Landslide-risk scenario of the Costa Viola mountain ridge (Calabria, Southern Italy)

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Abstract

The study area of the Costa Viola mountain ridge is strongly exposed to shallow landslides triggered by rainfall. Starting from a susceptibility map, recently published by the same team, the related risk has been assessed, limitedly to landslide sources. The hazard has first been evaluated by considering the recurrence periods of triggering events. Economic value and physical vulnerability of the types of elements at risk have been assumed by considering land-use and the effects of similar events in Southern Italy, respectively. The 1:30,000-scale risk map (Main Map) has been produced by combining the above-mentioned layers. Low risk prevals in the study area, whilst the highest values are concentrated along the coast, where villages and the main infrastructure are located. The expected annual damage exceeds 570 million € (about 68% pertaining to low-risk cells). Risk maps produced through similar simplified geographic information system-based procedures may play a crucial role in accurate land-use planning and effective decision-making.

1. Introduction

Shallow landslides are among the most damaging natural hazards in terms of economic losses and casualties. Such phenomena are characterized by rapid dynamics and are widespread worldwide. As for other types of dangerous phenomena, in addition to direct damage – for example, those caused to buildings, transport infrastructure, agricultural crops, water supply networks, and sewerage and communication systems – indirect damage should be considered: for instance, conspicuous financial losses may occur due to the inability to use assets not directly affected by the landslides. Events characterized by the activation of widespread shallow landslides may hamper economic and social development for years after their occurrence. Furthermore, the same area may be affected by recurrent landslide events due to its intrinsic exposure to predisposing (e.g. steep slopes and lithology) and triggering factors (e.g. intense rainfall and seismic shocks).

Aimed at assessing hazard and risk, the evaluation and mapping of spatial triggering mechanisms of shallow landslides – that is, ‘source susceptibility’ – must first be accomplished. If a significant propagation downslope of the landslide source is expected (e.g. in case of soil slip-debris flow transition), the ‘propagation susceptibility’ must also be evaluated (Iovine, 2012). The occurrence of shallow landslides is usually strictly related to external triggering factors: therefore, hazard evaluations can be performed based on recurrence probabilities of the causal factors (e.g. rains or earthquakes), which can be estimated by statistical analyses of time series data. Finally, when the vulnerability and economic value of the elements exposed to risk are known, a further, multidisciplinary step towards total risk assessment can be undertaken (Dai, Lee, & Ngai, 2002; Gaprindashvili & van Westen, 2016; Varnes and IAEG Commission on Landslides and Other Mass Movements on Slopes, 1984).

Due to its geological history, and to present climatic and seismic characteristics, Calabria (Southern Italy) is mostly prone to shallow landslides (Carrara, Sorriso-Valvo, & Reali, 1982; Pellegrino & Borrelli, 2007). In fact, prolonged rainfall and rainstorms frequently occur; earthquake catalogues record several high-magnitude events over the last few centuries; weathered and tectonized terrains diffusey crop out along steep slopes cut by the hydrographic network on actively uplifted massifs. In Calabria, shallow landslides are mostly triggered by severe rain (Terranova & Gariano, 2014; Vennari et al., 2014). The frequency and intensity of rainstorms have increased in recent years, despite a reduction of annual rainfall amounts, due to the occurrence of medicanes favoured by the interaction between warm sea and rugged orography. A recent investigation allowed the identification of numerous landslide events that affected either small areas or large parts of the...
Calabrian territory over the last few decades (cf. Iovine, Greco, Gariano, Pellegrino, & Terranova, 2014, and references therein).

In this study, an example of rainfall-induced shallow-landslide risk evaluation at source locations is proposed for the Costa Viola mountain ridge (Calabria). The analysis is based on 'source susceptibility' evaluation, given the limited run-out generally observed in historical cases that have occurred in the study area. Recurrence periods of the triggering events were obtained through hydrological analyses of annual maxima of daily rainfall. The economic value of the elements at risk were assumed based on land-use. Physical vulnerability was obtained by taking into account the types of existing elements and intensities of expected phenomena, together with effects of similar events that have occurred in Southern Italy. The resulting risk map (at 1:30,000 scale) has been produced by combining, in a geographic information system (GIS), the above-mentioned layers.

