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A process-based model for the definition of hydrological alert systems in landslide risk mitigation

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Abstract. The definition of hydrological alert systems for rainfall-induced landslides is strongly related to a deep knowledge of the geological and geomorphological features of the territory. Climatic conditions, spatial and temporal evolution of the phenomena and characterization of landslide triggering, together with propagation mechanisms, are the key elements to be considered. Critical steps for the development of the systems consist of the identification of the hydrological variable related to landslide triggering and of the minimum rainfall threshold for landslide occurrence.

In this paper we report the results from a process-based model to define a hydrological alert system for the Val di Maso Landslide, located in the northeastern Italian Alps and included in the Vicenza Province (Veneto region, NE Italy). The instability occurred in November 2010, due to an exceptional rainfall event that hit the Vicenza Province and the entire NE Italy. Up to 500 mm in 3-day cumulated rainfall generated large flood conditions and triggered hundreds of landslides. During the flood, the Soil Protection Division of the Vicenza Province received more than 500 warnings of instability phenomena. The complexity of the event and the high level of risk to infrastructure and private buildings are the main reasons for deepening the specific phenomenon occurred at Val di Maso.

Empirical and physically-based models have been used to identify the minimum rainfall threshold for the occurrence of instability phenomena in the crown area of Val di Maso landslide, where a retrogressive evolution by multiple rotational slides is expected. Empirical models helped in the identification and in the evaluation of recurrence of critical rainfall events, while physically-based modelling was essential to verify the effects on the slope stability of determined rainfall depths. Empirical relationships between rainfall and landslide consist of the calculation of rainfall Depth-Duration-Frequency (DDF) curves, which allow one to determine rainfall depth (or intensity) as a function of duration for given return periods or probabilities of exceedance (frequencies). Physically-based modelling was performed through coupled seepage and slope stability analyses.

Combining results from empirical and physically-based modelling, the minimum alert threshold for a reactivation of the phenomenon was found in rainfall cumulated up to 60 days with a return period of 2 yr. These results were used to set up a hydrological alert system based on the calibration of DDF curves which can be used as a sort of abacus to plot in real time rainfall depths and to set increasing levels of alert on the basis of the degree of exceptionality of rainfall.

The alert system for Val di Maso was successfully tested by the rainfall events that produced displacements which have been recorded by extensometers placed in the crown area after the November 2010 landslide. However, further tests are recommendable to improve the process-based model that led to the implementation of the alert system. To this end, a monitoring system is currently being realized. In the near future, monitoring data will help in testing and improving landslide evolution and alert models.

The proposed hydrological alert system proves to be effective mainly because it can be applied to different scales of investigation and geological and geomorphological contexts. In fact, it might also be applicable to territorial scale analyses, as showed by the brief example provided in this paper on how the alert system could be used for landslide early warning in the area surrounding Val di Maso. Furthermore, it is easy to set up. The needed components are a rain gauge station, a software that compares rainfall data to rainfall events with different return periods and degree of alert, and a transmission system of the warning levels to authorities.

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1 Introduction

The implementation of alert systems represents one of the most powerful tools in the mitigation of risks due to rainfall-induced landslides. This is a very important issue based on the observation that a rapid increase in the frequency and intensity of heavy rainfall, possibly due to climate changes, has occurred in the last decades (Gong and Wang, 2000; Easterling et al., 2000; Fauchereau et al., 2003; Sillmann and Roeckner, 2008; de Luis et al., 2011). Frequency of rainfall-related phenomena, such as floods and landslides, increased as well together with the related economic losses and social implications (Jomelli et al., 2007; Pelfini and Santilli, 2008; Floris et al., 2010).

The definition of such systems requires a detailed knowledge of geological and geomorphological features of the territory, climatic conditions, spatial and temporal evolution of instability phenomena and characterization of landslide triggering together with propagation mechanisms. Critical steps for the development of alert systems consist in the identification of the hydrological variable (rainfall cumulated over n minutes/hours/days) related to landslide triggering and of the minimum rainfall threshold for landslide occurrence (Capparelli and Tiranti, 2010; Floris and Bozzano, 2008). This is tantamount to characterize overall relationships between rainfall and landslides. On this topic a large number of models have been proposed by several authors since the 1980s (De Vita et al., 1998; Guzzetti et al., 2007; Zhang et al., 2011). These models generally follow two main approaches. The first approach consists of the evaluation of the empirical relationships between the time of failure and the antecedent rainfall using probabilistic and statistical methods. The second approach considers the analysis of the physical phenomena that occur in the slope under a rainfall event using physically-based models, which take into account site conditions, water infiltration, seepage and accumulation processes, increase in driving forces and decrease in resisting forces.

Despite the wide bibliography, the theme of the complex relationships between rainfall and landslide is yet of great interest to the scientific community, which is proposing new methods and techniques of investigation, thanks to the availability, in recent years, of new technologies and tools in the field of numerical modelling, computer geosciences, monitoring, and laboratory tests. A search on the databases available in the ISI Web of Knowledge Website, using "rainfall induced landslide" as a key search on the topic of scientific journals, provides a list of 30 papers published in 2011. Most of these papers proposes new physically-based models which combine seepage and slope stability analyses (He et al., 2011; Rahimi et al., 2011), improve precedent numerical models by considering more complete datasets from laboratory and site tests (Ma et al., 2011; Lee et al., 2011; Rahardjo et al., 2011; Sharma and Konietzky, 2011; Vedie et al., 2011), propose the use of models that take into account the coupled processes of groundwater flow, gas transport and soil deformation in unsaturated soil slopes under rainfall events (Ehlers et al., 2011; Hu et al., 2011), test the performance of existing models introducing new parameters and comparing the results with real cases (Goetz et al., 2011; Keijsers et al., 2011; Hong and Wan, 2011; Montrasio et al., 2011; Tsai et al., 2011). Few papers propose new empirical models using probabilistic and statistical approaches (Ching et al., 2011; Li et al., 2011; Nefeslioglu and Gokceoglu, 2011; Santoso et al., 2011). In some cases, the authors report case studies with the description of rainfall events and detailed information on the geological and structural features of the areas affected by landslides (Leung et al., 2011; Panek et al., 2011; Petkovsek et al., 2011; Tsou et al., 2011).

The above mentioned papers refer mainly to shallow landslide phenomena, both at slope and basin scale and provide useful tools for the implementation of alert systems. The more comprehensive approach seems to be the combination of the results coming from the application of both empirical and physically-based models (Capparelli and Versace, 2011; Cascini et al., 2011), through multi-disciplinary studies and process-based models (Scheuner et al., 2011). In fact, empirical models allow one to identify the hydrological variable related to landslide triggering and the minimum rainfall threshold for the instability, and physically-based models allow one to verify that threshold, analysing the effects on slopes under given rainfall events. Finally, probabilistic and statistical methods allow one to evaluate the recurrence of instability conditions and set up alert systems. However, the combined use of the two approaches can be limited to specific geological and geomorphological contexts, especially in the case of small scale investigations.

In this paper we report a process-based model aimed at setting up a hydrological alert system for landslide early warning. The process consists of an explanation of geological model and climatic context of landslide-prone area; identification of rainfall pattern related to landslide and of minimum triggering threshold; building of geological-technical model; coupled seepage and slope stability analyses for different rainfall conditions; and definition of rainfall-induced landslide warning levels.

