study sites and two meteorological parameters (the daily temperature and
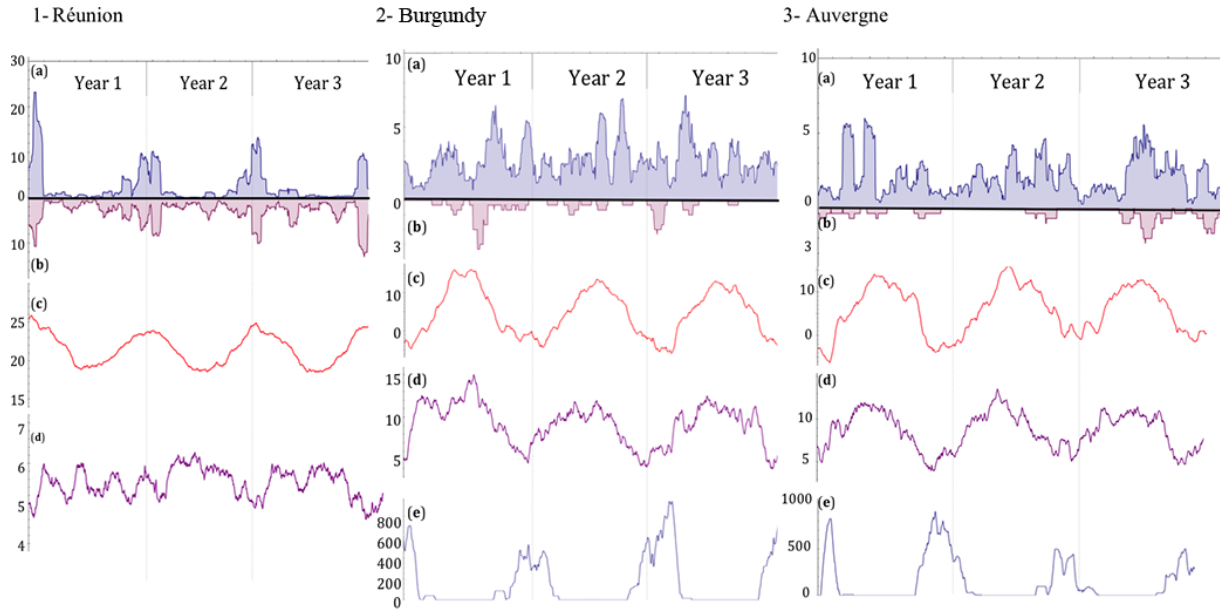
Figure 2. Temperature, rainfall, and rockfall for a 3-year period for the three studied sites (30-day moving average). **(a)** Precipitation (mm of rain). **(b)** Rockfall. **(c)** Minimum of temperature (°C). **(d)** Daily temperature amplitude (°C). **(e)** Duration of the freezing period (min).
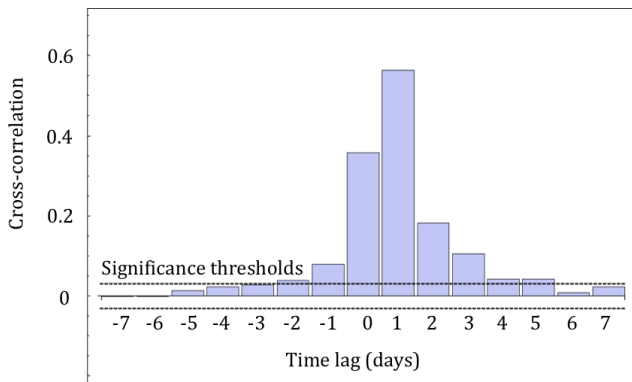

Figure 3. Cross-correlation of rockfall and rainfall for **(a)** Réunion and **(b)** Burgundy. The significance threshold, equal to 0.031, is represented by the dashed lines.

the daily freezing duration), but none of these yielded satisfactory results (maximum value of 0.07 with a significant threshold of 0.031).

3.3 Limitations of the typical approach

The preliminary analysis presented here only confirms the visual correlation between rainfall and rockfalls for Réunion. Although meteorological factors are frequently mentioned in the literature as an explanation of rockfalls there, no other correlations were identified for the two other databases.

This lack of significant results can be explained by the nature of databases: using only 3 % of the days in the database resulted in a relatively weak time series analysis.

Furthermore, these days typically contain only one event (1 % of days with rockfalls are days with several events in the railway databases). These characteristics lead to a smoothing of the results and do not permit us to draw any conclusions regarding potential correlations.

Our proposed method does not consider the delay in time, only the influence of the intensity of the parameters on rockfalls.

4 Suggested new methodology of analysis

4.1 Principle

The objective of the new methodology is to weight the number of rockfalls by the probability of occurrence of the studied triggering factor (rainfall, temperatures, and freezing period). To this end, three steps are required. These steps will now be detailed for the case of rainfall.

First, rainfall intervals $[P_i, P_{i+1}]$ are defined, where P designates the daily or cumulated rainfall. These intervals are defined such that (i) the number of days within this rainfall interval is equal or greater to five (to avoid non-statistically significant intervals) and (ii) at least one event occurs within this rainfall interval.