2. Study area

The Costa Viola mountain ridge extends approximately 82 km² along the SW coast of Calabria. The area includes short high-gradient drainage basins (the widest are named Favazzina and Sfalassà), which flow into the Tyrrhenian Sea between the villages of Scilla and Bagnara Calabra (Figure 1). The Palaeozoic basement of the area is mainly made of middle-high-grade metamorphic rocks and acid intrusive rocks, strongly tectonized and deeply weathered (Figure 2). The sedimentary cover (Late Miocene to Holocene deposits) unconformably lies on the basement, and is made of: conglomerate, arenite, clay, and marl with subordinate evaporite (Late Miocene-Middle Pliocene); sand and conglomerate, generally terraced (Middle Pliocene-Middle Pleistocene); alluvial and coastal gravel, sand, silt, and clay (Late Pleistocene-Holocene).

At the base of the mountain ridge, a NE–SW trending fault system is to be found. Such tectonic structures belong to the Calabrian–Sicilian Rift Zone, an active regional fault system that permitted the uplift of the Costa Viola with respect to the Tyrrhenian basin since Middle Pleistocene (Tortorici, Monaco, Tansi, & Cocina, 1995). In the area, seven orders of marine terraces were recognized along the Tyrrhenian coast (Tortorici et al., 2002 – cf. Figure 2(b)), as a result of the combined effects of regional uplift and eustatic sea-level changes.

Extensive flat areas characterize the study area, bordered by steep slopes and cut by deep canyons. Short high-gradient torrents, characterized by ephemeral discharges and flash floods, drain the western slope of the ridge. Along the densely urbanized coast, steep cliffs delimit outcrops of narrow and discontinuous deposits (alluvial/colluvial and marine).

In the area, average yearly rainfall varies between 600 and 900 mm y⁻¹ (Terranova, 2004; Terranova & Iaquinta, 2011). At the Scilla rain gauge, located by

![Figure 1](image-url). Location (a and b), and main villages and infrastructure of the study area (c). Elevation classes in (b) are: dark green, 0–500 m a.s.l.; light green, 501–1000 m a.s.l.; brown, 1001–2260 m a.s.l.
the coast and characterized by the longest available data record (from 1939 to 2015), annual amounts range from 507.2 to 1270.6 mm (mean 782.3 mm), mainly concentrated between October and March (ca. 74% of the annual amount). The maximum daily rainfall (147.8 mm) was recorded at Scilla-Solano on 1 November 2015.

The study area is scarcely urbanized. The only villages are Bagnara Calabra and Scilla: the first is located in the widest portion of the above-cited coastal deposits, whilst the ancient settlement of Scilla lies on a small rocky outcrop facing the sea with recent development by the coast. The main infrastructure are mostly to be found in the coastal sector: the railway, the highway (A3 ‘Salerno-Reggio di Calabria’), and the southern Tyrrhenian state road (SS.18) extend along a narrow strip.

In the study area, shallow landslides are mainly represented by debris slides and earth slides (often called ‘soil slips’, sensu Campbell, 1975; see also Cruden & Varnes, 1996), that commonly show limited run-out (~10 m). Subordinately, rock falls and debris flows are also to be found, characterized by greater run-out and destructive power; larger slope movements of various types are also present. As a whole, the run-out of the mapped landslides is ~50 m.

