Giuseppe Basile(1), **Marinella Panebianco**(2)

Experimental alert model for hydrogeological risk: a case study in Sicily

(1) **Geologist, Sicilian Department of Civil Protection, via Abela, 5 – 90141 Palermo, +390917071972**

(2) **Architect, Sicilian Department of Civil Protection, via Abela, 5 – 90141 Palermo, +390917071854**

Abstract The north-eastern part of Sicily (Messina district) is often hit by violent storms that cause great damage resulting from flash floods and debris flows. On 1st October 2009 there were 37 victims and on other occasions events have led to serious risks to both public and private safety.

The environment is characterized by the presence of high slopes, clay terrains deriving from mainly metamorphic rocks, and intensely inhabited territories: conditions that make risk mitigation measures particularly difficult.

Since there is very little time between the event of rainfall and the subsequent need for preventive intervention, the preparation of a civil protection system is a fundamental requirement.

For these reasons the Sicilian Department of Civil Protection has an ongoing series of initiatives that seek to reduce response times: instrument installation (rain and temperature sensors, X-band meteorological radar), development of an alert model based on critical rainfall thresholds, and the development of a plan for activating civil protection procedures.

Keywords Hydrogeological Risk, Soil Slip, Debris Flow, Rain Thresholds, Civil Protection Plan

The geographical and meteorological context

On 1st October 2009 a violent storm hit the northeast coast of Sicily in a restricted area from Pezzolo Village to Giampilieri Village, and from Scaletta Zanclea to Itala (about 25 square kilometres). The event was recorded by a single rain-gauge in Santo Stefano di Briga, a few kilometres north of the affected area (Figure 1).

In 7 hours about 225 mm of rain fell with a peak intensity of about 53 mm/h and an average intensity of about 32 mm/h (Figure 2). The ground-effects in the affected areas were widespread and very severe: 37 victims due to mudflows and floods and more than 600 shallow landslides (Ardizzone et al., 2009; Basile, 2009).

Since in the rain gauge area there was no corresponding damage of any significance, it is possible to estimate that the amount of precipitation in the affected area at considerably more than 225 mm.

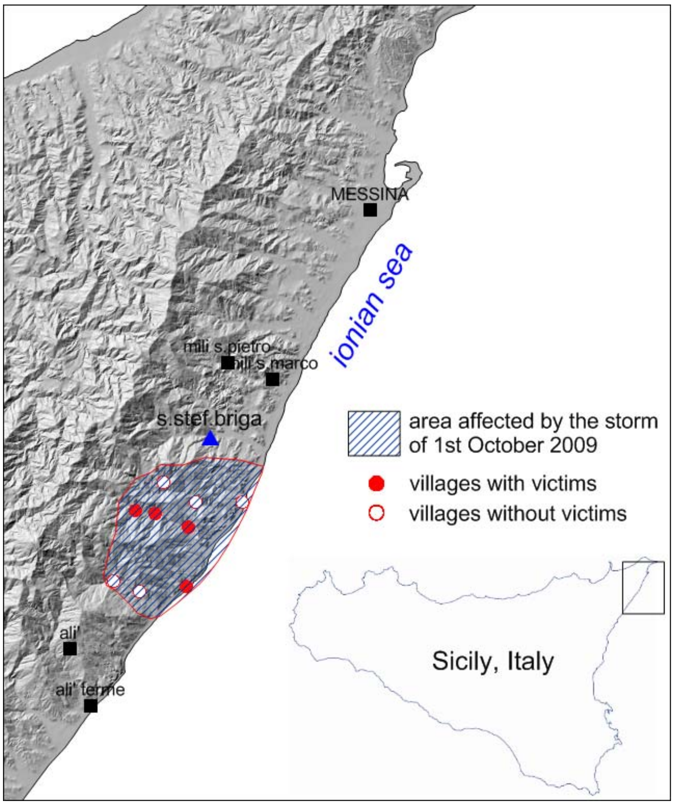


Figure 1 - The area affected by the storm of 1st October 2009

After the event the Sicilian Department of Civil Protection set up six real-time weather stations (data transmitted by radio signals) to measure the amount and the intensity of precipitation, the air temperature and the humidity in the affected area. Even more recently an X-band micro radar was installed.

