LANDSLIDE INVENTORIES: HOW EVENT LANDSLIDE DATABASES CONTRIBUTE TO THE EVALUATION OF UNCERTAINTY ASSOCIATED WITH HISTORICAL LANDSLIDE INVENTORIES

Inventarios de deslizamientos: Como las bases de datos de deslizamientos pueden contribuir a evaluar la incertidumbre asociada a los inventarios de deslizamientos históricos

S. C. Oliveira [(1)], J. L. Zêzere [(1)], R. A. C. Garcia [(1)]

(1) RISKam – Centro de Estudos Geográficos. IGOT - Instituto de Geografia e Ordenamento do Território, Universidade de Lisboa (PORTUGAL). cruzdeoliveira@campus.ul.pt.

Resumen: La integridad de los inventarios de deslizamientos depende, sobre todo, de la disponibilidad de datos de inestabilidad. En el área de estudio de Rio Grande da Pipa, Arruda dos Vinhos, Portugal se han identificado 1434 deslizamientos. De éstos, 220 son de un evento de inestabilidad ocurrido en 1983 y 254 en 2010. Así nos proponemos: i) evaluar el ajuste del inventario global de deslizamientos y de los eventos citados a la de distribución de frecuencia empírica propuesta por Malamud *et al*. (2004), ii) evaluar la magnitud de los eventos de inestabilidad de 1983 y 2010, y iii) evaluar la incertidumbre asociada al inventario global (histórico). El mejor ajuste a la distribución empírica se ha obtenido para el inventario del evento de 1983. Se concluye también que el número de deslizamientos que se han perdido en el tiempo debe ser al menos de 7 veces superior a los asignados en el inventario total. También se concluye que en el reciente evento de inestabilidad de 2010, los deslizamientos aumentan en tamaño y frecuencia.

Key words: landslides inventories, frequency-area statistics, event magnitude, uncertainty.
Palabras clave: inventarios de deslizamientos, estadísticas de frecuencia-área, magnitud, incertidumbre.

1. INTRODUCTION

A large number of natural and technical factors affect the reliability of landslide inventories. Their completeness, more than the techniques/methods used, depends of the availability of data related to specific instability events. To determine the future number and size of landslides, over a region, a statistical analysis of their frequency-area distribution has been adopted worldwide. Malamud *et al*. (2004), among others, observed that event-based landslide inventories tend to adjust to a general frequency-area distribution, where medium and large landslides have an inverse power-law relation and the smaller landslides show an exponential rollover. Nevertheless, it is common sense that historical landslide inventories are generally incomplete. Furthermore, the degree of fitness of the landslides size/frequency to the empirical distribution has been attributed to natural and anthropogenic constraints (e.g., Van Den Eeckaut *et al*., 2007). One way of dealing with uncertainty associated to historical landslide inventories is to use event-based landslide inventories in order to estimate the total number of landslides that have been missed over time. With this work we intend to evaluate: i) the adjustment of the total landslide inventory and event-base landslide inventories to the empirical frequency-area distribution suggested by Malamud *et al*. (2004); ii) the magnitude of the 1983 and 2010 instability events; and iii) the uncertainty associated with the total landslide inventory.

2. STUDY AREA

The study area of Rio Grande da Pipa, Arruda dos Vinhos, Portugal (Fig. 1) is a small basin of 110 km^2, tributary of the Tagus River that stands out in the regional instability context of area north of Lisbon.
Elevation in the study area ranges from 440 m in the West sector to 5 m near the confluence with the Tagus River alluvial

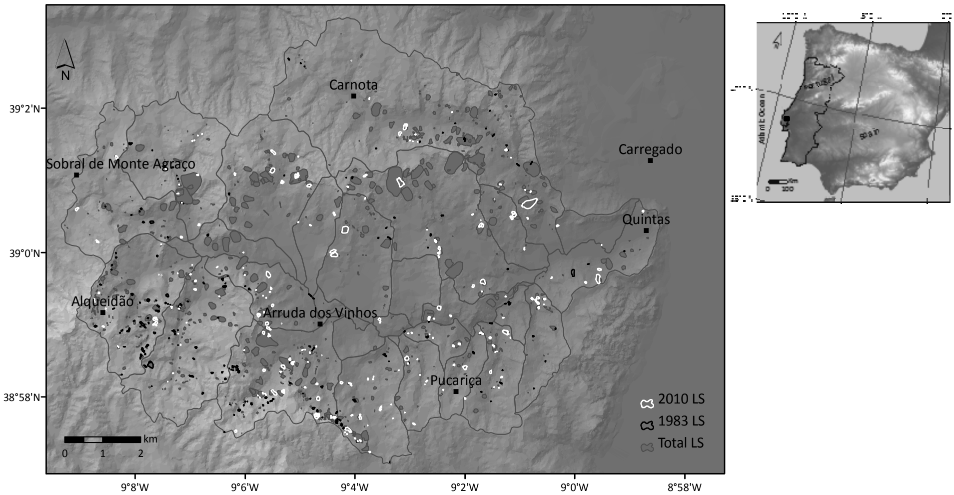

Fig. 1. Study area of Rio Grande da Pipa Basin, North of Lisbon (Portugal) and landslide inventories spatial distribution.

plain. The bedrock is mostly composed of sedimentary materials (e.g., limestones, marls, clays, sandstones). A tectonic rebound of a wide curvature angle defines the regional structure of the geological formations. Older rocks (marl and clay complex) cover approximately 58 % of the study area and lie in the center of the basin. The geomorphologic result is an erosive relief inversion. Above there is a belt of limestone cornices which are 20 m high and produce the steepest slopes in the basin. Nevertheless 87.5 % of the study area is characterized by gentle slopes under 15º.

