Rainfall Thresholds for Landsliding in Lisbon Area (Portugal)

J.L. Zêzere & M.L. Rodrigues
Centro de Estudos Geográficos - Universidade de Lisboa

ABSTRACT: Most slope movements in the Area North of Lisbon exhibit a clear climatic signal, confirmed by the number of movements activated in the wettest years as well as the nearly absolute inactivity in other years. A particular attention is put on the rainfall triggering of landslides verified in 1996 and 2001. The new rainfall data is incorporated in the previous rainfall analysis in order to improve the critical thresholds of precipitation (amount/duration) responsible for landslides events in the study area.
A general threshold was found plotting the cumulative rain and the duration of precipitation. Its validity is confirmed by the correct fitting of 89% of the rainfall events. A second threshold was defined crossing daily rainfall and 30-days calibrated antecedent rainfall. This trend line highlights both 80 mm of calibrated antecedent rainfall and 24 mm of daily rainfall as, simultaneous critical values for landslide triggering in the study area.

1 INTRODUCTION

Rainfall is the most common cause of landslides worldwide. Establishment of rainfall thresholds for landslide activity began with Caine's work (1980) that compiled available data trying to define a general "universal rule". As Polloni et al. (1996) and Dikau & Schrott (1999) pointed out, fully satisfactory thresholds of general validity cannot be found due to the complexity of the relationships between climate and landsliding, and the great influence of other factors in the instability system such as geomorphological, geotechnical and hydrogeological conditions. An additional problem is that both the frequency of movement and landslide type may be related to different rainfall threshold conditions, resulting in different patterns of activity under the same climatological conditions (Van Asch et al., 1999; Polemio & Petrucci, 2000; Zêzere, 2000).

Nevertheless, empirical and semi-empirical analysis of rainfall - landslides relationships at a regional level must be improved. Daily rain, cumulative rainfall for defined durations and calibrated antecedent rainfall (Crozier, 1986) are essential parameters for the definition of pluviometric thresholds above which landslides are triggered.

In other papers both the control and triggering factors of landslides in the Area North of Lisbon were discussed (Ferreira et al., 1987; Zêzere et al., 1999a, 1999b; Zêzere, 2000). Slope movements in the study area show a clear climatic signal, confirmed by the large number of movements triggered during the wettest years as well as the nearly absolute inactivity in other years. Thus, the state of activity of the different types of landslides depends basically on the return period of rainfall that triggers the slope movements.

2 REGIONAL FRAMEWORK

The Area North of Lisbon is located in the south flank of an anticline dipping 5° to 25° to Tagus River (Fig. 1). The bedrock is quite heterogeneous, consisting of alternating limestones, sandstones, basalts and volcanic tuffs, marls and clays, from upper Jurassic to Miocene age. The main landform consists of cuestas strongly dissected by fluvial cutting. Altitude does not exceed 350 m, but steep slopes are common namely on catacline valleys.

Climate is characterized by a mean annual precipitation (MAP) of 731 mm, occurring on 86 days each year. Most of the rain falls from October to March (78% of the total amount; 72% of the total rainy days). Besides, the average rainfall regime includes a great interannual irregularity (Fig. 2), one of the essential climate features in Portugal (Ferreira et al., 1987).

In Figure 2 we have marked the years with known slope instability events. These slope movements include: a) shallow translational slides moving along planar slip surfaces and almost exclusively affecting slope deposits (mean area, 558 m^2; mean volume, 267 m^3); b) deeper translational slides always affect the bedrock (mean area, 4153 m^2; mean volume, 4060 m^3); c) rotational slides mainly on homogeneous clay formations (mean area, 10625 m^2; mean volume, 46294 m^3); d) slope movements triggered by bank erosion (falls, topples and slides) confined to river banks, with modest dimensions (mean area, 397 m^2; mean volume, 596 m^3); e) complex and composite slope movements including some of the most significant landslides of the region, combining translational and rotational movements in the main slide bodies (mean area, 9747 m^2; mean volume, 42998 m^3).

Figure 1.The Area North of Lisbon in Portugal.