In order to better explain the adopted process, we consider the case study of Val di Maso landslide, located in the north-eastern Italian Alps and included in the Vicenza Province (Veneto region, NE Italy) (Fig. 1). The landslide was triggered by an exceptional flood event that occurred in November 2010. The main reasons for deepening this specific phenomenon is that its possible evolution threatens a road located in the crown area and some buildings at the toe of the unstable slope. In the next sections, the November 2010 event and the induced instabilities and damages are depicted. Data and methods are, then, described with particular emphasis to the role of rainfall in the landslide triggering. The conceptual model of a hydrological alert system is presented and the main results of the study are discussed and combined to set up the alert system for the Val di Maso landslide and for the

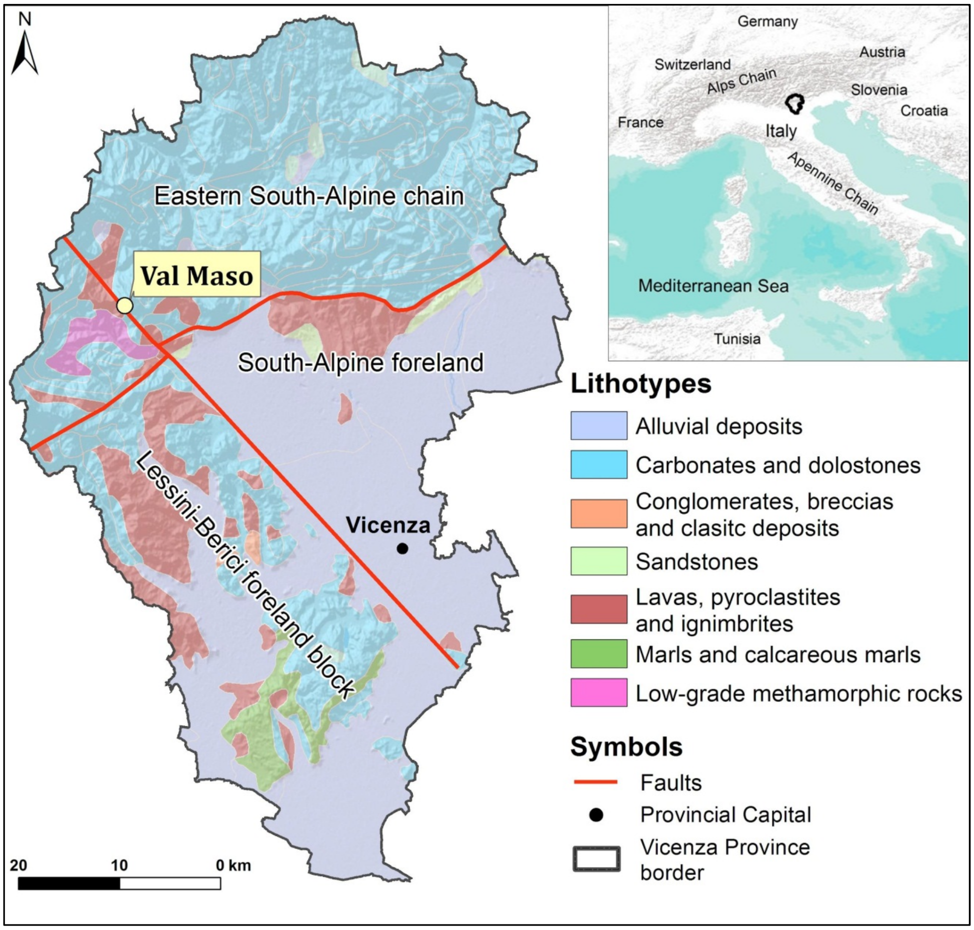

Fig. 1. Location of the Val di Maso landslide in the geological context of the Vicenza Province (Veneto region, Italy).

surrounding area strongly affected by instability phenomena after November 2010.

2 The November 2010 rainfall event

From 31 October to 2 November 2010, an exceptional rainfall event hit the Vicenza Province with a maximum cumulative rainfall of about 500 mm and a mean of 336 mm over the area. This event represents one of the most intense and catastrophic historical floods of the last 100 yr, together with the November 1966 and October 1992 floods, which affected the pre-Alps and piedmont sectors of Veneto region and the remaining part of Northern and Central Italy. The intense rainfall triggered a huge number of mass movements in the northern and western parts of the Vicenza Province (Fig. 2). In the alluvial plain area, the main rivers (e.g., Bacchiglione, Astico and Retrone rivers) overflowed their banks causing damages of about a billion euros to infrastructures, industrial activities, and private buildings.

Following the rainfall event, 500 warnings of landslides, distributed over 20 municipalities of the Vicenza Province, were received at the Soil Protection Division. Immediately after, researchers from the Department of Geosciences of the University of Padua and technicians of the Vicenza Province started field surveys in the affected areas. A simplified database for storing main data on landslides was realized in order to determine the priority of first remediation works. Data on geographical location of landslides, time and date, kinematics, involved rocks, possible evolution and, finally, caused and potential damages, have been collected (Fig. 2). Most of the phenomena have been classified as small to medium composite landslide (rotational/translational slide-earth flow), according to the Cruden and Varnes (1996) classification. Instabilities mainly involved debris cover damaging the road network. The estimated costs for remediation works are about 60 million euros.

To investigate which hydrological variable can be related to the triggering of landslides in Val di Maso and in the surrounding area, we considered maximum cumulative rainfall over 1, 3, 6, 12, and 24 h during the event and cumulative rainfall over 1, 2, 5, 10, 30, 60, 90, and 120 days. Based on the assumption that the more exceptional the rainfall event

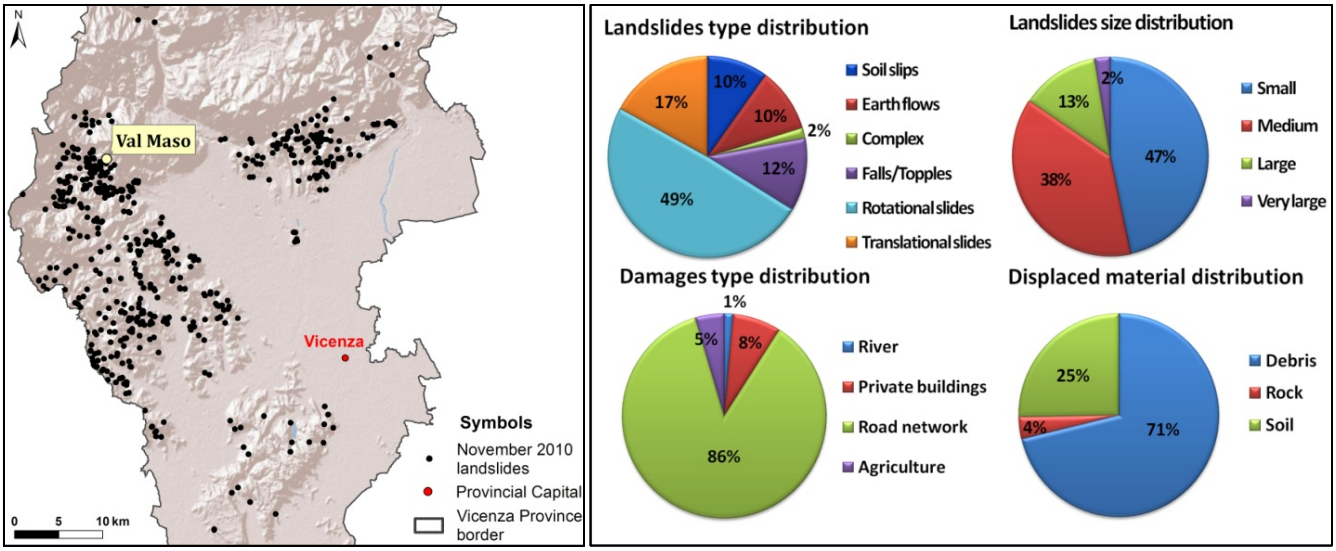

Fig. 2. Location of landslides triggered by the November 2010 rainfall event and main characteristics of landslides and induced damages.

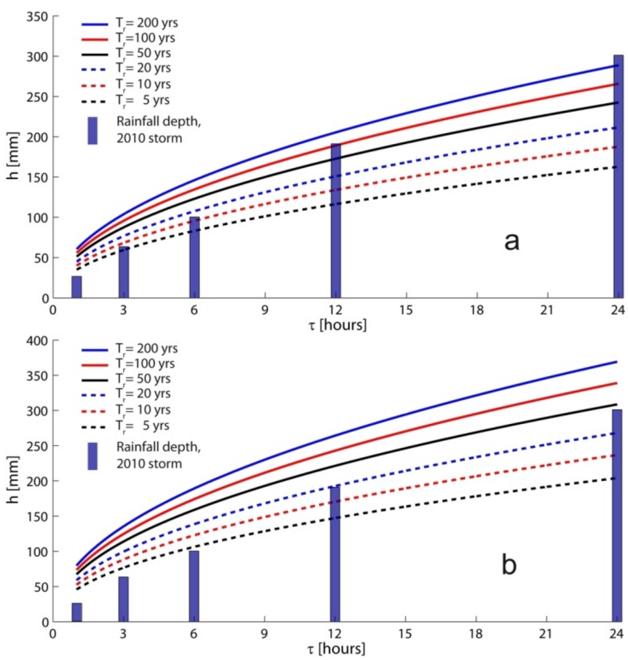

Fig. 3. Rainfall Depth-Duration-Frequency (DDF) curves determined by using 1925–1975 **(a)** and 1990–2009 **(b)** data series for the Ceolati rainfall station, located close to Val di Maso. Blue bars indicate the maximum cumulative rainfall over 1, 3, 6, 12 and 24 h during the November 2010 rainfall event.

