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Experiences of rapid landslides monitoring and warning at catchment scale in the Pyrenees. The example of the Rebaixader test site.

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ABSTRACT

Monitoring of rapid landslides, as rockfalls and debris flows, improves the understandings of these processes and also provides fundamental information for an efficient early warning and alarm system (EWAS). The Rebaixader site is a typical high mountain catchment, where sort of torrential phenomena occur with a sub-annual frequency. To investigate the triggering conditions and the post-failure behaviour of the rapid landslides, a monitoring system consisting of five stations was set up progressively since July 2009. Two stations monitor landslide propagation characteristics by using eigth geophones, an ultrasonic device and a video camera and infrared spot lights. Until March 2013, six debris flows, eleven debris floods and four rockfalls (two of them were large boulder falls, 55 and 18 m^3) were recorded at the site. The analysis of ground vibration signal allowed defining preliminary thresholds for distinguishing between debris flows, debris floods and rockfalls. The identification of processes was checked by the analysis of the video images and the post-event field evidences. Field surveys, ground vibration records and the movies recorded at the video camera provided unique information on the rapid landslides occurrence and dynamics, and gave an excellent opportunity to show the importance of monitored data for calibrating of simulation models. The monitoring results show that the data gathered by the geophones provides valuable information for the design of alarm systems for the event detection and distinction between processes.

Keywords: debris flows; rockfalls; monitoring; geophones; alarm system.

1 INTRODUCTION

Rapid mass movements and torrential processes like rockfalls, debris flows or debris floods are one of the most hazardous processes in mountainous areas and provoke road closures, building damage and fatalities.
Data measured at monitoring stations are of great importance to improve the understandings of triggering conditions, propagation behaviour, impact energy, and accumulation of these processes. Debris flows are being monitored of debris flows at several sites in around the world [1-5].

The installation of an early warning and alarm system (EWAS) is an important topic in risk assessment and mitigation of hydrological and geological processes. Generally, an early warning system (EWS) is able to advice the stakeholders and affected people hours or even days in advance of an approaching event. Most of the recent investigations on EWS for shallow landslides and debris flows include rainfall thresholds [6-10]. On the other side, an alarm system (AS) informs the stakeholders and affected persons immediately of the danger by optical or acoustic devices (e.g. light or siren). However, only very few alarm systems for rapid mass movements have been published in literature, and even fewer are operational [e.g. 11,12]. A total of three torrential-flows monitoring stations are actually running in the Pyrenees [13]: the Rebaixader and Erill sites and the Ensija site (Fig. 1a). At the first one, rockfalls are also detected to occur frequently. Currently, a station similar to that of the Rebaixader one is being installed for monitoring of rockfalls at the Solà d'Andorra (Andorra la Vella) by a IEA-CENMA / UPC consortium.

The purpose of this study is twofold. First, measurements recorded during the five years of monitoring in Rebaixader site are presented and the gathered experiences discussed. Second, implications for a warning and alarm system are examined. The monitoring system can be applied for warning of rapid landslides in roads.

2 SETTINGS

The Rebaixader site is located in the Central Pyrenees and drains an area of 0.53 km^2 (Fig. 1a). Bedrock consists of slates and the soil is a glacial (till) deposits. A large lateral moraine located between 1425 and 1710 m a.s.l. plays a major role on the debris-flow and rockfall activity. A steep accurate scarp in this lateral moraine forms the initiation zone for the debris flows with almost unlimited sediment availability (Fig. 1a). Slope angles in this initiation area are high and range from about 30 up to 70 degrees (Fig. 1c). A strongly incised channel zone with an average bed slope of about 21 degrees is located downstream the scarp between 1350 and 1425 m a.s.l. Finally, a debris fan with a mean slope angle of about 18 degrees drains the torrent into the Noguera Ribagorçana River.

The meteorological conditions of the site are affected by the vicinity of the Mediterranean Sea, the influence of the west winds from the North-Atlantic and the orographic effects of the Pyrenees. The annual precipitation in the area ranges from 800 to 1200 mm. The study of historic events showed that there are two typical rainfall conditions provoking debris flows in this area [14]: 1) short duration, high intensity rainfalls related to convective summer storms, and 2) moderate intensity and long-lasting rainfall during autumn/winter. Data from the five years of record show that the Rebaixader catchment is very active (the most active of the three sites monitored in the Pyrenees).

