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Definition of Environmental Indicators for a Fast Estimation of Landslide Risk at National Scale

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Abstract: The purpose of this paper is to propose a new set of environmental indicators for the fast estimation of landslide risk over very wide areas. Using Italy (301,340 km^2) as a test case, landslide susceptibility maps and soil sealing/land consumption maps were combined to derive a spatially distributed indicator (LRI—landslide risk index), then an aggregation was performed using Italian municipalities as basic spatial units. Two indicators were defined, namely ALR (averaged landslide risk) and TLR (total landslide risk). All data were processed using GIS programs. Conceptually, landslide susceptibility maps account for landslide hazard while soil sealing maps account for the spatial distribution of anthropic elements exposed to risk (including buildings, infrastructure, and services). The indexes quantify how much the two issues overlap, producing a relevant risk and can be used to evaluate how each municipality has been prudent in planning sustainable urban growth to cope with landslide risk. The proposed indexes are indicators that are simple to understand, can be adapted to various contexts and at various scales, and could be periodically updated, with very low effort, making use of the products of ongoing governmental monitoring programs of Italian environment. Of course, the indicators represent an oversimplification of the complexity of landslide risk, but this is the first time that a landslide risk indicator has been defined in Italy at the national scale, starting from landslide susceptibility maps (although Italy is one of the European countries most affected by hydro-geological hazards) and, more in general, the first time that land consumption maps are integrated into a landslide risk assessment.

Keywords: landslide; Italy; risk; soil sealing

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1. Introduction

Landslide risk is the possibility that a landslide occurs in a specific area and in a specific period of time, causing damages to population, buildings, infrastructure and services [1,2]. As a consequence, landslide risk is influenced by the overlapping in time and space of hazardous areas (where landslides are likely to occur) and potentially vulnerable exposed elements, resulting in an impact that could cause damages or losses. This has been traditionally translated into mathematical form by the classical equation [1]:

$$R = H \cdot V \cdot E \quad (1)$$

where R is the risk, H is the hazard (the probability for a dangerous event of a given intensity to happen in a certain place and time), V is the vulnerability (the degree of loss expected from the element impacted by the landslide) and E is exposition (the value of the elements exposed to the event).

Following this approach, quantitative risk analyses have been mainly published for small areas or, at the most, in regional scale applications [2–9].

A quantitative landslide risk assessment for very large areas (e.g., an entire nation) is still a very challenging objective, as it requires facing technical and scientific issues such as availability of complete, homogeneous and good quality input data of different natures (pertaining at least to the fields of geology, economy, demography and civil engineering) [10].

Italy is no exception to this, and to date the main strategies for assessing landslide risk at the national scale in Italy were based on different strategies. For instance, [11] proposed a statistical analysis on the spatial variability of recorded fatalities, to account for societal landslide risk in the whole Italian territory. Recently, [12] proposed a set of landslide risk indicators based on freely accessible data from an online governmental platform, including exposed population, number of buildings and landslide hazard zones as defined by the Italian regulation. Although representing a very complete overview of landslide risk in Italy, this approach has the drawback of presenting a spatial aggregation at the municipal level and leaving unexploited some scientific products that have a finer spatial resolution, such as landslide susceptibility maps, which have been proposed for several Italian regions [13–17] and for the whole Italian territory [18], or monitoring products of the artificialization of the territory such as soil sealing maps, which monitor the evolution of the processes of artificialization of the territory at high spatial resolution (10 m) at yearly time steps [19]. However, the approach of addressing national scale landslide risk problems with a set of simple indicators, rather than with a full QRA, seem promising and quite consolidated in landslide studies [10,20,21]. Undoubtedly, indicators are, by definition, simple means to describe and comprehend a complex phenomenon and are widely used in environmental studies by scientists and governmental agencies.

