Analysis of the rainfall thresholds that induced debris flows in the area of Apuan Alps -Tuscany, Italy (19 June 1996 storm)

A. ANNUNZIATI [a], A. FOCARDI [b], P. FOCARDI [c], S. MARTELLO [c], P. VANNOCCI [c].

[a] *Regione Toscana Dipartimento delle politiche territoriali e ambintali, Firenze - e-mail:* a.annunziati@mail.regione.toscana.it

[b] *Servizio Nazionale Dighe-Ufficio di Firenze - e-mail:* sndfirenze@tin.it

[c] *Università di Firenze - Dipartimento di Scienze della Terra - e-mail:* focardi@geo.unifi.it

ABSTRACT

Heavy rainfall during the June 9, 1996 storm triggered numerous debris flows in the Vezza and Turrite di Gallicano creek basins, in Apuan Alps, (western Tuscany, Italy). The rainfall data recorded during the event are elaborated using a spatial analysis method. Distribution patterns are highlighted by computing rain intensities in different duration of rainfall that show how maximum peak intensity varied locally.
The rainfall patterns are related to the frequency and distribution of debris flows in order to investigate the rainfall thresholds that triggered instability phenomena during this event. Intensity-duration curves are produced at the boundary of the debris-flow affected area to define significant intensity thresholds for the triggering of this kind of landslides.
The analysis shows that the frequency of instability phenomena increases abruptly above an upper threshold of rainfall intensity. This allows us to define, for the area in examination, different conditions of hazard with regard to these hydrological phenomena, therefore providing a useful tool for the activation of emergency plans.

1 INTRODUCTION

The high destructive effects of debris flows led to study the triggering thresholds as the limit of precipitation intensities that may initiate debris flows during heavy rainfall events.

Slope instability phenomena are often triggered by rainfall. The correlation between rainfall and landslides is a complex one, being dependent on a number of factors; among the others lithology, vegetation, slope. In fact, distribution of rainfall affects slope stability in a given area depending on many parameters such as hydraulic conductivity, cohesion, field capacity and the depth of the potentially unstable layer.

There is a long record of researches dedicated to the analysis of rainfall triggered landslides. De Vita and Reichenbach (1998) in a bibliography research mention more than 300 papers in which the triggering of both single and regional instability events have been analysed.

Due to the fact that only daily rainfall data are often available and that the moment at which landslides have been triggered is seldom known, most of these contributions delineate relationships between rainfall and landslides that are based on rainfall records extending over a period of 24 hrs, or on the amount of rain that has fallen during the period preceding the triggering of landslides or, finally, on statistical analysis that asses the frequency of recurrence time of the specific rainfall event. Thanks to the increase in the number of gauge stations that can record rainfall data and send it in real time, it is becoming increasingly possible to record rainfall events with a higher temporal detail, although the assessment of the exact time in which landslides have been triggered remains difficult. Consequently, the definition of rainfall thresholds for debris-flow initiation can contribute to the assessment of hazard and real time warning systems.

Our case study analyses the high number of landslides that occurred in the Apuane Alps on 19 June 1996 during an extremely intense storm and is aimed at providing an additional contribution on the definition of rainfall thresholds that induce debris flows and consequently lead to the mobilisation of materials with medium to coarse grain size distribution and limited soil depth. This event is of particular interest if one takes into account that these landslides had similar characteristics and the period was not preceded by significant rainfall events.

2 THE EVENT

On 19 June 1996 an intense storm hit the Apuane Alps with heavy rainfall in an area of approximately 170 sqKm (where the total amount of rainfall at the end of the day was higher than 200 mm). Extreme values of rainfall intensities were recorded in a smaller area around the ridge of the Apuan chain and the upper areas of the Turrite di Gallicano and Vezza valleys (Fig. 1).

The Apuan Massif, which forms the northern limit of the Apennines, is characterised, from a climatic point of view, by a very high yearly rainfall rate. This is due to its particular geographic and morphological settings. The rain gauges placed at higher altitude, record values above the mean 3000 mm per year. The meteoric event of 19th June 1996 was however of an exceptional magnitude, much stronger than any event previously recorded in the area. The precipitation caused immense damage, destroying houses and other infrastructures situated at the valley bottoms.

Figure 1: Area of study , landslides and slide density model.

The storm was characterised by two different phases of heavy rainfall: the first began at 4:00 a.m. and lasted around 6 hours affecting the western side of the chain; the second one, started at 11:00 a.m., and lasted around 3-4 hrs spreading over on the crests and on the eastern basins. Exceptional rainfall intensities were recorded especially for intermediate time windows (3-9 hours).

Even if the area is very rainy, the maximum rainfall intensities recorded during the 19 June 1996 event have been higher than all the historical maximum values. For most gauges, the rainfall data exceeded the values statistically expectable assuming a recurrence time of 500 years (Burlando P. and Rosso R. , 1998; Castelli *et al.* 1996).

A complex geological series outcrops in the basin and is mainly characterised by a Palaeozoic basement of marble rocks (*Grezzoni*) and metamorphic sandstones and schists (*Verrucano*) overlain by a sequence of Oligocene metamorphic rocks constituted mainly by the *Pseudomacigno,* meta-arenaceuos formation. This forms the ridge bases up to 900-1000 meters above the sea level. A widespread colluvial cover of around 0.5-2 m is present and most rock outcrops are confined to channel sides, morphological slope breaks and quarries. A dense forest cover of high chestnut trees is present. Conversely, marble rocks are to be found at the top of the mountain ridges at higher altitude where the landscape is characterised by sheer rock cliffs and steep slopes with a shallow discontinuous soil cover and scrub forests.