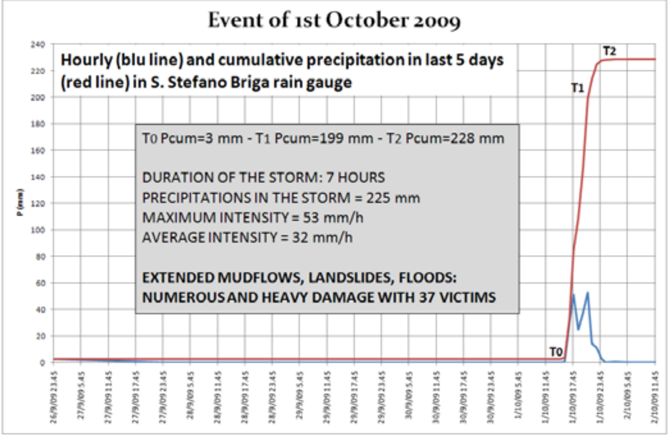


Figure 2 – Diagram of event of 1st October 2009

The determination of rainfall thresholds

Historical and statistical analysis

The question under consideration is how to assign rainfall thresholds and associated alert levels and how to decide what the civil protection system must do in order to mitigate hydraulic and geomorphic risks.

Several authors have examined the issue using approaches based on physical or empirical models. Most common empirical models study historic rainfall and their ground effects (Aleotti, 2004; Brunetti et al., 2010; Caine, 1980; Cannon et al., 2008; Cevasco et al., 2010; Chleborad et al., 2006; Corominas et al., 2002; Guzzetti at al., 2005; Iverson, 2000; Luino, 2008; Zêzere et al. 2008).

From these studies it is evident that the meteorological, morphological and geological characteristics of each geographic area induce different results with regard to the determination of rainfall thresholds for mudslides. For this reason threshold values may have only a local validity.

In the case in question we have only one rain gauge (the one at S. Stefano Briga) to study previous events, but its historical data does not include hourly rainfall intensity values.

The analysis of cumulative rainfall from 1 to 15 rainy days shows some relevant events with total amounts greater than in October 2009 (Figure 3).

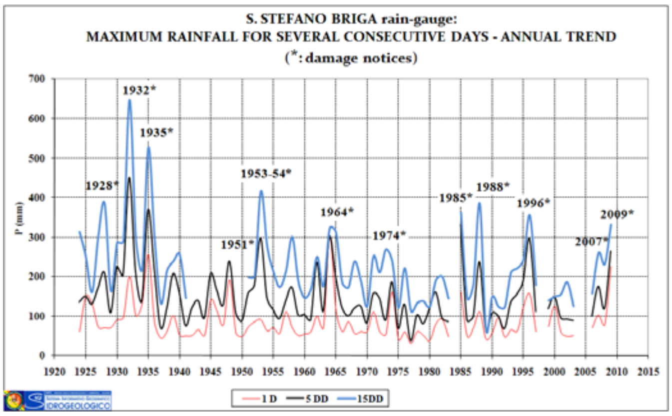


Figure 3 – Annual trend of S. Stefano Briga rain-gauge

From data examination it is possible to conclude that:

- very critical situations occurred often with P(1d)>100 mm, P(5dd)>150 mm, P(15dd)>200 mm;
- critical situations occurred occasionally with P(1d)>70 mm, P(5dd)>100 mm, P(15dd)>150 mm;
- sometimes critical situations occurred with sudden intense rainfall events >= 100 mm in a day without significant previous rainfall.

Filtering the entire data-set (from 1924 to 2009) we obtain 196 events with P(1d)>50 mm and we consider the average of these values to represent the most critical situation for the pre-conditional factors leading to hydrogeological risk.

The exponential fitting of these values is shown in Table 1:

Table 1. Average values for cumulative rainfall from 1 to 20 consecutive days (1924-2009 years) and best fit equation

P1d	P2d	P3d	P4d	P5d	P10d	P15d	P20d
72	87	97	105	110	139	164	181
[1] $K3 = 69.91*d^{0.307}$				**linear form**			
[1’] $K3 = 8.89*d^{-3.12}$				**logarithmic form**			

Criteria for threshold evaluation

The value of the ‘d’ parameter (rainy days before the generic event) in the previous equation is not of secondary importance because the alert levels depend on this value.

We may only assume that physical phenomenon induce soil slips and debris flows, but we do not know with precision the total amount of water required. Other unknown factors are the physical and mechanical constitution of the soil (mineralogy, density, porosity, permeability, cohesion, friction angle), the contribution of air temperature to evaporation, and the quantitative role of vegetation and burrowing animals.

Thus, although the system is influenced by many unknown variables, the only data of which we are sure is the amount of rainfall.

However, even if we know with certainty the exact physical process that causes the debris flows, in order to establish the threshold level we must also take into account human inertia factors.