Second, the following ratio is calculated for each interval:

$$E_i = \mathrm{Nr}_i/\mathrm{Nd}_i, \tag{2}$$

where Nr_i is the number of rockfall(s) that occurred within the given rainfall interval and Nd_i is the number of days in

Table 2. Number of rockfalls for various intervals of daily rainfall.

RN1 on Réunion			Burgundy			Auvergne		
Daily rainfall interval (mm day^{-1})	Frequency of the interval	Frequency of rockfalls in the interval	Daily rainfall interval (mm day^{-1})	Frequency of the interval	Frequency of rockfalls in the interval	Daily rainfall interval (mm day^{-1})	Frequency of the interval	Frequency of rockfalls in the interval
0–20	0.97	0.76	0–5	0.79	0.6	0–5	0.88	0.77
20–40	0.014	0.053	5–10	0.099	0.16	5–10	0.062	0.12
40–60	0.0077	0.072	10–15	0.051	0.13	10–15	0.022	0.049
60–80	0.0032	0.022	15–20	0.029	0.044	15–20	0.014	0.035
80–100	0.0014	0.02	20–25	0.014	0.022	20–25	0.0077	0.014
100–120	0.00075	0.013	25–30	0.0055	0.007	25–35	0.0072	0.007
120–140	0.00075	0.023	30–35	0.0055	0.022	35–60	0.0048	0.007
140–160	0.0005	0.022	35–50	0.0061	0.015			
160–180	0.00075	0.012						
180–220	0.00075	0.003						
220–370	0.00025	2						

this interval. Thus, E_i corresponds to the daily rockfall frequency for each interval.

Third, a linear regression analysis of the values E_i is performed with respect to P_i to search for a possible linear relationship between the magnitude of the triggering factor and the corresponding average number of rockfalls. To validate the correlation, we have considered the squared correlation coefficient R^2 and the p value of the linear regression. If the p value was less than 0.05 (significance level), the linear model was considered satisfactory, and the R^2 value corresponds to the best correlation.

To test the relevance of the method, virtual rockfalls and rainfall databases were created. To confirm the importance of the number of events in the database, rich and poor databases were generated such that the correlation between rainfall and the number of events could be determined in advance. The method was then applied to determine the correlations for different cases.

4.2 Validation of the new methodology: case study on virtual databases

4.2.1 Generation of virtual databases

For the first case study, the virtual databases were generated using Mathematica software (V9, Wolfram Research, Champaign, Illinois, USA). The following parameters were used as fixed components of the databases:

– the number of days in the entire database (N). N is considered as equal to 4015 days (11 years), similar to the real databases;

– the type of triggering meteorological factor and its distribution. The chosen factor is rainfall, which follows the same distribution as the measured rainfall of Réunion (Fig. 5). Overall, 43 % of the days were rainy;

– the ratio between rainfall and the number of events, which gives the number of rockfalls given the amount of rain for each day, is taken to be equal to 0.1 in the case of the virtual databases (a rainfall of 10 mm over 1 day is assumed to trigger one rockfall on the same day; in the case of a day without rainfall, zero rockfalls occur on this day);

– k, the time delay (in days) between a rain episode and the rockfalls that it may have triggered. k is always equal to zero in the virtual databases (because all rockfalls are assumed to occur within the same day of the rain episode).

Two other parameters will vary depending on the databases:

– the "correlation rate" C_r between rainfall and number of events. For example, a perfect correlation (correlation rate of 100 %) indicates that all rainy days are days with rockfalls, in accordance with the fixed proportionality coefficient. A correlation rate of 50 % means that half of the events are perfectly correlated with rainfall, whereas the others are randomly distributed throughout the database;

– the proportion x of days with events. Three cases were tested: (1) $x = 43$ %, corresponding to the proportion of rainy days in the Réunion database; (2) $x = 13$ %, corresponding to the proportion of days with events in the Réunion database; and (3) $x = 3$ %, corresponding to the proportion of days with events in the railway databases.

