Research Article

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National and regional-scale landslide indicators and indexes: Applications in Italy

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Abstract: Indicators and indexes are quantifiable parameters used in scientific disciplines to summarize and communicate complex data in a simple and explanatory manner. In the field of natural hazards, indicators and indexes have been used to characterize natural processes, and the associated risk conditions in terms of impact, vulnerability, exposure, and resilience. In this paper, we formalize indicators at the municipal level to differentiate the Italian territory based on the spatial distribution of landslides. The indicators were combined with other information to define indexes able to better characterize the stability conditions of the municipalities and quantify the possible impact of slope movements on the road network. Indexes were defined only for the Umbria Region (Central Italy), which was chosen as an example. The proposed indicators and indexes show, in a simple way, the severity of the instability on the territory and can be used to support decision-makers to assess, evaluate, and manage landslide mitigation activities and civil protection actions.

Keywords: landslide, environmental indicators and indexes, Italy

1 Introduction

The use of indicators and indexes is commonly utilized in the scientific disciplines to summarize and communicate complex data, often referred to wide study regions, in a simple and explanatory manner. In the literature, the terms indicator and index are frequently used as synonyms, despite the two words express different concepts. According to ref. [1], an indicator can be useful to assess the status/health of a system (economic, physical, biological, and human) and to translate a concept/phenomenon into a quantitative/qualitative form, in order to simplify the information and make it more accessible to an audience of non-specialists [2].

Complex environmental processes and their trend can be evaluated and monitored using indexes that can be defined as a combination of indicators [3]. As an example, the global Multidimensional Poverty Index that provides a measure of the poverty is derived by the combination of 10 indicators that evaluate health, education, and standard of living [4]. Different approaches to define the relationships between indicators and indexes have been suggested in the literature, especially in the definition of the rules chosen to aggregate indicators in indexes [5]. We accept the relationship proposed in ref. [6], where variables are located at the base of a pyramid, indicators are in a higher position, and indexes are at the vertex.

In the literature on natural hazards, indicators and indexes are used to characterize processes and phenomena, quantify risk conditions (i.e., flooding, seismic events, coastal erosion, landslides, and droughts), and evaluate the interactions between processes and population, in terms of impact, vulnerability, exposition, and resilience [2,5,7,8]. For landslides, indicators and indexes are defined mainly to quantify the risk [9–12]. As an example, Castellanos Abella and Van Westen [9] proposed a landslide risk index at a national scale for Cuba starting from 10 indicators of hazard (i.e., slope, land use, geology, rainfall, and earthquakes) and vulnerability (housing, transportation, population, production, protected areas). To obtain the index, the 10 indicators were weighted and combined, and the results were aggregated at provincial and municipal scales to support national decision-makers in managing funding for risk assessments. Puissant et al. [7], for the Barcelonnette Basin (South French Alps), proposed an index that combines direct (physical injury, and structural/functional damage) and indirect (socio-economic) impacts to obtain a map of total landslide impact.

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In Italy, Trigila et al. [13] proposed a set of risk indicators at municipal scale relating the distribution of landslide and flood (PAI – *Piano di Assetto Idrogeologico*, River Basin Plans from www.isprambiente.gov.it) with both the census (i.e., population, companies, families, buildings from www.istat.it) and the cultural heritage data (www.icr.beniculturali.it). Similar indicators were proposed by ISTAT and *Casa Italia* (www.casaitalia.governo.it) for different natural hazards. Donnini et al. [14], for the Umbria Region (Central Italy), proposed an evaluation of the economic exposure to landslides relating the susceptibility map [15] with the real estate market values (*Osservatorio del Mercato Immobiliare* 2018; www.agenziaentrate.gov.it) and the building density (www.istat.it). Salvati et al. [16] implemented a tool to acquire vulnerability indicators useful to identify possible criticalities to geo-hydrological events. Moreover, Segoni and Caleca [17] proposed a set of environmental indicators, developed from the combination of landslide susceptibility zonation and soil sealing/land consumption maps, to estimate landslide risk in Italy.

In this article, we define indicators and indexes able to describe the characteristics of the territory related to landslides' spatial distribution and their potential impact along the road network, to support land management and civil protection activities. The article is organized as follows. In Sections 2 and 3, we introduce the study areas and the description of the available thematic data. In Section 4, we describe the applied methodology, and in Section 5, we present the results. Section 6 discusses the main outcomes and Section 7 outlines the most relevant conclusions.

2 Study areas

We have selected Italy for the definition of landslide indicators and the Umbria Region (Central Italy) for the indexes. Italy extends for 302,068 km^2 in the middle of the Mediterranean Sea, and is formed by a NW–SE verging peninsula and two main islands. According to the 2019 national census (www.istat.it), the territory is subdivided into 20 regions and 7,926 municipalities with different areal extensions (Figure 1).

The national census classifies the municipalities into five elevation classes: plain, coastal hill, inland hill, coastal mountain, and inland mountain (Figure 2a). According to this classification, the majority of the territory (87.1%) is classified as inland mountain (33.63%), inland hill (30.30%), and plain (23.17%), and only a small part (12.9%) as coastal hill (11.34%) and coastal mountain (1.56%). As

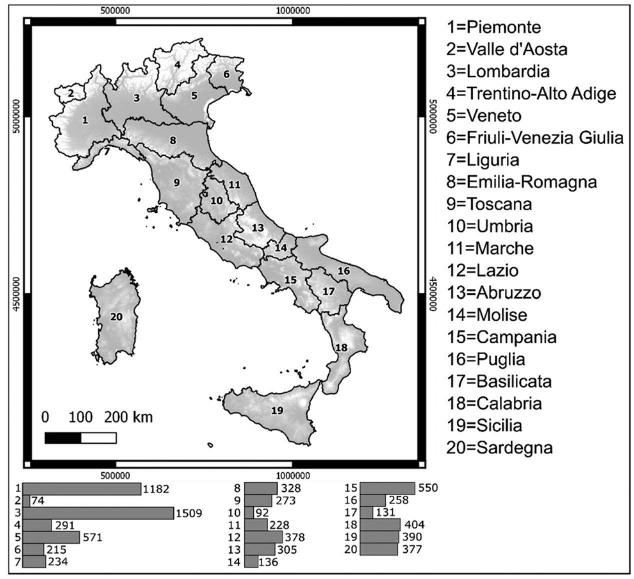

Figure 1: Administrative subdivision of Italy in regions. The digits at the right of the grey bars represent the number of municipalities for each region.

shown in Figure 2c, the territory can be roughly subdivided into seven sectors (i.e., Alps, Po Plain, Apennines, Apulia Foreland, Calabrian-Peloritan Arc, Sicilia, and Sardegna) [18,19], and in seven lithological classes (see the Italian map of the Hydrogeological complexes, ISPRA, 2007). In Figure 2e, the municipalities are classified into five groups according to the quantile distribution of the 2019 population density (www.istat.it). The most populated zone is the Po Plain, followed by some municipalities in the Northern part of Toscana, Lazio, and Campania Regions. Low population density characterizes the highest part of the Alps and Apennines, as some sectors of Calabrian-Peloritan Arc, Sicilia, and Sardegna Regions.

