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PROBABILISTIC APPROACHES FOR ASSESSING RAINFALL THRESHOLDS TRIGGERING SHALLOW LANDSLIDES. THE STUDY CASE OF THE PERI-VESUVIAN AREA (SOUTHERN ITALY)

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EXTENDED ABSTRACT

L'analisi delle condizioni pluviometriche connesse all'innesco di frane superficiali del tipo scorrimento-colata di detrito rapida (*debris slide – debris flow*) rappresenta un aspetto cruciale dei sistemi di gestione e mitigazione del rischio da frana nell'areale peri-vesuviano (Campania, Italia meridionale), che raggiunge un grado tra i più elevati in Italia (SALVATI *et alii*, 2010). A riprova di ciò possono essere annoverati molti eventi franosi catastrofici, verificatisi nei Monti di Sarno (es. 5-6 maggio 1998), Lattari e di Salerno (es. 24 ottobre 1910 e 25-26 ottobre 1954), che hanno provocato nell'ultimo secolo circa 600 vittime e danni molto ingenti ai centri abitati ed alle infrastrutture della fascia pedemontana. Tali fenomeni coinvolgono le coperture di origine piroclastica derivanti dalle più recenti eruzioni dell'apparato vulcanico del Somma-Vesuvio e, subordinatamente, dall'attività eruttiva del distretto vulcanico dei Campi Flegrei. L'assetto morfologico dei rilievi carbonatici, caratterizzato da versanti ad elevata pendenza, la variabilità degli spessori e delle condizioni stratigrafiche dei depositi piroclastici (da pochi decimetri ad alcuni metri) e le particolari proprietà idro-meccaniche degli stessi, vengono considerati come fattori predisponenti all'instabilità (GUADAGNO *et alii* 2005; DE VITA *et alii*, 2013). Da tutto ciò risulta una complessa relazione di causa-effetto tra l'accadimento di questo tipo di frane e l'occorrenza di eventi pluviometrici di elevata intensità e/o durata la cui comprensione è di fondamentale importanza per la predisposizione di sistemi di *early warning* basati sulla definizione di soglie pluviometriche affidabili.

Uno degli approcci seguiti per la definizione di soglie pluviometriche si basa sulla raccolta dei dati di pioggia registrati da stazioni prossime al luogo dell'innesco ed in concomitanza dell'evento stesso e nell'analisi, su base empirica, dei livelli di soglia ovvero dei valori minimi dei parametri pluviometrici che possono determinare l'innesco delle frane. Tale approccio è tuttavia affetto dall'incertezza connessa all'attendibilità delle registrazioni pluviometriche come anche alle variabili condizioni idrologiche antecedenti del suolo. Pertanto, al fine di considerare anche il grado di attendibilità e quindi di incertezza di questo tipo di analisi, nel presente lavoro si presentano approcci di analisi probabilistica applicati a modelli empirici per la stima di soglie pluviometriche, come l'Intensità-Durata (*I-D*) (CAINE, 1980) e quello basato sul confronto tra la pioggia registrata nel giorno dell'evento di frana (*P*) e la somma dei quantitativi di pioggia misurati nei giorni antecedenti (*Pa*) (CROZIER & EYLES, 1980), nel caso specifico considerata corrispondente ai 29 e 59 giorni antecedenti all'evento di frana. In particolare, è stato fatto sia riferimento al modello di precipitazione di forte intensità e breve durata, realizzato nell'ambito del Progetto VAPI (ROSSI & VILLANI, 1994) e basato sulla regionalizzazione delle piogge a differenti scale spaziali, che al modello della regressione logistica bivariata.

