Rainfall intensity-duration thresholds for triggering shallow landslides in the Eastern Ligurian Riviera (Italy)

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The Eastern Ligurian Riviera, including the famous Cinque Terre, is frequently hit by heavy rainfall, which often induces shallow landslides and floods, causing damage and sometimes death. In this context, the assessment of the rainfall thresholds for shallow landslides initiation is very important in order to improve forecasting and to arrange efficient warning systems. With this purpose, a detailed analysis of the main rainstorms was carried out. The hourly rainfall recorded from 1967 to 2006 was analysed and compared with the occurrence of shallow landslides. Critical threshold curves were defined, in terms of duration and intensity, applying statistical techniques (logistic regression) in order to separate rainfall events that induced failures and events that did not. The rainfall thresholds obtained in this work were compared with the local and regional curves proposed by various authors. The results of this analysis suggest that in the study area landslide activity initiation requires higher amount of rainfall and intensity than elsewhere.

Keywords: Shallow landslides, Rainfall thresholds, Logistic regression, Landslide hazard, Liguria

1. Introduction

The Eastern Ligurian Riviera (ELR, Fig. 1) is characterized by high environmental value, mainly attributable to its geographical position, morphological conformation and climate. This area, including the famous Cinque Terre, is in fact characterized by hills and mountains that overlooks the Ligurian Sea, reaching altitudes of 800 m a.s.l. These features originate a very particular landscape, with ancient terracing devoted to agricultural activity (the local vineyards are particularly vintage and renowned worldwide), located on steep slopes on the sea. This significantly influences the local micro-climate, with a relatively high value of mean annual precipitation (MAP, 1200-1500 mm) and occurrence of heavy rainstorms. In several cases, such rainstorms induce many shallow landslides, causing damage to population and territory (for example, the September 10, 1981 rainstorm triggered hundreds of soil slips).

Therefore, the individuation of critical rainfall threshold for triggering landslides assumes a strategic importance in order to predispose efficient warning systems and to manage risk scenarios, especially in regions with strong tourist attitude and problems with the road network.

2. Methodology

The main rainfall events recorded from 1976 to 2006 in the ELR (Fig. 1) were analysed with the goal of defining the rainfall thresholds for the initiation of shallow landslides. Rainfall data (cumulative rainfall, rainfall duration, mean intensity) were collected by three rain gauges: Levanto (2 m a.s.l.), Vernazza (160 m a.s.l.), Portovenere (20 m a.s.l.).

At present the critical rainfall thresholds were defined only for Levanto rain gauge (Fig. 1), which includes 276 significant rainfall events. These events were selected on the basis of the combination of the rainfall duration and cumulative rainfall. For example, events with low duration (1–2 h) and high intensity (20–45 mm/h) or high duration (80–100 h) and low intensity (1–3 mm/h) and intermediate events were considered.

For each rainfall event, a thorough research on its consequence in the study area in term of number of shallow landslides was carried out. Different sources of information were analysed including: archives of the local municipal councils, scientific papers, technical reports, and local newspapers. The main rainstorms inducing damage and landslides occurred in 1968, 1970, 1977, 1981, 1984, 1992, 1996, 1998 and 2000. Using the method proposed by Giannecchini et al. (2012), the rainfall events were subdivided into three groups:

1) events inducing ten or more shallow landslides (A events, in Fig. 2);
2) events inducing less than ten shallow landslides (B events, in Fig. 2);
3) events that did not trigger landslides (C events, in Fig. 2).

In order to create the rainfall intensity-duration (*I-D*) thresholds, all the duration *D* and intensity *I* data were plotted on a bi-logarithmic scale, where the A, B and C events were also plotted. This dataset was fitted using a generalization of the widely used method of logistic regression for binary outcomes. This extension, describing outcomes that can be classified as ordered categorical data, was first suggested by Aitchison and Silvey (1957), developed theoretically by Agresti (2010) and implemented by Christensen (2013) in the R package “ordinal”.

In the proposed model, the landslide occurrence has three levels (no landslides, less than ten landslides, ten or more shallow landslides). For each pair (*I, D*) of variables, and using the parameters obtained by fitting, it is possible to estimate the probability P_{A}, P_{B}, P_{C} (summing to unity) of events of type A, B and C, respectively. The model allows to compute the probability of A, B and C events (P_{A}, P_{B} and P_{C}) with the following:

$$P_{\mathrm{A}} = 1 - \frac{1}{1+\exp(-\beta_{\mathrm{A}}-\beta_D\tilde{D}-\beta_I\tilde{I})} \tag{1}$$

$$P_{\mathrm{B}} = \frac{1}{1+\exp(-\beta_{\mathrm{A}}-\beta_D\tilde{D}-\beta_I\tilde{I})} - \frac{1}{1+\exp(-\beta_{\mathrm{C}}-\beta_D\tilde{D}-\beta_I\tilde{I})} \tag{2}$$

$$P_{\mathrm{C}} = \frac{1}{1+\exp(-\beta_{\mathrm{C}}-\beta_D\tilde{D}-\beta_I\tilde{I})} \tag{3}$$

where $\tilde{I}$ and $\tilde{D}$ are the Briggs logarithm of the rainfall intensity I in mm/h and the duration D in h; β_{C}, β_{A}, β_D and β_I are parameters. Their maximum-likelihood estimates, that are obtained fitting the data, are: $\beta_{\mathrm{C}} = 53.9$, $\beta_{\mathrm{A}} = 63.1$, $\beta_D = -25.9$, and $\beta_I = -32.9$.

