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The alerting system for hydrogeological hazard in Lombardy Region, northern Italy: rainfall thresholds triggering debris-flows and "equivalent rainfall" method

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Abstract

The Functional Centre (CFMR) of the Civil Protection of the Lombardy Region, North Italy, has the main task of monitoring and alerting, particularly with respect to natural hazards. The procedure of early warning for hydrogeological hazard is based on a comparison of two quantities: thresholds and rainfall, both referred to a defined area and an exact time interval.

The CFMR studied 52 landslide events (1987–2003) in Medium-Low Valtellina and derived a model of the critical detachment rainfall, in function of the local slope and the Curve Number CN (an empirical parameter related with the land cover and the hydrological conditions of the soil): it's physically consistent and allows a geographically targeted alerting. Moreover, rainfall thresholds were associated with a typical probability of exceedance.

The processing of rainfall data is carried out through the "equivalent rainfall" method, that allows to take into account the antecedent moisture condition of the soil: in fact the hazard is substantially greater when the soil is near to saturation. The method was developed from the CN method and considers the local CN and the observed rainfall of the previous 5 days. The obtained value for the local equivalent rainfall, that combines rainfall (observed and forecasted) and local soil characteristics, is a better parameter for the evaluation of the hydrogeological hazard.

The comparison between equivalent rainfall and thresholds allows to estimate the local hydrogeological hazard, displayed through hazard maps, and consequently to provide a reliable alerting activity (even localized to limited portions of the region).

1 Introduction

The Functional Centre (CFMR) of the Civil Protection of the Lombardy region (North Italy) has the main task of monitoring and alerting, particularly with respect to natural hazards.

Regarding instability phenomena linked to the hydrogeological risk, the procedure of early warning is based on a comparison of two quantities: thresholds and rainfall, both referred to a defined area and an exact time interval.

2 Thresholds for landslide detachment

2.1 Selection of data

The CFMR developed a research study in 2008–2012, considering landslide events with:

- known moment of occurrence;
- measured rainfall data;
- known morphological, hydrogeological and land use data.

The Medium-Low Valtellina has been considered as experimental area, where 52 landslide events (27 of which located in the Valmalenco area) with the above-mentioned characteristics were reported from 1987 to 2003.

2.2 Rainfall data

Particular attention has been given to the use of rainfall data:

- only the rain gauges within 5 km from the landslide event were considered;
- in case of multiple gauges, the one that showed the best conditions (distance, altitude, slope orientation, rainfall data quality) was chosen.

Because of the lack of knowledge of the value of cumulative rainfall p_{cum} potentially responsible of the landslide detachment, the last 30 days data from the landslide event were elaborated to obtain the duration-cumulative rainfall curve $p_{\mathrm{cum}}(t)$: this returns the maximum cumulative rainfall p_{cum} observed for each duration t in the last 30 days.

The most marked picks of the $p_{\mathrm{cum}}(t)$ curve have been selected as most probable causes of the landslide detachment; each peak has been weighted (with a value between 0.2–1.0) according to its relative upper distance from a regression curves, of the form $p_{\mathrm{cum}} = \alpha t^{\beta}$, passing through the picks themselves.

2.3 Statistical analysis

These rainfall data (t, p_{cum}) have been analyzed with a weighted stepwise logarithmic multiple regression algorithm, together with morphological, hydrogeological and land use data: local slope i [deg], Curve Number CN (an empirical parameter, developed by the USDA Natural Resources Conservation Service, related with the land cover and the hydrological conditions of the soil), hydraulic conductivity K [$\mathrm{cm\,s^{-1}}$], average annual precipitation AAP [mm].

The purpose was to get an expression in the form $p_{\mathrm{cum}} = a \cdot b^{n} \cdot c^{m} \cdot \ldots \cdot t^{q}$ (in the variables $b, c, \ldots, t$ and parameters $a, n, m, \ldots, q$).

The algorithm involves the insertion of a variable at a time within the structure of the formula; after each new variable added, the entire set of variables was subject to a Fisher F test assessment.

The weighting in the algorithm was carried out using the above-mentioned weights.

In Table 1 we reported:

- for each model: determination coefficient R^2 and increment ΔR^2 of the same with respect to the simplest model (#1);
- for each variable in each model: regression value, SD and risk level (F test).

Many models have been obtained, but a significant increment of the R^2 could just be reached including (in order) the following variables: time interval t, CN (and its function S; see Sect. 3.2) and local slope i.

