TXT-tool 2.039-1.5 An Algorithm for the Objective Reconstruction of Rainfall Events Responsible for Landslides

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Abstract

The primary trigger of damaging landslides in Italy is intense or prolonged rainfall. Definition of the rainfall conditions responsible for landslides is a crucial issue and may contribute to reducing landslide risk. Criteria for identifying the rainfall conditions that could initiate slope failures are still lacking or uncertain. Expert investigators usually reconstruct rainfall events manually. In this paper, we propose an algorithm for the objective and reproducible definition of rainfall conditions responsible for landslides, from a series of hourly rainfall data. The algorithm, which is implemented in R (http://www.r-project.org), performs a series of actions: (i) removes isolated events with negligible amount of rainfall and random noise generated by the rain gauge; (ii) aggregates rainfall measurements in order to obtain a sequence of distinct rainfall events; (iii) identifies single or multiple rainfall conditions responsible for the slope failures. The result is the objective reconstruction of the duration, *D*, and the cumulated rainfall, *E*, for rainfall events, and for rainfall conditions that have resulted in landslides. We tested the algorithm using rainfall and landslide information for the period between January 2002 and December 2012 in Sicily, Southern Italy. The algorithm reconstructed 13,537 rainfall events and 343 rainfall conditions as possible triggers using the information on 163 documented landslides. The comparison between automatic and manually method highlights that most (87.7%) of the rainfall conditions obtained manually were reconstructed accurately. Use of the algorithm

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should contribute to reducing the current subjectivity inherent in the manual treatment of the rainfall and landslide data.

Keywords
Algorithm · Landslide · Rainfall · Rainfall event · Threshold

Contents

1 Introduction

Landslides are widespread phenomena that cause casualties and economic damage worldwide (Brabb and Harrod 1989; Keefer and Larsen 2007; Salvati et al. 2010; Petly 2012). In Italy, rainfall is a primary trigger of landslides. The prediction of rainfall-induced landslides relies largely on the definition of empirical rainfall thresholds. Generally, rainfall thresholds are determined using empirical distributions of rainfall conditions that have resulted in landslides, including rainfall intensity, *I*, versus rainfall duration, *D*, (e.g., Caine 1980; Aleotti 2004; Guzzetti et al. 2007, 2008; Cannon et al. 2008; Martelloni et al. 2012; Staley et al. 2012; Rosi et al. 2012, 2015; Lee et al. 2014) and cumulated event rainfall, *E*, versus rainfall duration, *D*, (e.g., Innes 1983; Cannon and Ellen 1985; Wieczorek 1987; Crosta and Frattini 2001; Kanji et al. 2003; Vennari et al. 2014; Gariano et al. 2015).

Rainfall thresholds are affected by uncertainties that limit their use in modern landslide warning systems (Aleotti 2004; Godt et al. 2006; Guzzetti et al. 2008; Bach-Kirschbaum et al. 2012; Komac et al. 2014; Segoni et al. 2015). A specific source of uncertainty lays in the characterization of the rainfall event responsible for the landslides (Guzzetti et al. 2007). An objective definition of the rainfall conditions responsible for the failure does not exist (Guzzetti et al. 2007) or is poorly formalized and ambiguous (Aleotti 2004). Criteria for establishing the duration of an event, or for deciding the conditions to separate (or to combine) successive events (Reichenbach et al. 1998; Guo 2002; Guzzetti et al. 2007; Saito et al. 2010; Shamsudin et al. 2010; Segoni et al. 2014a, b) are also lacking. Generally, investigators do not specify how individual rainfall events are determined. Subsequently, the identification and measurement of the rainfall conditions responsible for landslides remains subjective.

In this work, we propose an algorithm for the objective definition of rainfall events, and for the quantitative measurement of the rainfall conditions that characterize a rainfall event. The algorithm systematizes the actions performed and the decisions taken, by an expert investigator that defines heuristically rainfall events from a typical rainfall record and information on landslide occurrence (Guzzetti et al. 2007, 2008; Brunetti et al. 2010; Berti et al. 2012). Use of the algorithm will contribute to reducing uncertainty in the definition of landslide-triggering rainfall events, to compiling large catalogues of rainfall events with landslides and to determining reliable rainfall thresholds for possible landslide occurrence.

2 The Algorithm

The framework shown in Fig. 1 represent the structure of the proposed algorithm described in this section. Using a standard record of rainfall

