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COMPARISON OF THREE LANDSLIDE EVENT INVENTORIES IN CENTRAL AND NORTHERN ITALY

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ABSTRACT

Evidence exists that the statistics of landslides triggered by extreme natural events exhibit a "universal" behaviour, where for increasing landslide area, the frequency of landslides increases to a maximum value and then decreases following a power law. This allows us to make quantitative comparisons of populations of triggered landslide events obtained from landslide inventory maps. We first discuss the characteristics and limitations of landslide inventory maps, followed by a presentation of three recent landslide event inventories in central and northern Italy. For each inventory, we calculate the probability and frequency densities of landslide areas, compare these results to each other and with the "universal" landslide distribution, and finally estimate each inventory's landslide event magnitude.

1 INTRODUCTION

Earthquakes, rapid snowmelts, and high-intensity or prolonged rainfalls are each examples of triggers that can result in a few to many thousands of landslides. There is increasing evidence that the frequency-area statistics of the resultant landslide population exhibits a "universal" frequency-area probability distribution, where for increasing landslide areas, the frequency of landslides increases rapidly to a maximum value, where landslides are most abundant, and then decays following a power law (*Stark and Hovius*, 2001; *Guzzetti et al.*, 2002B). This "universal" probability landslide distribution can be used to compare and characterize different landslide inventories. In this paper, we use frequency and probability densities to compare and quantify three recent landslide inventories in central and northern Italy.

2 LANDSLIDE INVENTORIES

A landslide inventory is the simplest form of landslide mapping. For a given area, a landslide inventory map portrays the location and, where known, the date of occurrence and the type of landslides (*Hansen*, 1984). Inventory maps are prepared using different techniques, depending on the goals, the extent of the study area, the scale of the maps, and the resources available. Landslide inventory maps may show all the slope failures as the result of a single trigger, such as an earthquake, a rainstorm or a rapid snowmelt (event inventories), or they can show the cumulative effects of many landslide events over a period of several hundreds or even thousands of years (historical inventories). Usually a single map is used to portray different types of landslides; alternatively, a set of maps can be prepared, each map showing a different type of failure (*Guzzetti et al.*, 1999).

Completeness and resolution are two issues to consider when using a landslide inventory map. Completeness is the extent to which the inventory portrays the actual distribution of landslides. For landslide event inventories, completeness is the percentage of slope failures that are recognized and mapped with respect to the total number of landslides that actually occurred. Resolution defines the smallest landslide consistently recognized and mapped. Many factors affect the completeness and resolution of a landslide inventory, including (1) landslide freshness, (2) quality and scale of the aerial photographs and of the base maps, (3) presence of forest coverage, (4) morphological and geological complexity of the study area, and (5) the skill of the geomorphologist. Good quality event inventories should be reasonably complete, at least in the areas for which aerial photographs were available and/or where it was possible to perform field work. Landslide event inventories often cover only a partial part of the total geographic area associated with the landslide triggering event. Historical inventories are never complete, for two reasons: (1) the evidence for the existence of landslides is rapidly removed by erosion (including new landslides), growth of vegetation, and human activity and (2) with time, the boundary of a landslide becomes increasingly fuzzy, making it difficult (or impossible) for the geomorphologist to identify and map it precisely.

3 LANDSLIDE DATASETS

We now present three Italian landslide event inventories. The three inventories, representative of the landslide types and range of triggers in central and northern Italy, were prepared through the interpretation of medium- or small-scale aerial photographs taken a few weeks after the triggering event, and then supplemented by field surveys.

3.1 Dataset A: January 1997, snowmelt induced landslides in the Umbria region, Central Italy

In December 1996, a large snowstorm covered the Umbria region with a thick snow cover. A sudden change in temperature melted the snow, triggering thousands of shallow and deep-seated landslides (*Cardinali et al.*, 2000). Slope failures were mostly shallow soil-slips (53%) and slump earth-flows (9%). Deep-seated failures (38%) comprised complex or compound movements. The inventory map covers about 2,000 km^2 and contains 4,233 landslides. The total area of inventory landslides is 12.7 km^2 (0.6% of the study area) with average density 2.1 landslides per km^2. The inventory's smallest landslide is a soil slip with area $A_L = 3.9\times10^{-5}$ km^2 (39 m^2), and the largest landslide is a deep-seated slide with $A_L = 1.6\times10^{-1}$ km^2 (16 ha) (Table 1).