In Italy, landslides cause frequently severe damage to buildings and infrastructures, loss of human life, and significant societal and economic impact. A catalog of historical landslides with direct human consequences to the population of Italy [20,21] reported 1,178 fatal landslides that have caused 14,923 fatalities (including 14,887 deaths and 36 missing persons) at 1,079 sites, from 68 BC to August 2018. In the same period, 2,206 landslides caused 230,233 homeless and evacuees.

The Umbria Region extends for 8,464 km^2 in the middle of the Italian peninsula, along the Apennine chain. The municipalities pertain to two elevation classes (Figure 2b): inland hill (70.70%) and inland mountain (29.30%). From a geological point of view, the region is constituted by sedimentary deposits with the flyschoid rocks that are most abundant, followed by the Calcareous

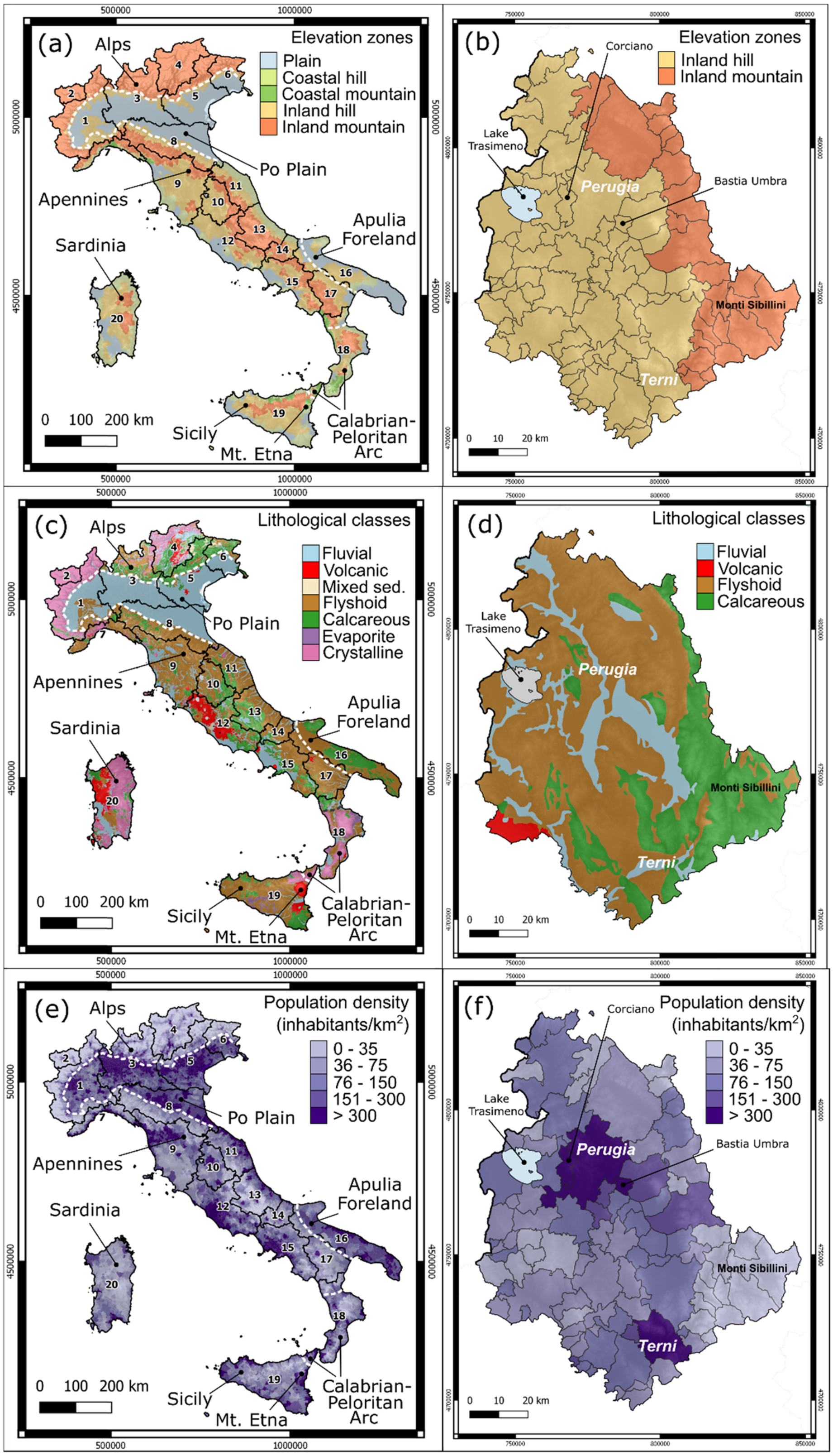

Figure 2: The Italian territory and the Umbria Region are classified according to (a) and (b) municipalities in five elevation zones (www.istat.it); (c) and (d) lithological classes as defined by ISPRA – Istituto Superiore per la Protezione e per la Ricerca Ambientale [22]; (e) and (f) municipalities classified according to population density as defined by the 2019 ISTAT census.

rocks along the Monti Sibillini chain (located in the SE sector of the region), and by the fluvial deposits along the principal fluvial valleys, while volcanic rocks crop out in the SW part of the region (Figure 2d). The lithological, morphological, seismic, and climatic setting of the region makes landslides a widespread phenomenon [23–25], and many inventories have been compiled by different authors for different purposes [26–28].

Figure 2f shows that the most densely populated municipalities are the neighboring cities of Perugia, Bastia Umbra, and Corciano, located in the Northern part of the region, and Terni, located in the Southern sector. Perugia is the capital city, Corciano and Bastia Umbra are two small towns hosting several small and medium enterprises (category of companies quite abundant in Italy), and Terni is a city characterized by the presence of important metallurgical and chemical plants.

