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► To cite this version:

Alexandre Remaître, Jean-Philippe Malet. Regional Rainfall Thresholds for Shallow and Deep-Seated Mass Movements Triggering in the South Eastern French Alps. Advancing Culture of Living with Landslides, Springer International Publishing, pp.183 - 192, 2017, 10.1007/978-3-319-53485-5_20 . hal-03075743

HAL Id: hal-03075743

<https://hal.science/hal-03075743>

Submitted on 8 Jan 2022

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Regional Rainfall Thresholds for Shallow and Deep-Seated Mass Movements Triggering in the South Eastern French Alps

Alexandre Remaître and Jean-Philippe Malet

Abstract

The main objective of this work is to propose hydro-meteorological thresholds for the triggering of shallow (slides, debris/mud flows) and deep-seated mass movements within a vast area of the South-East French Alps (Queyras, Ubaye, Tinée) characterized by various rainfall patterns. For this purpose, we exploit a landslide catalogue (containing more than 600 events) for the period 1928–2014 describing the date (and sometimes the hours) of occurrence, the type of mass movement, the geographical location and the nearest meteorological station. Rainfall data are available for 36 stations. A statistical analysis of rainfall conditions associated to triggering of shallow mass movements at various time scales (yearly, monthly, daily and hourly) reveals that rainfall thresholds are spatially highly variable.

Keywords

Triggering • Rainfall patterns • Rainfall thresholds

Introduction

Rainfall is worldwide a recognized trigger of landslides. Numerous studies were conducted in order to define relationships between rainfall and triggering or reactivation of landslides (Corominas 2000; Iverson 2000; Wieczorek and Glade 2005; Godt et al. 2006; Cannon et al. 2008). Hydrological triggering of landslides can be divided in three general types: (1) development of local perched water tables in the subsoil leading to shallow slides and gravitational flows, (2) long-lasting rise in permanent water tables leading to the triggering of deep-seated slope instabilities, and (3) intense runoff causing debris flows. Types (1) and (3) are usually observed for high rainfall intensity events (hourly and daily rainfall) associated to heavy storms; type (2) is usually observed through increasing water content in the

subsoil due to antecedent rainfalls (weekly or monthly rainfall) and/or massive snowmelt.

Many investigations have been carried out to determine the amount of precipitation needed to trigger slopes failures. A large state-of-the-art on rainfall thresholds can be found in Guzzetti et al. (2007, 2008). A threshold can be defined as the minimum or maximum level of some quantity needed for a process to take place (trigger) or a state of change (landslide reactivation). For rainfall-induced landslides, thresholds may be defined in terms of rainfall, soil moisture or hydrological conditions that, when reached or exceeded, are likely to trigger a movement (Guzzetti et al. 2007). Usually rainfall thresholds are defined using conceptual or physically process-based models (Crozier 1999; Glade et al. 2000; Crosta and Frattini 2003; Casadei et al. 2003; Aleotti 2004) or through statistical analyses (Caine 1980; Corominas and Moya 1999; Floris and Bozzano 2008; Li et al. 2011). The large variety of landslides (Cruden and Varnes 1996; Hungr et al. 2001) and the extreme variety of climatic conditions leading to the triggering or the reactivation of a landslides lead to a regional definition of relationships between landslide occurrence and associated climatic conditions. Most of

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the rainfall thresholds for the possible occurrence of a given landslide are valid only at a local or a regional scale (Brunetti et al. 2010) and are strongly correlated to local physiographic factors (e.g. landcover, topography, human influence).

The purpose of this work is to document the relationships between the triggering of two types of mass movements (debris flows and deep-seated landslides) and different patterns of rainfall at various temporal scales for the Southeast French Alps. For this purpose, we exploit a landslide catalogue and rainfall data to propose rainfall thresholds for both types of landslides.