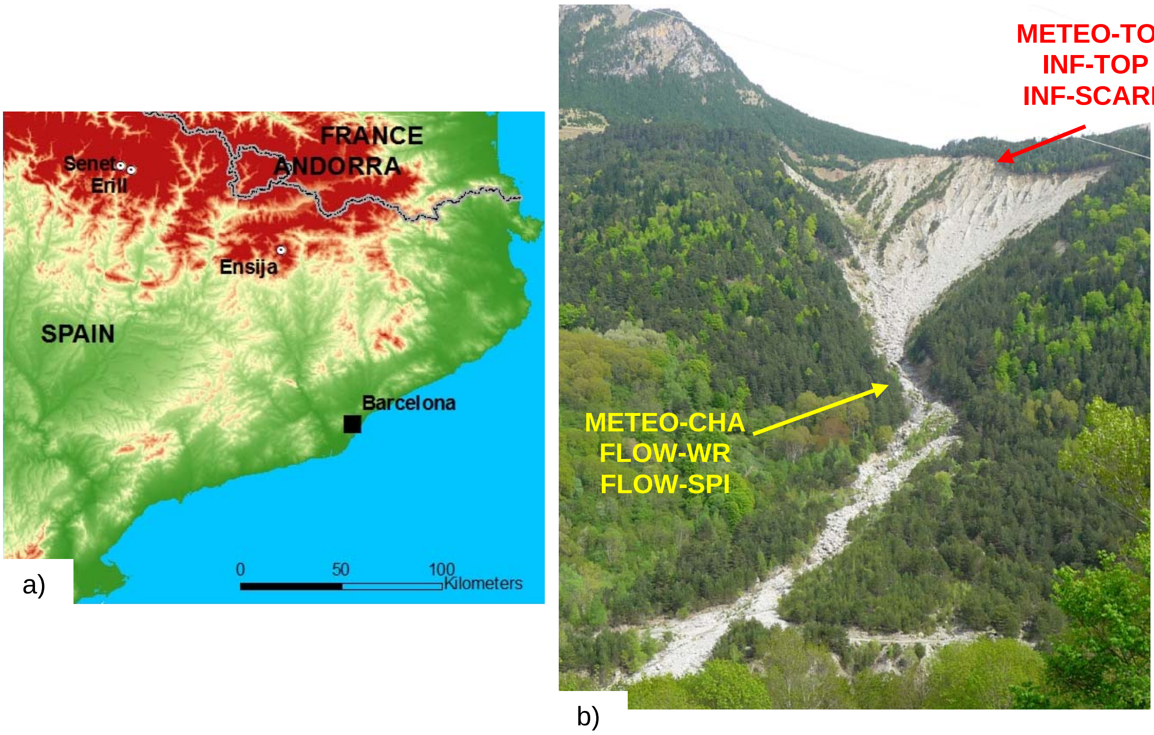

Figure 1. a) Location of the Rebaixader test site at Senet and the other two debris-flow monitoring stations in the Central Pyrenees. B) Overview of the Rebaixader site and location of the stations installed.

3 DESCRIPTION OF THE MONITORING SYSTEM

3.1 General aspects

The Rebaixader monitoring system incorporates a total of six stations (Fig. 1b): four stations recording information on the initiation mechanisms (two meteorological stations and two infiltration stations) and two stations focussing on the debris flow detection and the dynamic behaviour of the mass movements. A detailed description of the system can be found in [17].

Since summer 2009, when first sensors were installed, the monitoring system has continuously been improved. In a first phase, a wired sensors network included five geophones, an ultrasonic device and a meteorological station (FLOW-WR, Fig. 1b), which was complemented in 2011 by a video camera. The wired sensor network has standard characteristics, and incorporates a CR1000 and a CR216 Campbell data loggers and GSM modems for data transmission. This network is powered by 12 V batteries (7 and 24 Ah), which are recharged by solar panels.

During 2012, we developed a wireless monitoring system adapted to the specific needs of rapid landslides monitoring and a new seismic acquisition system and two wireless infiltration stations were installed (FLOW-SPI, INF-TOP and INF-SCARP, Fig. 1b). This new sensor network has been provided with wireless communication capabilities, showing ultra-low power consumption (up to 5 years battery life using AA standard cells) and long range communication (200-500 m). The wireless monitoring system is integrated by 7 nodes, which communicate in a multi-hop fashion to deliver the information into a gateway. Eventually, the data is transmitted periodically to a backend system in a database that provides metadata and has a safe backup strategy. A web-based user interface is also implemented to manage the network remotely.