3 Available data

To define the landslide indicators and indexes, we used the public domain data given in Table 1. Two datasets are available for the entire Italian territory: the IFFI landslide inventory map (*Inventario dei Fenomeni Franosi in Italia*, Inventory of Landslide Phenomena in Italy), and the PAI landslide zonation maps. For the Umbria region, we have used the following additional data: the landslide susceptibility map [15] and the road network map derived from DBprior (www.cisis.it) and Open Street Map (OSM, www.openstreetmap.org).

3.1 The IFFI landslide inventory map

The IFFI landslide inventory map was compiled by the Italian Institute for Environmental Protection and Research (ISPRA) in the framework of a dedicated project (www.progettoiffi.isprambiente.it). The map was realized following standardized and shared methods [28] and represents the most detailed inventory available for the entire Italian territory. The inventory includes 620,808 landslides, affecting an area of approximately 23,700 km^2, equal to 7.9% of the national territory. Landslides are available in vector format, as polygons with several associated information (e.g., locality, date, and type of landslide). In some regions, for example, Calabria, the landslide spatial distribution is underestimated, since the recognition was focused around the built-up areas and the main communication infrastructures. Figure 3a and b show the spatial distribution of the IFFI inventory for Italy and the Umbria Region.

3.2 The PAI landslide map

The PAI landslide maps were prepared for the Italian regions, in the framework of a dedicated national project (www.isprambiente.gov.it), that was focused to identify areas of possible evolution of existing landslides and areas where new landslides potentially may occur. In some regions, the original PAI maps prepared by the regional administrations were updated with local studies and investigations, recent landslide occurrences, and structural risk mitigation interventions. The PAI maps show polygons classified in five levels of severity: AA (area of attention), PAI1 (low), PAI2 (moderate), PAI3 (high), and PAI4 (very high). Figure 4a and b shows the spatial distribution of each level for Italy and the Umbria Region; Figure 4c shows for the single regions the percentage of the PAI levels.

3.3 The landslide susceptibility map

For the Umbria Region, a landslide susceptibility zonation [15] prepared with a statistically-based model is available [30].

Table 1: List of thematic data used in the analyses

Dataset name	Type	Scale	References
IFFI Landslide polygons	Vector	National	www.progettoiffi.isprambiente.it
PAI Landslide polygons	Vector	National	www.isprambiente.gov.it
Landslide susceptibility map	Raster	Regional	[15]
DBprior road network map	Vector	National	www.cisis.it
OSM (Open Street Map) road network map	Vector	Global	www.openstreetmap.org
2019 population census	Vector and Excel spreadsheet	National	www.istat.it

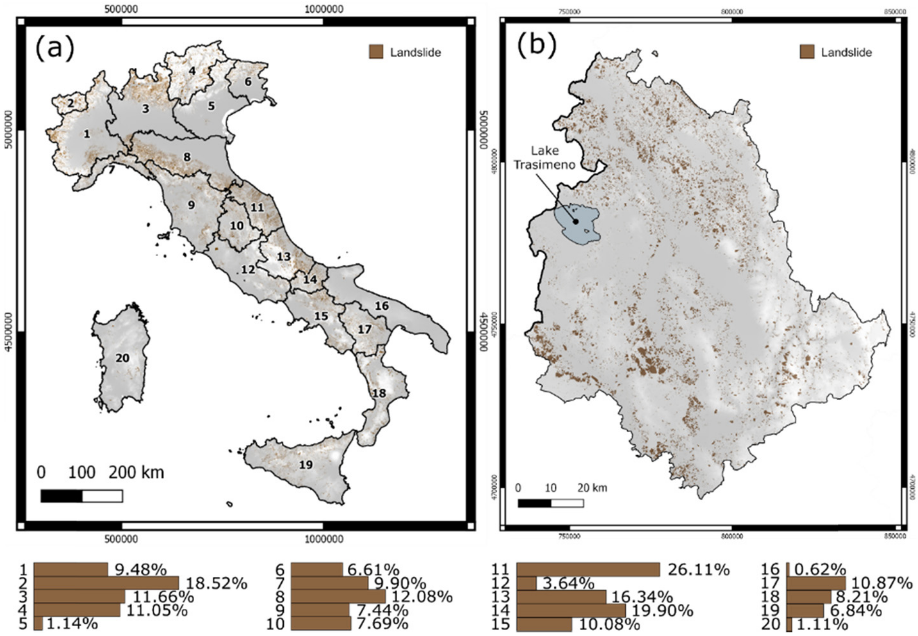

Figure 3: Landslide inventory map derived from the IFFI catalog (*Inventario dei Fenomeni Franosi in Italia,* Inventory of Landslide Phenomena in Italy) for (a) Italy and (b) the Umbria Region. The bars represent, for each region, the percentage of territory affected by landslides. See Figure 1 for region names.