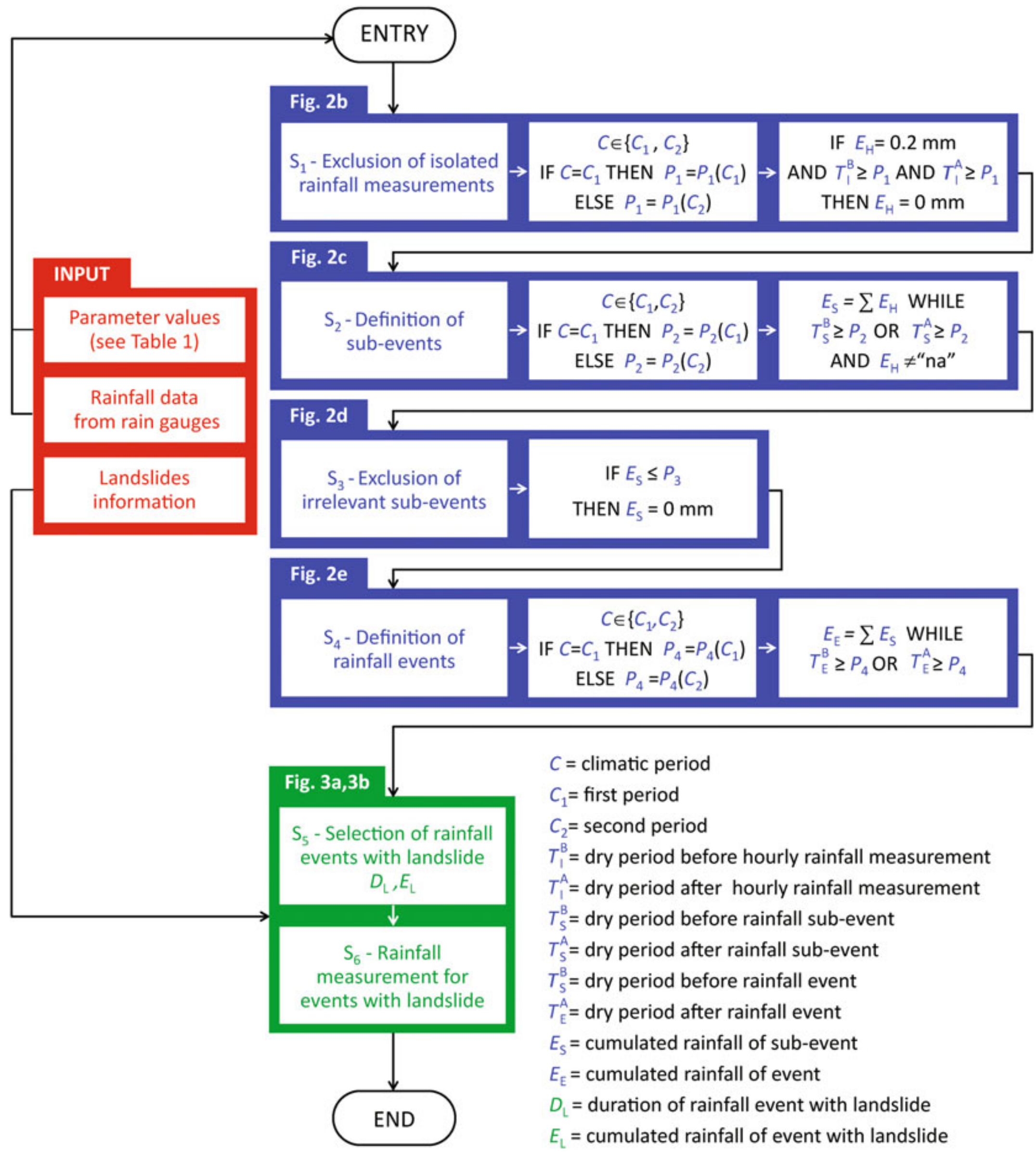

Fig. 1 Structure of the algorithm proposed for the objective reconstruction of rainfall events and of rainfall conditions responsible for landslides

measurements and a limited number of parameters, the procedure (1) detects rainfall events from a standard record of rainfall measurements, (2) determines the rainfall duration (D_E) and the cumulated (total) rainfall (E_E) for the detected events, (3) associates landslide information (or the lack of landslide information) to the detected rainfall events, and (4) measures the rainfall duration (D_L) and the cumulated rainfall (E_L) responsible for the landslide.

The structure of the algorithm includes two main logical blocks (Fig. 1). The first performs the automatic reconstruction of the rainfall events. The second selects the rainfall events responsible for the landslides. A rainfall event is a period of continuous rainfall or a chronological ensemble of periods of continuous rainfall in a rainfall record, separated from preceding and successive rainfall events by periods with no rainfall (i.e., dry periods, T). The length of the dry periods may vary, depending, e.g., on seasonal, meteorological or climatic conditions. To illustrate the algorithm, we use a record of hourly rainfall measurements obtained for a single rain gauge in Sicily, southern Italy. We then test the algorithm in the same geographical region using rainfall measurements obtained from a network of 105 rain gauges.

2.1 Reconstruction of the Rainfall Events

For the reconstruction of the individual rainfall events from a record of rainfall measurements, the algorithm perform a series of five steps including a pre-processing step (Fig. 1).

Step 0 *Pre-processing of rainfall data*

From a single rain gauge, the algorithm works on a continuous (hourly) record of rainfall measurements obtained in a period. These measurements are generally discontinuous (incomplete), with individual or multiple rainfall measurements missing in the record due to technical and operational problems. The gaps in the record can cover periods in a variable range from a minimum of 1 h to several days or weeks and are typically marked by specific "tags" in the record. In some cases, tags are missing in the rainfall record, and it is difficult—or impossible—to single out measurement gaps in the record. The algorithm checks the continuity of the record and detects the gaps. More specifically, the algorithm searches the rainfall record for tagged and untagged missing measurements and replaces them with the "na" tag (measurement not available). In addition, a rainfall record may contain hourly rainfall measurements, E_H, that are lower than the instrumental sensitivity of a rain gauge (e.g., G_S = 0.2 mm), $E_H < G_S$. In this case these measurements are considered noise in the rainfall record, and the algorithm sets the measurements to E_H = 0.0 mm. After these preliminary operations, the corrected rainfall record is ready to be processed to reconstruct the rainfall events. Figure 2a shows an example of a corrected rainfall record.