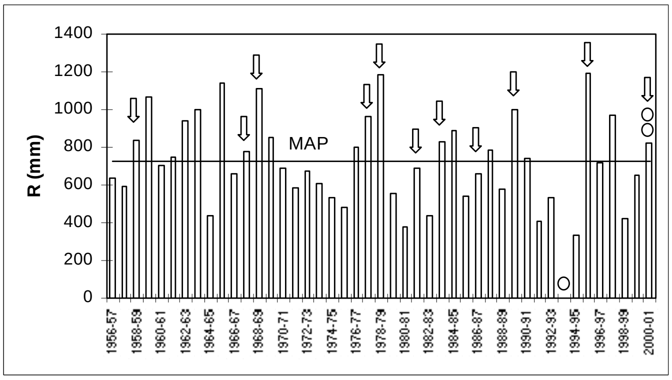

Figure 2. Annual rainfall distribution in the reference rain gauge (S. Julião do Tojal) from 1956-57 to 2000-01. MAP, Mean annual precipitation; arrows, landslide events; o, missing data; 8, incomplete data.

3 EARLIER RELATIONSHIPS BETWEEN RAINFALL AND LANDSLIDES IN THE STUDY AREA

Earlier relationships between rainfall and landslide incidence were discussed in Zêzere et al. (1999a and 1999b) and Zêzere (2000). Figure 3 shows the adopted methodology, which includes the reconstruction of both absolute and calibrated antecedent precipitations for periods of confirmed slope instability events (Table 1). Critical rainfall amount-durations were defined assuming as critical values the extreme combinations from the statistical point of view (D'Ecclesiis et al., 1991).

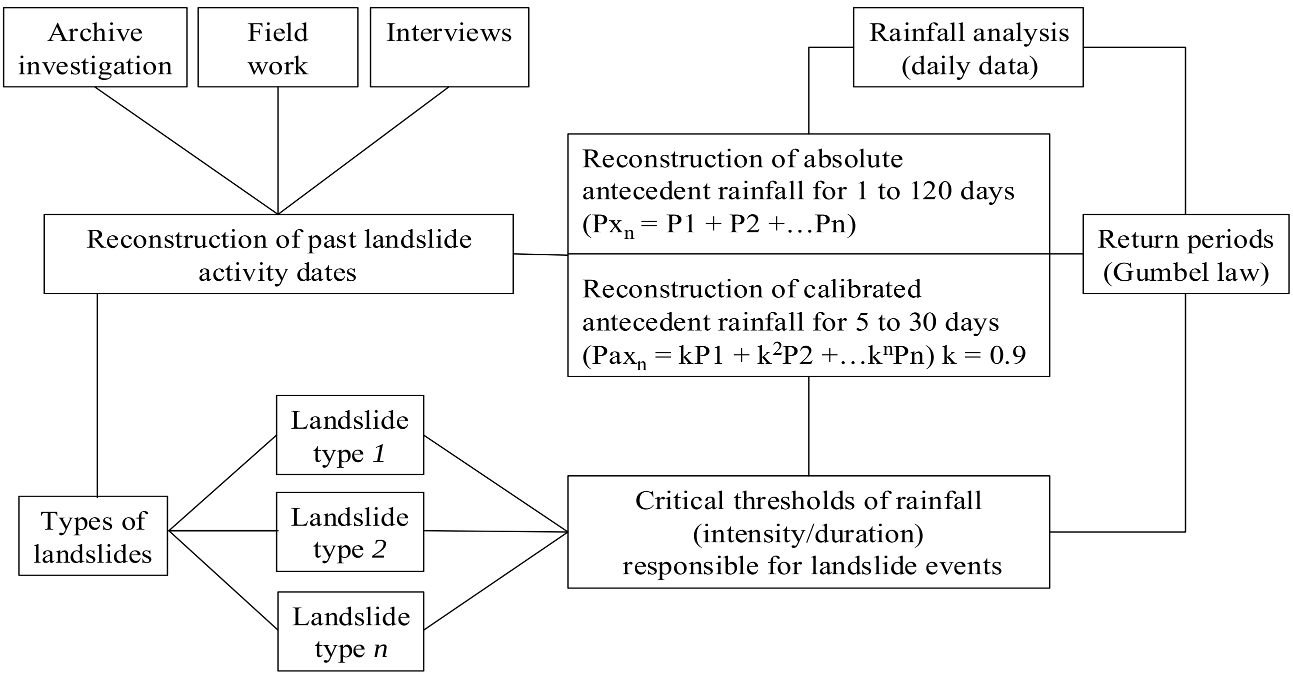

Figure 3. Methodology for rainfall triggering of landslides analysis.