The population’s “practice” to alerts is another unknown element that we must consider: while avoiding too many false alarms, we must not overlook the possibility of unexpected phenomena.

In addition, the software used by the weather stations has two kinds of alarms: for cumulative and for intense rainfall.

For these reasons, the thresholds are based on two indicators: the pre-conditional factors with cumulative rainfall and the triggering factors with rainfall intensity.

The above formula [1] shows the maximum level for pre-conditional factors while the lower levels are a fraction of the 'd' coefficient. Thus we have the following expressions (as shown in Figure 4):

$$K3 = 69.91 * d^{0.307} \quad [1]$$
$$K2 = 46.61 * d^{0.307} \quad [2]$$
$$K1 = 23.30 * d^{0.307} \quad [3]$$

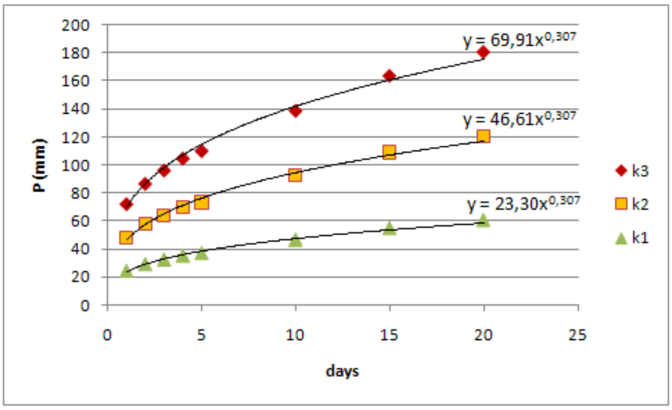


Figure 4 – Threshold equations related to cumulative rainfall

Triggering factors caused by rainfall intensity (mm/h) are unknown because of inexistent historical data. However, based on only a few events (October 25, 2007; November 15, 2008; October 1, 2009; March 1, 2011) we can assign the following levels (Figure 5):

I1 = 10 mm/h
I2 = 25 mm/h
I3 = 40 mm/h

To avoid alarm activation caused by a series of abrupt changes in rainfall intensity, the minimum duration of the intense event must be half an hour.

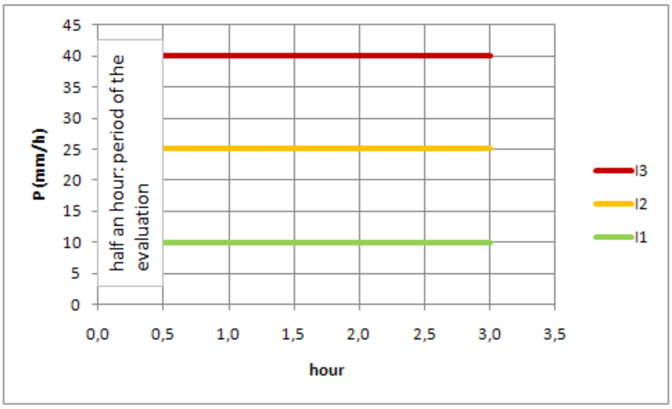


Figure 5 – Thresholds related to rain intensity

Respectively, the three thresholds identified four alert levels (LEV0, LEV1, LEV2, LEV3), as shown in Table 2:

cumulative rainfall

C_LEV0 < K1
K1 ≤ C_LEV1 < K2
K2 ≤ C_LEV2 < K3
C_LEV3 ≥ K3

rainfall intensity

I_LEV0 < I1
I1 ≤ I_LEV1 < I2
I2 ≤ I_LEV2 < I3
I_LEV3 ≥ I3

Table 2. Relations among thresholds and alert levels

Alert levels for cumulative rainfall

Thresholds	🟩	**K1**	**K2**	**K3**
Levels	C_LEV0	C_LEV1	C_LEV2	C_LEV3

Alert levels for rainfall intensity

Thresholds	🟩	**I1**	**I2**	**I3**
Levels	I_LEV0	I_LEV1	I_LEV2	I_LEV3

Criteria for alert level evaluation

Thresholds for both cumulative rainfall and rain intensity have to combine to assign alert levels and relative preventive actions (Figure 6). The alert levels (Quiet, Early Warning, Attention, Warning and Alarm) are related to those of the national and regional systems.