3. METHODOLOGY AND DATA

3.1. Methods

The application of a probability density function ($p(A_L)$) to complete landslide inventories, independently of the triggering mechanism, has demonstrated worldwide that landslide frequency is strongly dependent on landslide area. According to Malamud *et al*. (2004), this probability density function ($p(A_L)$) can be assigned to a three-parameter inverse-gamma probability distribution ($p(A_L;\ \rho,\ a,\ s)$) expressed by Eq. 1. For further details on this methodology see Van Den Eeckaut *et al*. (2007).

$$p(A_L;\rho,a,s) = \left(\frac{1}{N_{LT}}\frac{\delta N_L}{\delta A_L}\right) =$$

$$\frac{1}{a\Gamma(\rho)}\left[\frac{a}{A_L - s}\right]^{\rho+1} exp\left[-\frac{a}{A_L - s}\right] \text{ (Eq. 1)}$$

Where: (A_L) is the area of landslide; (ρ) is a parameter that defines the power-law decay for medium and large size landslides;(a) is the parameter that controls the maximum distribution probability position; (s) is the parameter that controls the exponential rollover of landslides of smaller dimensions; (N_{LT}) is related to the total number of landslides in a specific inventory; ($\delta N_L/\delta A_L$) is the number of landslides related to a certain interval class of landslide area; and ($\Gamma(\rho)$) is the gamma function of (ρ). The parameters for the best fitted distribution obtained by Malamud *et al*. (2004) for the three landslide inventories triggered by different mechanisms, based on this inverse-gamma distribution were (ρ) = 1.4; (a) = $1.28\text{x}10^{-3}$ km^2, (s) = $-1.32\text{x}10^{-4}$ km^2. This distribution was assigned to an inverse power–law decay with an exponent -(ρ+1) for medium and large landslides of -2.4. In order to define the magnitude of the landslide event (M_L) based on the number of landslide cases in a particular instability event Malamud *et al*. (2004), proposed the application of Eq. 2.

$$M_L = \log 10\, N_{LT} \qquad \text{(Eq. 2)}$$

When landslide inventories are incomplete, the assumption of applicability of the landslide probability distribution allows the extrapolation of the unknown landslide number or area for a particular landslide event by calculating the frequency-density ($f(A_L)$) as follows:

$$f(A_L) = \frac{\delta N_L}{\delta A_L} = N_{LT}\, p(A_L) \qquad \text{(Eq. 3)}$$

The last term of Eq. 3 can be used to determine the theoretical curves of ($f(A_L)$) for different landslide-event magnitudes (Eq. 2) by multiplying the probability distribution ($p(A_L)$) obtained in Eq. 1 with the number of landslide occurrences associated to a certain landslide event (N_{LT}).

3.2. Landslide databases

A detailed field survey and the interpretation of aerial photographs and orthophotomaps helped identify 1434 landslides in the study area (Fig. 1). Based on the data summarized in Table 1, it is possible to determine that the unstable area affects almost 6.5 km^2 which corresponds to 5.86 % of the study area. Landslide density is 13 landslides/km^2. The database was split into two sub-sets based on landslide events with different critical rainfall amount/duration patterns.

Table 1. Landslide (LS) databases properties

Inventory	# LS	A_L (m^2)	% of study area
Total LS	1434	6484402.1	5.86
1983 LS	220	161412.8	0.15
2010 LS	254	511820.2	0.46

The 1983 event was triggered by 164 mm of rain in one single day, with a return period of 194 years. The 2010 event is associated with a long lasting rainfall accumulation, i.e. 632 mm of precipitation in 90 days, with a calculated return period of 8 years (Zêzere and Trigo, 2011).

4. RESULTS

First, the adjustment of Total LS and event landslide inventories (1983 LS and 2010 LS) to the empirical frequency-area distribution suggested by Malamud *et al*. (2004) were evaluated. Better results were obtained iteratively by controlling the inverse power–law decay for medium and large landslides based on the assumption that ($-(\rho+1)=-\beta$) (e.g., Van Den Eeckaut *et al*., 2007). Table 2 summarizes the Inverse Gamma parameters obtained.