The inclusion of average annual precipitation AAP did not help to increase the precision of the regression.

Moreover the hydraulic conductivity K was not considered reliable for insertion in a model, due to the high risk level: the SD is too high compared to the regression value of the variable.

2.4 Model and thresholds

The model we choose is the #5 in Table 1. Considering the relationship between S and CN, the equation can be simplified into:

$$p_{\mathrm{cum}} = 12.268 \frac{(100-\mathrm{CN})^{0.382}}{i^{0.271}} t^{0.367}. \tag{1}$$

In addition to the above model, which represent the critical curve of detachment, we considered appropriate to set lower operational thresholds with a statistical significance; we defined a typical probability of exceedance for each threshold (Fig. 1):

- moderate (orange): the threshold represent, for each duration, the rainfall causing landslide detachment in the 20 % of cases;

$$p_{\mathrm{cum}}^{\mathrm{mod}} = 7.956 \frac{(100-\mathrm{CN})^{0.382}}{i^{0.271}} t^{0.367} \tag{2}$$

- ordinary (yellow): the threshold represent, for each duration, the rainfall causing landslide detachment in the 5 % of cases.

$$p_{\mathrm{cum}}^{\mathrm{ord}} = 5.257 \frac{(100-\mathrm{CN})^{0.382}}{i^{0.271}} t^{0.367} \tag{3}$$

The model was found to be the best for several reasons:

- it provides the best increment ΔR^2 and the minimum risk level: i.e. it is very unlikely that the inclusion of parameters within the model is random (due to the limited data), whereas they look well-correlated with the critical detachment p_{cum} values;
- the limited number of variables makes the model easy for operational use;
- it's physically coherent: observing the partial variation of the thresholds with respect to the single variables (Fig. 2), the hazard tends to increase in proportion with:
  - local slope i: the higher the slope, the higher the hazard;
  - CN: the more impermeable the soil, (generally) the higher the hazard.
- considering the local variability of soil characteristics, it can be used to draw threshold maps (Fig. 3).

3 Observed and predicted rainfall: the "equivalent rainfall" method

Ex-post evaluation of ground effects resulting from weather events led to the observation that, for a given rainfall expected, the hazard is substantially greater when the soil is near to saturation.

The CFMR has therefore developed a method to evaluate the hydrogeological hazard, based both on expected rainfall and on observed rainfall in the previous 5 days, which allows to estimate the moisture conditions of soils. Combining the two rainfall quantities, it's possible to obtain an "equivalent rainfall" value to be compared with the early warning thresholds.

This methodology has been implemented within the regional alerting procedure in 2011.

3.1 Modified CN method

The equivalent rainfall method is derived from the Curve Number method (CN method), introduced in hydrology to estimate the surface runoff of a basin after a rainfall event, modified by Singh (1982) and Mishra et al. (2004, 2006).

The modified CN method is based on a balance equation:

$$P = I_\mathrm{a} + F + Q \tag{4}$$

with the following variables, expressed in mm:

- P = total rainfall;
- I_a = initial abstraction;
- F = total infiltration;
- Q = surface runoff.

Each basin portion, according to its characteristics (land use and classification, condition of superficial soil), presents a typical CN value. This allows to estimate the maximum potential retention S [mm] of the soil, which includes all hydrological losses:

$$S = \frac{25\,400}{\mathrm{CN}} - 254. \tag{5}$$

The antecedent moisture conditions (AMC), used to increase/decrease the CN, can be obtained considering the antecedent rainfall. There's not an explicit indication about how many days to consider, but a well-established practice (recommended by the National Engineering Handbook of NRCS) suggests the last 5 days rainfall (P_5 [mm]) in order to choose among three discrete classes: I (dry), II (normal) and III (wet).

This methodology has the disadvantage of introducing sudden (and not realistic) changes in the values of runoff obtained, thus Mishra and Singh introduced the antecedent moisture M [mm] term.

This modified method is based on the assumption that runoff coefficient C, defined as ratio between net runoff and net rainfall, coincides with the degree of saturation Sr of the soil:

$$C = \frac{Q}{P - I_a} = \mathrm{Sr} \tag{6}$$

and requires the validity of the two following hypotheses:

$$\frac{Q}{P - I_a} = \frac{F + M}{S + M} \tag{7}$$

$$I_a = \lambda \frac{S^2}{S + M} \tag{8}$$

where λ is the coefficient of initial abstraction (usually taken between 0.05–0.2).