Step 1 *Detection and exclusion of isolated rainfall measurements*

The algorithm starts by searching for isolated hourly rainfall measurements in the corrected rainfall record (S_1 in Fig. 1). An isolated rainfall measurement is defined as an hourly measurement separated from the immediately preceding and the immediately following rainfall measurements by dry periods (T_I^B before, and T_I^A after) that exceed a given length P_1. The length of the dry period (P_1) depends on the seasonal or the local climatic conditions, i.e., $P_1 = P_1(C)$.

In Sicily, as in the whole Mediterranean area, two seasonal periods can be identified for landslide initiation: (i) a "warm" spring-summer period C_W, and (ii) a "cold" autumn-winter period C_C. For the C_W warm period the dry interval separating isolated rainfall measurements is P_1 = 3 h, and for the C_C cold period the dry interval is P_1 = 6 h (Table 1).

Study of the mean annual evapotranspiration (ETR) in Italy (Melillo 2009) using the Thornthwaite-Mather method (Thornthwaite and Mather 1957) revealed that the evapotranspiration in the warm period is about twice the evapotranspiration in the cold period, ETR(C_W) ≅ 2 · ETR(C_C). Here, we assume that the evapotranspiration is inversely proportional to the time necessary to dry the soil, and we set a factor of two between all relevant parameters in the C_W and C_C periods. Once the isolated rainfall measurements are identified, their individual relevance for the reconstruction of the rainfall conditions responsible for possible landslide occurrence is evaluated. We consider relevant the isolated hourly rainfall measurements that exceed a minimum value E_R (e.g., E_R = 0.2 mm), $E_H > E_R$, and irrelevant the measurements with $E_H = E_R$. The later measurements, shown by red

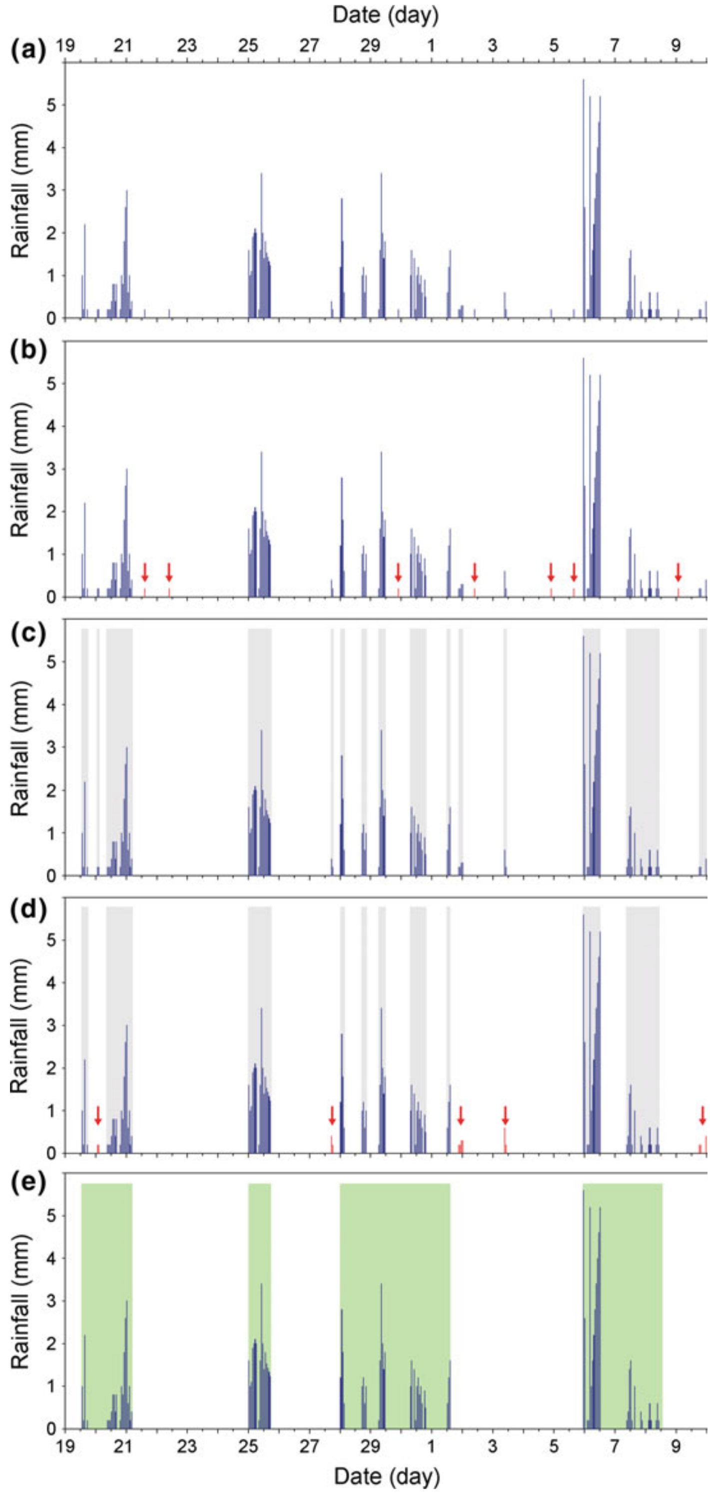

Fig. 2 Example of the application of the algorithm for the reconstruction of rainfall events. **a** *Blue bars* show hourly rainfall measurements obtained by the Aragona-Torre Salto rain gauge, Sicily, southern Italy, from 19 September to 10 October 2006. **b** Selection of the isolated hourly rainfall measurements (*red bars*), shown by *red arrows*. **c** Identification of the rainfall sub-events, highlighted by *grey-shaded* areas. **d** Selection of irrelevant sub-events (*red bars*), shown by *red arrows*. **e** Identification of rainfall events, highlighted by *green-shaded* areas

