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Automated reconstruction of rainfall events responsible for shallow landslides

G. Vessia^{1,2}, M. Parise², M. T. Brunetti^{3,4}, S. Peruccacci³, M. Rossi^{3,4},
C. Vennari², and F. Guzzetti³

¹Department of Engineering and Geology, University “G. d’Annunzio” of Chieti-Pescara, Via dei Vestini 31, 66031 Chieti Scalo (CH), Italy

²Institute of Research for Hydrogeological Protection, National Research Council, Via Amendola 122 I, 70126 Bari, Italy

³Institute of Research for Hydrogeological Protection, National Research Council, Via Madonna Alta 126, 06128 Perugia, Italy

⁴Department of Earth Science, University of Perugia, Piazza dell’Università 1, 06123 Perugia, Italy

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Correspondence to: G. Vessia (g.vessia@unich.it, g.vessia@ba.irpi.cnr.it)

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Abstract

Over the last 40 years, many contributions have been devoted to identifying the empirical rainfall thresholds (e.g. intensity vs. duration ID , cumulated rainfall vs. duration ED , cumulated rainfall vs. intensity EI) for the initiation of shallow landslides, based on local as well as worldwide inventories. Although different methods to trace the threshold curves have been proposed and discussed in literature, a systematic study to develop an automated procedure to select the rainfall event responsible for the landslide occurrence has rarely been addressed. Nonetheless, objective criteria for estimating the rainfall responsible for the landslide occurrence (effective rainfall) play a prominent role on the threshold values. In this paper, two criteria for the identification of the effective rainfall events are presented: (1) the first is based on the analysis of the time series of rainfall mean intensity values over one month preceding the landslide occurrence, and (2) the second on the analysis of the trend in the time function of the cumulated mean intensity series calculated from the rainfall records measured through rain gauges. The two criteria have been implemented in an automated procedure written in R language. A sample of 100 shallow landslides collected in Italy by the CNR-IRPI research group from 2002 to 2012 has been used to calibrate the proposed procedure. The cumulated rainfall E and duration D of rainfall events that triggered the documented landslides are calculated through the new procedure and are fitted with power law in the (D, E) diagram. The results are discussed by comparing the (D, E) pairs calculated by the automated procedure and the ones by the expert method.

1 Introduction

Rainfall is a known trigger of landslides and its role in initiating slope instability depends on the local geological, morphological, and hydrological conditions, and their complex interactions (De Vita and Reichenbach, 1998; Guzzetti, 1998; Wiczorek and Guzzetti, 2000). A common approach to relate rainfall measurements to the occurrence of land-

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slides is to use empirical rainfall thresholds (e.g., Caine, 1980; Innes, 1983; Crosta and Frattini, 2000; Aleotti, 2004; Cannon and Gartner, 2005; Guzzetti et al., 2007, 2008). To determine the thresholds, information on (i) the geographical location, (ii) the occurrence time of the landslide, and (iii) the amount of rainfall that presumably caused the slope instability is necessary. Location and time of landslide occurrence are commonly obtained from chronicles, historical archives, technical reports, and time series of historical landslides. Information on rainfall measurements, including rainfall duration D and cumulated event rainfall E , considered responsible for the slope failures is obtained typically from single rain gauges or from networks of rain gauges (Aleotti, 2004; Guzzetti et al., 2007), although examples exist of the use of satellite-derived rainfall estimates (Hong et al., 2006; Kirschbaum et al., 2009).

A problem with the definition of empirical rainfall thresholds for possible landslide occurrence consists in the subjectivity inherent to the determination of the rainfall conditions that have resulted in landslides (Aleotti, 2004; Guzzetti et al., 2007; Brunetti et al., 2010; Melillo et al., 2014). In an attempt to overcome this limitation, we present a procedure – and an associated code written in R, the free software environment for statistical computing and graphics (<http://www.r-project.org/>) – for the objective (i.e., reproducible) determination of the rainfall conditions that triggered the documented landslides. The procedure explores a record of rainfall measurements and determines the rainfall conditions (i.e., the rainfall duration D , in hours, and the cumulated event rainfall E , in mm) considered responsible for the failure, using information on the landslide occurrence time. The procedure does not consider the environmental (i.e., geological, morphological, hydrological, meteorological or climatic) conditions where the landslide occurred. We tested the procedure using a sample of 100 rainfall events that have resulted in landslides in Italy in the 11 year period from 2002 to 2012.

