Landslides
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Assessment of rainfall thresholds and soil moisture modeling for operational hydrogeological risk prevention in the Umbria region (central Italy)

Abstract Rainfall thresholds represent the main tool for the Italian Civil Protection System for early warning of the threat of landslides. However, it is well-known that soil moisture conditions at the onset of a storm event also play a critical role in triggering slope failures, especially in the case of shallow landslides. This study attempts to define soil moisture (estimated by using a soil water balance model) and rainfall thresholds that can be employed for hydrogeological risk prevention by the Civil Protection Decentrate Functional Centre (CFD) located in the Umbria Region (central Italy). Two different analyses were carried out by determining rainfall and soil moisture conditions prior to widespread landslide events that occurred in the Umbria Region and that are reported in the AVI (Italian Vulnerable Areas) inventory for the period 1991–2001. Specifically, a "local" analysis that considered the major landslide events of the AVI inventory and an "areal" analysis subdividing the Umbria Region in ten sub-areas were carried out. Comparison with rainfall thresholds used by the Umbria Region CFD was also carried out to evaluate the reliability of the current procedures employed for landslide warning. The main result of the analysis is the quantification of the decreasing linear trend between the maximum cumulated rainfall values over 24, 36 and 48h and the soil moisture conditions prior to landslide events. This trend provides a guideline to dynamically adjust the operational rainfall thresholds used for warning. Moreover, the areal analysis, which was aimed to test the operational use of the combined soil moisture–rainfall thresholds showed, particularly for low values of rainfall, the key role of soil moisture conditions for the triggering of landslides. On the basis of these results, the Umbria Region CFD is implementing a procedure aimed to the near real-time estimation of soil moisture conditions based on the soil water balance model developed ad hoc for the region. In fact, it was evident that a better assessment of the initial soil moisture conditions would support and improve the hydrogeological risk assessment.

Keywords Hydrogeological risk · Landslides · Rainfall thresholds · Soil moisture

Introduction

Landslides are frequent and widespread geomorphological phenomena that can cause the loss of human life and damage to property. In the period 1950–2009 in Italy, the population was impacted by an average of 16 harmful events per year, for which people died, were missing or injured (Guzzetti et al. 2003; 2005; Brunetti et al. 2010). The Italian Civil Protection System is organized by an early warning national office (called Central Functional Centre) and a network of 21 Regional Centres (called Decentrate Functional Centres, CFDs) whose main activities are the prediction, monitoring and evaluation of critical flooding and landslide events resulting from heavy rainfalls and (seldom) snowmelt.

The national alerting procedure adopted by the CFD of the Umbria Region, is based on three warning levels, i.e. Ordinary, Moderate and High Criticality, whose selecting criteria currently relies on assigned rainfall thresholds computed considering the regional rainfall frequency analysis procedure proposed in the VAPI project (Franchini and Galeati 1999). Specifically, for each duration (from 1 to 48 h), the Ordinary, Moderate and High Criticality levels are assigned to the rainfall values corresponding to a recurrence interval of 2, 5, and 10 years, respectively. These thresholds are compared against rainfall observations coming from hydrometeorological monitoring networks and from the Quantitative Precipitation Forecasts (QPFs) of the meteorological Limited Area Model COSMO-ME (Molteni et al. 2001; Marsigli et al. 2008); issued two times per day with a 3-hour time step. However, so far, in the Umbria Region no cause–effect relationship relating these thresholds to the effective occurrence of landslides was found, showing how the procedure might be weak in predicting landslide occurrence.

A wide scientific literature dealing with the use of rainfall thresholds for landslide triggering is available (Caine 1980; Wieczorek 1987; Reichenbach et al. 1998; Glade et al. 2000; Guzzetti et al. 2007; 2008). Basically, if the rainfall threshold is exceeded during a storm, an alert can be sent out by authorities for potential landslide occurrence. Although the procedure has the advantage of being relatively simple to implement, it does not take soil moisture conditions into account that, instead, play a critical role in triggering slope failure (see e.g. Iverson 2000; Segoni et al. 2010; Huggel et al. 2010; Hawke and McConchie 2011). The process leading to the slope instabilities should be investigated more in-depth with the perspective of achieving landslide temporal occurrence. Predicting where a landslide will take place (e.g. susceptibility maps, Guzzetti et al. 1999) together with indications of the timing of its occurrence, is essential from the point of view of alerting civil protection activities.