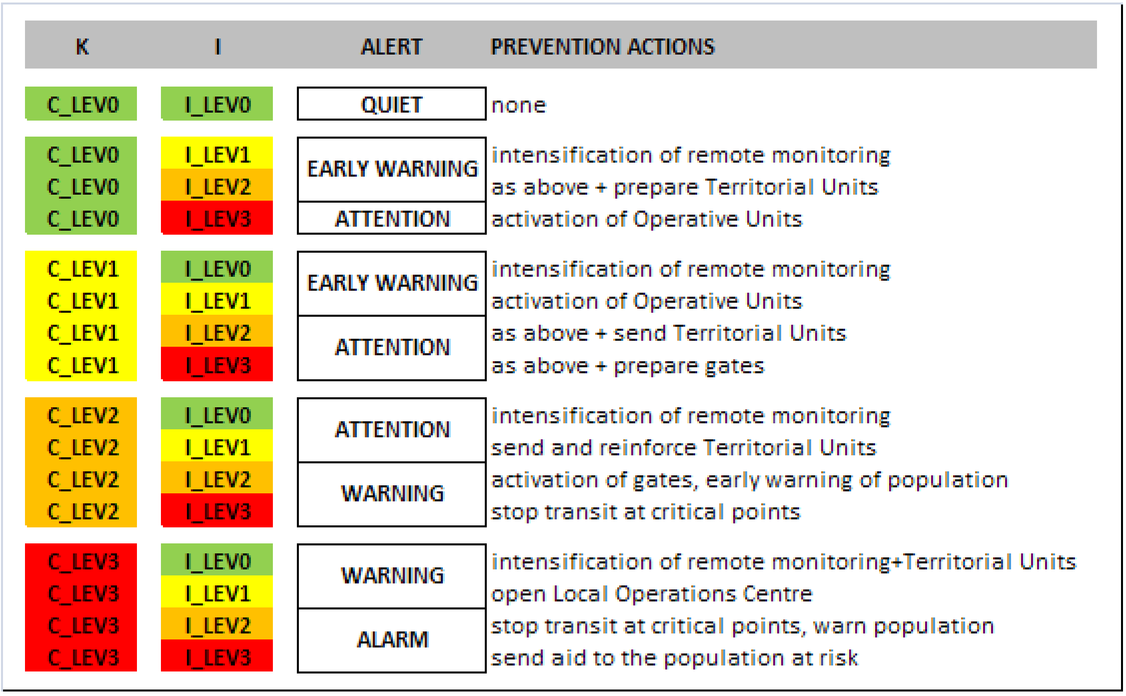
In order to understand what is indicated in figure 6, it should be noted that the Italian system of civil protection is organized as follows:

1) the "Functional Centre" (state or regional) issues the warning messages,
2) the Municipalities predispose all preventive activities by the Operative Units and the Territorial Units, and open a Local Operation Center during critical situations,
3) the regional and national system provides aid to Municipalities with men and equipment.

Obviously the preventive actions indicated are to be considered as a hypothetical model which needs to be developed according to the role and responsibility that each institution has within the civil protection plan.

The preventive actions represent a plan for the development of related roles and responsibilities of each institution within the civil protection plan.

All activities must be planned and discussed by the institutions involved and require repeated checks to ensure that the system works efficiently.



K	I	ALERT	PREVENTION ACTIONS
C_LEV0	I_LEV0	QUIET	none
C_LEV0	I_LEV1	EARLY WARNING	intensification of remote monitoring
C_LEV0	I_LEV2		as above + prepare Territorial Units
C_LEV0	I_LEV3	ATTENTION	activation of Operative Units
C_LEV1	I_LEV0	EARLY WARNING	intensification of remote monitoring
C_LEV1	I_LEV1		activation of Operative Units
C_LEV1	I_LEV2	ATTENTION	as above + send Territorial Units
C_LEV1	I_LEV3		as above + prepare gates
C_LEV2	I_LEV0	ATTENTION	intensification of remote monitoring
C_LEV2	I_LEV1		send and reinforce Territorial Units
C_LEV2	I_LEV2	WARNING	activation of gates, early warning of population
C_LEV2	I_LEV3		stop transit at critical points
C_LEV3	I_LEV0	WARNING	intensification of remote monitoring+Territorial Units
C_LEV3	I_LEV1		open Local Operations Centre
C_LEV3	I_LEV2	ALARM	stop transit at critical points, warn population
C_LEV3	I_LEV3		send aid to the population at risk

Figure 6 – Combination of threshold and alert levels

A retrospective analysis

With reference to the Santo Stefano di Briga rain-gauge, simulations were carried out to determine the most appropriate 'd' value in formulas [1], [2] and [3] in order to prepare the civil protection system.