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2 Background

Guzzetti et al. (2007, 2008) performed a critical review of the literature on empirical rainfall thresholds for possible landslide occurrence, pointing out inconsistencies in the use of terms, in the rainfall metrics, and in the methods used to determine the thresholds. Guzzetti et al. (2007) grouped the approaches used to determine the thresholds into three broad categories: (i) approaches that use precipitation measurements obtained for rainfall events that have resulted (or have not resulted) in landslides, (ii) approaches that consider the antecedent rainfall conditions, and (iii) other approaches that use combinations of indexes representative for both event and antecedent rainfalls calibrated on different case studies. The first two types of approaches are discussed hereafter.

Approaches of the first type consider solely the event rainfall (i.e., the rainfall fallen during the rainfall-triggering event), and do not take into account the antecedent rainfall conditions. Moreover, they do not suggest general rules to identify the rainfall responsible for landslide initiation. These studies focus on empirical evidences drawn from specific sites without attempting to derive criteria to be used elsewhere. Many are the contributions at this regard but herein only a few of them are cited. For instance, Onodera et al. (1974) showed that the number of landslides in Japan increased significantly when the cumulated event rainfall exceeded 150 to 200 mm, and the rainfall mean intensity exceeded 20 to 30 mm h⁻¹. Oberstelehn (1976) found that about 250 mm of cumulated event rainfall were necessary to trigger landslides in the San Benito County, California. Nilsen et al. (1976), working in the Alameda County, California, showed that landslides occurred when the cumulated event rainfall exceeded 180 mm. Brand et al. (1984) suggested that landslides in Hong Kong were triggered by rainfall events exceeding 175 mm in 24 h, or 70 mm in one hour.

Approaches of the second type take into account the antecedent rainfall conditions, i.e. the precipitation fallen in the period that precedes the rainfall event directly responsible for the landslide. These approaches are based on the identification of the length

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for the antecedent period that can vary from a few hours (Larsen and Simon, 1993; Wilson and Wieczorek, 1995) to several months (Govi et al., 1985; Calcaterra et al., 2000; Cardinali et al., 2006), depending on e.g. the rainfall history, the local physiography, the climatic conditions, and heuristic knowledge. Lumb (1975) suggested that the antecedent rainfall cumulated in a period of 15 days combined with the rainfall intensity for the event was responsible for the initiation of landslides in Hong Kong. Campbell (1975), working in southern California, proposed a combination of the cumulated rainfall necessary to bring the soil to field capacity, and an event rainfall intensity exceeding the minimum rate of surface infiltration to exceed soil drainage, to trigger soil slips in his study area. Govi et al. (1985), working in Piedmont, NW Italy, determined that a 60 day antecedent rainfall exceeding 140 mm was needed to trigger landslides, and that a total precipitation (i.e., the antecedent plus the event rainfall) exceeding 300 mm was likely to initiate the landslides. Ng and Shi (1998), working in Hong Kong, indicated a critical duration of the antecedent rainfall between three and seven days. Pasuto and Silvano (1998), working in the Cordevole River basin, NE Italy, established a 15 day period of cumulated rainfall for landslide occurrence, with the peak rainfall occurring two days before the failure. Rahardjo et al. (2001), working in Singapore, suggested five days of antecedent rainfall as the critical duration for landslide occurrence. Cardinali et al. (2006) established that landslides in SW Umbria, Italy, are likely to occur when the antecedent rainfall exceeds 590 mm in a 3 month period, or 700 mm in a 4 month period. Glade et al. (2000), working in New Zealand, proposed a combined model that considered the rainfall fallen during the day of the landslide and the antecedent rainfall in a period of 10 days before the landslide. The antecedent rainfall was weighted on the temporal distance from the day of the landslide.

Guzzetti et al. (2007) pointed out that, regardless of the adopted approach, a common problem to many investigations is the lack of unambiguous criteria for the identification of the duration of the rainfall event considered responsible for the landslide occurrence. Uncertainty in the duration of the rainfall affects the measurement of the cumulated event rainfall, and the computation of the rainfall mean intensity. Only a few



