A statistical model based on rainfall thresholds for landslides forecasting: implementation in the alert system of Emilia Romagna region (Italy) for civil protection purposes

G. Martelloni, S. Segoni, R. Fanti and F. Catani

University of Firenze, Earth Sciences Department, Via La Pira 4, 50121 Firenze, Italy.

Email: gianluca.martelloni@unifi.it

Università degli Studi di Firenze
DEPARTMENT OF EARTH SCIENCES
CENTRE OF COMPETENCE OF THE CIVIL PROTECTION DEPARTMENT
PRESIDENCY OF THE COUNCIL OF MINISTERS

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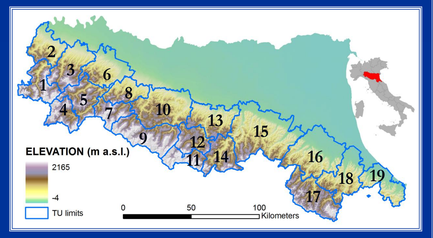
1) INTRODUCTION

In Italy landsliding is a recurrent phenomenon responsible of casualties, destruction of assets and infrastructures and major economical loss. Since rainfall represents the most common triggering factor, in Italy many Civil Protection agencies are setting up warning systems based on the interaction between rainfall and landslides. These agencies are responsible of large territories (e.g. regions or large subdivisions such as provinces), therefore they cannot rely on physically based approaches because of the difficulty of defining the exact spatial and temporal variation of the many involved factors (rainfall variation in space and in time, effect of vegetation, mechanic and hydraulic properties of both bedrock and soil layer). As a consequence, physically based approaches can effectively be applied only over small sites while at the regional scale the most diffuse methodology is the use of black box models based on empirical or statistical rainfall thresholds.

2) STUDY AREA

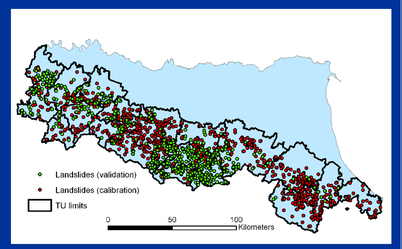
The Emilia Romagna Region (Northern Italy) is bordered by the Apennines mountains on the south and on the west, by the Adriatic Sea on the east and by the Po river on the north. The northern and eastern portion of its territory is a wide flat area constituted by the alluvial plain of the Po, the largest Italian river. Those portions of the region were not considered in the present work, which focuses only on landslide prone areas. The latter are located in the southern and western portion of the region, which is occupied by the fold and trust belt of the Apennines, whose maximum altitude reaches 2165 m. The study area is subdivided in 19 subareas named territorial unit (Tu).



The studied area is subject to a wide variety of landslides typology: rotational-translational slides (affecting mainly flysch), slow earth flows (occurring in clayey lithologies), complex movements (typically rotational failures at the head progressively changing into translational movements throughout the body and toe) and rapid shallow landslides (less recurrent but more frequently in the last few year). This could be connected with the recent climatic trends in the Mediterranean area, which are characterized by shortest and more intense rainfall. In every case, the main triggering factor of all the Emilia Romagna landslides is rainfall.

3) DATA ORGANISATION: RAINFALL AND LANDSLIDES DATABASE

For each TU an automated rain gauge was chosen to be used for the calibration of the model and, in the operative scenario, for the monitoring of the TU as well. In order to select the most proper rain gauges, the following criteria were considered: i) presence of a long historical series of rainfall recordings (at least 30 years), to ease a statistically correct calibration of the model; ii) hourly automatic measurements of precipitations; iii) central position among the TU; iv) elevation close to the mean elevation of the landslide prone areas of the TU.