The cross-correlation approach and the method developed were used for the virtual databases, and the results are presented in the next section. The comparison of the results allows for the detection and verification of correlations by the proposed method even in the case of the railway databases.
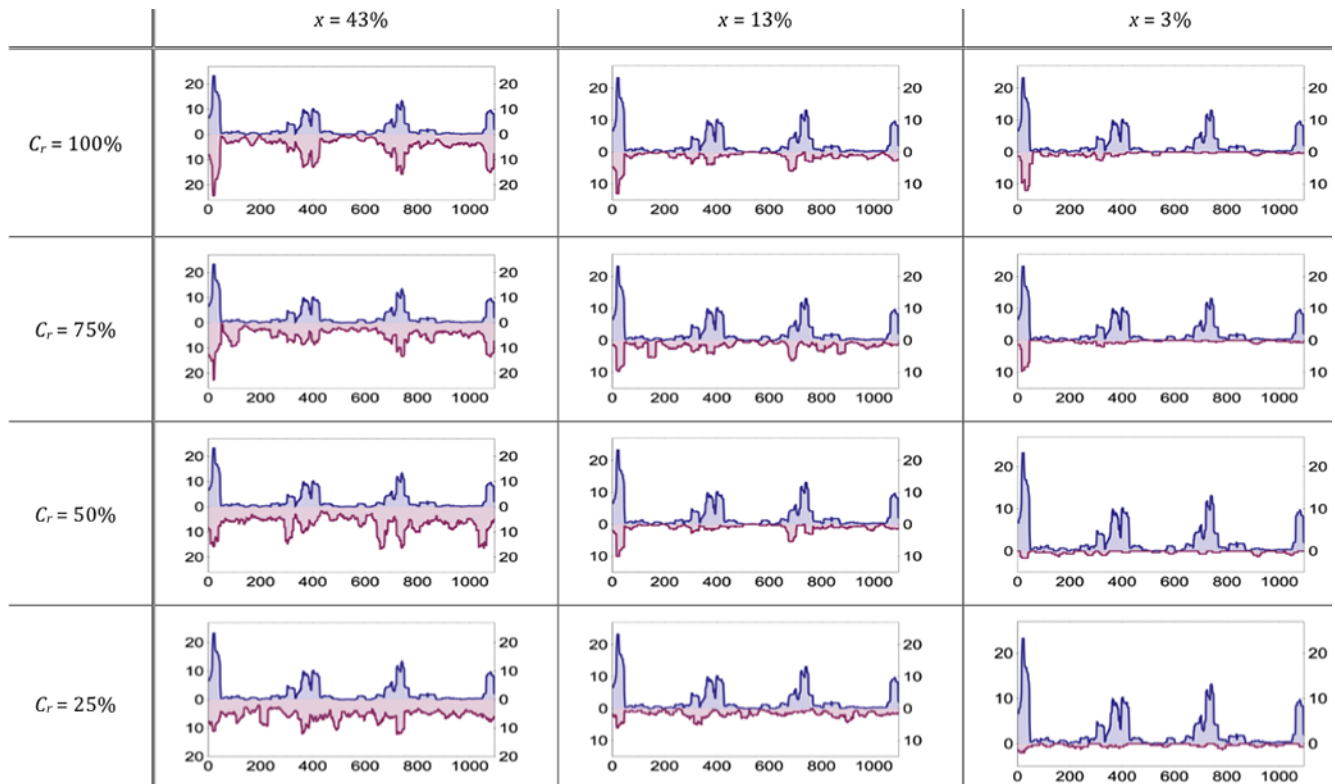
Figure 4. Qualitative correlation between rockfalls and rainfall (30-day moving average) for the 12 virtual databases. C_r corresponds to the "correlation rate" between rainfall and number of events, and x corresponds to the proportion of days with events. The x axis shows days. The y axis shows daily rainfall in mm (above zero) versus the number of rockfalls (below zero).

4.2.2 Results

Figure 4 shows the different cases tested and the correlations from a graphical perspective. The correlation is noticeable regardless of the proportion x of days with events if $C_r = 100\%$.

If this value decreases, the proportion of days with events has a stronger influence.

Table 3 presents the values of the cross-correlation function for all of the databases, obtained for a time delay $k = 0$. In the case of a high-frequency database ($x = 43\%$), the correlation was detected for $C_r = 50\%$. However, the cross-correlation did not permit the establishment of a correlation between rainfall and rockfalls for $C_r = 25\%$. The same negative conclusion applies to the case of a database with 13 % of days with events when $C_r = 50$ and 75 % for a "typical" database ($x = 3\%$). Thus, by analogy, the value of the maximum of the cross-correlation function (0.563) for the Réunion database indicated that at least 75 % of the events were correlated with rain.

Table 4 presents the results obtained with the proposed method, allowing us to identify the correlation between rainfall and number of rockfalls, provided that the number of rockfalls and rainfall events are 100 % correlated.

Similar tests were also performed with the rainfall distribution for Burgundy (Fig. 6), and the results were found to be similar to those presented here.

5 Application of the proposed method to the three real databases

Table 5 summarizes the correlations identified using the proposed method. Only the maximum correlation values are presented in the table. The new method confirms the existence of a positive correlation between rainfall and rockfalls on Réunion. This correlation exists with the daily rainfall and with the cumulative multi-day rainfall (Fig. 7) but is more significant in the case of the accumulated rains. The method also detects a correlation between the minimum and maximum temperatures and the rockfalls in the same region, which is not surprising because the rainy season is characterized by both high temperatures and intense rainfall. These correlations are maximal for a time delay of 1 day.