Table 1 Parameters used by the algorithm

Step	Parameter name	Parameter value		Unit
		P(C_W)	P(C_C)	
S_0	G_S	0.2	0.2	mm
S_1	E_R	0.2	0.2	mm
S_1	P_1	3	6	h
S_2	P_2	6	12	h
S_3	P_3	1	1	mm
S_4	P_4	48	96	h

The first column lists the step in the logical framework of the algorithm where the parameter is used (Fig. 1). Two climatic periods are considered: C_W a "warm" spring-summer period; and C_C a "cold" autumn-winter period

bars in Fig. 2b, contribute a negligible (irrelevant) amount of rain to the rainfall event (e.g., due to the presence of fog and/or humidity in the air). For the purpose of the analysis, the algorithm sets the isolated, irrelevant measurements to E_H = 0.0 mm.

Step 2 *Identification of rainfall sub-events*

After first step, the algorithm proceeds by searching for individual rainfall sub-events (S_2 in Fig. 1), where a rainfall sub-event is a period of continuous rainfall separated from the immediately preceding and the immediately following sub-events by dry periods with no rain. As before, the length P_2 of the dry period may vary, depending on the seasonal and the climatic conditions, $P_2 = P_2(C)$. The separation depends on the meteorological conditions and the rainfall characteristics in the two climatic periods. In the C_W warm period, rainfall is primarily brought to the study area by local convective storms, whereas in the C_C cold period rainfall is most commonly the result of regional frontal systems. When reconstituting a rainfall sub-event, the algorithm checks for the continuity of the rainfall record in the sub-event. If single or multiple "na" measurements (interruptions) are found in the rainfall record in the period covered by the sub-event, the sub-event is excluded from the analysis. If no "na" measurements are found, the sub-event is defined (grey shaded areas in Fig. 2c), and rainfall metrics are computed for the sub-event, including: (i) the sub-event duration D_S, computed by summing the number of hours in the sub-event, and (ii) the sub-event total rainfall E_S, computed by summing the hourly rainfall measurements in the sub-event, $E_S = \sum E_H$.

Step 3 *Exclusion of irrelevant rainfall sub-events*

Next, the algorithm searches for sub-events that can be considered irrelevant for the reconstruction of rainfall events responsible for landslide occurrence (S_3 in Fig. 1). For the purpose, a sub-event is considered irrelevant if the cumulated (total) rainfall for the sub-event is lower than a given threshold value $E_S \leq P_3$, regardless of the duration of the sub-event. In a Mediterranean climate, P_3 = 1 mm (Table 1) is a reasonable threshold to exclude sub-events whose contribution can be considered irrelevant for the possible initiation of rainfall-induced landslides. Irrelevant sub-events (red bars in Fig. 2d) are excluded from the subsequent analysis.

Step 4 *Identification of rainfall events*

In this step, the algorithm aggregates single or multiple sub-events to obtain single rainfall events (S_4 in Fig. 1). The single rainfall event is defined as a period of continuous rainfall, or an ensemble of periods of continuous rainfall, separated from the preceding and the successive events by dry periods. Again, the minimum length P_4 of the inter-event dry periods may vary, depending on meteorological and seasonal conditions i.e., $P_4 = P_4(C)$. As an example, to identify the rainfall events (Fig. 2c), we used a minimum dry period $P_4 = 48$ h for the C_W warm period, and a minimum dry period of $P_4 = 96$ h for the C_C cold period (Table 1). After the reconstruction of the rainfall events (green shaded areas in Fig. 2e), the algorithm calculates rainfall metrics for each of the detected rainfall events, including: (i) the event duration D_E, computed summing the number of hours in the rainfall event (including hours for which $E_H = 0$), and (ii) the event total cumulated rainfall E_E, computed by summing the sub-event rainfall $E_E = \sum E_S$.

2.2 Selection of the Rainfall Events Responsible for Landslides

In two additional steps, described in the following, the algorithm combines independent information on the temporal occurrence of landslide(s) with the information on the rainfall events obtained before (Fig. 1).

Step 5 *Selection of rainfall events with landslides*

In the first additional step, the algorithm selects the rainfall events for which information on landslide occurrence is available. We assign to each landslide a record of rainfall measurements obtained from a single rain gauge. Criteria to select the rain gauge include proximity, the elevation difference between the rain gauge and the landslide, and the local morphological setting (Brunetti et al. 2010; Peruccacci et al. 2012). The algorithm compares the dates (start date and end date) of the rainfall events identified by the first logical block, with a record listing the date (day and time) of occurrence of the landslides. Each landslide in the temporal record (Fig. 3a) is associated to a single rainfall event (Fig. 3b).

Step 6 *Rainfall measurements for events with landslides*

In this step the algorithm calculates the rainfall metrics responsible for the failure, namely: (i) the rainfall duration D_L, and (ii) the cumulated rainfall E_L. Note that the rainfall duration D_L and the cumulated rainfall E_L responsible for landslide occurrence are not necessarily the same as the rainfall duration D_E and the cumulated event rainfall E_E defined at the end of the first logical block for the entire rainfall event (Fig. 3b).