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authors have specified clear criteria to determine the duration of the rainfall event responsible for landslide occurrence. Aleotti (2004), working in Piedmont, NW Italy, proposed to use the rainfall duration between the time when the cumulated rainfall curve exhibits an abrupt (distinct) increase (i.e., significantly augmented rainfall intensity) and the time when the landslide occurred, or was reported. A disadvantage of this approach is that, albeit the criteria for the definition of the event and the computation of the rainfall metrics were specified, they were decided for site-specific conditions and no attempts were performed to calibrate them under diverse climatic and geographic conditions. Thus, no general rules are drawn up elsewhere for predicting the rainfall conditions for landslide initiation. In an attempt to overcome – or to mitigate – this problem, we propose an objective procedure for the identification of the duration D of rainfall events responsible for landslides. The automated procedure is based on a set of criteria that are similar to those used by Brunetti et al. (2010) to determine, manually, the rainfall conditions that have resulted in landslides in Italy (hereafter named the expert method). In section three, the expert method is recalled and described. Section four illustrates the automated procedure, which reconstructs automatically the rainfall (D, E) conditions that have resulted in landslides. Section five describes a case study. Finally, section six discusses results from the automated procedure and the expert method in terms of the (D, E) pairs and the empirical mean rainfall threshold curves.

3 The expert method

Brunetti et al. (2010) working in Italy proposed a heuristic, expert method that exploits landslide and rainfall information for determining the rainfall duration D (in h), and the rainfall mean intensity I (in mmh^{-1}) presumably responsible for the observed landslides.

The information on the geographical location of the landslide is used to select the rain gauge that likely measured the rainfall responsible for the slope failure (representative rain gauge). Criteria for selecting the representative rain gauge include (i) its



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geographical distance from the landslide, (ii) the difference between its elevation and the landslide elevation, and (iii) the general physiographical settings in the areas where the landslide and the rain gauge are located. When a representative rain gauge is selected, the method uses the known or inferred time of the landslide to determine the “end time” T_E of the rainfall event responsible for the failure. The end time is taken to coincide with the hour, the end of the period of the day (e.g., night, morning, noon, afternoon, evening), or the end of the day when the landslide occurred, depending on the temporal accuracy associated with each landslide information (Brunetti et al., 2010). For shallow landslides that failed after the end of the rainfall event (a rare but possible situation, e.g. Guzzetti et al., 2004), the end time is taken to coincide with the end of the rainfall event. The selection of the “start time” T_S of the rainfall event is more difficult, and requires additional selection criteria. Rainfall is not necessarily continuous, and consequently it results difficult to separate successive rainfall events. A typical rainfall event consists of periods of rain separated by dry periods without rain. Some of the dry periods are short (in the order of hours), and do not affect the identification of the rainfall event. When the dry periods are long, their effect can be relevant, and the preceding and the following rainfall measurements are considered as distinct rainfall events. In the heuristic method, a specific criterion determines the minimum length of the dry period to separate two rainfall events. Decision on the length of the dry period depends primarily on the local climatic conditions. Brunetti et al. (2010) considered a two-day (48 h) period without rainfall (dry period) to separate rainfall events during the late spring and summer period (May–September), and a four-day (96 h) period for the other seasons (October–April). Peruccacci et al. (2012) adopted the same criteria to identify rainfall events with landslides in the Abruzzo, Marche and Umbria regions, central Italy. Vennari et al. (2014), working in Calabria, southern Italy, used a two-day period without rainfall between April and October, and a four-day period between November and March to separate successive rainfall events.

Once the start time T_S and the end time T_E of a rainfall event are identified, the duration of the event is $D = T_E - T_S$ (in h) and the corresponding cumulated event rainfall



E is the sum of the rainfall fallen in the time interval D (in mm). The rainfall mean intensity is $I = E/D$ (in mm h^{-1}).

The heuristic, expert method is apparently straightforward to be applied, but it involves a high subjectivity. Further, results of a long-term project for the collection of information on the rainfall conditions that have resulted in landslides in Italy (Gariano et al., 2012) indicate that it is difficult for an investigator to apply rigorously the established criteria, and to be consistent with the identification of the rainfall events. The higher the number of investigators, the higher the subjectivity, that makes it difficult to prepare accurate catalogues of rainfall events with landslides for large geographical areas. Moreover, the heuristic reconstruction of rainfall events is a labour-intensive, time-consuming and error-prone activity that limits the definition of reliable rainfall thresholds for the possible occurrence of landslides.