Whereas the standard analysis did not identify any correlation for the two other databases, the new approach detected several correlations. Indeed, the new approach detected a correlation between the accumulated rainfall and rockfalls for Burgundy. More precisely, the method indicates that the

Table 3. Values of the cross-correlation between rainfall and rockfalls for three virtual databases, with a time delay of zero days. This value is compared to the significance threshold, which is equal to 0.031 in all cases. The results presented in italic identify the non-significant correlations (values equal to the threshold value were also considered insignificant).

|	$x = 43\,\%$	$x = 13\,\%$	$x = 3\,\%$
$C_r = 100\,\%$	Maximum value of cross-correlation = 0.65	Maximum value of cross-correlation = 0.42	Maximum value of cross-correlation = 0.23
$C_r = 75\,\%$	Maximum value of cross-correlation = 0.45	Maximum value of cross-correlation = 0.18	*Maximum value of cross-correlation = 0.031*
$C_r = 50\,\%$	Maximum value of cross-correlation = 0.23	*Maximum value of cross-correlation = 0.031*	*Maximum value of cross-correlation = 0.031*
$C_r = 25\,\%$	*Maximum value of cross-correlation = 0.031*	*Maximum value of cross-correlation = 0.030*	*Maximum value of cross-correlation = 0.026*
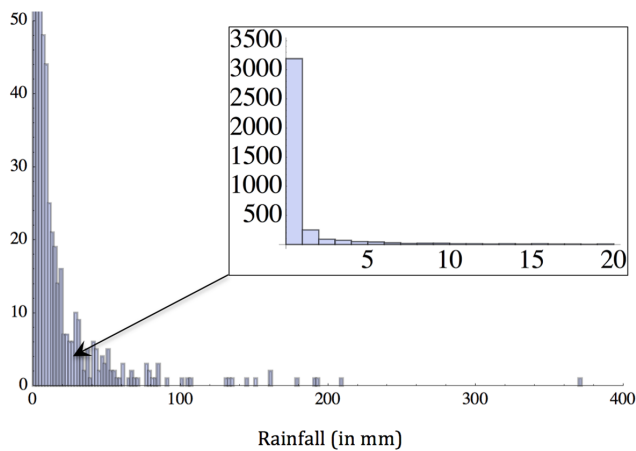
Figure 5. Histogram of rainfall for Réunion.

occurrence of two successive days with intense rainfall is the most favourable meteorological factor, among those studied, for triggering rockfall events (Fig. 8).

A correlation between the daily minimum temperature and number of rockfalls was also identified for the Auvergne database. The maximal correlation occurred for the minimum temperature recorded two days before the event (D_2) (Fig. 9). Temperatures lower than 0 °C also triggered rockfall events after a delay of two days.

For the two databases, no correlation was detected between rockfalls and the daily temperature amplitude or the freezing duration. Another marker of freeze–thaw activity could be the number of freeze–thaw cycle occurrences in a day. This marker is frequently cited in the literature (Douglas, 1980; Matsuoka and Sakai, 1999) and could be used to validate or invalidate our results. Unfortunately, this marker was not available for the studied data.

Table 4. R^2 and p values of the linear regression line obtained by the proposed method for three virtual databases. C_r corresponds to the correlation rate between rainfall and number of events, and x corresponds to the proportion of days with events. The results shown in italic identify non-significant correlations.

	$x = 43\,\%$	$x = 13\,\%$	$x = 3\,\%$
$C_r = 100\,\%$	$R^2 = 0.98$; p value $\sim 10^{-36}$	$R^2 = 0.93$; p value $\sim 10^{-18}$	$R^2 = 0.73$; p value $\sim 10^{-6}$
$C_r = 75\,\%$	$R^2 = 0.88$; p value $\sim 10^{-20}$	$R^2 = 0.81$; p value $\sim 10^{-12}$	$R^2 = 0.57$; p value $\sim 10^{-4}$
$C_r = 50\,\%$	$R^2 = 0.72$; p value $\sim 10^{-11}$	$R^2 = 0.71$; p value $\sim 10^{-7}$	$R^2 = 0.50$; p value $\sim 10^{-3}$
$C_r = 25\,\%$	$R^2 = 0.54$; p value $\sim 10^{-6}$	$R^2 = 0.41$; p value $\sim 10^{-4}$	*$R^2 = 0.47$; p value > 0.05 p value = 0.06*
$C_r = 10\,\%$	$R^2 = 0.25$; p value $\sim 10^{-3}$	*$R^2 = 0.18$; p value > 0.05 p value = 0.13*	–

6 Discussion

6.1 Physical processes involved in each study sites

The method presented in this paper highlights several statistical correlations between rockfalls and meteorological factors, depending on geology and the climate of the studied sites. Below are several physical interpretations of these correlations.