3.2 Sensors related to the initiation

The meteorological stations are located in the middle part of the channel zone (METEO-CHA) and a few meters above the main scarp (METEO-TOP)(Fig. 1b). The rain gauges are standard tipping bucket devices with a resolution of 0.1 mm. They record each five minutes. Because the rain gauges are unheated, temperature sensors are used to distinguish if precipitation has been rain or snow. Nevertheless, the water equivalent of the snowfall can only be approximated. This is an important drawback, because it has been observed that the initiation of some landslides has been affected by snowmelt [16]. This is the reason why additional ultrasonic sensor measuring the snow height was installed in Meteo-Top station.

3.3 Sensors related to the mass movement progression

In the Rebaixader test site, three types of devices focus on the flow behaviour: 1) geophones (GEOSPACE 20 DX-8Hz) measuring ground vibration of the moving flows and rock falls, 2) an ultrasonic device recording the flow height; and, 3) a video camera for visual observations. All these devices are installed in the channel zone of the torrent along a reach of about 175 m (Fig. 1b). Two approaches are used to monitor ground motion. On one side, the ground vibration is transformed by a signal conditioner into impulses (IS) and recorded at 1Hz, this is the method used at the FLOW-WR station, which includes five geophones. The transformation technique and its advantages are extensively explained in [17]. On the other side, the ground velocity signal is directly recorded at the FLOW-SPI station, which consists of three geophones located on the left torrent bank close (3 to 5 m) to the active channel, and that are connected to a 24 bits broadband seismic recording unit (Spider produced by Worldsensing), which allows digitizes the three channels at 250 Hz. Both stations have a GPS for time synchronisation.

The geophone data are used to detect mass movements and also to estimate a mean front velocity between the sensors. In addition, the geophones trigger the flow network from the “no-event mode” into “event mode” and recording of the other flow measuring devices installed along the torrent. The condition for network switching was calibrated along the initial phase of the monitoring period, and changed from 20 IMP/sec during one second, at the initial stage, to 20 IMP/sec during three consecutive seconds, which is the used since August 2010.

The ultrasonic device measures the flow depth of a passing debris flow, but can also be used in combination with the geophone to estimate a mean flow velocity and finally a discharge. Due to technical problems and the destruction of the sensor by a rockfall, this device was correctly running only during a few events. A video camera (MOBOTIX M12D-Sec Dnight) provides visual information on the moving flows and rockfalls behaviour. This visual information is necessary, to calibrate the ground vibration response caused by the different processes occurring at the torrent.

4 MONITORING RESULTS

In the following, two types of monitoring data will be presented focussing on a future implementation into an early warning and alarm system. First, the ground vibrations recorded from the passing flows and rock falls are discussed. This information can be used for an alarm system. Second, the critical rainfall conditions for debris-flow initiation are analysed. This information, once coupled with rainfall forecasting, can be used for an early warning system.

4.1 Analysis of ground vibration

Between August 2009 and October 2012, the station FLOW-WR has triggered 363 times the "event" mode. The available records of all these monitoring events were analysed and classified. The analytical procedure included: 1) geophone and ultrasonic data were analysed, when evidences of an event were detected; 2) a field survey was carried out searching for morphologic changes along the whole catchment and photos were taken at eight control points, more than; 30 field visits were carried out; finally 3) the video images were checked to verify the process classification.

After the classification of the 363 triggers, a total of 21 torrential events (6 debris flows, 11 debris floods, 4 major rock falls) and 342 "undefined" events were identified (Figure 2). Rock falls were unexpected initially, they corresponded to big boulders falls fell from the glacial diposit located in the source area which reached the channel zone and activated the "event" mode of the monitoring system. Figures 3 and 4 shows the typical transformed IS ground vibrations curves for the three types of processes recorded at the site. Rockfalls show very high values of IS (> 100-150 imp/sec) with a duration of a few seconds, a clear signal that allows distinguishing easily them from torrential flows.

