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REPORT ACTION 1.15

Reconstruction of relationship between slope instability and meteorological forcing

L. Del Maschio[1] , G. Gozza[1], S. Pignone[2], and M. Pizziolo[1]

[1] – Servizio Geologico Sismico e dei Suoli, Bologna, Italy.
[2] – ARPA - Servizio Idro Meteorologico, Bologna, Italy.

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Contents

ACRONYMS AND ABBREVIATIONS

ARPA-SIM = Hydro-meteorological Service of Emilia Romagna Region (http://www.arpa.emr.it/smr)

AVI = Italian Affected Sites by mass movements and floods

CNR = Italian National Research Council

MAP = Mean annual rainfall

DDFC = Determination of Depth Duration Frequency Curve

GIS = Geographic Information System

IRPI = Research Institute for Geo-Hydrological Protection of the Italian National Research Council (http://www.irpi.cnr.it)

NER = Normalized rainfall of meteorological event

NAR = Normalized antecedent rainfall

RE = Rainfall of meteorological event

RA = Antecedent rainfall

RP = Return period

SGSS = Geological Service of Emilia Romagna Region (http://www.regione.emilia-romagna.it/geologia)

1. INTRODUCTION

The term landslide is used to denote " the mass movement of a mass of rock, debris or earth down a slope" (Cruden 1991). The movement occurs when the destabilizing forces overcome the resisting forces and the rupture happens consequently along a slope until a new equilibrium is reached.

Rainfall precipitations constitute one of the most frequent causes to trigger landslides because it increases the soil moisture and the pore water pressure which reduces the shear strength.

The influence of rainfall depends on landslides dimensions, types, material involved etc.. Recently researches about the relationships between meteoric events and landslides, have been developed in order to define "precipitation thresholds".

Generally the term "threshold" defines the minimum or maximum level of some quantity needed for a process to take place or a state to change (White et al. 1996); a minimum threshold is the lowest level below which a process does not occur and a maximum threshold is the level above which a process always occurs (Crozier 1996). For rainfall induced landslide a threshold may represent the minimum intensity or duration of rainfall.

Two types of landslide – triggering rainfall thresholds can be established based on two different approaches:

- empirical thresholds based on historic analysis of relationship rainfall/landslide occurrence (Campbell 1975, Caine 1980, Croizer and Glade 1999)
- physical thresholds based on numerical models that take into account the relationship between rainfall pore pressure and slope stability by coupling hydrological and stability models (Montgomery and Dietrich 1994, Wilson and Wieczorek 1995, Crosta 1998, Crosta et al 2003).

The physical thresholds are not widely developed because they require detailed knowledge about hydrologic, hydrogeological, morphological and geotechnical parameters which are seldom available especially at a regional scale.

At the contrary empirical thresholds are more easy to determinate and to apply because they deal with antecedent rainfall, intensity, duration and cumulative rainfall.

The most commonly used thresholds are those defining the intensity-duration applied for shallow landslides and debris flow (Caine 1980, Cancelli e Nova 1985, Cannon & Ellen 1985, Wieczorek 1987, Larsen 1993, Ceriani et Al. 1994, Crosta & Frattini 2001).

The "intensity-duration" approach can be further refined by normalising the intensity value with the mean annual rainfall (MAP), thus emphasising the regionalization of the thresholds since the calculation takes into the account the climatic regimes of the study area (Cannon e Ellen 1985, Jibson 1989, Wieczorek et al. 2000, Aleotti 2004).

Another frequent approach correlates the total amount of rainfall event until landslide occurrence and the maximum recorded intensity (Govi et al 1985).

Other methodologies correlate the cumulative precipitation on an antecedent period until occurrence of landslide with the daily rainfall of the occurrence (Lumb 1975, DeVita 2002) or with the cumulative precipitation of whole meteorological event which causes instability (Chleborad A. F 2000). In same cases the antecedent rainfall can be considered as an indicator of the soil moisture (Crozier and Eyles 1980, Glade et al. 2000). It has been recognised in the literature that antecedent rainfall can be a predisposing factor in the activation of sol slips (Wieczorek, 1987). The influence of antecedent rainfall is difficult to quantify because it depends on several factors, including the heterogeneity of soils (strenght and permeability proprieties) and the regional climate. In tropical areas, for example, antecedent rainfall is not important factor (Brand 1992) as well as in slopes covered with coarse colluvium having large interparticle voids, debris flow can occur without significant antecedent rainfall (Corominas and Moya, 1999). On the contrary, in low permeability soils antecedent rainfall can be an important factor because it reduces soil suction and increase the pore water pressures in the soil.

Then the definition of empirical thresholds needs available historical data about precipitations and landslides. Besides the relationships defined between rainfall and landslide occurrences can be apply only for the selected region with geological and climatological homogeneous characteristic and cannot be exported in other regions.

Some researches have relatively been realized in Northern Apennines for large landslides for which the occurrence is related to the precipitation and to variations of ground water level.

This report has the purpose to define rainfall thresholds using a empirical approach through the observation of historical landslide events.

The thresholds are identified therefore through a statistical analysis of the data correlating cumulative antecedent rainfall before the meteorlogical event starts and the total rainfall of the meteorological event responsible of instability. A minimum and intermediate thresholds have been identified, the first one represents a level of precipitation under which the phenomenon is not verified, and the second one is intermediary threshold which indicates an increase of the severity of effects on the ground.

The present work has been developed for an sample area of the Northern Apennines identified by Reno river basin (province of Bologna and Ravenna), Panaro river basin (province of Modena), Secchia river basin (province of Modena and Reggio Emilia), Enza and Crostolo river basins (province of Reggio Emilia). This area has been selected both for its high density of landslides and because for these provinces it is present a consistent historical landslides database in which the dates of activation are brought.

2. CHARACTERISTICS OF LANDSLIDES IN EMILIA ROMAGNA

The geological structure of the Northern Apennine is dominated by rocks constituted in prevalence by silty-arenaceous-marly alternations, clay, and only subordinately from mostly arenaceous rocks (figure 2.1).

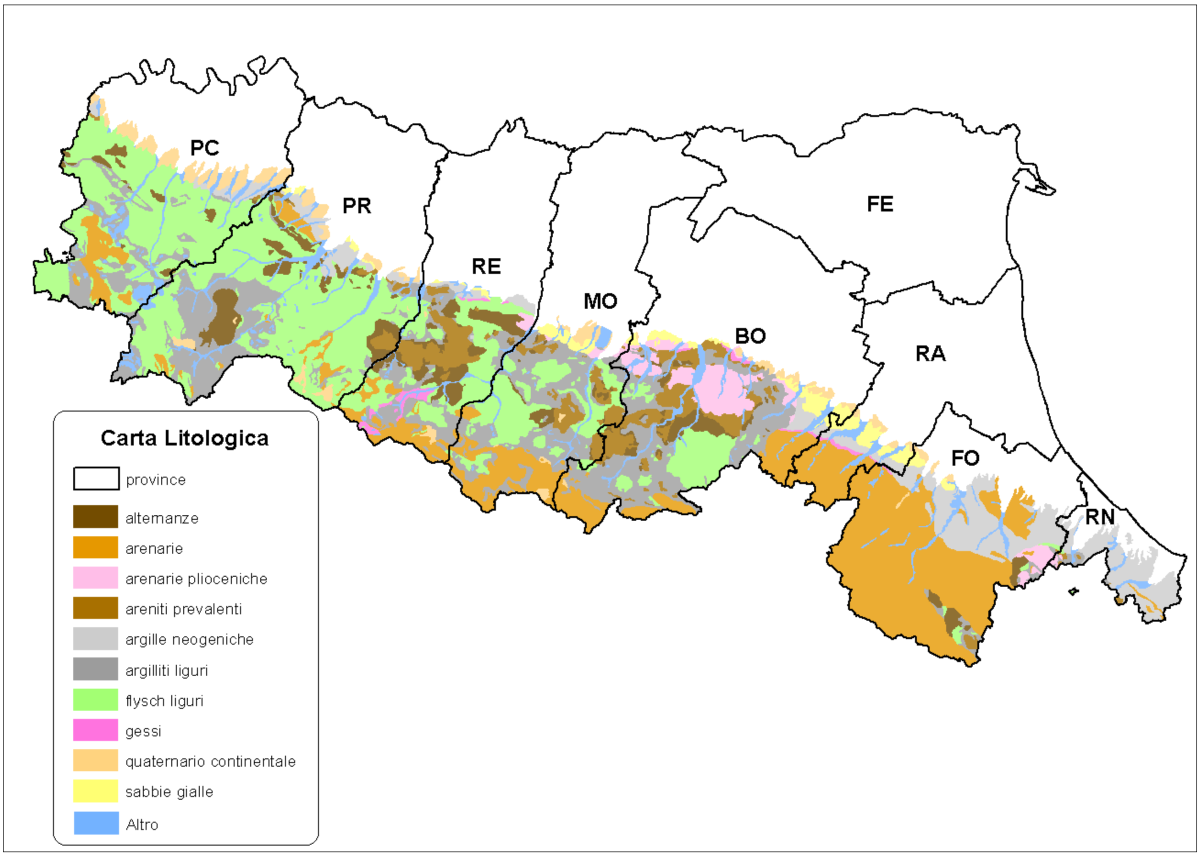

Figure 2.1: Lithological map of Emilia-Romagna Region.

This peculiar geologic conformation reveals the abundance of landslides which cover over the 20% of the mountainous territory. The diffused presence of clay minerals in the rocks, often in a chaotic structure e/o intensely fractured for tectonic action, produces a strong superficial degradation.
The clay minerals tend to absorb water, modifying their physical structure, with consequent reduction of the internal strength.
Clay lithology of outcrop rocks is more prevalent in the western sector of the Apennines, from Piacenza to Bologna, than in the eastern sector; as a consequence the density of landslides is higher in the western part than in the eastern one
A parameter which can be considered to define the landslide susceptibility of the territory is the “landsliding index” defined as the ratio (%) between the surface occupied by landslides for a given class and the area of the same class on the whole regional territory. The landsliding index has been used to classify lithology classes (figure 2.2) and river catchments (figure 2.3) with landslide susceptibility degree.

