An aid in the most accurate rainfall thresholds evaluation

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Abstract

In this paper a new methodology to identify the most accurate rainfall threshold in relation to some events is presented. The rainfall thresholds definition is one of the most important aspects in controlling slope stability in colluvial and detritic materials. For this purpose this study investigates the most important rainfall thresholds presented in literature: both empirical and physically based ones. With the aim of contributing to the landslide hazard forecasting, a comparison among the main rainfall thresholds and real cases was carried out. Data from different locations (in Alpine areas) and triggering rainfalls have been analyzed in order to define a methodology for choosing the best threshold in relation to the local conditions of the slope. On the basis of the available database, a detailed description of the applicability of the rainfall thresholds to features of the territory is presented. The effect of the geo-morphological conditions of the case studies is actually important in the choosing of the rainfall threshold. This paper suggests a methodology with some determinant rules for choosing the best available rainfall thresholds for the investigated case. This procedure is a useful instrument for civil protection services interested in landslide hazard management, especially for landslide reactivation.
Keywords: rainfall threshold shallow landslides, empirical and physical based models.

1 Introduction

Rainfall produces some of the most frequent causes that trigger landslide movement. In particular in debris flow, characterised by a sudden occurrence of extremely rapid cinematic, recognizing the conditions which produce landslides

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plays a fundamental role in foreseeing and preventing such phenomena, as well as in the management of associated ensuing emergencies.

It is therefore important to foresee what the meteorological events are that trigger landslides of this type. It's clear that the effect that rainfall can have on slopes obviously depends on elements from the topographic aspect (gradient, exposure of the slope), to litho logic elements (characteristic of surface deposits, rock strata, etc.), to vegetation and human activity in terms of dams, terracing and works in protecting water flow; though it's true that periods of high rain fall correspond to periods of increased landslide activity.

The concept of pluviometric thresholds was introduced for the first time in 1975 by Campbell [3] and implies a correlation between intensity and the minimum duration of rainfall necessary to trigger landslide movement. Numerous authors, departing from this concept, have developed methods (both empirical and physics-based) to evaluate the point of triggering thresholds. Each method presents different fields of application and for this reason in this document applies different methods to one meteorological event of high intensity, occurring in the Valtellina in the autumn of 2002 (November 17-27) in the Ardenno and Sirta areas and which provoked numerous debris flows. The objective of comparing a single event using different methodologies is to understand the particularity of each method, establishing that which is most suitable to produce forecasts in the area under examination; and to identify how some pluviometric thresholds act when being utilised in the analysis of different events, from those normally presented.

2 Methodology approaches

The approaches adopted to define threshold triggers can be classified in two categories:

a) statistic or empirical models: in which a direct correlation is sought between depth of precipitation, in a determined interval of time, and triggers of movement, without entering into a debate on the laws of physics which regulate the transformation of influx – seepage – piezometric response.

b) physics-based models: in which hydraulic models are utilised to forecast the different components of the scale of water slope (influx, draining, seepage) and hydrogeology models to forecast the relationship between piezometric depth and slope gradient. In theory each component of the models adopted should reflect the corresponding laws of physics that regulate water activity in the subsoil; in reality however, given the complexity of the problem, different parts of each model are substantially based on empirical laws.

Following is a brief outline of the principal empirical methods in order to identify the best methodology for the definition of the residual risk after events.

2.1 Empirical methods

As previously stated, these methods are based on a statistical analysis of historical data and allow for the existing empirical relationship between rainfall and landslide phenomena.

Fundamental in the sphere of this approach are the findings of a series of data on precipitation (hourly or daily intensity) providing an arc of significant weather statistics to which can be associated the probability of the occurrence of “threshold values”. The fundamental detail for this type of model is the temporal pattern of intensity of the precipitation, expressed in mm/hour or mm/day. Having available a series of data sufficiently detailed, it is possible to directly estimate the probability of a landslide event associated with each value. In particular, on the basis of the “threshold model” the probability associated with threshold value that directly expresses the probability of the occurrence of landslide phenomena. The concept of pluviometric thresholds was introduced by Campbell [3]. Departing from this theoretical basis many attempts, generally defined as the empirical approach have occurred to determine the minimum height or intensity necessary to trigger landslide movement (Caine [2], Cancelli and Nova [4], Ceriani et al [6], Crosta [7], Crozier [8]).