The method defines two lines (upper and lower thresholds) that subdivide the *I-D* field into three regions in which the most probable event is highlighted (Fig. 2). In the area below the continuous black line (lower threshold) P_{C} is the highest (>49.995%). Along the lower threshold B and C events have both probability (49.995%) and P_{A} is negligible (0.01%). In the area between the two lines, P_{B} is the highest (>49.995%). Along the dashed black line (upper threshold) A and B events have both probability (49.995%) and P_{C} is negligible (0.01%). In the area above the upper threshold P_{A} is the highest (>49.995%). Consequently, the *I-D* field can be subdivided into three parts with differing degrees of stability: stability conditions generally prevail below the lower threshold, instability conditions prevail above the upper threshold, while the field between the two curves includes intermediate or uncertain stability conditions.

The threshold curves are expressed in the form (Caine 1980):

$$I = \alpha \cdot D^{-\beta} \tag{4}$$

where I is the rainfall intensity (mm/h), D is the duration of rainfall event (h). Using a logarithmic scale on both axes, straight lines are obtained: α is the intercept and $\beta = \beta_D/\beta_I$ is the slope.

3. Results and discussion

The rainfall thresholds are sufficiently defined for the range of duration $1<D<100$ (Fig. 2). Considering rainfall events of duration of 6, 12 and 24 h, the lower threshold is exceeded with intensities of 10.6, 6.2 and 3.6 mm/h, respectively. Whereas, the upper threshold is exceeded with intensity of 20.1, 11.7 and 6.8 mm/h, respectively.

The *I-D* graph shows some misclassifications of the type of events. One A events falls into the B events field and vice versa. Such exceptions are probably due to the uncertainty in the areal extent of damage, which often is based only on historical description or information by newspapers. Other misclassifications occur between B and C events (17.9% of missing events), not related to definite causes. Occasional and extemporary causes probably add to the triggering rainfall and induce unexpected landslides. Otherwise, malfunctioning of the rain gauge could be an alternative cause.

The *I-D* thresholds defined for the study area (Fig. 2) can be compared with local and regional thresholds proposed for Italy (Fig. 3) obtained with different methods. They (1–2 in Fig. 3) fall in the range of rainfall intensity and duration defined by other thresholds for the North-western Tuscany.

In general, a high position, namely a higher mean intensity, is highlighted for the Levanto thresholds (1–2 in Fig. 3). This emphasizes the high critical rainfall value for triggering shallow landslide in the ELR. This may be probably related to the high MAP value and high frequency of rainstorms, as noted for the Apuan Alps area by Giannecchini (2006).

4. Conclusions

The use of the logistic regression allows us to obtain the *I-D* rainfall thresholds for shallow landslide initiation in the ELR. The comparison with other *I-D* local and regional thresholds for Italy highlighted the high rainfall values for shallow landslides initiation in the study area, probably associated to the high MAP value and frequency of rainstorms. This induces a natural, dynamic equilibrium between climatic features and slopes.

On October 25, 2011 a heavy rainstorm hit the study area, causing hundreds of shallow landslides, severe damage to villages, infrastructures and road network and 4 casualties in the Cinque Terre area (D’Amato Avanzi et al. 2013). Levanto rain gauge recorded 236.6 mm in 7 h (33.8 mm/h). This event (type A) fall into the proper field (instability field, area above the upper threshold in Fig. 2). However, more validation is needed and is in progress.

The rainfall thresholds defined in this study may provide guidance for setting up warning systems and planning emergency actions in managing the landslide risk. Decisions on warning and emergency response can be made on the basis of the comparison of the rainfall forecasts and real-time measurements with the threshold curves. When the combination of duration and rainfall intensity exceeds the upper threshold curve, the probability that tens of shallow landslides occur is more than 50% (actually 49.995%). If the rainfall events fall between the upper and the lower thresholds (intermediate stability), the probability that few shallow landslides is more than 50%. As consequence, on the basis of a reliable weather forecast, an appropriate scenario can be adopted and an emergency system activated.