Table 1. Temporal occurrence of rainfall triggered landslides in the Area North of Lisbon from 1956 to 1995.

Date	Critical rainfall amount/duration (mm/days)	Return Period (years)	Landslide typology
1958 (12/19)	149/10	3	a
1958 (03/9)	172/10	4	a
1967 (11/25)	137/1	55	a,d
1968 (11/15)	350/30	8	b
1978 (03/4)	204/15	4	d
1979 (02/10)	694/75	25	b,c,e
1981 (12/30)	224/10	25	a,d
1987 (02/25)	52/1	2.5	a,d
1989 (11/22)	164/15	2	a,d
1989 (11/25)	217/15	4.5	a,d
1989 (12/5)	333/30	6.5	b,c,e
1989 (12/21)	495/40	21	b,c,e

Landslide typology: a) shallow translational slides; b) deep translational slides; c) rotational slides; d) slope movements triggered by bank erosion; e) complex and composite slope movements.

Field work and rainfall statistical analysis allowed the definition of three distinct situations that trigger landslide events (Zêzere, 2000): i) *Moderate intensity rainfall episodes* (R= 160 - 220 mm in 15 days; return period from 2 to 4.5 years), are responsible for minor slides, falls and topples on the banks of river and shallow translational slides, mainly on man-made cuts and filling materials. ii) *High intensity rainfall episodes* (daily rainfall ≥130mm; return period >55 years), trigger flash floods, most bank erosion landslides and numerous shallow translational slides on steeper slopes, artificial embankments and filling materials. iii) *Long lasting rainfall periods* (R=459 mm in 40 days or R=690 mm in 75 days; return period from 21 to 25 years), are responsible for the rise of the groundwater table, development of positive pore water pressure and triggering of slope movements with deeper slip surfaces.

4 THE EXAMPLES OF 1996 AND 2001

After the rainy events reported in Table 1, the Area North of Lisbon experienced landslide activity in January/February 1996 and in January 2001.

4.1. *The 1996 occurrences*

The climatological year of 1995-96 was the wettest year the data series registered in S. Julião do Tojal (regional reference rain gauge), with a total amount of 1190 mm. The beginning of the rainy season was dry (September, 27 mm; October, 53 mm; Fig. 4), 28 mm below the average. November was a wet month (193 mm; average, 111 mm), as well as December (238 mm; average, 106 mm). January with 358 mm surpassed 3.6 times the average for this month.

Two sequences of continuous rainy days were particularly important in the triggering of slope movements: i) from December, 17 to January, 15 (30 days) 394 mm were registered, including 66.5 mm in a single day (January, 9). The duration of this rainy sequence largely surpasses the previous record of the rain gauge (18 days); ii) from January, 19 to February, 7 (20 days) were registered 203 mm. The daily rainfall surpassed 20 mm in January, 23 and 28, and in February, 1.

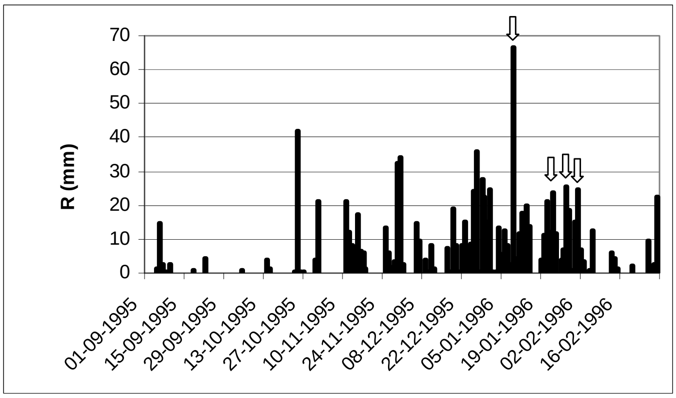

Figure 4. Daily rainfall data registered at S. Julião do Tojal from September 1995 to February 1996 (arrows indicate instability events).

As it can be seen in Figure 4, landslides occurred in the four days mentioned above. Slope movements were of rotational, deep translational and complex types, and affected mostly marls and clays of Jurassic and Cretaceous age. Movements developed in man-made cuts caused four fatal victims.