Combining these equations with the balance equation (Eq. 4), the total runoff is expressed as:

$$Q = \frac{(P - I_a)(P - I_a + M)}{P - I_a + S + M}. \tag{9}$$

Assuming that the soil is in dry conditions before the 5 day interval, the following equation allows to estimate the M term as a function of the rainfall P_5:

$$M = \sqrt{S\left(P_5 + \left(\frac{1-\lambda}{2}\right)^2 S\right)} - \left(\frac{1+\lambda}{2}\right) S. \tag{10}$$

3.2 The "equivalent rainfall" method formulation

The modified CN method can be used to estimate the hydrogeological hazard of a basin portion. Assuming the hazard degree to be proportional to the degree of saturation Sr of the soil, we could define the "equivalent rainfall" P_{eq}, associated with the predicted rainfall P, as “the predicted rainfall on the local dry soil necessary to cause a Sr equal to the one caused by the rainfall P preceded by the rainfall P_5”.

Combining the above equations (Eqs. 9 and 10) we obtained the system of equations to derive the P_{eq}:

$$\begin{cases} M = \sqrt{S\left(P_5 + \left(\frac{1-\lambda}{2}\right)^2 S\right)} - \left(\frac{1+\lambda}{2}\right) S \\ P_{eq} = P + P_{eq0} = P + M\left(1 + \frac{\lambda S}{S+M}\right) \end{cases} . \tag{11}$$

That is, the same Sr will be caused:

- by the predicted P, after the observed P_5;
- or by the predicted P_{eq} on local dry soil.

Even in the absence of predicted rainfall P, the “base equivalent rainfall” P_{eq0} (function of CN and P_5) stands for the worsening in hydrogeological hazard due just to the antecedent rainfall. Thus, the equivalent rainfall value is deemed more appropriate to indicate the hydrogeological hazard and should be compared with the threshold values.

It should be pointed that, when the assumption of dry soil before the 5 day interval is not acceptable, the same time interval can be properly increased.

The above described model is now included in the regional technical legislation (2008, 2011, 2013).

Further observations have shown that it is appropriate to give more importance to the most recent rainfall: it was found an empirical relationship that defines a weight π_j for the daily cumulated rainfall P_j of the jth day ($j = 1,\ldots,5$) prior to now. Thus P_5 is given by a weighted sum:

$$\begin{cases} \pi_j = j^{\beta\left(1-\frac{100}{\mathrm{CN}}\right)} \\ P_5 = \sum\limits_{j=1}^{5} \pi_j P_j \end{cases} . \qquad (12)$$

Currently it is used a value of 0.8 for the parameter β.

In Fig. 4 a graph shows the dependence of the base equivalent rainfall P_{eq0} from CN and P_5, in the hypothesis that each weight π_j is equal to 1.

It can be observed that the higher the CN, the lower the P_{eq0}: on mostly impermeable soil the infiltration rate is low and Sr (and therefore C) tends to approach quickly to the unit, mainly independently from the antecedent rainfall.

4 Discussion

The rainfall thresholds, obtained as described in Eqs. (1)–(3), and the equivalent rainfall method can be combined to evaluate the hydrogeological hazard.

Operationally the CFMR has created an automated system for the creation of hazard maps in real time, to allow a comparison of the equivalent rainfall with the thresholds.

The Lombardy region has been divided into computational domains of 1 km^2, on each of which:

- the threshold values, for each duration, are defined;
- the predicted equivalent rainfall is hourly computed, using:
  - observed rainfall data: PRISMA data (i.e. RADAR data corrected with the observed data from stations on the ground, Fig. 5), computed by ARPA Lombardia-SMR (Agenzia Regionale per la Protezione dell'Ambiente – Servizio Meteorologico Regionale);
  - forecasted rainfall data returned by meteorological models (such as COSMO-I7, Fig. 5);

- local soil characteristics, approximately summarized by the CN.

From the comparison between equivalent rainfall and thresholds, hazard maps are obtained with the hazard levels (Fig. 6): each single domain is colored according to a standard color scale (green-yellow-orange-red stand for absent-ordinary-moderate-high hazard).

From the observation of the distribution of hazard, the evaluation of vulnerable elements and potential emergencies in progress, the CFMR proceed to a summary in order to alert different "homogeneous areas" (Fig. 6), as required by the national (2004) and regional (2008, 2011, 2013) legislation.

