DOI: 10.4408/IJEGE.2019-01.S-01

PRELIMINARY RESULTS ON THE COMPARISON BETWEEN EMPIRICAL AND PHYSICALLY-BASED RAINFALL THRESHOLDS FOR SHALLOW LANDSLIDES OCCURRENCE

MASSIMILIANO BORDONI, BEATRICE CORRADINI, LUCA LUCCHELLI & CLAUDIA MEISINA

University of Pavia - Department of Earth and Environmental Sciences - Pavia, Italy
Corresponding author: massimiliano.bordoni@unipv.it

EXTENDED ABSTRACT

Le frane superficiali indotte da precipitazioni meteoriche sono tra i fenomeni franosi più diffusi e più pericolosi, a causa in particolare della loro rapidità di innesco e sviluppo, della mancanza di segni premonitori e dell'elevata densità di presenza in aree anche molto ristrette. Tra gli strumenti più utilizzati per la stima delle condizioni che possono portare all'innesco di questi fenomeni, le soglie pluviometriche risultano le più utilizzate, soprattutto all'interno di sistemi di allerta. Queste rappresentano le minime condizioni pluviometriche, espresse soprattutto in termini di durata e corrispondente precipitazione cumulata, al di sopra delle quali una frana superficiale si può innescare. Queste soglie sono solitamente ricostruite con un approccio empirico, basandosi sull'analisi delle condizioni pluviometriche di eventi passati accaduti in una carta area. Tuttavia, questa metodologia di analisi presenta alcuni limiti, legati alla disponibilità di informazioni sugli eventi passati, all'incertezza sull'individuazione dei momenti di innesco e al fatto che non considerano le condizioni idrologiche del suolo presenti immediatamente prima di un evento piovoso. Per colmare queste mancanze, un altro approccio di ricostruzione di soglie pluviometriche è quello di individuare le condizioni pluviometriche responsabili di instabilità superficiale attraverso l'applicazione di modelli fisicamente basati, che accoppiano la modellazione della risposta idrologica del suolo a seconda della pioggia di evento con una modellazione della stabilità del versante all'equilibrio limite. Di conseguenza, è necessario effettuare un confronto tra soglie ricostruite tramite questi diversi approcci, al fine di individuare quella più efficace per l'individuazione dei momenti di innesco di frane superficiali in un'area suscettibile. Questo confronto è stato realizzato per l'area dell'Oltrepò Pavese collinare (Appennino settentrionale, Italia settentrionale), dove le frane superficiali sono molto diffuse nei vari contesti geologici e geomorfologici dell'area. In particolare, per quest'area di studio, una soglia empirica è stata ricostruita attraverso l'algoritmo CTRL-T, a partire dai dati pluviometrici degli eventi di innesco avvenuti nel periodo 1990-2019. Le soglie pluviometriche fisicamente basate sono state ricostruite attraverso la modellazione di ipotetici eventi meteorici di innesco condotta mediante il modello idrologico di TRIGRS v.2 e un modello di stabilità all'equilibrio limite. Questa modellazione è stata fatta considerando tre diversi scenari di condizioni antecedenti di pressione interstiziale: i) -10 kPa, ii) -5 kPa, iii) 0 kPa. I risultati preliminari di questa analisi mostrano come le soglie ricostruite attraverso questi diversi approcci differiscono le une dalle altre soprattutto dal punto di vista della quantità di pioggia cumulata che innesca fenomeni franosi superficiali, a parità di durata dell'evento meteorico. La soglia empirica stima un quantitativo di pioggia cumulata di innesco molto inferiore rispetto a quello modellato dalle soglie fisicamente basate. Questa differenza è dell'ordine di 4-40 volte considerando diverse condizioni iniziali di pressione interstiziale. La soglia empirica ricostruita è, inoltre, caratterizzata da numerosi "falsi positivi", che corrispondono ad eventi che presentano condizioni pluviometriche simili a quelle di eventi di innesco, che tuttavia non hanno prodotto documentati fenomeni di franosità superficiali. Tra le soglie pluviometriche fisicamente basate ricostruite, quella realizzata per eventi con condizioni di pressione interstiziale antecedenti uguali a 0 kPa stima quantitativi di pioggia cumulata di innesco molto inferiori rispetto a quelli stimati per valori di pressione interstiziale antecedente uguali a -10 o -5 kPa. Inoltre, la soglia fisicamente basata per pressione interstiziale antecedente di 0 kPa stima correttamente tra i momenti di innesco anche alcuni eventi reali, per i quali è noto che le condizioni idrologiche del suolo prima dell'evento di innesco erano di completa saturazione. Questi risultati preliminari devono necessariamente essere raffinati, in particolare integrando la soglia empirica con altri eventi di innesco di frane superficiali e le soglie fisicamente basate con altre modellazioni in corrispondenza di altri contesti geologico-geomorfologici e di usi del suolo fortemente suscettibili a franosità superficiale. Da queste analisi, sarà possibile individuare il miglior tipo di soglia pluviometrica, che potrebbe, quindi, essere utilizzata per finalità di allerta. Questo lavoro è stato realizzato nell'ambito del progetto ANDROMEDA, finanziato da Fondazione Cariplo.