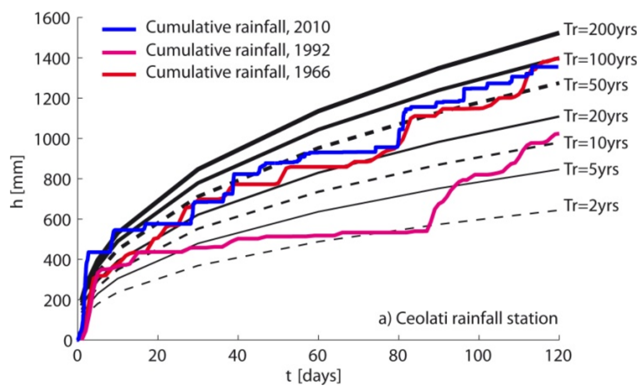

Fig. 4. Rainfall DDF curves for the most intense floods of the last 100 yr and rainfall cumulated backward from the last day of the flood events (day = 0) up to 120 days before, for the Ceolati rainfall station.

is the stronger the cause–effect relationship between rainfall and landslide triggering, we evaluated the degree of exceptionality of the mentioned hydrological variables calculating the rainfall Depth-Duration-Frequency (DDF) curves for Ceolati rainfall station, located close to Val di Maso landslide (Figs. 3 and 4). These curves allow one to determine rainfall depth (or intensity) as a function of duration for given return periods or probabilities of exceedance (frequencies). The Extreme Value Type I or Gumbel distribution is fitted to the annual rainfall maxima of the considered hydrological variables by using the method of moments. Subsequently, the estimated parameters of the Gumbel distribution are modelled as a function of duration to determine DDF curves, using the method of least squares.

Figure 3 shows that the cumulative rainfall depths over 1 h during the flood event do not intersect the lower DDF curves, displaying a value lower than the one obtained for a return period of five years. As the duration increases, the cumulative rainfall depths reach the DDF curves for increasing return periods. Cumulative rainfall over 24 h reaches the maximum degree of exceptionality, >200 yr and 50 yr in the case of the 1925–1975 (Fig. 2a) and 1990–2009 (Fig. 2b) rainfall dataset, respectively. This difference could be related to an increment of extreme rainfall events in the last two decades, possibly due to climate change (Floris et al., 2011).

In Fig. 4, cumulative rainfall depths over 1 to 120 days before the main three historical floods overlap the DDF curves. This allows us to investigate rainfall regime before the November 2010 event and to compare it with those which occurred in 1966 and 1992. Rainfall depths preceding the flood events are cumulated backward from the last day of the flood (day = 0) up to 120 days before. Such a procedure makes it possible to evaluate immediately the degree of exceptionality, in terms of the return period, of the rainfall cumulated before the flood events, and to investigate the hydrological conditions before the events. Figure 4 shows that the November 2010 event is characterized by the largest cumulative rainfall depths because during the 120 days before almost three rainfall events are present; so that the cumulative rainfall curve presents a more exceptional character than the 1966 and 1992 cumulative rainfall curves. The November rainfall event therefore occurred in a hydrological context that already presented critical characters.

3 Geological model of Val di Maso

In the Val Maso area the bedrock is composed of the Southern Alps Crystalline Basement (Valli del Pasubio Phyllites, FVP) and by Permo-Triassic sedimentary succession including the Val Gardena Sandstone (GAR), the Bellerophon Formation (BEL) and the Werfen Formation (WER) (Fig. 5). The FVP (pre-Permian) is composed of quartz and quartz-albite grey to grey-green phyllites. Quartz layers, nodules and lenses are present. The boundary with the sedimentary cover is an unconformity. The GAR (Upper Permian) represents alluvial deposits composed of yellow-brown fine-grained arenites and dark red or grey micaceous siltstones interbedded with grey dolostones. Marls and clay components increase upwards. The thickness varies from 15 to 75 m. The BEL (Upper Permian) represents marginal-marine deposits and is composed of carbonates, siltstones, marls and dolostones upwards interbedded with evaporites. In the study area, a grey dolomitic-calcareous facies is present at the top. The thickness varies from 20 to 40 m. The WER (Upper Permian-Lower Trias) also represents marginal-marine environment recorded by terrigenous and carbonate shelf sediments. The basal portion is constituted by light brown–yellow sandstone and brown–red–yellow micaceous siltstones, mudstones and marlstones interbedded with grey calcareous and calcareous-arenitic beds. The thickness varies from 150 to 250 m. The Rhyolitic-dacitic volcanites (VRD) represent the acid products of Upper Ladinian volcanic phase. This stratigraphic unit is interlayered with Permian to Triassic marine-continental sediments. The maximum thickness is 200 m (De Vecchi, 1986; Chendi, 1974). Along the lower contact between VRD and the colluvial/eluvial deposits, some mineral springs are present. Colluvial/eluvial deposits (DEP) are lithologically homogeneous and present a good sortening, whereas landslide debris deposits are lithologically heterogeneous and their block size is from metric to centimetric with a prevalent clayey matrix.

The study area is located close to two regional tectonic lineaments, the Schio-Vicenza transcurrent fault and the Bassano-Marana thrust. Some tectonic discontinuities (normal and inverse faults) related to polyphase deformations, including Mesozoic and Paleogene extension and Neo-Alpine shortening, dislocate the local succession (Fig. 5).

Hydrogeological conditions of the study area are rather complex. Considering the area affected by the landslide (cross section A–A′ in Fig. 5) and on the basis of macroscopic observations and bibliographic references, the following permeability values may be attributed to the different formations: a medium value to the debris cover (10^{-4} – 10^{-6} m s^{-1}); a highly variable but on the average low permeability to WER formation (<10^{-7} m s^{-1}); a medium value to BEL and GAR formations due to fracturing (10^{-4}-10^{-6} m s^{-1}); or a very low value to the cristalline basement (<10^{-9} m s^{-1}). Due to quite low permeability of WER formation, the debris cover contains an unconfined groundwater with significant water table fluctuations according to the rainfall regime. The maximum depth of the groundwater is relatively high: in the crown area, after a three months dry period after the landslide, the depth of water table was 16 m. In correspondence of the main scarp, an ephemeral spring is present at the contact with WER formation that represents an impermeable limit. The presence of this spring is due to the landslide that exposed the impermeable limit. Another ephemeral spring is present at the contact between the displaced material and the BEL formation on the right flank of the landslide.

On the basis of geological and geomorphological field surveys, and topographic, geognostic and geophysical investigations, the geological model of the landslide has been developed and it is displayed by the longitudinal cross section (A–A′) in Fig. 5. Two terrestrial laser scanning acquisitions allowed us to obtain the topography after November 2010 and to define the geometry of the landslide. Seven boreholes and four seismic and two electric tomographies (Fig. 6) allowed for defining the stratigraphy of displaced materials.