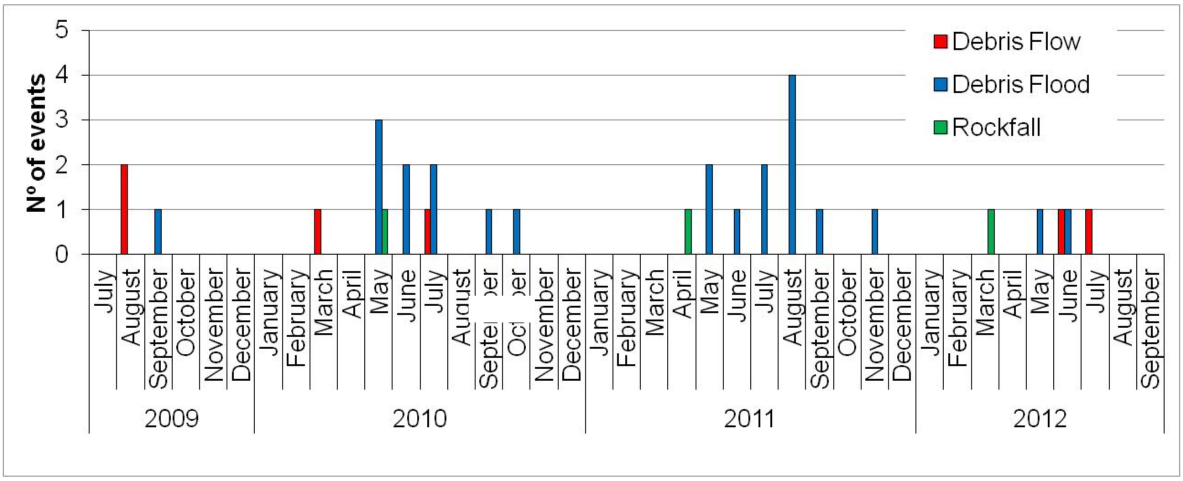

Figure 2. Temporal occurrence of monitoring events recorded at Rebaixader site.

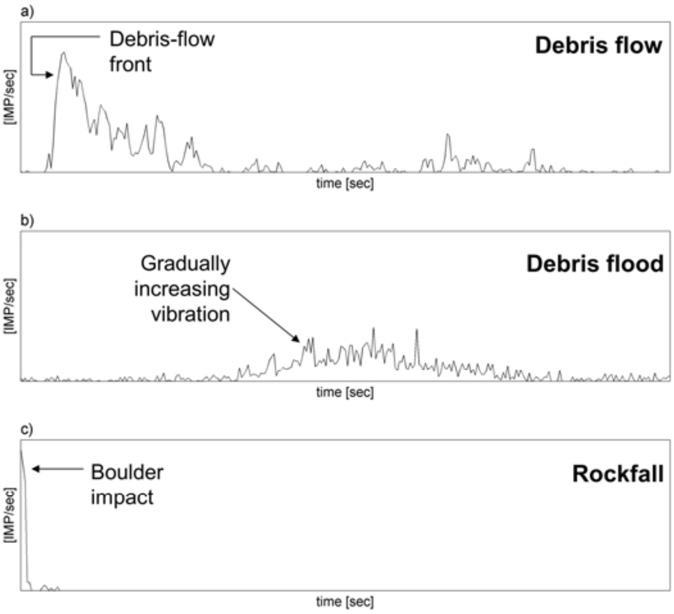

Figure 3. Typical shapes of the IS signal registered during a debris flow (a), a debris flood (b) and a rockfall (c). Horizontal and vertical scales are the same in the three cases.