General Overview of the Study Area

The study area is the Southeast part of the French Alps and consists of three large catchments (Queyras, Ubaye and Tinée, from the North to the South). Elevation ranges from sea level, along the Mediterranean coast, to more than 3500 m. Queyras and Ubaye exhibit highest elevations and steepest slopes while the Subalps of the Tinée area is divided into a series of massifs separated by deep valleys. South to Utelle (Fig. 1), the relief becomes softer towards the Mediterranean Sea.

The structural settings control the morphology of the area. Sedimentary rocks crop out in the entire area (Fig. 1) and consist mainly of marls and limestone within the Subalpine chain and flysch and sandstones within thrust sheets units. In the North, the “Queyras Nappe”, made of high-pressure metamorphic Mesozoic slates (blue- to green-schist facies), covers continental crustal rocks. “Ubaye valley” has extensive outcrops of autochthonous blue-black shales, known as Callovo-Oxfordian black marls (Maquaire et al. 2003), containing the occasional limestone bands. Black marls are overlain by Embrunais-Ubaye sheet thrusts which are made of calcareous sandstones and flyschs. The Tinée area is formed by folding and thrusting of Mesozoic limestones and shales together with the Tertiary foreland basin sediments. The eastern part of the Tinée is mostly made of plutonic rocks (external crust unit, Fig. 1).

In the three areas, weathering processes are very active: thick debris talus, moraines talus, landslide deposits, terrace fluvial and torrential deposits cover most of the hummocky hillsides. Summits are mostly made of bare rocks surrounded with large scree talus. Landslides of all types are abundant in the area. Landslide abundance and pattern vary spatially, and are controlled by the relative position of sedimentary and tectonic discontinuities, by the relative abundance of hard versus weak or soft rocks, and by the presence and attitude of permeable and impermeable layers (Flageollet et al. 1999; Maquaire et al. 2003; Cossart et al. 2008; Zerathe et al. 2014).

From a climatic point of view, Queyras and Ubaye areas are located in the dry intra-Alpine zone (Fig. 2). Its climate is characterized by (1) a mountain influence with a marked inter-annual rainfall variability (e.g. 667 ± 400 mm over the period 1928–2014 for the Barcelonnette station) and 130 days of freezing per year, (2) a continental influence with significant daily thermal amplitudes ($>20^\circ$) and numerous freeze-thaw cycles and (3) heavy spring rains on melting thick snow layers which can also lead to high discharges. The Tinée area climate is much more humid (900–1300 mm per year) and is characterized by a typical annual cycle with most of precipitation in autumn (about 35% of yearly precipitation) and a dry summer period. The mean temperature is slightly higher than the two other areas. This is particularly true in winter, with a lower number of freeze-thaw cycles and a thinner snow cover.

For the three areas, a strong Mediterranean influence leads to violent summer rainstorms yielding more than 50 mm h^{-1} on occasion (Turkington et al. 2016).

Landslides Catalogues, Meteorological Data and Methodology

Historical Landslide Catalogue

For landslides, the study builds up on existing catalogues of Flageollet et al. (1999) and Remaître and Malet (2010), which have been completed by a catalogue of RTM Service (Restauration des Terrain en Montagne) which has collected since 1880 a catalogue of historical landslides for the entire French Alps. The RTM catalogue is built from a systematic field reporting. The catalogue has been further completed with various data (technical reports, monographs, scientific papers and local inhabitants' interviews). Events reported in the catalogue correspond usually to landslides that resulted in damage, affecting buildings or roads, and were located near towns and villages. Nevertheless, this catalogue is probably not complete; some landslides are not listed because (i) they were not observed or (ii) they did not cause any damages.

