Mediterranean Storms
(Proceedings of the 3rd EGS Plinius Conference held at Baja Sardinia, Italy, October 2001)

COMPARISON OF TWO LANDSLIDE TRIGGERING EVENTS USING FREQUENCY-AREA STATISTICS

Paola Reichenbach[1], Fausto Guzzetti[1], Bruce D. Malamud[2], Donald L. Turcotte[3]

(1) CNR-IRPI Perugia, via della Madonna Alta, 126, 06128 Perugia, Italy, email: p.reichenbach@irpi.pg.cnr.it & f.guzzetti@irpi.pg.cnr.it
(2) Department of Geography, King's College London, London WC2R 2LS, United Kingdom, email: bruce@malamud.com
(3) Department of Earth and Atmospheric Sciences, Cornell University, Ithaca NY 14853-1504, USA, email: turcotte@geology.cornell.edu

ABSTRACT

The assessment of the relative intensity of landslide events is of interest for understanding the geomorphological evolution of a landscape shaped by mass-wasting process, and for landslide hazard-assessment studies. We examine the frequency-area statistics of two landslide populations, one in the Umbria region (central Italy) and the other in the Liguria region (northern Italy), both triggered by extreme climatological events. Landslides in Umbria were caused in January 1997 by a rapid snow-melting event and identified through medium-scale aerial photographs, supplemented by field mapping. A total of 4233 shallow and deep-seated landslides, covering 12.7 km^2, were mapped in an area of about 2000 km^2. Landslides in Liguria were caused by high-intensity rainfall in November 2000. A total of 1024 slope failures, covering 1.6 km^2 and mostly soil-slips and debris flows, were identified from large-scale aerial photographs. For landslides exceeding a minimum area, both landslide data sets show a robust frequency-area power-law (fractal) relationship. Below this minimum area, both data sets show the same deviation from the power-law fit. We discuss ways of comparing the relative intensity of the two data sets, showing that power-law statistics can provide the basis for quantifying triggered landslide events.

1 INTRODUCTION

Landslides are triggered by many different causes, including intense or prolonged rainfall, snowmelt and earthquakes, and they can occur individually or in groups of thousands simultaneously. In nature, landslide areas have been documented to span more than eight orders of magnitude and landslide volumes more than ten. Landslide velocities extend over fourteen orders of magnitude, from millimetres per year to hundreds of kilometres per hours. Despite the large differences in landslide types, sizes, distributions, and pattern and triggering mechanisms, there is increasing evidence that landslides obey power-law (fractal) frequency-size relationships (*Whitehouse & Griffiths,* 1983; *Ohmori & Hirano,* 1988; *Sasaki et al.,* 1991; *Yokoi et al.,* 1995;

Pelletier et al., 1995; *Hovius et al.,* 1997; *Malamud & Turcotte,* 1999; *Dai & Lee,* 2001; *Stark & Hovius,* 2001; *Guzzetti et al.,* 2001).

We compare the frequency-area statistics of two landslide populations, in the Umbria (central Italy) and Liguria (northern Italy) regions, both triggered by extreme climatological events. We show that the two landslide inventories follow robust power-law (fractal) relationships for landslides that exceed a minimum length scale, and we use the power-law relationship to compare two landslide events.

2 FREQUENCY-AREA STATISTICS

The frequency-area statistics of landslides can be presented using either cumulative or non-cumulative statistics (*Malamud and Turcotte,* 1999; *Guzzetti et al.,* 2001). With cumulative statistics, the cumulative number of landslides N_{CL} with areas greater than or equal to landslide area A_L is plotted as a function of A_L (**EQ.** 1)

$$N_{CL} = CA_L^{-\alpha} \tag{1}$$

where, α is the power-law exponent and C a constant. In a log-log plot (**EQ.** 1) is a straight line, with α the slope of the best-fit line, and C the y-axis intercept. The equivalent non-cumulative frequency-area distribution for (**EQ.** 2) is given by

$$-\frac{dN_{CL}}{dA_L} = C' A_L^{-\beta} \tag{2}$$

with β the power-law exponent, and C' a constant.

3 SNOW-MELT INDUCED LANDSLIDES IN UMBRIA, DATA SET A

During the last week of December 1996 a large snowstorm covered the Umbria region with 40–100 cm of snow, with average air temperatures well below 0 °C. From the night of 31 December 1996 to the morning of 1 January 1997, a sudden rise in the air temperature melted most of the snow. The rapid snowmelt caused a minor flood along the upper Tiber River and its tributaries, and triggered thousands of landslides (*Cardinali et al.,* 2000).