ABSTRACT

Rainfall induced shallow landslides are hazardous phenomena causing significant damages all over the world. Rainfall thresholds are the most used tool to predict the occurrence of such instabilities over large areas. Most of these thresholds are empirical, basing on past rainfall events triggered landslides. These present several limitations, due to the amount and the uncertainty of available data and neglecting antecedent soil hydrological conditions. Physically-based thresholds could take into account also for soil hydrological responses towards rainfalls. Thus, this work aimed to compare both these typologies of thresholds, reconstructed for a 250 km^2 area of northern Italian Apennines prone to shallow landsliding. Preliminary results of this research show the significant differences between thresholds reconstructed by means of different approaches. Empirical threshold estimates a lower triggering cumulated amount of rainfall than the values for physically-based thresholds, considering the same duration of rainfall event. Antecedent pore water pressure conditions have significant effects on reconstructed threshold, reducing the amount of rainfall leading to instabilities according to conditions approaching soil complete saturation. These preliminary results will be improved in order to create threshold useful for early warning strategies.

KEYWORDS: *shallow landslides, rainfall thresholds, Apennines*

INTRODUCTION

Shallow landslides affecting superficial deposits of small thickness (generally lower than 2 m) are common phenomena all over the world. They involve small volumes of soils, but they can be densely distributed across territories and, moreover, can affect slopes close to urbanized areas. For this reason, they can have negative effects on cultivations, infrastructures and, sometimes, human losses (PETLEY, 2012).

Rainfall is the most important triggering factor of these phenomena. Thus, the prediction of shallow landslides is generally based on the definition of rainfall thresholds, which are lower bounds of rainfall conditions that have resulted in landslides, including grainfall intensity vs. rainfall duration and cumulated event rainfall vs. rainfall duration (GUZZETTI *et alii*, 2008; SEGONI *et alii*, 2014; MELILLO *et alii*, 2018; PICIULLO *et alii*, 2018).

Empirical rainfall thresholds, derived from the analysis of the characteristics of past rainfall triggering events, are widely developed in different geological, geomorphological and environmental contexts (GUZZETTI *et alii*, 2008; MELILLO *et alii*, 2018). Instead, these are sometimes limited in their effectiveness, due to: i) the availability and quality of the rainfall and of the landslides information (NIKOLOPOULOS *et alii,* 2014; PERES *et alii*, 2018); ii) the definition of the rainfall features responsible for the slope failures (GUZZETTI *et alii*, 2008); iii) neglecting the antecedent soil hydrological conditions (PAPA *et alii*, 2013).

For overcoming these limits, several authors (FRATTINI *et alii*, 2009; PAPA *et alii*, 2013; PERES *et alii*, 2018) proposed physically-based approaches to reconstruct these thresholds. These approaches imply the definition of a reliable hydrological model of the studied area, that can assess the soil responses to real or synthetic rainfall events in terms of changes in soil water content or soil pore water pressure from an initial condition. The modeled hydrological response is inserted in a slope stability model, that estimates the possible occurrence of a shallow slope failure according to the input hydrological conditions. Thus, rainfall events responsible to cause soil hydrological conditions leading to modeled slope instability are identified and used to calibrate thresholds.

The wide use of rainfall thresholds in early-warning system tools for landslides prediction (PICIULLO *et alii*, 2018) encourages to make comparisons between empirical and physically-based approaches to define rainfall thresholds, allowing to identify the best solution to be implemented in a shallow landslides prone area. For these reasons, this work aimed to compare these two typologies of rainfall thresholds reconstructed to assess the shallow landslides triggering conditions at large scale, in a susceptible area towards shallow landsliding of the northern Italian Apennines. This area corresponded to the Oltrepò Pavese hilly sector (Lombardy region).