4 The automated procedure

The automated procedure reproduces the actions performed by an investigator who examines a record of hourly rainfall measurements searching for a rainfall period responsible for the initiation of a documented landslide. To identify the rainfall period in the record, the investigator (and the procedure) needs information on the start time T_S and the end time T_E of the rainfall event. As for the expert method, T_E coincides with the landslide occurrence time, most commonly obtained from chronicles, anecdotal information, or from a catalogue of landslide events (Brunetti et al., 2010). Again, when the landslide occurs after the end of the rainfall period, T_E coincides with the end of the rainfall period. In this work, we define a rainfall event as an ensemble of consecutive rainfall and dry periods responsible for the occurrence of a known landslide. The length of the dry periods that separate two successive rainfall events, ΔT_D , can vary depending on seasonal or climatic conditions (Peruccacci et al., 2012). To cope with this variability, the procedure uses different lengths of the dry periods. We test the

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automated procedure setting two dry period lengths, i.e., $\Delta T_D = 48$ h and $\Delta T_D = 72$ h. These values can be changed according to the local seasonal or climatic conditions.

In the following, we explain the new procedure, in five steps. Figure 1 shows the logical framework for the procedure.

5 4.1 Data input and preliminary processing

At the INPUT stage, the landslide occurrence time T_E is read (by the automated procedure) together with the rainfall measurements recorded by the representative rain gauge, for a time span P equal to 30 days (720 h) before T_E . The P value is a preliminary choice that the operator can change according to the climatic conditions.

10 In STEP 1, the record of hourly rainfall measurements (Fig. 2) is entered and checked by the procedure. As a matter of fact, before proceeding with the identification of the rainfall event start time T_S , the procedure identifies possible “missing data” in the record. These missing data, hidden in the rainfall records, correspond to temporary rain gauge out of service and can last many hours. They can be a source of errors in the identification of the (D, E) condition responsible for the failure. Hence, if these are detected the procedure interrupts and the reconstruction of that rainfall event is skipped.

4.2 Calculation of cumulated mean rainfall intensities

20 In STEP 2, starting from T_E and progressing backwards in time, the procedure calculates the rainfall mean intensity I within non-overlapping time windows of variable fixed length, W . Here, we use $W_1 = 3$ h, $W_2 = 6$ h, and $W_3 = 12$ h, but the window length can be changed according to specific requirements. The procedure calculates three time series of rainfall mean intensity values $\{I(W_1)\}$, $\{I(W_2)\}$, $\{I(W_3)\}$. Each intensity value is assigned to the end of the time window W . Hence, the intensity series show a zero value at T_E and the first intensity value at $T = W$. Figure 3a, d and f shows the preceding steps. Intensity series are useful to highlight the rainy pattern by smoothing the

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small amount of rains that are not relevant for the landslide initiation. The number of computed values N in the three time series decreases as the length of the time window increases, i.e., $N_1 = 240$, $N_2 = 120$, and $N_3 = 60$ for W_1 , W_2 and W_3 , respectively.

In STEP 3, for each time window W the procedure cumulates the calculated rainfall mean intensity values C , and outputs three cumulated time series of mean rainfall intensity values: $C_1\{I(W_1)\}$, $C_2\{I(W_2)\}$ and $C_3\{I(W_3)\}$ (Fig. 3b, d and f). Use of time windows W of different lengths is performed in an attempt to capture differences in the rainfall temporal pattern responsible for the landslide. For instance, for a rainfall characterized by short rainy and dry periods, a short window of three hours highlights well the rainfall conditions that caused the landslide, whereas for a rainfall with long rainy period separated by long dry periods, a window of 12 h is more suited to highlight the rainfall conditions that initiated the failure.

4.3 Examination of the cumulated rainfall mean intensity series

Next, in STEP 4, the procedure explores the three cumulated mean intensity curves $C_1\{I(W_1)\}$, $C_2\{I(W_2)\}$, $C_3\{I(W_3)\}$ starting from T_E . It searches for those portions of the curves characterized by negligible rainfall amounts that can reasonably be considered ineffective for the initiation of the landslide. These periods are flat (very-low gradient) portions of the cumulated curves. The case of $C_2\{I(W_2)\}$ is illustrated in Figs. 4a and the inset figure (Fig. 4b). To identify the flat portions, the procedure starts from T_1 (e.g. $T_1 = 6$ h in Fig. 4b inset) and calculates the difference between two cumulated values ΔC at $T_i + \Delta T_D$ and at T_i , where T_i varies between $T_1 = W_2$, $T_2 = T_1 + W_2 \dots T_N = T_{N-1} + W_2$ for $N = 112$. In the Fig. 4a inset, $T_1, T_2 \dots T_{11}$ are considered for $C_2\{I(W_2)\}$ and $\Delta T_D = 48$ h. Then, the procedure checks whether $\Delta C \leq \varepsilon$, where ε is the maximum rainfall mean intensity in the period ΔT_D that can be considered ineffective for the initiation of a landslide. The value of ε depends on multiple conditions, including the type of landslide, the meteorological and climatic conditions, and the local land use. For the discussion, we use $\varepsilon = 0.2 \text{ mm h}^{-1}$. This value can be changed by the operator.