On Réunion, intense rainfall events, typical of the island's tropical climate, are the main triggering factor for rockfalls. Their effect is very short term, lasting no longer than 1 day. Rockfalls here consist of a leaching of the cliff, during which already unconsolidated blocks of rock are swept along by temporary torrents flowing down the steep topography.
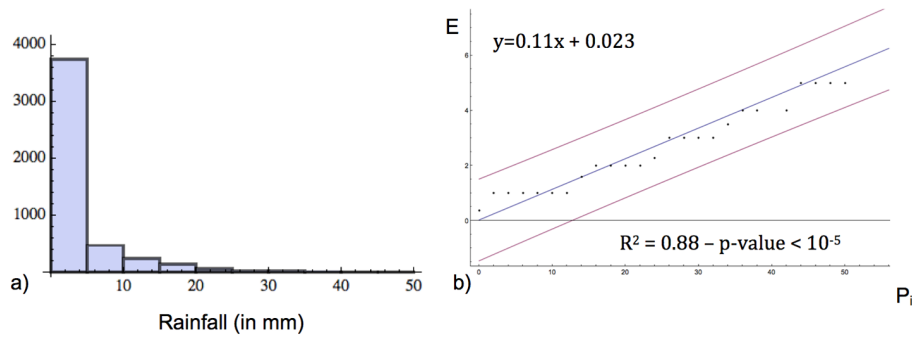
Figure 6. (a) Histogram of rainfall for Burgundy; **(b)** application of the method to a virtual database with 56 % of days with events and rain that fits the empirical distribution of Burgundy rainfall. For these days, the rockfall and rainfall magnitudes are 100 % correlated.
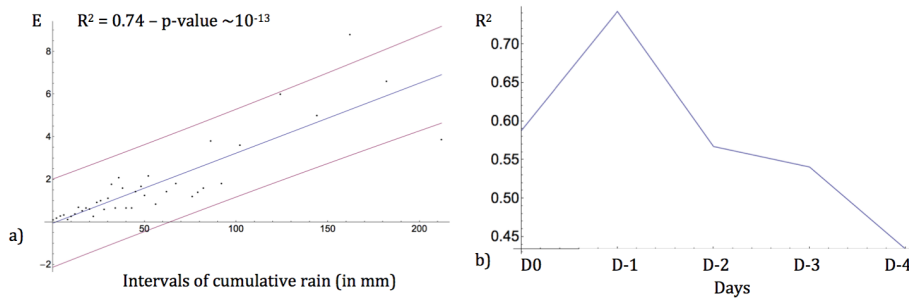

Figure 7. Réunion; **(a)** application of the method to cumulative rainfall over two days ($D_0 + D_1$); **(b)** R^2 of rockfall vs. rain accumulated over several days.
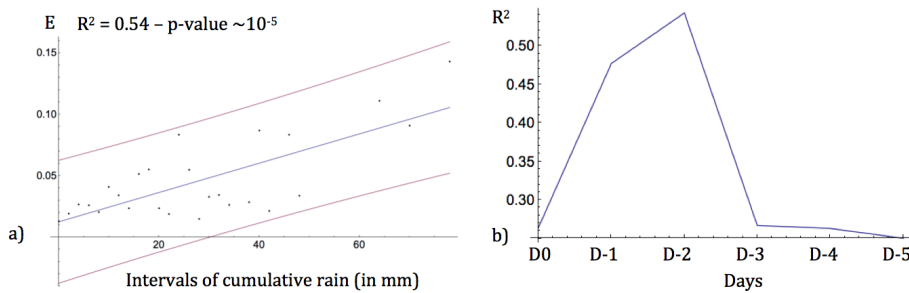

Figure 8. Same as Fig. 7 for Burgundy. Cumulative rainfall over three days ($D_0 + D_1 + D_2$) **(a)**. **(b)** R^2 of rockfall vs. rain accumulated over several days.
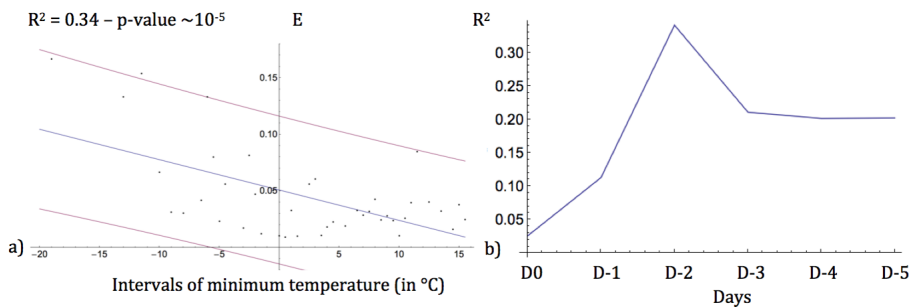

Figure 9. Same as Fig. 7 for Auvergne. Minimum temperature on D_2 **(a)**. **(b)** R^2 of rockfall vs. minimum temperature of several days.

Table 5. Correlations between the chosen meteorological factors and the daily number of rockfalls; results obtained with the proposed method on the real databases. Only the maximum correlations are presented here.

	Réunion	Burgundy	Auvergne
Daily precipitation (P)	For $D_1 - R^2 = 0.70$ p value $= 10^{-9}$ Correlation coefficient $= 0.12$	No correlation	No correlation
Cumulative daily precipitation (P_c)	For $D_1 - R^2 = 0.74$ p value $= 10^{-13}$ Correlation coefficient $= 0.10$	For $D_2 - R^2 = 0.54$ p value $= 10^{-5}$ Correlation coefficient $= 0.012$	No correlation
Daily minimum temperature (T_{min})	For $D_1 - R^2 = 0.69$ p value $= 10^{-6}$ Correlation coefficient $= 0.5$	No correlation	For $D_2 - R^2 = 0.34$ p value $= 10^{-5}$ Correlation coefficient $= 0.05$
Daily maximum temperature (T_{max})	For $D_1 - R^2 = 0.60$ p value $= 10^{-5}$ Correlation coefficient $= 0.8$	No correlation	No correlation
Daily temperature amplitude (T_{amp})	No correlation	No correlation	No correlation
Daily freezing duration	No correlation	No correlation	No correlation

D_0 is the day of the event(s) studied, and (D_n) identifies the n days before, with n varying from 1 to 10.