A tale scopo è stato inizialmente costituito un *database*, riferito a tutti gli eventi di frana noti da fonti cronachistiche o da pubblicazioni tecniche e scientifiche, comprendente la durata e l'intensità degli eventi di piogge innescanti, registrate alle stazioni pluviometriche maggiormente rappresentative, come anche l'intera serie storica di dati pluviometrici registrati dalle stesse stazioni. Per limitare i casi di sottostima delle piogge innescanti gli eventi franosi, imputabili a misurazioni non rappresentative per l'elevata localizzazione spaziale degli eventi di pioggia, e quindi al fine di ridurre l'incertezza predittiva del modello empirico, sono stati esclusi tutti gli eventi di frana con eventi pluviometrici innescanti con tempo di ritorno (*T*) inferiore ad un anno. Successivamente, mediante il confronto con il modello VAPI, sono state individuate quattro soglie *I-D* caratterizzate da differenti tempi di ritorno, quindi di probabilità di occorrenza: $1 < T < 2$; $2 < T < 5$; $5 < T < 10$; $T > 10$ anni.

Ad entrambi i modelli empirici adottati, *I-D* e *P-Pa,* è stato applicato il modello di regressione logistica bivariata; ciò ha permesso la stima del valore di probabilità di accadimento di frana per assegnate condizioni pluviometriche. Le soglie così determinate su base empirica sono state successivamente confrontate con quelle stimate mediante approccio deterministico, o fisicamente basato (DE VITA *et alii*, 2013; NAPOLITANO *et alii*, 2016), identificando una buona convergenza dei risultati. La confrontabilità dei risultati ottenuti con approcci differenti può essere intesa come validazione di entrambi i tipi di soglie pluviometriche.

ABSTRACT

Ash-fall pyroclastic soil deposits covering steep carbonate slopes in the peri-Vesuvian area (southern Italy) are periodically involved in shallow landslides (about 700 events were recorded during the last three centuries, as reported by CASCINI *et alii,* 2008), triggered by intense and/or prolonged rainfall events, which evolve as catastrophic debris flows. In the last decades, many studies have been focused on estimating reliable relationships among the triggering of shallow landslides and the amount and duration of rainfall events, as well as the role played by antecedent soil hydrological conditions. Results of these studies have been expected to give information on temporal hazard to landslide onset to be used for setting a reliable early warning system.

In this paper we present probabilistic approaches to assess rainfall thresholds triggering shallow landslides by classical empirical methods and to manage the uncertainties related to biases of data. At this scope, rainfall events related to the occurrence of debris flows along slopes of the Sarno and Lattari Mountains, known from chronicles of the last century, were analyzed by means of the empirical models of Intensity-Duration (*I-D*) (CAINE, 1980) and rainfall recorded in the day of the landslide occurrence (*P*) vs the antecedent cumulated rainfall *(Pa)* (CROZIER & EYLES, 1980). In order to limit and to assess uncertainties related to biases of rainfall data, a comparison with the regional probability model of high intensity rainfall, carried out in the framework of the VAPI Project (ROSSI & VILLANI, 1994) has been carried out. Moreover, rainfall data were processed by a bivariate logistic regression model resulting in the assessment of probability to landslide triggering, given an assumed rainfall event. The *I-D* empirical rainfall thresholds obtained by Caine model (1980) were compared to rainfall thresholds estimated by deterministic approaches (DE VITA *et alii*, 2013; NAPOLITANO *et alii*, 2016) showing a good match.

KEYWORDS**:** *ash-fall pyroclastic deposits, rainfall-induced debris flows, rainfall thresholds, landslide hazard, early warning*

INTRODUCTION

Ash-fall pyroclastic soil covers mantling carbonate mountain ranges that surround the Mt. Somma-Vesuvius volcano (Campania, southern Italy) are frequently involved in rainfall-triggered debris slides - debris flows (CRUDEN & VARNES, 1996) which usually have caused a high number of casualties (SALVATI *et alii*, 2010) and damage in towns located along the footslope areas.