Usually, for hazard assessment the estimation of the wetness conditions of the soil is addressed by using antecedent precipitation indices (Crozier 1999; Glade et al. 2000; Del Maschio et al. 2005; White and Schwab 2005; Jakob et al. 2006; Capparelli and Tiranti 2010). However, Pelletier et al. (1997), among others (Godt et al. 2006; Baum and Godt 2009; Segoni et al. 2010), recommended replacing the use of antecedent precipitation indices because, frequently, they are poorly correlated with the actual soil moisture observations (Brocca et al. 2005; 2008). Soil moisture can be estimated using in situ measurements, remote sensing techniques, and soil water balance simulation models. The integration of these three tools (in situ measurements, remote sensing and modeling) may provide reliable estimates of soil moisture at the temporal and spatial resolutions required for operational activities related to shallow landslide warning systems (Ray and Jacobs 2007; Capparelli and Versace 2010; Greco et al. 2010; Ray et al. 2010).

This study attempts to define a procedure for landslide warning by combining rainfall thresholds and estimates of soil moisture

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conditions derived from a soil water balance model calibrated and tested with local soil moisture observations. The procedure is developed by analyzing the most severe widespread landslide events that occurred in the Umbria Region during the period 1991–2001 and reported in the AVI (Italian Vulnerable Areas) inventory.

Study area and dataset

The Umbria Region (8,456 km^2) is located in central Italy and is characterized by hilly and mountainous topography with elevations ranging from 50 to 2,436 m a.s.l. The geology is comprised of post-orogenic marine and continental facies, flysch deposits consisting of clay-schist and clay-marl sediments, well-bedded limestones and volcanic rocks (Cardinali et al. 2002). 53.6% of the Region is covered by agriculture/arable land, the remaining area is 39.2% forest and 4.7% urban. One hundred percent of municipalities in Umbria have areas at hydrogeological risk, and about 9% (650 km^2) of the land area is covered by active landslides. More than 70% of the inventoried landslides are of dormant type, subject to reactivation with strong precipitations. Analysis of the landslide types shows that most of them (more than 70%) are the shallow ones characterized by a translational–rotational slow-moving type, about 4% are fast moving slides, and only 10% are deep-seated landslides. The precipitation regime can be classified as Mediterranean, with distinct dry and wet seasons. Higher monthly precipitation values generally occur during the autumn–winter period when landslides and floods, caused by widespread rainfall, normally occur. Mean annual precipitation is about 1,000 mm; mean annual temperature is 11°C; snowfalls at altitude below 500 m are unusual.

The territory is covered by a near real-time hydrometeorological network (1 station every 80 km^2 approximately with a data recording time interval 30 min), operating more than 20 years (see Fig. 1). The system is made up by 120 stations (72 stream gauges, 85 rain gauges, 74 weather stations, 12 radio repeaters, 1 Doppler C band Meteoradar). The historical rainfall database used for this analysis is composed of 56 rain gauges that are uniformly distributed on the territory and characterized by uninterrupted and high quality data during the period from 1989 to 2001. The temperature database is composed of 30 thermometers operating over the same period as that of the rain gauges.

The other source of data is the AVI landslide dataset (http://avi.gndci.cnr.it/en/archivi/frane_en.htm); the only inventory of sites affected by landslides available for the Umbria Region. The scope of the AVI project consisted of an inventory of areas affected by landslides and floods in Italy. In the AVI dataset a description of the type and trigger cause of the reported landslides is present along with the day of occurrence for the period 1989–2001. We can expect an accuracy of 24 h, since in the inventory only the day of occurrence for each landslide is given. Consequently, the analysis considering cumulative rainfall with duration longer than 24 h (i.e., 24, 36 and 48 h) can be considered more reliable. Moreover, the AVI landslide inventory probably only represents a fraction of the actual number of landslides that occurred; many were likely never reported due to the large area of the region (~8,500 km^2) and to the lack of systematic collection of landslide data. However, the landslides with high impact on territory were reported.

Methodology

Two different analyses were conducted in this study for detecting the rainfall and soil moisture thresholds tied to widespread landslide events over the Umbria territory. Specifically, a "local" analysis to address the major landslide events of the AVI inventory and an "areal" analysis subdividing the Umbria Region in ten sub-areas were carried out. In addition, the reliability of the rainfall thresholds currently applied in the Umbria Region CFD was evaluated. It's worth noting that these thresholds were obtained through the regionalization procedure based on recurrence interval of rainfall, without taking the effective activation of landslides into account. A key part of the analysis is based on the soil water balance model used for the assessment of the soil moisture conditions at the onset of each storm event and, for that, it's brief description is in the sequel.