Over the last 75 years, several slope instability events affected the study area (~0.6 events per year, cf. Figure 3), mainly related to debris slides, rock falls and, subordinately, debris flows, that damaged rural areas and the secondary road network. In the last 20 years, a remarkable increase of frequency of damaging events can be noted (up to ~1.3 events per year). On 12 May 2001 and 31 March 2005, in addition to numerous debris slides that struck the innermost portion of the study area, debris flows severely affected urbanized areas and the main transport infrastructure, causing train derailment (Bonavina et al., 2005). As an approximate underestimation of the economic loss produced by shallow landslides (except for debris flows) since 2001, the funds for remedial works allocated by either national or regional authorities amount to ~9.5 Million € (Basin Authority of Calabria – unpublished data).
Despite evidence of hydraulic erosion and shallow instabilities on the slopes, the return periods ($T$) of the rainfall recorded at the Bagnara Calabra and Scilla rain gauges over the last two decades are not notable, possibly due to the location of the rain gauges with respect to the rain cell centres. For instance, those related to the events occurred in 2001 and 2005 are not worthy of note ($T < 2$ y for daily maxima); low values ($T \sim 3$ y) also characterize rainfall recorded from 2008 to 2010, with $T < 14$ y for rainfall recorded at Scilla in 2011. Further similar events followed in recent years, the strongest thereof recorded at Bagnara Calabra on 31 October 2015 ($T \sim 75$ y).

3. Method and application

Aimed at evaluating shallow-landslide risk triggered by rainfall, source susceptibility was first analysed – based on a 20-m square-grid digital terrain model (DTM) – by means of logistic regression (LR), as discussed in Iovine et al. (2014). For this purpose, a multi-temporal inventory map of shallow landslides (at 1:10,000 scale) was employed, obtained through interpretation of two sets of aerial photographs (taken in 1954–1955 and in 1990–1991) and field surveys. Note that only source susceptibility was taken into account, whilst rock falls and debris flows (and, therefore, run-out issues) were ignored.

In particular (Figure 4), a first sample (made of 181 sources affecting $\sim121,689$ m$^2$, mapped through interpretation of the 1954–1955 photos) was used as a ‘training set’; a second sample (made of 81 cases affecting $\sim30,590$ m$^2$, recognized by analysing the 1990–1991 photos) was employed as a ‘validation set’. Based on previous studies in the same region (Iovine et al., 2013; Sorriso-Valvo, Greco, & Catalano, 2009), a set of 11 variables was selected (Table 1).

Shallow-landslide source susceptibility, in terms of probability $P(y)$, can be expressed as:

$$P(y) = \frac{1}{1 + e^{-(a_0 + \sum_{i=1}^{n} a_i x_i)}} = \frac{e^y}{1 + e^y},$$

where

- $y = a_0 + a_1 x_1 + \ldots + a_n x_n$;
- $x_1, \ldots, x_n$ is the set of $n$ explanatory independent variables (i.e. the causal factors);
- $a_0$ is the intercept;
- $a_1, \ldots, a_n$ are unknown partial regression coefficients, that can be estimated from the data using the maximum likelihood method, representing the weights of the independent variables $x_1, \ldots, x_n$.

The performance of the model was evaluated by means of the receiver operating characteristics (ROC) analysis (Hosmer & Lemeshow, 1989), by calculating and comparing the area under the curve (ROC-AUC). The susceptibility map is characterized by a ROC-AUC of 87.1% and 98.1% with respect to the...
calibration and validation sets, respectively. The values of the regression coefficients, $a_i$, are listed in Table 2 (intercept $= -7.982$).

Based on a hydrological analysis of the annual maxima of daily rainfall, the recurrence periods of the triggering events occurring in the study area could be computed. It was assumed that the probability of shallow-landslide activation depends, above a given threshold, on that of the above-mentioned maxima. Recently, Vennari et al. (2014) defined empirical rainfall thresholds for shallow-landslide occurrence in Figure 4.