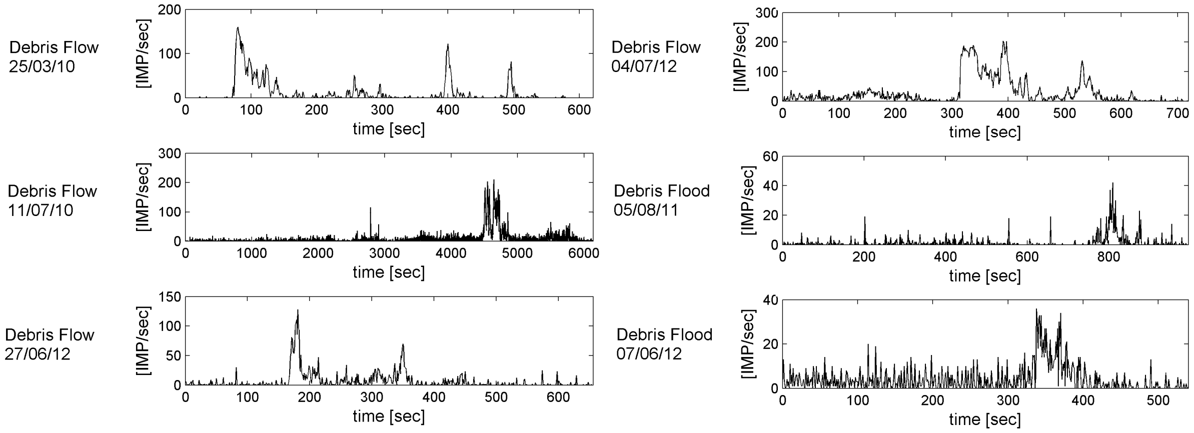

Figure 4. Time plots of the ground vibration (IMP/sec) during some debris flows and debris floods occurred in the Rebaixader monitoring site.

One of the major challenges in monitoring and alarm systems of debris flows is the differentiation between true events and false alarms. This task is of particular difficulty, if only ground vibration measurements by geophone are used. Most of the “undefined” events (216) were clearly false events provoked by short-circuits in the 2-wire cable connecting one of the geophones to the datalogger. The short-circuits were induced by a rockfall occurred in May 2010 cutting the cable and triggered the large amount of event modes between May and July (Fig 5a). In August 2010, an important improvement has been introduced in the system and the amount of false events has strongly been reduced. The threshold of ground vibration was enlarged from 1 second to 3 second, which means that during 3 seconds a minimum vibration of 20 IMP/sec must be recorded to switch the system to “event-mode”. The remaining 126 undefined events were related to small-scale mass movements in the scarp area that surpassed the ground vibration threshold at the uppermost geophones of FLOW-WR station [18].

The temporal evolution of the events shows that normally two debris flows were detected every year, except of 2011, when several debris floods occurred (Fig 2). The monthly distribution of the debris flows, debris floods and major rockfalls indicates that most of the events occurred during summer (57%) with a peak in July and August (Fig 5b). The other events took place in spring (24%) and in autumn (19%), while no event occurred during winter. The initiation of most of the spring events is related to snowmelt and freezing-thawing effects [16, 19]. The average monthly rainfall is added as general information.

The ground vibration time series of the 21 torrential events have been analysed in detail and some general conclusions could be obtained. Important differences of the ground response could be observed between events of a same type but also for each geophone even during the same event. These differences can be associated with different geomorphological situations as the location of geophone on bedrock or on a boulder and the distance between the geophones and the active channel. In spite of all these drawbacks, general preliminary correlations of ground vibration could be established. A comparison of the maximum IS values with the flow volume shows that, although the correlation is not good, a clear trend of IS increase with larger volumes is observed for the geophones located on bedrock and close to the active channel (Fig. 5).

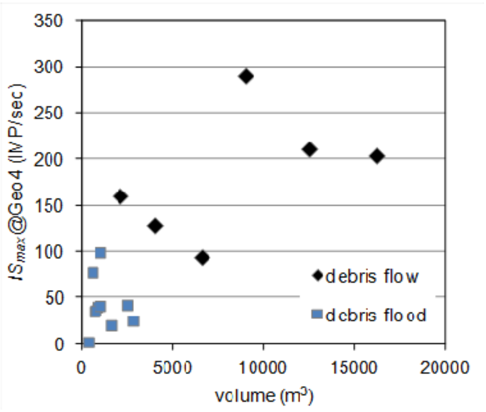

Figure 5 Duration of ground vibration versus maximum value of impulse per second measured at geophone 4, located on the bedrock and close to the active channel.