The outcome of the “intensity-duration” approach has been redefined to regulate the value of intense rain to that of average annual rainfall in such a way as to take into consideration the climactic conditions of the region being investigated (Cannon and Ellen [5], Jibson [12], Aleotti [1]).

Another frequent approach is that of measuring rainfall accumulated during the landslide event until the trigger and the maximum intensity registered during the event (Govi and Sorzana [11]). Other methodologies compare accumulated rainfall during a period previous to the landslide event with the rainfall on the day of the landslide trigger or with the accumulated rainfall during the meteorologic event that caused the landslide. In some cases the previous rainfall is considered as an indicator of the state of the saturation of the soil (Glade et al [10]). In the case of deeper landslides the relationship between intensity and duration presents itself as inadequate in how much the influence of previous precipitation in longer or shorter periods comes into play (Glade et al [10]). In these cases the parameter to take into consideration is the depth of accumulated rainfall over an arc of a period of days, even if the number of significant days n is not previously noted. Empirical methods, as previously indicated, are based on experimental data without prior research of any theoretical explanation. In fact, in their formulation, certified theories to explain the observed phenomena are not found – although eventually these are provided later. Therefore the possibility of defining empirical thresholds predicts that historical information will be available both relative to phenomena of instability as well as the level of precipitation. The precise relationship between rainfall and landslide is valid, and therefore it is only with difficulty that the homogenous geological and climactic characteristics within a defined region can be exported to other regions.

3 Application of the methods for defining threshold triggers for debris flow: the case of Sirta and Ardenno (North Italy, Sondrio)

After having briefly outlined the principal empirical methods which are generally used to define pluviometric thresholds of the departure point of landslides like debris flow, following is an analysis of some of these methods applied to a meteorologic event of intense elevation occurring in the Valtellina in the autumn of 2002 (between November 17 and 27), in Ardenno and Sirta. As will be seen the data which will be analysed refers to two very close and comparable areas that underwent the same pluviometric event but which had been exposed to different "history" and this enables the volume of rain accumulated in a given terrain to be quantified. In addition the comparison of the same event with different methodologies results in the understanding of the peculiarity of each single curve, establishing which is most suited to carrying out forecasts in the zone under scrutiny, and it is possible to verify how some pluviometric thresholds act when used to analyse different events from those presented in the treatment. The methodologies most suited to the stated aim are those of: Cancelli and Nova [4], Caine [2] and Giannecchini [9]. The first was chosen because its field of validity is similar to that adopted in the examination, the second is interesting since it was proposed by Caine [2] as a 'universal' threshold, and lastly Giannecchini [9] is taken into consideration for the particularity of presenting thresholds not as one curve only but as a band of possible limited values. For the study two types of data are considered, the first is the value of rainfall that is the origin of a landslide, the other however is the combination of intensity and duration that are revealed "innocuous". After having gathered the information relative to pluviometric events that have provoked shallow movements, rainfall data relative to the same period but that did not produce such an event is researched.

3.1 Elaboration of data from the "Cancelli–Nova" method

The formula developed by the two authors to determine the limit is:

$$\log I = 1{,}65 - 0{,}78 \log D$$

Inserting in a bilogarithmic scale graph, the data of rainfall measured obtained the results reported in fig.1.

The model developed by Cancelli and Nova [4] functions very well for Ardenno.

A crisis is noted only for values of long duration that in fact touch on the threshold without however being values that effectively give rise to ruin. The curve represented by the model of Moser, constructed for the Austrian Alps, is revealed as reliable because landslide events that are indicated on the graph as closer to the threshold line are also those that occurred with less force. Analysing the data of Sirta it is possible to note less reliable results for the threshold, in fact some calamitous events have not been singled out by the graph.