Figure 5 reproduce the evolution of both the absolute and calibrated antecedent rainfalls from November 1995 to February 1996. The critical duration concerning the absolute antecedent precipitations responsible for landslide events ranges from 60 to 90 days, with return periods from 13 to 35 days (Table 2). Table 3 stresses the importance of 30 days of calibrated antecedent precipitations for the whole instability events in 1996.

4.2. *The 2001 occurrences*

As in 1995-96, the beginning of the climatological year of 2000-01 was dry (September, 13 mm; October, 70 mm), 25 mm below the average. November registered a normal value (118 mm), but December and January were very wet months (272 mm and 220 mm, respectively), surpassing 2-2.5 times the mean values.

The most important rainy sequence range from December, 20 to January, 6 (18 days) with 258 mm of precipitation. Landslides took place at the end of this sequence (Fig. 6). Most of the slope movements were rotational slides developed on moderate slopes (10-20°), affecting clays, marls and marly limestones of Jurassic age. The largest of these rotational slides is the Alrota landslide, with a total unstable area around 58,000 m^2 and a slip surface deeper than 5 meters.

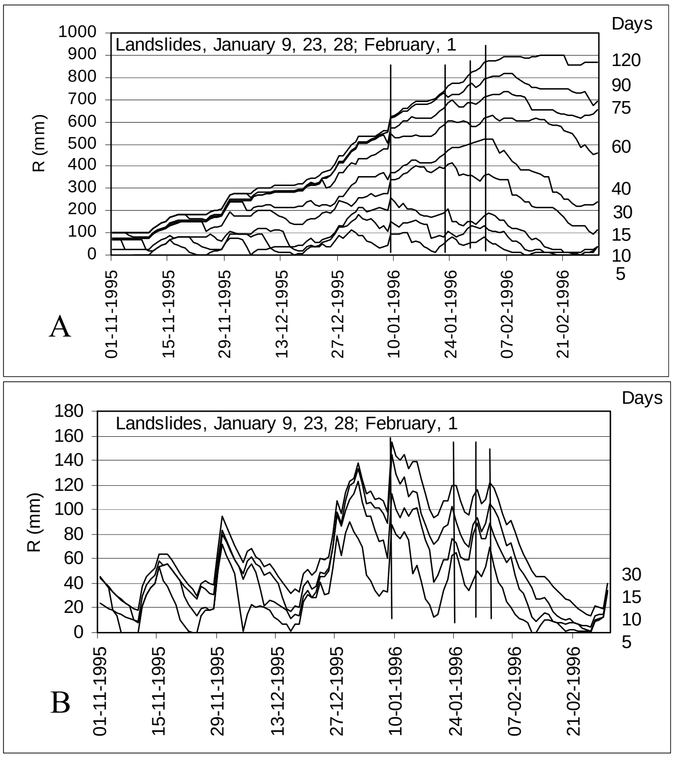

Figure 5. Evolutions of the absolute (A) and calibrated (B) accumulated rainfall in S. Julião do Tojal from November 1995 to February 1996.

Table 2. Absolute rainfall accumulated from 1 to 90 days and corresponding return periods for 1996 landslide events (rainfall data from S. Julião do Tojal; R, rainfall; R.P., Return period).

		1996 01/9	1996 01/23	1996 01/28	1996 02/1
1	R (mm)	66.5	23.6	25.5	24.5
day	R.P.(y)	3.5	1.1	1.2	1.2
10	R (mm)	149.1	105.3	119.8	130.6
days	R.P.(y)	2.6	1.4	1.8	2
30	R (mm)	341.5	410.6	361.3	357.9
days	R.P.(y)	7	21	8.5	8.5
40	R (mm)	372.3	473.9	495.2	522.6
days	R.P.(y)	6	17	21	28
60	R (mm)	**544.2**	605.4	596.1	618.8
days	R.P.(y)	**13**	21	18	23
75	R (mm)	569.2	**686.1**	684.7	712.4
days	R.P.(y)	9	**23**	23	30
90	R (mm)	617.2	711.5	**758.7**	**793.1**
days	R.P.(y)	9	20	**30**	**35**

Table 3. Calibrated antecedent rainfall from 5 to 30 days and corresponding return periods for the instability events of 1996 and 2001. (rainfall data from S. Julião do Tojal; R, rainfall; R.P., Return period).