In the weeks immediately after the event, a reconnaissance survey was performed and a preliminary landslide inventory map was prepared. In April 1997, 400 stereoscopic aerial photographs at 1:20,000 nominal scale and covering 1500 km^2, were taken in the areas most affected by the landslides. The interpretation of the aerial photographs allowed refining and updating the landslide inventory for the areas where the photographs were taken, and confirmed the relative abundance of the landslide types recognized in the field. Landslides were mostly shallow soil-slips (53%) and slump earth-flows (9%). Deep-seated failures (38%) comprised complex or compound movements.

The final inventory map (data set A) covers an area of about 2000 km^2 and has 4233 landslides, for a total landslide area of 12.7 km^2 (0.6% of the study area). This corresponds to an average density of 2.1 landslides/km^2. Locally, landslide density was much higher, exceeding 30 landslides/km^2.

Figure 1 shows the frequency-area distribution of the landslide areas. The smallest landslide (a soil slip) has an area of a few tens of square meters ($A_L = 3.95\times10^{-5}$ km^2), and the largest mapped landslide (a deep-seated, complex slide) has an area of several hectares ($A_L = 1.56\times10^{-1}$ km^2). The average landslide area is $A_L = 3.01\times10^{-3}$ km^2. The most frequent landslide area is about $A_L = 0.8\times10^{-4}$ km^2, corresponding to an average linear dimension $A_L^{1/2} \approx 28$ m. The later is computed assuming a landslide aspect ratio close to one. Due to the freshness of the snowmelt triggered landslides, and the quality and scale of the aerial photographs, the smallest landslide area consistently mapped is about 2.5×10^{-4} km^2 ($A_L^{1/2} \approx 16$ m).

Figures 2 show the non-cumulative frequency-area distribution of the 4233 landslide areas triggered by snow melting (data set A). *Guzzetti et al.* (2001) showed that for $A_L > 2\times10^{-3}$ km^2, the non-cumulative distribution of these landslide areas correlates well with a power-law relation (**EQ.** 2), taking $\beta = 2.5$ and $C' = 0.3$ (A_L in km^2).

4 RAINFALL INDUCED LANDSLIDES IN LIGURIA, DATA SET B

From mid-October to 22 November 2000, the western part of the Liguria region (northern Italy) experienced prolonged and intense rainfall, with cumulative rainfall values for a 45 days period exceeding 1000 mm. At the end of this very wet period, on 23–24 November 2000, an intense rainfall event hit the coast of the Ligurian Sea. More than 190 mm of rainfall were recorded in less than 12 hours at Imperia.

The high-intensity rainfall caused flooding and triggered several hundreds landslides. In January 2001, about 45 days after the event, aerial photographs were taken in the areas most affected by the landslides and floods. Two flights obtained 334 stereoscopic, colour aerial photographs at nominal scales of 1:13,000 and 1:5000, covering about 500 km^2.

Through aerial photograph interpretation, an inventory of all landslides triggered by the high-intensity rainfall event was prepared (data set B). The most abundant landslides (95% of the total number) were shallow soil-slips and debris flows. Some of these were very large, involving considerable volumes of material, and travelling long distances (up to 1.5 km). A few deep-seated landslides, comprising slump earth-flows, complex or compound movements, were also observed. Due to the freshness of the rainfall induced landslides, and the quality and scale of the aerial photographs, the smallest landslide area consistently mapped is about $A_L = 1.5\times10^{-4}$ km^2 ($A_L^{1/2} \approx 12$ m). The landslide inventory map contains 1024 landslides, for a total landslide area of about 1.6 km^2 (0.3% of the study area). This is equivalent to an average density of 2.1 landslides/km^2. Locally, landslide density was much higher, exceeding 50 landslides/km^2.

Figure 1 shows the frequency-area distribution of the landslide areas. The smallest landslide (a soil slip) has an area of few tens of square meters ($A_L = 4.92\times10^{-5}$ km^2), and the largest mapped landslide (a deep-seated slide) has an area of a few hectares ($A_L = 7.10\times10^{-2}$ km^2). The average landslide area is $A_L = 1.33\times10^{-3}$ km^2. The largest number of landslides have an area $A_L = 5\times10^{-4}$ km^2, corresponding to an average linear dimension $A_L^{1/2} \approx 22$ meters. Figure 2 shows the non-cumulative frequency-area distributions of the 1024 landslides areas triggered by the intense rainfall (data set B).