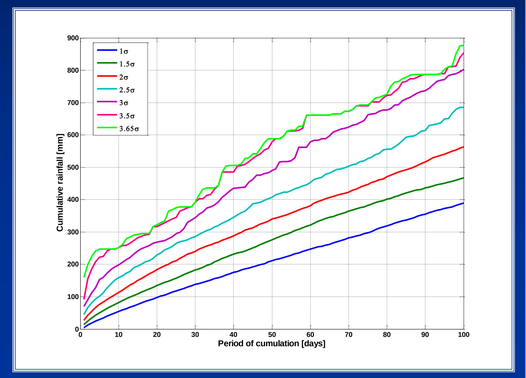


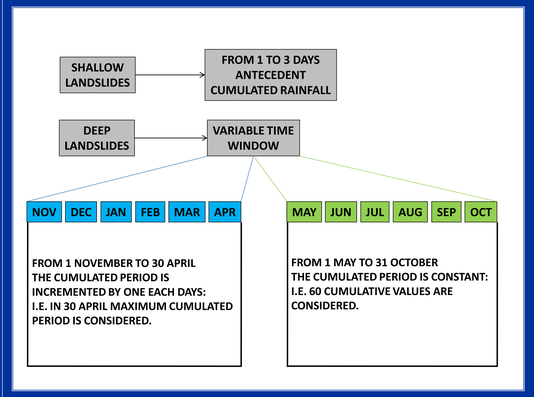
For the calibration and validation of the model, landslide data were collected from the records of the regional Civil Protection Department and they were organized in a geographical database in shapefile format. Landslides were geo-registered and the triggering dates were entered in a specific field.

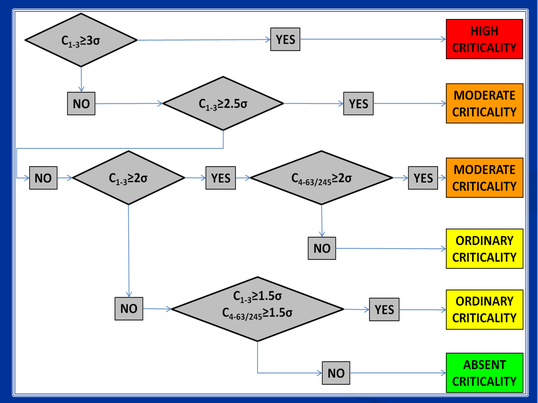
4) METHODOLOGY AND CALIBRATION

On the hypothesis that anomalous or extreme values of rainfall are responsible of landslide triggering, in the proposed model the statistical distribution of the rainfall series is analyzed, and multiples of the standard deviation (σ) are used as thresholds to discriminate between ordinary and extraordinary rainfall events. The name of the model, SIGMA, reflects the central role of the standard deviations in the proposed methodology.

Starting from the original series of daily precipitation (tipically 1951-2009), the time series of cumulated data from 1 to 365 days were built for each TU reference rain gauge. All cumulated rainfall series were characterized by an asymmetric distribution: the statistical cumulative distributions tend toward Lognormal for short periods and toward Normal for long periods, but in neither of the cases these theoretic distributions are fully matched. Therefore, to obtain probability values of not exceeding a given rainfall threshold, the data of the original distributions are adapted to a target function chosen as a model, in our case the standard Gaussian distribution.





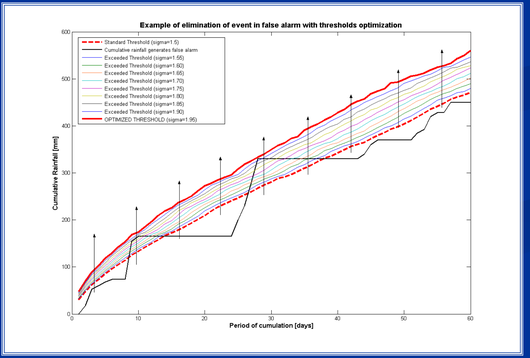


The σ curves are implemented in a decisional algorithm that constitutes the core of the SIGMA model. The latter operates separately for each TU and in real time applications the model works at daily time steps providing a level of criticality that depends on weather forecasts and rainfall recordings. For each TU, these rainfall amounts are cumulated at increasing time intervals ranging from 1 day to 245 days. Such cumulates are compared with the σ curves, which are actually used as thresholds. The decisional algorithm of the SIGMA model was developed to take into account both shallow and deep seated landslides.

The decisional algorithm with nominal σ curves (1.5σ, 2σ, 2.5σ, 3σ) constitutes a prototypal version of the SIGMA model and it can be implemented in other context where the only available data is the historical rainfall recordings.

The correspondence between σ thresholds and expected effects to the ground (landslides) was better constrained performing a calibration with respect to dated landslides of the period 2004-2007. We used an appropriate optimization algorithms that, for the whole calibration period and for each Territorial Unit, compares the daily model outputs with the corresponding number of occurred landslides. After a trial and error procedure, the algorithm identifies the σ curves that minimize the occurrence of threshold overcoming in days for which landslides were not reported.