In recent decades, especially after the high-magnitude debris flow event occurred on May 5-6 1998, which caused the loss of 160 lives, several studies were carried out to comprehend triggering mechanisms of these landslides and define criteria for risk reduction based on setting early warning systems (CROSTA & DAL NEGRO, 2003) as well as to understand the hydrological behavior of volcaniclastic soil covers (GRECO *et alii*, 2013; FUSCO *et alii*, 2017). A special research topic has been focused on analyzing cause-effect relationships between occurrence of intense and/or prolonged rainfall and triggering of these landslides, estimating rainfall thresholds (CAMPBELL, 1975; WILSON, 1989; WHITE *et alii*, 1996).

In particular, by analyzing debris flows events occurred in Sarno and Lattari Mountains, many empirical hydrological thresholds have been carried out based on correlation of rainfall Intensity-Duration *(I-D)* (CAINE, 1980), as in the cases of GUADAGNO (1991) and CALCATERRA *et alii* (2000). Moreover, to consider empirically the effect of antecedent hydrological conditions, as a predisposing factor to landslide initiation, an analysis of the relationship between the rainfall recorded in the day of the landslide event *(P)* and that cumulated in an antecedent period (*Pa*) (CROZIER & EYLES, 1980) was also carried out (DE VITA & PISCOPO, 2002).

Considering uncertainties of these empirical approaches, induced by the scarce consistency of landslide event records and reliability of rainfall measurements, physically based modelling approaches (GODT & MCKENNA, 2008) have been developed to assess rainfall thresholds conditions leading to debris flow triggering. In this case, rainfall thresholds were estimated by physically based approaches which were based on detailed hydro-geomorphological and geomechanical models reconstructed by field surveys and laboratory tests (DE VITA *et alii*, 2013; 2017; 2018). These models were further advanced by considering soil hydrological monitoring data which allowed to understand hydrological behavior of volcaniclastic soil covers (FUSCO *et alii*, 2017) and effects of antecedent soil hydrological conditions on rainfall thresholds (NAPOLITANO *et alii*, 2016).
Starting from such results, an advance on estimating rainfall thresholds is proposed in this paper by probabilistic approaches applied to *I-D* (CAINE, 1980) and *P-Pa* (CROZIER & EYLES, 1980) empirical models. Results are expected incorporating uncertainties of rainfall values, recorded by rain gauge stations at the occurrence of landslides, which are assumed as being related to planimetric and altimetric distance from the landslide source area and often to high spatial localization of rainfall events. Regional probabilistic model reconstructed for extreme rainfall events (ROSSI & VILLANI, 1994) in the framework of the VAPI Project (*Valutazione delle Piene* - Flood Estimation) and the bivariate logistic regression model were applied to rainfall data recorded at the landslide occurrences. Finally, results were compared to those obtained by physically-based or deterministic approaches previously achieved (DE VITA *et alii*, 2013; NAPOLITANO *et alii*, 2016) to carry out a mutual validation.

DATA AND METHODS

Study area and dataset

The study area includes the Sarno and Lattari Mountains (Campania, southern Italy), formed by Mesozoic-Cenozoic series (limestone and dolomite-limestone), whose steep slopes are covered discontinuously by ash-fall pyroclastic soils, varying in thickness from about 7 to 4 m on the Sarno Mountains and from about 3.0 to 0.5 m on the Lattari Mountains (FUSCO *et alii*, 2017).

These deposits are characterized by alternated pumiceous lapilli, mainly erupted by the Somma-Vesuvius volcano (DE VITA & NAPPI, 2013), and pedogenized horizons. Frequently, debris slides – debris flows (CRUDEN & VARNES, 1996) involve these surficial deposits depending on different predisposing factors, such as stratigraphic, natural and man-made morphological features of the slope (DE VITA *et alii*, 2013), and to both triggering and antecedent hydrological conditions (FIORILLO & WILSON, 2004).