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If $\Delta C > \varepsilon$ the test is not satisfied, and the procedure is repeated shifting backwards in time $T_i = T_j + W$, and repeating the calculation. If $\Delta C \leq \varepsilon$, then the corresponding T_i is selected and assumed as the approximate start time of the rainfall event, T_S^* . In Fig. 4b inset: $T_i = T_{11} = T_S^* = 66$ h.

5 4.4 Searching for the actual start time T_S

To decide which is the actual T_S , at STEP 5 the procedure goes back to the original hourly rainfall series in the selected time interval $[T_S^*, T_E]$ (as shown in Fig. 4c). The actual T_S is taken as the first rainy hour before the T_S^* . In the example, Fig. 4c, T_S^* is 66 h but T_S is identified at 63 h, due to the presence of three hours without rain.

10 Finally, the procedure calculates as the output values the rainfall duration D , the cumulated rainfall E , and the rainfall mean intensity I of the identified rainfall event.

4.5 Software

The described procedure is implemented in a specific script written for R, the free software environment for statistical computing and graphics (<http://www.r-project.org/>). The script reads the input rainfall and ancillary data from standard text files, and outputs the results in the form of standard text and Adobe[®] PDF files. The script is independent of the temporal resolution of the rainfall measurement. It is implemented and tested using hourly rainfall data, but it is applicable to sub-hourly data (e.g., rainfall measurements every 5, 10, 20, or 30 min), to rainfall cumulated over more than one hour (e.g., every 2, 3, 6, 12 h), or to daily rainfall measurements. The script works with rainfall data cumulated over fixed periods, and cannot be used on the raw data recorded by a rain gauge. Raw records of rainfall measurements consist typically of unevenly spaced sequences of timings when a rainfall measurement was recorded, and can contain spurious or service information (e.g., codes used to report specific errors or malfunctioning conditions). The raw rainfall measurements transmitted by the rain gauge need to be pre-processed before they can be used by the script.

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5 Discussion on possible applications of the automated procedure

The procedure is applied to reconstruct automatically 100 rainfall events that initiated 100 single landslides in the Italian territory. This is a small sample from a larger catalogue of more than 2000 rainfall events with landslide compiled by the CNR-IRPI research group (Rossi et al., 2012). Then, a discussion on the resulting 100 (D, E) pairs calculated by the new procedure and the expert method (see Sect. 3) is undertaken.

The procedure reads the rain gauge measures of rainfall time series resulted in shallow landslides and provides six (D, E) pairs obtained from the combinations of W (W_1 , W_2 , and W_3) and ΔT_D (48 and 72 h). For the 100 considered landslides, the procedure calculates 100 (D, E) pairs for each combination (black circles), which are compared with the 100 (D, E) pairs (red squares) obtained from the expert method (Fig. 5a–f). It can be appreciated that for each landslide the expert method proposes one rainfall event whereas the automated procedure calculates six possible rainfall events. The calculated 100 (D, E) pairs exhibit six mean power law trends (the best-fit curve resulting from the Ordinary Least Squares) close to the expert mean power law trend. However, the best agreement between the automated procedure and the expert method is achieved with the combination W_2 and $\Delta T_D = 72$ h. Furthermore, it is worth noticing that the six mean power law trends obtained using the new procedure show a slope higher or equal (W_2 and $\Delta T_D = 72$ h) than that obtained using the expert method. This means that the automated procedure reconstructs more severe rainfall conditions that triggered landslides than the expert method.

Figure 6a and b plots the grand total of 600 (D, E) pairs together with the 100 from the expert method: the two mean power law keep similar trends. The differences in the two trends are more evident in the log-log graph (Fig. 6a). Figure 6b shows the two trends plotted in a semi-logarithmic chart: the difference appears to be very slight, and constant in time.

In conclusion, the application to a sample of 100 rainfall-induced landslides shows that the automated procedure enables to reconstruct multiple (D, E) pairs responsible

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for the failures. A detailed calibration of the variables used within the procedure is needed to make it applicable to other settings with different climatic conditions.