The landslide that occurred in November 2010 (Fig. 7) can be considered as representative of instability phenomena triggered by the flood event. In fact, it can be classified as a roto-translational slide-earth/debris flow that involved eluvial/colluvial deposits and past landslide debris (Fig. 8). The volume of displaced material was about 200 000 m^3 and the maximum thickness 20 m. Behind the main scarp the phenomenon is rapidly retrogressing by multiple rotational slides, with a sliding surface located at 15–20 m depth in correspondence with the contact between debris cover and bedrock. The evolution is continuously monitored

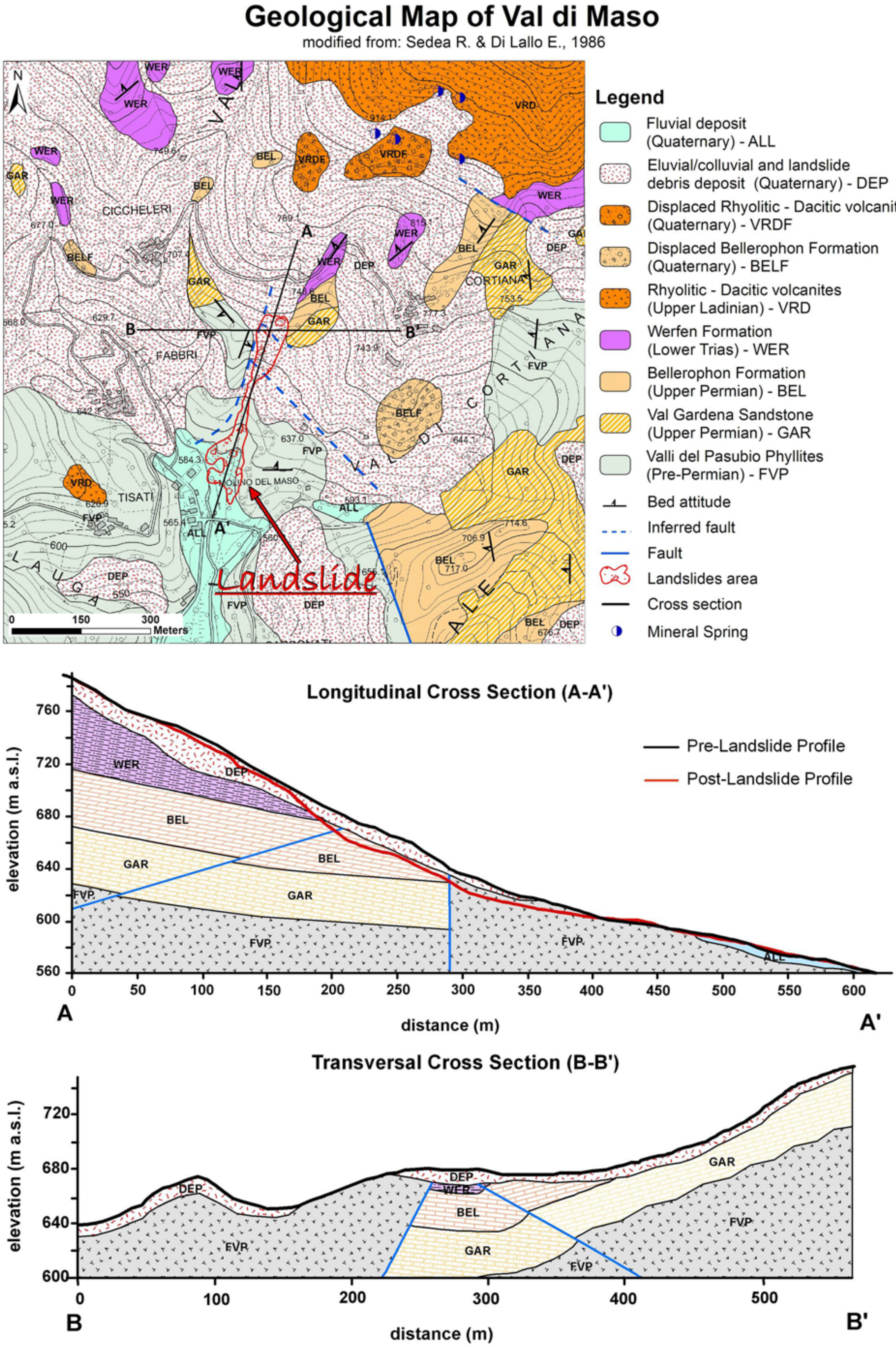

Fig. 5. Geological map of Val di Maso and longitudinal (A–A′) and transversal (B–B′) landslide cross section.

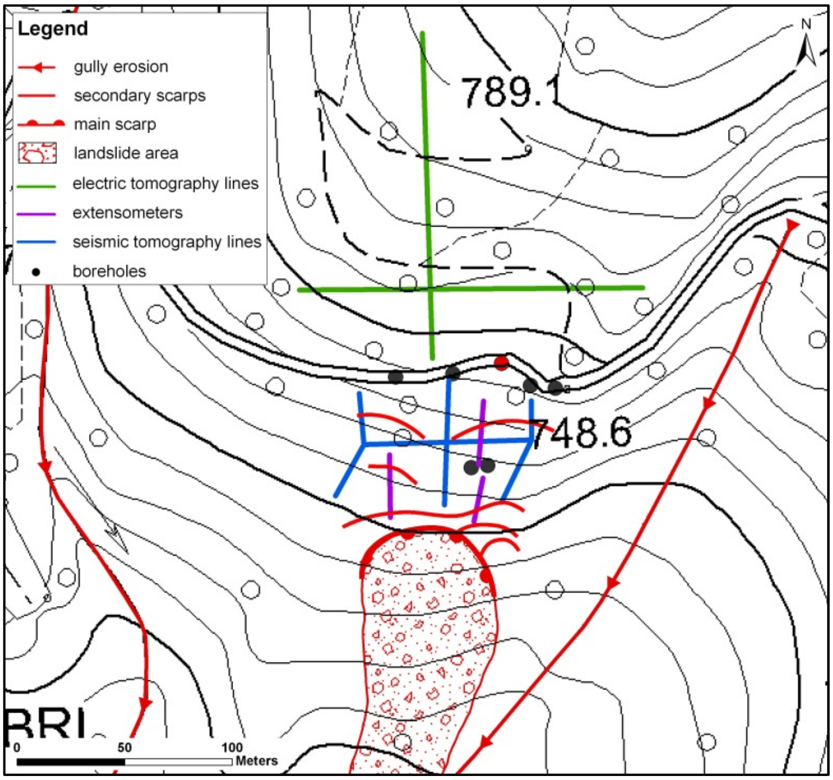

Fig. 6. Location of geognostic and geophysical investigations together with the main geomorphological elements of landslide area. The red solid circle indicates the borehole from which samples for laboratory tests have been collected (see Fig. 8).

Fig. 7. View of Val di Maso landslide. In the upper part (on the left) the main scarp is visible and in the lower part (on the right) displaced materials are shown.

by extensometers, which measured displacements up to 1.5 m in four months, correlated quite well with rainfall events (Fig. 9).

4 Seepage and slope stability analyses

Starting from the geological model of Val di Maso described in the previous section, numerical analyses were performed to investigate slope stability and its connection to rainwater infiltration and transient seepage in the crown area, where a retrogressive evolution of the landslide is expected. The behaviour of seepage and pore water pressure was analysed using the commercial finite element software Seep/w (Geoslope International Ltd., 2007a). Results were exported to Slope/w (Geoslope International Ltd., 2007b) to evaluate the influence of ground flow on the stability through the calculation of the factor of safety (FoS).

As a preliminary stage, a back stability analysis was carried out to test the geotechnical properties of the materials involved in the November 2010 landslide, which were taken from the scientific literature and deducted from grain size distribution (Fig. 8). Then, parameters from back analysis were used in a coupled seepage and slope stability analysis of the area behind the main scarp to forecast the effects of hydrological conditions due to different rainfall depths, i.e. to identify the minimum rainfall threshold for triggering the retrogression of the phenomenon.

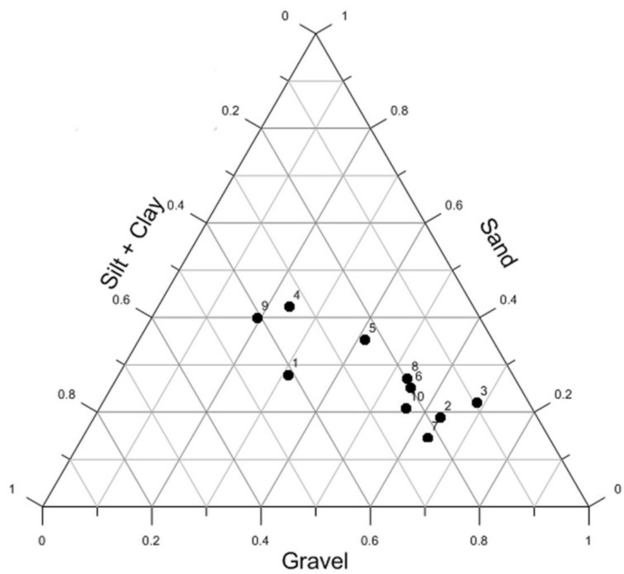

Fig. 8. Ternary plot presenting grain size composition of the samples collected from a borehole located on the road behind the main scarp (marked in red in Fig. 6). Each sample refers to 1.5 m thickness, from the soil surface (sample no. 1) to 15 m depth (sample no. 10).