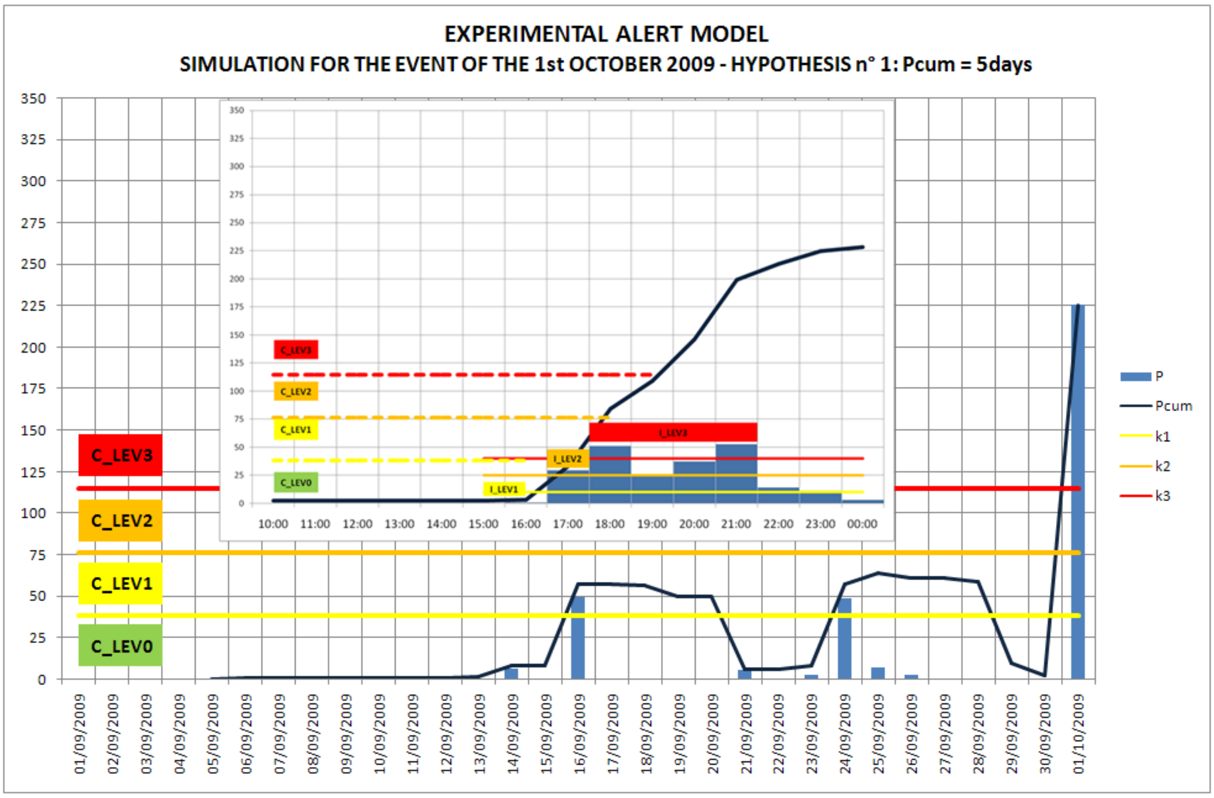


Figure 7 – Comparison between the accumulated rainfall in FIVE days, the intensity of precipitation and alert thresholds

As shown in Figure 7, if ‘d’=5 (days) the model would not alert the civil protection system: up to 16.00 hours on 1st October the alert level would be on QUIET (C_LEV0+I_LEV0); from 17.00 to 18.00 hours the system would pass to an ATTENTION level (C_LEV1+I_LEV2/I_LEV3); and only at 19.00 hours would the system pass to an ALARM level (C_LEV3+I_LEV3). In this case it would be too late to safeguard the population.

If ‘d’=10 (days), at 16.00 hours the alert level would be on EARLY WARNING (C_LEV1+I_LEV0); at 17:30 hours the system would pass to a WARNING level (C_LEV2+I_LEV2); and at 18.00 hours to an ALARM level (C_LEV3+I_LEV3) (Figure 8).

We cannot ascertain if this would be sufficient to save lives, but it would at least guarantee the presence of civil protection experts in the affected area who would be able to ascertain the seriousness of the situation.

We also analyzed another event that occurred in 2007 where there were similar ground-effects but different meteorological characteristics.

On 25th October 2007, the same area was affected by a severe storm that caused a lot of debris flows and considerable damage, but no casualties.

