Evaluating potential impact of landslides on roads: an example from the Southern Apennine Mountains, Italy

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Abstract

We investigate the potential impacts of slope instability on roads in a landslide-prone low-mountain area of Southern Italy. For comparative reasons, two adjacent municipal areas are considered. Using a detailed multi-temporal landslide inventory based on the digital stereoscopic interpretation of four sets of aerial photos covering a 50 year period, we first show that over 30% of the roads (in terms of their total length) cross landslide bodies. Then, we exploit the landslide intensity index which relies on the empirically estimated movement volume and the velocity inferred on the basis of the geomorphological criteria and local knowledge. The intensity index is combined with landslide hazard zones, which represent the areas of likely enlargement of the pre-existing landslides or the occurrence of new landslides. Through this approach we evaluate where and how, in terms of the expected intensity, the roads could be affected by future landslide activity. Moreover, for both municipalities, the road sections falling into specific landslide intensity scenarios are quantified as the percentage of the total length of the municipal road network. We also illustrate how the landslide inventory data can help the interpretation of road monitoring results obtained from satellite multi-temporal interferometry. The integrated information can assist the regional government in a rational allocation of funds for future prevention and mitigation measures.

1 INTRODUCTION

Transportation infrastructure is often exposed to instability and damage in landslide-prone areas (Turner and Schuster, 1996). While the associated risk to the population seems most significant in high relief mountainous regions e.g., due to fast movements (such as rock falls, debris flows), landslides can have significant impact also on roads in low mountains. The latter is the case of the Daunia region (or Daunia Apennines) located in the Southern Apennine Mountains of Italy (Figure 1).

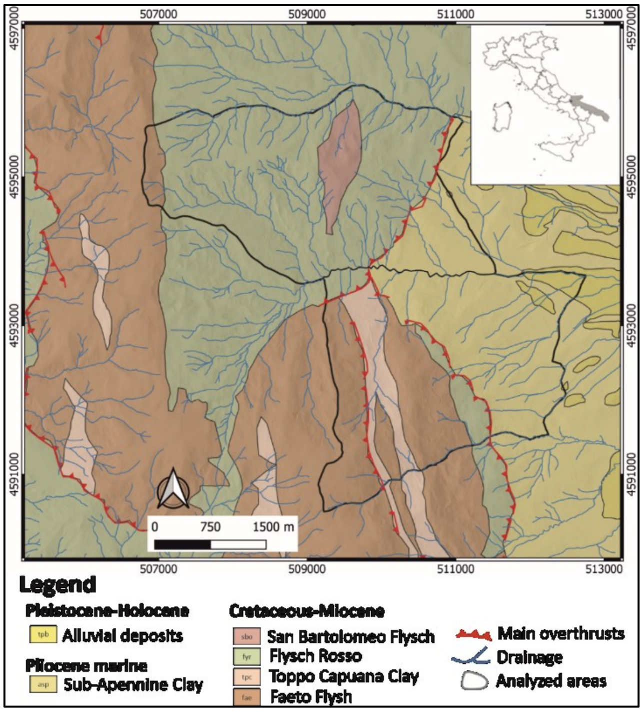

Figure 1. Geological map (modified after Pieri et al., 2010 and Zumpano et al., 2020) and location of the study area in the Apulia Region (in grey in inset), Italy.

The Daunia Apennines have long been known for recurrent landsliding with detrimental effects on the road network (e.g., Cotecchia, 1963). Although the landslides are typically very slow, in a long term their cumulative displacements can cause considerable economic damage or even lead to a temporary road closure (Wasowski et al., 2012). Indeed, due to the widespread presence of clay-rich lithologies and poorly drained slopes (Wasowski et al., 2010), the density of landslides in the Daunia region is very high (from 20 to 60 events per km^2; Zumpano et al., 2020). In situ controls are limited, and therefore, mitigation efforts aimed at reduction of road damage cannot be implemented in a timely manner. A more rational and focused approach to the mitigation planning is desirable.

In this paper, we present an approach that relies on the use of the information available from the new comprehensive landslide inventory compiled for the Daunia region (Zumpano et al., 2019). In particular, we use the example of two neighboring municipalities, with the population concentrated in two hilltop towns (Motta Montecorvino and Volturino). Landsliding is widespread and damage to the local road network recurrent in both areas. The potential impact on roads is first indicated in terms of the percentage of road length crossed by landslides. Then, following the geomorphological approach of Cardinali et al. (2002) and Reichenbach et al. (2005), we consider the landslide intensity (in terms of their volumes and velocities) and in addition, an area potentially affected by landslides. Moreover, we illustrate how the road deformation results obtained from satellite multi-temporal interferometry-MTI (see Wasowski and Bovenga, 2014 for background information) can be associated with detailed landslide maps to foster more reliable interpretations of MTI results and pin-point the sections of the road network affected by instability. The perimeters of the analyzed areas were drawn following a geomorphological criterion that delimits the ridges and the valley floors. The studied areas not only include the built-up zone but extend from the foot of the slopes to the hilltops, where the towns' historic centers are located. Hence, the most relevant elements at risk are included.

2 METHODS

2.1 Landslide mapping and classification

Landslide mapping was based on digital stereoscopic interpretation of black and white multi-temporal aerial photos. Such approach allows landslide mapping directly in a GIS environment and compile step by step the geodatabase related to the mapped features. For the analyzed areas, four sets of aerial photos in digital format were acquired from the Italian Military Geographical Institute (IGMI). Each set of aerial photos was analyzed by using dedicated software such as Erdas Imagine software, ArcGIS Software, and the open source software Qgis. The mapped landslides were classified following Cruden and Varnes (1996) and Hungr et al., (2014) and assigned the relative age with reference to the acquisition dates of the aerial photos. For each landslide, crown and deposit areas were distinguished. The recognition of the type of movement was based on the morphological characteristics of a landslide observed on aerial photos and in the field. The interpretation was also supported by the topographic information from a 1 m resolution LiDAR DTM of the Italian Ministry of Environment.

2.2 Landslide intensity assessment

Landslide intensity is assumed as a measure of the destructiveness of the landslide (Hungr 1997, Reichenbach et al., 2005), and is defined as a function of the landslide estimated volume and of the expected landslide velocity (Cardinali et al., 2002, Reichenbach et al., 2005). Combining the estimated volume with the estimated velocity it is possible to derive a qualitative assessment of the expected intensity. Such derived intensity index is represented by a two-digit code: the first one indicates the volume while the second indicates the velocity (Table 1).

Table 1. Volume and velocity classes used to estimate landslide intensity (after Cardinali et al., 2002).

		Estimated landslide velocity		
		Slow moving landslide (Slide, Earth Flow)	Rapid moving landslide (Debris Flow)	Fast moving landslide (Rock Fall)
Estimated Volume (m3)	<0.001			Slight (13)
	<0.5			Medium (23)
	>0.5			High (33)
	<500		Slight (12)	High (33)
	500-10000	Slight (11)	Medium (22)	High (33)
	10000-50000	Medium (21)	High (32)	Very High (33)
	>500000	High (31)	Very High (42)	
	>>500000	Very High (41)		

Considering the landslide characteristics, such as velocity, volume and mechanisms established through photo-interpretation and the repeated field visits to the study area in the last two decades, we estimated the plausible velocities for each of the mapped landslides.

The landslide volume was estimated based on the empirically-established relations area-volume (Innes 1983, Guzzetti et al., 2009 e Larsen et al. 2010), that take the general form of the equation (1):

$$V = \alpha \cdot A^{\gamma}, \qquad (1)$$

where V is the volume, A is the area and α and γ are coefficients.

In this case study application, the relation defined by Innes (1983) was used for flow type landslides, while the relation proposed by Guzzetti et al., (2009) was used for composite or compound slides.

The municipalities of Motta Montecorvino and Volturino are affected by slow-moving landslides, for this reason only four classes of intensity were identified (11, 21, 31, 41, in Table 1). For each intensity class, landslide hazard zones were defined by considering the possible future evolution of existing, mapped landslides (Cardinali et al., 2002; Reichenbach et al., 2005).

2.3 Landslide hazard zones

Landslides hazard zones are intended as areas of likely enlargement of the existing landslides or the occurrence of new landslides, based on the intensity and type of the movement, the state and style of activity of the existing landslides, the morphology of the slope, as well as the local geologic setting (Cardinali et al., 2002; Reichenbach et al., 2005). The definition of the hazard zones largely relies on geomorphological inferences, local knowledge and personal experience. In brief, we predict where and how (intensity) the existing landslides could evolve in a short-term period. The style of landslide activity documented via the analysis of the multi-temporal aerial photos is here of fundamental importance, and in particular the presence of the partial or total reactivations, involving lateral enlargements, retrogression or downslope movement propagation.

2.4 Roads

Road data were extracted from the Land Use Map of 2006 available at the regional cartographic database http://www.sit.puglia.it/portal/sit_portal. Then, this information was combined with landslide inventory data.

3 RESULTS

Road sections crossed by landslides were estimated by intersecting the landslide areas with the road networks (Figure 2). Subsequently, for comparative reasons, the outcomes were quantified as the percentage of the total road length. For the Motta Montecorvino and Volturino municipalities, the percentage of roads affected by landslides is very similar, respectively, 33.7%, and 34.7%. These numbers indicate the high susceptibility of the roads to damage due to landsliding.

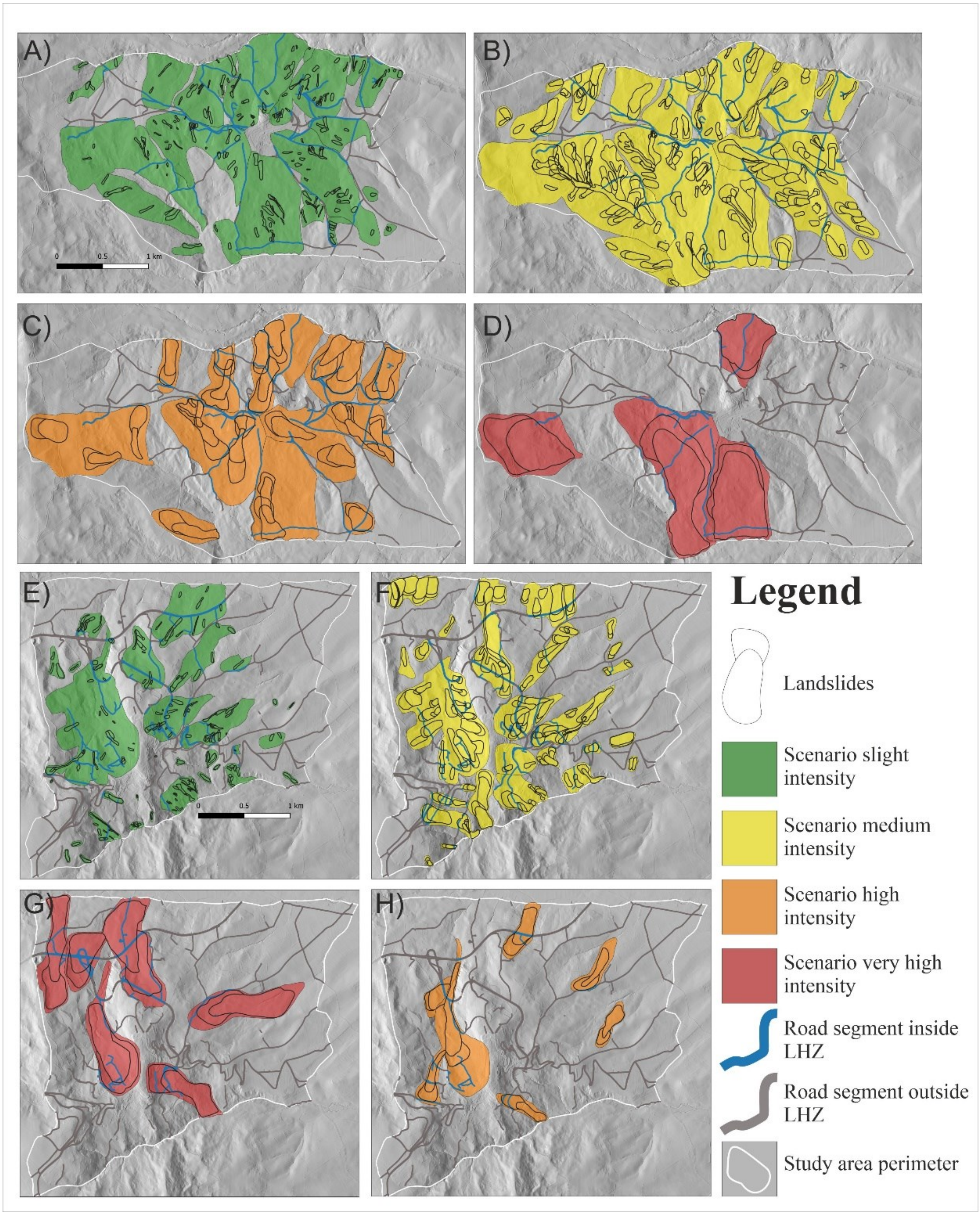

Figure 2. Roads potentially affected by landslides in Motta Montecorvino (A-D) and Volturino (E-H) areas according to different scenarios of landslide intensity (Slight A,E; Medium B,F; High C,G; Very High D,H); LHZ = Landslide Hazard Zone see Table 1 and text for explanations.

3.1 Potential impact of landslides on roads according to landslide hazard zones of different intensities

The hazard zonation data for different landslide intensities were intersected with the road network layer in order to evaluate where and how, in terms of the expected intensity, the roads could be affected by future landslide activity. Through this approach, we do not quantify the economic impact of landslides on roads, but assess, in relative terms, the potential negative influence of future landslide activity.

For both municipalities, the road sections falling into each scenario were quantified as the percentage respect to the total length of the road network (Table 2). Note that one road segment can fall into different landslide intensity scenarios.

Table 2. Proportion of roads falling into landslide hazard zones (LHZ) of different intensities in the municipalities of Motta Montecorvino and Volturino.

	Road distribution (in %) in landslide hazard zones (LHZ)	
Municipality	LHZ Intensity	total
Motta Montecorvino	Slight	61,5
	Medium	59,6
	High	24,1
	VeryHigh	18,1
Volturino	Slight	28,3
	Medium	33,4
	High	9,7
	VeryHigh	22,2

Analyzing scenarios for different landslides intensities (LHZ), we observe that the percentages vary from 61% (slight intensity) to 18% (very high intensity) in the Motta Montecorvino area, and from 28% to 22% in the Volturino area (Table 2). In fact, the higher landslide intensity scenarios cover more restricted areas, typically linked to a potential enlargement of a single landslide. Conversely, the lower landslide intensity scenarios (slight and medium) form some clusters that are generally more widespread involving a larger portion of a slope.

Comparing the two municipalities, we note that, in general, a higher proportion of the Motta Montecorvino road network is present in various landslide intensity scenarios (Table 2). This difference is much less evident when considering only the extent of the landslide areas (Figure 2).

3.2 Combining satellite interferometry and landslide inventory data

Here we consider the MTI surface displacement results available for the Volturino area (Wasowski and Bovenga, 2015a) together with the multi-temporal landslide inventory data (Figure 3). The MTI results rely on the high-resolution (3 m) X-band radar satellite imagery, which proved to be particularly useful for monitoring stability of engineering structures such as buldings, roads, dams (e.g., Wasowski and Bovenga, 2014; Wasowski et al., 2015b).

Figure 3 shows six road sections marked by the presence of extremely slowly (few mm/year) moving radar targets, which are indicative of local instabilities. The comparison of their locations with the landslide inventory map demonstrates that five of the road sections fall within the landslide bodies and one section is adjacent to a landslide. Thus, such a simple integration of information can directly aid the interpretation of MTI results and help identify the possible causes of road instability. In the cases examined (Fig. 3), the MTI-detected displacements could be related to post-failure “creep” of old (pre-1954) landslides or localized ground deformations within the pre-existing landslide bodies.

4 CONCLUDING REMARKS

This study showed that well over 30% of the roads (in terms of their total length) in the Motta Montecorvino and Volturino municipalities cross different age landslides. The potential future impacts of landslides on road network were estimated by associating the landslide intensity (based on their movement volume and velocity) with the LHZ maps. These maps take into account the likely enlargement of the pre-existing landslides and the occurrence of new landslides. The resultant landslide hazard scenarios indicated that the Motta Montecorvino road network could be more impacted in the future with respect to that of Volturino. Moreover, the MTI results integrated with the multi-temporal landslide inventory data revealed that the recently unstable road sections are spatially associated with old landslide deposits. Finally, we stress that the method has an empirical structure, and it presents some limitations attributable to the expert-based interpretation throughout the multiple steps.