The fact that the methodology is less reliable is probably attributable to the grade of relative humidity that is more elevated in this zone and which therefore leads to an earlier occurrence of phenomena. In this zone it would be opportune to utilise threshold values more in favour of safety given the event previously taken under examination. The crisis of the system in this case is given by the fact that in the preceding days to these landslides the rainfall in the locality of Sirta was more frequent and also that some events were reactivations. This phenomenon is not taken into consideration by the Cancelli and Nova [4] model and therefore would have to be evaluated separately to generate more accurate results.

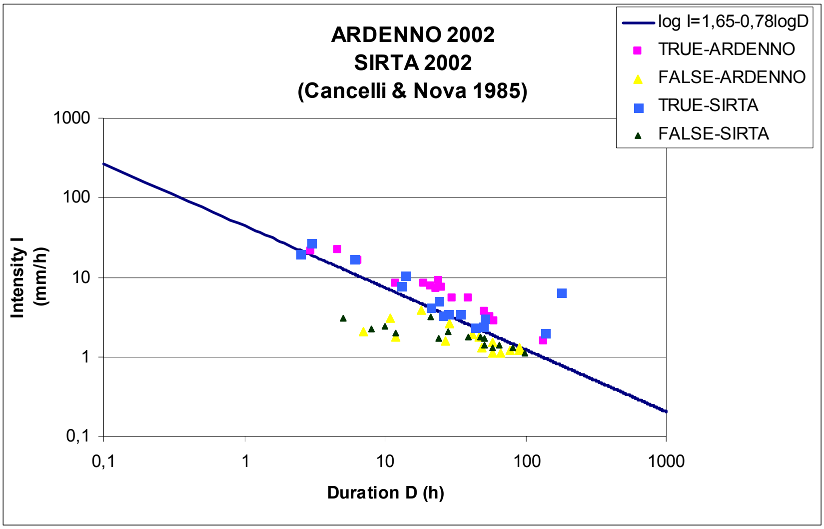

Figure 1: Rainfall thresholds for Ardenno and Sirta (Cancelli and Nova [4]).

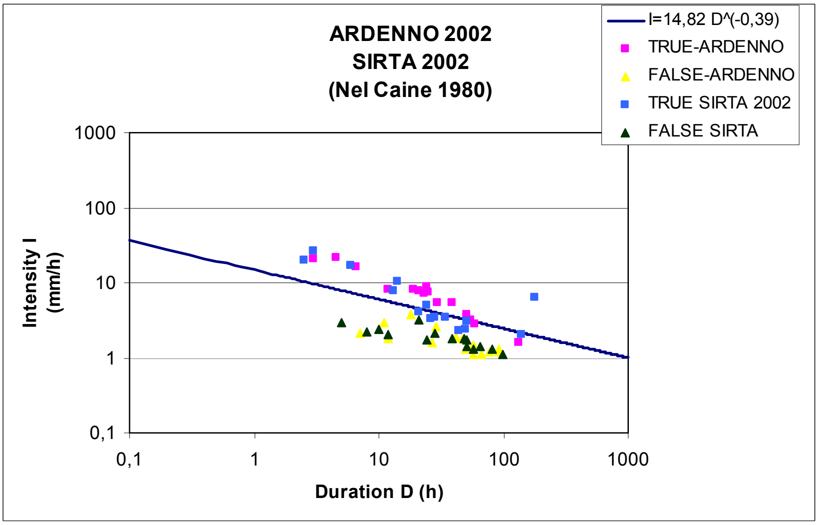

Figure 2: Rainfall thresholds for Ardenno and Sirta (Caine [2]).

3.2 Elaboration of data from the method of Caine

The graph (fig. 2) also in this case is in bilogarithmic scale and the limit is obtained through the formula:

$$d = 14.82\ D^{0.61} \qquad \text{Duration [hours], depth (rainfall) [mm]}$$

The Caine [2] model, despite being of a generic character, is still quite valid, demonstrating the level of precipitation necessary to generate crises in the porous material is sufficiently independent from the quality of the terrain (Ardenno).

As is foreseeable, this model shows some gaps with regard to intense rainfall, in fact in these zones the hypothesis of disregarding geologic peculiarities is no longer verified. This absence was already revealed by the same author who had advised against use above a certain limit of duration.