The purpose of this manuscript is to propose a new set of environmental indicators to characterize landslide risk over very wide areas and to apply it to characterize the Italian municipalities. The novelty in the proposed approach is to use advanced and high-resolution thematic layers: already existing landslide susceptibility maps [18] are used to identify hazardous areas, and soil sealing maps are used as they have a high resolution and constantly updated representation of the spatial distribution of the elements at risk (soil sealing maps are released on a yearly basis to monitor the expansion of urban fabric [19,22]). At the same time, the general objective is keeping the resulting indexes easy to understand, quick to update and flexible enough to be adapted at varying spatial units. In its basic formulation, a spatially distributed Landslide Risk Index (LRI) is defined on a pixel basis at 50 m resolution. Afterwards, we show an application to the whole Italian territory, in which the LRI is aggregated at the municipal level following two different approaches, generating two additional indexes that can be used to gain useful understanding on the interferences between geomorphological slope dynamics and urban expansion, which give birth to landslide risk.

2. Materials and Methods

2.1. Test Site

The study area considered for this work is the whole Italian territory (301,340 km^2) (Figure 1a). Italy is a peninsula located in Southern Europe and extending into the Mediterranean Sea. It is characterized by two main mountain ranges: the Alps, to the north, which separate Italy from the rest of Europe, and the Apennines, forming the backbone of the peninsula and running from NW to SE.