Table 1. Independent variables considered in this study.

| Factor                  | Categories                                                                 |
|-------------------------|---------------------------------------------------------------------------|
| Topographic factors     | Elevation (ELEV, from 20 m-DTM): 8 intervals of 200 m                    |
|                         | Slope angle (SLO, from 20 m-DTM): 6 intervals of 10 degrees              |
|                         | Aspect (ASP, from 20 m-DTM): 5 classes (flat, North, East, South, West) |
|                         | Downslope curvature (DCUR, from 20 m-DTM): 3 classes (concave, plane, convex) |
|                         | Topographic wetness index (TWI, from 20 m-DTM): 4 classes ($\leq 3$; $3-6$; $6-9$; $>9$) |
| Hydrological factors    | Rainfall anomaly (DR, from probabilistic regional analysis of daily annual maxima): 5 classes ($\leq 1.0$; $1.0-1.1$; $1.1-1.2$; $1.2-1.3$; $>1.3$) |
| Human-affected factors  | Land-use (LUS, from Corine land cover IV level): 9 land-use categories (discontinuous urban fabric; cultivation area; fruit trees and berries plantations; olive groves; discontinuous grassland; sparsely vegetated areas; transitional woodland-shrub; high Mediterranean mastic forest) |
|                         | Distance to road (RDIST, from road maps and field checks): 3 classes ($\leq 200$; $200-400$; $>400$ m) |
| Geo-lithological and pedological factors | Lithology (LU, from 1:25,000 geological map): 5 units (gravel, colluvium and debris; sand; conglomerate; acid intrusive rock; middle-high-grade metamorphic rock) |
|                         | Distance to fault (FDIST, from 1:25,000 geological map): 3 classes ($\leq 300$; $300-600$; $>600$ m) |
|                         | Soil sand percentage (SSP, from 1:25,000 pedological map): 4 classes ($\leq 55$; $55-65$; $65-75$; $>75$) |

Note: DR is a synthetic measure of the spatial and temporal variability of the annual maxima of daily rainfall, computed by means of regional statistical analyses for the entire Calabrian territory (Iovine et al., 2014).

Table 2. Regression coefficients, $a_i$, for each considered variable, maximum probability, $P(y)$ and area under curve, ROC-AUC (after Iovine et al., 2014, mod.).

| Variable | $a_i$ |
|----------|-------|
| LU       | 0.037 |
| LUS      | 0.036 |
| SSP      | -0.052 |
| ELEV     | 0.025 |
| SLO      | 0.032 |
| ASP      | 0.044 |
| DCUR     | 0.046 |
| TWI      | 0.011 |
| RDIST    | 0.019 |
| DR       | -0.015 |
| Max P(y) (%) | 81.3 |
| ROC-AUC (%) | 87.1 |
Calabria, at regional and sub-regional scales, using hourly rainfall data recorded at 192 rain gauges (i.e. 1 station per 78.5 km², unevenly covering the Calabrian territory): as for the Tyrrhenian sector, an amount of about 30.5 mm d⁻¹ was obtained, related to an estimated return period of ~1 y. Generally, results of such regional studies are affected by the density of the rain gauge network with respect to the average size of the convective cells (Penna, Borga, Aronica, Brigandi, & Tarolli, 2014). Moreover, the role of antecedent rainfall in determining the amount of rainfall needed to trigger shallow landslides is controversial (Rahardjo, Leong, & Rezaur, 2001). In some cases, its weight was considered significant (cf. the Wellington City case study, New Zealand – Crozier, 1999), while in other cases it could be neglected because of small soil depth or high soil permeability (cf. the Hong Kong case studies, caused by suction reduction – Brand, 1995).

Two rain gauges (Scilla and Bagnara Calabra) are to be found in the study area, managed by the Calabrian Regional Agency for Environmental Protection (ARPCAL), characterized by 73 and 49 years of daily records. From Table 3, similar hydrological features can be observed for the two rain gauges: therefore, the Scilla record can be assumed as representative of the study area. In addition, the Global Extreme Value (GEV, Jenkinson, 1955) distribution probability function was selected to interpret the series of daily annual maxima, as confirmed by the test of Anderson and Darling (1952).