6 Final remarks

The proposed procedure calculates the rainfall conditions responsible for the landslide initiation using measurements from rain gauges. This procedure is among the first attempts to recognise, in the series of rainy periods, objective rules for determining the rainfall conditions (D , E and I) that resulted in landslides. It is based on an algorithm that uses the three variables ε , W and ΔT_D . These must be calibrated as a function of the local climate and rainfall characters. In the present release the limitations of this procedure are (1) its empirical bases for the calibration of ε , and (2) its application to a limited number of rainfall events and to narrow territorial extension. The procedure has been applied to a sample of 100 landslides occurred in Italy in the period from 2002 to 2012, showing results similar to those obtained with the expert method in terms of mean power law trends. The new procedure seems therefore to be useful to build national or regional empirical rainfall thresholds. However, it shall be further validated on a wider sample of landslides, and on worldwide inventories as well.

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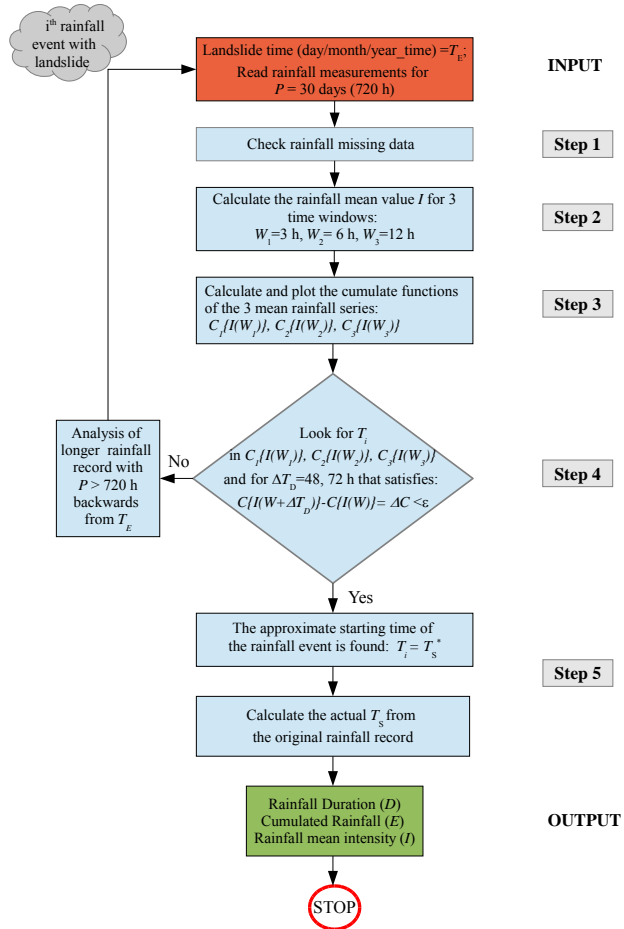


Fig. 1. Flowchart of the automated procedure summarized into five steps and two input and output steps.

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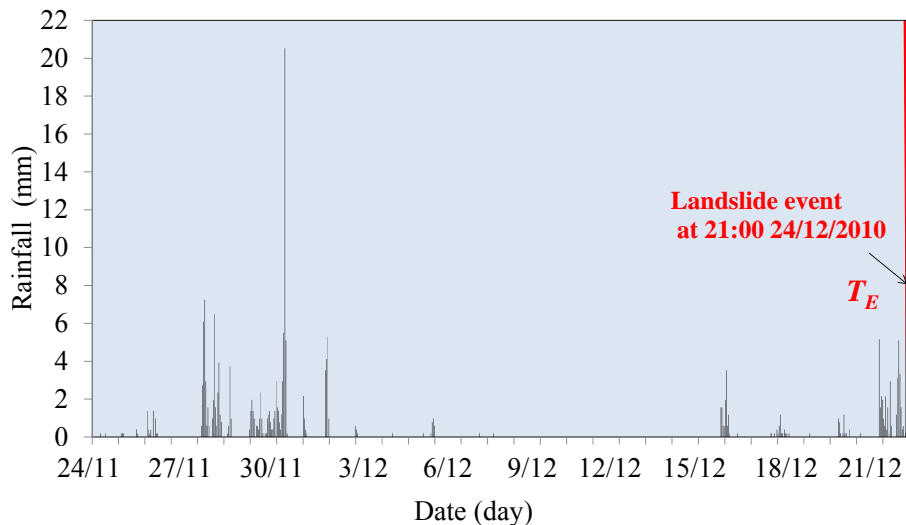


Fig. 2. The rainfall record read by the automated procedure (input step) whose time length is 30 days backwards the date of the landslide.