		5 days	10 days	15 days	30 days
1996	R (mm)	88.1	112.8	144.2	**154.9**
01/9	R.P.(y)	2	3	5.5	**6**
1996	R (mm)	62.3	75.8	102.0	**120.2**
01/23	R.P.(y)	1.3	1.4	2	**2.5**
1996	R (mm)	42.4	79.2	87.2	**110.0**
01/28	R.P.(y)	1.1	1.5	1.6	**2**
1996	R (mm)	69.1	89.4	104.4	**122.4**
02/1	R.P.(y)	1.4	1.8	2	**3**
2001	R (mm)	53.5	70.5	94.4	**111.7**
01/6	R.P.(y)	1.2	1.3	1.2	**2.5**
2001	R (mm)	41.4	66.5	81.8	**101.3**
01/9	R.P.(y)	1.1	1.2	1.5	**1.8**

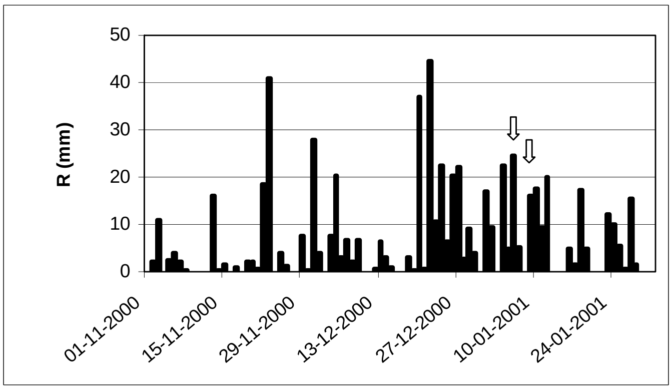

Figure 6. Daily rainfall data registered at S. Julião do Tojal from November 2000 to January 2001 (arrows indicate instability events).

As it can be seen in Table 4, 60 days is the critical duration of absolute antecedent precipitation responsible for landslide activity in 2001, having the corresponding rainfalls a return period of 5.5-6.5 years. Table 3 stresses the importance of 30 days of calibrated antecedent precipitations, although with lower values than 1996.

Table 4. Absolute rainfall accumulated from 1 to 60 days and corresponding return periods for 2001 landslide events (rainfall data from S. Julião do Tojal; R, rainfall; R.P., Return period).

		2001 01/6	2001 01/9
1	R (mm)	24.5	16.0
day	R.P.(y)	1.2	1
10	R (mm)	94.6	99.8
days	R.P.(y)	1.3	1.4
30	R (mm)	281.0	293.5
days	R.P.(y)	3.5	4
40	R (mm)	358.2	371.6
days	R.P.(y)	5	6
60	R (mm)	**446.6**	**467.4**
days	R.P.(y)	**5.5**	**6.5**

5 ASSESSMENT OF TRIGGERING RAINFALL THRESHOLDS

When we consider the rainfall episodes that triggered landslides a strong relationship is found between cumulative rainfall and rainfall event duration.

Data prior to 1995 allowed the establishment of this relation (Fig.7):

$$y = 8.1948\, x + 98.57 \quad (1)$$

being $R^2 = 0.9471$. When we plot 1996 and 2001 in the correlation graphic we can conclude that these recent episodes fit quite well with the statistical trend, although with some adjustments:

$$y = 7.3502\, x + 104.94 \quad (2)$$

being $R^2 = 0.9583$.

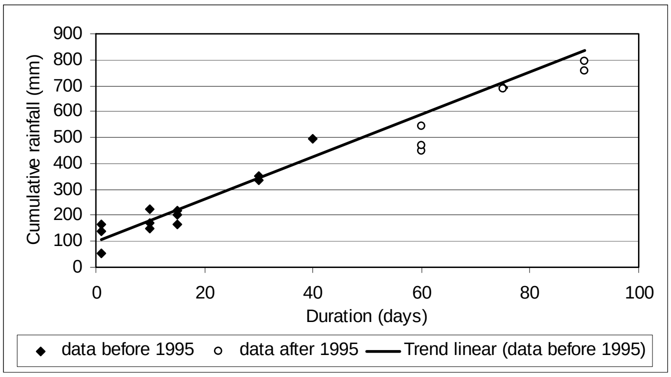

Figure 7. General trend between duration and cumulative rainfall for landslides events in the study area.