This work was made in the frame of the ANDROMEDA project, funded by Fondazione Cariplo.

THE STUDY AREA

The study area, the hilly sector of Oltrepò Pavese (265 km^2 wide, Fig. 1a), corresponds to the northern termination of Italian Apennines and is characterized by a complex geological and geomorphological setting.

The northern part of the area presents a bedrock geology dominated by Mio-Plicocenic successions, composed by sandstones, conglomerates, marls and evaporitic deposits. In this sector, superficial soils, derived from bedrock weathering, are mostly clayey or clayey-sandy silts, with thickness ranges between few tens of centimeters and about 2 m. Hillslopes are steep, with average slope angle between 15 and 20° and maximum values up to 35°. Instead, the central and southern parts of the study area are characterized by calcareous and marly flyshes, alternated with sandstones, marls and melanges with a peculiar block-in-matrix at the outcrop scale. Due to the different lithology of the bedrock, superficial soils have a clayey or a silty clayey texture and a thickness generally ranging between 1 and more than 4 m, also due to the presence of deep slow-moving landslides. Hillslopes have a medium steepness, with typical slope angle of 8-15°.

The climate of the area is characterized by an average yearly rainfall amount between 700 and 1000 mm, increasing from western to eastern sectors and from northern to southern sectors. There are two different rainy seasons, with maxima in May and October-November (Rossetti & Ottone, 1979).

The area is significantly prone to shallow landsliding induced by very intense, and sometimes concentrated, rainfalls (Bordoni *et alii*, 2015). Several triggering events occurred in Oltrepò Pavese since 1990s (Meisina, 2004; Meisina & Scarabelli, 2007). In particular, in the last 10 years, more than 2500 shallow landslides (Fig. 1b) occurred in this area, as a consequence of rainfall triggering events characterized by a duration between 30 and 62 h, a cumulated amount ranging between 40 and 160 mm, a mean intensity between 0.8 and 2.8 mm/h (Bordoni *et alii*, 2015).

Most of the shallow landslides are classified as complex phenomena, starting as roto-translational slides and evolving in flows (Cruden & Varnes, 1996). They are generally 10-70 m wide and 10-500 m long. Sliding surfaces are generally located at 1 m in depth, in correspondence of the contact between soil and weathered bedrock or between soil horizons characterized by different permeability (Bordoni *et alii*, 2015).

RECONSTRUCTION OF EMPIRICAL AND PHYSICALLY-BASED RAINFALL THRESHOLDS

Empirical rainfall thresholds were reconstructed by implementing CTRL-T tool, written in R open-source software and freely available at: http://geomorphology.irpi.cnr.it/tools/rainfall-events-and-landslidesthresholds/ctrl-algorithm/ctrl-code/CTRL_code.R/.

For a set of rain gauges and a multi-temporal shallow landslides inventory. this tool allows reconstruct empirical rainfall thresholds for the occurrence of such phenomena by means of the following steps: i) identification of distinct rainfall events along the time series of each rain gauge considering different lengths of dry periods, meaning significant times spans without rain, which depend on the climatic feature of the area (Tab. 1); ii) identification of rainfall conditions responsible for the triggering of the landslides present in the inventory; iii) definition of rainfall thresholds for possible landslide occurrence. Rainfall triggering conditions of each landslide in the inventory were estimated from the most representative rain gauge for that slope failure. This is identified automatically, from a set of rain gauges close to the landslide, as the closest rain gauge to the landslide between the ones located in a circular area centered. The radius of this area depends was chosen empirically according to the morphological features of the area and to the relative distances between each rain gauge.

Empirical rainfall thresholds and their uncertainties are, then, estimated adopting a frequentist method by sampling the rainfall conditions that triggered shallow landslides, in terms of duration in h (*D*) and cumulated amount in mm (*E*) of the events. The equation of the threshold is expressed as (eq. 1):

$$E = (\alpha)D^{(\mu)} \qquad \text{eq. 1,}$$

where α is a scaling constant and μ is the shape parameter of this power law function.

For further details on this method, we refer to Melillo *et alii* (2015, 2018).

This tool was applied considering hourly rainfall data collected in the period January 1990-January 2019 by a network of 20 rain gauges (average density of a rain gauge every 12 km^2; Fig. 1b). Moreover, an inventory collected all the shallow landslides triggered in the study area for the same time span was considered.