5 Conclusions

In the next future the critical detachment model will be subjected to a critical evaluation: the limited data used for the analysis and the inaccuracy of the time of occurrence of landslide events necessarily introduced uncertainty to the results.

In addition, a more accurate analysis on the role played by each parameter will be conducted.

The former equivalent rainfall method (Eq. 11) is now included in the regional technical legislation, but the calibration of the weights of the observed rainfall (Eq. 12) and other future improvements depend on the observation of its consistency in the alerting system.

The described approach has been used for a "homogeneous area" scale alerting, but recently the CFMR has implemented the method with the creation of localized alert documents, focused to limited portions of the region (typically at the scale of a river basin or less). This would be:

- more efficient, because it considers the local variability of rainfall and soil characteristics;

- more effective, as more targeted to the real needs of the alerted population and administrations.

Author contributions. Cucchi, A.: Project development, theory and statistical analysis, manuscript writing; Valsecchi, I. Q.: Project development, data collection; Alberti, M.: GIS analysis, data collection, computer implementation in real time; Fassi, P.: GIS analysis, data collection; Molari, M.: Project development; Mannucci, G.: Project development.

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References

Brunetti, M. T., Peruccacci, S., Rossi, M., Luciani, S., Valigi, D., and Guzzetti, F.: Rainfall thresholds for the possible occurrence of landslides in Italy, Nat. Hazards Earth Syst. Sci., 10, 447–458, doi:10.5194/nhess-10-447-2010, 2010.

Caine, N.: The rainfall intensity–duration control of shallow landslides and debris flows, Geogr. Ann. A, 62, 23–27, 1980.

Cancelli, A. and Nova, R.: Landslide in soil debris cover triggered by rainstorm in Valtellina (Central Alps, Italy), Proc. 4th Inter. Conf. and Field Workshop on Landslides, Tokyo, 1985.

Cardinali, M., Reichenbach, P., Guzzetti, F., Ardizzone, F., Antonini, G., Galli, M., Cacciano, M., Castellani, M., and Salvati, P.: A geomorphological approach to the estimation of landslide hazards and risks in Umbria, Central Italy, Nat. Hazards Earth Syst. Sci., 2, 57–72, doi:10.5194/nhess-2-57-2002, 2002.

Cascini, L. and Versace, P.: Eventi pluviometrici e movimenti franosi, Proc. A. G. I. XVI Convegno Nazionale di geotecnica, Vol. III, Bologna, Italy, 171–184, 1986.

Ceriani, M., Lauzi, S., and Padovan, N.: Rainfalls and landslides in the alpine area of Lombardia region – central Alps – Italy, Proc. Interpraevent 1992, Band 2, Bern, Switzerland, 9–20, 1992.

Ceriani, M., Lauzi, S., and Padovan, N.: Rainfall thresholds triggering debris-flows in the alpine area of Lombardia Region, central Alps – Italy, Proc. Man and Mountain, I Conv. Intern. per la Protezione e lo Sviluppo dell'ambiente montano, Ponte di legno (BS), 123–139, 1994.

Crozier, M. J.: Landslides: Causes, Consequences and Environment, Routledge, London, 1989.

De Vita, P., Napolitano, E., Godt, J. W., and Baum, R. L.: Deterministic estimation of hydrological thresholds for shallow landslide initiation and slope stability models: case study from the Somma-Vesuvius area of southern Italy, Landslides, 1–16, doi:10.1007/s10346-012-0348-2, 2013.

Direttiva del Presidente del Consiglio dei Ministri (DPCM) 27 febbraio 2004: Indirizzi operativi per la gestione organizzativa e funzionale del sistema di allertamento nazionale e regionale per il rischio idrogeologico ed idraulico ai fini di protezione civile, Gazzetta Ufficiale n. 59 of 11 March 2004.

Fell, R.: Landslide risk assessment and acceptable risk, Can. Geotech. J., 32, 261–272, 1994.

Frattini, P., Crosta, G., and Sosio, R.: Approaches for defining thresholds and return periods for rainfall-triggered shallow landslides, Hydrol. Process., 23, 1444–1460, 2009.

Godt, J. W., Sener-Kaya, B., Lu, N., and Baum, R. L.: Stability of infinite slopes under transient partially saturated seepage conditions, Water Resour. Res., 48, W05505, doi:10.1029/2011WR011408, 2012.

Guzzetti, F.: Landslide fatalities and evaluation of landslide risk in Italy, Eng. Geol., 58, 89–107, 2000.