Soil water balance model

A peculiarity of the soil water balance model is that its structure was developed using soil moisture observations carried out in experimental catchments located in the Umbria Region (Brocca et al. 2005; 2008). In particular, different expressions were considered for the different components of the model, such as infiltration, percolation and evapotranspiration. The analysis based on soil moisture measurements allowed the selection of the simpler soil water balance model which is schematized as a spatially lumped system wherein the following water content balance equation holds:

$$\begin{cases} \dfrac{dW(t)}{dt} = f(t) - e(t) - g(t) & W(t) \leq W_{\max} \\ W(t) = W_{\max} & W(t) > W_{\max} \end{cases} \tag{1}$$

$W(t)$ is the amount of water in the investigated soil layer, t is the time, $f(t)$ is the fraction of the precipitation infiltrating into the soil, $e(t)$ is the evapotranspiration rate, $g(t)$ is the drainage rate due to the interflow and/or the deep percolation, and W_{max} is the maximum water capacity of the soil layer. In particular, the ratio $W(t)/W_{max}$ represents the degree of saturation that varies between 0 and 1.

The infiltration rate, $f(t)$, is estimated by using the Green–Ampt equation:

$$\begin{cases} f(t) = K_s\left[1 - \dfrac{\psi}{L}\dfrac{(W_{\max} - W_i)}{F}\right] & f(t) \leq r(t) \\ f(t) = r(t) & f(t) > r(t) \end{cases} \tag{2}$$

K_s is the saturated hydraulic conductivity, ψ is the wetting front soil suction head, W_i is the amount of water at the beginning of the rainfall event, L is the thickness of the soil layer, F is the cumulated infiltration depth from the onset of the rainfall, and $r(t)$ is the rainfall rate.

For the drainage component, the following relation is adopted (Famiglietti and Wood 1994):

$$g(t) = K_s\left[\frac{W(t)}{W_{\max}}\right]^{3+\frac{2}{\lambda}} \tag{3}$$

Fig. 1 Morphology and hydrometeorological network of the Umbria Region. The location of the landslides reported in the AVI inventory and the subdivision in 10 sub-areas used for the areal analysis are also shown

λ is a pore size distribution index linked to the structure of the soil layer.

Evapotranspiration, which mainly controls the soil moisture temporal pattern in periods without rainfall, is represented by a linear relation depending on the potential evapotranspiration, $ET_p(t)$, and the soil saturation:

$$e(t) = ET_p(t)\frac{W(t)}{W_{\max}} \tag{4}$$

The potential evapotranspiration is computed through the empirical relation of Blaney and Criddle as modified by Doorenbos and Pruitt (1977):

$$ET_p(t) = -2 + b[\xi(0.46T_a(t) + 8.13)] \quad (5)$$

$T_a(t)$ is the air temperature in °C, ξ is the percentage of total daytime hours for the period used (daily or monthly) out of total daytime hours of the year (365×12) and b is a parameter to be calibrated.

As forcing data, the model uses as meteorological variables the rainfall and air temperature, which are routinely measured by standard hydrometeorological networks. Five parameters are involved in the model calibration (W_{max}, K_s, ψ/L, λ, and b). As these parameters are physically based and their value range is limited, the model was found consistent even when the calibration is done through a limited number of observations (Brocca et al. 2008). These characteristics allow to confidently use the model over large areas and for periods different from those employed for calibration. However, it is evident that the calibration of the model parameter values for the whole Umbria Region is not straightforward. In this study, the model parameters were kept the same for the whole area and equal to the average value obtained by outcomes of previous studies (Brocca et al. 2008; 2010b). Therefore, the output of the model should be seen as a soil moisture index allowing us to estimate the relative wetness conditions of the soil before a storm event rather than the actual soil moisture value.

The model, originally developed for hydrological studies aimed at flood prediction and forecasting, showed a high degree of reliability in simulating the near-surface soil moisture temporal pattern in the experimental catchments located in the Umbria Region. In particular, it outperforms models based only on antecedent precipitation (Brocca et al. 2005; 2008) usually employed for investigating the rainfall inducing landslides. Moreover, the model was successfully implemented as a component of a rainfall–runoff model (Brocca et al. 2010a; 2011), also showing reliable performance if compared with soil moisture estimates retrieved from remote sensing (Brocca et al. 2010b). We refer the matter to the cited works for more details.

Local analysis

The local analysis consists of computing rainfall and soil moisture conditions corresponding to several widespread landslide events selected from the AVI database; Fig. 2 summarizes the different steps of the procedure. Only landslides highly correlated with the major rainfall events that occurred in the regional territory were selected. Specifically, landslides separated by more than 3 days from the rainfall events, as those combined with snow melting, were not considered. For that, the results of this work must be considered valid only for landslides directly related to rainfall, i.e., commonly, for shallow landslides, which are the most critical landslide types for the warning activities of the CFD. Following this procedure, 13 widespread rainfall events that occurred in the period 1991–2001 were selected and associated with a total of 104 single landslides; on average, 8 landslides for each rainfall event. Table 1 summarizes the main characteristics of the selected rainfall events in terms of number of landslides, maximum cumulative rainfall and initial degree of saturation as computed by the soil water balance model.