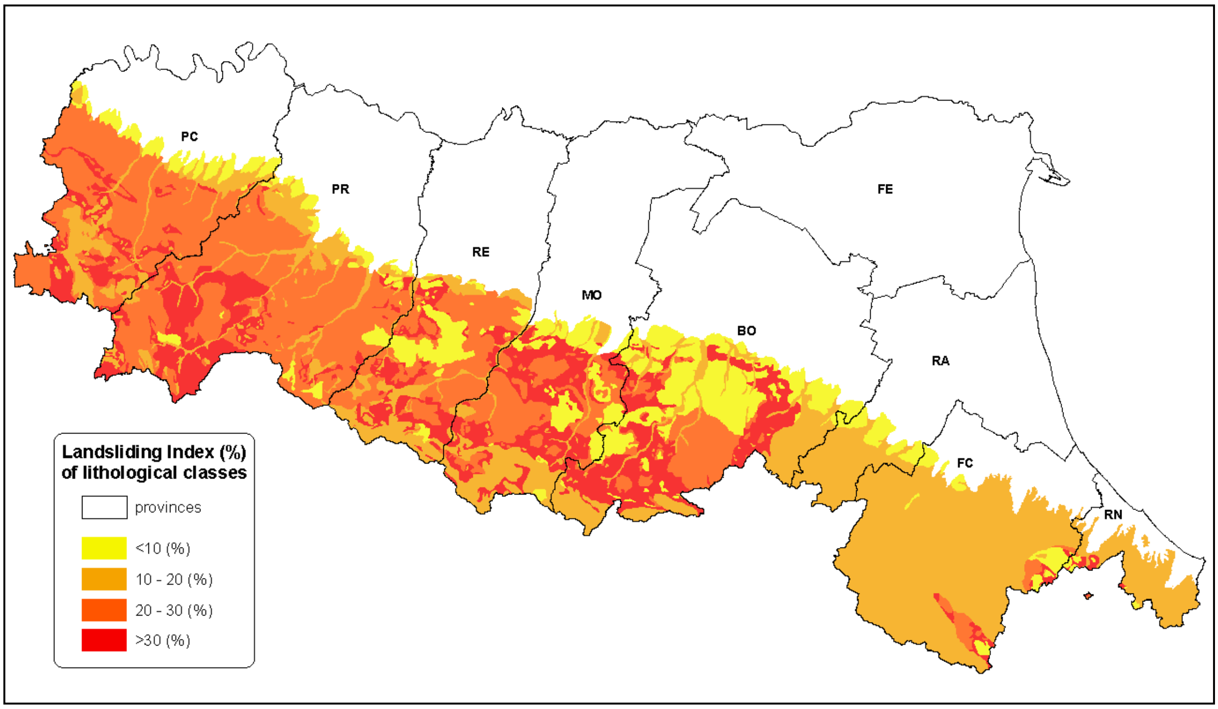

Figure 2.2: Landsliding Index map of lithological classes in the northern Apennines.

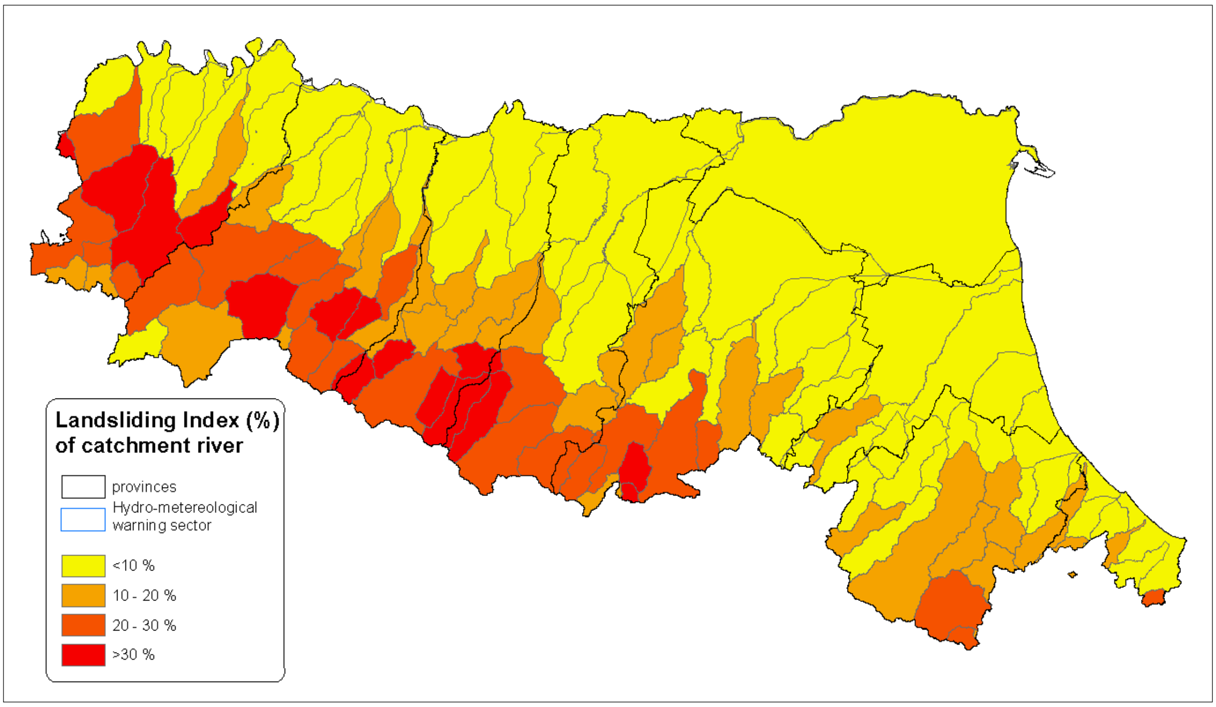

Figure 2.3: Landsliding Index map of single catchment river in the northern Apennines.

The SGSS has realized geological maps at scale 1:10000 for all Emilia-Romagna territory and over 30.000 landslides have been identified. According to the classification of Varnes (1978) the most frequently recurring landslide types are rotational or translational slide and debris or mud flow, often complex movements due to the combination of slide with flow. Approximately 45% of landslides are active and remaining are dormant (figure 2.4). Most of them alternates periods in which no movements happen for decades or centuries, with periods of reactivation, generally of varying duration, from some days until some years. Those types of landslides are easily recognizable due to physical characteristics and allow suitably cartography.

As regards the dimensions of landslide bodies surveyed in Emilia-Romagna Apennines, at least 1300 have a volume exceeding 1 million meters cubic (figure 2.5), 4647 have a surface exceeding 10^2 m^2 and 534 of them have a surface more than $0.5 km^2$

Most of landslide bodies has been occurred during extreme climatic events, some of which have been taken place thousand years ago. Some recent studies testify the remarkable persistence of the landslide bodies in time and space, exceeding, in some cases, the duration of thousand years (C^{14} dating).

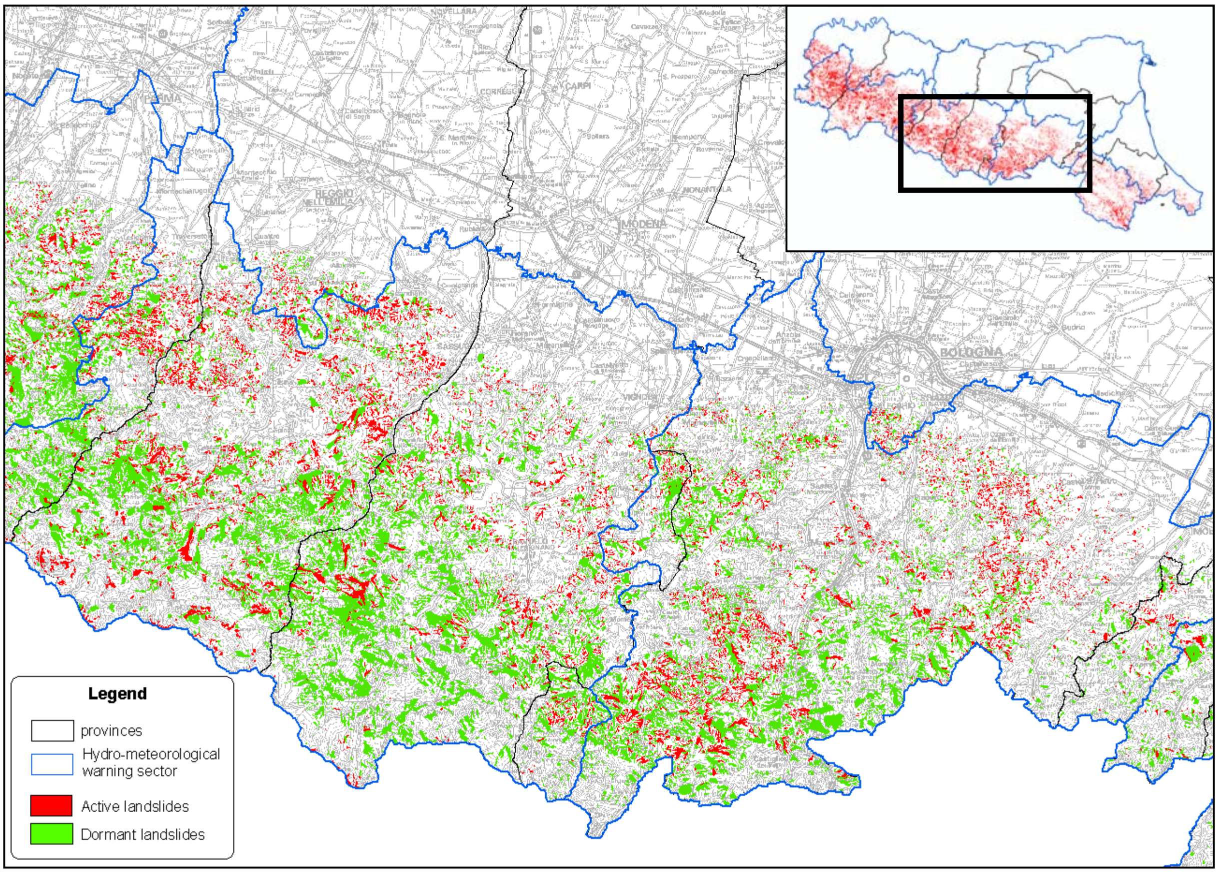

Figure 2.4: Distribution of Emilia-Romagna landslides, with particular to the “pilot-area”.