Physically-based rainfall thresholds were reconstructed identifying synthetic rainfall features, in terms of duration and cumulated amount, which could cause slope instability, modeled through a limit equilibrium slope stability model that computes slope safety factor (*Fs*). When Fs is equal or lower than 1, unstable conditions are reached and slope instability occurs. In this framework, a hydrological model based on the Richards' equation for mono-dimensional vertical infiltration with a Gardner (1958) negative exponential soil water characteristic curve (TRIGRS v. 2; Baum *et alii*, 2008) simulates the response of soil pore water pressure (ψ) to an input rainfall. Modeled pore water pressure is then, inserted, in a limit equilibrium model to calculate Fs for both saturated and unsaturated conditions (eq. 2):

$$Fs = tan\varphi'/tan\beta + (c' - \psi\gamma w\ tan\varphi')/(\gamma z sen\beta cos\beta) \qquad \text{eq.2,}$$

where φ' is the soil friction angle, c' is the effective cohesion, γw is the unit weight of the water, β is the slope angle, γ is the unit weight of the soil and z is the depth below the ground level at which a potential sliding surface could develop.

Each rainfall event, that causes a reduction of *Fs* to values lower or equal to 1, is considered a triggering event and is used to build the rainfall threshold.

As for the empirical ones, physically-based thresholds are estimated since the triggering events adopting a frequentist method by sampling the rainfall conditions that triggered shallow landslides, in terms of *D* and *E*.

Synthetic rainfalls used as input in physically-based approach corresponded to events characterized by average intensities of 1, 2, 5, 8, 10, 15, 20, 30, 50, 75, 100 mm/h, for a duration ranging between 1 and 120 h. 600 synthetic rainfall events were then obtained. The input soil properties and slope angle of the slope stability model corresponded to typical values measured in hillslopes prone to shallow landslides in Oltrepò Pavese area (BORDONI *et alii*, 2015; Tab. 2). Furthermore, different thresholds were reconstructed, considering different initial pore water pressure conditions, typical of the most wet periods in the study area: -10, -5 and 0 kPa (BORDONI *et alii*, 2015; Tab. 2).

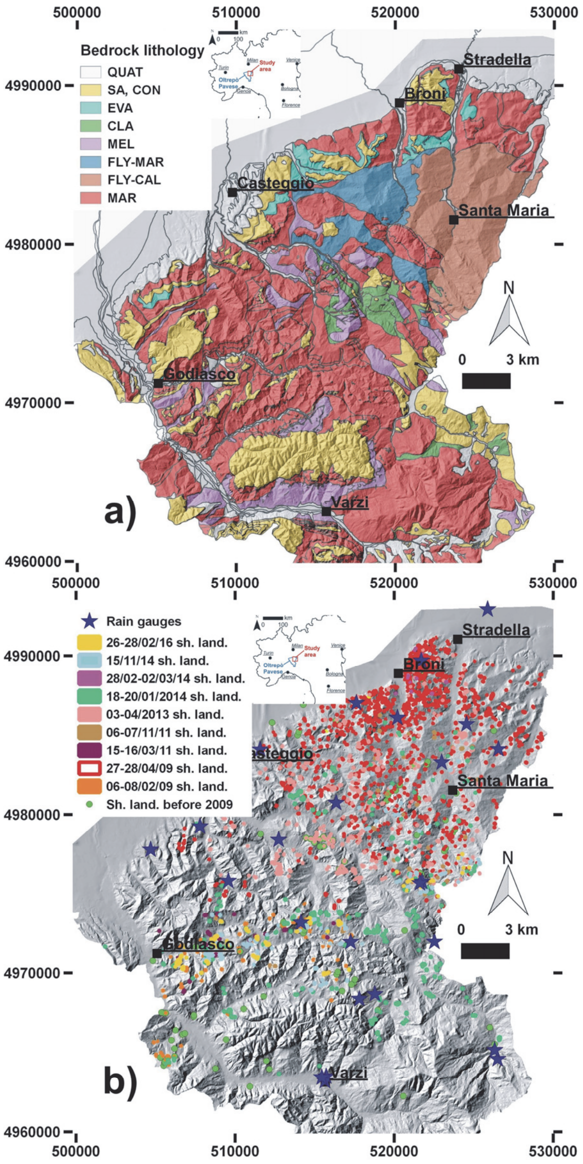

Fig. 1 - The study area (hilly sector of Oltrepò Pavese): a) lithological map of the bedrock (LEGEND: QUAT) quaternary alluvial deposits; SA, CON) sandstones and conglomerates; EVA) evaporitic deposits; CLA) claystones; MEL) melanges; FLY-MAR) flysches with predominant marly component; FLY-CAL) flysches with predominant calcareous component; MAR) marls); b) shallow landslides and rain gauges distribution