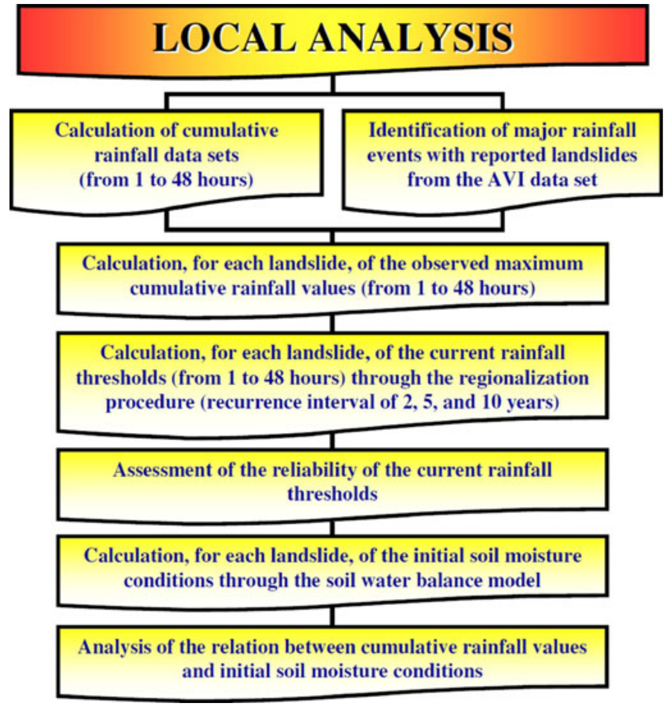

Fig. 2 Flux diagram of the local analysis

Therefore, the analysis intends, on the one hand, to assess the reliability of the rainfall thresholds currently used within the Umbria Region CFD, and, on the other hand, to investigate if a relationship between the cumulative rainfall values and initial soil moisture conditions before a landslide event can be identified. As far as rainfall thresholds are concerned, the influence of the soil moisture conditions on the rainfall thresholds will be investigated in-depth. At the moment, in order to shift from dry to wet soil conditions, a fixed reduction of rainfall threshold value equal to 30% is used in accordance with previous studies (DPCN-Regione Piemonte 2004) while for the rainfall–soil moisture relationship, the particular type (linear, non linear) will be assessed and quantified.

Before investigating the influence of soil moisture conditions, a preliminary analysis on adopted rainfall thresholds by CFD was also carried out to estimate the rainfall value reliability linked to the possibility of occurrence of widespread landslide events in the Umbria Region territory. For this purpose, for each soil slips (104 in total), the rainfall events corresponding to the landslide were identified and the maximum cumulative rainfall values referring to seven different durations (1, 3, 6, 12, 24, 36, and 48 h), defined as "experimental" thresholds, were computed. At the same time, the values of the current thresholds inferred through the regionalization procedure were computed. Through this procedure, current and experimental thresholds can be compared as average values of the whole Umbria Region thus obtaining a first impression of the current threshold reliability. It has to be noted that the current thresholds are obtained with a regionalization procedure only based on a quite arbitrary selection of three recurrence intervals (2, 5 and 10 years) without any linking with the effective occurrence of landslide in the territory. Therefore, the assessment of the correspondence of these rainfall thresholds and the occurrence of landslides is clearly needed.

Table 1 Main characteristics of the widespread landslide events reported in the AVI inventory

Id	Event date (MM/DD/YYYY)	no. of observed landslide	Maximum cumulative rainfall (mm)							Initial degree of saturation (%)	
			1 h	3 h	6 h	12 h	24 h	36 h	48 h	Min	Max
1	11/16/1991	5	14.4	23.1	30.1	41.8	53.7	56.4	58.0	68	84
2	11/20/1991	7	15.2	24.8	31.0	40.9	52.3	56.5	59.0	75	84
3	11/24/1991	12	9.1	15.5	23.4	32.7	36.6	52.5	60.5	75	85
4	10/10/1992	6	8.0	13.7	19.7	23.7	36.4	40.0	44.4	59	67
5	10/20/1992	6	27.3	38.8	42.4	48.3	51.7	52.5	52.5	70	82
6	12/08/1992	8	12.6	21.2	29.2	42.6	49.3	51.1	56.5	64	84
7	10/08/1993	6	16.3	20.1	23.6	26.4	28.2	49.3	53.1	66	77
8	10/21/1993	8	11.0	21.1	29.6	48.0	65.5	65.6	65.6	62	81
9	04/03/1996	4	12.3	19.3	31.6	47.0	52.3	52.3	52.3	68	83
10	09/22/1996	8	13.7	20.6	26.1	36.7	47.8	56.3	64.9	61	80
11	12/14/1996	10	17.7	28.3	34.9	51.4	72.8	91.9	107.0	54	82
12	11/08/1997	4	14.4	21.3	30.2	37.6	42.5	43.5	43.8	71	83
13	12/15/1999	7	8.8	15.7	21.9	37.0	54.1	59.1	60.8	73	84

Areal analysis

In order to extend local analysis results to large scale, an areal analysis was carried out (see Fig. 3). This is consistent with the actual operational conditions of the Umbria Region CFD, which necessarily evaluates scenarios at the regional level or for sub-areas of alert and not in a local manner except for particular landslides.

