# Rain-induced debris and mudflow triggering factors assessment in the Santiago cordilleran foothills, Central Chile

**Sergio A. Sepúlveda · Cristóbal Padilla**

**Abstract** Debris and mudflows are some of the main geological hazards in the mountain foothills of the Chilean capital city of Santiago. There, the risk of flows triggered in the basins of ravines that drain the range into the city increases with time due to the city growth. A multivariate statistical study based on the logistic regression method is presented. The model provides equations that allow the computation of combined meteorological triggering factors associated with a probability of rain-induced flow occurrence. Daily rainfall, accumulated rainfall and the snowfall level, traditionally considered as the relevant factors, are analysed for a 25-year period. The results show a strong relevance of the rainfall on the day of the flow event over the other factors. However, the relatively low probabilities returned for some real flow events suggest that the model does not capture all the significant variables and the problem is more complex than as it has been traditionally assumed, and further investigations are needed to develop predictive models of flow triggering.

**Keywords** Debris flows · Triggering factors · Geological hazards · Logistic regression

## 1 Introduction

Mass movements are one of the most important types of geological hazards in Chile. The territory is prone to be affected by landslides, due to the geological, geomorphological and climatic conditions of the country. Mass movements have caused great human and economic losses, being debris and mudflow events in the city of Antofagasta in 1991 and the capital city of Santiago in 1993 (Fig. 1; Naranjo and Varela 1996; Hauser 1997; Sepúlveda et al. 2006a) the most significant disasters due to landslides in the last two decades. Together, both events caused 153 fatalities and estimated losses of US$71 million (Sepúlveda et al. 2006a). Other mass movements of great impact on society are laharic flows, especially related to southern Chile volcanoes.

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**Fig. 1** Location map of Santiago de Chile

A landslide-triggering factor is an external stimulus that causes a near-immediate response of the slope as a mass movement, where the conditions are favourable (Wieckzorek 1996). From different types of debris and mudflow generation factors, meteorological factors, such as rainfall and temperature are the most important, the former with a direct impact on landslide triggering, while the latter indirectly drives triggers such as rapid snowmelt and rises in the snowfall level. This is defined in this article as the altitude above sea level over which the precipitation type during a storm is snow that deposits on the ground.

In Chile, there are a few studies on rain-induced landslide triggering factors. For the Andean region of Santiago, Hauser (1985) established, based on a simple statistical analysis of daily rainfall data, that there is a 50% of probability that rainfall over 60 mm/day triggers debris and mudflows. In a comprehensive review of landslide events in Chile, Hauser (2000) suggests that rainfall accumulated in the previous days or weeks is another important meteorological factor for landslide triggering. The May 3, 1993 event that caused several debris and mudflows in the Santiago foothills and other zones in Central Chile (Naranjo and Varela 1996; Hauser 2000), occurred under abnormal conditions of the snowfall level, which rose from about the normal height of 2,000 m to about 4,000 m a.s.l. due to high temperatures. Since then, the snowfall level is considered as an important factor to trigger debris flows in Central Chile, as rises on it increase the amount of liquid precipitation into the drainage basins.

This work analyses different meteorological triggering factors of rain-induced debris and mudflows in the Santiago foothills, the area where the 1993 events occurred. Using multivariate statistical analyses, the relative importance of those triggering factors usually assumed as the most relevant in the area is tested. These factors are the rainfall during the day of the flow event, the accumulated rainfall and the snowfall level. The analyses will provide information on the impact of these factors on landslide hazard and on whether they are sufficient to develop alert systems based on threshold values of these factors. The analyses do not consider other debris flow triggering factors, such as rapid snowmelt after storms or due to high temperatures, earthquakes or volcanic events.

## 2 Study area

### 2.1 Geology and geomorphology

The area of study corresponds to the foothills of the Andes at the latitude of Santiago (33.5° S). Here, a mountain chain known as the San Ramón Range, that runs with a north–south trend between the Mapocho and Maipo rivers bounds the Santiago basin, located immediately to the west (Fig. 2). The study area is defined as the western slope of the range, which peak altitude is the San Ramón hill (3,250 m a.s.l.). The area includes a series of 32 ravines and creeks that drain the range towards the Santiago basin. These ravines are usually the paths of debris and mudflows originated in the higher areas of the drainage basins. The most important ravines are San Ramón and Macul (Garrido 1987; Fig. 2). Lo Cañas ravine, although smaller, together with the former show an important landslide activity, particularly debris and mudflows (Sepúlveda 1998; Sepúlveda et al. 2006b). Alluvial fan deposits located along the foot of the whole range show that the activity of detritic flows has been significant along the Pleistocene and Holocene.