Parameter	Value		Unit
	C_w	C_c	
G_s	0.1	0.1	mm
E_r	0.2	0.2	mm
P_1	3	6	h
P_2	6	12	h
P_3	1	1	mm
P_4	24	48	h
R	10	10	km

Tab. 1 - Parameters used in CTRL-T tool for reconstructing empirical thresholds:
G_S, E_R and P_3) cumulated rainfall amounts, which are removed from the rainfall series under specific conditions; P1, P2 and P4) time periods used to remove irrelevant amount of rain and to reconstruct rainfall events; R) radius of the buffer to assign each landslide to the closest rain gauge; C_W) warm period in a year (spring-summer); C_C) cold period in a year (autumn-winter)

Parameter	Value	Unit
θ_s	0.42	m^3/m^3
θ_r	0.03	m^3/m^3
ω	0.006	kPa^{-1}
K_s	$1.5 \cdot 10^{-6}$	m/s
φ'	33	°
c'	0	kPa
γ	18.3	kN/m^3
z	1	m
β	30	°

Tab. 2 - Parameters used in the models used for reconstructing physically-based thresholds:
θ_s) saturated water content; θ_r) residual water content; ω) fitting parameter of soil water characteristic curve; K_s) saturated hydraulic conductivity; φ') soil friction angle; c') soil effective cohesion; γ) soil unit weight; z) soil depth; β) slope angle

RESULTS AND DISCUSSION

Figure 2 and Table 3 presented the main features of the estimated rainfall thresholds for different methodologies.

Shape parameter of the power law curved were similar between the different thresholds ($\mu = 0.01$-0.11).

Instead, the scaling constant α testified significant differences between the reconstructed curves, which resulted in different amount of rain responsible to trigger shallow landslides.

In fact, considering the same duration of a rainfall event, the modeled triggering cumulated amount was lower for the empirical threshold, compared to the ones of the physically-based thresholds.