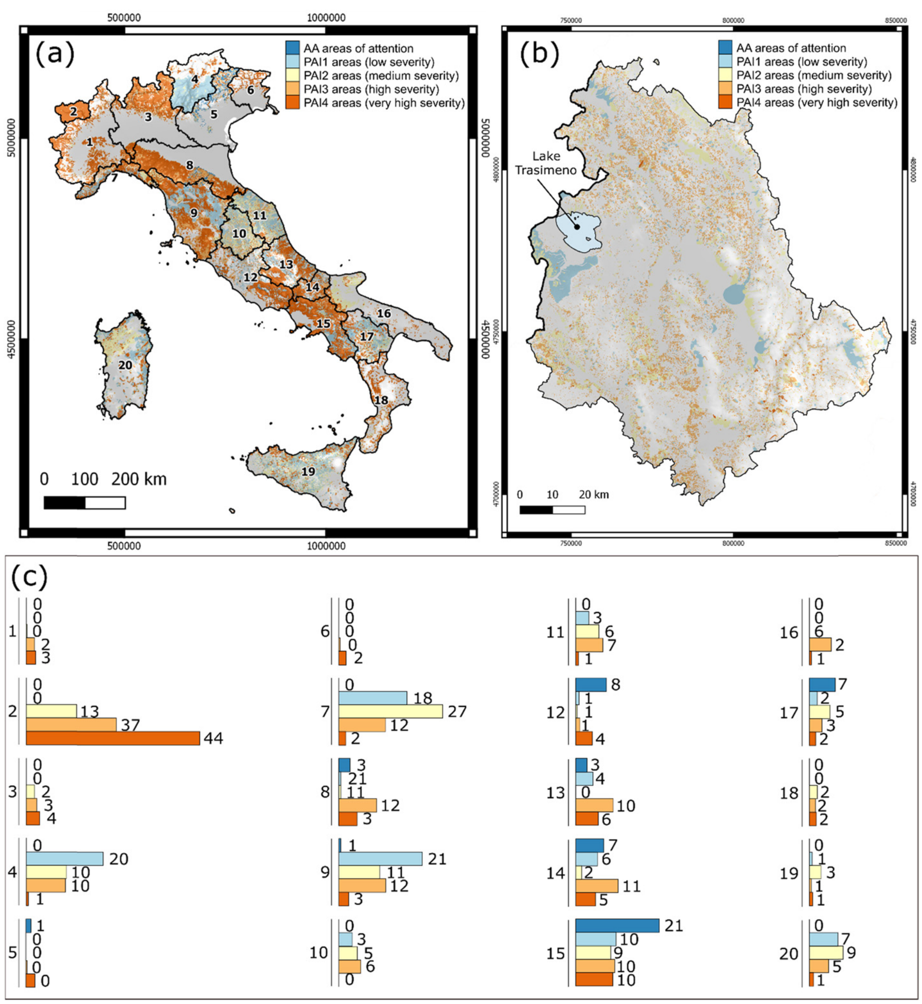

Figure 4: Spatial distribution of the PAI levels (AA, PAI1, PAI2, PAI3, and PAI4): (a) Italy; (b) Umbria Region. (c) For each region, the colored bars illustrate the percentage of territory in the PAI levels. See Figure 1 for region names.

Landslide susceptibility evaluates the degree to which a terrain can be affected by future slope movements, and estimates where landslides are likely to occur based on the local terrain and environmental conditions [25,31,32]. The susceptibility zonation was prepared considering only shallow and deep-seated slides that are the most abundant types in the area [33]. Figure 5a shows the susceptibility map in five classes: very high (0.80–1.00); high (0.55–0.80); medium (0.45–0.55); low (0.20–0.45); and very low (0–0.20). Over 47% of the hilly and mountainous territory falls into high and very high classes along the Apennine chain, while the non-susceptible areas are located in the floodplains of the main rivers.

3.4 The road network map and the population density

For the Umbria Region, the road network map was obtained by merging data from DBprior (www.centrointerregionale-gis.it) and Open Street Map (OSM, www.openstreetmap.org) projects. DBprior was published in the framework of an institutional project by the Inter-regional Center for the Geographic and Statistics Information Systems (www.cisis.it); the OSM derives from a collaborative project aimed to prepare a free and editable map of the world (Figure 5b). The two databases contain motorways, state, regional, provincial, and municipal roads. The length of the roads in the inland hill zone is 6,449 km (75.37%), with a density of 1.08 km/km^2, while in the mountain zone is 2,107 km (24.63%), with a density of 0.85 km/km^2.

Information on the population density derives from the 2019 ISTAT census, grouped at municipality level (www.istat.it, Figure 2e and f).

4 Methods to define indicators and indexes

In this article, we have accepted the ranking schema proposed by Hammond [6], which suggests a higher degree of complexity for the indexes.

The indicators were computed as a percentage of a selected thematic information within a mapping unit, where:

$$i_a = \frac{\text{Area}_a}{\text{Area}_{\text{mapping unit}}} \times 100, \tag{1}$$

i_a is a generic indicator related to a thematic information; Area_a is the extent of the mapping unit (i.e., the municipality) occupied by a; and $\text{Area}_{\text{mapping unit}}$ is the extent of the municipality. For this purpose, we selected the municipality extent as mapping unit.

The indexes derive both from the aggregation of different indicators and from the combination of indicators with different thematic data. In the first case, indexes were computed applying the equation:

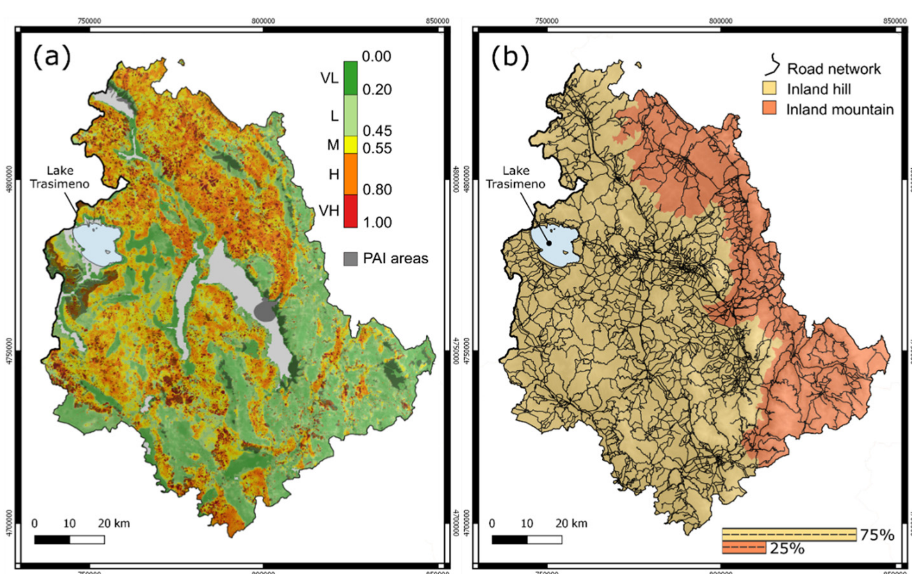

Figure 5: (a) Landslide susceptibility zonation (Modified after ref. [15]) overlapped with the PAI areas (grey polygons). (b) Elevation zones (Figure 2b) with the road network map. The bars at the bottom show the percentage of road in each elevation zone.

$$I = (i_a \times w_1) + (i_b \times w_2) + (i_c \times w_3) + (\cdots) + (i_n \times w_n). \quad (2)$$

where I represents a generic index; i_a, i_b, i_c, ..., i_n represent different indicators previously normalized from 0 to 1; and w_1, w_2, w_3, ..., w_n represent the weights of each indicator. The weights are defined heuristically by an expert judgement, that may consider for example the data type and quality. The sum of the weights of the different indicators must be equal to 1 ($w_1 + w_2 + w_3 + ... + w_n = 1$).

5 Results

Landslide indicators are computed for Italy whereas the indexes are evaluated for the Umbria Region chosen as an example. Table 2 summarizes names, descriptions, and input data for indicators and indexes, which will be described in the following sub-sections.