With the introduction of data (Sirta) that takes into account previous rainfall accumulated in the terrain, the complete unreliability of the model proposed by Caine [2] is verified. The introduction of this variable in fact undermines another hypothesis of this methodology which is reliable only for brief and intense rainfall.

3.3 Elaboration of data with the Giannecchini model

The formulae developed by Giannecchini [9] to obtain the two curves are:

$$\text{A) } I= 38.363\ D^{-0.743} \qquad \text{valid for } D< 12 \text{ hours}$$
$$\text{B) } I = 76.199\ D^{-0.6922} \qquad \text{valid for } D < 12 \text{ hours}$$

Formulae are used with a scope of validity inferior to 12 hours given that the data considered regards events significantly less than such limits. The interior of the two curves represents the maximum and the minimum of the threshold and which is therefore no longer a straight line but an extensive area that provides for a field of uncertainty. Figure 3 shows the results for this method.

It is noted that events of longer duration triggering landslides are found above the curve of minimum threshold, therefore it can be supposed that the model for Ardenno is acceptable.

In the case of Sirta the points close to the minimum threshold give rise to instability which should not happen.

The method developed by Giannecchini [9] manifests the greatest difference between its application to the event occurring in Ardenno in comparison to that of the locality of Sirta.

Such activity can be explained by the fact that this threshold is linked to the factor of accumulated rainfall; therefore the exportation of such methodology, having been obtained by a number of experimental data, is strongly discouraged.

To be noted is that the points provoking landslide phenomena are always included between the two curves, which however is an area where uncertainty exists and therefore should always be occupied by both types of data.

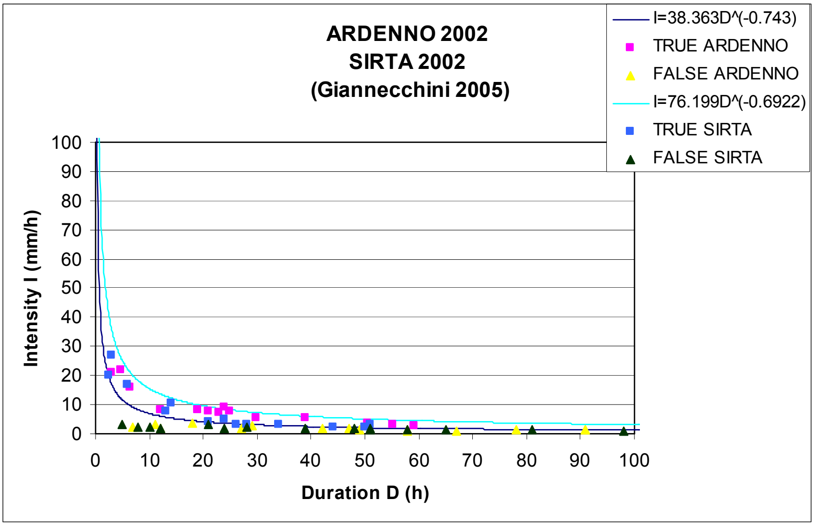

Figure 3: Rainfall thresholds for Ardenno and Sirta (Giannecchini [9]).

4 Comparison of the data of the two areas investigated

Having noted the discrepancies between the values found at Ardenno compared to those revealed in the area of Sirta, it was decided to compare the data to better comprehend the phenomena and in addition to derive a new qualitative trend.

It can be said that the models are always reliable for brief durations since the local geomorphologic factors do not have time to manifest themselves; in fact a ‘universal’ threshold such as that produced by Caine [2] can be taken into consideration only in cases of events of intense but brief duration. When rainfall is however less intense but prolonged, many local factors enter the equation that only an ad hoc study can illuminate (in this case it will be better to use physical models). So, the problem is concerning the data about 10 h and 100 h of duration. In fig. 4 it is possible to analyze the false data. For Sirta it is clear that all these data are concerning some reactivations. For this observation in fig. 4 some data is concerning activations and reactivation, also for some new data from different studies (one in Cortenova, in the North of Italy, and the other from Caine’s study-1980) have been analyzed. The main assumption in this case is that reactivation of a landslide will occur with a different threshold. Consequently a translation of the threshold based on this new consideration is suggested.