The analysed catalogue consists of 668 historical landslides and debris flows for the period 1930–2014 (Fig. 3). For each event, the catalogue includes: (1) the location, (2) the precise time, date or period of failures, (3) the landslide type, (4) the rainfall condition that resulted in slope failures, including the daily rainfall, the antecedent rainfall for various periods and for some stations the total event rainfall, the rainfall duration, the mean rainfall intensity and peak rainfall intensities, and (5) the affected rock types and/or superficial formations. Analysis of the geographical distribution of the landslide events listed in the catalogue revealed a geographical bias, with the majority of the

Fig. 1 Geological sketch of the South French Alps

Fig. 2 Mean annual precipitation (MAP) map of the South East French Alps (data from the website of Météo-France: <http://www.meteofrance.fr/>) and location of raingauges within the study area. Raingauge ID can be found in Table 1

Fig. 3 Debris-flow and landslide database for the South French Alps

slow-moving landslide events respectively in the Ubaye area (45%) and the Tinée area (48%).

Meteorological Data

We used 36 meteorological stations (Table 1), 10 for the Queyras area, 6 for the Ubaye area and 20 for the Tinée area.

Information on rainfall events was cross-checked in order to identify duplicate landslide events, landslide events for which rainfall information was not considered as relevant or sufficiently documented. These landslide events were excluded from the catalogue.

At the end of the review process, we build two catalogues for two different objectives: (i) a catalogue of 668 events (542 shallow mass movements (e.g. debris flows) and 126 deep-seated mass movements (e.g. landslides)) for the analysis of antecedent precipitation at various time scales (from 1 to 180 days) with daily rainfall data (1930–2014); (ii) a catalogue of 259 events (186 debris flows and 73 landslides) for the identification of rainfall threshold through the analysis of hourly rainfall data (1998–2014).

Results and Analysis

Historical Landslide Time Series: Seasonal and Geographical Repartition

The seasonal occurrence of mass movements exhibits a clear distinction between debris flows and deep-seated landslides for the entire study area (Fig. 4a): debris-flow occurrences show a clear activity peak in June, July and August. In contrast, mudslides occurrences show two peaks in spring (March, April and May) and autumn (October and November).

Comparison of the seasonal distribution of landslide events for the three areas is instructive (Fig. 4b, c). If the distribution is quite similar for Ubaye and Queyras (especially for debris flows), the Tinée area exhibits a different pattern. In the Tinée area, the period of debris-flow activity is much longer and extends from June to November. This must be put in relation with the peculiarity of the monthly distribution of rainfall in the Tinée where October and November are the wettest months. A similar observation can be made for the deep-seated landslides distribution: in Ubaye, most of the landslides occur during spring (snow melt and seasonal rainfall). In Tinée, a majority of landslide occurs in autumn with long (at least 24 h) and sometimes intense rainfall episodes.

Daily Rainfall and Antecedent Rainfall Analysis

Daily rainfall versus antecedent rainfall analysis is of primary interest for landslides hazard assessment. When using antecedent rainfall measurements to estimate landslide occurrence, a key difficulty is the definition of the period over which to accumulate precipitation. Usually, such analyses revealed a significant scatter according to the considering period (e.g. Guzzetti et al. 2007). In this work, several periods have been investigated: 180, 150, 120, 90, 60, 30, 14, 7, 6, 5, 4, 3 and 2 days before the event. Figure 5 plots all the considered antecedent rainfall periods for all the events.

Once again, a clear distinction is observed for both types of mass movements. Most of the debris flows occurs after a 7-day dry period while deep-seated landslides triggering or reactivation needs at least 40 mm of antecedent precipitation during the last 7 days. For a larger time scale, results show that debris flows never occurred when the antecedent rainfall for the 180-days period exceeds 410 mm. On the contrary, antecedent rainfall for a 180-days period has to be at least 205 mm in order to trigger a deep-seated landslide. But these facts have to be put in relationship with the climatic characteristics of each study area and also the seasonal occurrence of both types of events: summer for debris flows, and spring and autumn for deep-seated landslides.