For this analysis, the Umbria Region was subdivided in ten homogeneous sub-areas considering the spatial distribution of the rain gauge network and the hydrological catchment boundaries (see Fig. 1). For each sub-area, the time series of spatially averaged rainfall, temperature and estimated soil moisture were determined; the latter through the soil water balance model application. Then, the significant rainfall events that occurred in the study period (1991–2001) were extracted by adopting a specific procedure. A significant rainfall event was defined if the total rainfall is greater than 10 mm; each event is distinguished from another if a total rainfall less than 1 mm occurred for at least 10 h. Then, for each rainfall event, its duration, the seven cumulative rainfall values (between 1 and 48 h), the average rainfall, the total rainfall and the antecedent soil moisture conditions were assessed. Finally, the results were cross-checked with the AVI database, by identifying the rainfall events associated with the report of a landslide inside the analyzed sub-area.

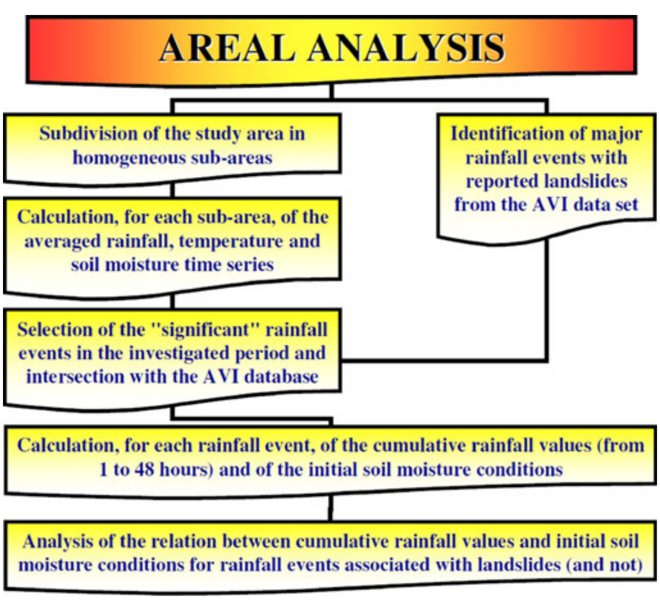

Fig. 3 Flux diagram of the areal analysis

This analysis allows us to determine the characteristics of rainfall events that triggered landslides but also rainfall events not associated with reported landsliding that are useful to investigate false alarms. For that, the rainfall–initial soil moisture relationship obtained by local analysis was applied for testing if it can be considered a useful tool to distinguish false alarms from "true" landslide events. This procedure, however, is affected by the completeness of the AVI inventory noted previously. By way of example, during a rainfall event that occurred in December 2008, 300 mm of rainfall in 12 days was registered (the mean of maximum monthly rainfall is around 240 mm), with 120 landslides reported to the Regional Civil Protection Office; this one was an event of "Moderate Criticality". However, for past rainfall events of similar characteristics (e.g. December 1996) the AVI inventory contains no more than 20 landslides. This can be explained because the AVI inventory is mainly based on analysis of newspapers and technical publications for which only information over urban areas or roads are reported. For this reason, it is not possible to treat such procedure as an accurate analysis of false alarms, as the number of hits recorded by the reported landslides is surely much lower than those that actually took place; anyway, the goals described above are still maintained.

Results

First of all, the local analysis was carried out to assess the reliability of the current rainfall thresholds operative within the CFD. Figure 4 shows an example of the employed procedure for three of the five landslides that occurred during the rainfall event of 16th November 1991 (see Table 1). In the figure, the comparison between the current dry thresholds and the experimental ones for each duration is shown. Seeing the observation period of about 10 years, we have, on average, 1.3 events per year and, hence, the current thresholds corresponding to the "Ordinary Criticality" level, i.e., to a recurrence interval of 2 years, are considered in this analysis. As can be seen, experimental thresholds are always lower than the current ones, likely due to the wet soil moisture conditions of the soil prior to the selected storm event (degree of saturation equal to ~0.7, see Fig. 4a), underlining once again the importance of initial soil moisture conditions before landslide.