The indicator i_{IFFI} classifies the municipalities based on the percentage of landslides mapped by IFFI, whereas $i_{PAI\text{-}L}$ and $i_{PAI\text{-}H}$ consider the areas with low (AA, PAI1, and PAI2) and high (PAI3 and PAI4) PAI severity levels. Figure 6 shows the spatial distribution and the count of the municipalities in five classes with increasing level of instability (i.e., 0 – null, L – low, M – medium, H – high, and VH – very high).

The landslide indexes characterize the municipalities according to all the landslide information, the susceptibility zonation, and the potential impact of slope movements on the road network. The landslide distribution index, I_{LD}, is computed using the IFFI and PAI datasets. In the Umbria Region, we ascertained that IFFI and PAI-H areas often (more than 50%) represent the same features. To avoid redundancy, we have merged the IFFI landslides with the PAI zones PAI3 and PAI4 to obtain a new indicator $i_{(IFFI+PAI\text{-}H)}$. I_{LD} was then estimated by combining the indicators $i_{PAI\text{-}L}$ and $i_{(IFFI+PAI\text{-}H)}$ using two different weights (0.65 and 0.35, respectively, see equation (2)).

The landslide susceptibility index, I_{LS}, is based on the landslide susceptibility map [15] combined with the PAI zones, following the scheme proposed in Table 3. The scheme is based on expert judgments [9] and assign to each pixel of the combined map the worst class. When the two maps do not overlap, we consider the values of the susceptibility zonation.

The susceptibility map [15] was prepared using landslides derived from the geomorphological inventory map [28] and it is independent of the PAI zones that are defined using a geomorphological approach. The landslide susceptibility index I_{LS} is calculated for each municipality as the percentage of the area classified in the combined susceptibility map with values higher than 0.55.

The landslide exposure index, I_{LE}, is a proxy of the potential impact of mass movements on the road network. The index is obtained using the combined landslide susceptibility map, and the road network (Figure 5b) rasterized with the same pixel size of the susceptibility map. The landslide exposure index is computed as the percentage of road corresponding to the combined susceptibility values higher than 0.55.

Figure 7 shows the municipalities classified according to the landslide indexes in six classes with increasing level of severity (i.e., 0 – null, L – low, M – medium, H – high, VH – very high, and VVH – extremely high). The histograms show the number of municipalities in each class of indexes.

6 Discussion

The use of indicators and indexes to classify the territory based on geo-hazards is rather limited. For Italy, we have proposed three indicators resulting from dataset available for the entire country. The first indicator (Figure 6a) derived from the IFFI map reveals that 5,385 municipalities (out of 7,926) have part of their territory affected by landslides with an average of 11%, and a maximum

Table 2: Names, descriptions, and input data for indicators and indexes

	Name and description	Input data
Indicators	i_{IFFI} = IFFI distribution	IFFI inventory
	$i_{PAI\text{-}L}$ = PAI-low severity	PAI maps
	$i_{PAI\text{-}H}$ = PAI-high severity	PAI maps
Indexes	I_{LD} = landslide distribution	IFFI inventory, PAI maps
	I_{LS} = landslide susceptibility	Landslide susceptibility zonation and PAI maps
	I_{LE} = landslide exposure	PAI maps, landslide susceptibility zonation, road network

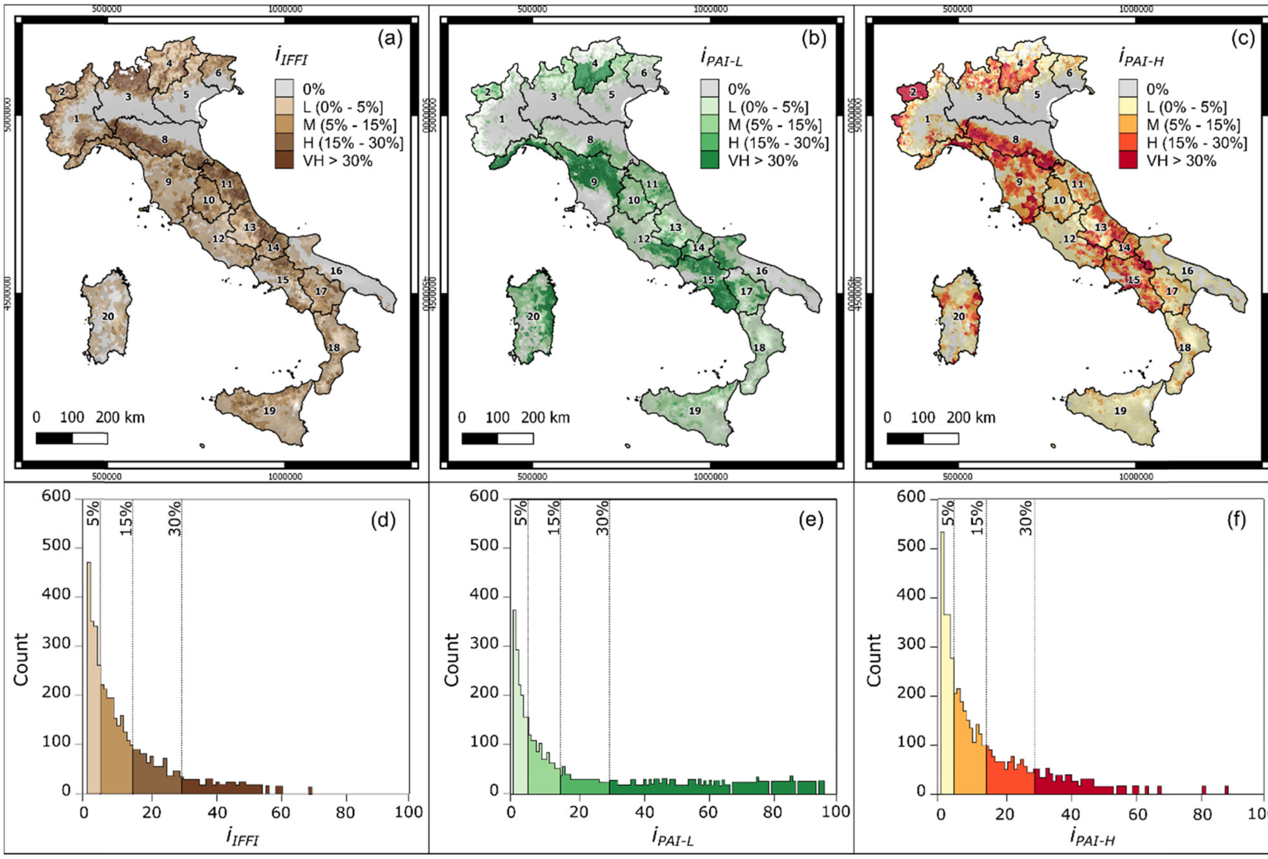

Figure 6: Italian municipalities are classified according to landslide indicators: (a) i_{IFFI}, (b) $i_{\mathrm{PAI\text{-}L}}$, (c) $i_{\mathrm{PAI\text{-}H}}$. The histograms show the number of municipalities with different percentages of (d) i_{IFFI}, (e) $i_{\mathrm{PAI\text{-}L}}$, and (f) $i_{\mathrm{PAI\text{-}H}}$. In the histograms, the 0% classes are not shown. See Figure 1 for region names.