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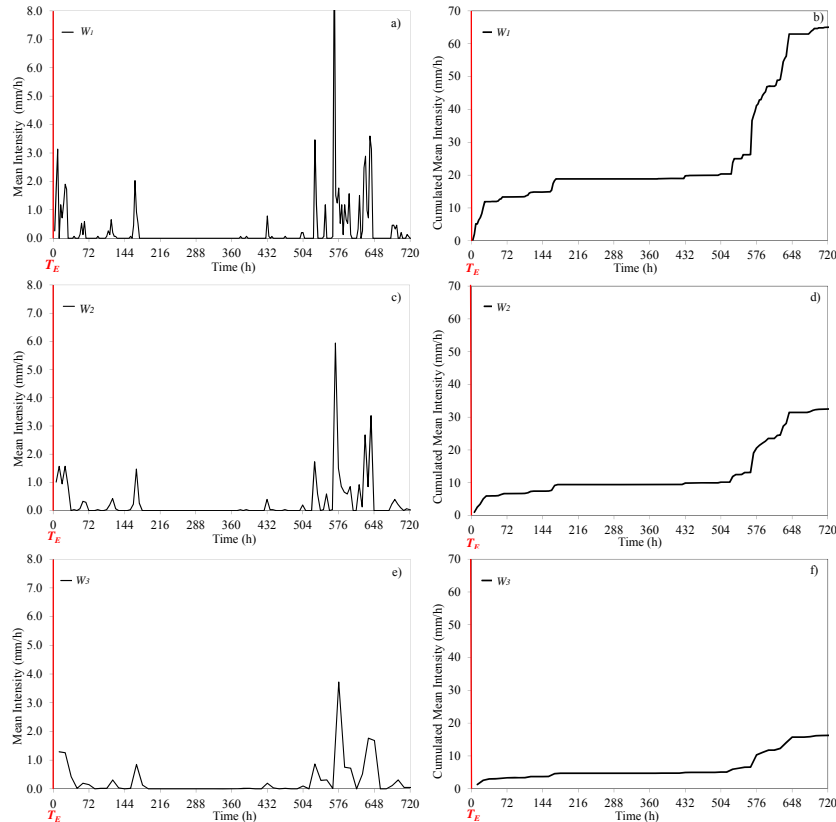


Fig. 3. The automated procedure STEPS 2 and 3 (Fig. 1) are applied to the case study reported in Fig. 2. Starting from the INPUT rainfall record, the time series of the mean intensities (**a**, **c**, **e**) and the cumulated mean intensities (**b**, **d**, **f**) are calculated. These series of one month (720 h) are plotted with the time axis inverted, that is the time 0 coincides with T_E . The plots (**a**) and (**b**) refer to the time window W_1 ; the plots (**c**) and (**d**) to W_2 and the plots (**e**) and (**f**) to W_3 .

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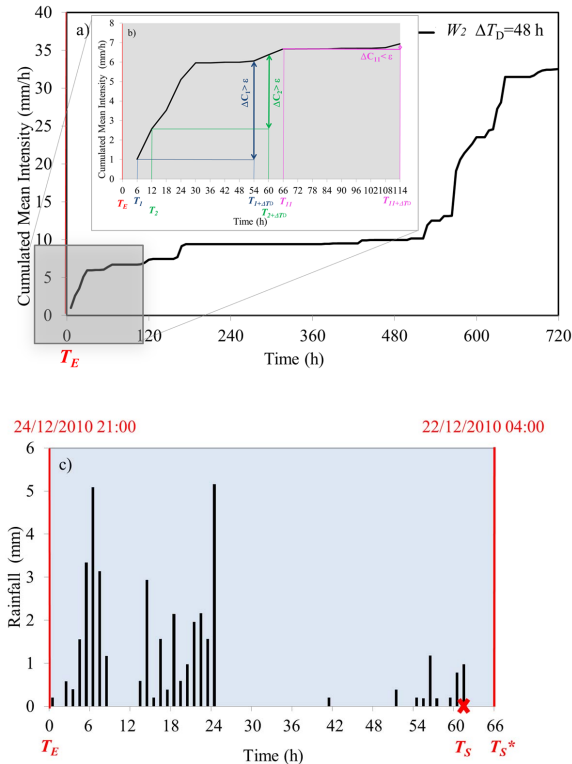


