Landslide hazard assessment project in the Messina municipality area (Sicily, Italy): preliminary remarks

In the last 4 years Messina Municipality has been hit four times by extreme rainfall events that triggered a great number of debris flows. Due to the 2009 event, Natural Risks Prevention and Mitigation Laboratory of ENEA started researching on landslide hazard in some river catchments, south of Messina Municipality. In March 2011, Messina's Public Authority administration commissioned ENEA to study the entire municipality area.

This paper presents the preliminary results of the study focused on localising source areas and runout of debris/mud flows, triggered by heavy rainfall in the Giampilieri and Briga catchments, and on assessing their intensity. Starting from an inventory of the several debris flows occurred in the area after the event of October 1, 2009, an evaluation of the factors that make the area prone to these events was used as input for GIS-based hazard prediction model.

The knowledge of the actual landslides impact may promote sustainable measures of land planning and risk mitigation for mountain source and transit areas as well as for urban areas prone to the deposit of debris flows

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Progetto di valutazione della pericolosità da frana nel territorio del Comune di Messina (Sicilia, Italia): risultati preliminari

Negli ultimi quattro anni il Comune di Messina è stato colpito quattro volte da precipitazioni intense che hanno innescato un gran numero di colate detritiche. In seguito all'evento del 2009, il Laboratorio Prevenzione dei Rischi Naturali e Mitigazione degli Effetti dell'ENEA ha dato avvio ad una serie di ricerche sulla pericolosità da frana nei bacini della porzione meridionale del Comune. Nel marzo 2011 l'amministrazione comunale di Messina ha incaricato l'ENEA di realizzare uno studio sull'intero territorio comunale.

Questo documento presenta i risultati preliminari dello studio focalizzato sulla localizzazione delle aree di origine e recapito di colate di detrito e fango innescate da precipitazioni abbondanti nei bacini di Giampilieri e Briga e sulla valutazione delle loro intensità. Basandosi su di un inventario dei diversi flussi detritici che si sono verificati nella zona durante l'evento dell'1 ottobre 2009, una valutazione dei fattori che rendono la zona soggetta a questi eventi è stata utilizzata come input per un modello di rischio predittivo basato su GIS.

La conoscenza del reale impatto delle frane può promuovere misure sostenibili di pianificazione territoriale e mitigazione del rischio per le aree di innesco e transito poste sui versanti nonché per le aree urbane soggette al recapito di colate detritiche

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Mud and debris flows are the most dramatic among landslides phenomena in terms of loss of life. In recent past, several disasters have occurred in Italy that are attributable to such phenomena (Piemonte 1994, Versilia 1996, Sarno, 1998, Cervinara 1999, Val d'Aosta and Valle Anzasca, 2000, Ischia 2006 and 2009; Messina 2007 and 2009), with over 300 victims. In 2011, a catastrophic balance has been registered with four events concetrated in the Messina province (March 1^{th}: Mili river basin; November 22^{th}: Saponara village) and in the Ligurian Region (October 25^{th}: Cinque Terre and Lunigiana; December 04^{th}: Genoa town). The high risk of rapid flow is accompanied by the difficult hazard assessment. In fact, the source areas of these phenomena are rarely located twice in the same slope portion. Being primarily first generation phenomena, their spatial prediction is particularly problematic. This difficulty is closely related to the triggering causes of these landslides – consisting essentially of sporadic and sudden rainfall events – and to the extreme horizontal and vertical variability of the characteristics of the landslide material involved, essentially the bedrock's soil cover. An increasing trend in precipitation and a decrease in their duration have been documented over the past 50 years in Italy [1]. This scenario leads to assume an increase in debris-mud rapid flows hazard in the next future.

A methodology to assess landslide hazard has been developed by ENEA during the last decade and tested in about 15 national and international areas at different scales. By applying this methodology to the entire Sicilian Region in the Synarma European project, the condition of susceptibility of Messina's territory to five landslide typologies was evidenced (Figure 1) [2, 3].