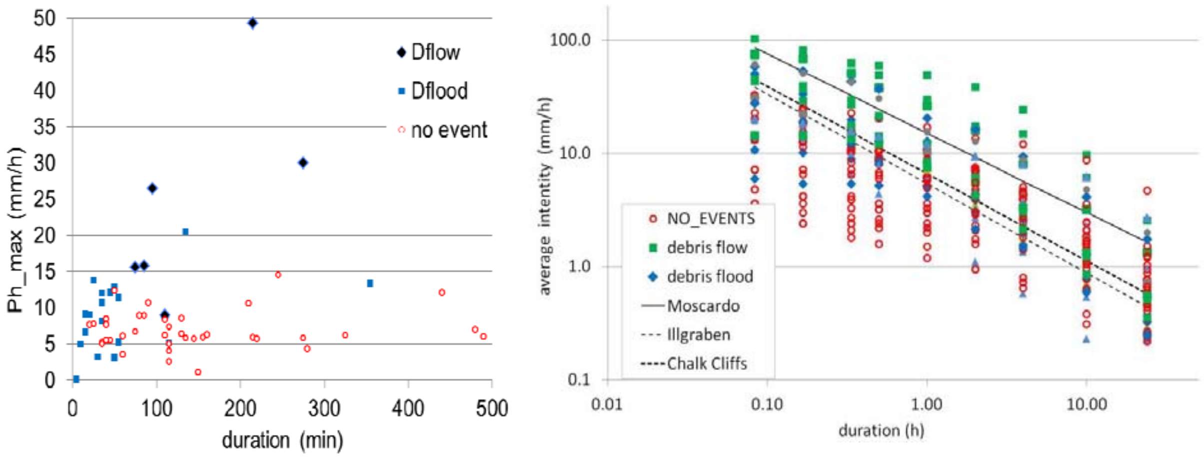

Figure 6. a) Rainfall duration versus maximum hourly rainfall . b) Rainfall intensity – duration relationship of the Rebaixader data compared with thresholds established at other debris-flow monitoring sites (see references in text).

4.2 Analysis of critical rainfall

The data recorded at station METEO-CHA show that the debris flows and debris floods in the catchment were triggered by short high-intensity rainstorms in summer (Fig. 6a). In contrast to torrential processes, that show a clear relationship with rainfall, no link was observed between rainfall and rockfall occurrence. The duration of rainfalls triggering flow processes was always smaller than 220 minutes for both and mostly around 2 hours for debris flows. The peak hourly rainfall, Ph_max, better allows defining preliminary thresholds for separating between rainfalls that caused debris flows, debris floods and no events. Critical hourly rainfall amounts, which cause debris flows in the Rebaixader torrent, might be around 15 mm/h for summer and even lower than 10 mm/h during spring. The flow triggering in spring seems to be affected by a combination snowmelt and soil thawing. The influence of antecedent rainfall was also analysed, but neither 3-days nor 10-days antecedent rainfall revealed that this effect has played an important role in the triggering of torrential flows.

The well-known relation between rainfall duration and average rainfall intensity was plotted for the events observed at Rebaixader (Fig. 6b). The graph shows that short time intervals up to one hour seem to be more useful for the distinction between debris-flow / debris-flood events and no events. Most of the events that not fit the distinction in this short duration can be explained, when detailed rainfall records are analysed. For example, the 5th July 2012 debris flood (Ph_max of 4.5 mm because of rainfall duration was only 45 min) can be related to a rather high rainfall episode the day before; or the 25th March 2010 debris flow that may have been affected by additional water in the initiation area from snowmelt. The data were compared with the thresholds established at three debris-flow monitoring sites: the Moscardo torrent in Italy [20], the Illgraben torrent in Switzerland [21] and the Chalk Cliffs basin in United States [22]. This comparison shows that the Rebaixader data fits rather well with the one established at Illgraben. Anyhow, we consider that additional events are necessary in order to define a specific rainfall threshold for Rebaixader site.

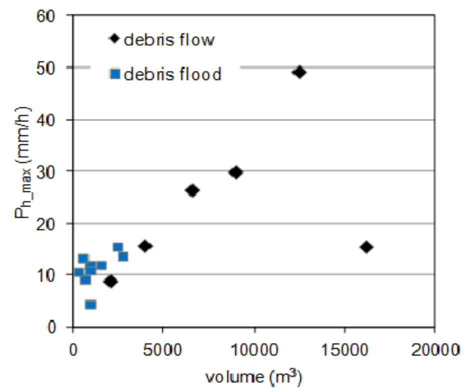

Figure 7. Relationship between the maximum hourly intensity of triggering rainfalls and flow volumes, distinguishing between debris flows and debris floods triggering rainfalls.