Most commonly, landslides occur before (and sometimes well before) the end of a rainfall period, and the rainfall after the landslide occurrence cannot be considered relevant for the initiation of the slope failure. In this case, $E_L < E_E$ and $D_L < D_E$. Occasionally, landslides fail after the end of the rainfall event (Guzzetti et al. 2004). In this case, the cumulated rainfall responsible for the landslide corresponds to the cumulated event rainfall, $E_L = E_E$, and the rainfall duration is $D_L = D_E$. The algorithm considers the different conditions, and calculates the correct values for D_L and E_L.

For complex rainfall events (Fig. 3b)—which are the majority in a typical rainfall record—it is often difficult (or impossible) to decide a single duration, and the corresponding cumulated amount of rain responsible for the landslides. In this case, the algorithm reconstructs multiple aggregations of rainfall sub-events that are likely to trigger landslides. In Fig. 3c, d and e we show that the complex rainfall event portrayed in Fig. 3b is characterized by three sub-events with significantly different rainfall durations (D_L = 28, 91 and 178 h) and cumulated rainfall amounts (E_L = 104.2, 218.4 and 263.2 mm). Without external information, the three sub-events identified by the algorithm are equally probable as possible landslide triggers.

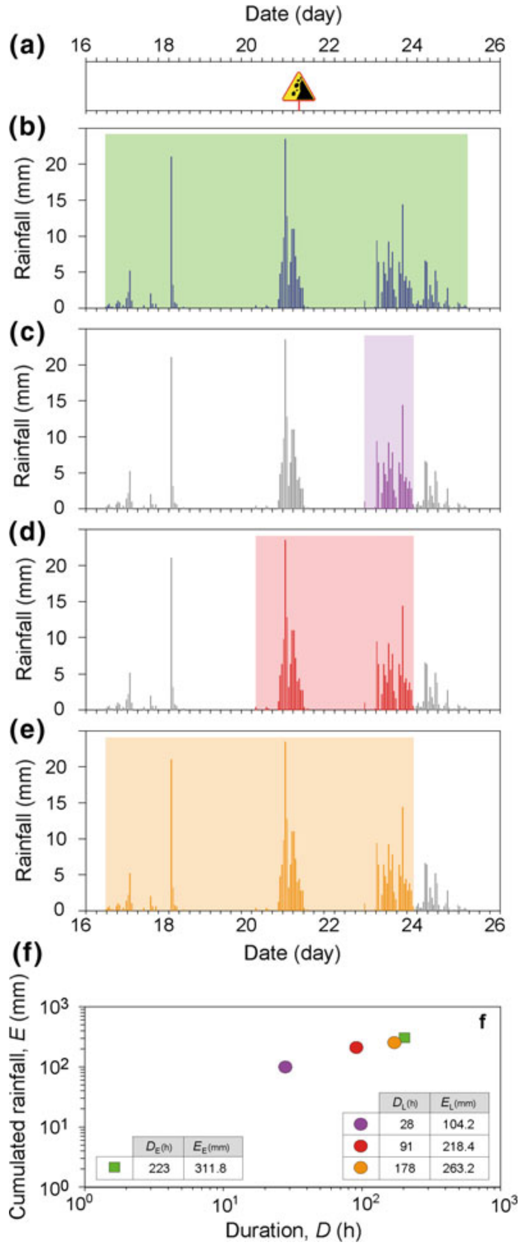

Fig. 3 Application of the algorithm for the reconstruction of rainfall events that have resulted in landslides. **a** Time period from 16 to 26 December 2006. *Traffic sign* shows time of occurrence of a landslide near to the Riposto-Praiola rain gauge, Sicily, southern Italy. **b** *Blue bars* show hourly rainfall measurements obtained by the Riposto-Praiola rain gauge between 16 and 26 December 2006. The *green-shaded* area highlights the rainfall event identified by the first logical block of the algorithm. *Purple*, *red*, and *orange bars* in (**c**)–(**e**) show rainfall measurements that represent the first, second, and third sub-events, respectively. **f** Rainfall conditions for the identified events. *Green square* shows the rainfall duration, D_E, and the cumulated rainfall, E_E, for the rainfall event considered in (**b**). *Purple*, *red*, and *orange dots* show the D_L and E_L conditions that have resulted in landslides for the three periods considered in (**c**)–(**e**) respectively

3 Software

We developed a code for the proposed algorithm using the R open-source software for advanced statistical computing and graphics, release 2.15.2 (http://www.r-project.org). The software uses two text files as input: one listing the rainfall record, and a second file with the necessary landslide information. The software is available from: http://geomorphology.irpi.cnr.it/tools/rainfall-events-and-landslides-thresholds/definition-of-rainfall-events-and-rainfall-events-with-landslides/algorithm/, together with the rainfall and landslide data used to prepare Figs. 2 and 3

4 Test Case

We tested the proposed algorithm using rainfall and landslide data available in Sicily, Southern Italy (Fig. 4). The rainfall data consisted of hourly rainfall measurements collected in the 11-year period from 1 January 2002 to 31 December 2012 by a network of 105 rain gauges operated by the Sistema Informativo Agrometeorologico Siciliano (SIAS). Figure 4 shows the geographical distribution of the 105 rain gauges (white and red squares). The landslide information consisted of the geographical location and the occurrence time of 163 rainfall induced landslides in the period from July 2002 to November 2011 (yellow dots in Fig. 4). The information on landslide occurrence was collected from digital archives of national and local newspapers and blogs, and from technical reports provided by local Fire Brigades in Sicily.