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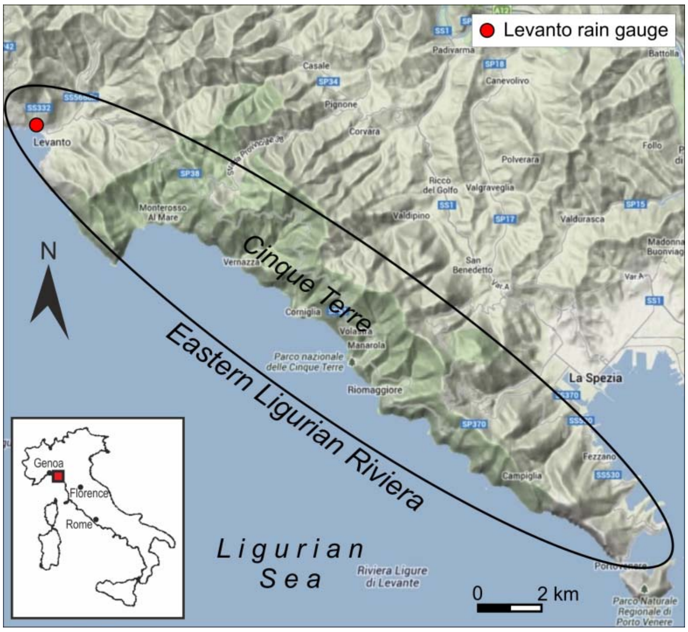

Fig. 1 Map of the Eastern Ligurian Riviera and location of the Levanto rain gauge (base map of Google Maps, 2013)

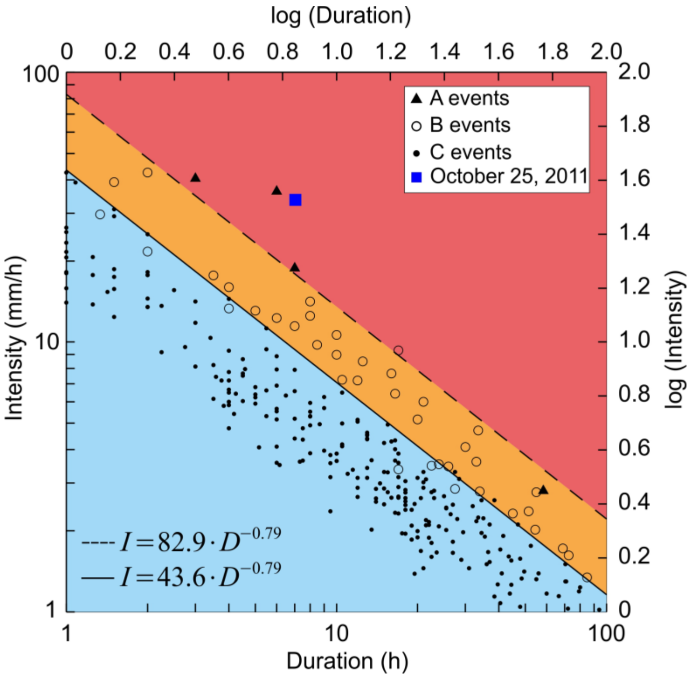

Fig. 2 *I-D* correlation for Levanto rain gauge. The lower (black) and upper (dashed black) thresholds are shown as well as the October 25, 2011 rainfall event. The areas below the lower line, above the upper line and between the two lines highlight the stability, instability and intermediate fields, respectively

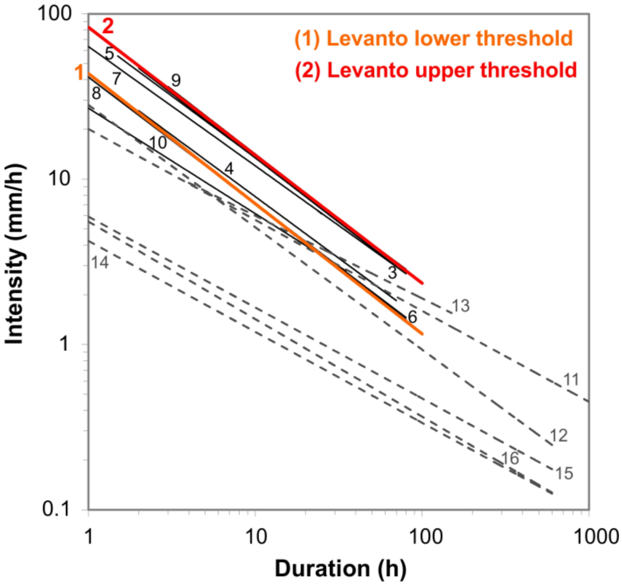

Fig. 3 Comparison between the Levanto *I-D* thresholds and some local (black) and regional (grey dashed) thresholds. Source: 1-2, this work; 3-8, Serchio River Valley (Giannecchini et al. 2012); 9-10, Southern Apuan Alps (Giannecchini 2006); 11, Lombardy (Ceriani et al. 1994); 12, Campania (Calcaterra et al. 2000); 13, Piedmont (Aleotti 2004); 14-16, Abruzzo (Brunetti et al. 2010)