Fig. 4. The automated procedure STEPS 4 and 5 (Fig. 2) are applied to the case study reported in Fig. 2. STEP 4: **(a)** the cumulated mean intensity related to the case $W = 6$ h and ΔT_D is analyzed to find out the cumulated mean intensity difference $\Delta C < \epsilon = 0.2 \text{ mm h}^{-1}$, where a flat trend is detected. **(b)** The zoom in the cumulated mean intensity shows, in detail, how this difference is calculated between $T_1 \dots T_{11}$ and $T_{1+48h} \dots T_{11+48h}$. STEP 5: **(c)** when T_S^* is found out, the procedure goes back to the rainfall series and analyses the record portion between $[T_S^*, T_E]$ in order to calculate T_S .

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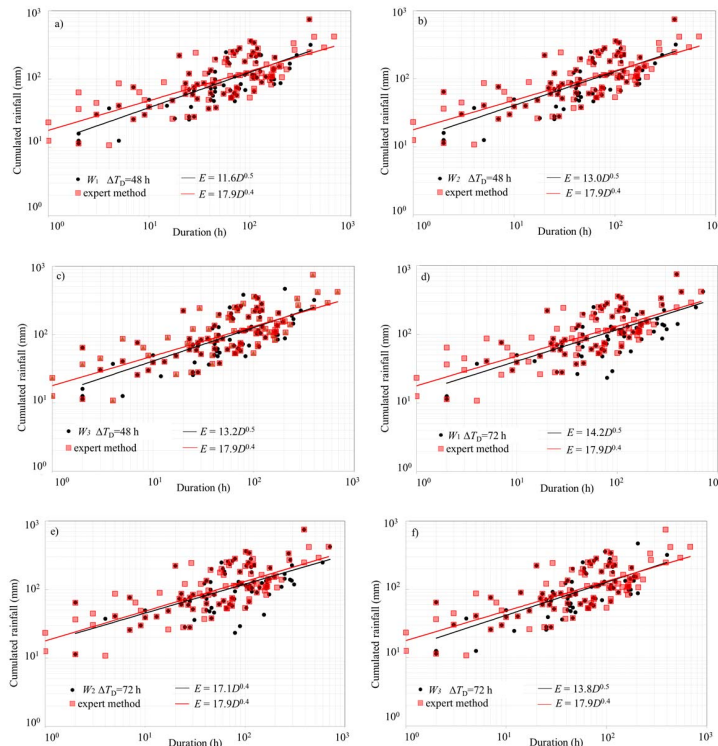


Fig. 5. The plots of 100 (D, E) pairs calculated by the expert method (red square) and the automated procedure (black circle) for six combinations of W and ΔT_D : **(a)** W_3 and $\Delta T_D = 48$ h; **(b)** W_2 and $\Delta T_D = 48$ h; **(c)** W_1 and $\Delta T_D = 48$ h; **(d)** W_3 and $\Delta T_D = 72$ h; **(e)** W_2 and $\Delta T_D = 72$ h; **(f)** W_1 and $\Delta T_D = 72$ h. Black and red lines are the mean trends of the automated and expert procedures, respectively.

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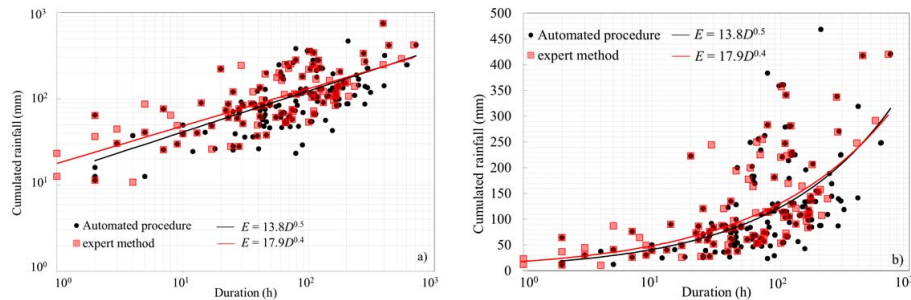


Fig. 6. The plots of (D, E) pairs and their mean trend lines (red for the expert method and black for automated procedure) for 100 pairs calculated by the expert method (red square) and 600 pairs by the automated procedure (black circle): **(a)** log–log graph; **(b)** semi-logarithmic chart.

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