In addition, the volume of debris flows and debris floods were compared with the total triggering rainfall, Ptot, and maximum hourly rainfall, Ph_max (Fig. 7). Both graphs show a general trend indicating that the event volume increases with both larger rainfall amounts and larger rainfall intensities. Only the largest debris flow, which occurred on 4th July 2012 and mobilized a total volume of about 16200 m^3, does not match this trend and rainfall values are smaller. This may be related with the fact that no debris flow occurred along 2011 and a large amount of material remained accumulated in the torrent head at the beginning of summer 2012. A similar connection between sediment availability and debris flow occurrence has also been proposed for the Moscardo torrent [20].

5 IMPLICATIONS FOR A WARNING AND ALARM SYSTEM

As previously mentioned, two types of data must be analysed previously to the design of the early warning and alarm system. On one side the critical rainfall conditions must be defined for the EWS, which could advise the stakeholder person hours before a possible event. On the other side, critical ground vibration and/or flow depth have to be delimited for the alarm system (AS), which should emit an alarm by optical or acoustic devices (e.g. lights or siren). These two issues are discussed in the following.

Two types of rainfall information should be distinguished for an early warning system [e.g. 6]: 1) the antecedent rainfall; and 2) the triggering or event rainfall. The effect of antecedent rainfall, however, is very site specific and strongly depends on the lithological, morphological and hydrological characteristics of a catchment. Alternatively, there are studies that indicate the irrelevance of antecedent rainfall on debris-flow triggering. In the case of Rebaixader, only a small influence of antecedent rainfall could be observed but it may be included into a warning system.

In contrast, the triggering rainfall related to short-duration and high intensity rainstorms are easier to incorporate into an EWS. The most common implementation is the use of an empirical rainfall threshold combining duration and mean intensity. The data gathered in Rebaixader provide first important information on the rainfall conditions, which can trigger debris flows. The Rebaixader data suggests that a mean intensity about 15 mm/h during 80-90 minutes is necessary for causing debris flows in the Rebaixader torrent in summer (Fig. 6b) and even lower than 10 mm/h during spring, but do not yet allow the determination of a reliable threshold.

The Rebaixader data indicate that the definition of a threshold for critical ground vibration is a very complex task. In particular, the short time available between the initiation of ground vibration and the decision between “true event” or “false event” complicates the correct functioning of an alarm system. The experiences gathered in Rebaixader indicate that a ground vibration of duration of at least 3 second may be adequate in order to avoid false alarms. A similar condition is actually applied in the Illgraben alarm system, where a predefined number of impulses per second during 5 seconds must be exceeded to trigger the alarm [12]. Rockfalls could be clearly distinguished from torrential processes in real time analysing the ground vibration as IS, whereas real time differentiation of debris flows from debris flood is much more difficult to be implemented because it requires analysing the time evolution of the signal for detecting morphology of flow fronts and of secondary surges. In that sense, sensors measuring the flow depth may complete and improve the alarm system, but it previously necessary to solve effects due to the super-elevation of surges and increase installation efforts and costs.

6. CONCLUSIONS

The installation of early warning and alarm systems is an important topic in risk assessment and the mitigation of geological processes. The data and experiences collected at the Rebaixader monitoring site show that a sophisticated EWAS should consist of two parts: 1) an early warning module focussing on the critical rainfall, and 2) an alarm module focussing on ground vibration. There are several regions where empirical rainfall thresholds have been incorporated into a debris-flow or landslide warning system, but all of these systems include important uncertainties. New technologies and sensors may improve these systems crosschecking rainfall measurements at a rain gauge with the data from weather radars or sensors related to soil moisture [e.g. 8].

The geophone measurements seems to be very site specific, but the preliminary results show that most of the false alarms can be avoided by an selection of an adequate vibration intensity and duration. However, more investigation is necessary in order to establish clear thresholds (not only for the duration, but also for the vibration intensity) in order to achieve a reliable alarm system.

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REFERENCES

[1] Marchi L, Arattano M, Deganutti AM. 2002. Ten years of debris-flow monitoring in the Moscardo Torrent (Italian Alps). *Geomorphology* 46:1-17.

[2] Hürlimann M, Rickenmann D, Graf C. 2003. Field and monitoring data of debris-flow events in the Swiss Alps. *Canadian Geotechnical Journal* 40:161-175.

[3] La Husen R. 2005. Debris-flow instrumentation. In: Jakob M, Hungr O (Eds.), *Debris-flow Hazards and Related Phenomena*. Springer, Berlin, pp. 291-304.

