Debris-Flow Monitoring for the Set-Up of a Warning and Alarm System -Experiences from the Pyrenees-

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Debris-flow monitoring sites provide many important inputs on their mechanics and strongly improved the understanding on this hazardous process. Monitoring data are the basis for future early warning systems (EWS) and alarm systems (AS). In this study, results from the Rebaixader monitoring are presented and evaluated for the implementation in an EWS and AS at catchment scale. The key parameters are the rainfall thresholds for the warning and the ground vibration produced by the moving debris flow for the alarm emission. At regional scale, a preliminary EWS for a test area in the Central-Eastern Pyrenees is evaluated. The EWS is based on quantitative precipitation estimates obtained from the weather radars and a simple susceptibility model, which is applied in each basin of the test area. The experiences gathered in the Pyrenees show that the knowledge on initiation and flow behaviour of debris flows has strongly advanced and facilitate the set-up of operational EWS or AS. However, there are still remaining various uncertainties (especially related to the adequate definition of thresholds), which must be evaluated and continuously eliminated.

Key words: debris flow, monitoring, early warning, alarm, Pyrenees

1. INTRODUCTION

Debris flows are common natural hazards in most mountain ranges of the world and cause important economic loss and also fatalities. The occurrence of debris flows in the Pyrenean mountain range is less analyzed than in other regions, but recent data on their incidence have shown their significance [e.g., Alcoverro et al., 1999; Portilla et al., 2010].

Early warning and alarm systems are powerful tools for the risk mitigation by reducing the consequences and finally the economic loss [UNEP, 2012]. Most of the recent publications on early warning systems (EWS) include rainfall thresholds and are related to shallow slides and debris flows [e.g., Aleotti, 2004; Baum and Godt, 2010; Jakob et al., 2006; Brunetti et al., 2010; Tiranti and Rabuffetti, 2010]. However, there are also some EWS based on the soil moisture [e.g., Baum and Godt, 2010; Greco et al., 2010]. On the other side, an alarm system (AS) informs the responsible and affected persons immediately of the danger, by optical or acoustic devices (e.g., flash lights or sirens). Only very few alarm systems for torrential processes have been published in literature, and even fewer are operational [e.g., LaHusen, 2005; Arattano and Marchi, 2008; King et al., 2008; Badoux et al., 2009]. A combination of EWS and AS is herein abbreviated as EWAS.

The base of EWAS is a solid understanding of the debris-flow initiation and dynamic behavior. In the last two to three decades, the insights on debris flows have been improved among others by in-situ monitoring. At the moment, most of the existing debris-flow monitoring systems are situated in the European Alps [e.g., Scotton et al., 2011; Comiti et al., 2014; Navratil et al., 2013; Hürlimann et al., 2003a], in China [Zhang, 1993], Japan [Suwa et al., 2009], Taiwan [Yin et al., 2011] or the USA [Mccoy et al., 2012], and in the Pyrenees [Hürlimann et al., 2014].
The main purpose of this work is to evaluate the possibility of defining EWAS for debris flows at catchment and regional scale for the Central Pyrenees. The experiences gathered during five years at a test site are presented and discussed. They constitute key inputs for the EWS and AS.

2. SITE DESCRIPTION

2.1 General settings

The study areas are situated on the South flank of the Central-Eastern Pyrenees (Fig. 1). On one side, there is the monitoring site at Rebaixader torrent and on the other side we selected a test area of 2180 km², both of them located in the Axial Pyrenees. The lithology in this area consists almost entirely of igneous and metamorphic Paleozoic rocks tectonised during the Hercynian and Alpine orogenies. The bedrock is covered by colluvium and glacial deposits.

The climatic conditions are affected by three factors: the west winds from the North-Atlantic, the vicinity of the Mediterranean Sea and the orographic effects of the Pyrenees. There are two common rainfall types triggering debris flows in the area [Hürlimann et al., 2003b]: 1) short duration, high intensity rainfalls related to convective summer storms, and 2) moderate intensity and long-lasting rainfall during autumn/winter.

2.2 The rebaixader monitoring site

The Rebaixader torrent (Fig. 1) is the most active of the three debris-flow monitoring sites installed in the Pyrenees [Hürlimann et al., 2011]. The bedrock of the 0.53 km² large drainage basin consists of slates, which are partly covered by colluvium and glacial (till) deposits. The initiation area of the debris flows is located in a large and steep scarp developed on a lateral moraine.