We selected a subsample of 59 rain gauges in the vicinity of the single landslides (red squares in Fig. 4) to reconstruct the rainfall sub-events responsible for the failures.

Prior to the development of the algorithm, we had determined the rainfall duration D_L^* and the corresponding cumulated event rainfall E_L^* responsible for the ensemble of 163 rainfall-induced landslides in Sicily. For the purpose, we used the heuristic approach proposed by Brunetti et al. (2010) and updated by Peruccacci et al. (2012).

To separate two rainfall events with the heuristic approach we used a dry (no rain) period of two days (48 h) between April and October, and a dry period of four days (96 h) from November to March. Due to the Mediterranean climate (Köppen 1931; Trewartha 1968) in Sicily the warm period is longer (7 months from April to October) than the cold period (5 months from November to March). We determined the rainfall conditions for a

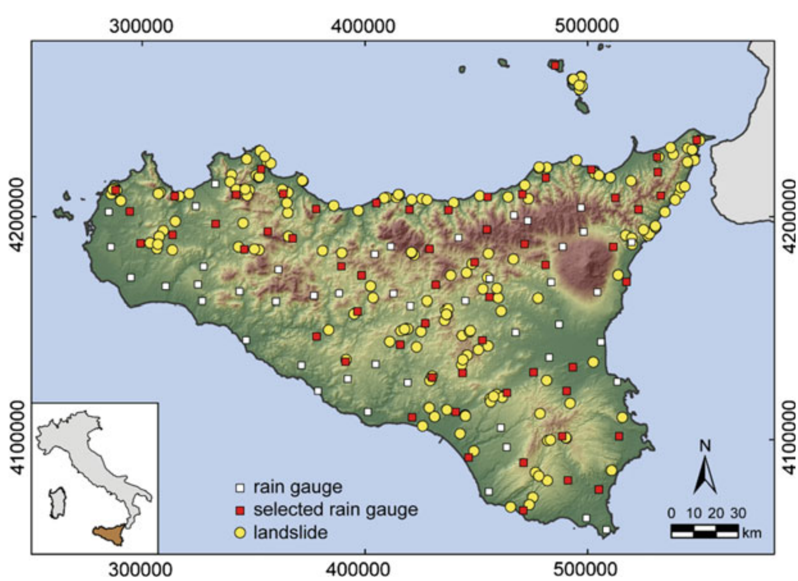

Fig. 4 Map showing the geographical location of 105 rain gauges in Sicily (*squares*). *Yellow dots* show the location of 163 rainfall-induced landslides in the period from July 2002 to November 2011. *Red squares* show the locations of the 59 rain gauges used in this study

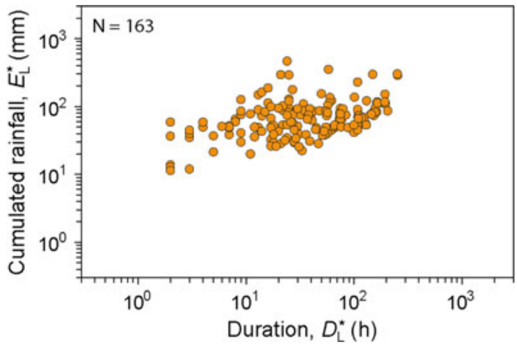

Fig. 5 Rainfall duration, D^*_L, and cumulated event rainfall, E^*_L, conditions (N = 163) responsible for the 163 landslides. Expert investigators determined the rainfall conditions using a heuristic approach

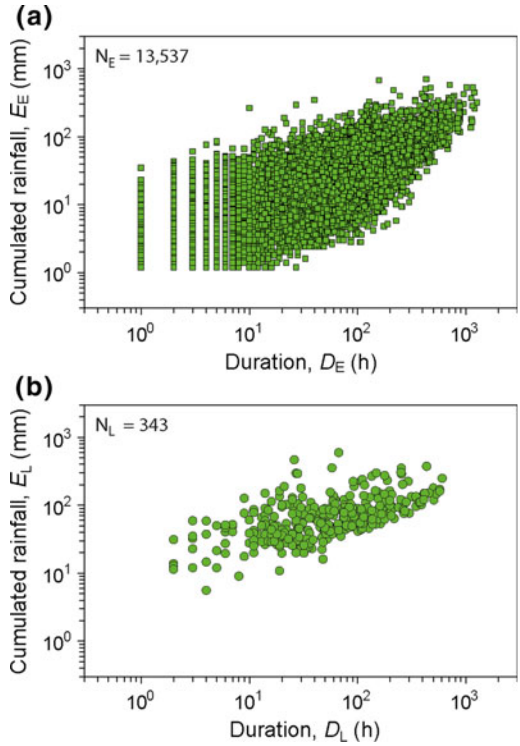

Fig. 6 **a** *Green squares* show the rainfall duration, D_E, and cumulated event rainfall, E_E, events (N_E = 13,537) reconstructed by the algorithm in the 11-year period from 2002 to 2012 using rainfall measurements obtained by 59 rain gauges (*red squares* in Fig. 4) and the parameters listed in Table 1. **b** *Green circles* show rainfall duration, D_L, and cumulated event rainfall, E_L, conditions for the subset of N_L = 343 rainfall events responsible for the 163 landslides shown by the *yellow dots* in Fig. 4

number of ambiguous cases based on experience. For each triggered landslide, a single set of rainfall (D_L, E_L) conditions considered responsible for the landslide was determined. This is a typical result obtained when deciding heuristically the rainfall conditions for possible landslide occurrence (Guzzetti et al. 2007, 2008; Brunetti et al. 2010; Peruccacci et al. 2012). Figure 5 portrays the N = 163 rainfall (D^*_L, E^*_L) conditions responsible for slope failures in Sicily reconstructed manually through expert judgment.