The maps reported in Figure 1 were obtained with data ranging in scale from 1:250,000 to 1:100,000. Hence, they cannot be used for local planning though they clearly show the most critical areas that need further investigation. The maps show that Messina's area is particularly prone to falls (Figure 1d). The susceptibility to debris-mud flows (Figure 1e) is generally high except for the southern area, affected by the 2009 event, where it is very high. In addition there are wide areas showing a very high susceptibility to rotational slides (Figure 1a) while the susceptibility to planar slides is generally less significant (Figure 1b).

In the last 4 years Messina Municipality has been hit four times (25/10/2007, 27/09/2009, 01/10/2009, 01/03/2011) by extreme rainfall events that triggered a great number of debris flows. Following the 2009 event, the Natural Risks Prevention and Mitigation Laboratory of ENEA started researches about landslide hazard in the injured area. In March 2011 Messina's the Public Authority administration encharged ENEA with a study of the entire municipality area in order to obtain a support tool for a sustainable urban planning and to raise awareness about the geomorphologic risk both in technicians and in local population.

The preliminary results of the study come from the river basins of Giampilieri and Briga in the Ionian coast of the Messina Municipality, affected by the event of October 1^{th}, 2009. On the night of 1–2 October 2009 the Ionian coast and the Peloritani Mountains have

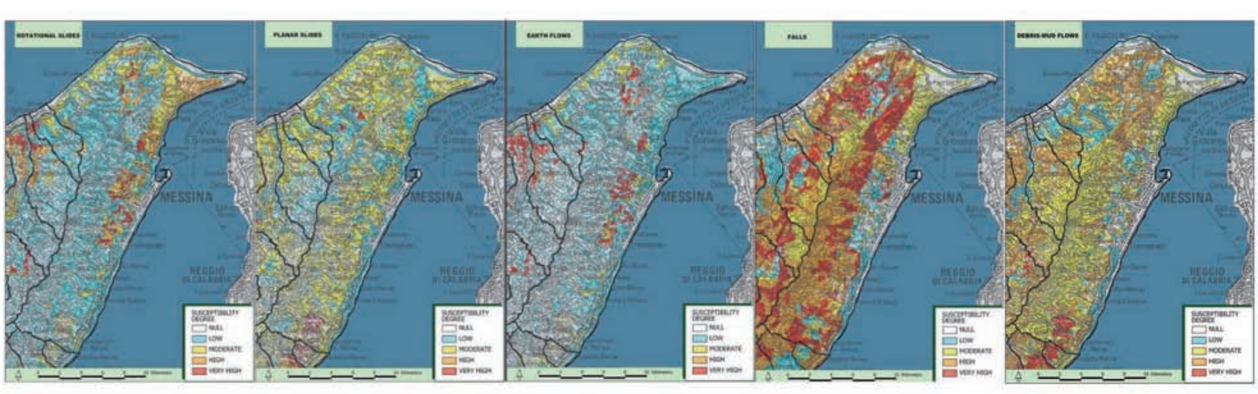

FIGURE 1 Susceptibility map of Messina territory: rotational slides (a), planar slides (b), earth flows (c), falls (d) and debris-mud flows (e) [2, 3]

FIGURE 2 Panoramic view of a slope interested by a pervasive series of mud/debris flows in the Briga catchment and damages after the October 1, 2009 event in Briga village

been affected by a sudden downpour, accompanied by strong winds and lightning. It is estimated that more than 200 mm of rain fell in seven hours (according to the Sicilian Agrometeorological Information Service – SAIS). This meteoric event triggered about a thousand debris/mud flows. Giampilieri Superiore, Briga Superiore and Scaletta Zanclea, small villages situated few kilometres southward from the city of Messina, were the most injured areas (Figure 2).

Study area

The Peloritani represent the southern termination of the Calabro-Peloritano Arc and are characterized by metamorphic units of pre-Alpine age. Involved in Hercynian and Alpine orogenic processes, these units are tectonically superimposed to sedimentary Maghrebidi units [4]. The crystalline-schistose formations show different metamorphic degrees (phyllites, schists, marbles, gneisses) and are extensively covered by a thick layer of colluvium. Peloritani Mountains range stretches along the coast and is characterized by narrow and steep small-sized catchments (5-10 km^2) and with time of concentration in the order of few minutes. The morphology of the Peloritani was influenced especially by metamorphic lithology and by complex geostructural conditions related to the orogenic processes active in the area since the late Miocene. Recent tectonic uplift rates, up to ~2 mm/yr [5], give the area a very high relief energy with up to 1000 meters drop in about 5 km.

The steep slopes of the valley profiles and the low permeability of the bedrock give to the drainage network a remarkable ability to erosion and transport. The hydrological regime is markedly torrential, typical of the “fiumare”, with little or no runoff in spring and summer and large runoff in autumn and winter. These factors increase the energy of runoff waters, causing high stream capacity and transport of solid blocks, even decametric, during rainfall events. The huge rainfall events may cause rapid gravitational phenomena classified as rapid debris-mud flows, which affect the shallow natural or anthropic debris layer. These phenomena have led to the development of wide debris cones at the mouth of the streams and in the floodplains of the major tributaries, as well as extensive debris bands at the base of the slopes. These morphological and hydrological conditions made the flows, triggered by heavy rainfall on October 1, 2009, reach the main valley’s bottom, the fluvial-gravitational fans and the urban areas located along the Ionic coast in a few minutes and with great energy, causing heavy damage and casualties.

The first two river basins of this study are situated 15 km south of the City of Messina and extend from the sea up to the the Peloritani watershed. The catchment of the Giampilieri stream (maximum altitude 1040 m a.s.l.) has an area of approximately 9.2 km^2 and a length of about 8.5 km. Inside it, there are the villages of Giampilieri Marina, Giampilieri Superiore, Altolia and Molino. The catchment of the Briga stream (maximum altitude 1016 m a.s.l.) has an area of about 9.6 km^2 and a length of about 9 km. Inside it, there are the villages of Briga Marina, Briga Superiore and Pezzolo.

Methods

This study followed the ENEA-Roma Tre methodology as developed in several national and international other case studies [6, 7, 8, 9, 10]. The first step of this study was an analysis of past events in order to localise source, transportation and runout areas of debris flows and to obtain a landslide inventory. More than 1000 debris flows have been recognised in the Giampilieri and Briga basins trough a detailed geomorphological and morphometric field survey (1:5,000-1:10,000) and aerial photos analyses. The inventory, recorded in a GIS data base, was focused on identifying Discriminating Parameters (necessary but not sufficient conditions, like slope angle in the niche zone and lithology on which the rupture surface is imposed) and Predisposing Factors (factors affecting the slope instability like geomorphological, geological, lithotechnical, hydrogeological and land use features). Each factor has been mapped and implemented as a layer in a GIS project. By GIS overalapping of these factors, which are assigned a different degree through a site-specific function, the susceptibility map of the area was obtained. The kinematic characteristics of the past events allow to estimate the runout, velocity and intensity of potential events. By assigning a soil layer thickness to the highest susceptibility areas and consequently obtaining their volume, the runout distance of potential events was estimated [11]. Velocity measurements [12] were realised in different points of the occurred landslides and in the same points the energy released was calculated. These results were then applied to some potential events. So it was possible to model the expected energy in each morphological part of potential debris/mud flows.

Preliminary results

The methodology was first applied to the two catchments of Giampilieri and Briga, with the aim of highlighting critical issues to be overcome before application to the entire study area [13].

Landslide inventory and susceptibility maps

All the 1119 phenomena collected in the inventory are classified as debris and mud flows. Each event has been attributed the specific morphological elements: the Landslides Identification Point (PIFF; Figure 3), source areas, transit areas, accumulation areas and the Landslide Foot Identification Point (PIP). Source areas have been classified into "channeled", when bundled into a pre-existing drainage line, and " not channeled". On the basis of a frequency distribution analysis, the discriminating parameters for rapid flows are constituted by the cristalline units of the bedrock and by a specific angle of the original slope in the source area. The slope angle in the niches observed in the field survey ranges from 22° to 73°, but the most significant range of slopes, based on its relative frequency, is between 36° and 56°.
In all the surveyed landslides, the predisposing factors were identified. According to a heuristic and statistical approach, the most significant predisposing factors are summarized in Table 1.

Discriminating parameters	Predisposing factors
Cristalline units	Bedrock lithology
	Land cover
	Anthropic elements
Specific slope angle	Longitudinal slope curvature
	Slope aspect

TABLE 1 Discriminating parameters and predisposing factors used in this study

In order to quantify its influence in the susceptibility assessment with respect to the other, each factor was assigned a weight increase from 0 to 5. Instead, each class of each predisposing factor was assigned an index increase from 0 to 9.
Once digitized, discriminating parameters and predisposing factors have been integrated through a GIS overlapping with the aim of producing Homogeneous

Territorial Units (HTU). The following susceptibility function has been applied:

$$S = \left(Icop \times Ipend\right) \times \frac{\sum_{i=1}^{n}(i_n \times P_n)}{\sum_{i=1}^{n} P_n}$$

where:
S = Susceptibility
Icop = soil layer discriminating parameters index
Ipend = slope angle discriminating parameters index
i_n = index of the n_{th} predisposing factors
P_n = weight of the n_{th} predisposing factors.

This function draws a susceptibility map initially subdivided into 9 levels. Then they are qualitatively grouped into 5 classes (Figure 3), described in the Table 2.

Level	Susceptibility
0	Null
1-3	Low
4	Moderate
5	High
6-9	Very high

TABLE 2 Conversion from levels to susceptibility classes

Debris flow intensity

Intensity may be expressed in a relative scale, referred to damage or loss levels, or in terms of characteristic variables of the phenomenon (*e.g.*, speed, volume, energy). In this study, intensity is considered as equal or proportional to the kinetic energy developed by the landslide, since the ratings for speed and size may be partial. All quantities needed to evaluate the kinetic energy were calculated for both past and potential phenomena. These measures are: the mobilized volume in the triggering and transit areas, the propagation distance and the speed of flows.

The product of the maximum depth of the niche (which varies from 0.5 to 2.5 meters) was calculated by the extension of the source area, obtained by photo-interpretation, in order to estimate the mobilized volume of each debris/mud flow. This product was then reduced by a correction form factor, experimentally obtained. Also the mobilized volumes along the transit areas were considered. The mean thickness of these zones varies from 0.3 to 1 m, as observed in the field survey. Once multiplied these values by the transit area extension, the product was summed to the source area volume.

Following the Rickenmann's [11] appraoch, effective

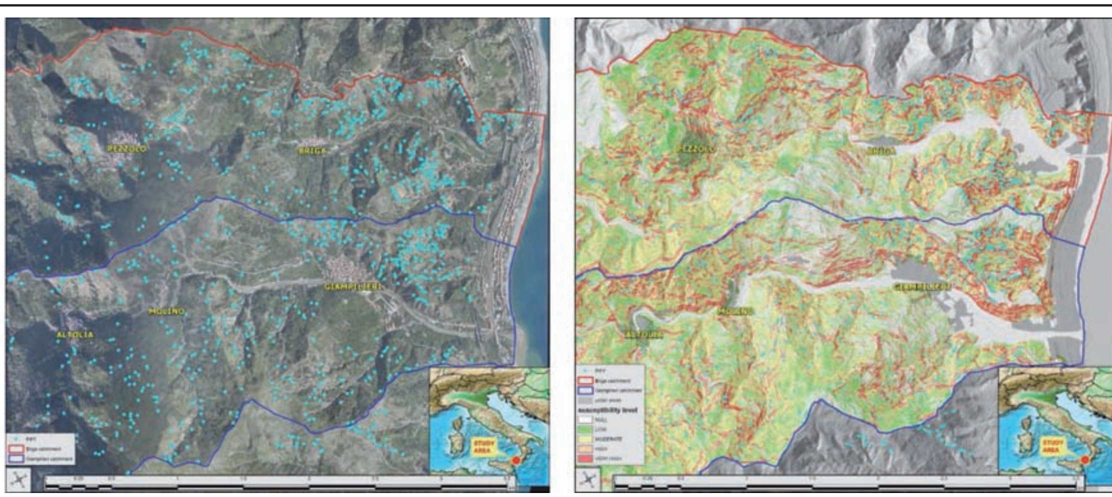

FIGURE 3 Landslides Identification Point (PIFF; light blue dots) and susceptibility map of the first study area (in red the highest class areas)

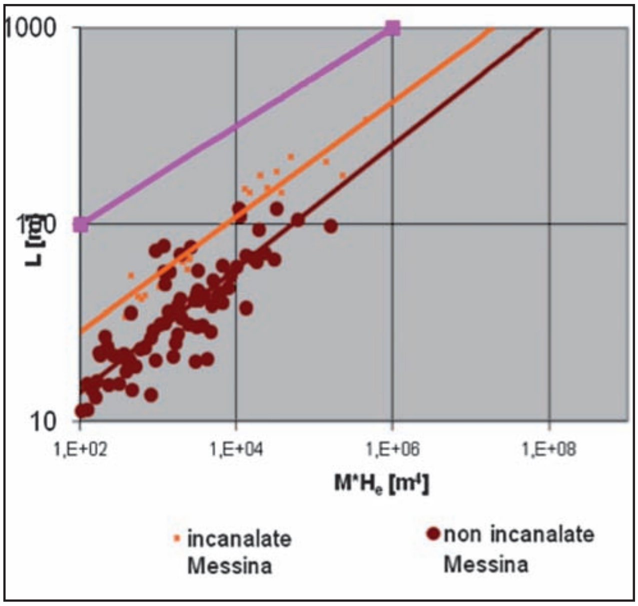

FIGURE 4 Site specific equations about debris flows runout in comparison with the Rickenmann formula (orange: channelled; brown: not channelled; pink: Rickenmann)

distance traveled from PIFF to PIP, for each occurred phenomenon, was measured using 3D photo-interpretation and GIS analysis, and the runout "site specific" laws have been generated, both for channeled and not channeled flows (Figure 4):

- channeled flows: $L = 6.147(V \cdot \Delta)^{0.3078}$
- not channeled flows: $L = 3.266(V \cdot \Delta)^{0.3078}$

where:
L = travel distance of the mass movement;
V = total volume mobilized by the debris flows
Δ = elevation difference between the starting point and the lowest point of the deposition of the mass movement.

During the field survey some points were identified in order to measure the speeds achieved by mud and debris flows occurred in October 1, 2009. By adopting the Johnson & Rodine approach [12], it was possible to estimate the average speed of a flow by measuring the raising that occurs in the outer portion of a curve due to the centrifugal force. The identified measurement points were characterized by the presence of traces left by the passage of the debris flow like mud deposits or abrasions in the tree bark. The formula used to calculate the average speed is:

$$V = \sqrt{R \cdot g \cdot \cos i \cdot tgb}$$

where:
V = average speed,
R = radius of curvature of the stream axis,
g = acceleration of gravity,
i = slope angle of the stream in the measurement point,
b = angle of the fluid mixture surface in motion across the curve.

By applying this formula to different points of the debris flow paths, specific velocities were calculated, in order to outline the deceleration curves for different censused debris flows. Maximum speed values range between 8 and 16 m/s. Once obtained the runout distance and the debris flow velocities of past events, the energy developed by investigated rapid flows has been evaluated (Figure 5).
Along the path traveled by the considered debris flow, at each point where speed was calculated, the value of the developed kinetic energy was obtained. The maximum developed energies were estimated in the order of thousands of kilojoule (Figure 6a).
Finally the volume, the distance of propagation and the velocity were estimated for some potential phenomena, identified by the susceptibility map to achieve an estimation of the potential energy in differ-

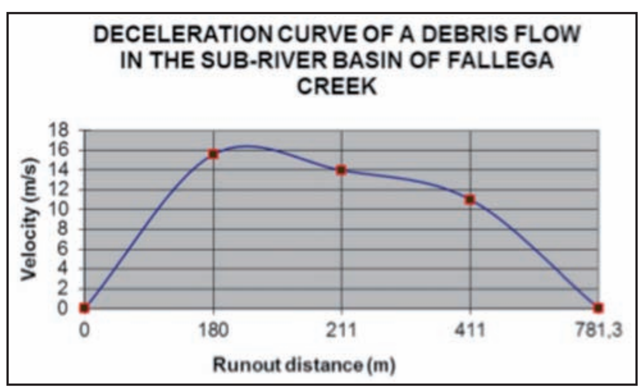

FIGURE 5 Example of deceleration of a past debris flow

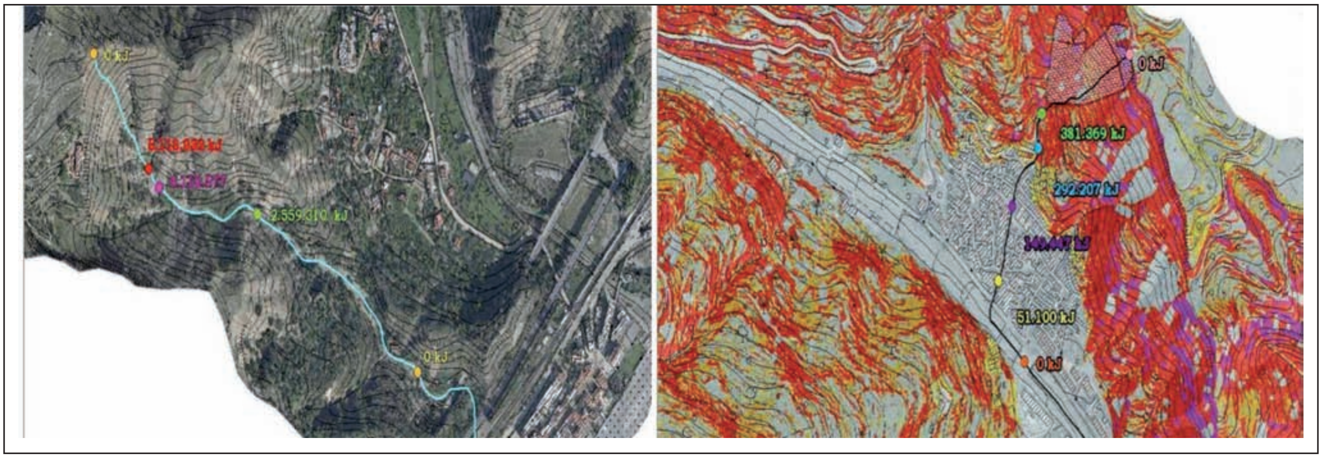

FIGURE 6 Maximum developed energies in the Fallega creeks between Giampilieri Marina (a) and Briga Marina and maximum energies of the potential debris flow in the Giampilieri village (b)

ent points along the path in which new phenomena could be developed (Figure 6b).

Conclusions

The preliminary results highlight the huge and complex problems in the Giampilieri and Briga river basins in reference to the geomorphological hazard. Landslide processes are broadly diffused in the area, specially the debris flows whose hazard, in term of susceptibility and intensity, is very high. The development of towns and villages up to the creeks outlet, the transformation of riverbeds in streets and the abandonment of terracing, led to increase the geomorphological risk of the area.

The proposed methodology constitutes a contribute to the development of a quantitative geomorphological approach in landslide investigation. The knowledge of current landslides characteristics and activity may promote sustainable mitigation measures for source and transit areas as well as for urban areas prone to deposit of debris flow. With the necessary improvements, this approach will be applied to the entire Messina Municipality by the end of 2012. With the aim of strengthening the hazard assessment, the statistical elaboration of the predisposing factors will be performed. An evaluation of the rainfall and soil moisture thresholds will be provided at the end of the study. This issue, in fact, plays an important and strategic role in predisposing efficient early warning systems and contributes to the definition of a Civil Defense Plan. Given the current dynamic and non-stationary climate conditions and the related difficulties in the definition of the periodicity of the triggering rainfall, the study will give less importance to establish return times of extreme events.

In conclusion, the study will provide a framework of the degree of landslide hazard in the territory of Messina and will constitute a necessary basis for subsequent phases of vulnerability of the exposed elements assessment, and, ultimately, for the definition of risk scenarios targeted at risk mitigation.

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Notes

[1] 1 The energy estimation ($E=1/2MV^2$) was performed by calculating the product of mass (M), considered constant and equal to the product of volume by the average density (estimated at 2000 kg/m^3), by speed (V) in the considered points.