The monitoring has been continuously improved since the initial set-up in summer 2009. At the moment, the monitoring system includes six different stations: four stations recording information on the initiation mechanisms (two meteorological stations and two infiltration stations), and two stations focusing on the debris flow detection and the dynamic behaviour of the flows. All the details on sensor types, technical specifications of the set-up, exact locations of the sensors, data gathering etc. can be found in Hürlimann et al. [2014].

In this study, the records of the rain gauge located inside the Rebaixader catchment, are analysed. Moreover, the infiltration stations, which include soil moisture and suction sensors, are also investigated but in a marginal way.

3. EARLY WARNING SYSTEM

An early warning system for debris flows refers to a possible occurrence of an event and predicts the debris flow even before its initiation. Most EWS are implementing rainfall thresholds and thus the analysis of the critical rainfall patterns is a fundamental research task. There are two main classes of thresholds: the physical or process-based ones [e.g., Crosta and Frattini, 2003; Godt et al., 2008; Papa et al., 2013] and the empirical or statistical ones [e.g., Brunetti et al., 2010; Berti et al., 2012].

In the following, we firstly present an approach of empirical rainfall thresholds based on data gathered at the Rebaixader monitoring site and secondly a physical one based on the method proposed by Papa et al. [2013].

3.1 Empirical rainfall thresholds

Between August 2009 and October 2013, a total of 7 debris flows and 17 debris floods were detected by the monitoring system installed in the Rebaixader torrent. The process distinction was performed as described in Hürlimann et al. [2014] or Abancó et al. [2014]. We analysed the data of the raingauge METEOCHA, which is close to the active channel in the transit zone. The gauge is a standard tipping bucket apparatus (RM YOUNG 52203) with a resolution of 0.1 mm. The sample rate of the
rainfall measurements was 5 min.

In a first step, different parameters were calculated for three classes of rainfalls: 1) rainfalls triggering debris flows, 2) rainfall triggering debris floods, and 3) rainfall not triggering any of the two processes (herein called “no event” rainfalls). The calculated parameters included rainfall duration, $D$, total rainfall, $P_{tot}$, mean rainfall, $P_{mean}$, maximum hourly rainfall, $P_{h\_max}$, and other maximum values for various time intervals (e.g. 10, 20, 30 min). In addition, the antecedent rainfalls of 3 and 10 days, $P_{ant\_3d}$ and $P_{ant\_10d}$, were calculated.

Finally, we had a total dataset of 156 rainfalls, including 6 rainfalls that triggered debris flows, 15 rainfalls that provoked debris floods, and 135 “no event” rainfalls. The difference between the number of this dataset and the original number of events can be explained by the fact that rainfall measurements were not available for all debris flows and debris floods. Problems with the rain gauge measurements mostly occurred due to the blocking of the inlet of the gauge by leaves, dust etc.

In a second step, the different parameters were evaluated and compared in order to define some critical conditions for debris flow and debris flood initiation. Fig. 2a) shows the relation between duration and maximum hourly rainfall for the three classes of rainfalls. It can be seen that debris flows are triggered by short and high-intensity rainstorms. In contrast, debris floods are mostly caused by rainfalls of short duration and an intensity that cannot clearly distinguished from the “no event” rainfalls. In addition, the standard intensity – duration graph was plotted and two preliminary thresholds levels were added manually without using probabilistic criteria (Fig. 2b)).

### 3.2 Physical rainfall thresholds

In this study, the physical model proposed by Papa et al. [2013] was applied, which calculates shallow slope failures by the infinite-slope stability analysis in every cell of a digital elevation model (DEM). Apart from the DEM, the geotechnical parameters for the different soil units have to be introduced. In additional, an antecedent rainfall amount can be incorporated in the model, if necessary. The final result is the unstable area within a catchment (expressed in %; Fig. 3).
3.3 Preliminary EWS at regional scale using rainfall data

The physical model described above was implemented in a preliminary regional-scale early warning system. For this reason, the physical rainfall thresholds were calculated in each drainage basin of our test area and subsequently combined with a simple susceptibility analysis [Berenguer et al., 2014]. The selected susceptibility model incorporated four morphologic parameters, which were calculated from a 5x5 m² digital elevation model. The final warning levels were determined by applying fuzzy logic membership functions.