To quantify the relationship between soil moisture conditions and rainfall thresholds, Fig. 5 shows the maximum cumulative rainfall values for 24, 36 and 48 h against the initial degree of saturation (simulated by the soil water balance model) for all the 104 landslide events. As expected, a clear decreasing trend can be found for these durations with statistically significant correlation coefficients (p-value < 0.01) ranging between 0.41 (for 24 h) and 0.62 (for 48 h). These results are in accordance with previous studies (Crozier 1999; Del Maschio et al. 2005; Baum and Godt 2009) that obtained a similar linear decreasing trend between the rainfall thresholds and the initial soil moisture conditions even though a surrogate based on the antecedent precipitation was frequently used. For shorter durations (up to 12 h), however, a correlation between increasing levels of soil saturation and decrease of maximum rainfall was not detected. This result, as mentioned above, might be due to the characteristics of the AVI database for which only the day of the landslide occurrence is reported (and not the hour). It is expected that if a more detailed landslide inventory was available also for these durations a better correlation between the rainfall thresholds and soil moisture would have been achieved. It is also possible to observe that in dry soil conditions (e.g. for a degree of saturation equal to 0.4) the rainfall thresholds are in a very good agreement with the current thresholds previously adopted.

The linear trend between the rainfall and the initial soil moisture conditions was inspected in-depth in terms of implications on the areal analysis. In Fig. 6, the overall results