[4] Suwa H, Okano K, Kanno T. 2009. Behavior of debris flows monitored on test slopes of Kamikamihorizawa Creek, Mount Yakedake, Japan. *Int. J. of Erosion Control Engineering* 2:33-45.

[5] Huebl J, Kaitna R. 2010. Sediment delivery from the Lattenbach catchment by debris floods and debris flows, *EGU General Assembly 2010*, pp. 10585.

[6] Aleotti P. 2004. A warning system for rainfall-induced shallow failures. *Engineering Geology* 73: 247-265.

[7] Salameh T, Zêzere J, Trigo R. 2009. Development of an early warning system for precipitation triggered landslides in Portugal, *EGU General Assembly 2009*. *Geophysical Research Abstracts*, Vienna, pp. 2458.

[8] Baum RL, Godt JW. 2010. Early warning of rainfall-induced shallow landslides and debris flows in the USA. *Landslides* 7:259-272.

[9] Brunetti MT, Peruccacci S, Rossi M, Luciani S, Valigi D, Guzzetti F. 2010. Rainfall thresholds for the possible occurrence of landslides in Italy. *Nat. Hazards Earth Syst. Sci.* 10:447-458.

[10] Tiranti D, Rabuffetti D. 2010. Estimation of rainfall thresholds triggering shallow landslides for an operational warning system implementation. *Landslides* 7 (4):471-481.

[11] Arattano M, Marchi L. 2008. Systems and Sensors for Debris-flow Monitoring and Warning. *Sensors* 8 :2436-2452.

[12] Badoux A, Graf C, Rhyner J, Kuntner R, McArdell B. 2009. A debris-flow alarm system for the Alpine Illgraben catchment: design and performance. *Natural Hazards*:517-539.

[13] Hürlimann M, Abancó C, Moya J, Raïmat C, Luis-Fonseca R (2011) Debris-flow monitoring stations in the Eastern Pyrenees. Description of instrumentation, first experiences and preliminary results. *4th Int. Conf. on Debris-Flow Hazards Mitigation*, Padua, pp. 553-562.

[14] Hürlimann M, Corominas J, Moya J, Copons R. 2003. Debris-flow events in the Eastern Pyrenees. Preliminary study on initiation and propagation. In: Rickenmann D, Chen C (Eds.), 3rd Int. Conf. on Debris-Flow Hazards Mitigation. Davos, pp. 115-126

[15] Hürlimann M, Abancó C, Moya J, Vilajosana I. 2014. Results and experiences gathered at the Rebaixader debris-flow monitoring site, Central Pyrenees, Spain. Landslides: in press, DOI 10.1007/s10346-013-0452.

[16] Hürlimann M, Abancó C, Moya J. 2010. Debris-flow initiation affected by snowmelt. Case study of the Senet monitoring site, Eastern Pyrenees. *Mountain Risks: Bringing Science to Society*, Florence, Italy, pp. 81-86.

[17] Abancó C, Hürlimann M, Fritschi B, Graf C, Moya J. 2012. Transformation of Ground Vibration Signal for Debris-Flow Monitoring and Detection in Alarm Systems. *Sensors* 12:4870-4891.

[18] Abancó C, Hürlimann M, Moya J. 2013. Analysis of the ground vibration produced by debris flows and other torrential processes at the Rebaixader monitoring site (Catalan Pyrenees, Spain). *Natural Hazards and Earth System Science*: in press.

[19] Hürlimann M, Abancó C, Moya J. 2012. Rockfalls detached from a lateral moraine during spring season. 2010 and 2011 events observed at the Rebaixader debris-flow monitoring site (Central Pyrenees, Spain). *Landslides* 3:385–393.

[20] Deganutti AM, Marchi L, Arattano M. 2000. Rainfall and debris-flow occurrence in the Moscardo basin (Italian Alps). In: Wieczorek GF, Naeser ND (Eds.), *Debris-Flow Hazards Mitigation*. Balkema, pp. 67-72

[21] McArdell B, Badoux A. 2007. Influence of rainfall on the initiation of debris flows at the Illgraben catchment, canton of Valais, Switzerland. *Geophysical Research Abstracts* 9:08804.

[22] Coe JA, Kinner DA, Godt JW. 2008. Initiation conditions for debris flows generated by runoff at Chalk Cliffs, central Colorado. *Geomorphology* 96:270-297.