Geologically, the steep slopes in Burgundy are mainly characterized by alternating layers of limestone and marl. The marls are capable of absorbing rainwater that infiltrates and causes creeping of the clay minerals contained within the substrate (Peck and Terzaghi, 1948). This process is relatively slow and is primarily related to low-intensity rainfall episodes lasting several days. Repeated water infiltrations cause the rupture of the overlying pre-fractured limestone layers via a fatigue effect (Pariseau and Voight, 1979).

Auvergne differs significantly from Burgundy in that the rupture processes leading to block detachments are associated with different geological settings and triggering factors. Auvergne is located in a region of volcanic and plutonic magmatic rocks, and the main meteorological factor observed to correlate well with rockfalls in this region is a strong negative temperature gradient occurring 2 days before the rockfalls. This correlation can be explained by the freeze–thaw process, inducing progressive expansion and loosening of rock fractures by repeated diurnal freezing and thawing of water-filled cavities (Coutard and Francou, 1989; Matsuoka and Sakai, 1999; Matsuoka, 1994, 2008).

6.2 Conditional probabilities used for risk management

The new approach also allows the estimation of the conditional probability of rockfall given the interval of rain ($[P_i, P_{i+1}]$), to be determined as follows:

$$P \text{ (rockfall given the interval)} = \frac{\text{Nr}_d}{N_d}, \qquad (3)$$

where Nr_d is the number of days with at least one event within the considered interval and N_d is the total number of days within the considered interval.

Table 6 provides the conditional probabilities for (1) the accumulated rainfall over 2 days for Réunion, (2) the accumulated rainfall over 3 days for Burgundy, and (3) the temperature minimum for D_2 for Auvergne. The values of the conditional probabilities (Nr_d/N_d) can be compared to the daily rockfall probability in each case (number of events divided by the total number of days in the database). Given the interval for the meteorological factor (e.g. the daily rainfall), the infrastructure manager can then estimate the probability of rockfall and make a risk management decision based on a rainfall forecast (a rainfall prediction provided at least a day in advance). Specifically, for both Réunion and Burgundy, when 15 mm of cumulative rainfall is reached (over 2 and 3 days, respectively), the probability of a fall is doubled compared to the daily rockfall probability. For Auvergne, this probability is doubled when $-5\,°C$ is reached. When 120 mm of rain falls in Réunion, the conditional probability of rockfall reaches 1, which means that the daily rockfall probability is multiplied almost by 8. In the most unfavourable case, this probability is multiplied by 5.5 for Burgundy and by 3.5 for Auvergne.

Table 6. Probability of having at least one event on a day falling within a given interval of daily rainfall (Réunion and Burgundy) and different intervals of daily minimum temperatures (Auvergne).

Réunion		Burgundy		Auvergne	
Interval of cumulative daily rainfall over 2 days $(D_0 + D_1)$ (mm day^{-1})	Probability of at least one event	Interval of cumulative daily rainfall over 3 days $(D_0 + D_1 + D_2)$ (mm day^{-1})	Probability of at least one event	Interval of daily minimum of temperature (D_2) (°C day^{-1})	Probability of at least one event
Daily rockfall probability 0.13		Daily rockfall probability: 0.02		Daily rockfall probability: 0.029	
0–5	0.09	0–5	0.013	−20; −10	0.1
5–10	0.16	5–10	0.026	−10; −5	0.052
10–15	0.25	10–15	0.036	−5; 0	0.039
15–20	0.32	15–20	0.041	0–5	0.024
20–30	0.39	20–30	0.032	5–10	0.023
30–40	0.45	30–40	0.03	10–15	0.029
40–50	0.55	40–50	0.043	15–22	0.027
50–70	0.54	50–70	0.053		
70–90	0.64	70–136	0.111		
90–120	0.64				
120–150	1				
150–200	1				
200–516	0.73				

6.3 Advantages and drawbacks of the proposed approach

The correlation between rockfalls and meteorological factors is a typical observation. However, the correlations are difficult to detect (cf. Part 3) for databases with fewer rockfalls (such as the Burgundy and Auvergne databases) (Frayssines and Hantz, 2006). By testing the proposed method on a virtual database (cf. Table 4), it was confirmed that with a correlation rate (C_r) of 100 %, a correlation could be detected even within databases containing very few events $(x = 3\%)$. By reducing the correlation rate, a correlation can still be detected for only 50 % of days with events completely correlated $(C_r = 50\%)$. In terms of the size of the intervals used in the correlation analysis, we conducted several tests using either the smallest or largest possible interval size when at least one event and 5 days were observed. The results, expressed in terms of the p value, did not change significantly. However, the R^2 values increased slightly in the largest intervals. Our evaluation of the cross-correlation method using the virtual databases (cf. Table 3) demonstrated that no cross-correlation is detected if there are fewer than 3 % of days with events. Moreover, the cross-correlation analysis appears unsuitable if only one event occurs per day (given that the cross-correlation is calculated as a function of the daily number of rockfalls).