Table 3: Schema to obtain the combined landslide susceptibility map

Susceptibility map [15]	**PAI zone**			
	PAI4 (VH)	**PAI3 (H)**	**PAI2 (M)**	**PAI1 (L)**
VH (0.8–1.0)	1	1	0.8	0.8
H (0.55–0.8)	1	1	0.8	0.8
M (0.45–0.55)	1	1	0.6	0.6
L (0.20–0.45)	1	0.8	0.4	0.4
VL (0–0.20)	1	0.8	0.2	0.2

value of 99.8% in the municipality of Sauze d'Oulx (Piemonte Region). The indicators derived from the PAI maps (Figure 6b and c) are subdivided into two levels ($i_{\mathrm{PAI\text{-}L}}$ and $i_{\mathrm{PAI\text{-}H}}$). The low level $i_{\mathrm{PAI\text{-}L}}$ with an average value of 17.4% reaches the maximum of 99.6% in the municipality of Loiri Porto San Paolo (Sardegna), and presents the lower values in Trentino-Alto Adige, Toscana, Campania and Sardegna. The high level $i_{\mathrm{PAI\text{-}H}}$ has an average of 11.4%, a maximum of 97.5% (Municipality of Rhêmes-Saint-Georges, Valle d'Aosta), and presents the highest levels in Valle d'Aosta, Emilia Romagna, and Campania. The three histograms in Figure 6 show the number of municipalities with different percentages of i_{IFFI}, $i_{\mathrm{PAI\text{-}L}}$, and $i_{\mathrm{PAI\text{-}H}}$, with a positive skewed distribution in which most values are clustered around low and medium classes. The graphs do not show the class with percentage equal to zero that amount, for the three indicators, 32, 40, and 30%, respectively.

For each region, we compared the three indicators ranking for visual purpose, the i_{IFFI} from low to high values (Figure 8). The different patterns reveal different distributions of information. In some regions (i.e., Piemonte, Lombardia, Veneto, Friuli-Venezia Giulia, Umbria, Marche, Calabria, and Sicilia), the $i_{\mathrm{PAI\text{-}L}}$ and $i_{\mathrm{PAI\text{-}H}}$ have lower values than i_{IFFI}, whereas in the others (i.e., Trentino-Alto Adige, Liguria, and Toscana) their values are higher, with the $i_{\mathrm{PAI\text{-}L}}$ greater than $i_{\mathrm{PAI\text{-}H}}$. Lower values of $i_{\mathrm{PAI\text{-}L}}$ and $i_{\mathrm{PAI\text{-}H}}$ with respect to i_{IFFI} may be explained by the use of the landslides mapped by the IFFI to define the PAI zones.

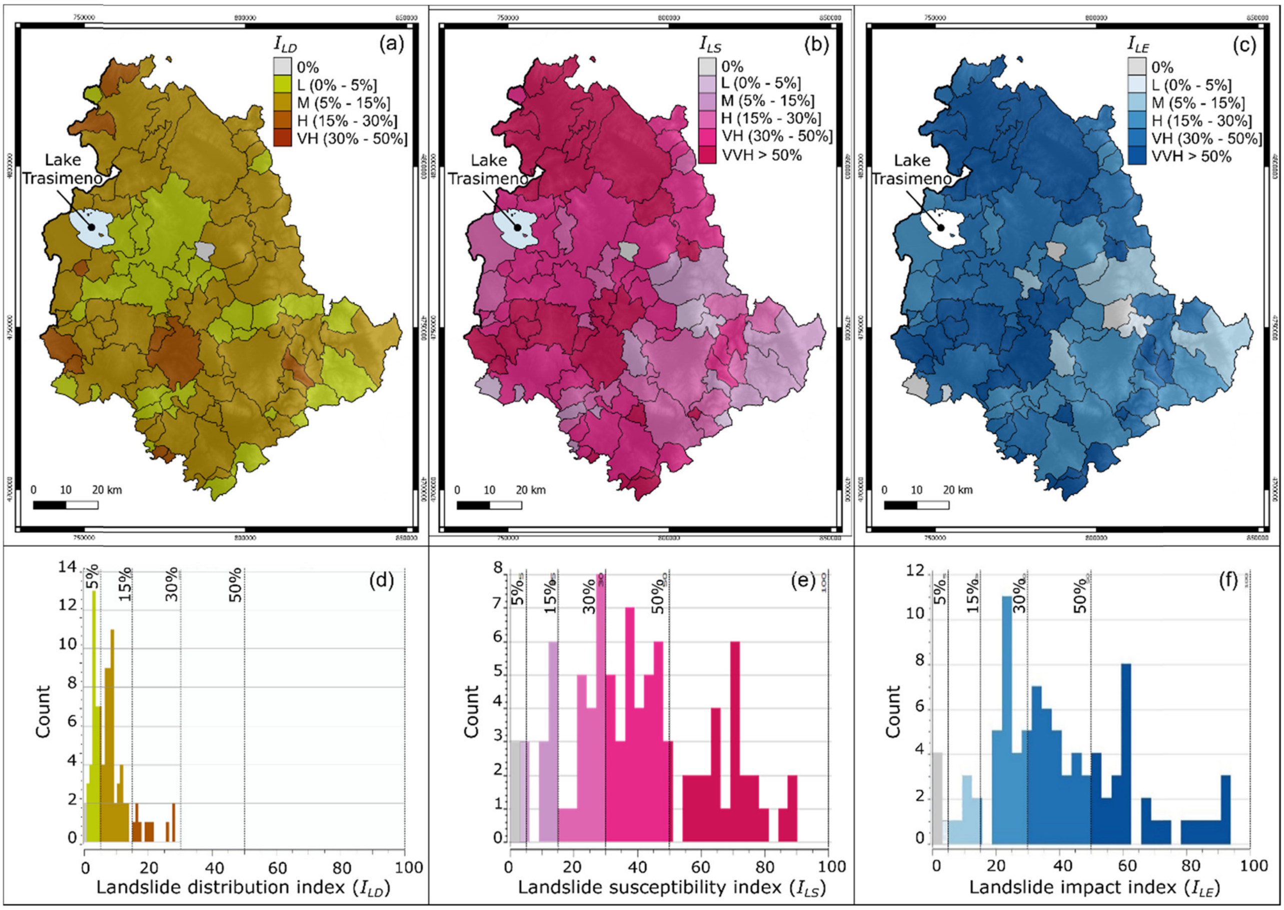

Figure 7: (a) Landslide distribution index (I_{LD}), (b) landslide susceptibility index (I_{LS}), (c) landslide exposure index (I_{LE}). The histograms show the number of municipalities with different values of (d) I_{LD}, (e) I_{LS}, and (f) (I_{LE}).