The magnitude of the rainfall episodes was calculated by radar-based quantitative precipitation estimates obtained from the Doppler weather radars of the Meteorological Service of Catalonia. The rainfall amount was incorporated in the preliminary EWS by 30 minutes accumulations.

Fig. 4 Example of the preliminary early warning system over the test area on 23 July 2010 at 01:30 UTC. a) 30-minute rainfall intensity estimated from radar observations; b) resulting warning level (green for lowest level and red for highest level) estimated in each sub-basin (sub-basins with recent debris-flow activity are indicated with a horizontal line pattern).

Fig. 5 Example of infiltration measurements during a debris flood triggering. The two soil moisture sensors measuring volumetric water content (VWC) are installed at 15 and 30 cm depth in the initiation area.

An example of the application of this preliminary EWS for the rainstorm of 23 July 2010 is shown in Fig. 4. This rainstorm was characterized by many convective cells over the test area. The rainfall amount estimated for a 30-min interval indicates that maximum rainfall of around 50 mm/h was observed in the south-eastern part of the area. Subsequently, these rainfall estimates were combined with the susceptibility model in order to generate the resulting map, where the warning levels are illustrated (Fig. 4 b)).

The preliminary EWS was tested in the Rebaixader and other catchments for several rainstorms and gave satisfactory results [Berenguer et al., 2014]. However, the applied model only includes landslide-induced debris flows and not the ones that initiate by channel-bed scouring. That’s why the actual EWS will be completed and cross-checked by empirical rainfall threshold curves that will be established at regional scale for the entire Central-Eastern Pyrenees.

3.4 Implementation of soil moisture

A preliminary analysis was performed with the measurements of the soil moisture sensors installed in the initiation zone of the Rebaixader torrent. Thus, only some general outcomes can be presented for a future implementation in a EWS at this catchment. First results show that high-intensity rainstorms produce a fast and sharp increase of the soil moisture in the superficial layers, where the sensors are installed. An example of the debris flood
triggering is given in Fig. 5, where the fast increase in the volumetric water content (VWC) at two sensors is clearly visible. However, a larger dataset of infiltration measurements and a comprehensive analysis are necessary to establish clear trends between soil moisture and debris-flow/debris flood occurrence and to finally define thresholds.

4. ALARM SYSTEM

An alarm system informs the responsible and affected persons immediately of the danger by sending out alarm messages and turning on optical or acoustic devices (e.g., flash lights or sirens).

There are different types to detect a moving debris flow in the channel. Here, we selected a contactless method based on the ground vibration produced by the passing debris flow and measured by geophones installed along the channel.

In the Rebaixader torrent, four geophones measure the ground vibration and transform the initial signal into impulse per second (IS) time series [Abancó et al., 2012]. This transformation depends on a threshold value and the definition of this threshold is a key point of a reliable alarm system.

Abancó et al. [2014] discussed this aspect in detail and presented a comprehensive analysis, which included data gathered at Rebaixader. There is another approach of simplifying the seismic raw data at real-time, but both of them enable a fast and easy analysis of the resulting time series [Arrattano et al., 2014].

In the Rebaixader monitoring site, a total of 7 debris flows and 17 debris floods have been detected between August 2009 and October 2013. A detailed analysis of all the ground vibration time series revealed that the expected positive relationship between event volume and the maximum registered IS-value (IS_{max}) was detected [Hürlimann et al., 2014]. However, a clear trend of this relationship was especially visible at the geophone (GEO4) that was installed at the most downstream position (Fig. 6). The IS_{max} – values recorded at that geophone can furthermore be used to distinguish between debris flows and debris floods. Thus, two preliminary ground vibration thresholds for an alarm system can be defined at this geophone: a threshold for debris floods at IS = 20 IMP/sec and a threshold for debris flows at IS = 90 IMP/sec.

5. CONCLUSIONS

The present work shows the benefits of monitoring data for the design of early warning and alarm systems. Especially, the definition of thresholds is simplified, if there are some previous results obtained by an existing monitoring site in the area under consideration. However, the definition of thresholds must be checked and adapted for a new catchment or study area.