For the proposed method to be applicable, the database must be as complete as possible and re-established on a daily basis, as is the case when patrolling is performed daily. The study of the correlations between the events of the day (D_0) and the meteorological factors of the days before (D_n) is not possible if these conditions are not met. Furthermore, the studied site should present homogeneous geological conditions to allow the statistical analyses to be relevant to the entire database. Indeed, differences in geological conditions may lead to differences in the failure mechanisms (Douglas, 1980; Fityus et al., 2013; Luckman, 1976); in such an event, it is probable that both the triggering factors and statistical conclusions will differ. To be more precise in the analysis, the Burgundy and Auvergne databases could be divided into different parts according to the geology. However, the databases are not sufficiently rich to allow this partitioning.

Moreover, the assessment of the conditional probability of rockfall given the interval of the meteorological factor allows us to compare each of the conditional probabilities with the daily rockfall hazard, which corresponds to the proportion of days with events in the entire database.

At present, one of our objectives is to investigate other fields by testing this method on databases involving events other than rockfalls. This extension will permit us to examine the scope of this method, particularly in the study of slow phenomena (at least 15 days between the factor and the event).

7   Conclusions

The objective of this study was to identify any possible correlation between meteorological factors and rockfalls, even in the case of databases containing very few events. Preliminary statistical analyses helped to identify several correlations in the case of a "rich" database. However, no correlation was detected in the more typical "poor" databases due to the sparse representation of days with several rockfalls. The proposed method uses the probability of occurrence of the chosen triggering factor to assess the influence of this factor on the rockfalls. This approach serves to highlight the correlation between a small number of events and a meteorological factor. For a database containing only 3 % of days with events, the method used to detect a correlation assessed whether approximately 50 % of the events were perfectly correlated with the meteorological factor chosen. The use of this method confirms the positive correlation between rainfall and rockfalls in the Réunion database. It highlights a correlation between the cumulative rainfall and rockfalls in Burgundy, and it detects a correlation between the daily minimum temperature and rockfalls in the Auvergne database. The proposed method allowed the probability of events to be estimated given the value of the meteorological factor studied. These probabilities should be helpful in terms of risk management, for example, for optimizing the patrolling services for each site according to the susceptibility of that site to the meteorological factors.

References

André, M.-F.: Holocene rockwall retreat in Svalbard: a triple-rate evolution, Earth Surf. Proc. Land., 22, 423–440, 1997.

Baillifard, F., Jaboyedoff, M., and Sartori, M.: Rockfall hazard mapping along a mountainous road in Switzerland using a GIS-based parameter rating approach, Nat. Hazards Earth Syst. Sci., 3, 435–442, doi:10.5194/nhess-3-435-2003, 2003.

Berti, M., Martina, M. L. V., Franceschini, S., Pignone, S., Simoni, A., and Pizziolo, M.: Probabilistic rainfall thresholds for landslide occurrence using a Bayesian approach, J. Geophys. Res., 117, F04006, doi:10.1029/2012JF002367, 2012.

Brunetti, M. T., Guzzetti, F., and Rossi, M.: Probability distributions of landslide volumes, Nonlin. Processes Geophys., 16, 179–188, doi:10.5194/npg-16-179-2009, 2009.

Bull, W. B., King, J., Kong, F., Moutoux, T., and Phillips, W. M.: Lichen dating of coseismic landslide hazards in alpine mountains, Geomorphology, 10, 253–264, 1994.

Chau, K. T., Wong, R. H. C., Liu, J., and Lee, C. F.: Rockfall hazard analysis for Hong Kong based on rockfall inventory, Rock Mech. Rock Eng., 36, 383–408, 2003.

Coutard, J.-P. and Francou, B.: Rock Temperature Measurements in Two Alpine Environments: Implications for Frost Shattering, Arct. Alp. Res., 21, 399–416, doi:10.2307/1551649, 1989.

Douglas, G. R.: Magnitude frequency study of rockfall in Co. Antrim, N. Ireland, Earth Surf. Proc., 5, 123–129, 1980.

Durville, J. L.: Remarks on the use of probability techniques in the field of natural hazards: The cas of landslides, Bulletin des laboratoires des Ponts et Chaussées, 249, 3–17, 2004.

Dussauge, C., Grasso, J. R., and Helmstetter, A.: Statistical analysis of rockfall volume distributions: Implications for rockfall dynamics, J. Geophys. Res., 108, 2286, doi:10.1029/2001JB000650, 2003.

Fityus, S. G., Giacomini, A., and Buzzi, O.: The significance of geology for the morphology of potentially unstable rocks, Eng. Geology, 162, 43–52, doi:10.1016/j.enggeo.2013.05.007, 2013.