Based on data of the AVI inventory (GUZZETTI *et alii*, 1994), scientific papers (AVERSANO & RUGGIERO, 2000; DE VITA 2000; CALCATERRA *et alii*, 2003) and chronicle reports, a complete catalogue of debris flow occurrences and related rainfall records was reconstructed for the study area, since the beginning of the last century. In detail, an inventory of 205 landslide events, occurred between 1921 and 1998, was created, which can be subdivided in: 46 for the Sarno Mountains and 159 for the Lattari Mountains. Instead, rainfall data were gathered by recordings of the meteorological network carried out by the *Servizio Idrografico e Mareografico Nazionale* (SIMN), which has been the government body in charge to gather hydrological data across the entire national territory until 1999.

Rain gauges (Lauro, Sarno, Mercato San Severino, Palma Campania, Salerno, Sorrento, Nocera Inferiore, Piano di Sorrento, Castellammare, Gragnano, Agerola, Ravello, Cava dei Tirreni, Tramonti, Amalfi, Maiori, Minori and Scala) and related recordings were selected considering the proximity to landslide source areas (Fig. 1).

Empirical rainfall thresholds

Empirical analysis of rainfall recorded at the occurrences of landslide events was oriented to identify threshold values of both Intensity and Duration (*I-D*) (CAINE, 1980) and rainfall recorded in the landslide-event day and that cumulated in antecedent days (CROZIER & EYLES, 1980) (*P-Pa*). Firstly, negligible rainfall conditions associated to debris flow occurrences were filtered out by their return time (*T*) to exclude rainfall events not relevant for landslide triggering because affected by unrepresentativeness or measurement errors. Return time of rainfall events was determined using results of VAPI model (*Valutazione delle Piene* - Flood Estimation) (ROSSI & VILLANI, 1994) derived by a national project aimed at the regional analysis of frequency of extreme rainfall and river floods. This model is based on the analysis of extreme rainfall, using the TCEV (Two Components Extreme Value; ROSSI *et alii*, 1984) as a probabilistic model for the estimation of annual maxima of daily and sub-daily rainfall. The model is coupled with a three-levels hierarchical procedure for the regional estimation of its parameters. In the first level, the adoption of the TCEV probabilistic model is statistically validated for recordings of hourly maximum annual rainfall data of all rain gauge stations considered. In the second level a homogeneous region is identified by the constancy of variance of hourly maximum annual rainfall data recorded by rain gauge stations. In the third level, six homogeneous sub-regions were identified by the correlation between the mean of the hourly maximum annual rainfall data and altitude of rain gauge stations. For each of them, a statistical relationship between mean annual daily rainfall maxima, duration of rainfall and altitude was used to estimate the return time (*T*) of rainfall events through a regression analysis. Both the Sarno and Lattari Mountains are located in the sub-region A_2, thus allowing to carry out a unique probabilistic assessment.

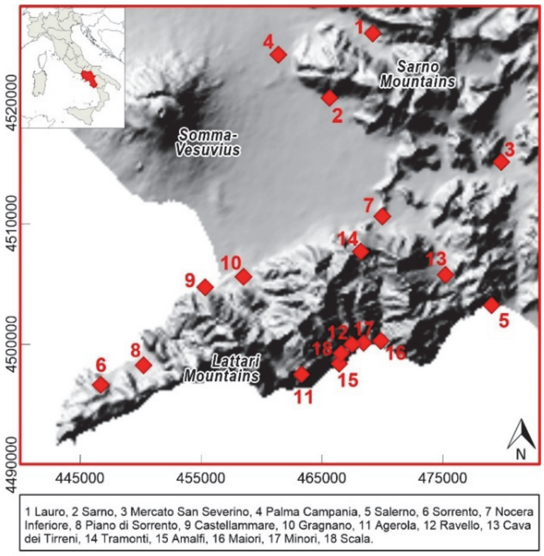

Fig. 1 - Rain gauges considered for records of rainfall events that triggered debris slides-debris flows in the study area

The first step of the analysis consisted in excluding rainfall events recorded at the landslide occurrences with $T \leq 1$ year. After that, four *I-D* rainfall thresholds were identified, with different levels of probability and performance: $1 < T < 2$; $2 < T < 5$; $5 < T < 10$; $T > 10$ years.