Slope failures occurred mainly as debris flows that were triggered by the sudden access of water from the heavy rain and affected vast areas of the colluvial deposits mantling the slopes. They involved relatively small quantities of materials that transformed into flowing masses, which in turn increased the sediment transport during their path, due to the mobilisation of additional material deposited on their track or on channel banks. In some cases bedrock has been exposed, whilst in others failures extended within the overlying soils. The vast majority of debris flows originated on hollows, high up on open slopes containing no significant drainage channels. Failures typically occurred on slopes ranging from 25 to 45 degrees. The mobilised material flowed towards the catchment outlet and stopped forming deposits as thick as 12 m.

3 DATA COLLECTION

3.1 Debris flows

Several surveys have been carried out after the event to map the extent of the landslides. The number of landslides mapped in the study area is 340. Unfortunately, these investigations don’t provide useful information to establish the exact time the instability phenomena occurred during the event.

Detailed descriptions of the phenomena are reported in the work from of Caredio F. *et al.* (1996) and Brugioni M. and Marzocchi A. (1998). Data about the properties of the materials involved and the cinematic of the phenomena are reported by Focardi A. *et al.* (1997), while the main geometric characteristics of the landslides were classified synthetically by Gambetta- Vianna G., (1997) and Leonasi G. (1997).

This paper considers only the geographic distribution of the landslides as mapped by several investigators, mainly Caredio *et al.*, (1996), Gambetta Vianna G., (1997), Leonasi G. (1997), Brugioni M. and Marzocchi A. (1998).

3.2 Rain data

During the event the real time rain gauge system of local "Ufficio Idrografico" office was operating. The system recorded rain and hydrometric data with a time step of 5'.

For this study data from 27 different rain gauges were collected, covering an area of around 700 Km^2 . The location of the gauges nearest to the area of study is reported in Fig. 1 where the main hydrographical network is also shown.

4 DATA ELABORATION

A spatial model based on a grid structure with a 100 m cell size was designed to elaborate the collected data. Computation was performed using the GIS software ArcView and several utilities specifically developed.

4.1 The landslide density grid

For each grid cell landslide density was defined as the number of instability phenomena within a circle centred on the cell and with an area of 1 Km^2. The grid depicting the landslide density is shown in Fig. 1.

4.2 The rain distribution grid

The record of the event for each rain gauge was elaborated in order to compute the maximum rainfall height within time windows of different lengths, namely - 1h - 3h - 6h - 12h and 24h.

Elaborating local data with the traditional method of TIN (triangulated irregular network), the different patterns of iso-rain intensity were build.

The different spatial rain models are shown in Fig. 2 overlying the slide density model.

Fig. 2: Slide density and rainfall models (rain max in 1,3,6,12 and 24 hours).

5 DEFINITION OF THRESHOLDS

The analysis was performed through the comparison of the two different grids, i.e. landslide density and distribution of rain intensity. The overlay of the two models was carried out for the rainfall time windows shown in Fig. 2, where we evidence how the distribution of slide phenomena is mainly depending on the total amount of rainfall in time windows of 12 hrs or more.

The fact that maximum of rainfall doesn't coincide perfectly with maximum of slide density can be explained if one consider that the model doesn't evaluate the local geomorphological conditions: in fact the debris-flows phenomena occurred only in the areas were a layer of soil or debris was in place. That's the reason why some high elevations areas, where this colluvial cover was missing, were not involved.

In order to delineate the minimum rainfall below which debris flows did not occur, the landslide density of each grid cell has been compared to its rainfall distribution. Through a scatter diagram, in which the landslide density is plotted versus the rainfall distribution for each grid cell, it has been possible to define this relationship.

In figure 3 the results of such representation are shown for the different time windows that have been taken into account (1h - 3h - 6h - 12h and 24h). The graph shows that there is a rainfall height for each time window below which slide phenomena did not occurred. It can also be noticed that there is a rainfall height above which a severe increase in the values of landslides can be observed.

These values define two significant thresholds that can be drawn on a graph of rainfall duration and depict two thresholds which correspond to:

- the limit below which debris-flows are not to be expected (threshold A);
- the limit above which high concentrations of instability phenomena are to be expected (threshold B).

6 CONCLUSIONS

The analysis of the 19 July 1996 storm, during which extreme rainfall amounts were recorded following a dry period, led to the following conclusions about the possible relationships between debris flow and rainfall intensity.

By comparing the debris-flows distribution and the maximum amount of rainfall in different time windows, we evidence as more significant, for the instability, the effects of rainfall on time window of 12 h.

By examining the maximum height of rain for the time windows of 1, 3, 6, 12 e 24 h it is possible to define two important thresholds: the limit A shows

Fig. 3: Slide density vs. amount of rainfall (max values for the time windows of 1, 3, 6, 12 and 24 hours).

Fig. 4: Rainfall thresholds that induced debris- flows.

the amounts of rain below which debris-flows did not occur, whilst rainfall events exceeding limit B caused catastrophic landslides.

In figure 4 the threshold A and B are compared with iso-frequency storm curves, computed with traditional statistical method for different recurrence time (20-200 and 500 years): this comparison shows that such triggering phenomena can be expected in this area with a recurrence time of about 20 years. The recurrence time for the upper thresholds is 500 years.

However these thresholds have been defined for our specific case study which occurred after a dry period: we wont to emphasize that, after a period of extended rainfall or in snowmelt conditions, the threshold values can be lower because of the increase of the soil or debris water content (degree of saturation).

A real time rainfall data system can provide useful support for the setting up of warning systems that are related on rainfall thresholds. This can allow for the development of real-time techniques for monitoring hazardous areas so that traffic diversions, evacuations, or other emergency actions can be taken.

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