The geology of the area is relatively homogeneous, mainly formed by andesitic volcanic rocks with interbedded sedimentary rocks assigned to the Abanico Formation (Oligocene-Miocene), intruded by Miocene sills, lacolithes and stocks of dioritic to andesitic composition (Thiele 1980). Three main units of Quaternary deposits can be identified, according with the works of Naranjo and Varela (1996) and Rauld (2002) in the area. The oldest is a sequence of early Pleistocene fluvial, debris flow and landslide deposits, over 150 m thick, mainly composed of coarse granulometry with clay and silt interbeds, that form the Calán, Apoquindo, los Rulos and La Cabrería hills (Fig. 2), as well as the mid and lower sectors of the Macul Ravine. The second unit is formed by middle to late Pleistocene inactive alluvial and colluvial cones and landslide deposits, formed by silt and clayey silt

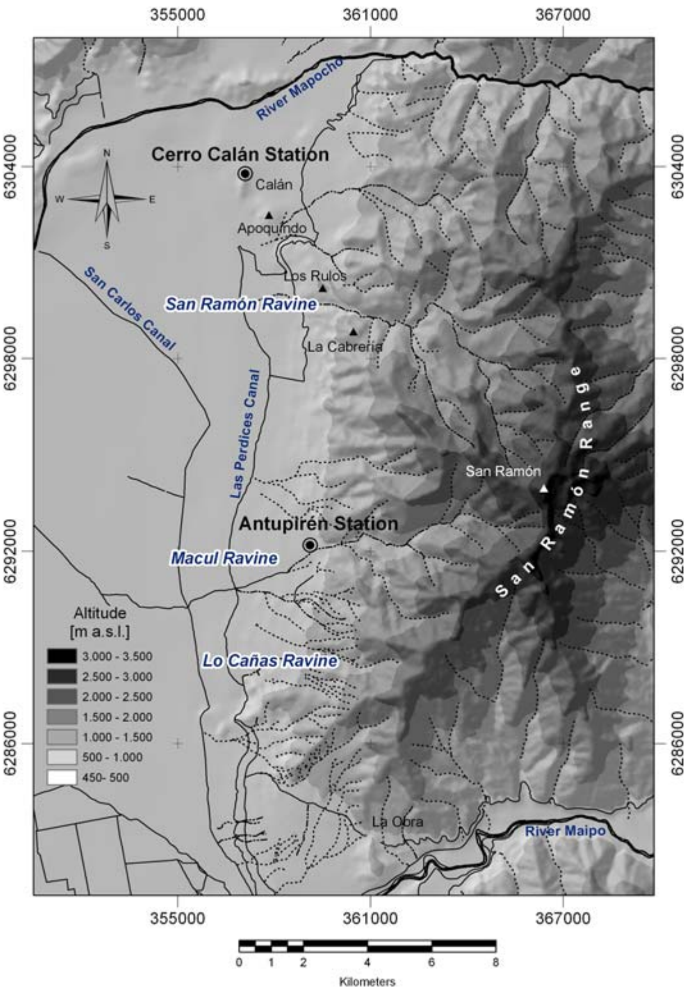

**Fig. 2** Digital elevation model of the Santiago foothills, showing the location of meteorological stations mentioned in the study

with sand, gravel and volcanic ash interbeds. The youngest unit of Quaternary deposits is located in the westernmost area, forming the Holocene active alluvial fans. A major fault known as the San Ramón fault cuts these deposits and locally put them in fault contact with the Abanico Fm rocks (Rauld et al. 2006).

## 2.2 Climate and pluviometry

The climate in Central Chile (31−41° S) may be classified as Mediterranean, characterised by a dry and hot summer season and a cold and rainy winter season (Miller 1976; Fuenzalida 1982).

The climatic characteristics of Chile are conditioned by two main atmospheric factors: The Southeastern Pacific Subtropical Anticyclone, and frontal systems associated to extra-tropical migratory depressions. These factors directly condition the pluviometric regime in

Central Chile (Fuenzalida 1982). In Santiago, frontal precipitations concentrate between 70% and 90% of the annual average rainfall of 330 mm, occurring mainly between April and September (Garreaud and Rutllant 1996; Montecinos 1998; see Fig. 3).

The most frequent rainfall events in the study area are 1–2 days long (Garreaud 1993). This represents more than 80% of the events, accumulating 50% of the annual rainfall (Montecinos 1998). The snowfall level during winter storms varies between 1,500 and 2,000 m a.s.l., with a mid value of 2,100 m a.s.l. (Garreaud and Ruttlant 1996).