In the Santo Stefano di Briga rain-gauge, the storm was preceded by a fair amount of rain; so, if the experimental model had been active we would have had the following conditions (Figure 9 and Figure 10).

‘d’=5 (days)
15 o’clock: ATTENTION level (C_LEV2+I_LEV0),
16 o’clock: ALARM level (C_LEV3+I_LEV2)
17 o’clock: ALARM level (C_LEV3+I_LEV3)

‘d’=10 (days)
15 o’clock: WARNING level (C_LEV3+I_LEV0),
16 o’clock: ALARM level (C_LEV3+I_LEV2)
17 o’clock: ALARM level (C_LEV3+I_LEV3)

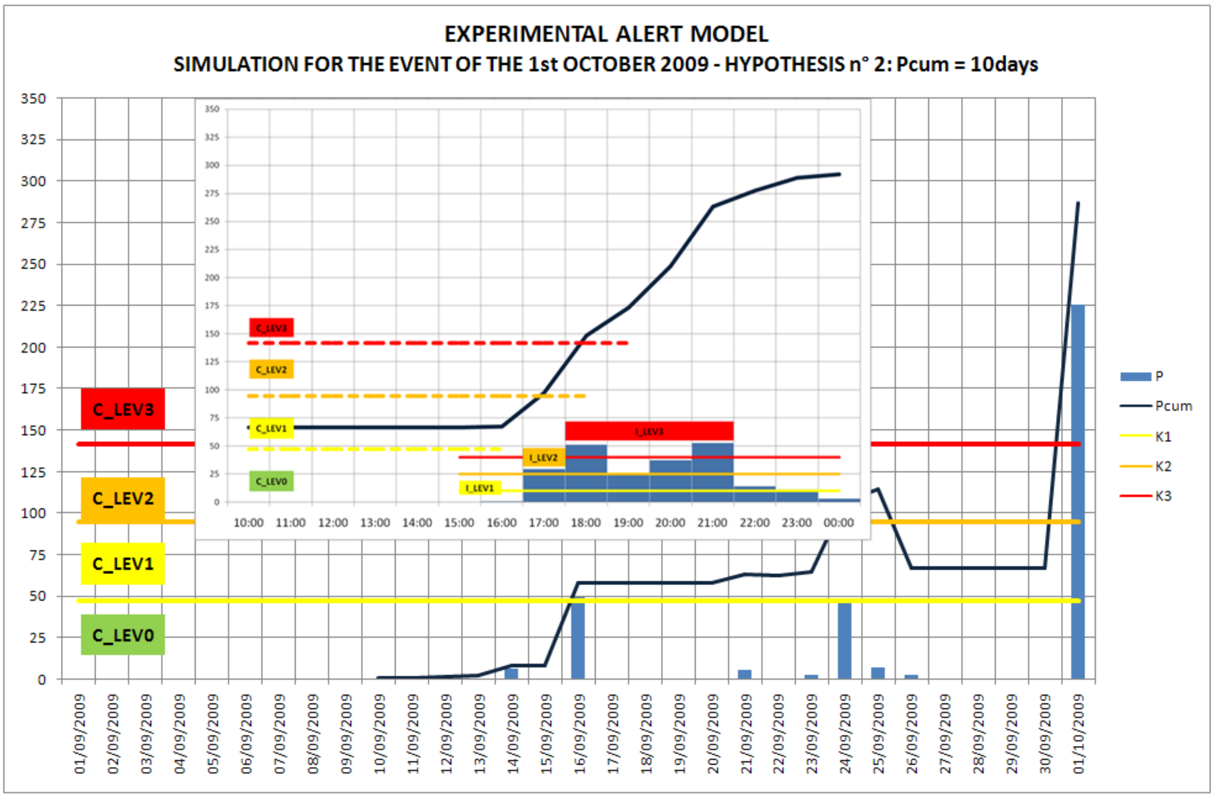


Figure 8 – Comparison between the accumulated rainfall in TEN days, the intensity of precipitation and alert thresholds