While the most common input in an early warning system is the critical rainfall, the ground vibration produced by a moving debris flow can easily trigger an alarm system. In contrast to an alarm system, where only one threshold is selected, an early warning system can incorporate various warning levels. Such warning levels can be defined by probabilistic techniques like a Bayesian method, which considerably improve the EWS.

Another important advance in debris flow EWS, which are based on rainfall thresholds, would be the incorporation of rainfall forecasts. These would considerably extend the response time, but also increases the uncertainty.

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REFERENCES

Abancó, C., Hürlimann, M., Fritschi, B., Graf, C. and Moya, J. (2012): Transformation of ground vibration signal for debris-flow monitoring and detection in alarm systems, Sensors, Vol. 12, No. 4, pp. 4870-4891.
Abancó, C., Hürlimann, M. and Moya, J. (2014): Analysis of the ground vibration produced by debris flows and other torrential processes at the Rebaixader monitoring site (Catalan Pyrenees, Spain), NHESS, Vol. 14, pp. 929-943. 
Alcoverro, J., Corominas, J. and Gomez, M. (1999): The Barranco de Arás flood of 7 August 1996 (Biescas, Central Pyrenees, Spain), Eng. Geology, Vol. 51, pp. 237-255. 
Aleotti, P. (2004): A warning system for rainfall-induced shallow failures, Eng. Geology, Vol. 73, No. 3-4, pp. 247-265. 
Arattano, M. and Marchi, L. (2008): Systems and sensors for debris-flow monitoring and warning, Sensors, Vol. 8, pp. 2436-2452. 
Arattano, M., Abancó, C., Covelli, V. and Hürlimann, M. (2014): On the techniques for processing the ground velocity signal produced by debris flows: the methods of amplitude and impulses compared, Computers & Geosciences, Vol. 73, pp. 17-27. 
Badoux, A., Graf, C., Rhyner, J., Kuntracer, R. and McArvell, B. (2009): A debris-flow alarm system for the Alpine Illgraben catchment: design and performance, Nat. Hazards, pp. 517-539. 
Baum, R.L. and Godt, J.W. (2010): Early warning of rainfall-induced shallow landslides and debris flows in the USA, Landslides, Vol. 7, No. 3, pp. 259-272. 
Berenguer, M., Sempere, D. and Hürlimann, M. (2014): Combined susceptibility and radar rainfall analysis for debris -flow hazard assessment at regional scale, NHESSD, Vol. 2, pp. 6295-6338. 
Berti, M., Martina, M.L.V., Franceschini, S., Pignone, S., Simonini, A. and Pizziolo M. (2012): Probabilistic rainfall thresholds for landslide occurrence using a Bayesian approach, J. Geophys. Res., Vol. 117, F04006. 
Brunetti, M.T., Peruccacci, S., Rossi, M., Luciani, S., Valigi, D. and Guzzetti, F. (2010): Rainfall thresholds for the possible occurrence of landslides in Italy, NHESS, Vol. 10, pp. 447-458. 
Comiti, F., Marchi, L., Macconi, P., Arattano, M., Bertoldi, G., Borga, M., Brardinoni, F., Cavalli, M., Agostino, V.D., Penna, D. And Theule, J. (2014): A new monitoring station for debris flows in the European Alps: first observations in the Gadria basin, Nat. Hazards, Vol. 73, No. 3, pp. 1-24. 
Crosta, G.B. and Frattini, P. (2003): Distributed modelling of shallow landslides triggered by intense rainfall, NHESS, Vol. 3, pp. 81-93. 
Godt, J.W., Baum, R.L., Savage, W.Z., Salciarini, D., Schulz, W.H. and Harp, E.L. (2008): Transient deterministic shallow landslide modeling: Requirements for susceptibility and hazard assessments in a GIS framework, Eng. Geology, Vol. 102, pp. 214-226. 
Greco, R., Guida, A., Damiano, E. and Olivares, L. (2010): Soil water content and suction monitoring in model slopes for shallow flowslides early warning applications, Physics and Chemistry of the Earth, Vol. 35, No. 3-5, pp. 127-136. 