The presence of El Niño events generates a raise in the days with rainfall along the year, which according with Garreaud (1993) is recognised by an increase in the number of moderate intensity storms (10–20 mm/day) and extreme storms (>50 mm/day). Furthermore, the frequency of storms of duration longer than 2 days increases during humid years. Garreaud et al. (1995) show that the occurrence of rainfall events with intensities over 5 mm/h is about seven times higher during El Niño events compared with years without El Niño. García (2000), Sepúlveda et al., (2006a) and Vargas et al. (2006) have shown a strong correlation between the presence of El Niño and the triggering of debris and mudflows in Northern and Central Chile, which can be explained by the strong observed relationship between intense rainfall and flow triggering, as it will be discussed later.

## 3 Methodology

### 3.1 The logistic regression method

There are a number of methodologies that have been applied for the statistical analysis of meteorological triggering factors of landslides. Most of the methods use linear or nonlinear regression tools. These methods allow the definition of thresholds of the triggering factors under consideration, over which the occurrence of landslides will be highly probable. The factors considered are usually the amount or the intensity of rainfall, the duration of the storm and the accumulated rainfall in the days or weeks previous to the triggering storm (e.g. Caine 1980; Glade 1998; Crosta 1998). A summary of these methodologies can be found in Terlien (1998).

In this study we use the logistic regression method. This multivariate statistical method has been widely used for different scientific applications. There are recent examples of the use of logistic regression for the study of landslides, such as for the determination of

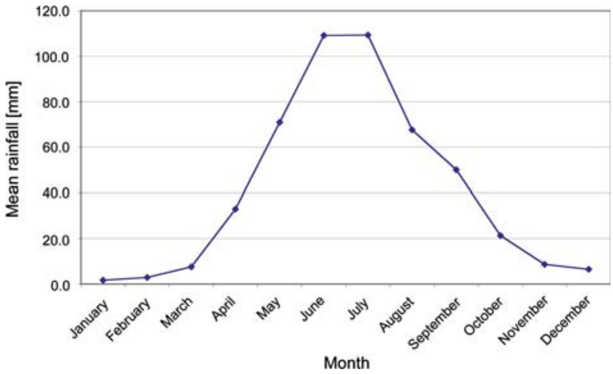

**Fig. 3** Chart of average monthly rainfall in Antupirén station, between 1980 and 2004

rainfall thresholds to trigger landslides in Colombia (González and Mayorga 2004) and for the production of landslide susceptibility maps (e.g. Nandi and Shakoor 2006).

The logistic regression model allows defining a mathematical expression that relates multiple triggering factors to an occurrence probability of the landslide event, in our case, debris and mudflows. The general expression for the logistic regression model (Hosmer and Lemeshow 2000) is:

$$p(Y = 1/x') = \frac{1}{1 + e^{-(\beta_0 + \beta_1 \cdot x_1 + \ldots + \beta_p x_p)}} \tag{1}$$

The left term is the conditional probability that $Y = 1$, defined as the flow occurrence, given a vector of $p$ triggering factors $x' = (x_1, x_2, \ldots, x_p)$. The regression coefficients $\beta_i$ establish the relationship between the variables.

In order to evaluate the validity of the logistic regression models, different statistic significance tests are applied. In this case we use the Wald and the goodness of fit tests (Vivanco 1999; Hosmer and Lemeshow 2000). The former allows evaluating the predictive ability of each variable. Values of significance below 5% are a sign of a good predictive capacity of the variable. For the goodness of fit test, significance values over 5% indicate a good agreement of the model to the observed conditions.

In order to measure the contribution of each variable to the model, the Partial Correlation Coefficient is used. This coefficient allows checking the contribution of each variable independent of its order of magnitude, therefore it lets comparing the weight of the variables in the model in a better way than using directly the regression coefficients.

### 3.2 Definition of variables

In this study, we develop logistic regression models using as independent variables different meteorological triggering factors of landslides, in particular rain-induced debris and mudflows. Conditioning factors, such as drainage basin morphometry, geology or sediment availability, are not included as variables in the model.

In general, it is widely accepted that heavy rainfall in a short period of time (usually less than 24 h) is the most common and effective mechanism to trigger mass movements, besides seismic activity (e.g. Varnes 1978; Hauser 1985, 1993; Takahashi 1991; Selby 1993; Naranjo and Varela 1996). In this article, we use daily rainfall data as a variable. In those cases of daily rainfall linked to the occurrence of flows, it will be called event rainfall. The use of hourly rainfall data was discarded because in the area of study there is not enough data to perform statistical analyses.