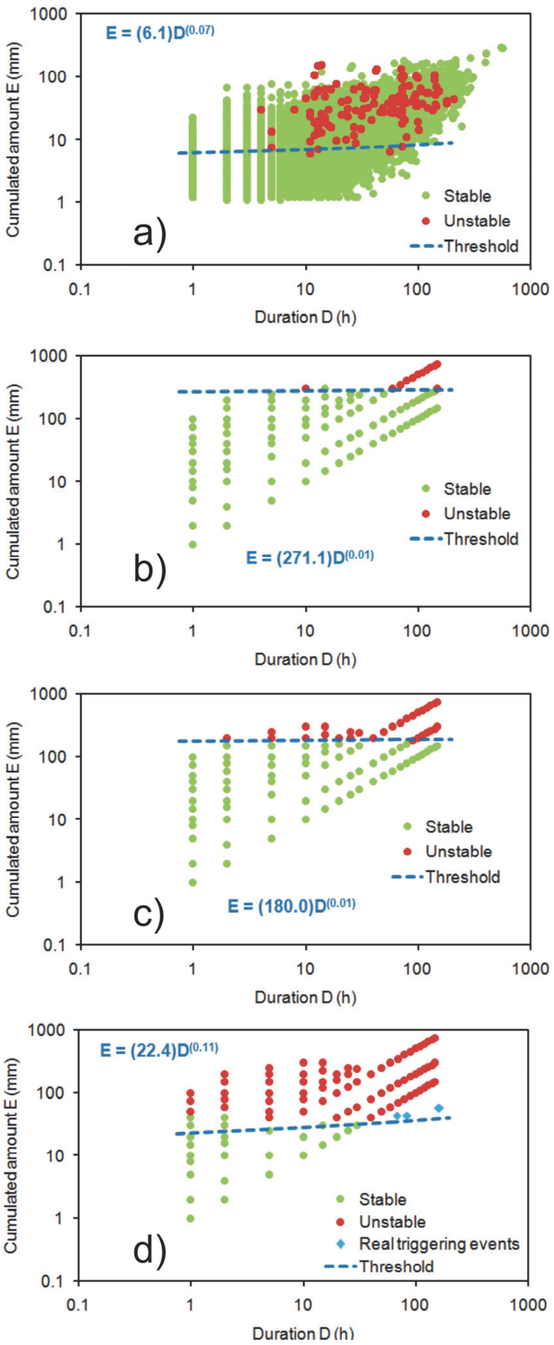

Fig. 2 - Rainfall thresholds reconstructed through empirical and physically-based approaches: a) empirical threshold; b) physically-based threshold considering an antecedent pore water pressure of -10 kPa; c) physically-based threshold considering an antecedent pore water pressure of -5 kPa; d) physically-based threshold considering an antecedent pore water pressure of 0 kPa

Threshold	α	µ
Empirical	6.1	0.07
Physically-based since -10 kPa	271.1	0.01
Physically-based since -5 kPa	180.0	0.01
Physically-based since 0 kPa	22.4	0.11

Tab. 3 - Parameters and skill scores of the reconstructed thresholds: α) scaling constant of these power law functions; µ) and shape parameter of these power law functions

In particular, the empirical threshold estimated, for a particular rainfall duration, a triggering rainfall cumulated amount: i) 4 times lower than the one of physically-based threshold with an antecedent pore water pressure of 0 kPa; ii) 29 times lower than the one of physically-based threshold with an antecedent pore water pressure of -5 kPa; iii) 44 times lower than the one of physically-based threshold with an antecedent pore water pressure of -10 kPa. Furthermore, this analysis demonstrated that the triggering rainfall amount changed significantly starting from antecedent pore water pressure conditions, with differences till 40 times from one to each other.

It is worth noting that a significant number of events, which did not provoke the triggering of shallow failures in the study area, were characterized by similar rainfall features of those ones that caused slope instabilities (Fig. 2a). This meant that this type of threshold determined a significant number of "false positive" events. Instead, the physically-based thresholds were not affected by this uncorrected information, presenting only rainfall events, whose model assessed landslides triggering, above the threshold line (Fig. 2b-d). Moreover, it is important to highlight that the physically-based threshold for antecedent pore water pressure condition equal to 0 kPa modeled correctly two shallow landslides triggering events (blue dot points in Fig. 2d) occurred for antecedent soil conditions of complete saturation (Bordoni *et alii*, 2015): i) 27-28 April 2009 (160 mm in 62 h); ii) 28 February-2 March 2014 (69 mm in 42 h).

CONCLUSIONS

This work presented the preliminary results of the comparison between rainfall thresholds for shallow landslides triggering reconstructed by means of different approaches in an area of northern Italian Apennines (Oltrepò Pavese hilly sector) very susceptible to these slope failures.

These results show that different types of thresholds are obtained using different methodologies. The difference on the reconstructed thresholds are significant, especially in terms of the cumulated rainfall amount estimated to be responsible of triggering shallow landsliding, considering the same rainfall duration. The empirical rainfall threshold estimates a lower amount of rainwater leading to triggering shallow failures than the ones assessed through the physically-based ones. Moreover, pore water pressure conditions before the beginning of an event have an important role on the triggering rainfall features. In fact, the more the pore water is close to nil values, the lower is the amount of rainfall which could induce the triggering of shallow landslides in the study area.

Since these preliminary analyses, a physically-based threshold seems to estimate better the rainfall conditions leading to shallow slope failure. The one modeled considering an antecedent pore water pressure equal to 0 kPa allows to recognize correctly the rainfall cumulated amount and duration which caused the triggering of shallow failures for initial soil conditions of complete saturation, as demonstrated for the events of 27-28 April 2009 and 28 February-2 March 2014. This is modeled without identifying several false positives, as occurred for the empirically reconstructed threshold.

Future developments of this work will be the refinement of both the typologies of rainfall thresholds, taking into account for other past landslides triggering events or to model rainfall conditions leading to shallow landsliding in correspondence of other prone settings (e.g. other soil types, particular land uses). This will allow to reconstruct the most effective thresholds, that may be implemented for early warning strategies.

ACKNOWLEDGEMENTS

This work has been in the frame of the ANDROMEDA project, which has been supported by Fondazione Cariplo, grant n°2017-0677.

REFERENCES

BAUM R.L., SAVAGE W.Z. & GODT J.W. (2008) - *TRIGRS - A Fortran program for transient rainfall infiltration and grid-based regional slope-stability analysis, version 2.0.* U.S. Geological Survey Open-File Report, 2008-1159: 75 pp.