We then applied the algorithm to the same rainfall data and landslide information. To be consistent with the expert-based, heuristic method, we set the warm period C_W from April to October, and the cold period C_C from November to March. Table 1 lists the values for the parameters P_1, P_2, P_3, and P_4 used by the algorithm to reconstruct the rainfall events.

Figure 6a shows the distribution of the cumulated rainfall E_E as a function of the event duration D_E for N_E = 13,537 rainfall events in the 11-year period from 1 January 2002 to 31 December 2012 reconstructed by the algorithm using the subset of 59 rain gauges in the vicinity of the single landslides, and Fig. 6b shows the sub-set of N_L = 343 rainfall events with landslides reconstructed by the algorithm.

Because the heuristic method defined a single set of rainfall conditions for each landslide, the number of rainfall conditions reconstructed heuristically (Fig. 5) equals the number of landslides (N = 163). For each landslide, the algorithm reconstructed a variable number of rainfall conditions (from one to six) as possible landslide triggers. As a result, the number of rainfall conditions responsible for landslides identified by the algorithm is larger, N_L = 343 (Fig. 6b). Inspection of the reconstructed events revealed that for 71 landslides (43.6%) the algorithm reconstructed a single rainfall event, for 40 landslides (24.5%) two rainfall events, and for four landslides (2.5%) six events. For the remaining 48 landslides (29.5%) the algorithm reconstructed between three and five events. We stress that the multiple rainfall conditions identified by the algorithm for a single landslide are all equally probable as possible triggers of the landslide.

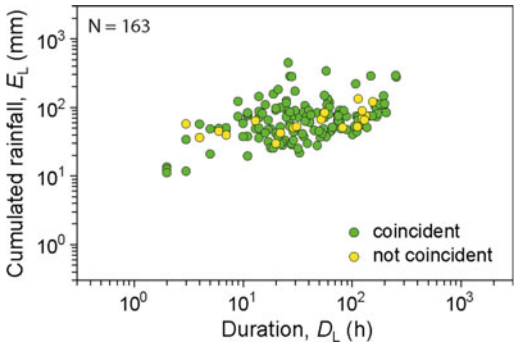

Fig. 7 Comparison of rainfall (D_L, E_L) conditions reconstructed by the algorithm or obtained manually by an expert investigator. *Green dots* (N_L = 143, 87.7%) show events for which the durations decided by the algorithm and by the expert investigator differed by <10% and were considered corresponding (equal) events. *Yellow dots* (N_L = 20, 12.3%) are "not coincident" events for which the durations decided by the algorithm and by the investigator differed by 10% or more

To study the differences between the events selected by the algorithm and those identified by the heuristic method, we selected the 163 rainfall events (one event for each landslide) for which the rainfall duration identified by the algorithm D_L was most similar to the corresponding duration defined heuristically by the expert investigator, D_L^*. We decided that two paired events have the same duration when their values for D_L and D_L^* differ by less than 10%. This is a reasonable assumption considering the uncertainties associated to the definition of the time of occurrence of a landslide. We further verified that for all the corresponding events, the values for the cumulated rainfall measured by the algorithm E_L and by the expert investigator E_L^* differ much less than 10%. We found that for 143 events (87.7%) (green dots in Fig. 7) the algorithm and the expert investigator provided coincident results. We consider this a measure of the ability of the algorithm to reproduce consistently the results obtained by the expert investigator. We investigated the 20 non-coincident events (12.3%) (yellow dots in Fig. 7), and found that the differences were due to subjective interpretations made by the investigator that resulted in the definition of systematically shorter rainfall events, i.e., $D_L^* < D_L$.

5 Discussion

The algorithm here presented applies the decisions taken by an expert investigator that reconstructs manually (i.e., heuristically) the rainfall events, and measures the rainfall conditions that have resulted in landslides.

The algorithm has several advantages over the traditional, manual methods. The first advantage is the fact that the algorithm performs an objective and reproducible reconstruction of the rainfall events. Experience gained in a national project for the collection of information on the rainfall (D_L, E_L) conditions that have resulted in landslides in Italy (Gariano et al. 2012) indicates that it is difficult for an investigator who has to analyse hundreds of landslides and multiple rain gauges to be consistent in the identification of the rainfall events, and in measuring the rainfall conditions responsible for the landslides. The problem is exacerbated when the number of investigators increases, making it difficult to prepare accurate catalogues of rainfall events with landslides covering large geographical areas (e.g., a nation). Use of the algorithm significantly reduces the uncertainty (operational variability) introduced by the presence of multiple investigators.

Another obvious advantage is the fact that use of the code reduces significantly the time necessary to determine the rainfall events, to associate the landslide information to a rainfall event, and to determine the rainfall duration (D_L) and the cumulated rainfall (E_L) responsible for landslide occurrence. We estimate that the time required by the expert investigators to determine the rainfall conditions responsible for the 163 landslides in Sicily between July 2002 and November 2011 (yellow dots in Fig. 4), and to search the results for possible errors, was about one month. Using the algorithm, a single investigator completed the equivalent operations in three hours.