In the literature it has been shown that the amount of accumulated rainfall in the days or weeks before the landslide event is also usually significant to trigger landslides (Terlien 1998; Glade 1998; Crosta 1998; González and Mayorga 2004; Ko Ko et al. 2005). The combined effect of heavy rainfall on the day of the event and accumulated rainfall would be in many cases the trigger of mass movements. For this reason, we consider the accumulated rainfall as the second variable in our models. In this work, we test different periods of accumulated rainfall, developing a regression model for each case, to discriminate in a second phase which period of accumulated rainfall would be more significant. The tested intervals are 5, 10, 15, 20, 25 and 30 days.

In Central Chile, there have been many suggestions that the snowfall level in the day of the event is another important factor to trigger debris flows. Naranjo and Varela (1996), Ayala et al. (1996), Lara (1996), Vargas (1999) and García (2000) show some relationships between the snowfall level and the landslide occurrence in the area. This factor is important when the snowfall level rises during the storm, producing liquid precipitations in a larger area of the drainage basin, increasing the overland flow on the slopes and the degree of saturation of the soils. For these reasons, the snowfall level is also considered in the analyses.

In summary, in this work the debris flow triggering factors represented as variables in the logistic regression models are the daily rainfall, the accumulated rainfall over different periods and the snowfall level. With the results of the statistical models, the actual connotation of these variables, traditionally considered as the key triggering factors for debris flows in Central Chile, will be tested and discussed.

## 3.3 Meteorological record

The meteorological record used in the study includes pluviometric and thermometric data. The pluviometric record from two stations close to the area of study is used. The stations are called Cerro Calán and Antupirén (Fig. 2), both of which have a continuous record of daily rainfall from 1980.

The snowfall level for stormy days is calculated from the minimum and maximum daily temperatures, according with empirical relationships determined for the area of study (Stowhas and Seguel 1985; Vargas et al. 1988; Lara 1996):

$$\mathrm{SL} = H_E - \frac{1000}{G}\left[\frac{1}{7}(T_{\max} + 6T_{\min}) - 1^{\circ}\mathrm{C}\right] \tag{2}$$

where SL is the snowfall level (in m a.s.l.) $H_E$ is the altitude of the thermometric station, $T_{\max}$ and $T_{\min}$ are the maximum and minimum daily temperatures (in °C) at the station and $G$ is the thermic gradient, which at the area of study is equal to $-5.68°\mathrm{C}/1{,}000$ m (Vargas et al. 1988). This method is applicable only in days with rainfall. The thermometric record is then constituted by extreme daily temperatures at the Cerro Calán station.

The analysed meteorological record extends from 1980 to 2004. As the snowfall level can be calculated only from days with precipitations, only these will be used for the regression models.

## 3.4 Debris and mud-flow record

From 1908 it is possible to found suggestions of landslide events in Eastern Santiago. Before 1980, three events in 1908, 1936 and 1957 that are likely to be classified as debris flows are identified, mainly from press reports. However, as the description of these events is ambiguous, the only meteorological data in that period is from downtown Santiago and the inclusion of these cases does not significantly increase the number of events for the statistical analysis, we chose to analyse from 1980 onwards, when the information is more abundant and unequivocal. According to press and bibliographic reviews (Urrutia and Lanza 1993; Hauser 1993; Ayala et al. 1996), in the period 1980–2004 is possible to clearly identify six debris and mudflow events in the area of study (Table 1).

For the logistic regression models, the days with flow events are assigned a value of 1 for the dependent variable, while a value of 0 is used for the rest of the days.

**Table 1** Debris and mudflow events in the area of study between 1980 and 2004 (from Urrutia and Lanza 1993; Hauser 1993; Ayala et al. 1996; Sepúlveda 1998 and this study)

| Date | Description | Daily rainfall (mm) | Antecedent precipitation (mm) | | Snowfall level (m a.s.l.) |
|---|---|---|---|---|---|
| | | | 5 Days | 30 Days | |
| 27/06/1982 | Hyperconcentrated flow in Macul Ravine, deposited between 750 and 1,150 m a.s.l. | 88.0 | 64.5 | 264.8 | 2,026.8 |
| 15–17/06/1986 | Hyperconcentrated flow in Macul Ravine, deposited between 800 and 1,150 m a.s.l. | 52.0 | 32.5 | 208.0 | 2,313.5 |
| 14/07/1987 | Heavy rainfall over 2,500 m a.s.l. triggered debris flows in several catchments of Central Chile. | 72.0 | 140.5 | 143.0 | 2,421.6 |
| 25/12/1991 | Mudflows in Macul and Lo Cañas Ravines. | 61.5 | 0.0 | 0.0 | 2,821.5 |
| 03/05/1993 | Series of debris and mudflows in Macul, San Ramón and Lo Cañas Ravines. These are the largest events in historic records. | 35.8 | 15.5 | 153.0 | 3,198.8 |
| 12/11/2004 | Debris and mudflow in Lo Cañas Ravine. | 82.5 | 3.0 | 5.0 | 3,294.4 |

## 4 Results

The analysis includes the construction of 12 logistic regression models, six of them using the pluviometric data from Antupirén station and the other six with the Cerro Calán station records. The models consider different accumulated rainfall periods (with 5, 10, 15, 20, 25 and 30 days). The analyses were performed with the software SPSS 13.0.