For the P-P_a threshold, rainfall of antecedent days cumulated in 29 (Pa_{29}) and 59 (Pa_{59}) days before the landslide event were considered. In this case, given the longer time span of rainfall events, return times (*T*) were calculated by fitting distribution of cumulated rainfall daily data with a log-normal distribution.

The role of antecedent rainfall has been considered by the "Soil Water Status Index" model (Glade *et alii*, 2000), based on the following formula:

$$r_n = r_1^{k} + r_2^{k*2} + \ldots + r_{n\text{-}imo}^{k*n} \qquad (1)$$

where r_n is the cumulative rainfall (mm) in n days, and k is a constant representing the outflow from the ash-fall pyroclastic soil cover. The k value was set equal to 0.8, according to results of analyses of pressure head time series (Fusco *et alii*, 2017), representing the velocity of drainage processes after rainfall events. This value resulted very close to that used by Glade *et alii* (2000) for New Zealand landslides.

Then, in order to validate empirical thresholds obtained, a comparison with physically-based thresholds and the receiver operating characteristic (ROC) analysis (Fawcett, 2006) was carried out. The ROC analysis allows the identification of: "true positive" (TP) of empirical parameters located above the threshold, resulting in single landslide; "true negative" (TN) of a point below them, not resulting in known landslides; "false positives" (FP) when the rainfall conditions exceeded the threshold and landslides did not occur; "false negative" (FN) occurs when the rainfall conditions were below the threshold and landslides occurred. For each obtained threshold, the TP, FP, TN, and FN categories were identified and the true positive rate (TPR), also called sensitivity, and false positive rate (FPR).

Calculation of landslides probability

Rainfall thresholds for landslides initiation have been estimated also by applying a probabilistic approach, based on a bivariate logistic regression technique, to *I-D* (Caine, 1980) and *P-Pa* (Crozier & Eyles, 1980) empirical models. Specifically, this technique considers that the dichotomous dependent variable Y can assume only values 1 and 0 corresponding to landslide/no-landslide occurrence, respectively. Moreover, the model has two predictors, X_1 and X_2, which correspond to I and D and to P and P_a, respectively. Therefore, the variable Y can be defined as:

$$Y = \alpha + \beta_1 \times X_1 + \beta_2 \times X_2 \qquad (2)$$

where α, β_1 and β_2 are the parameters of the models. Finally, the probability is given by:

$$P(X_1|X_2) = \frac{e^{\alpha+\beta_1 X_1+\beta_2 X_2}}{1+e^{\alpha+\beta_1 X_1+\beta_2 X_2}} \qquad (3)$$

RESULTS

I-D and *P-Pa* data reconstructed at occurrences of landslide events, together with all rainfall events with no landslide occurrences, formed the database used for the analysis (Figs. 2 and 3). By the visual observation, some of these data corresponding to landslide occurrences appear as being inconsistent due to low rainfall value and not correlated to a typical power law or any other linear correlations. Therefore, as the first probabilistic approach used, *I-D* rainfall thresholds were identified considering only rainfall data recorded at the landslide occurrences having the following return times: $1 < T < 2$; $2 < T < 5$; $5 < T < 10$; $T > 10$ years.

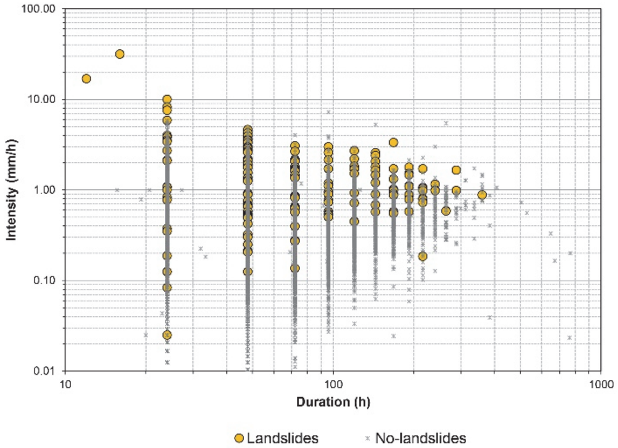

Fig. 2 - Intensity and duration of rainfall events which caused a landslide (yellow circle) and of rainfall events which did not cause a landslide (grey cross)