Guzzetti, F., Reichenbach, P., Cardinali, M., Ardizzone, F., and Galli, M.: The impact of landslides in the Umbria region, central Italy, Nat. Hazards Earth Syst. Sci., 3, 469–486, doi:10.5194/nhess-3-469-2003, 2003.

Guzzetti, F., Peruccacci, S., Rossi, M., and Stark, C. P.: The rainfall intensity–duration control of shallow landslides and debris flows: an update, Landslides, 5, 3–17, 2008.

Iverson, M.: Landslide triggering by rain infiltration, Water Resour. Res., 36, 1897–1910, 2000.

Iverson, R. M., Reid, M. E., and LaHusen, R. G.: Debris flow mobilization from landslides, Annu. Rev. Earth Planet. Sc., 25, 85–138, 1997.

Johnson, A. M.: Debris flow, in: Slope Instability, edited by: Brunsden, D. and Prior, D. B., Wiley, New York, 257–361, 1984.

Lehmann, P. and Or, D.: Hydromechanical triggering of landslides: from progressive local failures to mass release, Water Resour. Res., 48, W03535, doi:10.1029/2011WR010947, 2012.

Malet, J. P., Laigle, D., Remaître, A., and Maquaire, O.: Triggering conditions and mobility of debris flows associated to complex earthflows, Geomorphology, 66, 215–235, 2005.

Mishra, S. K., Jain, M. K., and Singh, V. P.: Evaluation of the SCS-CN-based model incorporating antecedent moisture, Water Resour. Manage., 18, 567–589, 2004.

Mishra, S. K., Sahu, R. K., Eldho, T. I., and Jain, M. K.: An improved Ia-S relation incorporating antecedent moisture in SCS-CN methodology, Water Resour. Manage., 20, 643–660, 2006.

Montgomery, D. R. and Dietrich, W. E.: A physically-based model for topographic control on shallow landsliding, Water Resour. Res., 30, 1153–1171, 1994.

Papa, M. N., Medina, V., and Bateman, A.: Derivation of Critical Rainfall Thresholds for Debris Flow Warnings Through Mathematical and Numerical Modeling, 5th International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction and Assessment, 14–17 June 2011, University of Padua, Padua, Italy, 2011.

Papa, M. N., Medina, V., Ciervo, F., and Bateman, A.: Derivation of critical rainfall thresholds for shallow landslides as a tool for debris flow early warning systems, Hydrol. Earth Syst. Sci., 17, 4095–4107, doi:10.5194/hess-17-4095-2013, 2013.

Regione Lombardia: Frane di Lombardia. Centri abitati e infrastrutture a rischio frana in Lombardia, Direzione Generale Protezione Civile, Polizia Locale e Sicurezza, 2012.

Regione Lombardia, Giunta Regionale: Determinazioni in merito alla gestione organizzativa e funzionale del sistema di allerta per i rischi naturali ai fini di protezione civile, d.g.r. 8/8753 of 22 December 2008, BURL of 27 January 2009.

Regione Lombardia, D. G. Protezione Civile, Polizia Locale e Sicurezza: Approvazione dell'aggiornamento tecnico della direttiva regionale per la gestione organizzativa e funzionale del sistema di allerta per i rischi naturali ai fini di protezione civile, approvata con d.g.r. 22 dicembre 2008 n. 8/8753, d.d.u.o. n. 12722 of 22 December 2011, BURL of 10 January 2012.

Regione Lombardia, D. G. Sicurezza, Protezione Civile e Immigrazione: Aggiornamento tecnico della direttiva per la gestione organizzativa e funzionale del sistema di allerta per i rischi naturali ai fini di protezione civile (d.g.r. 8753/2008), d.d.u.o. n. 12812 of 30 December 2013, BURL of 13 January 2014.

Regione Lombardia-IReR (Istituto Regionale di Ricerca della Lombardia) and CNR-IRPI (Consiglio Nazionale delle Ricerche – Istituto di Ricerca per la Protezione Idrogeologica): Definizione delle soglie pluviometriche d'innesco di frane superficiali e colate torrentizie: accorpamento per aree omogenee, 2008.

Regione Lombardia-IReR (Istituto Regionale di Ricerca della Lombardia) and CNR-IRPI (Consiglio Nazionale delle Ricerche – Istituto di Ricerca per la Protezione Idrogeologica): Lo sviluppo delle attività del Centro Funzionale nel campo del sistema di allerta per i rischi naturali ai fini di Protezione Civile, 2011.