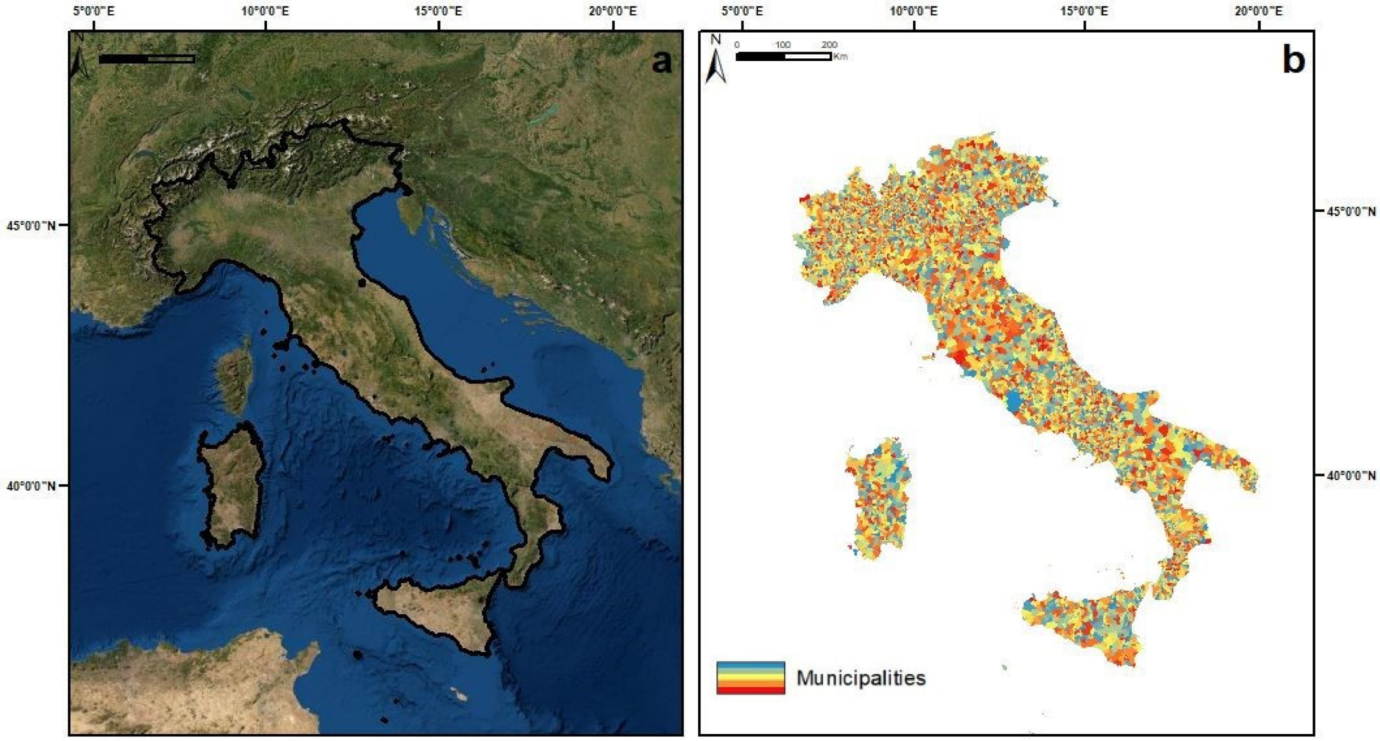

Figure 1. (**a**) Overview of Italy; (**b**) administrative subdivision into 7904 municipalities.

The geological setting and morphological features of the Italian peninsula are the result of a still active geological process that led to the formation of the two mountain chains [23]. The Alps are the typical example of a collisional belt: it was generated during the Cretaceous period by the convergence of the Adriatic continental upper plate (Argand's African promontory) and a subducting lower plate including the Mesozoic ocean and the European passive continental margin. In the Eocene, a complete closure of the ocean marked the onset of the Adria/Europe collision. The collisional zone is represented by the Austroalpine-Penninic wedge, a fossil subduction complex, showing that even coherent fragments of light continental crust may be deeply subducted in spite of their natural buoyancy [24]. The Apennines extend from the northwest part of the peninsula to the isle of Sicily, and link the western Alps with the Magrebian chain of North Africa [25]. The Apennines are a NW–SE oriented fold-and-thrust belt formed during the Oligocene period by the closure (started during the Cretaceous period), of the Mesozoic Tethys Ocean and following the collision between the European (Corso-Sardinian block) and African plates [26,27].

From a geomorphological point of view, Italy has a marked energy of relief: mountains are present in every Italian region and occupy more than the 35.2% of the territory. The greatest part of Italy, however, is characterized by hills, representing the 41.6% of the land surface. This juvenile morphological setting, in a still tectonically active territory, brings the consequence that landslide hazard is widespread in every part of Italy, excluding flat alluvial and coastal plains.

Landslide hazard is further exacerbated by climatic and meteorological constraints. Due to the large latitude range covered by Italy, the climate varies largely: from the cold climate of the north, EFH according to Koppen classification, typical of the highest mountain peaks, with annual precipitation higher than 2000 mm, to the Subtropical climate (BS in Koppen classification) of the southernmost coastal areas of Sicily, Apulia, Sardinia and Calabria, with long, hot, dry summers and precipitation less than 400 mm in Sicily [28]. Recently, due to the effects of climate change, periods of precipitation are becoming shorter and more intense in many parts of Italy [29,30], causing an increase in landslide activity and in the number of harmful landslide events per year [31,32].

For a full understanding of the application reported in this study, it is worth noting that Italy is subdivided into 7904 municipalities (Figure 1b), which represent the smallest administrative subdivisions of the territory and that have important responsibilities in territorial planning, urban design and risk management.

2.2. Landslides in Italy: National Inventory and Existing Susceptibility Maps

For the reasons explained above, each year hundreds to thousands of landslides affect Italy, causing victims and damages to buildings, infrastructure and cultural heritage [12,32–34]. An official landslide database exists at the national scale that is managed by ISPRA (National Institute for Research and Environmental Protection). The database is called IFFI (Italian National Landslide Inventory) and maps all known landslides (both active and inactive), mapped at the 1:10,000 scale by means of field surveys, remote sensing techniques and collection of ancillary data. According to IFFI, 620,808 landslides are present, covering about the 7.9% of the Italian territory. IFFI is openly accessible via an online platform [12] and it is acknowledged to be one of the most complete and homogeneous national-scale inventories in Europe [35–37]. IFFI is widely used as a base for landslide hazard and risk assessments at various scales [12,15,38–40].