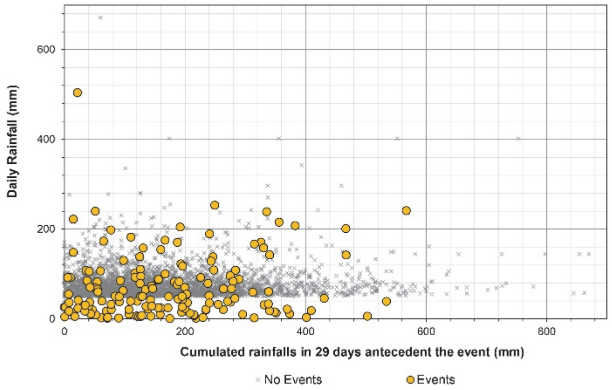

Fig. 3 - Rainfall referred to landslide-event day (P) vs cumulated rainfall (Pa_{29}).

With such an approach, *I-D* rainfall thresholds with different return time values were defined (Fig. 4). These thresholds were compared to those estimated by a physically approach for Sarno Mountains area and considering typical winter and summer antecedent soil hydrological conditions (De Vita *et alii*, 2013; Napolitano *et alii*, 2016). The comparison shows a good match and in particular the empirical thresholds for $T \geq 2$ years well replicates the winter deterministic threshold, even if being lower than the summer one, which identifies more extreme antecedent and triggering rainfall conditions (Fig. 4).

To test the performance of *I-D* rainfall thresholds, the ROC-AUC analysis was carried out considering rainfall events associated to landslide occurrences with $T \geq 1$ years. The resulting *ROC* curve is characterized by an area under the curve with AUC = 0.90, which confirmed that I-D rainfall thresholds estimated provide a good predictive capability (Fig. 5).

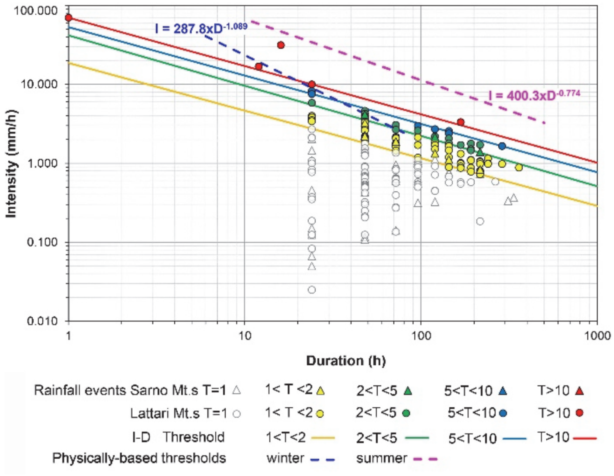

Fig. 4 - Empirical I-D rainfall thresholds, estimated for rainfall events which caused landslides, which were classified depending on their return time: 1<T<2; 2<T<5; 5<T<10 and T>10. Physically-based rainfall thresholds (NAPOLITANO et alii, 2016) are also shown. Triangles indicate landslide events of the Sarno Mountains, while circles indicate those of the Lattari Mountains

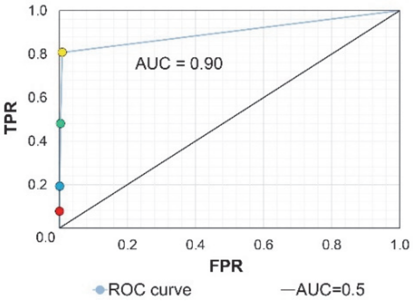

Fig. 5 - Receiver Operator Characteristic (ROC) curves estimated for the four I-D thresholds and its area under the curve (AUC) value.