### 4.1 Regression models for Antupirén station

The results of the regression models for Antupirén station are summarised in Fig. 4. The logistic regression coefficients (Fig. 4a) and the partial correlation coefficients (Fig. 4b) show a greater influence of the daily rainfall variable in the model. For the models with 20 or more days of accumulated rainfall, the contribution from the accumulated rainfall and the snowfall level is quite similar, but lower than the role of daily rainfall.

With respect to the significance tests (Fig. 4c and d), the Wald test shows that only in those models with accumulated rainfall over 20 days all the variables show a good predictive capacity. The goodness of fit test shows a good fit for all the models, therefore it does not allow discriminating among them.

In order to decide which model is the most representative, further analyses were performed for those days with effective flow occurrence. The model that maximizes the product of the probabilities for each day with flow events, is chosen. Results are shown in Fig. 5. The model with better predictive capacity and that meets the requisites of the significance tests is that built using an accumulated rainfall period of 25 days.

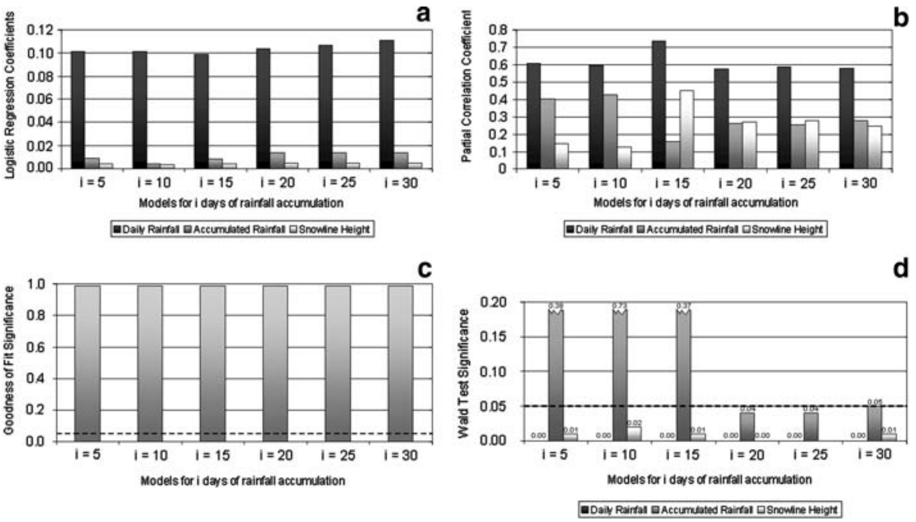

**Fig. 4** Logistic regression coefficients (**a**), partial correlation coefficients (**b**), goodness of fit (**c**) and Wald (**d**) significance tests for the models for Antupirén station data. In the significance test charts, the critical 5% level is shown with a dotted line

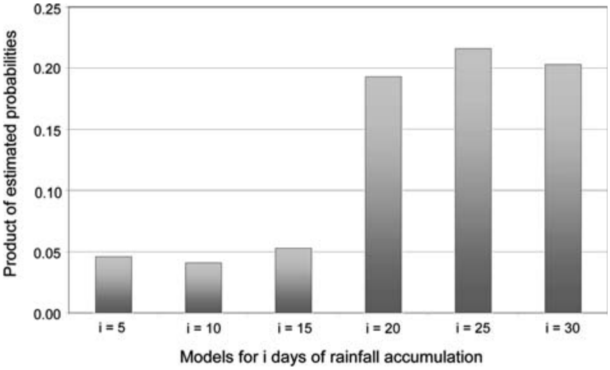

**Fig. 5** Product of the normalized estimated probabilities for the models of Antupirén station

## 4.2 Regression models for Cerro Calán station

Results from the analyses using the Cerro Calán records are shown in Fig. 6. Regression and partial correlation coefficients suggest again a greater control of day of event rainfall over the other variables. The Wald test shows that only the models with 20 and 25 days of accumulated rainfall have an acceptable predictive capacity, while the goodness of fit test does not allow discriminating among the models.