The non-cumulative distribution correlates well with a power-law relation (EQ. 2), taking $\beta = 2.2$ and $C' = 0.11$ (A_L in km^2), for landslides with $A_L > 5\times10^{-4}$ km^2.

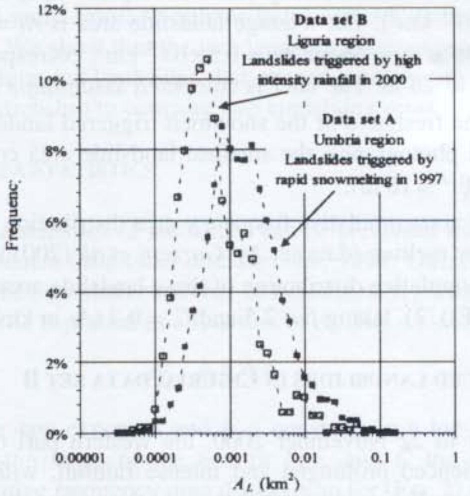

Figure 1. Frequency-area distributions of landslide areas in Umbria (data set A) and Liguria (data set B). The *x*-axis (landslide area, A_L) is logarithmic.

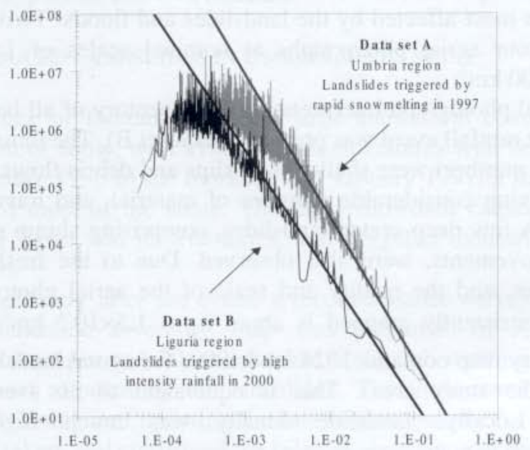

Figure 2. Non-cumulative frequency-area statistics of landslide areas in Umbria (data set A) and Liguria (data set B).

5 Data sets comparison

The frequency-area statistics of both data sets follow a robust power-law scaling for the medium and large landslides, with best-fit power-law exponents (**Eq.** 2) of $\beta = 2.5$ (data set A) and $\beta = 2.2$ (data set B). The deviation from the power law scaling occurs at about $A_L < 2\times10^{-3}$ km^2 and $A_L < 5\times10^{-4}$ km^2, respectively. The slopes found are comfortably in the range $\beta = 2.5 \pm 0.5$, values reported by *Guzzetti et al.* (2001) for many different world-wide landslide inventories over a broad variety of physiographic and climatic regions.

Figure 2 suggests a characteristic dimension (length-scale) for which landslides are most frequent, i.e. the position at which the rollover occurs. Figure 2 also shows that this dimension is slightly different for the two data sets: larger for data set A ($A_L \approx 8\times10^{-4}$ km^2 or $A_L^{1/2} \approx 28$ m), and smaller for data set B ($A_L \approx 5\times10^{-4}$ km^2 or $A_L^{1/2} \approx 22$ m). The difference in the length scales is small ($\approx 20\%$), but may be indicative of different geomorphological settings. Soils are thicker in Umbria, and slopes are steeper in Liguria. Landslide types were also slightly different. In Umbria, possibly due to the geotechnical properties of the clay-rich soils (*Cardinali et al.*, 2000; *Guzzetti et al.*, 1996), soil slips stopped shortly after failures and did not mobilize into debris flows, as was the case in Liguria. Additionally, the snowmelt that triggered landslides in Umbria probably produced a slower (and possibly larger) infiltration of water into the soil than in Liguria, where infiltration was quicker, due to the high rainfall intensity. More research is needed to understand the geomorphological reasons for the rollover.