Aiming at determining the return time ($T$) of daily annual maxima able to trigger shallow landslides in the study area, a tentative reference value ($Tr = 10$ y) was assumed. Based on GEV results, a fractile of 83.1 mm of daily rain corresponds to $Tr$ for the rain gauges of the study area. In Table 4, occurrences with $T > Tr$ are listed for Scilla and Bagnara Calabra: a marked spatial variability of rainfall can be appreciated in some cases; values of $T$ range from 10 to over 100 y. The historical maximum occurred in 1988 (i.e. 2–3 years before the flight used for validation), whilst maximum daily rainfall recorded in 1948 and 1951 have $T = 20.4$ and $24.4$ y, respectively. Annual maxima of daily rainfall from 1947 to 1955, and from 1974 to 1988, may be considered responsible for the slope movements recognized in the 1955 and the 1990 flights (i.e. those employed for calibration and validation), respectively. As a result, the susceptibility map obtained by taking into account the calibration set of shallow landslides can be related to triggering rains with about a 20 y of return period, therefore depicting a hazard scenario ($H$) with $T = 20$ y (cf. $H$ in Figure 5).

The hazard was derived from the original (unclassified) susceptibility map. In theoretical terms, the probability of occurrence, $P$, of an event (e.g. a rainfall able to trigger a given type of landslide) can be obtained from its return period, $T$, as: $P = 1/T$. Hazard related to an event of given intensity can also be computed from the classical formula $H = 1 - (1 - (1/P))^N$, in which $N$ is the extent of the considered temporal window (cf. e.g. Gostelow, 1992). Nevertheless, information needed for such types of evaluation are commonly inadequate in landslide analyses at regional scale. Hence, either approximated or empirical approaches must be adopted. In the present study, hazard was computed from susceptibility values, by considering the ca. 20 y return period of the triggering rainfall responsible for the landslide population used for calibration: Susceptibility values were then adopted as a proxy for hazard with respect to a scenario of 20 y, being assumed representative for the temporal window.

### Table 3. Statistics of annual maxima of the daily rainfall at Scilla and Bagnara Calabra.

| Statistics            | Scilla | Bagnara Calabra |
|-----------------------|--------|-----------------|
| Sample size (years)   | 73     | 49              |
| Min (mm)              | 20.2   | 21.0            |
| Max (mm)              | 125.5  | 120.0           |
| Range (mm)            | 105.3  | 99.0            |
| Mean (mm)             | 56.1   | 53.7            |
| Variance (mm²)        | 412.9  | 422.1           |
| St. dev. (mm)         | 20.3   | 20.5            |
| Coefficient of variation | 0.36 | 0.38           |
| Standard error (mm)   | 2.38   | 2.93            |
| Skewness (–)          | 0.96   | 1.08            |
| Kurtosis (–)          | 0.95   | 1.20            |
| Percentile (mm)       |        |                 |
| 5%                    | 30.0   | 29.0            |
| 10%                   | 32.4   | 31.1            |
| 25% (q1)              | 41.4   | 40.7            |
| 50% (median)          | 52.3   | 51.0            |
| 75% (q3)              | 65.4   | 64.7            |
| 90%                   | 89.7   | 87.2            |
| 95%                   | 96.0   | 94.3            |
| Gev parameters        |        |                 |
| $K_{gev}$             | 0.023  | 0.0655          |
| $\Sigma_{gev}$ (mm)   | 15.78  | 15.22           |
| $M_{gev}$ (mm)        | 46.64  | 43.88           |

### Table 4. Maximum daily rainfall (in mm) and return periods ($T$, in y) of events with $T > Tr$.

| Year | Scilla $T$ | Bagnara Calabra $T$ |
|------|------------|----------------------|
| 1929 | –          | 120.0                |
| 1930 | –          | 90.5                 |
| 1931 | –          | 98.0                 |
| 1947 | 86.0       | 90.3                 |
| 1948 | 98.6       | 69.9                 |
| 1951 | 95.3       | 57.8                 |
| 1954 | 97.5       | 87.2                 |
| 1955 | 90.8       | 69.8                 |
| 1974 | 95.3       | 44.0                 |
| 1977 | 51.2       | 86.1                 |
| 1982 | 91.1       | 15.4                 |
| 1988 | 125.5      | 111.1                |
| 2011 | 88.0       | 13.3                 |
| 2015 | 122.4      | 88                   |