Using the same methodology that for the Antupirén stations records, in this case the model that maximizes the probability of occurrence for the days with flow events is that with 20 days of accumulated rainfall (Fig. 7).

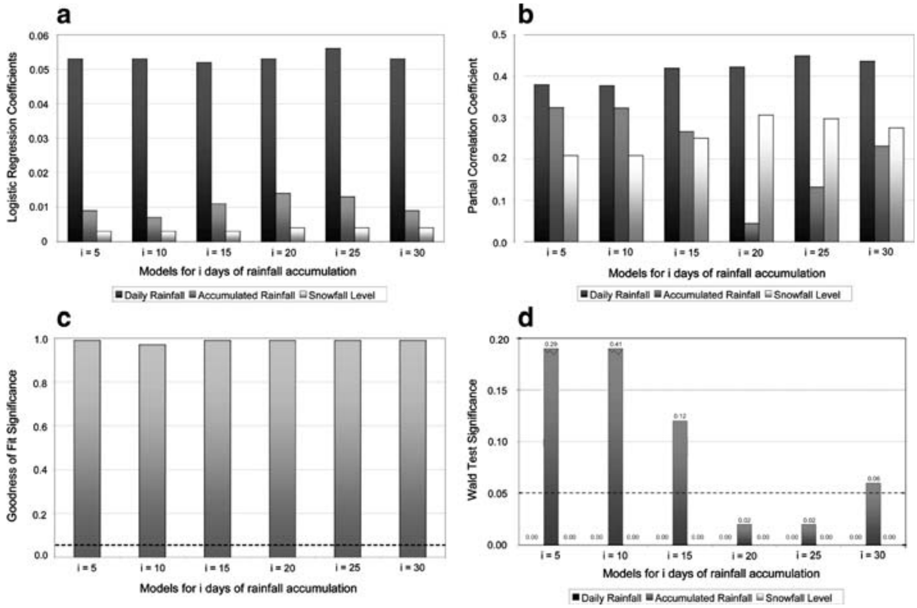

**Fig. 6** Logistic regression coefficients (**a**), partial correlation coefficients (**b**), goodness of fit (**c**) and Wald (**d**) significance tests for the models for Cerro Calán station data. In the significance test charts, the critical 5% level is shown with a dotted line

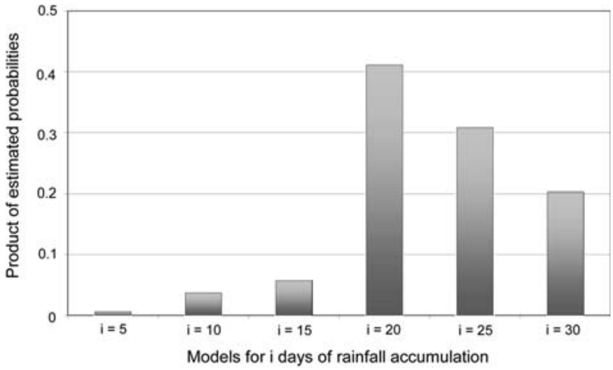

**Fig. 7** Product of the normalized estimated probabilities for the models of Cerro Calán station

### 4.3 Model selection and thresholds definition

From the models selected as more representative for each meteorological record, one of them was chosen to define thresholds of the variables related to debris and mudflow occurrence. The criterion is to determine the model that forecasts in better way the known flow events in the area. Figure 8 shows that the model using the pluviometric record of Antupirén station shows higher probabilities for those days with flow events.

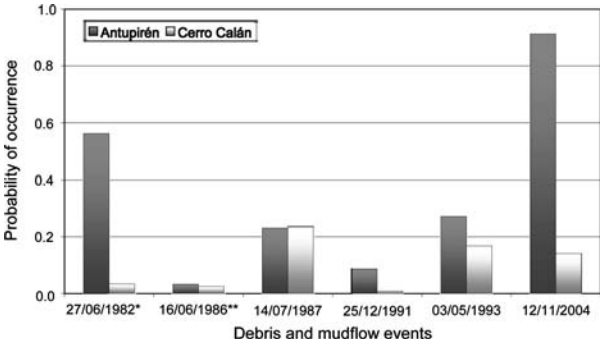

**Fig. 8** Estimated probabilities for the days with effective debris flow occurrence in the period 1980–2004

The selected model, which uses a period of accumulated rainfall of 25 days, is:

$$P(F) = \frac{1}{1 + e^{-(0.107 \cdot R_E + 0.014 \cdot \mathrm{RA}_{25-\mathrm{d}} + 0.005 \cdot \mathrm{SL} - 23.181)}} \tag{3}$$

where:

$P(F)$ = Probability of occurrence of a flow event.
$R_E$ = Daily rainfall in the day of the flow event [mm/day].
$\mathrm{RA}_{25-\mathrm{d}}$ = Accumulated rainfall in the 25 days prior to the flow event [mm].
SL = Snowfall level [m a.s.l.].