3.2 Dataset B: November 2000, rainfall induced landslides in the Imperia province, Northern Italy

On 23 November 2000, a sudden and intense rainfall occurred on the coast of the Liguria Sea, with 200 mm of rain over 12 hours, triggering several hundred landslides (*Guzzetti et al., 2002A*). Landslides were primarily shallow soil slips (59%) and debris flows (35%). The few deep-seated failures (6%) were slump-earth flows and complex slides. The inventory map covers about 500 km^2 and contains 1,024 landslides. The total area of inventory landslides is 1.6 km^2 (0.3% of the study area) with average density 2.0 landslides per km^2. The inventory's smallest landslide is a soil slip with $A_L = 4.9\times10^{-5}$ km^2 (49 m^2), and the largest landslide a deep-seated slide with $A_L = 7.2\times10^{-2}$ km^2 (7.2 ha) (Table 1).

3.3 Dataset C: November 1994, rainfall induced landslides in the Tanaro River basin, Northern Italy

During November 1994, high intensity and prolonged rainfall triggered thousands of shallow and deep-seated landslides in the Piedmont region (*Regione Piemonte,* 1998). Following the event, *Aleotti et al.* (1996) mapped landslides in areas where landslides were most abundant, the Seno d'Elvio, Cherasca, Talloria and Rea catchments, four tributaries of the Tanaro River. Landslides were chiefly (92.3%) shallow soil slips, debris slides and debris flows. The remaining landslides (7.7%) were deep-seated block slides. The inventory map covers about 260 km^2 and contains 1,289 landslides. The total area of inventory landslides is 2.6 km^2 (0.7% of the study area) with average density 5.0 landslides per km^2. The inventory's smallest landslide is a soil slip with $A_L = 4.8\times10^{-5}$ km^2 (48 m^2), and the largest landslide is a deep-seated block slide with $A_L = 1.2\times10^{-1}$ km^2 (12 ha) (Table 1).

3.4 Completeness of the event inventories

The three landslide inventories cover different areas, 350–2,000 km^2, and average densities range from 2.0–5.0 landslides per km^2 (Table 1). Due to the freshness of the landslides when preparing the inventories, and the quality and scale of the available aerial photographs, the smallest landslides consistently represented in the three maps is very small, smaller than the size for which landslides were most abundant (the "rollover") in each of the three inventories.

Table 1. Comparison of the three landslide event inventories. N_{LT} is total number of landslides; A_{LT} is total landslide area; A_{Lmin}, A_{Lmax} and $\bar{A}_L$ are minimum, maximum and average landslide area, respectively; d_L is density, # of landslides per km^2; M_L is the landslide-event magnitude.

DATASET	EVENT LOCATION	EVENT TRIGGER	EVENT YEAR	MAPPED AREA	INVENTORY STATISTICS						LANDSLIDE-EVENT MAGNITUDE
				km^2	N_{LT} #	A_{LT} km^2	A_{Lmin} km^2	A_{Lmax} km^2	$\bar{A}_L$ km^2	d_L $\#/km^2$	M_L
A	**Umbria** region	snowmelt	1997	~2,000	4,233	12.7	3.9×10^{-5}	1.6×10^{-1}	3.0×10^{-3}	2.1	3.6
B	**Imperia** province	rainfall	2000	~500	1,024	1.6	4.9×10^{-5}	7.2×10^{-2}	1.3×10^{-3}	2.0	3.0
C	**Tanaro** basin	rainfall	1994	~260	1,289	2.6	4.8×10^{-5}	1.2×10^{-1}	2.2×10^{-3}	5.0	3.1

The three landslide inventories are recent and detailed, and are considered substantially complete by the authors (*Aleotti et al.*, 1996; *Cardinali et al.*, 2000; *Guzzetti et al.*, 2002A), i.e., only a very small percentage of landslides that actually occurred are missing from the inventories. However, the study areas themselves differed in their ability to record the full spatial extent of the landslide event. For Dataset A, in the Umbria region, a few landslides were reported outside of the study area. Additionally, aerial photographs were not available for the entire study area, and field surveys were completed to fill the gaps. Nonetheless, the inventory covers most of the territory where landslides were induced by the rapid snow melting. For Dataset B, in the Imperia province, aerial photographs were taken only along the coast and main valleys. Fortunately, due to the local geomorphological setting, these areas are where the largest percentage (>95%) of landslides occurred. A few small shallow landslides recognized in France are not included in the inventory.

Dataset C, in the Tanaro River basin, is more problematic. The inventory covers only a fraction of the total region affected by the intense rainfall, but this fraction is where landslides were most abundant (*Regione Piemonte*, 1998). Dataset C is therefore representative of the different landside types that occurred in the Piedmont region during November 1994, but is not entirely representative of the spatial distribution and frequency of landslide areas triggered.

Another difference between the three inventories is the technique used to estimate the landslide areas. For Datasets A and B, information obtained from aerial photographs or in the field was transferred on the base maps and successively digitized and stored in a GIS layer, from which the area of each landslide was then obtained. For Dataset C, the length and width of each landslide was estimated from aerial photographs and in the field, and the information stored into a database. The area of each landslide was then obtained by multiplying each landslide's width and length.

4 FREQUENCY-AREA STATISTICS AND LANDSLIDE EVENT MAGNITUDE

We now compare the three landslide event inventories using frequency-area statistics. *Reichenbach et al.* (2002) used non-cumulative, frequency-size statistics of landslide areas to compare the snowmelt-induced landslides in Umbria (Dataset A) with the rainfall-induced landslides in Imperia (Dataset B). We introduce a more rigorous approach based on the probability densities of landslide area, $p(A_L)$, and we compare these two inventories (Datasets A and B) with the new inventory of rainfall-induced landslides obtained for the Tanaro River (Dataset C).

Figure 1A shows, in log-log space, the probability densities computed for the three datasets. The distributions exhibit the typical trend of frequency-area distributions of landslides (*Stark and Hovius*, 2001; *Guzzetti et al.*, 2002). The abundance of slope failures increases with the landslide area up to a maximum value, where landslides are most frequent, then it decays along a power law. The slope of the power law tail is about –2.4.

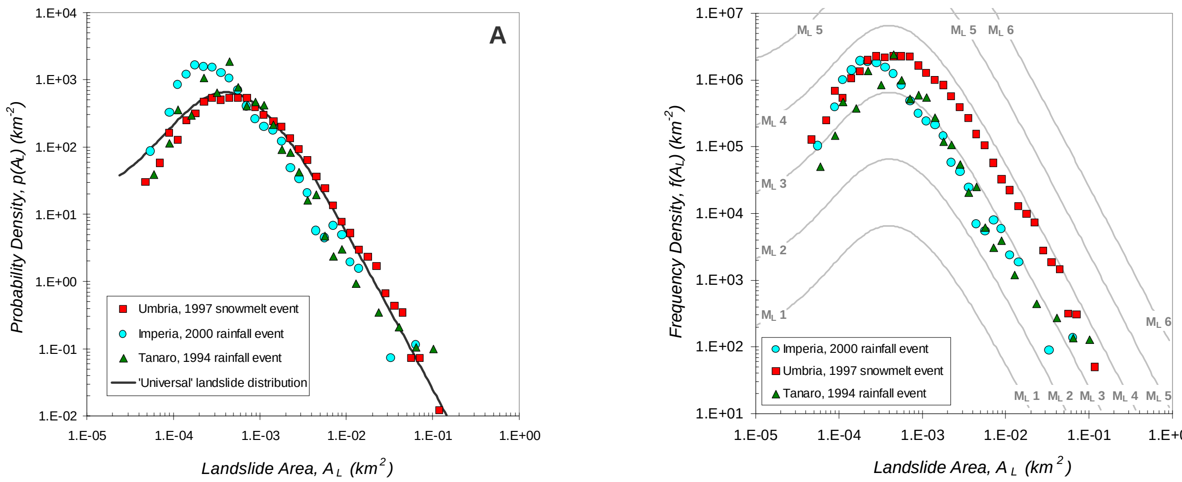

Figure 1. (A) Probability density, $p(A_L)$, as a function of landslide area A_L (km^2), plotted on logarithmic axes. *Dataset A (red squares)*: 4,233 landslides triggered by snowmelt in January 1997 in the Umbria region. *Dataset B (blue circles)*: 1,024 landslides triggered by rainfall in Imperia province. *Dataset C (green triangles)*: 1,289 landslides triggered by rainfall in the Tanaro River basin. *Grey line*: "universal" landslide probability distribution (*Malamud et al.*, 2002). (B) Frequency density, $f(A_L)$, as a function of landslide area (km^2), plotted on logarithmic axes. *Grey lines*: landslide magnitude curves, M_L = 1–6. Other symbols as in part A.

The probability densities for the three landside inventories (Figure 1A) are in reasonably good agreement with each other. The size of the most abundant landslides (the "rollover") ranges from $A_L = 2.2\times10^{-4}$ km^2 (~15×15 m^2) for the Imperia inventory to 4.7×10^{-4} km^2 (~22×22 m^2) for the Umbria inventory. This is not a significantly large difference considering the complexity of the landslide phenomena, and the errors and uncertainty associated with the identification and mapping of landslides from the aerial photographs or in the field. In both cases, the resolution, or area of landslides consistently mapped, is below this rollover.

The probability densities shown in Figure 1A can be fit by different functions, including a double Pareto (*Stark and Hovius*, 2001) and an inverted Gamma (*Malamud et al.*, 2002). The line in Figure 1A portrays a "universal" inverted gamma distribution obtained by *Malamud et al.* (2002) when they fit three (including Dataset A from this paper) high-quality and substantially complete landslide event inventories from different physiographic regions in the world. Datasets B and C follow reasonably well the "universal" distribution for the larger landslides, i.e., a power law tail with exponent –2.4, and deviate for the area for which landslides are most abundant. Hence, the "universal" curve predicts fewer smaller landslides than what was actually recorded in Datasets B and C. For Dataset C, this may be partly due to a censoring effect connected with the technique used to estimate the landslide areas. For Dataset B, the higher frequency of small landslides is real. The "universal" curve also predicts an average landslide area (0.00307 km^2 or

~55×55 m^2) slightly larger than what was observed in the two datasets, i.e., 0.00133 km^2 (~36×36 m^2) for Dataset B, and 0.00202 km^2 (~45×45 m^2) for Dataset C.

Malamud et al. (2002) used the "universal" landslide distribution (thick grey line in Figure 1A) to introduce a landslide hazard scale for landslide events. They propose that the magnitude of a landslide event is the logarithm of the total number of landslides triggered by the event, i.e., $M_L = \log(N_{LT})$. The definition assumes that the event inventory used to estimate the landslide magnitude is substantially complete. Our three event inventories, which are substantially complete (with the limitations outlined in section 3.4) have landslide-event magnitudes $M_L = 3.6$ for the Umbria region snowmelt event, $M_L = 3.0$ for the Imperia province rainfall event, and $M_L = 3.1$ for the Tanaro River basin rainfall event (Table 1). Figure 1B portrays the frequency densities of the three inventories as a function of landslide area. The frequency density is the number of landslides in a given bin, divided by that bin size. However, the probability density is the frequency density divided by the total number of landslides in the inventory (N_{LT}), and assumes that the distribution is substantially complete. In addition to frequency densities, Figure 1B shows different "universal" curves, corresponding to landslide-event magnitudes M_L=1–6.

The given definition of landslide-event magnitude does not include the extent of the study area or the extent of the area associated with the triggering event. Care should be taken when comparing landslide-event magnitudes obtained from inventories that cover very different areas or that are not representative of the full extent of the region affected by a trigger, i.e., a rainstorm or a snowmelt.

5 CONCLUSIONS

We use probability densities of landslide areas to compare three event inventories recently prepared for areas affected by severe meteorological events in central and northern Italy. The three distributions exhibit a characteristic landslide-event frequency-area distribution, i.e., the abundance of landslides rapidly increases with increasing landslide area to a maximum value, then decreases as a power law function with exponent –2.4. The three distributions compare reasonably well with the "universal" frequency-area distribution recently proposed by *Malamud et al*. (2002). The "universal" distribution predicts fewer small landslides and an average landslide area slightly larger than what was observed in our event inventories. The three substantially complete landslide inventories have landslide-event magnitudes M_L = 3.0–3.6.

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