Notes: Annual maxima of daily rainfall from 1947 to 1955, and from 1974 to 1988, may be considered responsible for slope movements recognized in the 1955 and 1990 flights employed for calibration and validation, respectively. Further cases with $T > Tr$ are listed in italics. Asterisks mark the greatest discrepancies among return periods of the rain gauges. Dashes mark unavailable data. Maximum values are shown in bold.
Economic value ($W$) of the elements at risk were calculated (Table 5, second column) based on land-use. Values were assigned from market surveys (mainly for buildings), construction costs for transport infrastructure, and asset values compared with the results of market surveys for agricultural and urban uses. Note that the adopted economic values span a range of four orders of magnitude.

By taking into account previous events that had occurred in the same environment (Bonavina et al., 2005; Iovine et al., 2014), the potential propagation of soil slips in form of debris flows (run-out) could be ignored. In addition, based on intensities of expected phenomena and on the effects of previous shallow-landslide events that had occurred in Southern Italy in the last few decades (Sarno, May 1998; Soverato, September, 2000; Messina, October 2010 – cf. Antronico, Gullà, & Terranova, 2002; Ardizzone et al., 2012; Iovine, Terranova, & Gariano, 2009; Sorriso-Valvo et al., 2004), physical vulnerability ($V$) were assumed for the types of elements at risk recognized in the study area (e.g. buildings, roads, agricultural crops – cf. Table 5, third column). Vulnerability values, determined by expert knowledge, range from 0.1 to 0.9.

Accordingly, the potential worth of loss ($W_L = V \times W$) could be computed (Table 5, last column; cf. $W_L$ in Figure 5). By considering the variability in space and time of land-use in the study area, values of $W_L$ were ranked into 4 classes: $W_L < 10$; $10 \leq W_L < 100$; $100 \leq W_L < 1000$.

Given the unavoidable uncertainties affecting the considered parameters (mainly, $W$ and $V$), the median values of the $W_L$ class were used in the next step of risk evaluation. Based on the above assumptions and computations, the total risk scenario ($R$), related to triggering rainfall characterized by $T = 20 \text{ y}$, could be evaluated as hazard ($H$) times potential worth of loss ($W_L$) for each cell of the computational domain. Obtained values of expected damage per year range from less than 1 cent to over 400 € m$^{-2}$ (cf. $R$ in Figure 5).

Note that, in the present study, hazard and physical vulnerability scenarios were actually hypothesized. Therefore, the results described in the following section should be considered in terms of methodological example.

### 4. Results and conclusions

The shallow-landslide risk map (Main Map) of the Costa Viola mountain ridge shows prevailing low values (expected damage $\leq 11$ € m$^{-2}$ y$^{-1}$), with the highest risk mainly concentrated along the coast (up to $401$ € m$^{-2}$ y$^{-1}$), including the urbanized areas of Scilla and Bagnara Calabra. As the extent of each cell is $400$ m$^2$, an annual damage of about $150,000€$ is expected for the cells exposed to the worst risk conditions (cf. 3 points on the right in Figure 6). As a whole, the expected annual damage in the study area exceeds $570$ million €; about $68\%$ of such an amount pertains to the cells exposed to the lowest risk values (i.e. $5$ € m$^{-2}$ y$^{-1}$).

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**Table 5.** Types of elements ($E$) at risk in the study area, with economic values ($W$, in € m$^{-2}$), assumed physical vulnerabilities ($V$), and worth of loss ($W_L$, in € m$^{-2}$), with respect to shallow landslides.