Singh, K. P.: Runoff conditions for converting storm rainfall to runoff with SCS Curve Numbers, State Water Survey (University of Illinois) Contract Report 288, April 1982.

Takahashi, T.: Debris Flow, IAHR Monograph Balkema, Rotterdam, 1991.

Takahashi, T.: A review of Japanese debris flow research, Int. J. Eros. Cont. Eng., 2, 1–14, 2009.

US Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS), Conservation Engineering Division: Urban Hydrology for Small Watersheds, Technical Release 55 (TR-55), 2nd Edn., Washington, D.C., June 1986.

US Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS): National Engineering Handbook – Part 630 Hydrology (Chapter 10: Estimation of direct Runoff from Storm Rainfall), Washington, D.C., 2004.

Wieczorek, G. F.: Effect of rainfall intensity and duration on debris flows in central Santa Cruz Mountains, California, Reviews in Engeneering Geology – Vol. VII (Debris flows/Avalanches: Process, Recognition and Mitigation), Geological Society of America 93-104, Geological Society of America, Boulder, CO, 1987.

Wilson, R. C. and Wieczorek, G. F.: Rainfall thresholds for the initiation of debris flows at La Honda, California, Environ. Eng. Geosci., 1, 11–27, 1995.

Wilson, R. C., Mark, R. K., and Barbato, G.: Operation of a realtime warning system for debris flows in the San Francisco Bay area, California, in: Vol. II, Proceedings of Hydraulic Engineering 1993, edited by: Shen, H. W., Su, S. T., and Wen, F., ASCE, New York, 1908–1913, 1993.

Table 1. Regression models for the critical curve of detachment.

Model	R^2	ΔR^2	Variable	Value	SD	F risk level
#1	0.557	–	t	0.371	0.020	$< 10^{-4}$
			constant	19.218	–	–
#2	0.559	+0,4 %	t	0.375	0.019	$< 10^{-4}$
			AAP	0.416	0.011	$< 10^{-4}$
#3	0.589	+5,7 %	t	0.369	0.018	$< 10^{-4}$
			S	0.229	0.047	$< 10^{-4}$
			constant	6.137	–	–
#4	0.597	+7,2 %	t	0.369	0.018	$< 10^{-4}$
			S	0.335	0.031	$< 10^{-4}$
			CN	0.314	0.039	$< 10^{-4}$
#5	0.613	+10,0 %	t	0.367	0.017	$< 10^{-4}$
			S	0.397	0.034	$< 10^{-4}$
			CN	0.461	0.054	$< 10^{-4}$
			i	-0.271	0.070	$< 10^{-4}$
#6	0.612	+9,9 %	t	0.368	0.017	$< 10^{-4}$
			S	0.411	0.040	$< 10^{-4}$
			CN	0.458	0.053	$< 10^{-4}$
			i	-0.265	0.070	$< 10^{-4}$
			$-\log_{10}K$	-0.080	0.115	48.8 %

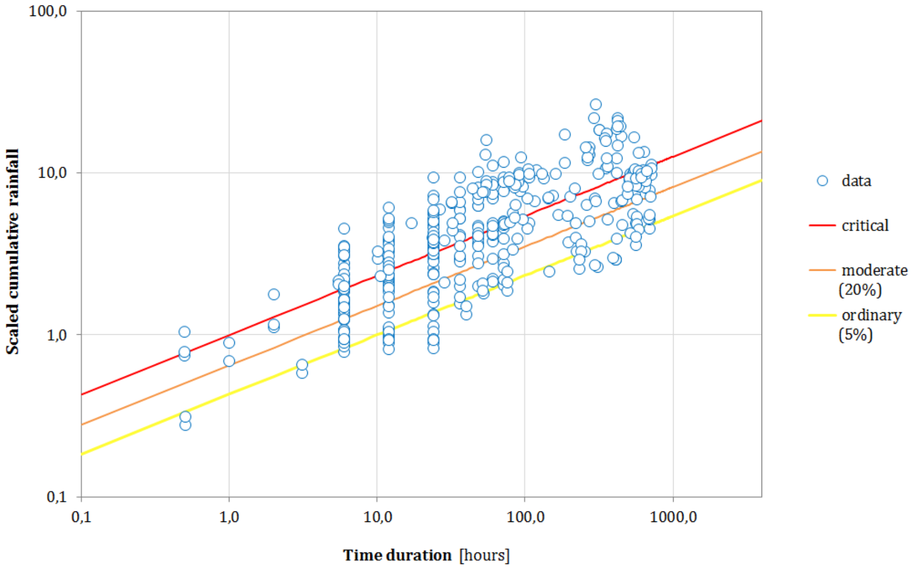

Figure 1. Best regression model (red line), with moderate (orange line) and ordinary (yellow line) thresholds. The graph shows, for each duration [h], the critical cumulative rainfall, scaled with respect to powers of CN and i (see Eq. 1): the scaling is necessary to represent the data in a 2-D-graph.