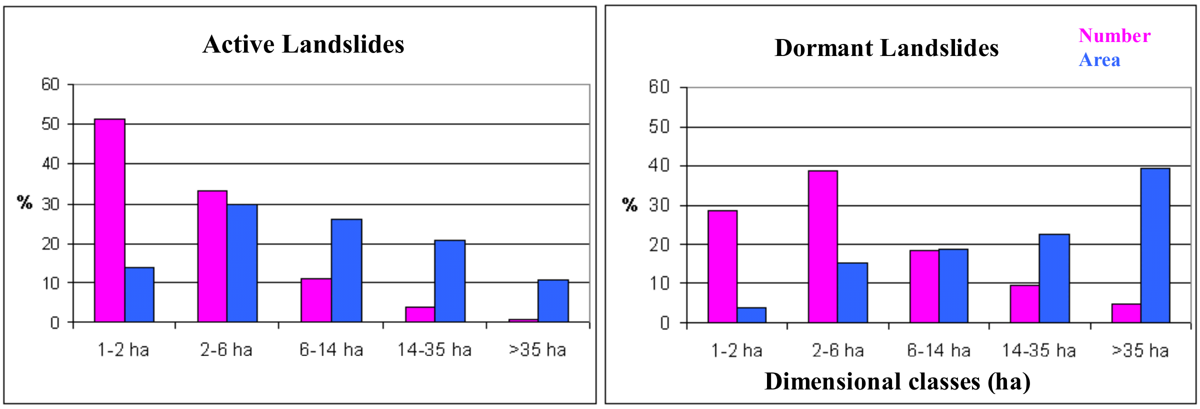

Figure 2.5: Number of landslides (%) and its own area (%) per dimensional class (landslide body surface) in Emilia-Romagna region (www.regione.emilia-romagna.it/geologia).

The individuation of shallow landslides is more difficult because this type of mass movements involved a limited area (from few to ten square meters) and takes place predominantly in arable and pasture lands where the bodies are often removed by the daily agricultural activity.
Unlike the shallow landslides (soil-slip) occur and described in alpine region, such types of movement don't usually evolve in granular flow, with elevated speeds (m/s order), because of a meaningful clay component that checks their evolution.
Only few cases have been marked during extreme rainfall events and occured in sandy-marly lithological class. Such characteristics render the landslides of Emilia-Romagna region peculiar and different with those considered in the scientific work produced on the argument.

3. DETERMINATION OF RAINFALL THRESHOLDS TO TRIGGER LANDSLIDES

From the analysis of the landslide database it has resulted that the occurrence of mass movement is related to time period characterized by intense and prolonged precipitation.
The relationship of rainfall and frequencies of landslides are showed in figure 3.1 where the distribution of the occurrence of landslides during the year follows the monthly variation of rainfall amount. It can be noted that:
- there are two annual maximum of rainfall (one in autumn and one in spring) and two minimum of rainfall (one in summer and one in winter). There is one maximum of distribution of landslides which is in November, that represent the rainiest month of autumn. Nevertheless even if the autumn rains start in September and they are remarkable in the month of October, landslides occur more frequently in November. This phenomenon can be explained considering that, after the summer, it takes a span of time to reach soil moisture conditions needed to generate instability after rain starts.
- the second maximum of landslides is identified in March and April; the maximum of March is in advantage in comparison with the rainy month which is April. This can be due also to the snowmelt which increase the soil moisture.

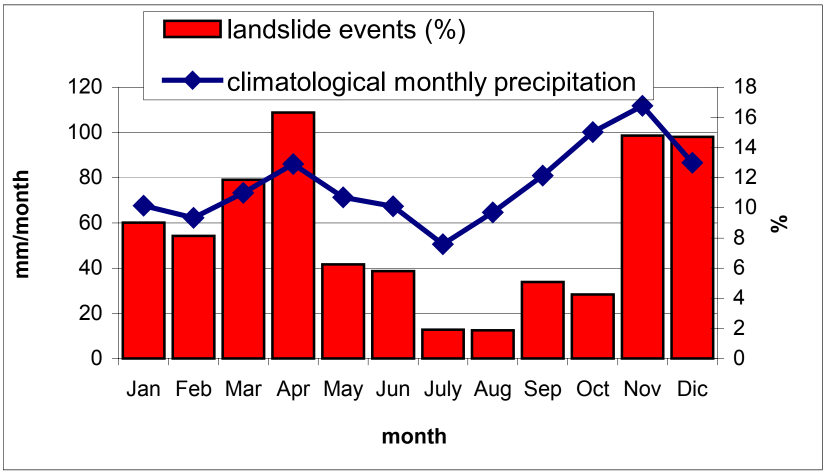

Figure 3.1: Distribution of landslides during the year and the climatological monthly precipitation in Emilia-Romagna region.

In order to understand the relationship between rainfall and the occurrence of landslides it is necessary to define an amount of rainfall as a minimum threshold. The definition of "critical threshold" is a complex operation because it depends on several factors as lithology, geotechnical characteristics, morphology, land use, soil moisture and temperature which change during the time. For that reason critical threshold should be a function of time.
In this chapter the following points are illustrated:
1-input data (historical landslide database and historical time series precipitation);
2-determination of Depth Duration Frequency Curve (DDFC);
3-methodology developed;
4-individuation of "threshold curve" and results;
5-validation and application of "threshold curve".

3.1 INPUT DATA

3.1.1 HISTORICAL LANDSLIDE DATABASE

Emilia-Romagna Region has been planned a research program about landslides triggered in the last centuries in order to evaluate the landslide hazard and risk on the whole regional territory.
A regional historical landslide database was realized by SGSS according with the methodology developed by IRPI of Torino inherent flood and slope instability phenomena (Caroni et al., 1990; Govi et al. 1985; Govi and Turitto 1994, 1995; Tropeano, 1989). In order to create an historical landslide database which collects several information distributed in time and in space, it was necessary to consult several and different sources as:

1) - the geological and technical bibliography produced from the second half of the last century
2) - the documentation produced or picked up by Administrative Services or Private corporation from last century;
3) - the national and local press from the second half of the last century;
4) - the historical literature, archaeological and naturalistic, published for the Apennine region (works of good quality are available from the beginning of Eighteenth century).

The following criteria have been adopted to collect data:
- to transfer the data directly from the original documents without manipulations in order to allow objective analysis and to preserve the original information;
- to insert only phenomena for which it was possible to identify with precision dates of occurrence and geographical location;
- to verify the congruity of the information about same landslide if they came from different sources.

Movements, which have occurred since thirteenth century, have been found out and actually the database has been completed for the territory of Reggio Emilia, Modena and Bologna (table 3.1) provinces and is in progress to be extended for all the rest of the Region.
For each landslides are reported the principals parameters as:

- Geographic location in term of exactly place with own administrative subdivision (municipality and province it belongs);
- Briefly description on landslide (type and material convolved, length, width and depth);
- Triggering causes;
- Damages especially if the phenomenon has involved hydrographical network and

All the collected data are stored in tables with MS Excell 2000 and the locations of mass movements are stored in environment G.I.S and identified on the "Landslide Inventory Map", 1:25.000 scale, realized by SGSS.
In the database there are 4223 landslides which have a data of occurrence and only 3696 of them are mapped correctly.

Table 3.1: Synthesis of landslides reported in the historical database for Reggio Emilia, Modena and Bologna provinces

	Total collected landslide activations				Total collected mapped landslide activations			
	BO	**MO**	**RE**	**TOTAL**	**BO**	**MO**	**RE**	**TOTAL**
Landslides	1378	2235	610	4223	1215	1871	610	3696
Landslide activations	1841	3553	1217	6611	1620	1424	1182	4226

The Historical Regional Database is the principal source of data for this project and it was integrated with the data which came from the AVI database realized by CNR.
These two database have been homogenised to have only one summarized table with the same fields of information and to give a unique code to each landslide movement.
AVI was useful especially for the provinces for which the historical regional database has not been completed yet. A degree of reliability has been attributed to the precision of date of occurence (table 3.2). For this purpose, the determination of rainfall thresholds, only the activations of landslides which have exact date with degree of reliability from 1 to 3 have been undertaken. Since the study has been made for the "pilot area", only landslides activations of this territory have been considered, that are 3277 (figure 3.2).

Table 3.2: Number of landslides grouped by degree of reliability.