For example, in the Umbria Region, we ascertained a spatial correspondence of about 52% between the IFFI and PAI polygons distribution. The different patterns shown in Figure 8 can also be explained by different levels of updating performed by the regional administrations. Similar problems may also occur when administrations adopt different methodologies to collect data/information, and this should be evaluated when using indicators to perform analyses at the national scale.

To consider a higher level of complexity, we have introduced three indexes that are shown as an example for the Umbria Region where additional data are available. The landslide distribution index classifies the municipalities by weighing the available landslide information. Figure 7a reveals that the majority of the municipalities are in the medium class, with the highest values located in areas characterized by a rough morphology and weak geological conditions that make hillslopes prone to mass movements. On the other side, municipalities in the low class are located in areas with gentle slopes and resistant lithologies (central zone and southeast). The definition of I_{LD} is partially subjective because it is associated with the choice of the weights, that are based on the expert judgement. The experience and the knowledge of the expert strengthen the choice of the weights. The advantage of using weights provides the possibility to identify different combinations, considering for example, the quality and the accuracy of the data. As such, indicators obtained from a low-quality dataset, should have lower weights than those obtained from high-quality data. In the Umbria Region, higher weights were associated with the indicators playing the most relevant roles in the I_{LD} calculation (i.e., $i_{(IFFI+PAI\text{-}H)}$).

The landslide susceptibility index (I_{LS}), and the landslide exposure index (I_{LE}) were estimated considering the combined landslide susceptibility map. As shown in Figure 7b, municipalities with slopes extremely prone to landslides (VVH class >50%) are located in the Northern and Western portions of the region, where flysch deposits outcrop (Figure 2). Most of the municipalities located in

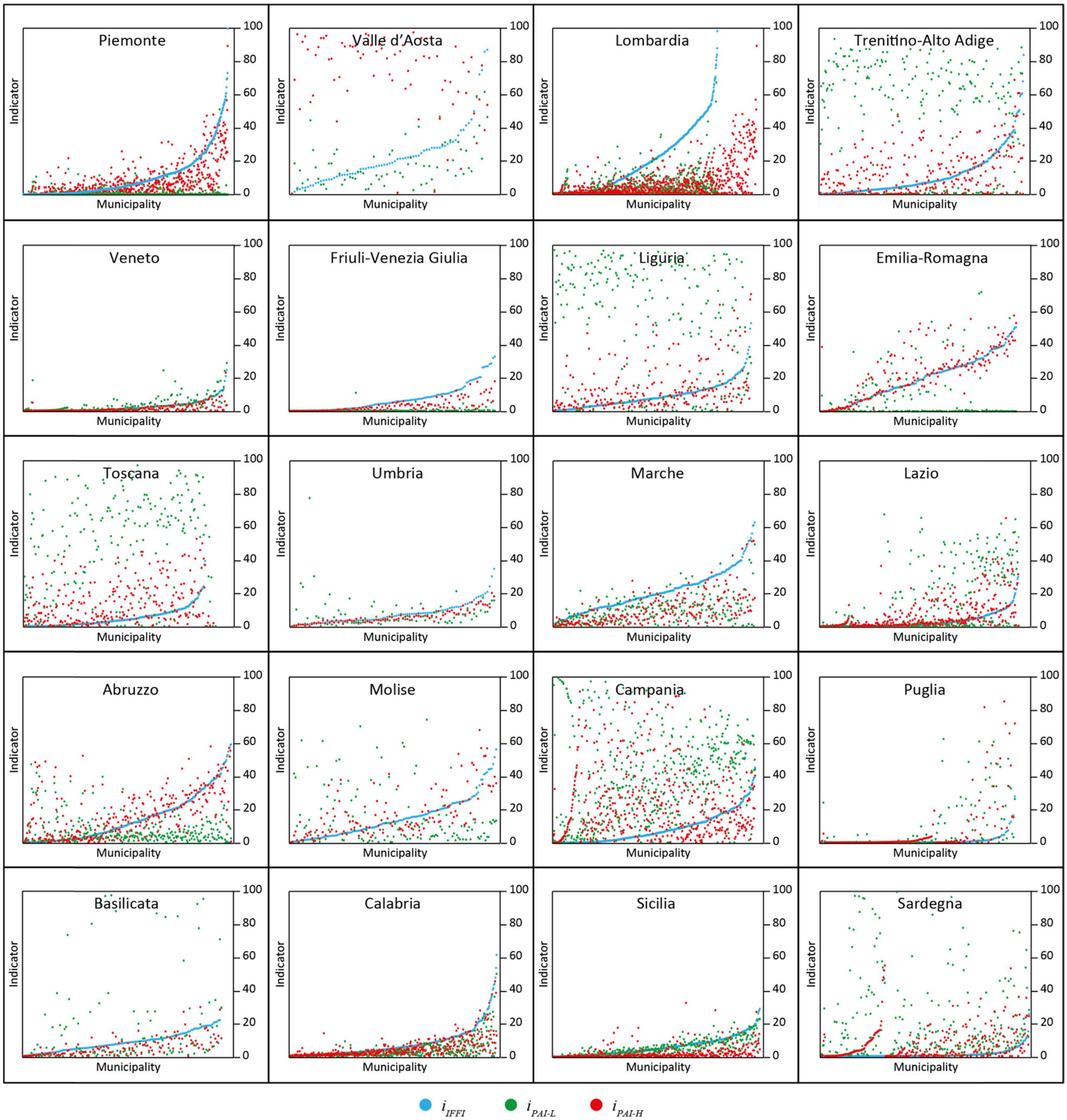

Figure 8: i_{IFFI}, $i_{\mathrm{PAI\text{-}L}}$, and $i_{\mathrm{PAI\text{-}H}}$ values for each municipality within the 20 Italian regions.

the Monti Sibillini chain, the highest mountainous area located in the South-Eastern part of the region, are classified in the medium and high classes. The most abundant lithologies are constituted by calcareous rocks that are mainly prone to rock falls that are not considered in the zonation. Most of the municipalities are classified with I_{LS} values lower than 50%, and only 24 out of 92, are characterized by extremely higher values. The I_{LS} index can be formalized when it is available as a susceptibility zonation, a type of map that is becoming common worldwide at different scales [34].