The procedure was repeated separately for each TU, as a result for each of them the decisional algorithm was provided with specific σ thresholds. It is important to highlight that the calibration procedure does not change the sigma curves, but it chooses a customized set of sigma curves for each TU.



5) RESULTS AND VALIDATION

The model was validated making use of landslides and rainfall recordings from the period 2008-2010. In the validation test the SIGMA model was run with the rainfall recorded by the reference rain gauges in the period 2008-2010 and for each TU the daily alert level provided by the decisional algorithm was compared with dated and georegistered landslides from the same period, which were organized in a constantly updated geodatabase. In the validation period 764 landslides occurred and 84% of them were correctly predicted.

	False Alarms			Missed Alarms		N° of landslides				N° of Days with landslides			
TU	Ordinary	Moderate	High	N° days	N° landslides	Ordinary	Moderate	High	TOTAL (missed alarms included)	TOTAL (missed alarms included)	Ordinary	Moderate	High
1	54	7	0	2	3	14	30	0	47	14	8	4	0
2	46	15	0	0	0	21	10	3	34	10	3	6	1
3	42	25	0	1	1	5	14	0	20	10	2	7	0
4	28	32	1	0	0	1	5	0	6	5	1	4	0
5	40	15	0	2	2	4	17	7	30	16	3	6	5
6	24	12	1	3	3	11	54	0	68	13	4	6	0
7	22	20	4	0	0	0	7	4	11	7	0	5	2
8	28	7	1	1	3	19	6	0	28	6	3	2	0
9	46	5	1	6	14	23	18	1	56	19	6	6	1
10	49	12	0	7	9	22	0	0	31	18	11	0	0
11	53	17	2	1	1	15	15	31	62	26	8	8	9
12	30	3	0	22	55	30	19	0	104	35	9	4	0
13	55	11	1	7	14	5	1	2	22	14	4	1	2
14	54	19	0	2	5	17	60	86	168	30	10	17	1
15	35	6	0	6	6	13	45	0	64	18	8	4	0
16	23	5	0	5	5	0	0	0	5	5	0	0	0
17	6	1	0	2	2	0	0	0	2	2	0	0	0
18	8	1	0	1	1	5	0	0	6	5	4	0	0
19	35	10	1	0	0	0	0	0	0	0	0	0	0
Sum	678	223	12	68	124	205	301	134	764	253	84	80	21

6) CONCLUSION

In order to forecast the occurrence of landslides at regional scale, a black-box model named SIGMA was defined and applied to the territory of Emilia Romagna Region, Italy. The model is based on a set of statistical rainfall thresholds defined on the basis of a single parameter (cumulate rainfall). SIGMA model was implemented in an operative warning system for internal use of the Emilia Romagna regional Civil Protection Department. For each reference rain-gauge, a software combines rainfall recordings from the regional automated network with rainfall forecasts and compares the resulting cumulative rainfalls with the thresholds. In the TU where the latter are exceeded, the software provides the corresponding alert level, according to the decisional algorithm. The model could theoretically be used to automatically generate warnings and alerts, but longer calibration and validation periods would be required. Anyhow, at present, the SIGMA model represents an useful tool for Civil Protection personnel in suggesting an expected warning level, to be confirmed or modified by expert evaluations.

The major advantages of the proposed methodology consists in:

1. extreme simplicity and rapidity of the forecasting procedure, which can therefore be easily implemented into operational early warning systems;
2. the output of the model can be directly associated to the levels of criticality (absent, normal, moderate, high) to give a quick indication of the warning level even without an expert interpretation;
3. limited number of input data, which consists only in daily precipitation values, easily accessible in countries with sufficiently organised meteorological networks;
4. a calibration of the rainfall thresholds with respect to the severity of landslide events allows to strengthen the correspondence between thresholds and warning levels.
5. all landslide types are taken into account, in particular shallow and deep seated movements are detected by two different cumulative time intervals.

Based on the paper "Rainfall thresholds for the forecasting of landslide occurrence at regional scale". Martelloni, Segoni, Fanti, Catani. Submitted to Landslides

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