In order to analyse the overall effect of precipitation on the activity of landslides, we plot the cumulative rain and the duration of precipitation (Fig. 8), as it was done by Corominas & Moya (1999) for Llobregat region (Eastern Pyrenees). We included 18 rainy events between 1956 and 2001 (see tables 1, 2 and 4), which have produced landslides. Furthermore, for the remaining 30 years without observed landslides we selected the yearly maximum rainfall values for the durations of 1, 5, 10, 15, 30, 40, 60 75 and 90 days, in a total of 270 cases. A line was drawn to divide the rain events that are linked with landslide activity from those that are not. This line has the following equation:

$$Cr = 6.3D + 70 \quad (3)$$

where *Cr* is the cumulative rainfall in mm, and *D* is the duration in days. Therefore, Cr includes both the 24 hours rain and the antecedent rain of the considered duration.

The obtained equation is consistent with regional data, mostly with slope movements triggered by long lasting rainfall periods, such as rotational and deep translational slides, as well as complex as composite slope movements (group 1 in Fig. 8). In what concerns shorter durations it is also well marked another group of more superficial slope movements (group 2 in Fig. 8), although more rainfall events without observed landslides fall above the threshold line. A possible explanation for these cases may be due to the small size of the landslides that may be produced in such situations, so they were not identified in the fieldwork or reported in the literature.

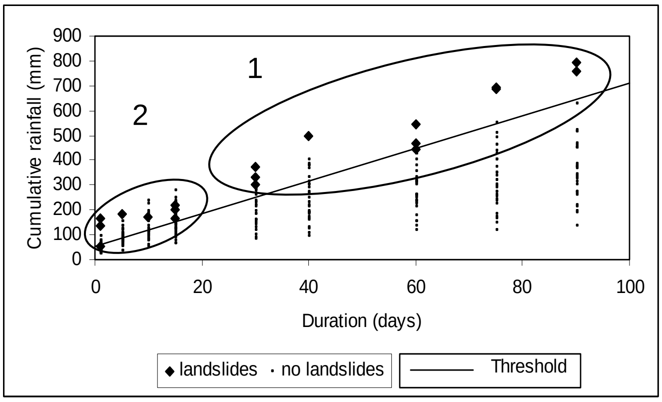

Figure 8. Cumultive rainfall - duration threshold for landslide activity in the Area North of Lisbon.

Concerning all data shown in Figure 8, we can use the values of the equation (3) in the Area North of Lisbon. In fact, 89% of the rainfall events fall within the rainfall threshold for landsliding.

In Figure 9 we plot the daily rainfall and the calibrated antecedent rainfall in 30 days for the abovementioned 18 events, which have produced landslides in the study area. As it can be seen, most of the instability episodes were related with calibrated antecedent rainfall higher than 80 mm. Simultaneously, these episodes were marked by daily rainfall higher than 24 mm in 83% of the events, pointing out the importance of 24-hours antecedent rain in landslide triggering.

Figure 9 also shows the that daily rainfall needed to produced slope instability decreases with increasing 30-days calibrated antecedent rainfall. The trend line for this relation has the following equation:

$$Dr = -0.76\, Car + 90 \quad (4)$$

where *Dr* is the daily rainfall in mm, and *Car* is the calibrated antecedent rainfall for 30 days in mm.

6 CONCLUSIONS

The importance of rainfall as a triggering factor for landsliding is clear in the study area. Relationships between rainfall and landslides were analysed for two periods: before and after 1995. After 1995 two rainy episodes occurred in study area (1996 and 2001), which have triggered rotational, deep translational and complex slope movements. These rainfall episodes are conforming to the main trend defined by the previous events data.