| $E$                  | $W$  | $V$  | $W_L$ |
|---------------------|------|------|-------|
| House               | 1600 | 0.30 | 480   |
| School              | 1500 | 0.50 | 750   |
| Shop and repository | 850  | 0.90 | 765   |
| Urban area          | 1500 | 0.30 | 450   |
| Highway             | 800  | 0.10 | 80    |
| Railway             | 1000 | 0.30 | 300   |
| State road          | 400  | 0.20 | 80    |
| Province road       | 300  | 0.20 | 60    |
| Municipal road      | 150  | 0.25 | 37.5  |
| Secondary road      | 50   | 0.50 | 25.0  |
| Cultivation area    | 2.20 | 0.90 | 1.98  |
| Fruit plantation    | 3.70 | 0.80 | 2.96  |
| Olive groves        | 3.35 | 0.80 | 2.68  |
| Discontinuous grassland | 0.14 | 0.90 | 0.13  |
| Sparsely vegetated areas | 0.30 | 0.90 | 0.27  |
| Transitional woodland-shrub | 0.80 | 0.90 | 0.72  |
| High Mediterranean macchia | 0.60 | 0.80 | 0.48  |
| Forest              | 1.10 | 0.70 | 0.77  |

Note: In bold and italics, the maximum and minimum values are evidenced, respectively.
According to the present analysis, in the study area the worst expected annual damage related to activation of rainfall-induced shallow landslides is therefore to be found along the coastal sector. It must be underlined that most of the transport infrastructure and urbanized sectors fall in the riskiest zones, along the narrow coastal strip of land at the base of the mountain ridge. Here, severe rainfall events have frequently triggered shallow landslides in the last two decades (on average 1.3 events per year), causing notable damage to both public and private property (in several cases, also with debris propagation downstream). A rough estimate of the damage caused along the secondary road network exceeds 10 million €. In fact, such meteorological events, despite characterized by high return periods at local scale, are now recorded more often in the Mediterranean area due to climate change. Consequently, expected cumulative costs over time are significant.

The risk map (Main Map) was produced through a simplified, GIS-based approach. The adopted procedure is based on source susceptibility and neglects run-out issues, thanks to the observed behaviour of most debris slides triggered in the study area. All the thematic layers used to compute risk are affected by varying degrees of uncertainty, that may be reduced when more accurate information is available.

In general, susceptibility maps depend on adopted modelling techniques (e.g. artificial neural networks, support vector machines, etc.), and on methods used for selecting factors and subsampling data for calibration/validation (cf. e.g. Corominas et al., 2014; Guzzetti, Reichenbach, Ardizzone, Cardinali, & Galli, 2005; Pradhan, 2013; Petschko, Brenning, Bell, Goetz, & Glade, 2014). Physical vulnerability and the economic value of the elements at risk may be obtained through more detailed surveys and also considering their variation in time (e.g. due to urban development, innovative building techniques). Further uncertainties originate from geomorphological mapping of landslide inventories, and probabilistic analyses of hydrological data. Overall, such types of uncertainties generally affect any risk evaluation: in the present study, a simplified approach has been adopted to handle input layers affected by significant uncertainties and/or temporal variations.

The performed analysis refers to a temporal window of 20 years, based on hydrological considerations. By refining historical investigation, the evaluation of $T$ of the triggering rainfall could be improved. Moreover, economic values for land-use and physical vulnerabilities may be updated and determined in greater detail, taking into account their temporal fluctuation. Finally, run-out issues may be included to consider the additional risk posed by the possible propagation of high-mobility types of phenomena (e.g. debris flows) – even though they are not very common in the study area.

Many historical centres of Calabria have been suffering from geo-hydrological instability in the last few centuries. Since the beginning of the twentieth century, some centres were declared eligible for significant remedial work or relocation. Starting in the 1950s, remarkable population growth and urban development has caused abandonment of rural areas and small settlements, whilst new areas have been urbanized. Quite often, new settlements were established in hazardous areas, previously discarded, even in spite of legal constraints (followed by amnesties). As a result, landslides severely limit economic and social growth. In such an environmental context, risk analyses and
maps – obtained through simplified GIS-based procedures, as the ones presented in this study – may play a crucial role in view of more accurate land-use planning and effective decision-making.

**Software**

Mapping was carried out using Esri ArcMap 10.1; minor editing was performed using Adobe Photoshop CS5.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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