Table 2. The three inverse-gamma distribution parameters of distribution functions based on β

Inventory	A_L(m^2)	β	β-1=ρ	*a*	*S*
Total LS	>±300	1.609	0.609	199.5	-70
1983 LS	>±300	2.148	1.148	310	-39.6
2010 LS	>±2000	1.880	0.880	335	-81

The hypothesis related to the distribution form was not rejected, according to the *Kolmogorov-Smirnov*´s test, for a significance level (α) of 20 % for the 1983 LS, of 5 % for the Total LS, and of 2 % for the 2010 LS. Figure 2 shows that the distribution of the 1983 LS is the one that best fits the theoretical distribution suggested by Malamud *et al*. (2004). In addition, it is clear that, if only the larger landslides are considered, the power-law decay adjusts better for all three landslide databases.

The second objective was to evaluate the magnitude associated to the 1983 and 2010 instability events. The criteria to determine (M_L) was based on the number of landslide occurrences in each instability event. Applying Eq. 2, results in M_L = 2.3 for the 1983 LS and M_L = 2.4 for the 2010 LS. From here it becomes possible to extrapolate the probable number of individual landslides and the corresponding unstable area.

It follows that evaluation about the uncertainty associated to historical landslide inventories (Total LS) is now possible.

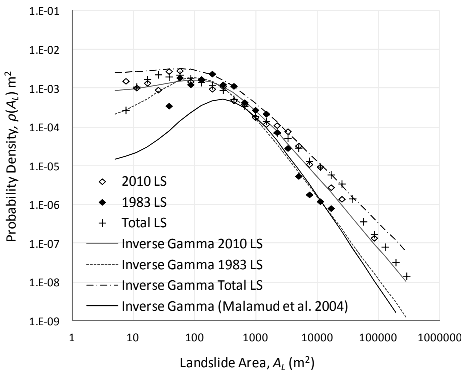

Fig. 2. Dependence of landslide probability densities on landslide area for three landslide inventories according to the three-parameter inverse-gamma distribution ($p(A_L; \rho, a, s)$) proposed by Malamud et al. (2004).

Similar to the work of Malamud *et al.* (2004), the 1983 instability scenario was selected and Eq. 2 applied in order to derive successive M_L lines (Fig. 3).

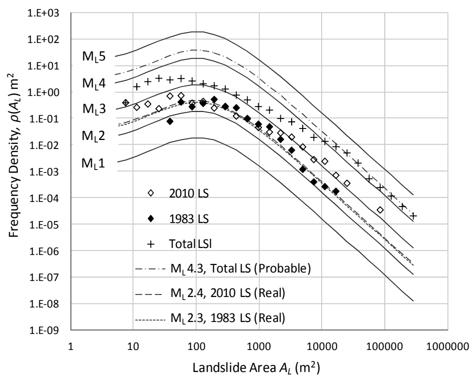

Fig. 3. Dependence of landslide frequency density on landslide area ($f(A_L)$). Magnitudes based on 1983 LS landslide frequency distribution.

It is clear that the adjustments of the calculated M_L for the 1983 and 2010 events are good, although a change in landslide pattern is evident in the 2010 event. In particular, it seems clear that for the most recent event (2010) landslides increase in size and frequency. In the case of Total LS, and considering the good adjustment of its distribution to landslides larger than 10,000 m^2, it is then possible to estimate, based in the uncertainty associated with M_L determination (M_L = 4 or 4.3), that Total LS should have a total number of landslides between 10,000 and 20,000. Even for the best scenario ($M_L = 4$), c. 8,500 individual landsides with an area smaller than 10,000 m^2 were erased through time.

5. CONCLUSIONS

This study contributes to the definition of uncertainty associated to the historical landslide inventory. Based on 1983 LS event it was estimated that the number of landslides erased from the landscape through time may be 7 times higher than the mapped landslides. It was also verified that during the recent 2010 landslide event, landslides increased in size and frequency.

Acknowledgements:
This work was done within the framework of Project Développement d'Outils pour le Suivi des Mouvements de Sols dans le but d'aider au développement durable de la région SUDOE, (DO-SMS- SOE1/P2/F157), Interreg IV B SUDOE. The first author was funded by a PhD Scholarship (SFRH/BD/31454/2006) from the Portuguese Foundation for Science and Technology (FCT).

REFERENCES

Malamud, B.D., Turcotte, D.L., Guzzetti, F. and Reichenbach, P. 2004. Landslide inventories and their statistical properties. *Earth Surface Processes and Landforms*, 29 (6), 687–711.

Van Den Eeckaut, M., Poesen, J., Govers, G., Verstraeten, G. and Demoulin, A. 2007. Characteristics of the size distribution of recent and historical landslides in a populated hilly region. *Earth and Planetary Science Letters*, 256, 588-603.

Zêzere, J.L. and Trigo, R. 2011. Impacts of the North Atlantic Oscillation on Landslides. Vicente-Serrano, S. and Trigo, R. (Eds.): *Hydrological, Socioeconomic and Ecological Impacts of the North Atlantic Oscillation in the Mediterranean Region, Advances in Global Change Research*, Vol. 46, Springer, 199-212.