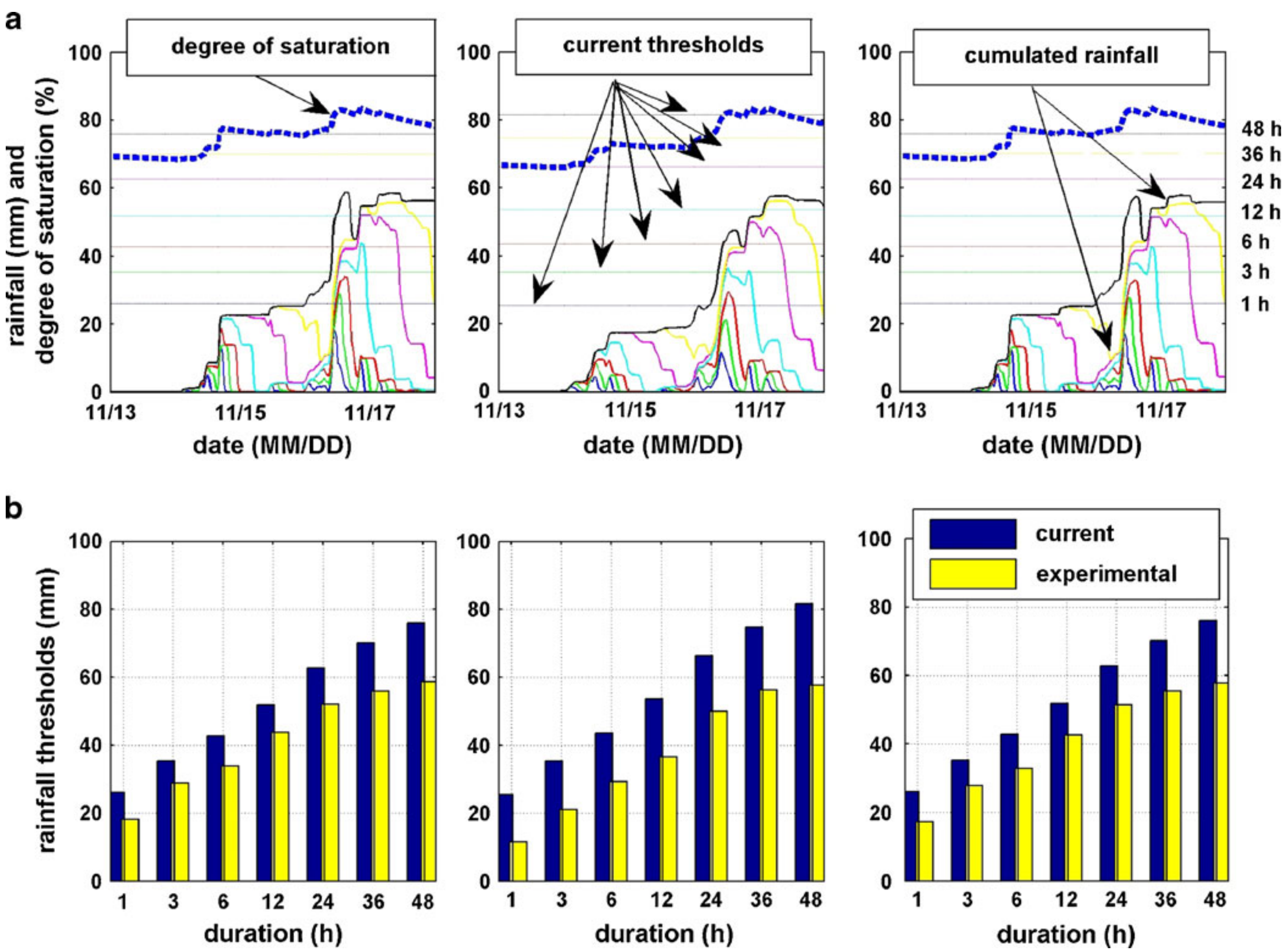

Fig. 4 Analysis of three landslides occurred during the rainfall event of 16th November 1991. **a**) The cumulated rainfall for the different durations is reported along with the corresponding current thresholds (T_r=2 years) and the degree of saturation simulated by the soil water balance model. **b**) Comparison between the experimental and the current rainfall thresholds for all the durations

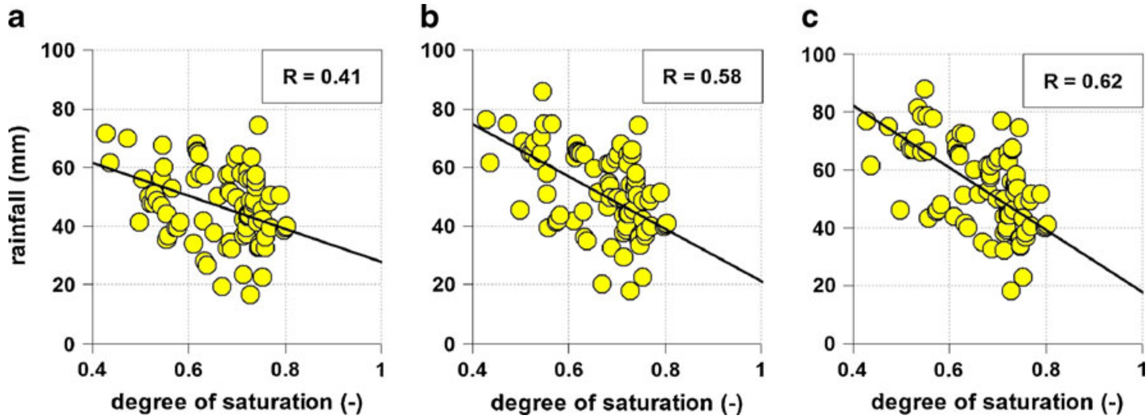

Fig. 5 Cumulated rainfall values over 24 (**a**), 36 (**b**) and 48 (**c**) hours versus the simulated initial degree of saturation for the landslide events reported in the AVI database and considering the period 1991–2001

of the areal analysis are shown by plotting together the 10 homogeneous sub-areas, for the cumulated rainfall values of 24, 36 and 48 h. Specifically, the open circles correspond to all the rainfall events while the filled circles are those rainfall events matching with a record of landslide in the AVI inventory. In addition, the regression lines obtained by the statistical analysis of the regional rainfall events described in the previous paragraph are also shown. The small cluster of landslide events characterized by low values of cumulative rainfall–degree of saturation was found related to landslide events that mainly occurred in the months of May and September. During these months a transition between dry and wet (or wet and dry in September) conditions occurs and, hence, it is well-known that the predictability of the soil moisture conditions is strongly reduced (Zehe and Sivapalan 2009).

Discussion

Results of the local and the areal analyses allow for the evaluation of the current reliability of the thresholds and, most importantly, their relationship with the antecedent soil moisture conditions.

As can be seen in Fig. 4, the current rainfall thresholds in dry conditions present values higher than the experimental ones; this is justifiable because the rainfall events analyzed show generally wet soil conditions (winter period), and, further, the 2-year recurrence interval referred to the current thresholds is slightly higher than the time recurrence of the landslide events found in the AVI dataset. Therefore, the obtained experimental thresholds can be considered reasonable for the first level of alert ("Ordinary Criticality") and, likely, the recurrence interval of 2 years is overestimated. In addition, the current wet rainfall thresholds would seem to underestimate the experimental ones for durations greater than 12 h, pointing out the need to improve these thresholds by including explicitly the effects related to the initial soil moisture conditions. In fact, the soil moisture conditions strongly affect the initiation of landslides (e.g. Hawke and McConchie 2011) and hence it is extremely useful to attempt to establish a relation between soil saturation and cumulated rainfall, thus setting aside the fixed 30% drop value currently used to address wet conditions.