Using this model, it is possible to define a threshold for a given probability of occurrence. From Eq. 3, it is possible to obtain a linear relationship between the three variables:

$$R_E = C - 0.131 \cdot \mathrm{RA}_{25-\mathrm{d}} - 0.047 \cdot \mathrm{SL} \tag{4}$$

where

$$C = 216.645 - 9.346 \ln \frac{1 - P(F)}{P(F)} \tag{5}$$

For example, for a 20% and 50% probability, the relationship is given by:

$$R_{E(20\%)} = 203.689 - 0.131 \cdot \mathrm{RA}_{25-\mathrm{d}} - 0.047 \cdot \mathrm{SL} \tag{6}$$

$$R_{E(50\%)} = 216.645 - 0.131 \cdot \mathrm{RA}_{25-\mathrm{d}} - 0.047 \cdot \mathrm{SL} \tag{7}$$

Equations 6 and 7 may be graphically represented by a planar surface that represents the threshold for the given probability (Fig. 9). The points in the space over the threshold surface represent combinations of triggering factors with a probability higher than the probability for which the threshold is defined.

From Fig. 9a it can be observed that the 1982, 1987, 1993 and 2004 events have a probability over 20%, while the 1986 and 1991 events were generated in a scenario with probability below 20%. Only the 1982 and 2004 events return probabilities over 50% (Fig. 9b).

## 5 Discussion

The results of the regression models show surprisingly low forecasted probabilities for the scenarios of the real flow events, most of them below 50% (Figs. 8 and 9b). This may have

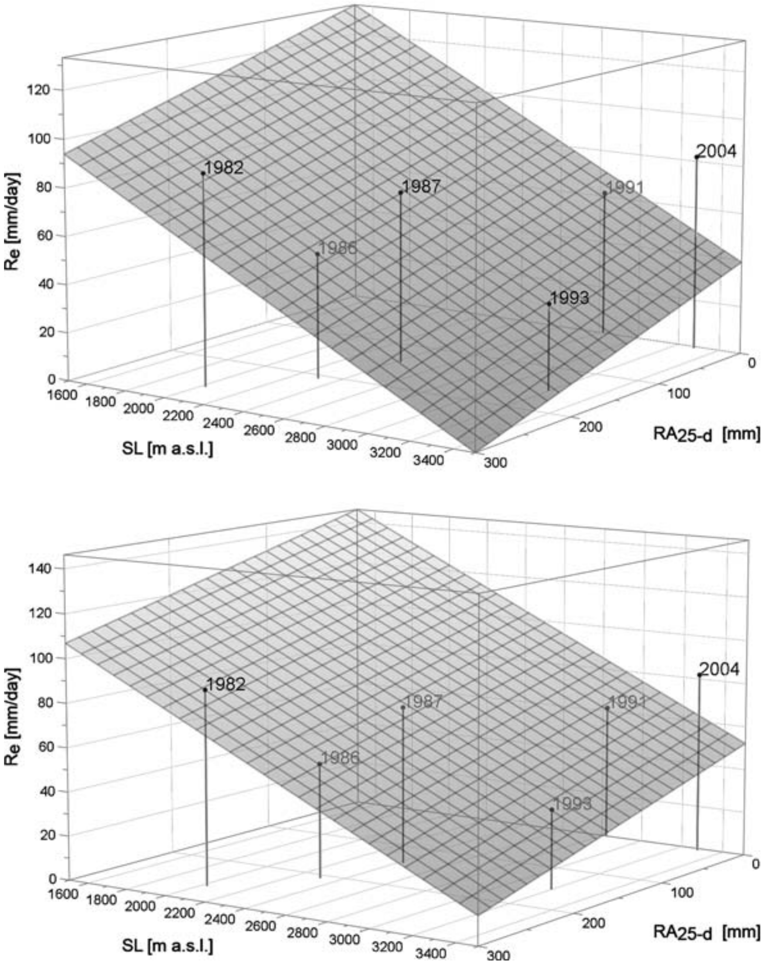

**Fig. 9** Triggering meteorological factor thresholds for (**a**) 20 % and (**b**) 50% probability, from Eqs. 6 and 7, respectively. The combination of variables for the six studied flow events are shown. SL: snowfall level; $R_E$: daily rainfall in the day of the flow event (mm/day); $\mathrm{RA}_{25-\mathrm{d}}$: accumulated rainfall in the 25 days prior to the flow event (mm)

two possible explanations: the model is not capturing all the necessary variables, or the data are insufficient. The variables used are the two most frequently assumed in the literature as the most important, the rainfall intensity and the accumulated rainfall, and a factor that has been locally considered as relevant, the snowfall level.