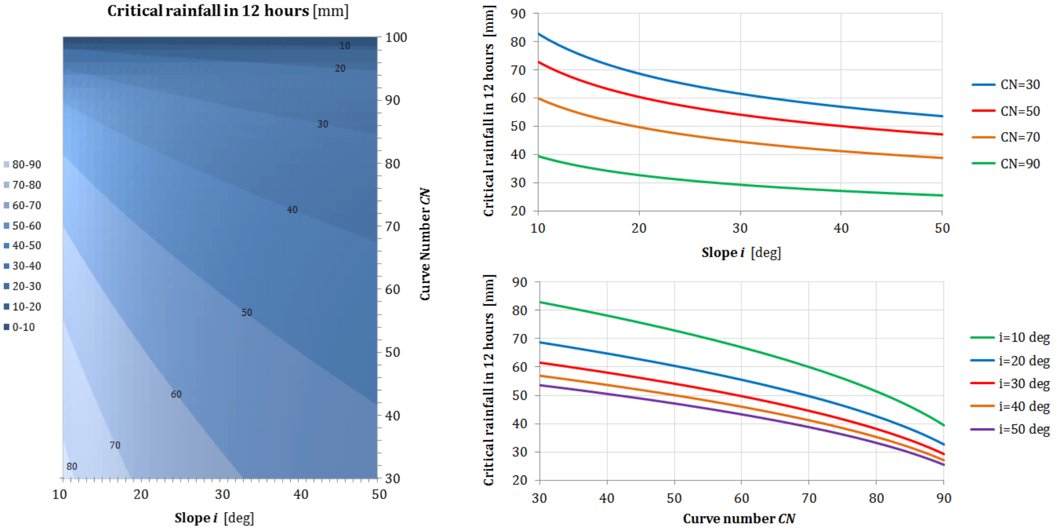

Figure 2. Variation of the critical rainfall [mm] in 12 h with respect to the local slope *i* [deg] and the Curve Number CN.

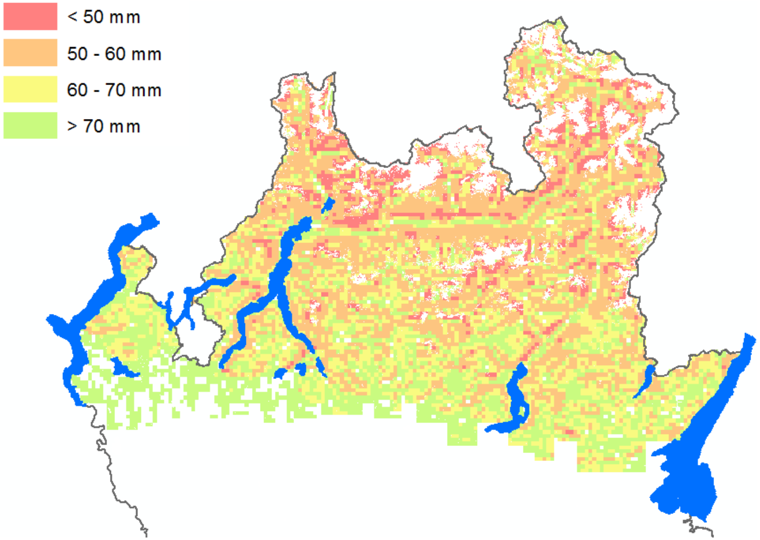

Figure 3. Example of a threshold map for the Alpine and Prealpine areas of Lombardy region: it shows the critical detachment rainfall [mm] for a duration of 12 h.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀▌
▶▌
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