4.1 Back analysis

The first stage of the back analysis consists of the simulation of hydrological conditions characterizing the slope. A seepage analysis was conducted on the longitudinal cross section A–A′ (Fig. 5), considering all the deposits completely saturated and imposing a water table at the ground surface with filtration parallel to the slope. These exceptional and unfavourable conditions proved to be plausible because of the exceptional rainfall of November 2010.

Saturated hydraulic conductivity (K_{sat}) of debris cover was established considering the range of values suggested in the literature, as reported in the previous section, and taking into account results from sieve analyses performed on dry samples. In particular, the observation of the percentages of gravel, sand and silt-clay suggests that the percentage of fine material, characterized by a diameter smaller than 2 µm, was generally higher than 20 % (Fig. 8). This large value significantly influences the permeability of debris deposit which was assimilated to a sandy loam. Hence, a K_{sat} of 5×10^{-6} m s^{-1} was set in agreement with the value proposed from Geoslope International Ltd. database for this material. The K_{sat} value-assigned to WER Formation was 3×10^{-8} m s^{-1} on the basis of macroscopic observations of samples collected from boreholes, and typical Werfen properties defined in literature and in the Geoslope International Ltd. database, assimilating this layer to a silty-clay. A K_{sat} value equal to 10^{-6} m s^{-1} was assigned to BEL and GAR and a K_{sat} value of 10^{-9} m s^{-1} was attributed to FVP in accordance with typical values proposed in literature for these kinds of rocks. Once all these parameters were set, a steady state seepage analysis was performed to define water pressures and water flow rates characterizing the slope when the November 2010 landslide occurred. The pore pressure distribution from seepage analysis was then used in the slope stability analysis.

The geological model before the November 2010 event was simplified for the stability analysis, focusing on the debris cover parameters and considering all the other deposits as bedrock (Fig. 10). The analysis was performed by imposing the slip surface identified by comparing the bottom topography before and after the landslide. Based on values collected from technical literature, the geotechnical parameters were set as follows: unit weight equal to 20 kN m^{-3}, cohesion of 15 kPa, and friction angle of 30°. To account for uncertainty in the input parameters, the analysis was conducted in a probabilistic way. Input parameters were considered as random variables following a normal probability density function with a mean equal to values taken from the literature and standard deviation of 2. Then, a Monte Carlo method was used to calculate the probability function of the resulting safety factors (Fig. 11). Since the probability of FoS < 1 is 100 %, a condition that indicates the instability occurred in November 2010, the input parameters were considered as reliable and used in the forecasting analysis.

4.2 Forecasting analysis

In this case the simplified section of Fig. 12 was analysed under different rainfall conditions to investigate the evolution of the landslide and identify the minimum rainfall threshold over which a movement can occur. Thus, debris and Werfen deposits were considered in the seepage simulation and only debris cover in the slope stability analysis. This simplification seemed to be reasonable based on the observation that the main interest of the analyses carried out herein is focused on slope instability phenomenon, which should mainly involve debris cover. Therefore, the key factor influencing FoS of the slope is the groundwater, depending on rainfall intensity and duration.

The initial groundwater condition was fixed considering the minimum measured water level, about 4 m above the interface between Werfen deposits and debris cover. A steady state seepage analysis was carried out to define pore water pressures and initial conditions for the subsequent transient seepage analysis. For the latter, a saturated/unsaturated model was adopted, requiring non-linear functions describing hydraulic conductivity and volumetric water content with respect to pore water pressures. Functions of permeability vs matric suction and volume water content vs pore water pressure were extracted from database of curves available in the Geoslope International Ltd. database (2007a). Figure 13a and b shows characteristic curves used for the debris cover,

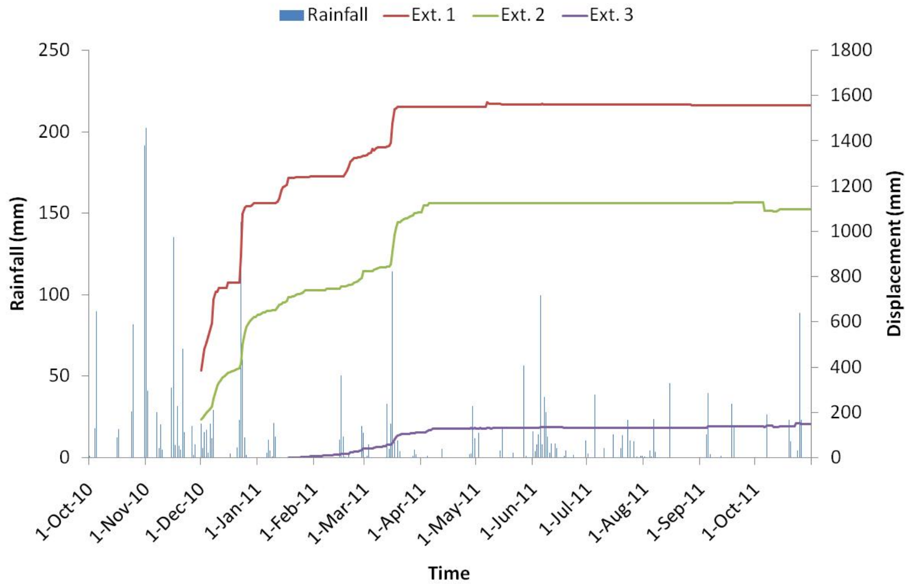

Fig. 9. Daily rainfall and displacements recorded by extensometers placed in the crown area after the November 2010 landslide event.

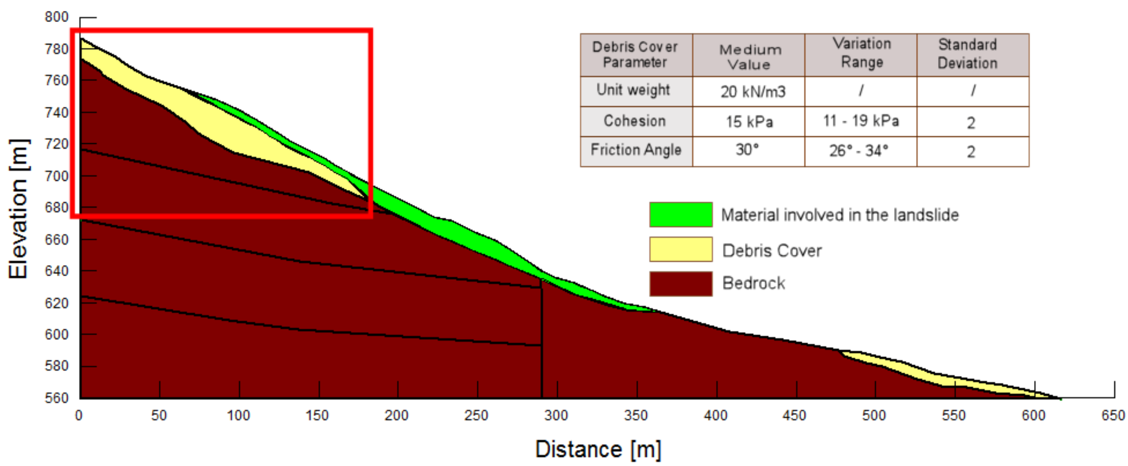

Fig. 10. Results of the coupled seepage and stability back analysis of the Val di Maso landslide that occurred after the November 2010 event. Red inset indicates the portion of the slope investigated in the forecasting analysis.

whereas Fig. 13c and d shows the respective functions used for WER Formation.

Once a steady state condition was reached, different incoming fluxes corresponding to the DDF curves of Fig. 4 were applied to the slope surface. To account for the effective infiltration, 50 % of total rainfall was considered. Then, slope stability analyses, using the Morgenstern-Price method, were performed calculating the safety factor after 3, 10, 30, 60, 120 days. These intervals were considered in order to account for the variation in the infiltration rate due to the shape of DDF curves. For example, to determine the factor of safety after 10 days in the case of a return period of 2 yr, we considered the correspondent DDF curve (Fig. 4), and proceeded as follows. We divided the 10-day period in two subintervals, namely 1–3 days and 4–10 days (see Table 1), and computed the effective rainfall for the first 3 days, which was equal to is 6.00×10^{-2} m, and the mean incoming flux, which read 2.0×10^{-2}m day^{-1} (Table 1). We then considered the 4–10 day interval and determined the correspondent effective rainfall (5.9×10^{-2} m) and the mean incoming flux (equal to 8.57×10^{-3} m day^{-1}). This allowed us to compute, the factor of safety for a rainfall with a return period of 2 yr, which was equal to 1.07 (Fig. 14).

The mean value of the incoming flux for each DDF curve is reported in Table 1 and the related factor of safety is shown in Fig. 14. Even if it should be considered useless to indicate the variation of FoS for values <1, in this case it can be useful

Table 1. Infiltration rate due to rainfall cumulated from 1 to 120 days for return periods of 2, 5, 10, 20, 50, 100, 200 yr.

	Unit flux [m day^{-1}]						
T [days]	Tr2	Tr5	Tr10	Tr20	Tr50	Tr100	Tr200
1–3	2.00E-02	2.92E-02	4.00E-02	4.33E-02	4.83E-02	5.17E-02	5.67E-02
4–10	8.57E-03	8.93E-03	7.86E-03	9.64E-03	1.14E-02	1.32E-02	1.46E-02
11–30	3.25E-03	4.75E-03	4.88E-03	6.13E-03	6.88E-03	7.38E-03	7.63E-03
31–60	2.08E-03	2.58E-03	3.33E-03	3.25E-03	3.75E-03	4.33E-03	5.08E-03
60–120	1.21E-03	1.71E-03	2.00E-03	2.38E-03	2.71E-03	3.08E-03	3.21E-03

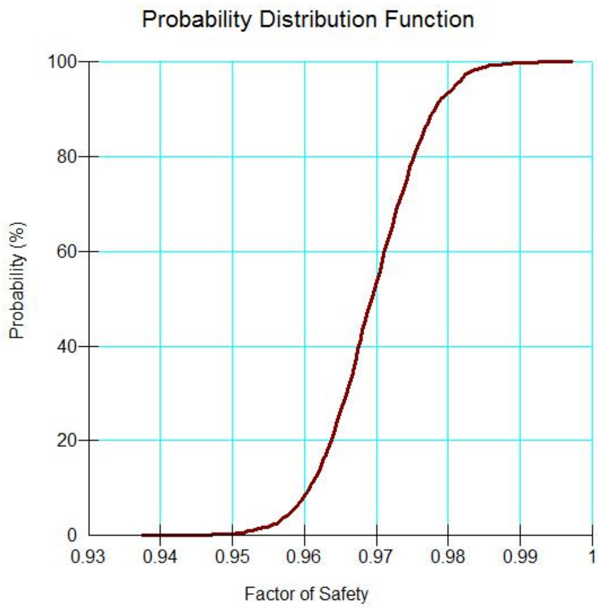

Fig. 11. Factor of safety probability of failure.

to observe the influence of different hydrological conditions on the ratio of resisting driving forces.

Results highlight that FoS generally decreases for rainfall cumulated up to 60 days, then it increases for cumulative rainfall over 120 days (Fig. 14). These findings could be explained in relation to values of unit flux assigned as input condition and time intervals elapsed between each stability analysis. The amount of precipitation progressively decreases as described in Table 1, but seepage increase in the first 60 days, due to lack of time necessary for groundwater drainage. Afterwards, from daily step 60th to 120th, the intensity of precipitation and time intervals allowed groundwater to drain, showing drawdown behaviour and causing the factor of safety to increase. Furthermore, increasing the return period of cumulated rainfall over 2 months (i.e. increasing the amount of rainwater) causes the factor of safety to decrease. However, all values of FoS are very close to one showing the precarious equilibrium of the crown area, as emphasized by field evidence.

5 Hydrological alert system

The rainfall Depth-Duration-Frequency (DDF) curves can be used to build up an alert system based on the degree of exceptionality of cumulative rainfall (Fig. 15). During the monitoring of rainfall through an automated rain gauge, at $T = 0$, where the time unit depends on the monitored phenomena (see next paragraph) after a rainfall event, plotting on the DDF curves the cumulative rainfall calculated backward from the event (bleu line in Fig. 15) makes it possible to evaluate the degree of exceptionality and, as in the case showed in the figure, to issue the first level of alert (Fig. 15a). Then, at $T = 25$, if it stops raining, it emerges that the cumulative rainfall is not exceptional and the alert is stopped (Fig. 15b). However, if it continues to rain, the degree of exceptionality of the rainfall event increases and the level of alert becomes higher (Fig. 15c). At $T = 75$, if it stops raining (Fig. 15d and e), the level of alert is always lower, but, if another exceptional rainfall event occurs, the cumulative rainfall is revealed to be more exceptional than at $T = 0$ and the highest level of alert is reached.

The conceptual model of the hydrological alert system can be applied in early warning at different scales, local and regional scale, and for single landslides with different type and dimensions. In fact, DDF curves represent a sort of abacus which can be calibrated depending on the type and dimension of landslides. The calibration consists in the identification of the hydrological variable related to the triggering and of the minimum alert threshold for landslide occurrence. For example, in the case of shallow landslides or debris flows, which are triggered by high intensity and short duration rainfall events (e.g. Floris et al., 2010), the x-axis of the DDF plot should be set to hourly or minutely time resolution. In the case of deep landslides, the DDF plot should be set to cumulative rainfall over n days depending on the geologic and climatic context of the study area (i.e. hydrogeological features and rainfall regime). Therefore, the period that potentially influences soil water content before the failure, and infiltration, seepage and accumulation processes inducing instability conditions should be chosen on the basis of empirical and deterministic modelling.

Regarding the case of the Val di Maso landslide, results from a statistical analysis suggest that the triggering rainfall

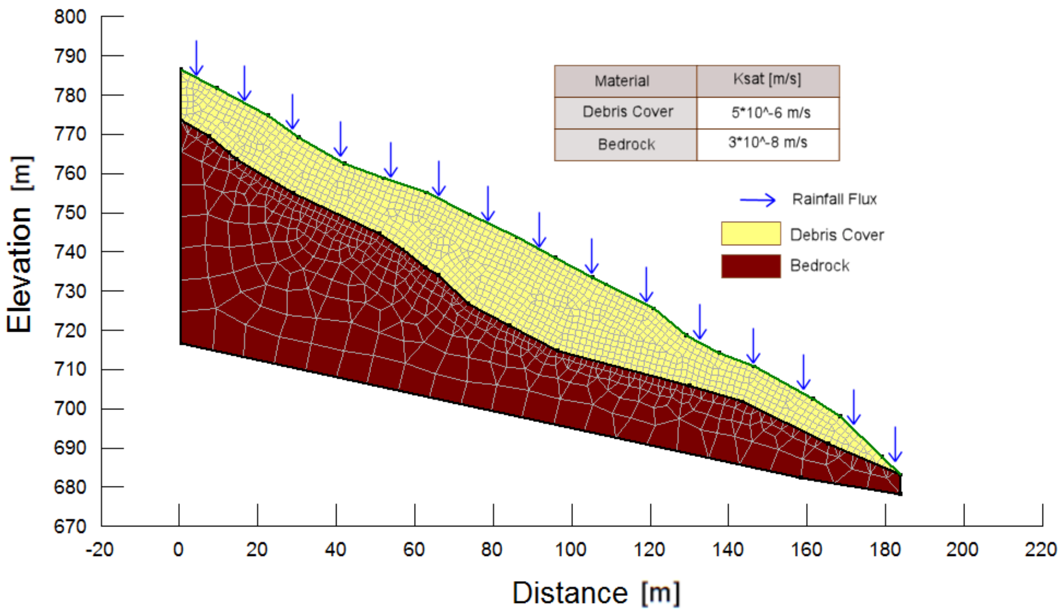

Fig. 12. Simplified model used to perform slope stability analysis in seepage conditions due to rainfall depths with different return periods.

event was so intense and exceptional, that it represented an extreme event in which the failure of the slope could be considered as a consequence not statistically significant. The results from the coupled seepage and slope stability analyses performed in the sector behind the main scarp of the November 2010 landslide, reveal to be quite interesting. These analyses point out that the factor of safety decreases introducing seepage conditions related to rainfall cumulated up to 60 days, then increases for rainfall cumulated over 120 days (Fig. 14). Thus, the rainfall pattern of the last 60 days has to be considered to build up the alert system. The minimum threshold and level of alert can be set to rainfall events with a return period of 2 yr, which can induce values of the factor of safety very close to one. Higher threshold alerts can be assigned taking into account the increase in the degree of exceptionality in correspondence to the DDF curves for increasing return periods.

Data from extensometers placed in the crown area after the landslide were used to test the alert system defined for Val di Maso. In fact, recorded displacements are related to cumulated rainfall with a return period longer than 2 yr that represents the first level of alert, while most less intense and exceptional cumulated rainfall did not induce instability conditions (Fig. 16). In Fig. 17 cumulative rainfall over 60 days before the most intense rainfall events after the November 2010 flood are plotted on the hydrological alert system for Val di Maso. The figure shows that the 23 December 2010 event, which induced the maximum registered displacements (Fig. 9), is characterized by a return period of about 5 yr corresponding to the second level of alert, but following the proposed conceptual model, the alert is bigger due to the occurrence of rainfall events during the last 60 days. The other two considered events, dated 16 March 2011 and 6 May 2011, are very similar, but the latter did not induce any displacement, confirming that in the case of rainfall-induced landslides, once a fixed rainfall threshold is exceeded, an unknown probability of failure exists. In fact, rainfall has to be considered as a necessary condition for triggering mass movements, but it is not a sufficient one because landslide occurrence is induced by a combination of factors, some of which are often unknown or cannot be evaluated (Aleotti and Chowdhury, 1999; Floris and Bozzano, 2008).

Considering the area surrounding Val Maso (about 100 km^2) that was strongly affected by landslides after the November 2010 event, the hydrological variable related to landslides after flood events is the rainfall cumulated up to three days, as it can be deduced by comparing Figs. 3 and 4. In fact, the highest degree of exceptionality is reached by rainfall events lasting one to three days before all the three historical flood events of the last one hundred years. However, the rainfall regime before flood events has also to be taken into account because it can promote the occurrence of critical conditions, both in terms of soil moisture and groundwater, as a consequence the number of landslides and the extent of damages can increase. Because the Val di Maso landslide can be considered representative of instability phenomena occurring in the west part of the Vicenza Province, rainfall cumulated up to 60 days has to be considered to set up the alert system. For this purpose, a minimum rainfall triggering threshold is needed. Comparing the main historical floods, it emerges that the 1992 rainfall event was the less intense and exceptional in terms of cumulated rainfall being

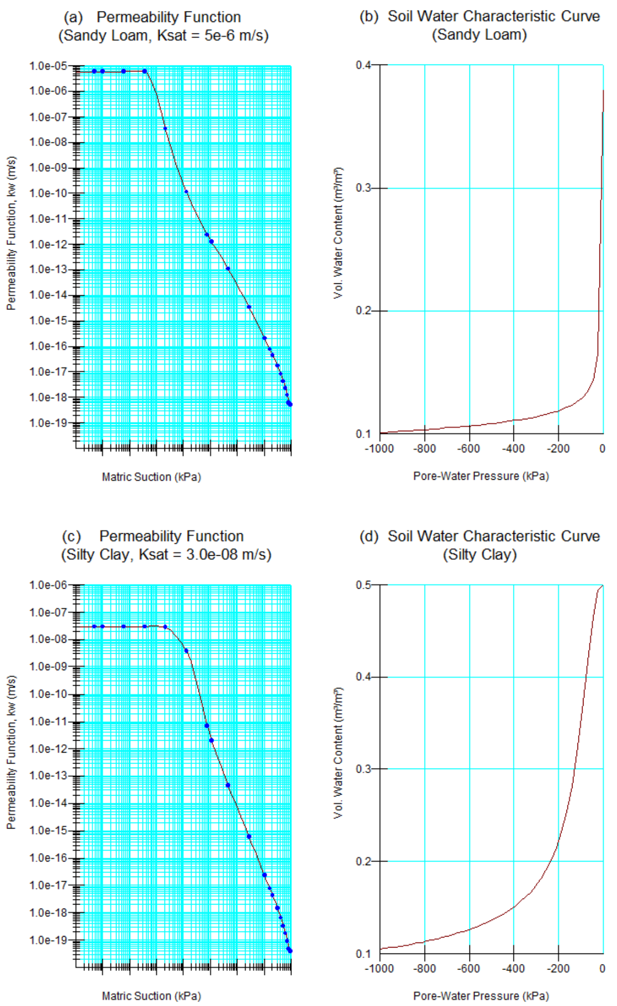

Fig. 13. Unsaturated permeability function and soil water characteristic curve assigned to debris cover assimilated to a sandy loam (**a** and **b**) and to Werfen deposits assimilated to a silty-clay (**c** and **d**).

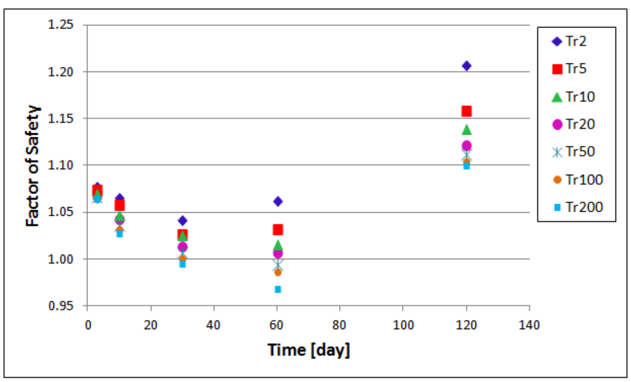

Fig. 14. Variation of factor of safety for rainfall cumulated from 3 to 120 days with different return periods.

characterized by a return period of 10 yr for the cumulative rainfall over the 2 days before the flood (Fig. 4). Thus, the DDF curve with a return period of 10 yr can be considered as the minimum rainfall triggering threshold for the occurrence of landslides after flood events. As in case of the alert system for Val di Maso landslide, increasing levels of alert can be set to DDF curves with increasing return period.

6 Conclusions

Combination of results from empirical and physically-based modelling of the relationships between landslides and rainfall patterns before the time of failure should be considered in developing hydrological systems of alert for rainfall-induced landslide early warning. Empirical models can help in the identification of the rainfall patterns linked to landslides and in the evaluation of recurrence of critical conditions. Physically-based models are essential to verify the effects on the slope stability of determined rainfall events and to set a minimum alert threshold over which a movement can occur. As a consequence, physically-based models allow one to set the first level of alert, whereas empirical models make it possible to set increasing levels of alert following the criteria that once the minimum threshold has been reached, as the degree of exceptionality of the rainfall event increases, the probability of failure increases as well.

The combined use of the two approaches can be always feasible to single slope analysis, while at territorial scale, in the prevision of landslides triggered by flood events, the application of physically-based models is limited to the case of homogeneous geological and geomorphological contexts. Actually, landslides induced by flood events consist of different types, even if most of the phenomena are shallow movements, such as soil slips and earth flow, also falls and deep landslide reactivations can occur. Therefore, at regional scale empirical models are often the only tool available in the prevision, prevention and management of landslides induced by flood events.

Physically-based models are crucial in studies at the slope scale. In the case study reported in this paper (Val di Maso landslide) deterministic modelling was of help to analyse different features of the problem. In particular, coupled seepage and slope stability back analysis of the landslide that occurred in November 2010 allowed us to determine, with quite good accuracy, the geological and technical parameters which were used to model the possible future evolution of the landslide. Such parameters are difficult to evaluate in a complex geological context as seen in the area of Val di Maso, also through specific in situ and laboratory tests. Furthermore, thanks to physically-based modelling we were able to identify the minimum rainfall alert threshold for the triggering of a retrogressive evolution of the Val di Maso landslide and we obtained information on the rainfall pattern related

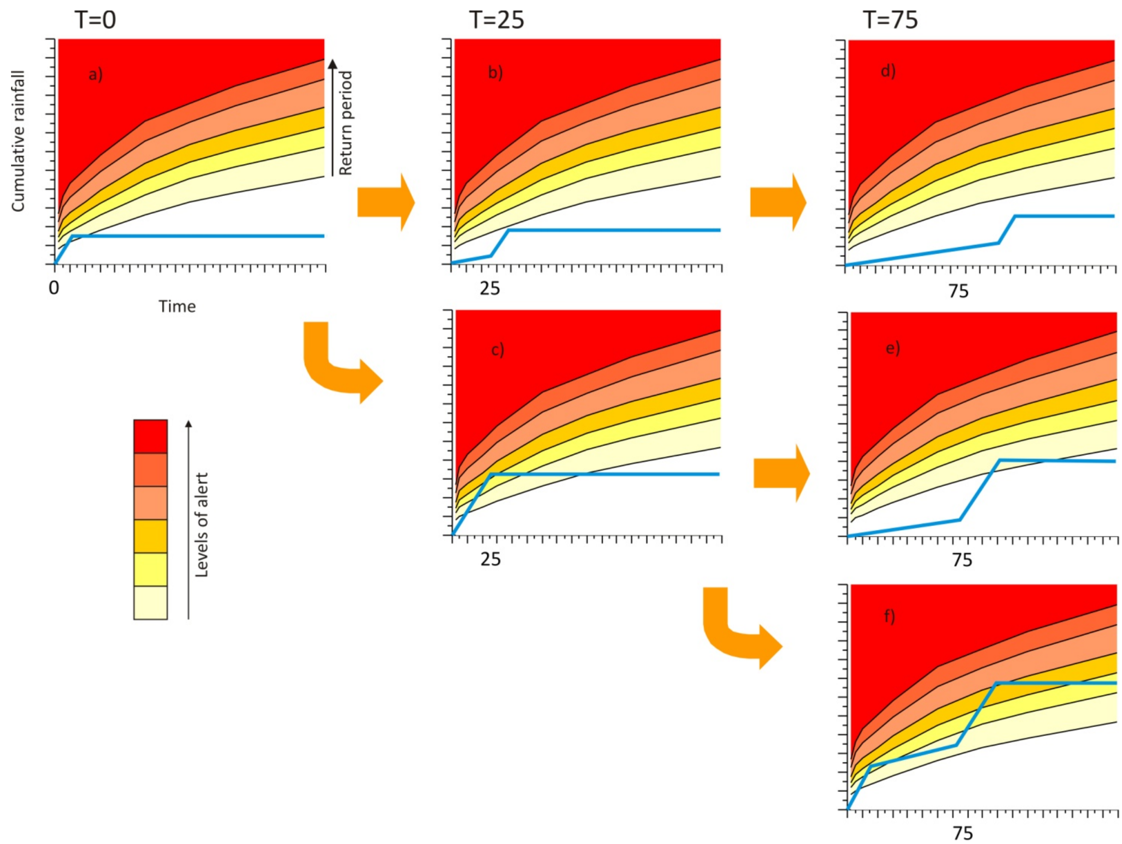

Fig. 15. Conceptual model of the hydrological alert system. Continuous black lines represent DDF curves, color fills show levels of alert, and the blue line indicate cumulative rainfall calculated backward from $T = 0$.

to the landslide occurrence in the west part of the Vicenza Province after flood events.

The process-based model followed in this study led to propose a hydrological alert system based on the computation of rainfall Depth-Duration-Frequency curves which allow one to evaluate the degree of exceptionality of rainfall events possibly related to landslide triggering. The proposed system proves to be effective, mainly because it can be applied to different scales of investigation and geological and geomorphological contexts. Furthermore, it is easy to set up. The needed components are a rain gauge station, a software that compares rainfall data to rainfall events with different return periods and degree of alert, and a transmission system of the warning levels to authorities.

The performance of the alert system proposed for the case of Val di Maso has been tested on the basis of extensometer and rainfall data collected after the landslide occurred in November 2010, but it should be further tested. A possible test could be a flood event or a reactivation of Val di Maso landslide, but this is not desirable. However, due to the high degree of risk induced by the evolution of Val di Maso landslide, a monitoring system and remediation works are currently being realized. Monitoring consist of load cells, piezometers, extensometers, topographic net and GPS points. We are investigating the possibility of monitoring superficial displacement through interferometric RADAR techniques. In the near future, monitoring data will help in testing and improving landslide evolution and alert models.

The approach used in this study, as well as the conceptual findings, are quite similar to those of some recent papers mentioned in the Introduction. Capparelli and Versace (2011) and Rahimi et al. (2011) at the local scale, and Goetz et al. (2011) and Cascini et al. (2011) at the basin scale provide examples on the effectiveness of combining empirical and deterministic approaches in rainfall-induced landslide forecasting. In some cases, physically-based modelling does not improve significantly the prediction, but helps to clarify some physical aspects which allow the use of empirical relationships in forecasting (Goetz et al., 2011). This is the case of this paper, where results from deterministic analysis at the slope scale allowed for identifying rainfall patterns linked to landslides at small scale and to propose an alert system in the area surrounding Val di Maso. The papers mentioned above do not provide any scheme of alert system, but proposed methods to forecast rainfall-induced landslides that could be used for this purpose. Such methods are rather more complex

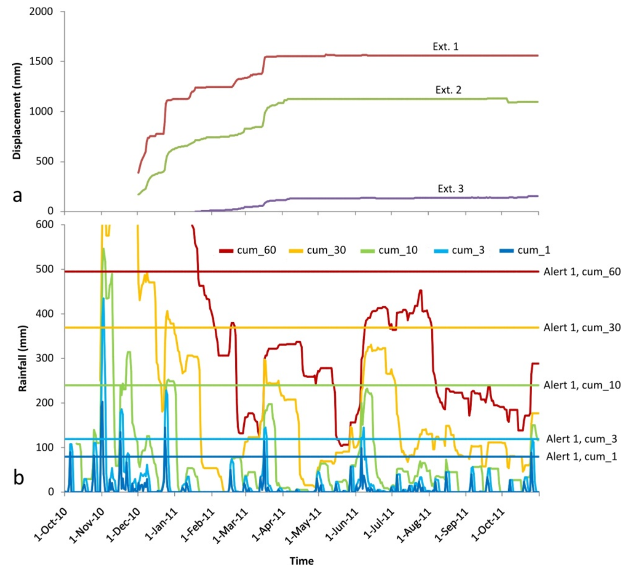

Fig. 16. Displacements measured after Val di Maso landslide by extensometers placed in the crown area **(a)** and variation of rainfall cumulated over 1, 3, 10, 30, 60 days. The straight lines (in panel **b**) indicate the minimum alert (return period = 2 yrs) set for each variable in the hydrological alert model developed for Val di Maso (Fig. 15).

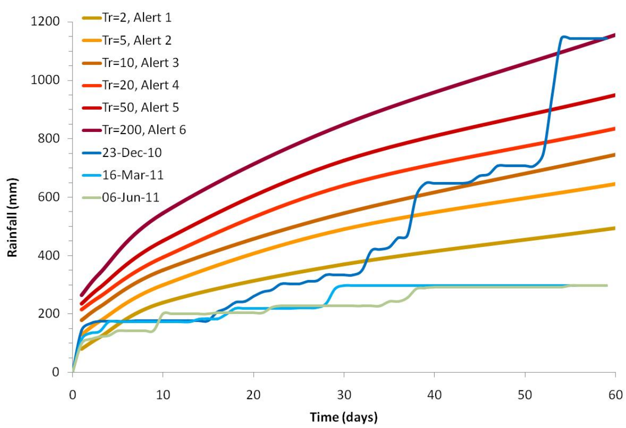

Fig. 17. Hydrological alert system for Val di Maso and 60-days rainfall cumulated backward from the most intense rainfall events after the November 2010 flood. The 23 December 2010 and 16 March 2011 events induced displacements measured by extensometers placed in the crown area.

than those provided in this work, but the use of complex mathematical models does not always improve the precision and accuracy of forecasting models. To this end it could be useful to refine deterministic models inserting a more complete dataset from laboratory and site tests, and deepening physical phenomena which occur in the slopes under given rainfall events, as suggested by many other authors as recalled in the Introduction.

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