Hürlimann, M., Rickenmann, D. and Graf, C. (2003a): Field and monitoring data of debris-flow events in the Swiss Alps, Canadian Geotechnical Journal Vol. 40, No. 1, pp. 161-175. 
Hürlimann, M., Corominas, J., Moya, J. and Copons, R. (2003b): Debris-flow events in the Eastern Pyrenees. Preliminary study on initiation and propagation, 3rd Int. Conf. on Debris-Flow Hazards Mitigation, Davos, Vol. 1, pp. 115-126. 
Hürlimann, M., Abancó, C., Moya, J., Raimat, C. and Luis-Fonseca, R. (2011): Debris-flow monitoring stations in the Eastern Pyrenees. Description of instrumentation, first experiences and preliminary results, 5th Int. Conf. on Debris-Flow Hazards Mitigation, Padua, pp. 553-562. 
Hürlimann, M., Abancó, C., Moya, J. and Vilajosana, I. (2014): Results and experiences gathered at the Rebaixader debris-flow monitoring site, Central Pyrenees, Spain, Landslides, DOI: 10.1007/s10336-013-0452-y 
Jakob, M., Holm, K., Lange, O. and Schwab, J.W. (2006): Hydrometeorological thresholds for landslide initiation and forest operation shutdowns on the north coast of British Columbia, Landslides, Vol. 3, No. 3, pp. 228-238. 
Kung, H.Y., Ku, H.H., Wu, C.I. and Lin, C.Y. (2008): Intelligent and situation-aware pervasive system to support debris-flow disaster prediction and alerting in Taiwan, J. of Network and Computer Applications, Vol. 31, No. 1, pp. 1-18. 
LaHusen, R. (2005): Acoustic flow monitor system - user manual, USGS, Open-File Report 02-429, p. 16. 
McCoy, S., Kean, J., Coe, J., Tucker, G., Staley, D. and Wasklewicz, T. (2012): Sediment entrainment by debris flows: In situ measurements from the headwaters of a steep catchment, J. Geophys. Res., Vol. 117 (F3):F03016. 
Navratil, O., Liébault, F., Bellot, H., Travaglini, E., Theule, J., Chambon, G. and Laigle, D. (2013): High-frequency monitoring of debris-flow propagation along the Réal Torrent, Southern French Prealps, Geomorphology, Vol. 201, pp. 157-171. 
Papa, M.N., Medina, V., Ciervo, F. and Bateman, A. (2013): Derivation of critical rainfall thresholds for shallow landslides as a tool for debris flow early warning systems, Hydrology and Earth System Sciences, Vol. 17, No. 10, pp. 4095-4107. 
Portilla, M., Chevalier, G. and Hürlimann, M. (2010): Description and analysis of major mass movements occurred during 2008 in the Eastern Pyrenees, NHESS, Vol. 10, pp. 1635-1645. 
Scotton, P., Genevois, R., Moro, F., Zorzi, L., Girardi, G. and Praticelli, N. (2011): The debris-flows monitoring system of acquabona torrent (Cortina d’Ampezzo, Belluno, Italy), 5th Int. Conf. on Debris-Flow Hazards Mitigation, Padua, pp. 595-603. 
Suwa, H., Okano, K. and Kanno, T. (2009): Behavior of debris flows monitored on test slopes of Kamikamihoriza Creek, Mount Yakedake, Japan, International Journal of Erosion Control Engineering, Vol. 2, pp. 33-45. 
Tiranti, D. and Rabuffetti, D. (2010): Estimation of rainfall thresholds triggering shallow landslides for an operational warning system implementation, Landslides, Vol. 7, No. 4, pp. 471-481. 
United Nations Environment Programme (2012): Early warning systems: a state of the art analysis and future directions,
division of early warning and assessment, United Nations Environment Programme (UNEP), Nairobi, p. 63.
Yin, H.Y., Huang, C.J., Chen, C.Y., Fang, Y.M., Lee, B.J. and Chou, T.Y. (2011): The present development of debris flow monitoring technology in Taiwan - a case study presentation, 5th Int. Conf. on Debris-Flow Hazards Mitigation, Padua, pp. 623-631.

Zhang, S. (1993): A comprehensive approach to the observation and prevention of debris flows in China, Nat. Hazards, Vol. 7, pp. 1-23.

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