The second probabilistic approach analyzed *I-D* (Fig. 2) and *P-Pa* (Fig. 3) rainfall data, corresponding to both landslide and no-landslide events, by a bivariate logistic regression technique. In this way, four probability classes were identified: *i*) low: 0-5%; *ii*) medium: 5-15%, *iii*) high: 15-30%, *iv*) very high: 30-100% (Fig. 6). The main aspects emerging from the discussion of results can be focused on the non-linear increase of probability as rainfall intensity and/or duration increase (Fig. 6a). Specifically, landslide probability results high for about I ≥ 5 mm/h and a minimum duration of 10 h. Following, the high probability exists for *10 h ≤ D ≤ 250 h* but with a decreasing rainfall intensity. Finally, for D ≥ 250 h, high probability exists also for very low rainfall intensity values. Finally, the probability for triggering a landslide, derived by *P-Pa* empirical model (Figs. 6b and 6c), increases as *P* and *Pa* increase, while the lowest landslide probability is given for low *Pa* and *P* values.

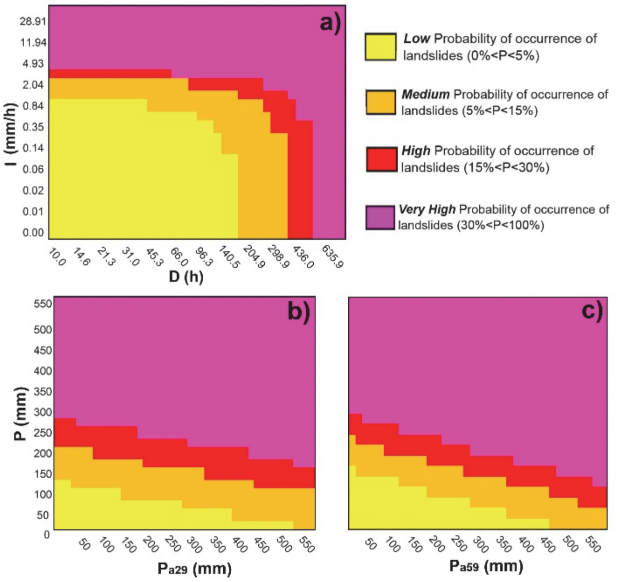

Fig. 6 - Results of bivariate logistic regression technique applied to: a) I-D empirical model; b) P-Pa$_{29}$ empirical model; c) P-Pa$_{59}$ empirical model.

CONCLUSIONS

This study was focused on the assessment of rainfall thresholds triggering debris flows in the peri-Vesuvian area (southern Italy) by probabilistic approaches applied to classical empirical models (CAINE, 1980; CROZIER & EYLES, 1980) and aimed at assessing and managing the inherent predictive uncertainties. Such uncertainties are fundamentally controlled by representativeness of rainfall records at the debris flows occurrences, due to planimetric and altimetric distance between rain gauge and landslide source areas, variable antecedent soil hydrological conditions, which are controlled by seasonality, and measurement errors. These uncertainties are known to affect relevantly the predictive capabilities of empirical rainfall thresholds (NIKOLOPULOS *et alii*, 2014).

In such a framework, the probabilistic approach based on processing rainfall data, recorded at the landslide occurrences, by a regional probabilistic model for extreme rainfall, allowed to filter out inconsistent rainfall data as well as to estimate I-D rainfall thresholds with different probability or return time. Moreover, the probabilistic approach based on the bivariate logistic regression technique allowed to estimate *I-D* and *P-Pa* rainfall thresholds by incorporating uncertainties of data in the form of probability. Results obtained with both approaches can be conceived as advancing the knowledge about rainfall conditions triggering debris slide-debris flows in the peri-Vesuvian area and to be used as a reference for setting early warning systems.

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