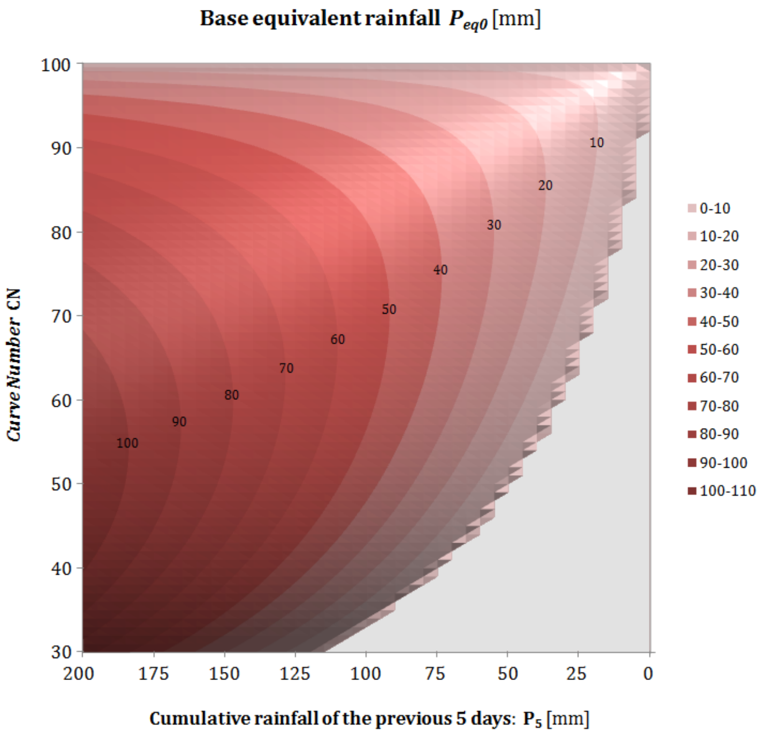

Figure 4. Dependence of the "base equivalent rainfall" P_{eq0} from CN and P_5, in the hypothesis that each weight π_j is equal to 1.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

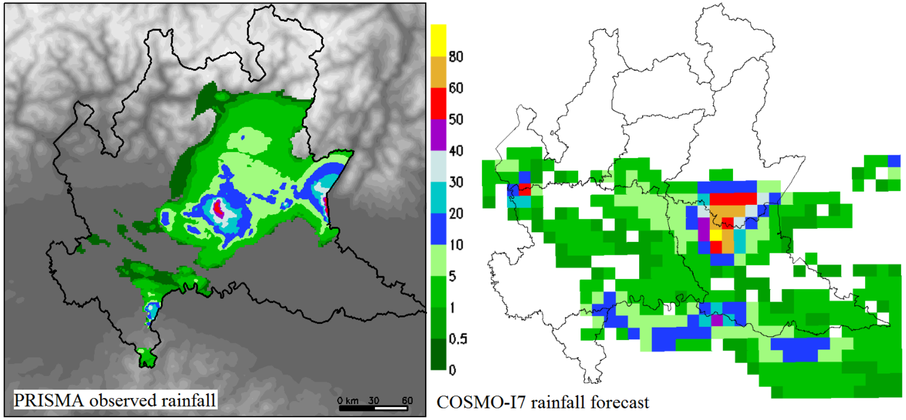

Figure 5. Example of observed rainfall data (PRISMA: RADAR corrected with observed data from stations on the ground) and forecasted rainfall data (COSMO-I7 model).

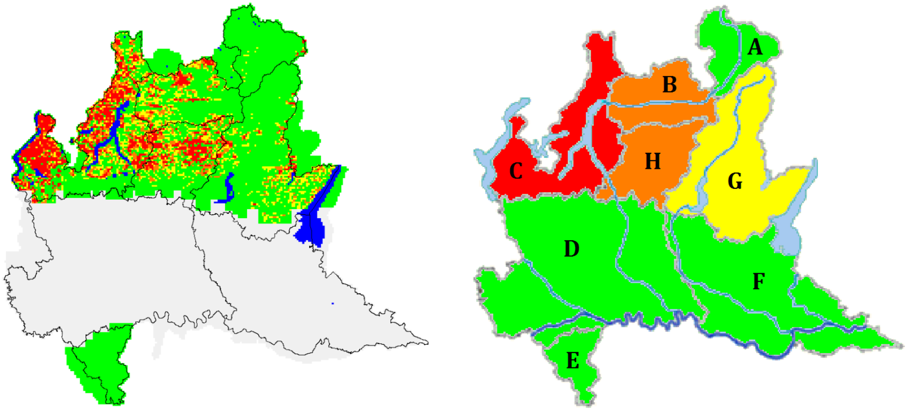

Figure 6. Example of a hazard map, with a 1 km discretization, and its translation in alert on “homogeneous areas”.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀I
▶I
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion