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Assessing landslide risk through unique condition units

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ABSTRACT: Some 10,000 landslides from a territory of about 1000 km^2 extending over part of Campania and Basilicata regions, Italy, have been inventoried and stored in a GIS-database. Geolithological and geomorphological maps, as GIS-overlays, were used to produce the homogeneous domains for the statistical analysis. Such domains represent specific mapping units, the Unique Condition Units (UCU), which define the classification of each slope-instability factor into a few significant classes stored into a single map, or layer. After the integration of the UCU with the Landslide-inventory map, the susceptibility assessment is then extended to landslide-free areas by applying a statistical method. Finally, a Landslide Risk map is produced by overlaying Susceptibility and Maximum Expected Damage layers. Following the description of the procedure adopted and the main results obtained, some final considerations are offered.

1 INTRODUCTION

The 2008 official report on landslides in Italy inventoried more than 480,000 events, with a density of 1.6 events per km^2 (ISPRA 2008). These data, stored into the Italian Landslide Inventory (IFFI Project), are continuously integrated and updated by Italy's River Basin Authorities (RBAs), which are the reference territorial entities charged with land planning and management. The main goal of RBAs is pursued through the Basin Plan, a comprehensive planning act structured through specific plans such as the one aimed at downgrading the landslide and flood risk (Hydraulic-geological Setting Plan—HSP).

Italian laws rank risk in four grades, from R4 (very high) to R1 (low). However, these laws do not prescribe the procedure to be followed in order to define the basic factors crucial for the risk assessment, i.e. hazard and vulnerability. As a consequence, a variety of methods have been used by the various RBAs to classify the Italian territory in terms of landslide hazard. Landslide hazard assessment requires not only identification of landslide-prone areas but also determination of the temporal probability of slope failure (IAEG 1984). However, in Italy practically all the official maps showing areas threatened by landslides can not be considered as true hazard maps because the probability of occurrence of landslides is not taken into account. Hence, according to Brabb (1984), they should be considered as landslide susceptibility maps.

Moreover, Italian laws state that HSPs should be revised periodically, but, due to chronic paucity of funds, this was enforced only recently. Such revisions are fundamental especially in those regions where, for various reasons (methods adopted, time allowed, logistic difficulties, etc.), the inventoried data underestimate the actual instability conditions. This is largely the case for Campania and Basilicata, two neighbouring regions in southern Italy, where, at present, about 23,000 and 9000 landslides have been identified.

In this paper, a methodology for the landslide risk assessment is presented, which has been applied to a part of the Sele River Basin, extending over both Campania and Basilicata regions.

2 PHYSICAL SETTING

Seven lithological complexes crop out in the study area (Fig. 1), where some formations and/or tectono-stratigraphical units are grouped according to their geological history and/or position (Patacca & Scandone 2004; Allocca et al. 2005; Bonardi et al. 2009). The highest and innermost units (no. 7 in Fig. 1), are part of allochtonous sheets (Liguride and Sicilide Complexes), mostly ocean-derived that were piled up to form an accretionary wedge during the Early Miocene. Units grouped under complexes nos. 5 and 6 share a lower structural position, being represented by Mesozoic-Tertiary sedimentary sequences derived from platform-and-basin paleogeographic domains. After the main orogenic phases, dated to upper Miocene, further clastic formations (nos. 3 and 4 in Fig. 1) were emplaced both in internal areas and on the chain front showing characters of thrust-top sequences and resting unconformably on the above units. The lithostratigraphical succession is closed by marine, transitional and continental deposits (nos. 1 and 2 in Fig. 1), which are ubiquitous over the study area.

The highly variable landscape of the study area, extending from the Tyrrhenian Sea to some of the highest peaks of the southern Apennines, can be described by a few Large Geomorphological Units (LGU), i.e. large portions of territory characterized by quite homogeneous morphological features (Cinque & Romano 2001; Guida 2001). Accordingly, four LGUs can be recognized: carbonate terrain, hilly terrain, coastal plains and intra-mountain depressions.

The *carbonate terrain* occupies the backbone of the southern Apennines reaching elevations between 1500 and 2000 m asl. This unit is characterised by first-order NW-SE and NE-SW trending faults, which, in turn, delineate a number of monoclines. In the northernmost

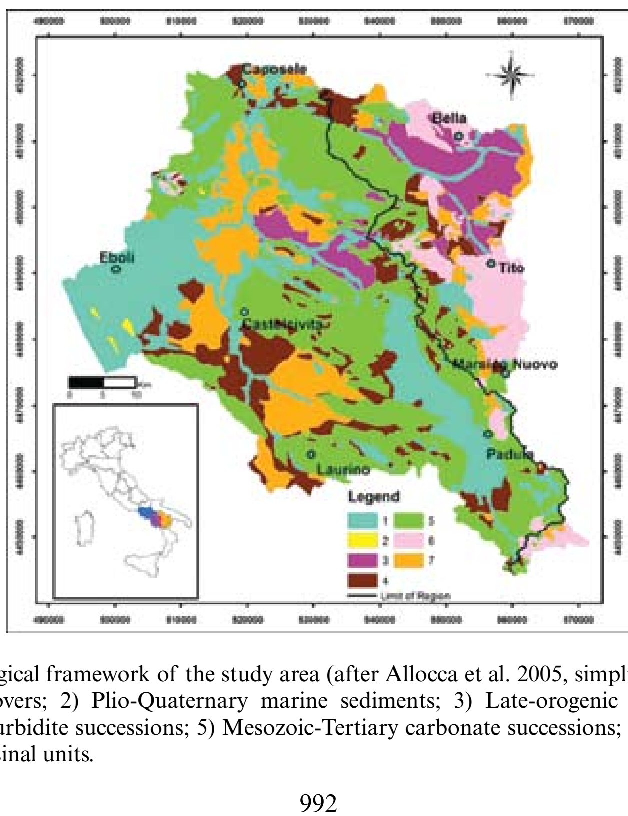

Figure 1. Geological framework of the study area (after Allocca et al. 2005, simplified and redrawn). 1) Quaternary covers; 2) Plio-Quaternary marine sediments; 3) Late-orogenic molassic deposits; 4) Syn-orogenic turbidite successions; 5) Mesozoic-Tertiary carbonate successions; 6) External basinal units; 7) Inner basinal units.

sector of this LGU, slopes are mantled by a thin (<5 m) cover of loose vulcaniclastic deposits (ashes, pumice, paleosoils), related to the main explosive eruptions of the active volcanos of the Campania region (Somma-Vesuvius and Phlegrean Fields). Carbonate terrain typically comprise high-angle slopes (30°–40° to 90°), occasionally with intervening low-angle surfaces (<10°–15°), the latter due to prolonged karst and fluvio-karst processes active during relatively stable Quaternary stages. A variety of surficial and hypogene karst morphotypes can also be found in all the main carbonate structures.

The *hilly terrain* can be found in both the southwest and northeast of the study area. The main feature of this LGU is the presence of structurally complex, Mesozoic to Tertiary formations, where clayey materials often dominate. Mio-Pliocene clastic sequences cover the older sediments in places. The landscape of this LGU is directly controlled by the outcropping lithologies: high-angle slopes can be found where the coarser sandstones and conglomerates are present, while low-angle slopes with highly developed channel networks and flat summit plateaus characterise the areas where clay-dominated sequences crop out.

One of the three main *coastal plains* of the Campania region, the Sele River Plain, is partly included in the studied area. This plain is a tectonic depression which followed the Quaternary extensional tectonic phases; its evolution was characterised by altenrating continental, transitional and marine sedimentary environments. The prevailing downward trend of the plain has, from time to time, been interrupted by uplift stages, in turn responsible for the terraced morphologies of the inner sectors of the Plain itself.

The morphostrucutral depressions generated within the Apennines as a consequence of the Pleistocene extensional tectonic phase can be defined as *intra-mountain depressions* (Cinque & Romano 2001). The main morphostructures of this LGU are the Tanagro valley and the *Vallo di Diano*, where continental sediments are present in both. The main depositional morphologies include fluvial terraces, talus, *glacis* (i.e. mountain piedmont low-angle sediment accumulations—Burt et al. 2008), alluvial and mixed fans, some of which still active (Santangelo et al. 2006).

3 LANDSLIDES

The landslide inventory has been performed through a traditional geomorphological survey, based on field work and aerial photo interpretation. Accordingly, more than 10,000 landslides have been recognized over about 1000 km^2 of hilly and mountainous territory, with an average density of about 10 events per km^2: in total, the areal extent of the landslides is about 430 km^2.

The outcropping geology controls the mechanical and hydrological behaviour of the slopes and hence the development of landslides, whose frequency by type is shown in Figure 2.

Rainfall- and earthquake-induced first generation landslides and surficial reactivations of deeper dormant or relict landslides characterise the instability of the hilly terrain, where structurally complex formations prevail (Fig. 3). Rotational slides evolving into earthflows

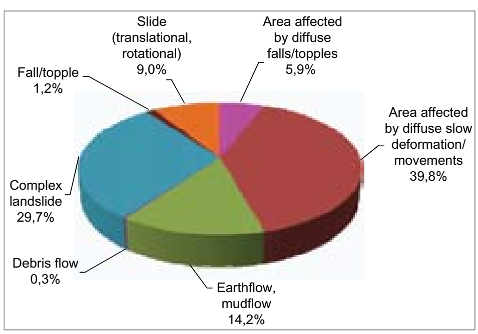

Figure 2. Frequency distribution of inventoried landslides with relation to type.

Figure 3. a) Rockfall-prone carbonate slope (S. Arsenio). b) Rotational component of a complex movement (Serra dell'Acquara, Senerchia).

are common with movement generally slow or intermittent and with a complex style of activity (WPWLI 1993; Cruden & Varnes 1996). In higher relief slopes, falls, topples and slides predominate.

Falls, topples, planar and wedge failures frequently affect the calcareous-dolomitic rocks in the study region (Fig. 3) with volumes ranging up to a few thousand cubic metres.

Active, reactivated, suspended and dormant landslides are almost equally present over the study territory, while stabilized and relict phenomena form less than 0.5% of the area.

The inventoried landslides have also been classified in terms of their intensity as expressed by the maximum expected velocity, as commonly found in the literature (e.g. Varnes 1978; Hungr 1981; Cruden & Varnes 1996). This parameter allows an effective and reliable indicator of the possible adverse effects for the elements exposed to mass movements. In this respect, low ($v < 1.6$ m/yr), average (1.6 m/yr $< v <$ 1.8 m/hr) and high intensity ($v > 1.8$ m/hr) landslides have been identified. Average intensity landslides (earthflows, slumps, slides, most of the complex events, areas affected by diffuse slow movements) clearly prevail with 95% of the total, while the remaining 5% pertains to the high intensity movements (falls, topples, debris flows); the slowest landslides (lateral spreads and deep seated gravitational slope deformations) comprise less than 0.1%.

4 LANDSLIDE RISK ASSESSMENT

4.1 *Method*

The procedure schematically shown in Figure 4 was adopted for evaluating the landslide risk of the study area based on three basic parameter maps (geology, geomorphology, landslides). By grouping geological formations and geomorphological elements a quite small number of geolithological and geomorphological districts have been defined. Combining both groups of districts led to the Homogeneous Territorial Unit (HTU) map, comprising a spatially lumped aggregation of land portions in discrete units. The latter can be defined as Unique Condition Units (UCU—Bonham-Carter 1994; Chung et al. 1995; Guzzetti et al. 1999), since they are defined by a unique combination of attributes. In southern Italy, HTUs-based mapping procedures have been successfully tested in the past (e.g. De Vita et al. 1994; Guida et al. 1996).

A Landslide Scenario map was produced from the Landslide-inventory map, utilising information on type, state of activity and intensity (in our case, maximum expected velocity) through an intermediate map. The Landslide Scenario map defines the "real" susceptibility of each area, affected by landslides, for each of which the intensity (I_n) and state of activity are taken into account, by means of the matrix shown in Figure 5a.

A further map, derived by combining HTUs and landslides, displays the HTU susceptibility and is obtained by assigning to each HTU the landslide attributes (intensity and state

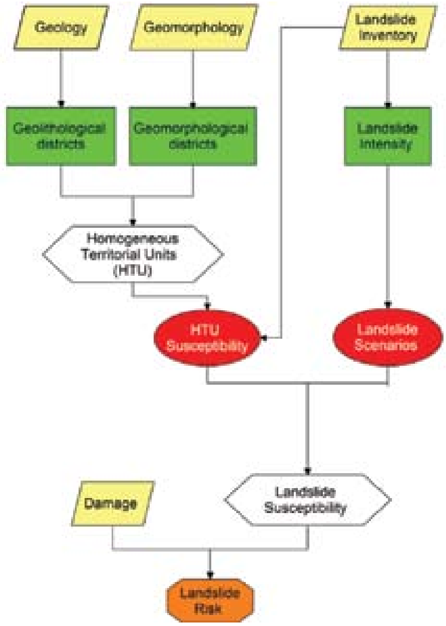

Figure 4. Conceptual framework for the definition of the landslide risk.

a)

	I1	I2	I3
Inactive	Pf1	Pf1	Pf2
Dormant	Pf1	Pf2	Pf3
Active	Pf2	Pf2	Pf3

b)

		Landslide Index			
		1	2	3	4
Activity classes	1	$P_{HTU}1$	$P_{HTU}1$	$P_{HTU}2$	$P_{HTU}2$
	2	$P_{HTU}1$	$P_{HTU}2$	$P_{HTU}2$	$P_{HTU}3$
	3	$P_{HTU}2$	$P_{HTU}2$	$P_{HTU}3$	$P_{HTU}4$
	4	$P_{HTU}2$	$P_{HTU}3$	$P_{HTU}4$	$P_{HTU}4$

c)

	$P_{HTU}1$	$P_{HTU}2$	$P_{HTU}3$	$P_{HTU}4$
D1	$R_{HTU}1$	$R_{HTU}1$	$R_{HTU}2$	$R_{HTU}2$
D2	$R_{HTU}1$	$R_{HTU}2$	$R_{HTU}2$	$R_{HTU}3$
D3	$R_{HTU}2$	$R_{HTU}2$	$R_{HTU}3$	$R_{HTU}4$
D4	$R_{HTU}2$	$R_{HTU}3$	$R_{HTU}4$	$R_{HTU}4$

d)

	Pf1	**Pf2**	**Pf3**
D1	Rf1	Rf2	Rf3
D2	Rf1	Rf2	Rf3
D3	Rf2	Rf3	Rf4
D4	Rf2	Rf3	Rf4

Figure 5. Matrices used for the definition of the Landslide Scenarios (a), HTU Landslide Susceptibility (b), HTU Risk (c) and Landside Risk (d).

of activity), considering the spatial distribution of each landslide type within a single HTU. Since a HTU can be affected by various kinds of mass movements, a Landslide Index (l_i) is introduced, which corresponds to the percentage of a HTU area affected by any type of landslide deposit (landslide area/ HTU_n area). Accordingly, each landslide type is given an index, which is eventually subdivided into four classes. To this aim a statistical analysis using the standardised distribution is carried out as follows:

1. the natural logarithm is calculated for each l_i (LN_l_i)
2. mean and standard deviation of the values obtained at (1) are calculated (M_LN_l_i and DS_LN_l_i)
3. each l_i is standardised according to the formula STD = (LN_l_i−M_LN_l_i)/(SD_LN_l_i)

4. the standardised values are classified in four classes:

if	$STD < -1$	then class 1
if	$0 > STD \geq -1$	then class 2
if	$1 > STD \geq 0$	then class 3
if	$STD \geq 1$	then class 4.

With the aim of obtaining only one landslide index for a given HTU, irrespective of the number of landslide types, the various l_i are summed up and weighted by multiplying each of them with respect to their intensity (I = 1 for high intensity; I = 0,75 for average intensity; I = 0,5 for low intensity):

$$LI = (l_{i1} \times I) + (l_{i2} \times I) + \cdots + (l_{in} \times I) \quad (1)$$

Eventually, the HTU Susceptibility is assessed through a specific matrix (Fig. 5b).

The resulting Landslide Susceptibility map, derived from the overlay of the Landslide Scenario with the HTU Susceptibility, gives information on both the landslide propensity of a HTU and the threat posed to the territory and its man-made elements. The final Landslide Risk map is produced by overlaying Susceptibility and Maximum Expected Damage (Fig. 6), the latter ranked in four grades, in terms of both population and building density over an assigned territorial cell. The final Risk map has a double legend which accounts for both Landslide Scenarios and HTU Susceptibility (Fig. 5c–5d). Such a map denotes land use restrictions of different severity, depending upon the presence of either an existing mass movement or of factors predisposing to future slope instability.

4.2 *Results*

Eight geolithological and seven geomorphological districts have been obtained from the original 32 geological formations and 34 geomorphological elements, respectively. Only 41 of the 56 possible unique conditions actually resulted, for a total of over 100,000 polygons because the thematic variables are spatially correlated.

Thirtynine HTUs were originally identified as containing landslides, i.e. affected by any part of a landslide, either depletion, transit or accumulation zone. When the percentage of failed area was lower than 1%, the HTU was considered as landslide-free, mainly due to errors in data collection and digitization. However, some of these areas, even if small in size, have been considered still physically meaningful (outliers) and saved for the successive stages. By doing so, a final number of 17 landslide-bearing HTUs was obtained, leaving the remaining HTUs as having a "null" landslide propensity.

About 355 km^2 of territory has been classified in the intermediate susceptibility class (Pf2 in Figure 5a), corresponding to about 83% of the whole territory affected by landslides (ca. 430 km^2). Dormant and active high intensity movements (Pf3) involve about 15% of the unstable territory, while the remaining 2% is attributed to the Pf1 susceptibility class.

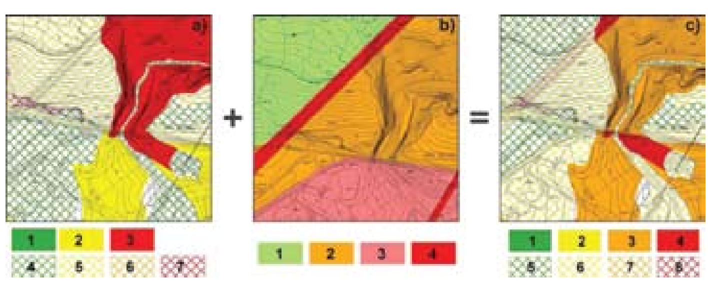

Figure 6. An example of overlay between landslide susceptibility (a) and Maximum expected damage (b) maps, resulting into the final risk (c) map. Key to symbols: a) landslide susceptibility: Pf1 (1); Pf2 (2); Pf3 (3); $P_{HTU}1$ (4) $P_{HTU}2$ (5) $P_{HTU}3$ (6) $P_{HTU}4$ (7); b) Damage: D1(1); D2 (2); D3 (3); D4 (4); c) Risk: Rf1 (1); Rf2 (2); Rf3 (3); Rf4(4); $R_{HTU}1$ (5) $R_{HTU}2$ (6) $R_{HTU}3$ (7) $R_{HTU}4$ (8).

Combining the four levels of expected damage and the three classes of landslide susceptibility (Fig. 5d), most of the inventoried landslides can be classified in the "average" risk class (Rf2 = 73%) followed by the "high" class (Rf3 = 24%), with areas affected by very high (Rf4) and moderate risk (Rf1) accounting for 1% and 2% respectively.

About 48% of the studied zones (503 km^2) could be affected by future landslides showing the same features of previous instabilities. Only about 10% of the overall territory were revealed to be neither landslide-free nor susceptible to future landslides. Again, due to the prevalence of landslides falling in the Pf2 class, most of the HTUs are assigned to the intermediate susceptibility classes (Fig. 5b), with a 41% of $P_{HTU}2$ and 38% of $P_{HTU}3$ areas; the remaining 22% of territory is classified into $P_{HTU}1$ (16%) and $P_{HTU}4$ (6%). The distribution of the "potential" risk shows that HTUs with moderate to average landslide susceptibility predominate given that 48% of areas fall in the $R_{HTU}2$ class and 43% in the $R_{HTU}1$ class.

5 DISCUSSION AND CONCLUSIONS

The main aim of this research was to assess the landslide susceptibility and risk of a large, 1000 km^2 territory affected by a variety of landslide types. The territory has been investigated through a 1:5000 scale digital topographic map, which has meant performing a regional-scale hazard analysis by means of a large-scale map. This may sound incongruous. In fact, as well known (Van Westen 1993), a regional-scale susceptibility analysis allows very large areas (on the order of 1000 km^2 or more) to be investigated with quite low detail. By contrast, 1:10,000 and 1:5000 maps allow large-scale susceptibility analysis, where the expected detail is definitely higher.

In our case-study, considering the great number and variety of landslides affecting a variety of lithological complexes, it appeared unfeasible to perform an in-depth statistical, quantitative analysis of the predisposing and causative factors relevant to each type of mass movements. Consequently, the procedure schematically shown in Figure 4 was adopted, which seemed a reasonable solution to overcome the peculiar working conditions and difficulties. To this end, the basic time-invariant factors (geology and geomorphology) together with landslides, can provide a first order predictive susceptibility model, based upon the fundamental assumption that landslides will occur in the same conditions as in the past (IAEG 1984; Hutchinson 1995).

Several authors (e.g. Chung et al. 1995; Guzzetti et al. 1999) have examined potentials, advantages and drawbacks of the various landslide hazard/susceptibility assessment approaches and methods based upon a specific mapping unit (grid cells; terrain units; unique condition units; slope units; topographic units). As regards unique condition units, Guzzetti et al. (1999) have observed that they perform well where thematic information layers completely cover the territory, while problems arise with linear features, such as faults or scarps. In our case, linear elements have been buffered, which allowed them to be included in the analysis. A further drawback confirmed by our study is given by the intrinsic subjectivity in treating the meaningfulness of the domains derived from the map overlay. As stated above, most of the smaller polygons have been rejected as geologically meaningless; however, some outliers have been saved, even though of small size, because of their significance. This evidence simply means that the expert knowledge of the earth-scientist is still useful, if not crucial, even in our "GIS-age". To this respect, Van Westen (1993) clarifies that "subjectivity" in a hazard analysis is not necessarily intended as a disqualification: subjective analysis may result in a very reliable map when it is executed by an experienced researcher. In any case, as stated by Hutchinson (1995), the only way a landslide predictive map can be validated is through time.

In conclusion, we believe that the method proposed here provides a useful tool to understand the present distribution of slope instability and to predict the possible evolution of landslide-free domains. It also indicates the areas where conditions for landslide occurrence are absent. Further efforts will be devoted to improve the susceptibility maps which represent the first step in the landslide risk assessment in the study area.

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