In particular, in Italy, an overwhelming literature exists about landslide susceptibility studies. Landslide susceptibility maps (LSMs) represent, over appropriate spatial units, the spatial probability of the occurrence of landslides, and they are usually obtained by a statistical analysis of the spatial distribution of a set of predisposing factors [41]. Although LSMs do not contain temporal predictions, they are usually considered the starting point for landslide hazard and risk assessment. This is also the approach used for this work, but a literature review showed that most of the published LSMs refer to basin-scale studies [42–46]. Some examples of regional-scale susceptibility assessments also are present [13–16,47], but the use of a combination of regional maps obtained with different approaches to compose a nation-wide mosaic of landslide susceptibility would pose huge problems of consistency of the data. To our knowledge, the only LSM at the Italian scale available to be used as input data for this work is the national scale susceptibility assessment performed by [18]. The susceptibility assessment was performed separately for three different landslide typologies (rockfalls, rapid shallow slides, slow deep slides), producing three susceptibility maps at 50 m resolution. A Random Forest algorithm [48], which is a machine learning technique widely consolidated in LSM studies [49–51], was calibrated with the IFFI landslide inventory and a set of environmental variables including lithology, land cover, morphometric parameters (elevation, slope gradient, aspect, curvature), and hydrological parameters (topographic wetness index, stream power index, upslope contributing area). Overall, 196,087 sample points (50% randomly sampled inside landslides and 50% randomly sampled outside the mapped landslides) were used to train the Random Forest model and 84,641 independent points were used to quantify its accuracy in terms of AUC (area under receiver-operator characteristic curve), which is reported as 0.85.

2.3. Soil Sealing in Italy

In addition to the natural physical features (such as geological and climatic settings), anthropogenic dynamics are also deeply involved in landslide risk in Italy. On one hand, urban elements (such as buildings and infrastructure) may contribute to destabilizing slopes, acting as predisposing factors for landslide hazard. On the other hand, the ongoing expansion of urban fabric and infrastructure generates, at an alarming rate, new elements that are exposed to hazard, determining a relevant degree of landslide risk.

Since 2015, ISPRA has undertaken a nation-wide monitoring program of soil sealing. Soil sealing is the most intense form of artificial land take and it can be defined as the removal or covering of soil by buildings, constructions or other totally or partly impermeable artificial material [52]. Since then, every year, a national cartography of soil sealing is produced by remote sensing techniques and it is released as a raster map (pixel size 10*10 m), in which the whole Italian territory is classified into two classes: sealed soil/not sealed soil [53,54]. Sealed soil includes built-up areas, paved areas, railways, airports, ports and even reversible land consumption such as dirt roads [54]. Although all those elements are not distinguished from each other, the information conveyed by the soil sealing maps is very useful for the aim of this study because it provides useful information (updated on a yearly basis) about all anthropic elements exposed to risk, with a relatively very high spatial resolution.

To this regard, it should be stressed that, typically, urban areas in Italy are not clustered and are characterized by a peculiar diffuse pattern (referred to as "sprawl" and "sprinkling") [19]. As a consequence, other land cover/land use monitoring products (such as Corine Land Cover) are not able to adequately capture the spatial and temporal evolution of this phenomenon [54]. Moreover, the remote sensing techniques developed by ISPRA are specifically conceived and calibrated to detect the diffuse and scattered patterns of Italian urban fabric [19].

2.4. Methodology

Italian regulation (D. P. C. M. 27/12/1998) dictates that environmental assessment should be performed by subdividing the environment into environmental components, each of them described and characterized by indicators, which are parameters used to describe a given phenomenon and that should have the following characteristics: being concise, easy to understand and easy to measure and update.

In this framework, the objective of this study is to propose a set of indictors at a national scale to characterize landslide risk by depicting how urban expansion interferes with geomorphological slope processes. To this end, we started with some input data that consists of the outputs of bigger ongoing or concluded research activities, and we combined them by means of GIS analyses.