DATE OF ACTIVATION	DEGREE OF RELIABILITY	NUMBER OF OCCURRENCES
Precise date (d/m/y)	1	2178
Uncertain date (uncertain day)	2	1183
Interval of days (d1-d2/m/y)	3	217
month	4	659
Two consecutive month	5	84
Season	6	162
Two seasons	7	49
Year	8	370
More Year: 1973-1978	9	80
Century	10	44

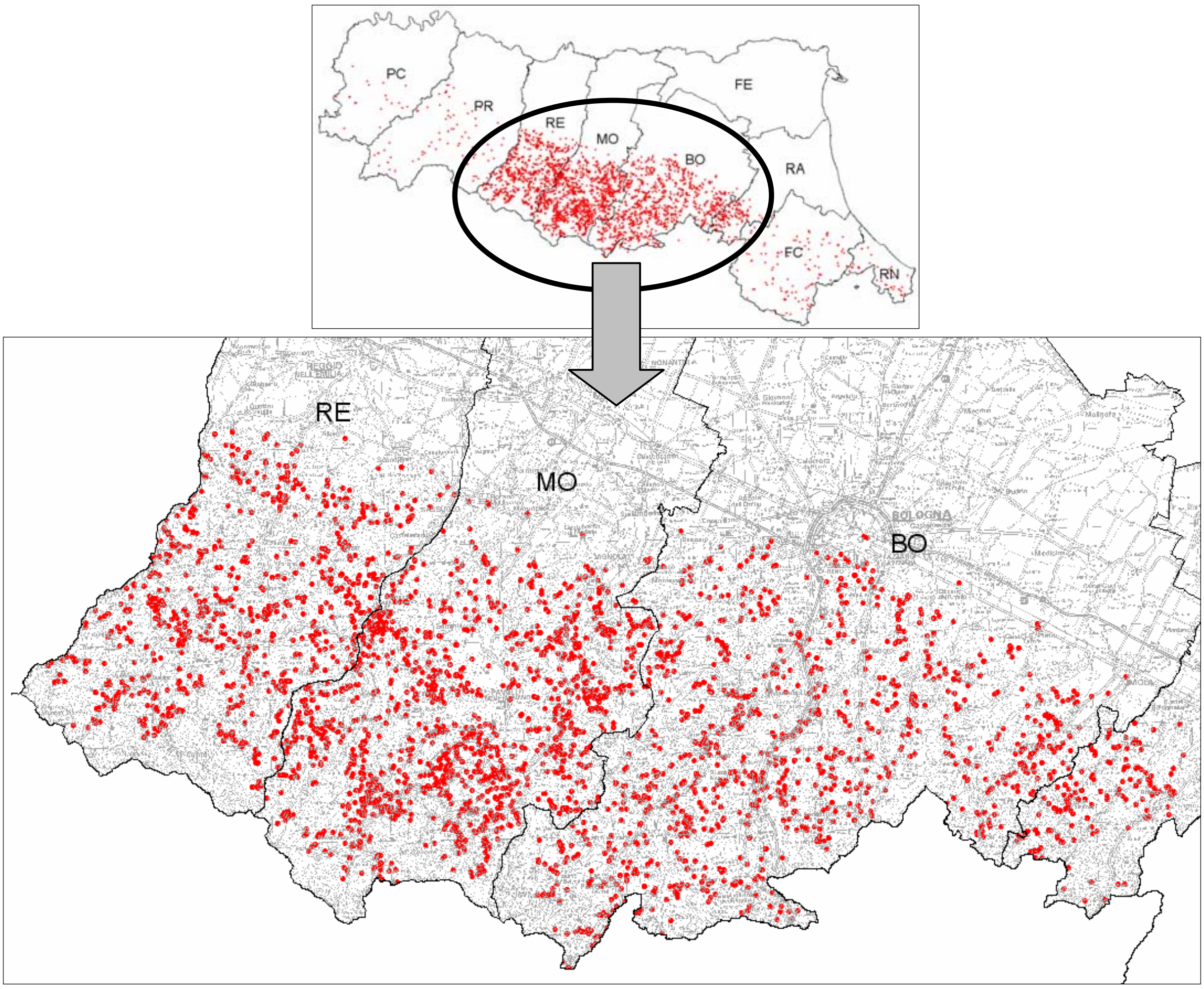

Figure 3.2:Distribution of landslides derived from Regional and AVI database with particular of study area.

3.1.2 PRECIPITATION TIME SERIES DATA

The monitoring rain gauge network of the Emilia-Romagna Region, managed by ARPA-SIM, consists of over 200 tele-metering rain-gauges.

It can be noted that the distribution of rain-gauges is homogeneous over the entire regional territory especially in the mountainous part. The tele-metering rain-gauges have been installed since 2001 integrating and partly replacing the mechanical rain-gauges (figure 3.3). The tele-metering are usually placed near the mechanical rain-gauges; in fact it results that the 70% of the tele-metering rain-gauges are situated to a distance less than 3 kilometres from the mechanical rain-gauges.

In this work only the mechanical rain-gauges which have a historical daily precipitation time series, for ten years at least, have been considered. The mechanical rain-gauges of the study area are almost 134 but only 90 measures are available for each selected event due to the gap of historical time series of precipitation data.

The historical data considered are:

- daily precipitations (mm/24h) to calculate the cumulated rainfall amounts for “event rainfall” and for “antecedent rainfall”. The historical series of data starts from 1950 to 2002 and only for the Province of Bologna the data starts from 1916.daily intense precipitation with duration from 1 to 5 days to calculate the DDFC. monthly precipitation from 1950 to 2002
- annual precipitation from 1950 to 2002.

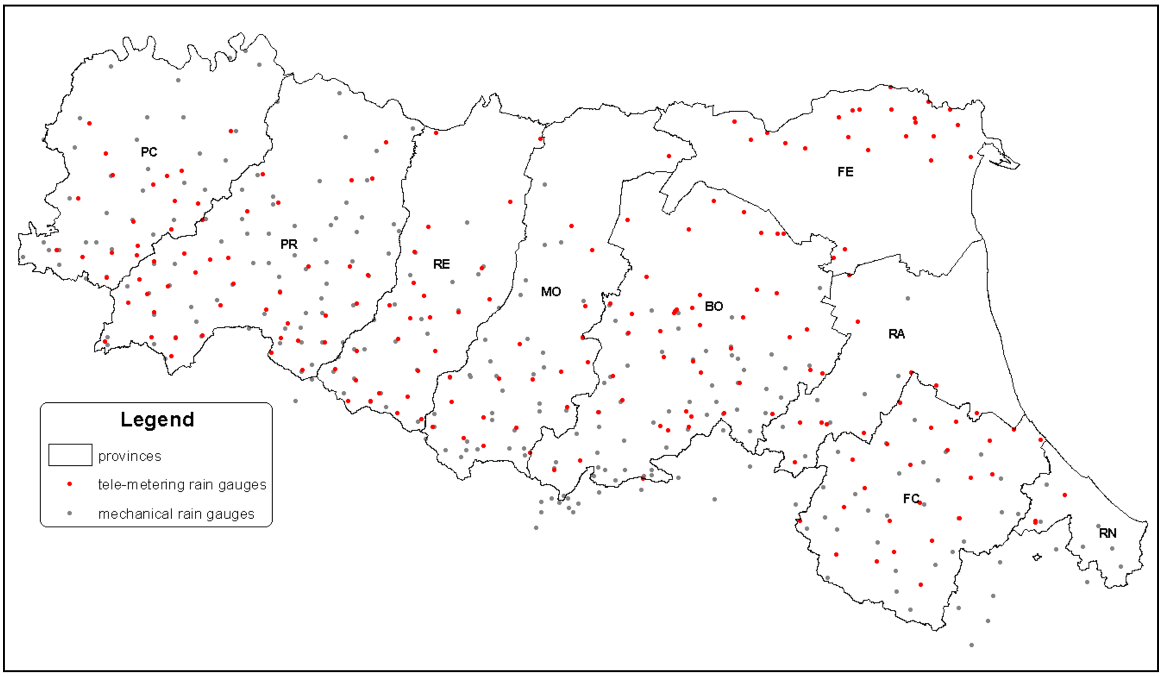

Figure 3.3: Rain gauges on the Emilia Romagna Region.

3.2 DEPTH DURATION FREQUENCY CURVE

DDFC shows the amount of rainfall h[mm] for a particular duration d [hours] and for a selected return period RT [year] in a certain area. DDFC are calculated for each rain-gauge on the regional territory, in order to estimate the return period of the meteorological events which cause landslides.

In the present report the results of the regional frequency analysis of the intense rainfall are described. The statistical method have been executed using GEV probabilistic model. It was chosen a durations of 24, 48, 72, 96 and 120 hours and return period of 2, 5, 10, 20, 50, 100 years. It was chosen to deal with daily intense rainfall because the analysis of the historical landslide events has confirmed that the activations of the landslides are due principally to prolonged rainfall (from 3 to 5 days). For this purpose historical daily intense precipitation with duration from 24 to 120 hours have been collected from Hydrological Annals.

The annual rainfall series have been then processed with statistical methods for estimating the amount of rain with assigned value of return period in the interest site.

The technique of regional frequency analysis, used for the construction of the rainfall thresholds, is completely similar to one adopted in VAPI project (CNR) (also from ARPA Piedmont, 2004 and Prof. Ing. Brath, 2004, for calculating the rainfall thresholds of the Emilia-Romagna Region with hourly duration (1 to 24 h.)) and is founded on the theoretical approach of the "index flood".
Obtained the maximum heights of rain between 24 and 120 hours (1-5 days), and assuming that the probability distributions of the maximums (for given area and duration) are invariant less than a scale factor, it's enough to define:

- an only adimensional frequency distribution or "*growth curve*", valid for the whole "*homogenous region*";
- a law that, to varying the geographical position inside the homogenous area, defines the scale factor or " *index flood*".

So the determination of the precipitation height becomes the resolution of two different aspects: the determination of the "growth curve" and the calculation of the "index flood".
The rainfall event ***h* (*d*,*T*)** comes expressed like:

$$h(d,T) = m_d K(d,T) \qquad (1)$$

where m_d defines the "*index flood*" and K (d,T) defines the adimensional frequency distribution or "*growth curve*".
The index flood, which is estimated at the catchment scale, generally becomes equal to the medium value of the maximum series of considered duration d.
The growth curve, which is estimated at regional scale, represents the tie between the height of precipitation and the return period T and assumes the same value to all rain-gauge stations considered in the homogenous area.
For estimating the growth curve we have been decided to use, in the present report, the Generalized Extreme Value distribution - GEV - (Jenkinson, 1969), that it reassumes all the distributions of extreme values (EV1, EV2 and EV3) to varying of k.
It has the following expression:

$$P(x) = \exp\left\{-\left[1-\frac{k(x-\xi)}{\alpha}\right]^{\frac{1}{k}}\right\} \quad \text{for } k \neq 0 \qquad (2)$$

where ξ it is a location parameter, α a scale parameter and *k* a shape parameter. The Gumbel distribution is obtained from (2) placing k=0. The medium value μ of X represents the index flood. The growth curve of variable X'= X/μ is formally identical to the described equation (2), with parameters $\xi' = \xi/\mu$, $\alpha' = \alpha/\mu$ and k'= k.
The coefficient of variation (*CV*) and skew (*CS*) of two variable X and X' are the same, so that allows, for the calculation of parameters of the theoretical distribution, to use the regional technique based on the method of the linear moments (*L-moments*), proposed by Hosking (1990, 1991).
The linear moments are analogous to conventional moments but they can be expressed in terms of linear combinations of order statistics. Analogous to the conventional statistical moment ratios, like the coefficient of variation (*CV*), skewness *(CS)* and kurtosi, are the L-

moment ratios: L-CV, L-CS and L-kurtosi. Using this approach it has been possible to obtain the values of the regional linear moments for each rain gauge, in relation to the different durations of the analyzed rainfall event. The determination of the linear moments has allowed to resolve the probabilistic distribution and to estimate the "*quantili*" of rainfall for a given duration and a given return period.