Frayssines, M. and Hantz, D.: Failure mechanisms and triggering factors in calcareous cliffs of the Subalpine Ranges (French Alps), Eng. Geology, 86, 256–270, doi:10.1016/j.enggeo.2006.05.009, 2006.

Gunzburger, Y., Merrien-Soukatchoff, V., and Guglielmi, Y.: Influence of daily surface temperature fluctuations on rock slope stability: case study of the-Rochers de Valabres-slope (France), Int. J. Rock Mech. Mining Sci., 42, 331–349, 2005.

Helmstetter, A. and Garambois, S.: Seismic monitoring of Séchilienne Rockslide (French Alps): analysis of seismic signals and their correlation with rainfalls, J. Geophys. Res., 115, F03016, doi:10.1029/2009JF001532, 2010.

Hipel, K. W. and McLeod, A. I.: Time Series Modelling of Water Resources and Environmental Systems, European Environment Agency – EEA, available from: http://www.eea.europa.eu/data-and-maps/indicators/chlorophyll-in-transitional-coastal-and/methodologyreference. 2012-07-08.9058722654 (last access: 7 November 2013), 2005.

Hoek, E.: Practical rock engineering, http://www.rocscience.com/education/hoekscorner (last access: 2013), 2007.

Hungr, O., Evans, S. G., and Hazzard, J.: Magnitude and frequency of rock falls and rock slides along the main transportation corridors of southwestern British Columbia, Can. Geotech. J., 36, 224–238, doi:10.1139/t98-106, 1999.

Ilinca, V.: Rockfall Hazard Assessment. Case study: Lotru Valley and Olt Gorge, in: Revista de geomorfologie, vol. 11, Paper presented at the "IAG Regional Conference on Geomorphology: Landslides, Floods and Global Environmental Change in Mountain Regions", 15–25 September 2008, Braşov, Romania, 101–108, 2008.

Jaboyedoff, M., Dudt, J. P., and Labiouse, V.: An attempt to refine rockfall hazard zoning based on the kinetic energy, frequency and fragmentation degree, Nat. Hazards Earth Syst. Sci., 5, 621–632, doi:10.5194/nhess-5-621-2005, 2005.

Jeannin, M.: Approches quantitatives de l'érosion des versants rocheux. Etude des gorges de l'Arly et du sillon Alpin, DEA report, Lirigm, Univ. Joseph Fourier, Grenoble, 2001.

Luckman, B. H.: Rockfalls and rockfall inventory data: Some observations from surprise valley, Jasper National Park, Canada, Earth Surf. Process., 1, 287–298, doi:10.1002/esp.3290010309, 1976.

Matsuoka, N.: Diurnal freeze–thaw depth in rockwalls: Field measurements and theoretical considerations, Earth Surf. Process. Land., 19, 423–435, doi:10.1002/esp.3290190504, 1994.

Matsuoka, N.: Frost weathering and rockwall erosion in the southeastern Swiss Alps: Long-term (1994–2006) observations, Geomorphology, 99, 353–368, doi:10.1016/j.geomorph.2007.11.013, 2008.

Matsuoka, N. and Sakai, H.: Rockfall activity from an alpine cliff during thawing periods, Geomorphology, 28, 309–328, 1999.

Pariseau, W. G. and Voight, B.: Rockslides and avalanches: Basic principles and perspectives in the realm of civil and mining operations, in: Rockslides and Avalanches, 2. Engineering sites, edited by: Voight, B., Elsevier, Amsterdam, 1–92, 1979.

Peck, R. B. and Terzaghi, K.: Soil mechanics in engineering practice, John, available from: http://sypdf.yombabook.com/ralph_soilmechanicsin_pdf8828310.pdf (last access: 22 May 2014), 1948.

Rapp, A.: Recent development of mountain slopes in Kärkevagge and surroundings, northern Scandinavia, Geografiska Annaler, 42, 65–200, 1960.

Rat, M.: Optimisation de la gestion de la route du littoral à la Réunion vis-à-vis du risque de chutes de blocs, Bulletin des laboratoires des Ponts et Chaussées, 263–264, 43–52, 2006.

RTM Isère: Inventaire des mouvements rocheux, secteur de l'Y grenoblois, Service de Restauration des Terrains en Montagne de l'Isère, Grenoble, France, 1996.

Varnes, D. J.: Landslide hazard zonation: a review of principles and practice, Unesco, Paris, 1984.

Vidrih, R., Ribičič, M., and Suhadolc, P.: Seismogeological effects on rocks during the 12 April 1998 upper Soča Territory earthquake (NW Slovenia), Tectonophysics, 330, 153–175, 2001.

Wieczorek, G. F., Snyder, J. B., Alger, C. S., and Isaacson, K. A.: Yosemite historical rockfall inventory, US Geol. Surv. Open File Report 92-387, US Geological Survey, 38 pp., 1992.

Zellmer, J. T.: The unexpected rockfall hazard, Bull. Ass. Eng. Geol., 24, 281–283, 1987.