There are many factors that have to be accounted for. First, the rainfall records are not taken in the upper section of the drainage basins, where the flows are triggered; therefore the records are biased because they are not accounting for the orographic control on rainfall, and the variability of rainfall intensity along the basins. Secondly, the rainfall data has a daily frequency. It is known that the hourly intensity of rainfall is a much better predictor, as the flows are usually triggered within a period of hours of intense precipitation (e.g. Terlien 1998; Hauser 2000). The scarcity of pluviographic instruments with continuous recording is a major deficiency to assess the influence of rainfall intensity in the

Chilean mountain areas. It is very important the installation of pluviographic equipments near or in the drainage basins to improve the forecasting ability of the models. Detailed review of the daily rainfall records (Padilla 2006) showed that there are many cases of storms with higher daily precipitation that some of those that triggered flows, that did not trigger any landsliding. This emphasises that the hourly intensity is more important than the daily intensity, or that there are some other variables that strongly influence the generation of flows and that are not considered in the general practice. Although there are some pluviographic records in the cities of the central valley, such as in downtown Santiago, its distance with the flow generation areas add further uncertainties to the analysis, hence their use is not the solution. In the last years the problem has been gradually solved with the installation of new pluviographic stations, but it will take several years to get enough records for statistical analysis.

The 25 years time span of the analysed rainfall and temperature records is not optimum, although this time span is considered as adequate by the official hydrological agency for the rainfall statistical analysis in the country (DGA 1991). In the future, as the rainfall database and the landslide inventory get larger, these types of analyses will be more representative and their accuracy will surely improve. Furthermore, a larger database will allow including in future models the influence of El Niño seasons on the generation of debris flows in the area, which has been shown by García (2000) and Sepúlveda et al. (2006a) for Central Chile.

Despite the low predictability of the model, the results show the stronger influence on debris flow triggering of the event rainfall, over the accumulated rainfall and snowfall level. This is shown by the regression and partial correlation coefficients. Nevertheless, preliminary studies (Padilla 2006) show that the regression analysis with all the three variables have better statistical adjustment and higher probabilities for the known flow events than analyses using a single variable or pairs of variables. This suggests that the three used variables are in fact important but the model is missing other relevant factors to be considered.

Some considerations must be taken about scale effects. The study considers records from two meteorological stations close to the drainage basins where the flows are triggered. It has been observed that the spatial distribution of rainfall intensity is large and difficult to predict with one or two stations, due to orographic control and the occurrence of local storm cells, which complicates the modelling (Lara 2007). Another scale effect is related with the fact that the model uses only meteorological triggering factors, assuming that the conditioning factors, such as the geological, geomorphological and geotechnical properties of the foothills are homogeneous, and therefore the susceptibility of generating flows along the range is assumed as constant. This is valid at a regional scale, as the whole area of study is within the same regional geological formation and geomorphological unit. However, the factors that condition the susceptibility of debris flows may have important local variations. Therefore, it is difficult to separate the triggering from the conditioning factors at the scale of this study, which is conditioned by the scarcity of meteorological stations and, most importantly, of documented flow events. Some conditioning factors that should be investigated altogether with the triggering factors are the lithology, shear strength of soils and rocks, slope angle and morphology, drainage basin morphometry, amount of available loose material, vegetation, hydrological and hydrogeological conditions. Research in this direction is currently being carried out by the authors and colleagues (e.g. Lara et al. 2006; Lara 2007).

In summary, the results show that the analysed variables are indeed relevant in the debris flow generation process, but they are not sufficient to determine reliable threshold values to be used in alert systems. Further data is needed for the development of a complete model that allows forecasting of flow occurrence in the mountain foothills of Santiago.

## 6 Conclusions

Rain-induced debris and mudflows are some of the most important types of geological hazards in Central Chile. Statistical analysis of meteorological triggering factors traditionally considered as the most significant, the rainfall of the day of the event, accumulated rainfall and the snowfall level, show that although important, they are insufficient to fully characterise the hazard, given the high complexity of the problem. Further detailed geological and geotechnical studies at drainage basin scale and a larger and more detailed spatial and temporal database of meteorological records are needed to develop a reliable model with predictive capacity that allows complete risk analysis and the implementation of forecasting and alert systems in the area based on thresholds of the meteorological factors.

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