Input data are:

- Susceptibility maps of Italy at 50 m spatial resolution (as described in Section 2.2) [18]. Three separate maps exist, each focusing on a peculiar kind of landslides typically affecting Italian territory: rockfalls, shallow rapid slides, and deep-seated slow slides. Each map is in raster format and each raster cell expresses, with a numerical susceptibility index ranging from 0 to 100, the spatial probability of occurrence of a landslide of that typology.
- Soil sealing map of Italy, which identifies in the Italian territory the soil sealed or consumed by anthropic activities. In its basic form, the map can be used to subdivide the territory into (semi)natural soil cover and artificially covered soil, but the latter category is not further subdivided into sub-classes and the elements contributing to soil sealing cannot be assessed. Considering the scale of application, the scarce thematic accuracy is compensated by a high spatial and temporal accuracy: the map is in raster format, at 10 m pixel size, and is updated yearly. In this work, the most recent update available was used (monitoring of the reference year 2019, officially released in 2020). The map can be visualized as a binary raster assuming value 1 where sealed soil has been detected and 2 where it has not.
- Shapefile of municipalities borders, with reference coordinate system WGS84.

In short, the procedure consists of identifying a landslide risk following a revised and simplified version of Equation (1). For our purposes, hazard is considered equal to the spatial probability of occurrence (thus, equal to susceptibility). Over the susceptibility we superimpose the spatial distribution of anthropic elements (depicted by the soil sealing map), in order to consider elements at risk only on a presence/absence basis. Vulnerability is neglected (mathematically it is considered equal to 1 in Equation (1)) for different reasons: first, it would be nearly impossible to assess separately the physical vulnerability of each element (e.g., buildings) at national scale (and, to our knowledge this is a still unattempted task); and second, the soil sealing map does not effectively allow for distinguishing between different typologies of buildings or infrastructure. Moreover, in national scale studies, the approach of considering vulnerability as equal to 1 (the maximum possible degree) is considered a viable and cautionary approach [12]. The resulting index is then aggregated at the municipality basis.

The first step of the proposed procedure consists of blending the three susceptibility maps into a single information. It can be considered quite unlikely that, in a single spatial unit of the susceptibility map (pixel with 50 m size), two or more landslides of different typologies could be contemporarily present. Indeed, every predictive landslide model should first make a typological prediction, trying to predict what kind of landslide will take place [55]. As a consequence, the three susceptibility maps were imported into ArcGis software, and the "cell statistics" operation was performed to assess the "maximum" value. In this way, the output is a raster map in which the susceptibility index associated to each cell is the highest value found in the three input maps. This is equivalent to considering the landslide type with the highest susceptible value as the most probable to occur in a given location, and surmising that this landslide typology is the one that will be most likely affecting that area, controlling the related hazard. The resulting raster will be called "hazard index map" henceforth (Figure 2).