Intensity-Duration of Rainfall Events Associated to Rainfall-Induced Mass Movement (Deep-Seated Landslide and Debris Flow)

259 events (186 debris flows and 73 deep-seated landslides) were used for this analysis. Figure 6 presents the scatter plot of the available Intensity-Duration (ID) data. A clear distinction concerning the mean rainfall intensity appears for the two types of landslides: for debris flows, the mean intensity ranges from 1.4 to 27.8 mm h⁻¹, and the total duration of the rainfall event ranges from 1 to 57 h. For deep-seated landslides, the mean intensity ranges from 0.5 to 6.4 mm h⁻¹, and the total duration of the event ranges from 8 to 38 h.

Some authors (e.g. Godt et al. 2006; Cannon et al. 2008) have suggested that for the purposes of threshold estimation, and in order to better constrain the threshold within a range of durations, the storms should be characterized using both mean intensities and also peak intensities for a selection of durations. From a general point of view, the general shape of the curves of peak intensities (Fig. 7) are quite similar, and show a clear descending trend of the minimum level of average rainfall intensity with increasing rainfall duration.

Table 1 Meteorological station characteristics. M.A.P. is the mean annual precipitation index (the location of the stations can be found at Fig. 3)

ID	Station name	Area	Elevation	Daily date		Hourly	M.A.P.
				Start	End	Start	mm
1.	VILLAR ST PANCRACE	Queyras	1310	2003		20/08/2003	600–700
2.	CERVIERES	Queyras	1615	1933			700–800
3.	ARVIEUX	Queyras	1825	1947		10/07/2007	900–1000
4.	ABRIES	Queyras	1560	1931			700–800
5.	RISTOLAS	Queyras	1670	2004		05/10/2004	800–900
6.	CHATEAU-VILLE-VIEILLE	Queyras	1355	1932			600–700
7.	ST CREPIN	Queyras	906	2006		30/08/2006	700–800
8.	ST VERAN	Queyras	2006	1929			700–800
9.	CELLAC	Queyras	1665	1931			700–800
10.	VARIS	Queyras	1850	1931	2000		800–900
11.	ST PAUL	Ubaye	1908	1971			900–1000
12.	LA CONDAMINE	Ubaye	1325	1955	2004		700–800
13.	J AUSIE RS-ST ANNE	Ubaye	1240	1960			600–700
14.	BARCELONNETTE	Ubaye	1155	1928		03/02/1998	600–700
15.	UVERNET FOURS	Ubaye	1660	1955			900–1000
16.	ALLOS	Ubaye	1400	1971		26/05/2010	1000–1100
17.	SAINT-DALMAS-LE-SELVAGE	Tinée	1880	1931	2002		1000–1100
18.	ST ETIENNE DE TINEE_SAPC	Tinée	1150	1952		29/03/2007	900–1000
19.	ISOLA 2000	Tinée	1912	1972			1200–1300
20.	ST MARTIN D'ENTRAUNES_SAPC	Tinée	1642	2007		05/07/2007	1000–1100
21.	PEONE	Tinée	1784	1951		20/11/2002	1000–1100
22.	BEUIL-OBS	Tinée	1460	1928			1000–1100
23.	GUILLAUME-OBS	Tinée	803	1931	2014		900–1000
24.	TENDE-OBS	Tinée	898	1952		01/01/1993	1000–1100
25.	ST-SAUVEUR-SUR-TINEE	Tinée	487	1932	2007		900–1000
26.	ST-MARTIN-DE-VESUBIE-OBS	Tinée	994	1950			1100–1200
27.	VALDEBLORE	Tinée	1058	1936	2001		1000–1100
28.	RIMPLAS_SAPC	Tinée	1130	2006		15/02/2007	900–1000
29.	SAINT MARTIN VESUBIE_SAPC	Tinée	899	1950		01/11/2013	1000–1100
30.	LANTCSQUE_SAPC	Tinée	550	1932		27/12/2006	800–900
31.	PUGET THENIERS_SAPC	Tinée	442	1931		02/12/1997	800–900
32.	MOULINET	Tinée	817				1000–1100
33.	BREIL SUR ROYA	Tinée	319	1931		09/01/1993	900–1000
34.	ASCROS	Tinée	1173	1987		01/01/1993	800–900
35.	SOSPEL	Tinée	843	1928		04/11/2004	900–1000
36.	LEVENS	Tinée	691	1933		16/05/2008	800–900