For this purpose, the decreasing trend obtained in Fig. 5 can be used to continuously adjust the rainfall threshold knowing the

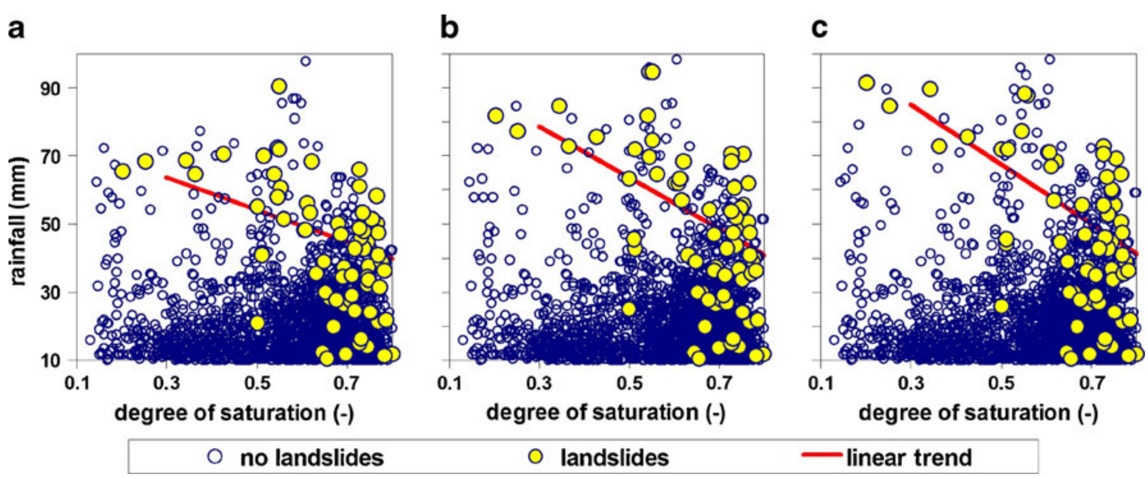

Fig. 6 Cumulated rainfall values over 24 (**a**), 36 (**b**) and 48 (**c**) hours versus the simulated initial degree of saturation for the extracted rainfall events (*empty circles*) in the 10 sub-areas of the Umbria Region during the period 1991–2001. The *filled circles* are the rainfall events associated to a landslide and the linear trend lines are those obtained by the local analysis

degree of saturation. For instance, for the duration of 48 h, if the degree of saturation is equal to 0.40 then the rainfall threshold will be about 80 mm; on the other hand, for the degree of saturation equal to 0.80 the threshold will decrease to 40 mm. On this basis, an automatic system allowing to compute both the soil moisture conditions (through the soil water balance model) and the rainfall thresholds for the different durations is going to be implemented within the Umbria Region CFD for hydrogeological risk prevention. Specifically, we decide to adopt the regression lines for the 24 h, 36 h, and 48 h durations to adjust the rainfall threshold values in near real-time. Finally, by using the Quantitative Precipitation Forecasts (QPF) of the meteorological model already implemented, the forecast of the probability of occurrence of landslide for 72 h ahead can be addressed.

The evidence of the clustering of the landslide events in the saturation zone over the value of 0.65, which is a considerable value because it represents an average value over an extended area, is reported in Fig. 6. For lower values of the degree of saturation, a fairly good agreement with the trend of the regression line based on the local analysis was observed. Indeed, by inspecting Fig. 6, most of the events located below the regression line are detected as no landslide; vice versa, the false alarms taking place over the linear trend are less than that of detected landslide. This is a simple procedure to improve the one only based on current rainfall thresholds that does not vary with the degree of saturation. Therefore, soil moisture conditions represent another important factor to be investigated along with rainfall thresholds that, so far, are frequently used as the single indicator in landslide forecasting.

Conclusions

Based on the analysis of the widespread landslide events available within the AVI database, a linear trend between the rainfall thresholds and the initial soil moisture conditions was found with correlation coefficients up to 0.60, showing the key role of soil moisture on landslide triggering. Therefore, the correlation established between the maxima cumulative rainfall values and the soil moisture prior to the triggering of landslides would allow to dynamically adjust the rainfall thresholds which is of paramount interest for warning activities. Although the proposed analysis is a first attempt to improve the CFD procedure for landslide detecting, these results might provide a contribution to the near real-time landslide risk assessment for the Umbria Region territory, decreasing the uncertainties tied to the application of the rainfall thresholds only.

Moreover, the obtained results confirm the capability of the hydrological monitoring for setting up early warning systems for real slopes. In fact, collected data can be used both for the effective calibration of physically based models of infiltration and for establishing correlations for empirical models of landslide triggering.

Future investigations will be addressed for improving the calibration of the soil moisture model and for coupling the combined soil moisture and rainfall threshold systems with GIS based vulnerability maps in order to derive the main components of a WEB GIS system addressed to the development of a near real-time landslide risk scenario tool.

Based on the above insights, a real-time soil moisture sensor network across the whole Umbria Region is going to be set up with the purpose of enhancing the reliability of soil moisture simulations and, hence, of the overall warning system. The use of soil moisture information retrieved from remote sensing satellites will be also tested in forthcoming studies.

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