Interestingly, both frequency-area distributions (Figure 1) exhibit primary maximum values ($A_L \approx 8\times10^{-4}$ km^2 and $A_L \approx 5\times10^{-4}$ km^2) and secondary maximum values ($A_L \approx 0.8\times10^{-3}$ km^2 and $A_L \approx 1\times10^{-3}$ km^2). Data set B also exhibits a third maximum, at $A_L \approx 8\times10^{-3}$ km^2. The relative maximums can certainly be attributed to sampling or binning problems, but may also represent inherent characteristics of the two data sets, related to different landslide types or terrain characteristics.

We can attempt a comparison of the two data sets. Comparing total landslide area (12.7 km^2 vs. 1.6 km^2, or 8:1) would suggest that the Umbria event was 8 times larger than the Liguria event. Comparing the percentage of the study area affected by landslides (0.6% vs. 0.3%, or 2:1) would indicate that the snowmelt event was twice as severe as the rainfall event. Comparing the average number of landslide per km^2 (2.1 vs. 2.1, or 1:1) would suggest that the two events had the same intensity. The last two comparisons are inappropriate because the two study areas may include zones that were affected by landslides (i.e., flood plains, valley bottoms, flat mountain tops) in differing percentages. Taking the number of triggered landslides (4233 vs. 1024, or 4:1) may also be inappropriate if the two data sets are not complete.

We suggest that a more reliable way of comparing the two data sets is to compare their power-law scaling (*Guzzetti et al.*, 2001). Let us assume that both data sets are complete for medium and large landslides (the right part of the tail). Evidence that this is true comes from field observations. Let us also assume the power-law relations for datasets A and B are the same (within the error bars). Comparing the C' values (**Eq.** 2) for both distributions (0.30 vs. 0.11) gives a ratio of 3:1. Since the area under the two frequency-area distributions represents the relative total landslide area for each data set, changing C' by 3 is the same as changing the area under the frequency-area curve by a factor of 3. Therefore, based on the frequency-area distributions, the snowmelt-triggered landslide event in Umbria was 3 times more intense than the rainfall-triggered landslide event in Liguria. Since the two data sets are both reasonably complete, this is not very different than comparing the number of landslides mapped in both data sets (4:1).

Acknowledgements. This work has been supported by NASA grant NAG5-9067. The paper is CNR-GNDCI Publication No. 2448.

References

Cardinali, M., Ardizzone, F., Galli, M., Guzzetti, F., & Reichenbach, P. Landslides triggered by rapid snow melting: the December 1996–January 1997 event in Central Italy, *Proceedings of the 1st Plinius Conference on Mediterranean Storms*, Maratea, Italy, 14–16 October 1999, edited by Claps P., and Siccardi F., Bios Pub., Cosenza, 2000, 439–448.

Dai, F. C., & Lee, C. F. Frequency-volume relation and prediction of rainfall-induced landslides, *Eng. Geol*. 59, 2001, 253–266.

Guzzetti, F., Malamud, B.D., Turcotte, D.L., & Reichenbach, P. Power-law correlations of landslide areas in Central Italy. *Earth and Planetary Science Letters*, 2001, in press.

Hovius, N., Stark, C.P., & Allen, P.A. Sediment flux from a mountain belt derived by landslide mapping, *Geology* 25, 1997, 231–234.

Malamud, B.D., & Turcotte, D.L. Self-organized criticality applied to natural hazards, *Natural Hazards* 20, 1999, 93–116.

Ohmori, H. & Hirano, M. Magnitude, frequency and geomorphological significance of rocky mud flows, landcreep and the collapse of steep slopes, *Zeit. Geomorph. Supple*. 67, 1988, 55–65.

Pelletier, J.D., Malamud, B.D., Blodgett, T., & Turcotte D.L. Scale-invariance of soil moisture variability and its implications for the frequency-size distribution of landslides, *Eng. Geol*. 48, 1997, 255–268.

Sasaki, Y., Abe, M., Hirano, I. Fractal of slope failure size-number distribution, *J. Jap. Soc. Eng. Geol*. 32, 1991, 1–11.

Stark, C.P., & Hovius, N. The characterization of landslide size distributions, *Geophys. Res. Lett*., 28, 2001, 1091–1094.

Whitehouse, I. E. & Griffiths, G.,A. Frequency and hazard of large rock avalanches in the central Southern Alps, New Zealand, *Geology* 11, 1983, 331–334.

Yokoi, Y., Carr J.R., & Watters, R.J. Fractal character of landslides, *Env. Eng. Geol*. 1, 1995, 75–81.