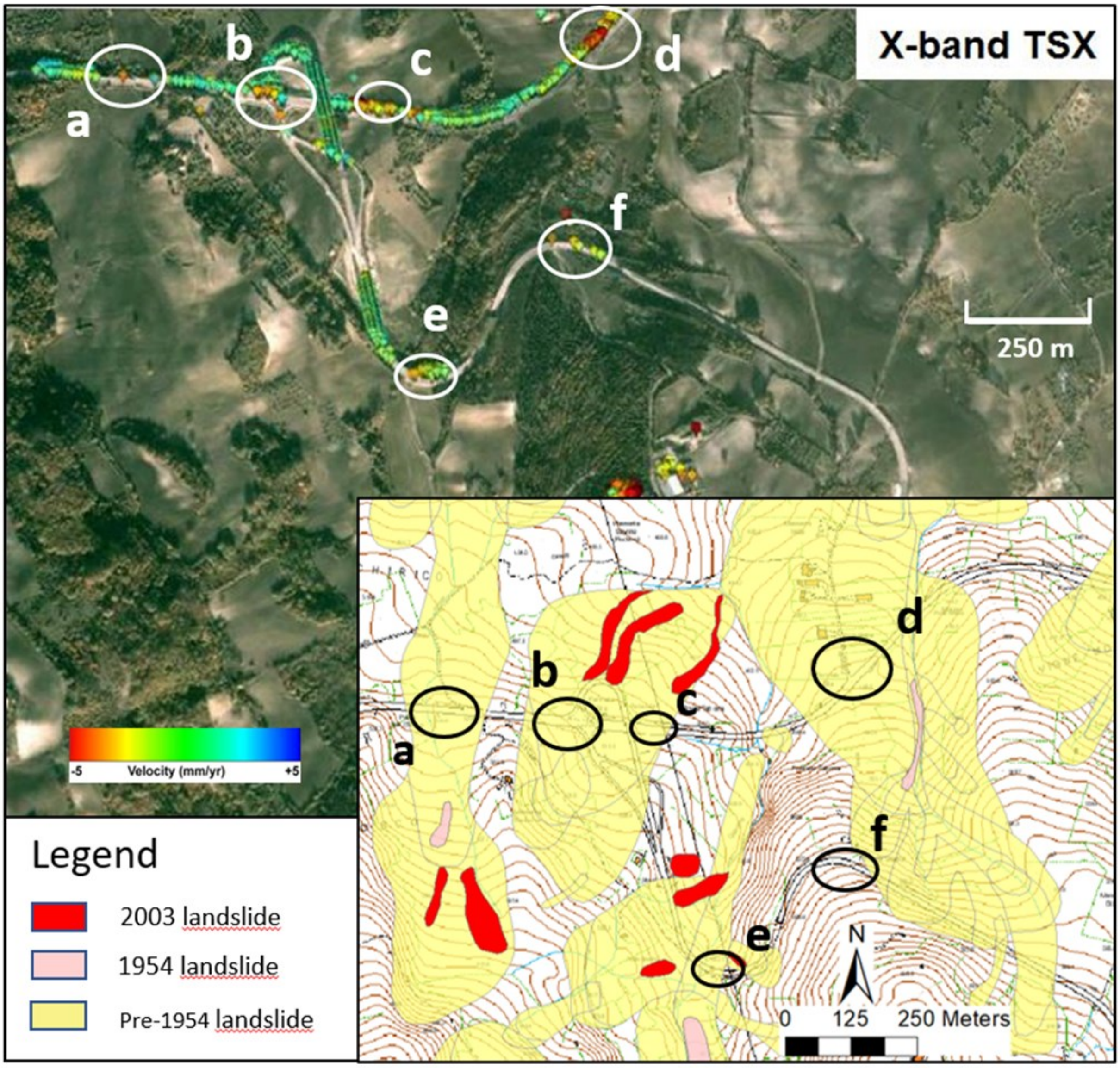

Figure 3. Upper: Google Earth image highlighting road sections (a – f) with moving radar targets (reddish-yellowish color dots) in northern part of Volturino municipality (multi-temporal interferometry – MTI data from Wasowski and Bovenga, 2015a); TSX stands for high resolution TerraSAR-X radar satellite; Lower: Portion of multi-temporal landslide inventory map of the same the area shown in the upper image. The highlighted road sections are spatially associated with old landslides.

However, it is a useful approach when no quantitative data are available or when large areas must be analyzed. Of course, the results obtained through this empirically-based method can guide further efforts relying on quantitave analysis.

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The Authors declare that they do not have Conflict of Interest with the contents and authorize the Editorial Committee of XIII ISL to publish the paper during the next two years, according of Authors Instructions.

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