BORDONI M., MEISINA C., VALENTINO R., LU N., BITTELLI M. & CHERSICH S. (2015) - *Hydrological factors affecting rainfall-induced shallow landslides: from the field monitoring to a simplified slope stability analysis*. Engineering Geology, **193**: 19–37. DOI:10.1016/j.enggeo.2015.04.006

CRUDEN D.M. & VARNES D.J. (1996) - Landslide types and processes. IN:TURNER A.K. & SCHUSTER R. (EDS.).*Landslides: investigation and mitigation*. 36-75, National Academy Press, Washington D.C.

FRATTINI P., CROSTA G. & SOSIO R. (2009) - *Approaches for defining thresholds and return periods for rainfall-triggered shallow landslides*. Hydrological Processes, **23**: 1444-1460. DOI:10.1002/hyp.7269.

GARDNER W.R. (1958) - *Some steady-state solutions of the unsaturated moisture flow equation with application to evaporation from a water table.* Soil Science, **85**: 228-232.

GUZZETTI F., PERUCCACCI S., ROSSI M. & STARK C.P. (2008) - *The rainfall intensity-duration control of shallow landslides and debris flows: an update*. Landslides,**5**, 1: 3–17. DOI: 10.1007/s10346-007-0112-1.

MEISINA C. (2004) - *Swelling-shrinking properties of weathered clayey soils associated with shallow landslides*. Quaterly Journal of Engineering Geology and Hydrogeology, **37**, 2: 77-94. DOI: 10.1144/1470-9236/03-044.

MEISINA C. & SCARABELLI S. (2007) - *A comparative analysis of terrain stability models for predicting shallow landslides in colluvial soils*. Geomorphology **87**: 207-223. DOI:10.1016/j.geomorph.2006.03.039.

MELILLO M., BRUNETTI M.T., PERUCCACCI S., GARIANO S.L. & GUZZETTI F. (2015). An algorithm for the objective reconstruction of rainfall events responsible for landslides.Landslides, **12**, 2: 311-320. DOI:10.1007/s10346-014-0471-3.

MELILLO M., BRUNETTI M.T., PERUCCACCI S., GARIANO S.L., ROCCATI A. & GUZZETTI F. (2018) - *A tool for the automatic calculation of rainfall thresholds for landslide occurrence*. Environmental Modelling & Software **105**: 230-243. DOI:10.1016/j.envsoft.2018.03.024.

NIKOLOPOULOS E.I., CREMA S., MARCHI L., MARRA F., GUZZETTI F. & BORGA M. (2014) - *Impact of uncertainty in rainfall estimation on the identification of rainfall thresholds for debris flow occurrence*. Geomorphology,**221**: 286-297. DOI:10.1016/j.geomorph.2014.06.015.

PAPA M.N., MEDINA V., CIERVO F. & BATEMAN A. (2013) - *Derivation of critical rainfall thresholds for shallow landslides as a tool for debris flow early warning systems*. Hydrology and Earth System Sciences, **17**: 4095-4107. DOI: 10.5194/hess-17-4095-2013.

PERES D.J., CANCELLIERE A., GRECO R. & BOOGARD T.A. (2018)- *Influence of uncertain identification of triggering rainfall on the assessment of landslide early warning thresholds.* Natural Hazards and Earth System Sciences, **18**: 633-646. DOI: 10.5194/nhess-18-633-2018.

PETLEY D. (2012) - *Global patterns of loss of life from landslides*. Geology,**40,** 10: 927-930. DOI: 10.1130/G33217.1.

PICIULLO L., CALVELLO M. & CEPEDA J.M. (2018) - *Territorial early warning systems for rainfall-induced landslides*. Earth-Science Reviews, **179**: 228–247. DOI: 10.1016/j.earscirev.2018.02.013.

ROSSETTI R. & OTTONE C. (1979) - *Esame preliminare delle condizioni pluviometriche dell'Oltrepò Pavese e dei valori critici delle precipitazioni in relazione ai fenomeni di dissesto*. Geologia Applicata e Idrogeologia, **14**: 83-99.

SEGONI S., ROSSI G., ROSI A. & CATANI, F. (2014). *Landslides triggered by rainfall: a semiautomated procedure to define consistent intensity-duration thresholds* Computer and Geosciences, **63**: 123-131.DOI: 10.1016/j.cageo.2013.10.009.