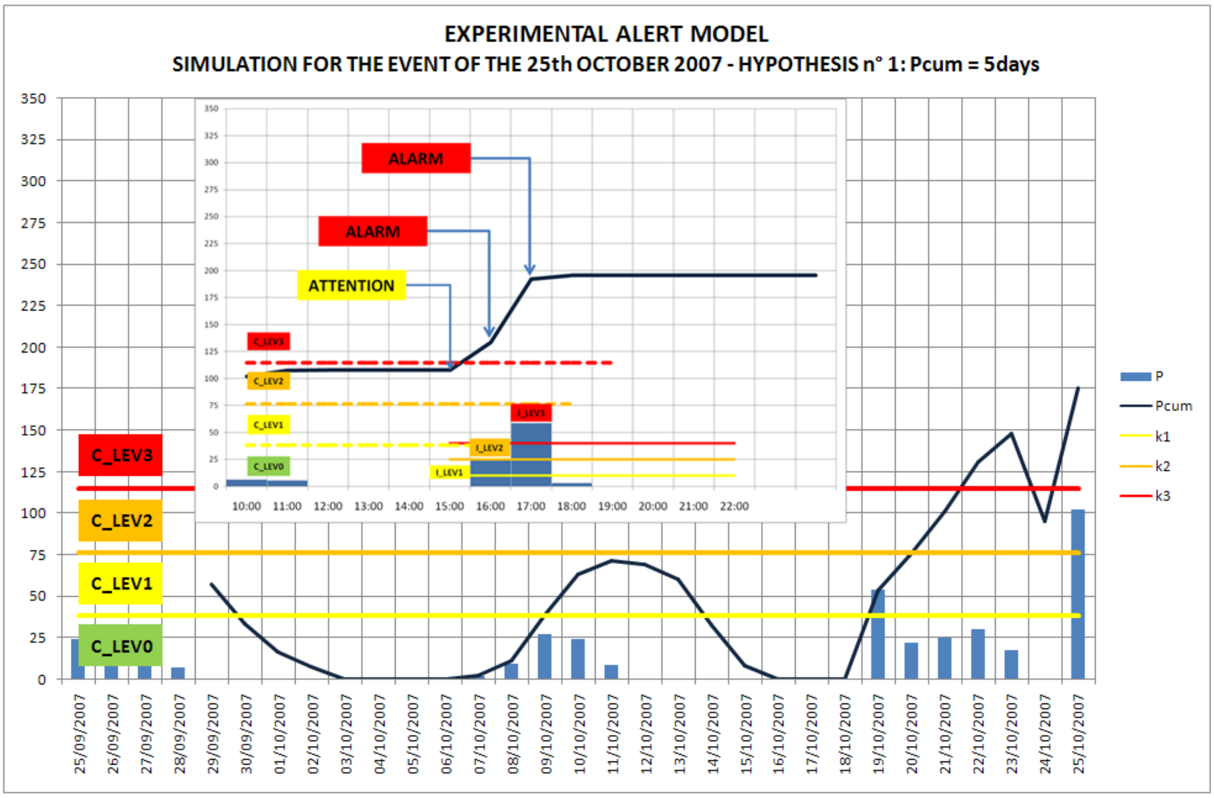


Figure 9 – Comparison between the accumulated rainfalls in FIVE days, the intensity of precipitation and alert thresholds