Fig. 4 Monthly distribution of historical mass movements for the period 1930–2014. **a** Monthly distribution of debris flows and deep-seated landslides for the entire area. **b** Monthly distribution of debris flows per sub-areas. **c** Monthly distribution of deep-seated landslides per sub-areas

Fig. 5 Antecedent cumulative rainfall for debris flows and deep-seated landslides in the three study areas for different periods: 180, 150, 120, 90, 60, 30, 14, 7, 6, 5, 4, 3 and 2-days periods before the event

Fig. 6 Mean rainfall intensity versus event total duration for debris-flows (in *blue*) and deep-seated landslides (in *red*) for the Southeast French Alps

Fig. 8 Mean rainfall intensity versus event total duration for debris-flows in the three sub-areas: Queyras (*green dots*), Ubaye (*blue dots*) and Tinée (*red dots*)

Fig. 7 Peak rainfall intensity versus event total duration for debris-flows (in *blue*) and deep-seated landslides (in *red*) for South Eastern French Alps

Plotted peak intensities show a similar trend than observed on Fig. 6; a clear distinction between rainfall patterns concerning debris flow or deep-seated landslides can be observed: Events characterized by high rainfall intensity

(average and peak) and short episode duration (e.g., mostly the result of localized convective storms) will trigger mostly debris flows in relatively permeable soils (e.g., moraines, scree or poorly sorted slope deposits).

Long rainfall periods characterized by low to moderate average and peak rainfall intensity (e.g. the result of multiple and successive storms during a period of several weeks or months) can trigger or reactivate shallow and deep-seated landslides in low permeability soils and rocks (e.g., black marls).

Comparing rainfall thresholds for the three study areas was only pertinent for debris flows. Indeed, lack of deep-seated landslide events in the Queyras area makes the comparison irrelevant for such kind of landslides. Figure 8 plots the ID relationship for debris flows per sub-areas.

Inspection of Fig. 8 confirms the linear scaling of the minimum level of rainfall intensity likely to trigger debris flows in the range of duration from 1 to 58 h for the three sub-areas. Comparison of the threshold curves reveals that the minimum levels of rainfall intensity likely to generate debris flows in the three areas are different. If Queyras and Tinée exhibit a very similar threshold, the ID threshold for the Ubaye area is slightly lower. This could be put in relation with the geomorphological settings of the Ubaye area, where active erosion processes provide available sediments more frequently and/or in a larger quantity (Remaître et al. 2011; Turkington et al. 2016).

Conclusion

At the monthly scale, a clear distinction can be observed for debris flow (strong storm associated to a 7-day dry period) and deep-seated landslides (at least 40 mm of antecedent precipitation during the last 7 days and at least 200 mm during the last 180 days).

At the hourly scale, the ID relationship for debris flows for the three areas were built and show a similarity for the three areas even in the Ubaye area exhibits a lower ID threshold. These results could be improved through the analysis of rainfall-radar data. Since 2012 3 on-site meteorological radars were installed in the South Eastern French Alps. The analysis of these radar data will (1) reduce the uncertainty of rainfall intensities calculation and (2) increase significantly our knowledge about the spatial distribution of the rainfalls and the preferential paths of storm cells and rainfalls fields.

Acknowledgements This research was funded through the French ANR Project 'SAMCO', the European Project FP7 'SafeLand: Living with landslide risk in Europe' (2009–2012) and through the European Project FP7 ERA-NET CIRCLE 'Changing Risks' project.

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