The new rainfall threshold (reported in fig. 4 and in fig. 5) is representing by this equation:

$$I= 37\ D^{-0.75}$$

This equation is very similar with that represented by Giannecchini [9], but this is valid in particularly for 10<D<100 hours and less in the first part of the graph.

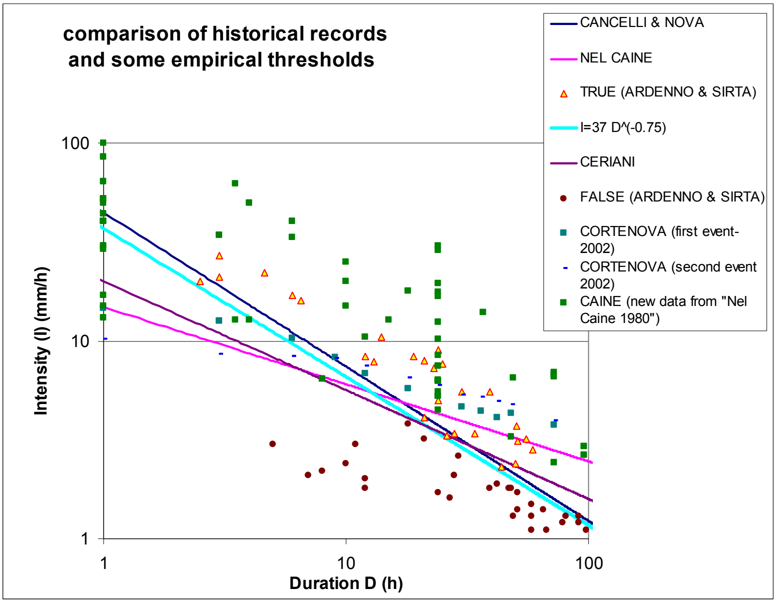

Figure 4: Comparison of different records and records for Ardenno, Sirta, Cortenova with some empirical threshold relationships

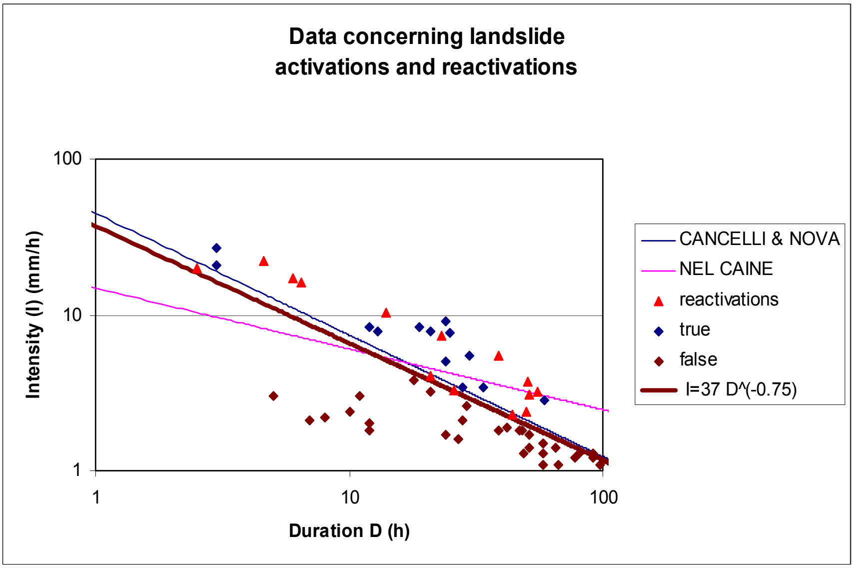

Figure 5: New methodology for landslides reactivation.

Finally, to be noted is the reactivation data (in particular about Sirta) that are closely linked to the geological-geomorphologic features and it is more easy to have a reactivation, so it was necessary to use this new threshold in order to evaluate also this particular cases that have a great residual risk

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