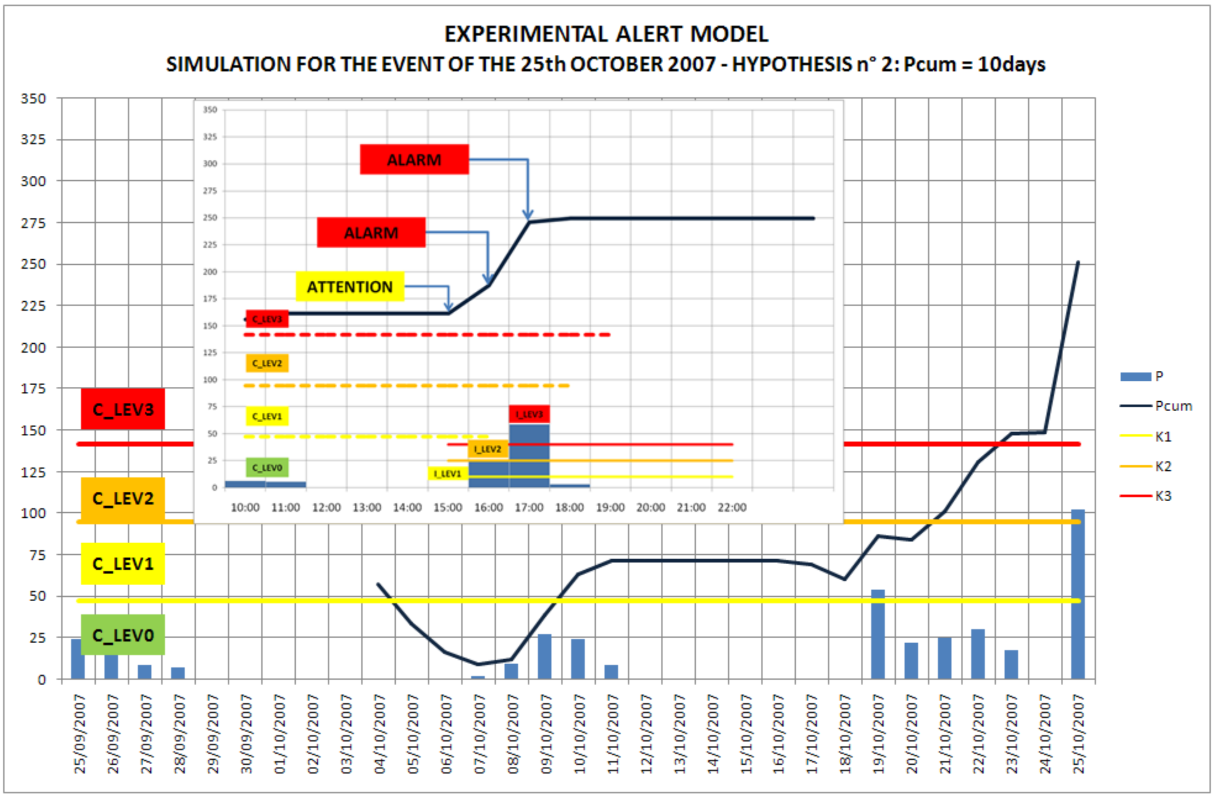


Figure 10 – Comparison between the accumulated rainfall in TEN days, the intensity of precipitation and alert thresholds

In this case, there is no substantial difference between the two positions (d=5, d=10) in alert messages. Probably, in a real-time system with d=10 position the ALARM level would have taken half an hour before reaching d=5.

Other simulations were made for similar events in the same area (October 2010, March 2011). In all cases, it seems that the most representative 'd' value is 10 days for a balanced activation of the civil protection system. However, the frequency of unexpected (and so far unpredictable) storms requires constant attention because of the rapid evolution of meteorological phenomena in the Straits of Messina district.

Conclusions

The proposed experimental alert model regards a restricted area of north-eastern Sicily that is frequently hit by extreme rainfall events that cause serious damage.

After the disastrous event of the 1st October 2009, six rain-gauges were installed in this area with real-time data transmission. The monitoring system's on-board software can establish three thresholds for cumulative precipitations and for rain intensity.

In order to determine the rain thresholds that could trigger the phenomenon of hydrogeological instability, the historical rainfall archives of the station at Santo Stefano di Briga (Osservatroio delle Acque), the only useful nearby reference point, were analyzed and compared with other damage-related data deriving from further archival research.

The elaboration of the data has allowed for the identification of two types of numeric expression:

$k_i = a_i{*}d^n$ for accumulated rainfall

(k_i=critical threshold, a_i,n=parameters depending on the law of distribution, d=in days)

Ii = m for intense rainfall

(Ii=critical threshold, m=rainfall value in mm/h)

The analyses carried out after a number of significant rainfall events have allowed for the identification of a 'd' value that provides greater guarantees in terms of prevention.

In the assigning of threshold and relative alert levels, the time required for the activation of civil protection procedures has been taken into account. In fact, thanks to the direct experience of the Regional Department of the Civil Protection together with other local organizations (town and county), it has been possible to ascertain that the amount of time needed to activate risk prevention actions - checking and verifying data, communicating with local organizations, activating operative and territorial centres, activating other system components - is a critical factor considering the speed with which the phenomenon of hydrogeological instability generally progresses.

The calculated thresholds and relative procedures would appear to be sufficient for the correct activation of preventive measures. However, the uncertainty of the working model, together with the poor correlation between rainfall and mudslides, is considerable and as a consequence "false alarms" and "missed alarms" are possible during the inevitable initial calibration period. These, however, will help to make the necessary corrections to the system.

In the current absence of more sophisticated procedures that take into account other parameters (for example: the air temperature and the consequent variations of the quantity of water held in the soil) which could have an effect on the development of mudflows and debris flows, the only other currently available instruments of preventive analysis are those which observe rainfall in real time. Only relatively recently has a band X meteorological micro radar been installed in the area which could help the real time monitoring of rainfall distribution.

Nonetheless, bearing in mind the predisposition to hydrogeological instability of the area concerned and the high level of urbanization, a suitable emergency plan that is able to activate a timely risk prevention action is of fundamental importance.

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