3.3 DETERMINATION OF "RAINFALL THRESHOLDS"

The definition of rainfall thresholds is based on the observation of principal meteorological events which caused more than ten landslides in the last 50 years. Considering that the purpose of this research is to understand the meteorological event responsible of landslides, the cumulated rainfall from the beginning of the event until the landslide occurrence was considered. Also in order to make a qualitative estimation of soil moisture, cumulated rainfall are computed for antecedent periods preceding the meteorological event. The principle sketch of methodology is showed in the graph in figure 3.4

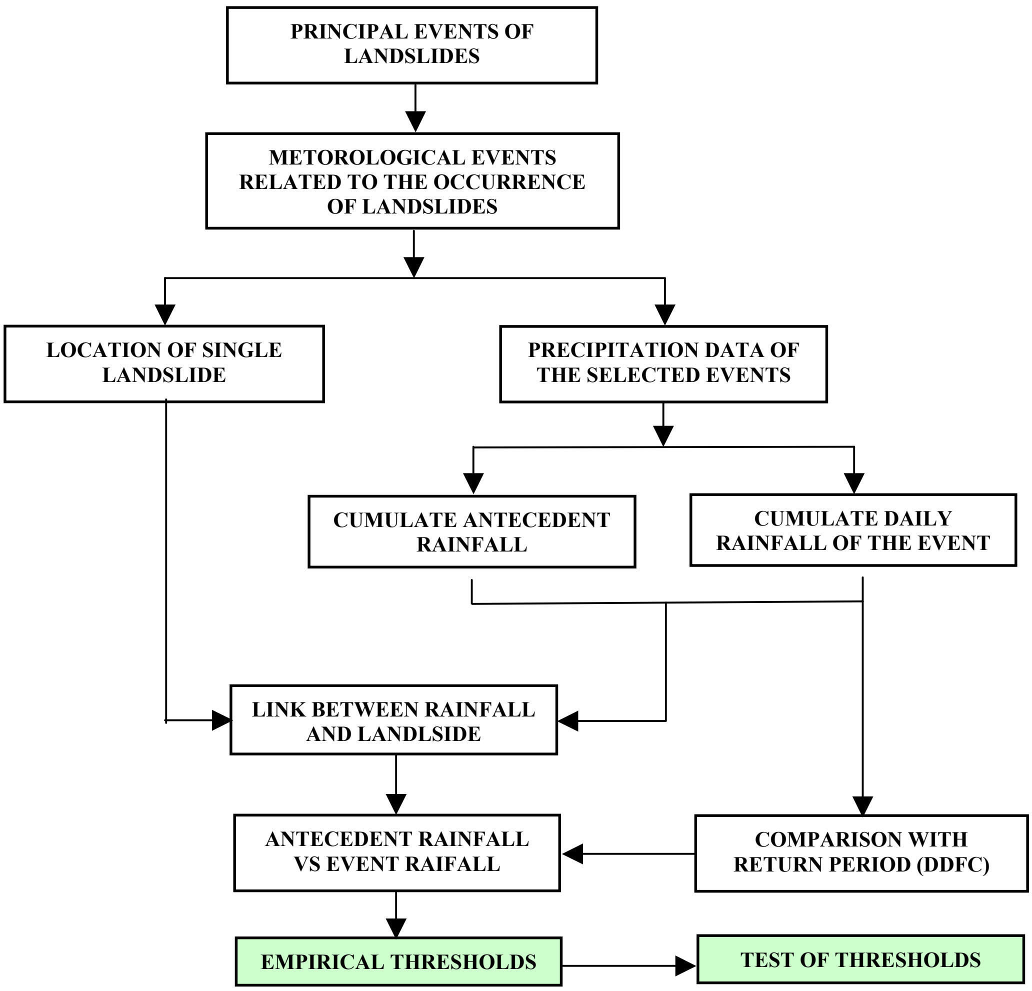

Figure 3.4: Diagram of sketch methodology.

The first step was to select only landslide activations with accurate date of occurrence (degree of reliability 1, 2 or 3) from the database. It was noted that several activations have happened in the same month and sometime in the same week or even the same day because they occurred as consequences of same meteorological event. In this context it was defined as "*meteorological event*" a continuous sequence of rainy days which had been alternating at the most for one day without rain (24h < 5mm). The landslide activations have been grouped based on the month of occurrence and in according with the previous definition only the meteorological event which are responsible of more than ten landslides, have been selected as case studies (table 3.3). Nevertheless meteorological events with less than ten landslides have been considered if they follow another important event. Also the event of April 1956 has been selected as case study even though it has only eight landslide activations associated because all of occurred exactly the same day.

Table 3.3: Main meteorological event from 1939 to 2002 and related landslide activation.

DATE OF EVENT	NUMBER OF OCCURRENCES
29 May – 2 June 1939	248
6-13 February 1951	17
22-27 February 1951	19
30 April 1956	8
16-17 April 1958	9
30 November – 6 December 1959	44
10-14 December 1959	38
13-18 f February 1960	23
19-20 April 1960	74
30 April – 1 May 1960	14
14-16 March 1964	18
28 March – 4 April 1964	65
10-15 April 1965	5
17-20 April 1965	14
4-6 November 1966	66
8-11 September 1972	28
15-16 September 1972	16
24-26 September 1973	40
28-30 April 1974	37
3-5 January 1977	8
12 January 1977	13
13-16 April 1978	52
8-10 November 19882	19
30 November – 3 December 1982	15
24-26 November 1990	68
5-9 December 1992	32
10-14 June 1994	85
8-9 October 1996	20
3-6 December 2002	52
18–20 December 2002	20
TOTAL	1165

Sometime landslides happened few days (one or maximum ten days) after the end of the meteorological event. This delay is due to partly to an inaccuracy of the day of occurrence and

partly because some phenomena happen or produce visible damages with a delay in comparison to the conclusion of the rainy event. Since the objective is the determination of the rainfall amount of event which is responsible of landslides, all the cumulated precipitation from the beginning to the end of the event was computed for landslides which occurred in delay. Besides when the day of occurrence is indicated with interval days (for example 25-26 April 1956) it was chosen the last day as day of occurrence in order to consider all the rain of the event. In the cases when landslide has the exact day which precedes the end of rainy event, the amount of rain was calculated from the start of event until the day of landslide occurrence.
Cumulated rainfall amounts are computed starting on the day of occurrence for periods up to 60 days preceding the event. The following data are extracted from measurements of mechanical rain-gauges (table 3.4):

- daily rainfall of the day of occurrence (mm/24h)
- cumulated rainfall using daily precipitation from the day of occurrence up to 2,3,4,5,6,7 days for the characterization of meteorological event and up to 15, 30, 60 days for quantify the antecedent conditions.

Table 3.4: Example of table of extraction of rainfall data for the event of 10-14 June 1994: in this case the starting data is 23 June.

Rain-Gauge	1Day	2 Days	3 Days	4 Days	5 Days	6 Days	7 Days	15 Days	30 Days	60 Days	90 Days
Baiso	78	167,6	177,4	187,2	187,2	187,2	187,2	187,2	201,6	296,6	390,6
Barco	32,6	113,6	123,6	135,8	135,8	135,8	135,8	136,2	209,8	325	462,6
Barigazzo	63	215	241	247	247	247	247	247	280	396	553
Bologna Idro	39,2	107,4	120,2	139	139	139	139	141,8	152,8	214,4	310,8
Bologna S.Luca	27	100,4	113	131,4	131,4	131,6	131,6	135,8	147,6	211,8	295,2
Bombiana	30,4	114,4	124,6	127,8	127,8	127,8	127,8	128	162,8	245,4	311,8
Borgo Tossignano	67,8	129,8	206	206	206	206	206	223,8	236,8	289	370,2
Calderara di Reno	47,4	86,8	99,2	103,2	103,2	103,2	103,2	108,4	122	186,4	282,4
Canova	43	85	144	201	249	249	249	249	272	442	579
Casola Valsenio	44,4	179,4	189,6	200,6	200,6	200,6	200,6	206	218,4	277,2	369
Castel del Rio	42	122	172,1	192,3	192,3	192,3	192,3	192,3	196,3	285,6	377,2
Castellarano	48	139	150	155	155	155	155	155	173	266	335
Cognento	26,6	32,8	33,4	35,4	35,4	35,4	35,4	54	85,4	153,2	241,6
Collagna	64	158,7	171,9	178,5	178,5	178,5	178,5	178,5	214,3	318,7	470,1
Cottede	44	132,2	163,6	175,8	175,8	175,8	175,8	175,8	238,8	375,4	533,2
Diga del Brasimone	43	143	173	180,4	180,4	180,4	180,4	180,4	234,6	372,8	491,2
Diga di Pavana	42,4	149,4	176,6	179	179	179	179	179	218	338,4	462,2
Diga di Suviana	39,6	143,4	165,8	169,8	169,8	169,8	169,8	169,8	207,2	313,8	406,6
Farneta	59	172,6	186,4	192,4	192,4	192,4	192,4	192,4	213,2	343	464
Febbio	44	168	187	195	195	195	195	195	220	333	470

The following parameters are computed from those precipitation data (table 3.5):

- **Rainfall Event (Re)** = amount of precipitation of the selected meteorological event until landslide occurrence. It is computed considering the cumulated rainfall up to 7 days.
- **Normalized Rainfall Event (NER)** = ratio between each Re and the climatological annual rainfall at a certain rain-gauge.
- **Antecedent Rainfall (Ra)** = amount of precipitation which happened before that the meteorological event starts. It is computed considering the cumulated of rainfall from 15 days up to 60 days.
- **Normalized Antecedent Rainfall (NAR)** = ratio between Ra and the climatological annual rainfall at a certain rain-gauge

Table 3.5: Example of used data.