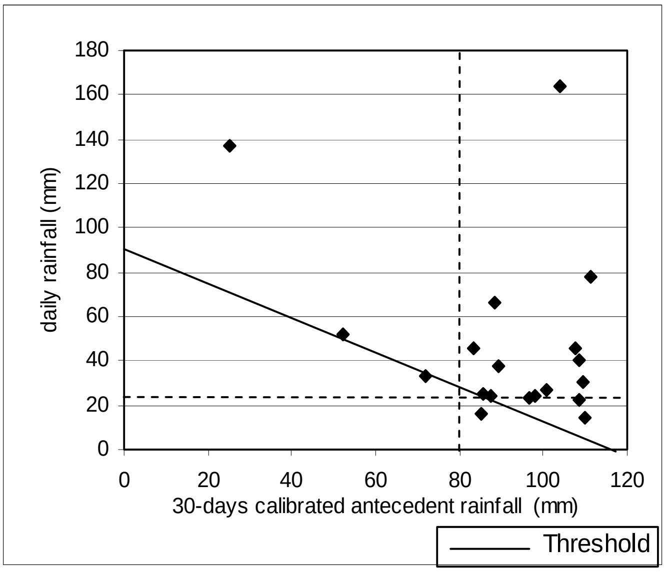

Figure 9. Daily rainfall - 30-days calibrated antecedent rainfall threshold for landslide activity in the Area North of Lisbon.

In order to analyse the overall effect of precipitation on the activity of landslides, we plot the cumulative rain and the duration of precipitation. A general threshold was found (Equation 3), who's validity is confirmed by the fitting of 89% of the rainfall events within the rainfall threshold for landsliding.

Another threshold was defined crossing daily rainfall and 30-days calibrated antecedent rainfall (Equation 4). This trend line highlights both 80 mm of 30-days calibrated antecedent rainfall and 24 mm of daily rainfall, as simultaneous critical values for landslide triggering in the study area.

REFERENCES

Caine, N. 1980. The rainfall intensity-duration control of shallow landslides and debris flows. *Geografiska Annaler*, 62A, 1-2: 23-27.

Corominas, J. & Moya, J. 1999. Reconstructing recent landslide activity in relation to rainfall in the Llobregat River basin, Eastern Pyrenees, Spain. *Geomorphology*, 30, 1-2: 79-93.

Crozier, M. 1986. *Landslides: Causes, Consequences and Environment*. London: Croom Helm.

D'Ecclesiis, G., Grassi, D., Merenda, L., Polemio, M. & Sdao, F. 1991. Evoluzione geomorfologica di un'area suburbana di Castronuovo S. Andrea (PZ) ed incidenza delle piogge su alcuni movimenti di massa. *Geologia Applicata e Idrogeologia*, XXVI: 141-163.

Dikau, R. & Schrott, L. 1999. The temporal stability and activity of landslides in Europe with respect to climatic change (TESLEC): main objectives and results. *Geomorphology*, 30, 1-2: 1-12.

Ferreira, A.B., Zêzere, J.L. & Rodrigues, M.L. 1987. Instabilité des versants dans la région au Nord de Lisbonne. Essai de cartographie géomorphologique. *Finisterra*, XXII, 43: 227-246.

Polemio, M. & Petrucci, O. 2000. Rainfall as a landslide triggering factor: an overview of recent international research. In E. Bromhead, N. Dixon & M.-L. Ibsen, (eds.), *Landslides in Research, Theory and Practice*, vol. 3, London, Thomas Telford: 1219-1226.

Polloni, G., Aleotti, P., Baldelli, P.& Nosetto, A. 1996. Heavy rain triggered landslides in the Alba area during November 1994 flooding event in the Piemonte Region (Italy). In Senneset (ed.), *Landslides, Proceedings of the 7th International Symposium on Landslides*, Rotterdam, Balkema: 1955-1960.

Van Asch, T., Buma, J. & VanBeek L. 1999. A view on some hydrological triggering systems in landslides. *Geomorphology*, 30, 1-2: 25-32.

Zêzere, J.L. 2000. Rainfall triggering of landslides in the Area North of Lisbon. In E. Bromhead, N. Dixon & M.-L. Ibsen, (eds.), *Landslides in Research, Theory and Practice*, vol. 3, London, Thomas Telford: 1629-1634.

Zêzere, J.L., Ferreira, A.B. & Rodrigues, M.L. 1999a. The role of conditioning and triggering factors in the occurrence of landslides: a case study in the area north of Lisbon (Portugal). *Geomorphology*, 30, 1-2: 133-146.

Zêzere, J.L., Ferreira, A.B. & Rodrigues, M.L. 1999b. Landslides in the North of Lisbon Region (Portugal): Conditioning and Triggering factors. *Physics and Chemistry of the Earth (Part A)*, 24, 10: 925-934.