The susceptibility zonation was also used to evaluate the road exposed to landslides, that is a proxy for the potential interference of mass movements along the network (Figure 7c). As shown in Figure 7c and f, most of the municipalities are classified in the most severe classes.

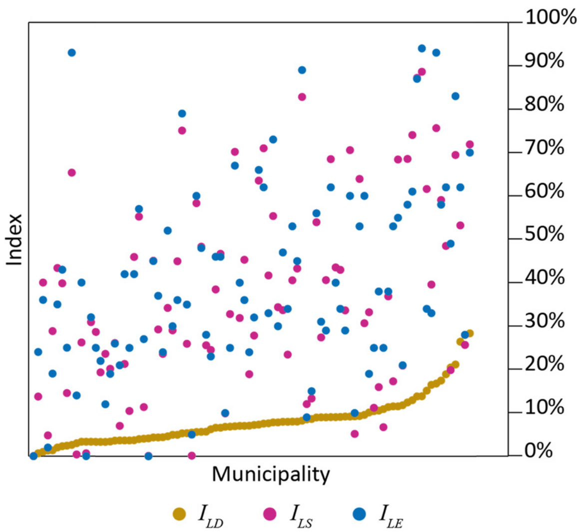

Figure 9: I_{LD}, I_{LS}, and I_{LE} values for the municipalities of the Umbria Region. Along the *x*-axes, the municipalities ranked by the I_{LD} value are shown.

Specifically, the extremely high class is located in the northern and western parts of the region, where flyschoid lithologies crop out.

We have focused our analysis on the road network because it is the element most frequently affected by landslide damage. As an example, Italy [35] reported 21,483 roads and 8,234 buildings damaged by landslides. Worldwide, several authors investigate and discuss the exposure of road network to landslides [36–44].

Figure 9 shows a synoptically view of the indexes (I_{LD}, I_{LS}, and I_{LE}), ranking the I_{LD} values. The plot shows that the majority of I_{LS} and I_{LE} values are higher than I_{LD}, confirming that the territory of the municipalities prone to failures has a spatial extension greater than the mapped landslides. The susceptibility zonation, prepared using statistical evaluations and considering geological, geomorphological, geomorphometric, and land use settings, provides evidence of possible spatial landslide occurrence also in areas where mass movements have not been recognized.

To support the emergency response strategies and the quantification/allocation of possible resources, the index computed by using the inventory maps should be associated with that evaluated using susceptibility zonation. In fact, areas prone to instability where landslides have not been reported or recognized can be particularly relevant for planning purposes and landslide hazard management.

We have tried to formalize the impact on the population using the landslide indexes (Figure 10). In the Umbria Region, the most populated municipalities are located in areas with low landslide indexes not highly prone to failures. The four municipalities with a density higher than 300 inhabitants/km^2 (i.e. Bastia Umbra, Terni, Perugia, and Corciano) have quite low I_{LD}, I_{LS}, and I_{LE} values.

Figure 10 reveals that municipalities highly prone to landslides, with high exposure indexes are those characterized by low population density and this represents a valuable information for regional administrators and authorities of civil protection.

7 Conclusions

Indicators and indexes have received little attention to provide information on landslide distribution, despite their widespread use in social and economic environments and in other natural processes. This study suggests indicators and indexes that can characterize the hillslope stability conditions at the municipal scale, to support local authorities in land use management. Based on available data, we proposed three indicators that can be used as a measure of the landslide spatial distribution. In addition, we have introduced three indexes to provide supplementary information on the landslides distribution and impact.

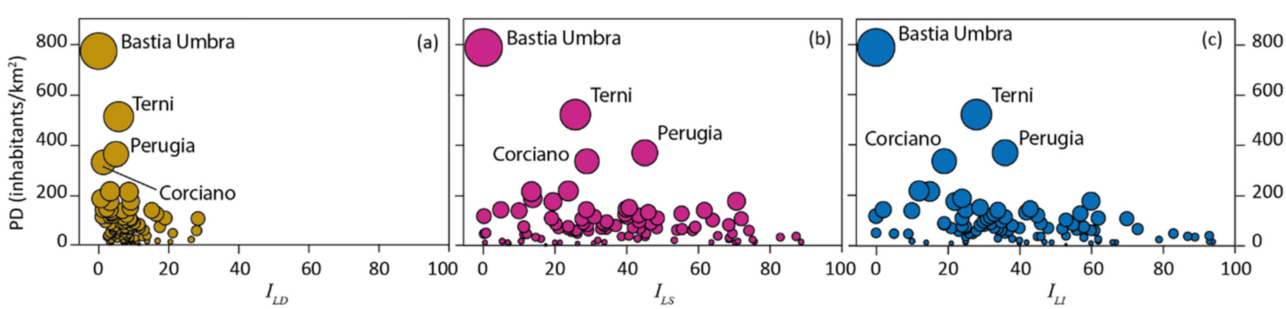

Figure 10: (a) I_{LD}, (b) I_{LS}, and (c) I_{LE} values for each municipality plotted versus population density (PD, inhabitants/km^2) as defined by the 2019 ISTAT census. The dimension of the circles is proportional to the population density.

The described approach can represent a useful support to optimize the land planning and management practices, specifically aimed at reducing the exposure and vulnerability of people. Moreover, the landslide exposure index may help to identify critical situations, to plan mitigation strategies and allocate public funds for a more sustainable planning. Mitigation strategies should reduce both the processes and the exposure/vulnerability of the population. As for all the parameters and models obtained using thematic information, the reliability and uncertainty of indexes and indicators depend on the quality of the data used to prepare them. An evaluation of the variables [6] should be done before their use in order to avoid not-reliable operations.

The user-friendly approach allows its reproducibility, following the concept of open science [45], making it easily applicable to other countries where landslide-related information is available. The proposed indicators are easy to be prepared, interpreted, and updated considering possible changes of the input data (e.g., availability of new landslide inventories). At the same time, the proposed indexes can also be useful to aggregate other indicators obtained with different approaches to support end-users and stakeholders in decision-making processes.

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