ID Land	Year	Day	Month	Date	Raingauge	duration	PR	Re	Ra30	Ra60	NER%	NAR30%	NAR60%
605	1992	9	12	10-dic	Riola di vergato	5	2	108,8	25,4	173,0	11,1	2,6	17,6
700	1992	9	12	9-dic	Vergato	4	2\5	107,4	36,6	160,4	10,7	4,1	18,1
710	1992	9	12	10-dic	Vergato	4	2\5	107,4	36,6	160,4	10,7	4,1	18,1
1001	1994	13	6	13-giu	Baiso	4	50\100	187,0	14,6	109,6	22,0	1,7	12,9
1030	1994	13	6	13-giu	Monte S.Pietro	3	50	186,0	58,6	158,6	21,5	6,8	18,3
1210	1996	9	10	07-ott	Borgo Toss.	3	10\20	175,0	216,4	305,6	19,3	23,9	33,8
1212	1996	9	10	08-ott	Fontanaluccia	3	2\5	126,8	98,0	181,0	9,6	7,4	13,7

The normalized rainfall allows to homogenize the data and to compare values measured in the zones where generally the quantities of precipitation are different.
A last step was to associate the rainfall data to the landslide; each landslide was associated to the data measured by the nearest rain-gauge and placed in the same river catchment.

3.3.1 ANALYSIS OF THE RESULTS AND DETERMINATION OF “THRESHOLD CURVE”

For each meteorological event the following parameters have been computed:
- Duration of the event (days)
- RP of the event for its duration in order to estimate the intensity.

It was considered:
1. The most part of landslide activations takings in examination (84%) is triggered after a continuous rainy days (from 3 to 5 days - figure 3.5);
2. The 28% of landslide activations are triggered by meteorological events with a RP less than 2 years; in these cases it is necessary to valuate soil moisture condition using RA. The 38% of landslide activations are triggered by meteorological events with a RP among 2 and 10 years; extreme cases represent only the 34% of the total activations and are related to meteorological event with RP major than 20 years (figure 3.6);
3. The landslides triggered with one day of rain are principle due to antecedent rainfall conditions because the RP of event is less than 2 years; only few landslides are linked to intense event with RP greater than 20 years;
4. Observing the matrix in table 3.6 it can be noted that frequently landslides happen with 3 or 4 days of rain which has low RP (less than 5 years). This means that the

antecedent rainfall should be considered because influence the soil moisture and the degree of instability;

5. If the duration of event increases, RP increases easily (figure 3.7).

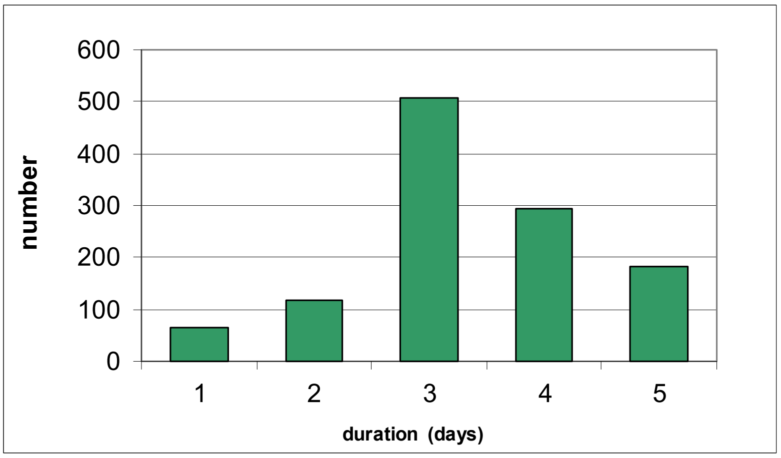

Figure 3.5: Number of landslide activations per duration of triggering meteorological event.

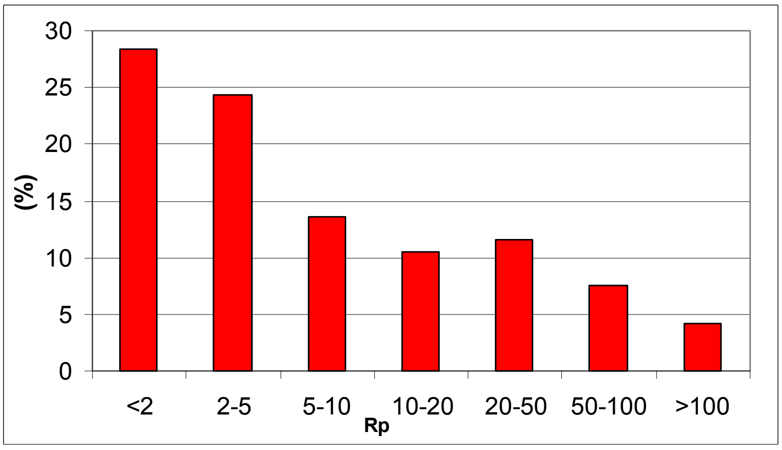

Figure 3.6: Percentage of landslide activations per RP of triggering meteorological event

Table 3.6: Matrix with the percentage of landslide activations per duration and RP of the triggering event.

Duration RP	1DAY	2 DAYS	3 DAYS	4 DAYS	5 DAYS	TOTAL
<2	3,3	4,9	10,3	7,4	2,6	28,4
2-5	1,7	3,1	4,9	10,0	4,5	24,3
5-10	0,0	1,2	8,2	0,9	3,3	13,9
10-20	0,0	0,5	6,7	1,2	2,1	10,5
20-50	0,3	0,1	7,0	1,8	2,5	11,6
50-100	0,3	0,1	5,3	1,7	0,1	7,5
>100	0,0	0,3	1,2	2,1	0,5	4,1
total	5,5	10,1	43,6	25,2	15,6	100

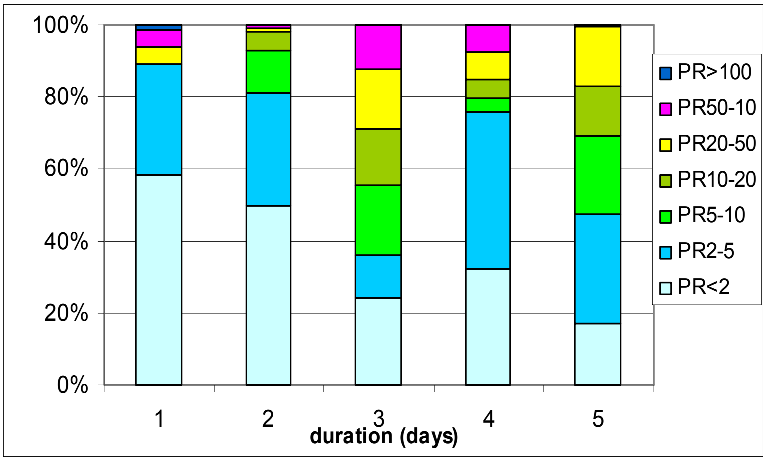

Figure 3.7: percentage of landslide activations per duration of triggering meteorological event subdivided by PR.

Finally calculating the mean rainfall of the 30 days antecedent and the mean rainfall of the event for each case studies and comparing them with the climatological monthly rain of the pilot area, it can be noted that (figure 3.8):

- In many cases the antecedent rainfall overcomes the climatological monthly rain; it means that in 30 days it has rained more than the monthly average. In those cases the rainfall event is lower to testify the fact that under conditions of saturated soil a normal amount of precipitation is enough to trigger landslides.
- When the RA is inferior to the climatological monthly rain, the RE is very influenced on landslide triggering and overcomes climatological monthly rain.

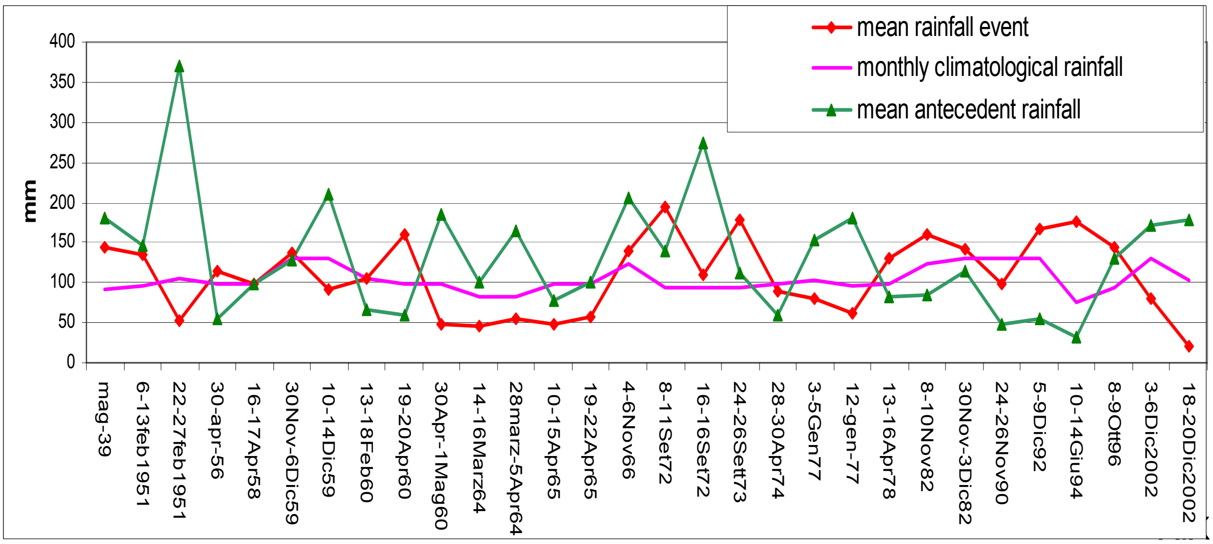

Figure 3.8: Correlation between mean rainfall event and mean 30 days antecedent event of each case studies and the climatological monthly rainfall.