Furthermore, the automation becomes a particular advantage where multiple rainfall records have to be tested for the same landslide, i.e., where multiple rain gauges exist near a landslide. The algorithm can be easily improved to select automatically or semi-automatically the most representative rain gauge for a specific landslide from a pool of rain gauges, and to evaluate the influence of the selection of different rain gauges in the definition of the rainfall conditions responsible for the landslide. This leads to the possibility of quantifying the uncertainty related to the selection of the rain gauges in the definition of rainfall thresholds for possible landslide occurrence, a problem currently unresolved (Guzzetti et al. 2007, 2008).

To explain how the algorithm operates, we have used rainfall measurements cumulated over a period of one hour. However, the algorithm is independent of the temporal resolution of the rainfall record, and it is applicable to sub-hourly rainfall data (with measurements every, e.g., 5, 10, 20, or 30 min), to rainfall cumulated over more than one hour (e.g., every 2, 3, 6, 12 h), and even to daily rainfall measurements. To operate, the algorithm uses six parameters, listed in Table 1. These parameters can be changed and adjusted to different physical (e.g., climatic, meteorological) or operational (e.g., type of rain gauges) conditions. The algorithm is independent from the local or regional climatic conditions, and from the operational settings of the rain gauge network.

The algorithm checks the rainfall record for missing measurements. This allows singling out incomplete rainfall events, which can be eliminated from the subsequent analyses reducing the uncertainty associated to the definition of the rainfall conditions responsible for the landslides. Manual check of a rainfall record is a time consuming, and error-prone operation. Due to the inherent lack of consistency of an investigator, the manual operation might not detect all the gaps in a rainfall record. This is a further advantage of the software code.

As explained before, when applied to a typical record of rainfall measurements, the algorithm identifies multiple rainfall (D_L, E_L) conditions that can be responsible for landslides (Fig. 3f). Conversely, due to practical and operational constrains, when an investigator searches a rainfall record manually to define the rainfall conditions responsible for landslides, the investigator identifies only a single set of rainfall conditions. Nevertheless, in the absence of external information, all the events are equally probable as possible landslide triggers. This implies that all the events should be considered equally for the statistical analysis of the events, or for reconstruction of rainfall thresholds. This is an advantage over the existing manual procedures.

To reconstruct the rainfall events, the algorithm uses information on the separation between successive events decided by the investigator. This is the same information used—explicitly or implicitly—by an investigator that searches a rainfall record and separates two successive events manually. The problem of the manual method is twofold: (i) the criteria for the separation of the events are often not clear or explicit, or are not applied consistently by the investigator, and (ii) for operational and practical problems, only a single set of criteria is used to separate successive events manually. This can condition the subsequent analyses. The software allows changing the separation criteria, and rapidly reconstructing the rainfall events and the rainfall conditions responsible for landslides using different parameter values (Table 1). This is an advantage over manual methods that opens to the possibility of evaluating the uncertainty introduced by selecting different criteria to separate (or to combine) successive rainfall events.

An additional advantage of the proposed algorithm is the fact that the rainfall events are defined independently from the landslide information, using only the rainfall record and a set of event separation criteria. Indeed, the landslide information is associated with a rainfall event only after the event has been identified. This is a significant advantage over traditional methods that—with a few exceptions (e.g., Onodera et al. 1974; Lumb 1975; Jibson 1975; Corominas and Moya 1999; Biafiore et al. 2002; Marchi et al. 2002; Zezere and Rodriquez 2002; Pedrozzi 2004; Giannecchini 2005; Berti et al. 2012; Segoni et al. 2014a, b)—consider the rainfall events that have resulted in landslide and ignore all the other events, which are the majority in a rainfall record. The ability to reconstruct independently the rainfall events and the rainfall events that have resulted in landslides is important because it allows using conditional probability and Bayesians inference to establish rainfall thresholds for possible landslide occurrence (Berti et al. 2012). This is a significant improvement for the application of rainfall thresholds in modern landslide warning systems (Aleotti 2004; Godt et al. 2006; Guzzetti et al. 2008; Bach-Kirschbaum et al. 2012; Rossi et al. 2012; Segoni et al. 2015). Further, the ability to reconstruct rainfall events independently from the landslide information opens to the possibility of using the algorithm to investigate processes and hazards different from landslides, including, e.g., high-intensity rainstorms, flash flooding, and droughts.

6 Conclusion

We developed and tested an algorithm for the objective and reproducible reconstruction of rainfall events, and of rainfall events that have resulted in landslides. The algorithm exploits a continuous record of rainfall measurements, and information on the time of occurrence of landslides, to determine: (i) the duration and the cumulated rainfall of rainfall events, and (ii) the duration and the cumulated rainfall of single or multiple rainfall conditions responsible for the landslide initiation. Use of the algorithm accelerates considerably the slow and tedious process of the definition of the rainfall conditions responsible for landslides, and reduces the subjectivity inherent in the manual treatment of the rainfall and landslide data. This decreases the uncertainty associated to the definition of the rainfall events.

We expect that the proposed algorithm, and the software that implements the algorithm that is made publicly available, will be used for the objective and reproducible definition of large sets of rainfall conditions that have resulted in landslides in different geographical areas, and will contribute to reduce at least part of the uncertainty associated with the definition of rainfall thresholds for possible landslide occurrence. Rainfall thresholds characterized by a reduced uncertainty, or for which the uncertainty is known, will contribute to more reliable landslide warning systems.

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