In the last step the correlation between NAR and NER was done using all the rain data associated to the landslide activations of the case studies. The antecedent rainfall was computed for 15, 30, 60 days before the meteorological event starting (figure 3.9, 3.10, 3.11). It can be noted from the graph above that 30- days antecedent period is more significant than 15 and 60 days because it is more evident that if the NAR increases the NER decreases and vice versa; on the contrary if 15-days antecedent period is undertaken, the NAR is underestimate because several values are zero and the cloud of points is homogenous with 60-days period.

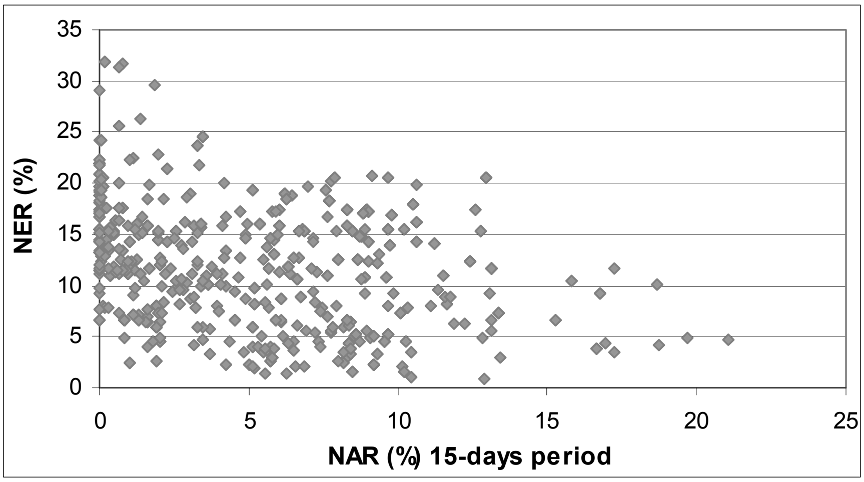

Figure 3.9: NAR versus NER of precipitation data associated to landslide activities of the case studies. NAR is calculated on 15-days antecedent period.

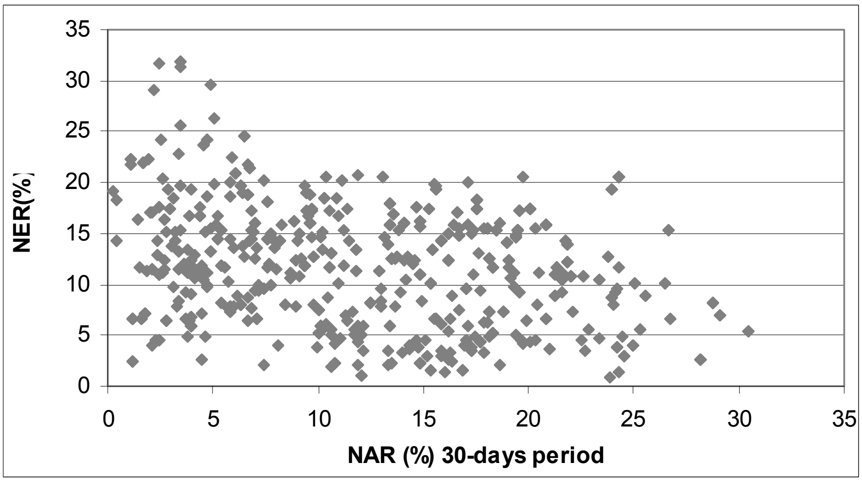

Figure 3.10: NAR versus NER of precipitation data associated to landslide activities of the case studies. NAR is calculated on 30-days antecedent period.

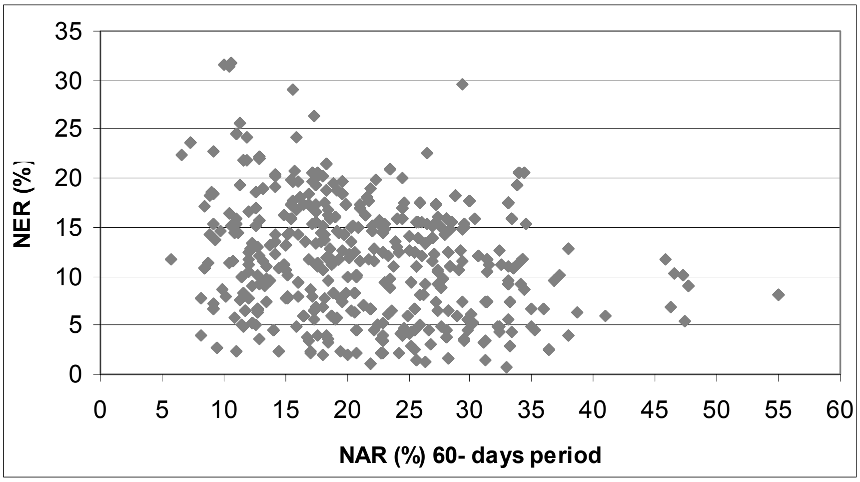

Figure 3.11: NAR versus NER of precipitation data associated to landslide activities of the case studies. NAR is calculated on 60-days antecedent period.

Starting from 30-days antecedent period, a curve has been drawn which should represent a empirical threshold to explain the occurrences of landslide events. As it can be noted from figure X2, the distribution of the points is notably missed and therefore any curve is able to interpolate the data with coefficient of correlation. Nevertheless a mathematical function has been found out for whole distribution of the points. Such function, denominated "Curve A." has been chosen after having tested 2979 non linear functions (figure 3.12).
Its equation is:

$$\boxed{y = \frac{a}{\sqrt{1+2a^2bx}}}\quad \text{with } X>0,\ a>0,\ b>0$$

Its statistic parameters are

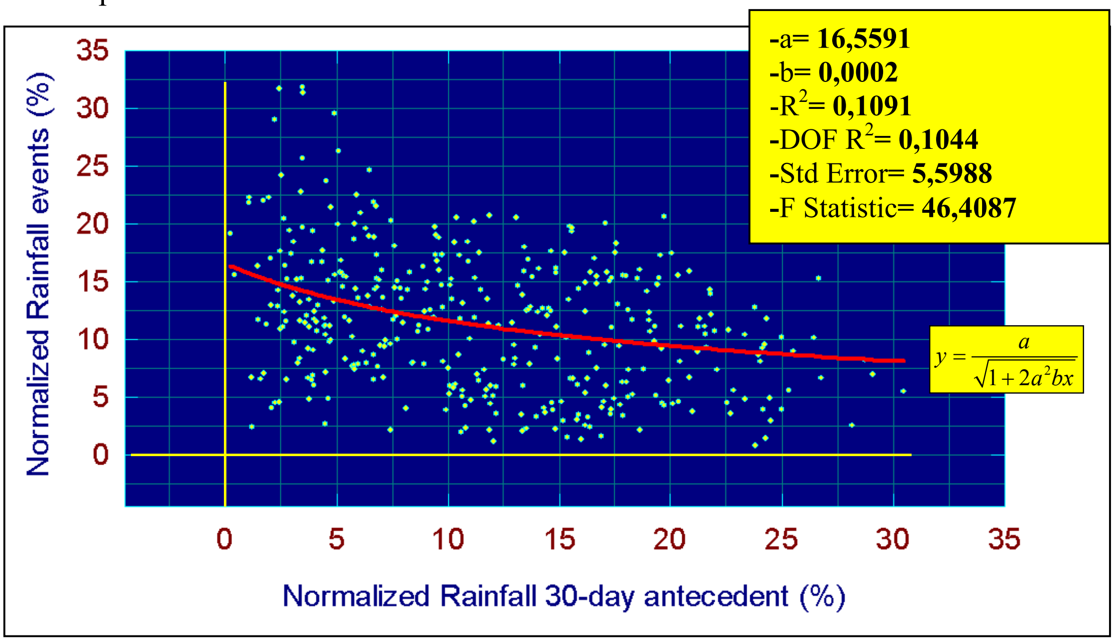

Figure 3.12: Function interpolating rainfall events.

The curve A has been subsequently translated downward in the diagram in order to separate the 10% of the points below from 90% above the curve. In this way it constitutes the minimum threshold or ordinary threshold (**curve "ordinary" of figure 3.13**) for triggering landslides; it separates the stable area below where no phenomena should occur, from the instable area above. The necessary parameters for the construction of the curve are:

$$\boxed{y = \frac{a}{\sqrt{1+2a^2bx}}}$$ with

a = 9,67 **b** = 0,002

The statistical meaning of this curve is that only the 10% of landslide activations have occurred with rainfall conditions which have values of NER and NAR lower than the threshold. Such percentage which represents almost 110 of the 1165 landslide activations, can be reasonably explained considering that this work is dealing with historical data and it can be possible to have errors about rainfall measurements or about data of occurrences.
The ordinary curve has been used only within an interval of values, delimited by a vertical line parallel to the axle Y (red vertical line in figure 3.13) which is located on 3.4% of NAR; 3.4% is tenth percentile of all the distribution of the NAR values. From a statistical point of view, the points which are located at the left part of the vertical line are few and the sample is not representative to be interpolated; from a physical point of view if the rain of 30 days period is less than 3.4% the soil moisture is dry and the NAR is not influence and intensity of the meteorological event ha a significant role in triggering landslides.
Also all the landslides events are disposed on a vertical ranges depending on the RP of the meteorological event. For this reason it is possible to determinate another threshold translating onward the ordinary curve; in this way a moderate curve (**curve "moderate" of figure 3.13)** has been drawn which divided events with RP less than 2 years from events with higher RP. This means that at the same antecedent conditions if the insensitive of meteorological event (RP) increases, landslide events can be more dangerous. This curve is likewise interrupt to the vertical line and its parameters are:

$$\boxed{y = \frac{a}{\sqrt{1+2a^2bx}}}$$ with

a= 14.49 **b**= 0.00035

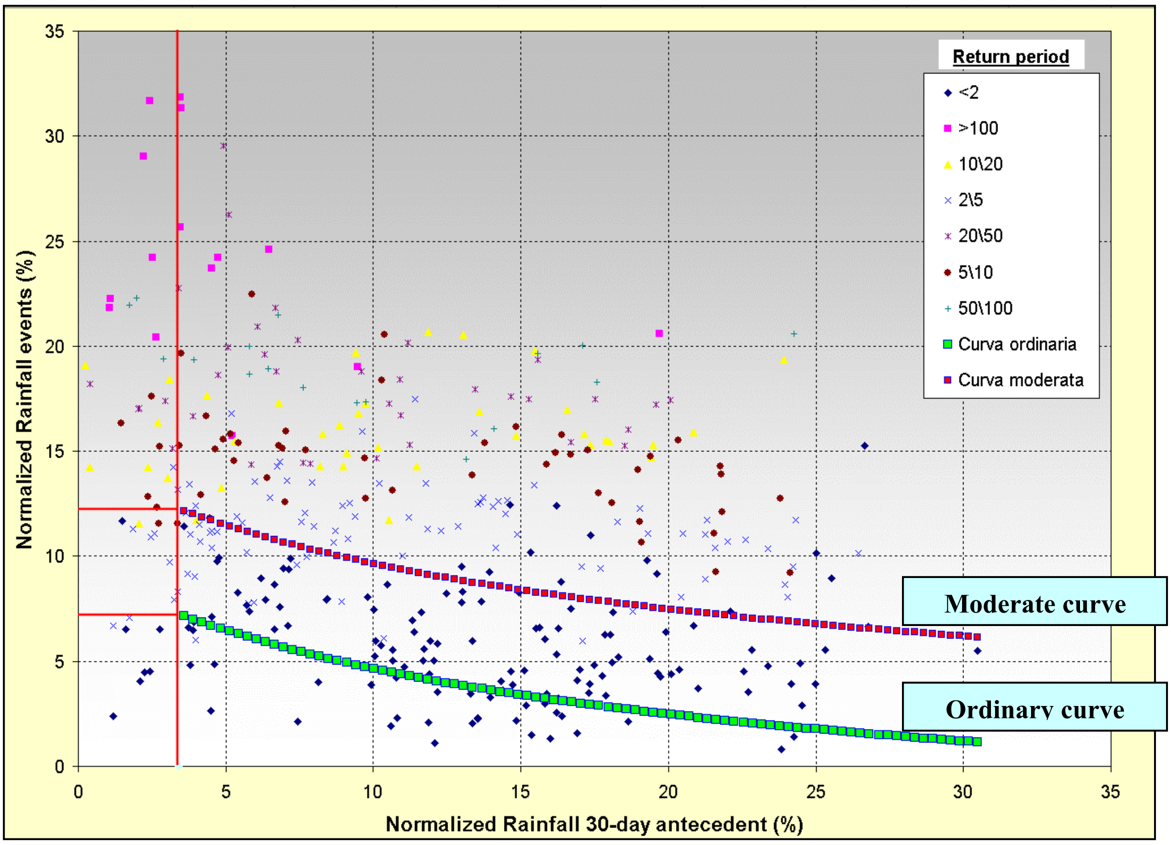

Figure 3.13: Rainfall thresholds to trigger landslides based on NAR versus NER.

3.3.2 TEST OF CURVE THRESHOLDS

A fundamental part of all the statistic methodologies results the verification of the reliability of the selected methodology. In the present work it has been valued if the established curves represent indeed of the critical thresholds to trigger landslides.

The verification has been computed selecting other meteorological events connecting to slope instability for which the NER and NAR have been calculated. The procedure previously described has been applied to twenty-four meteorological events which are characterized by lower intensity in compare with the main events using to calculate the curves (table 3.7); it is to notice that the 82% of mass movements are triggered by rainfall events with RP less that 2 years (figure 3.14).

Finally all the NER and NAR values associated to the landslide activations have been inserted in the graph and it had been verified if they place below or above the thresholds (figure 3.15); it is noticed that around 70% of the landslides are located above the curve of ordinary threshold and the most greater part of the events it is below the curve of moderate threshold. If it is considered that meteorological events which are characterized by low RP and have been triggered few landslides, have been chosen for the test, the location of the 30% of the points under the ordinary curve can be explained considering that those mass movements can be linked to other causes or can have uncertain data of occurrence.

Table 3.7: Events undertaken for the threshold test.

DATE OF EVENT	NUMBER OF OCCURRENCES
16-19 November 1959	12
8-11 December 1960	4
17-18 December 1960	7
28-27 November 1965	5
25-22 February 1968	6
24-26 March 1969	16
3–6 April 1969	13
14 April 1969	5
26-25 April 1972	10
14-17 February 1979	10
15-19 November 1979	10
10 March 1980	8
14-17 March 1980	7
27 January 1985	8
10-11 May 1991	11
20-25 November 1991	12
22 September 1994	6
15-18 December 1985	8
1 January 1996	10
6-8 January 1996	8
20-22 February 1996	13
9-6 November 1999	10
17-18 November 2002	5
24-27 November 2002	10
TOTAL	213

XX

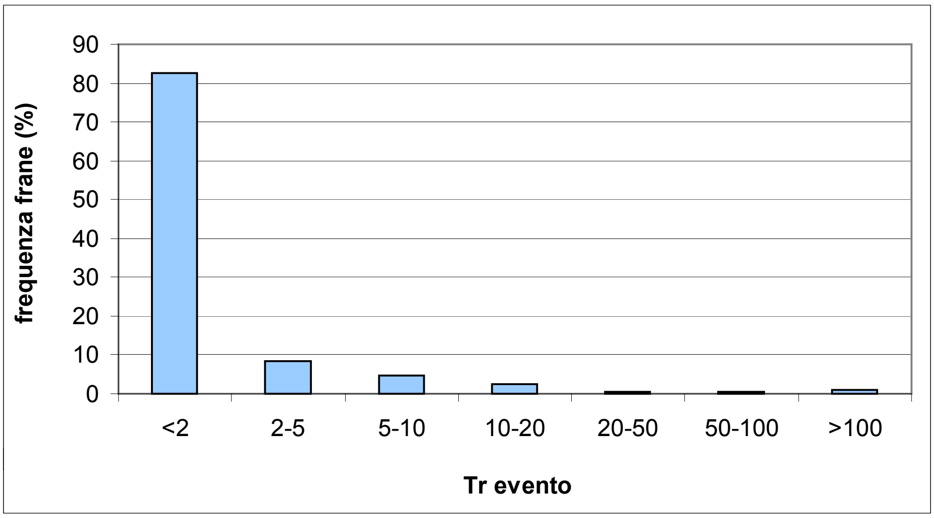

Figure 3.14: Number of activations per RP of meteorological events selected for the test.

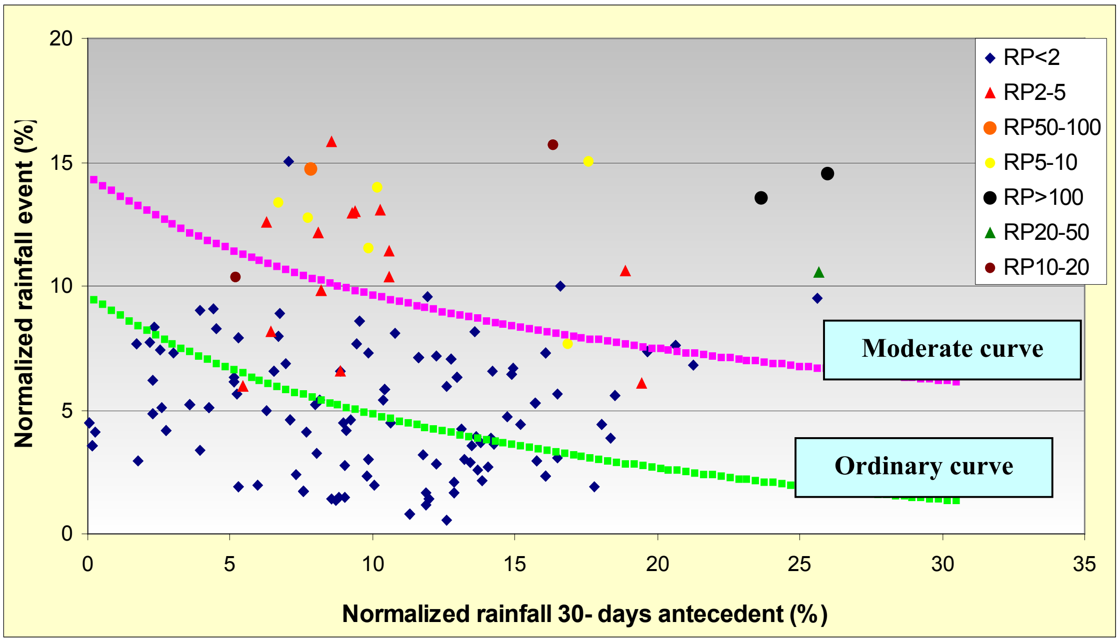

Figure 3.15: Rainfall thresholds with the events selected for the test.

4. CONCLUSION AND REMARKS

The present work represents a first attempt to define rainfall thresholds to trigger landslides in the Northern Apennines. The analysis of the antecedent rainfall conditions and meteorological events, related to over 1150 reactivations, has allowed to define empirical curve threshold based on NAR and NER. It was found out that 30 days are significant interval time to evaluate antecedent rainfall condition in order to estimate soil moisture. Nevertheless one of the future development will be to seek “curve threshold” for different intervals (60 and 90 antecedent days) related with the seasons.
This curve will be applied on the future events that will happen during 2005 in the whole regional territory and, at the same time, will validate with the past events happened on neighbourhood provinces of the study area.
Also other parameters as lithology characteristic and dimensions of mass movements will be analysed to define the thresholds better.
Finally statistic test will be provided to the minimize the missed and false warnings based on historical precipitation time series.

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