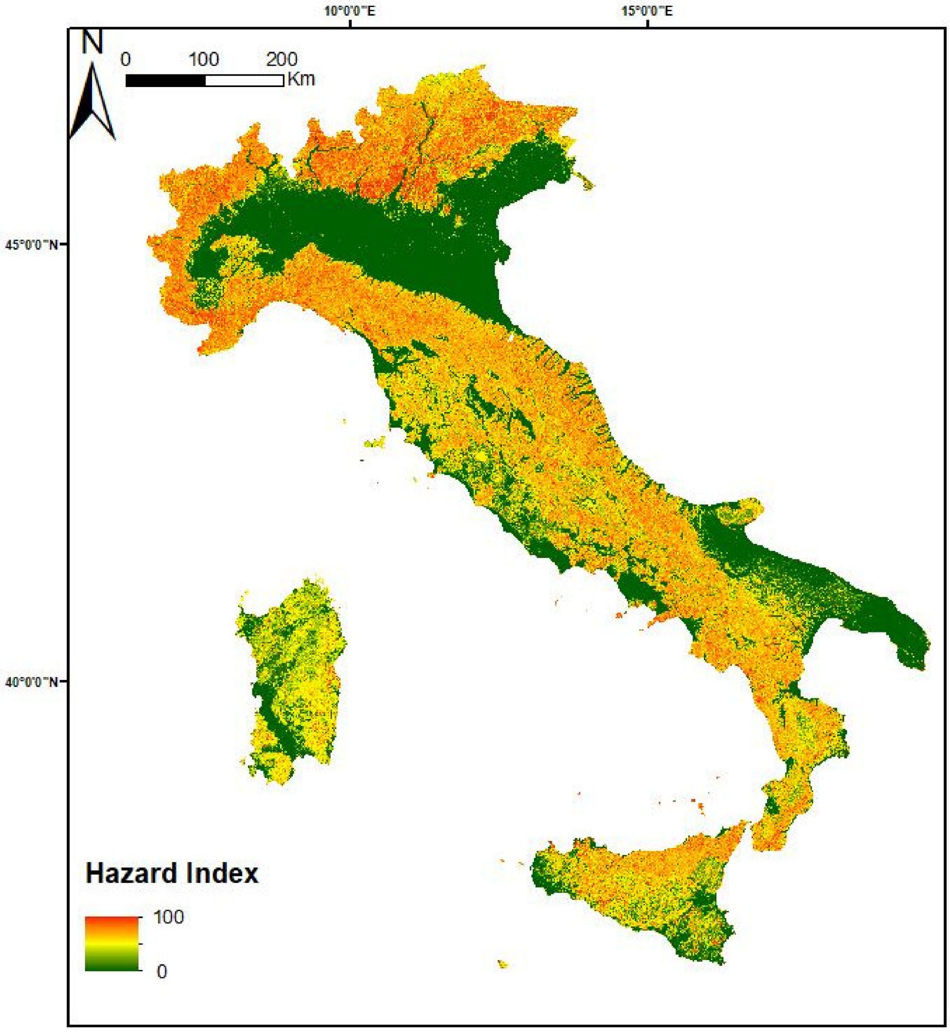

Figure 2. Hazard index map.

Before overlying the soil sealing map to the hazard index map, a procedure of homogenization is needed as the two raster maps have different cell sizes. Using ArcGis "block statistics" function, the resolution of the soil sealing raster was changed from 10 m to 50 m. Despite the loss of spatial resolution, this operation was necessary for the perfect match of soil sealing map with landslide hazard map, and some authors demonstrated that this spatial resolution is a good compromise in wide-area landslide hazard assessment studies [49]. The "minimum" statistics type was used: in this way the resulting raster obtains the value 1 (sealed soil) if at least one 10 m cell of sealed soil is present in each 50 m block. This choice determines a small expansion of the sealed soil that could be considered precautionary, and that is more desirable than alternate approaches. For instance, we verified that using the "majority" operator, many small infrastructure are completely neglected (e.g., roads cutting rural or mountain areas usually represent a small fraction of the 10 m pixels inside the 50 m block, and a relevant source of landslide risk would be completely ignored). In addition, it should be noted that the original soil sealing map represents the presence of sealed soil, but it is widely acknowledged [19] that the effects of the sealing may extend also to the surrounding areas (e.g., concerning hillslope hydrology, small surficial drainage systems connected to infrastructure could have discharge outlets a few meters away from the sealed area).

The resulting raster was reclassified, assuming a value of 1 in soil-sealed 50 m pixels and "no data" elsewhere. From a mathematical point of view, the reclassified soil sealing map and the hazard index raster were combined with a multiplication by means of the "raster calculator" tool of ArcMap. From the point of view of spatial information, the values "1" and "no data" in a multiplication act as a filter that maintains unaltered the input value of spatial probability of occurrence only in correspondence of anthropic elements, while far from them the index is not defined (conceptually, it is similar to assuming a risk equal to zero). This output raster was named Landslide Risk Index (LRI), because it accounts for the interaction between hazard and anthropic elements, giving a spatially distributed picture of how much they are exposed to landslide risk (Figure 3). It should be observed that a thorough assessment of the interaction between landslides and elements at risk would require accounting for the propagation of mass movements (for which run-out models would be necessary). This element is rarely encompassed in landslide susceptibility assessments, especially in wide-area applications; this shortcoming will be further investigated in the discussion of the results.

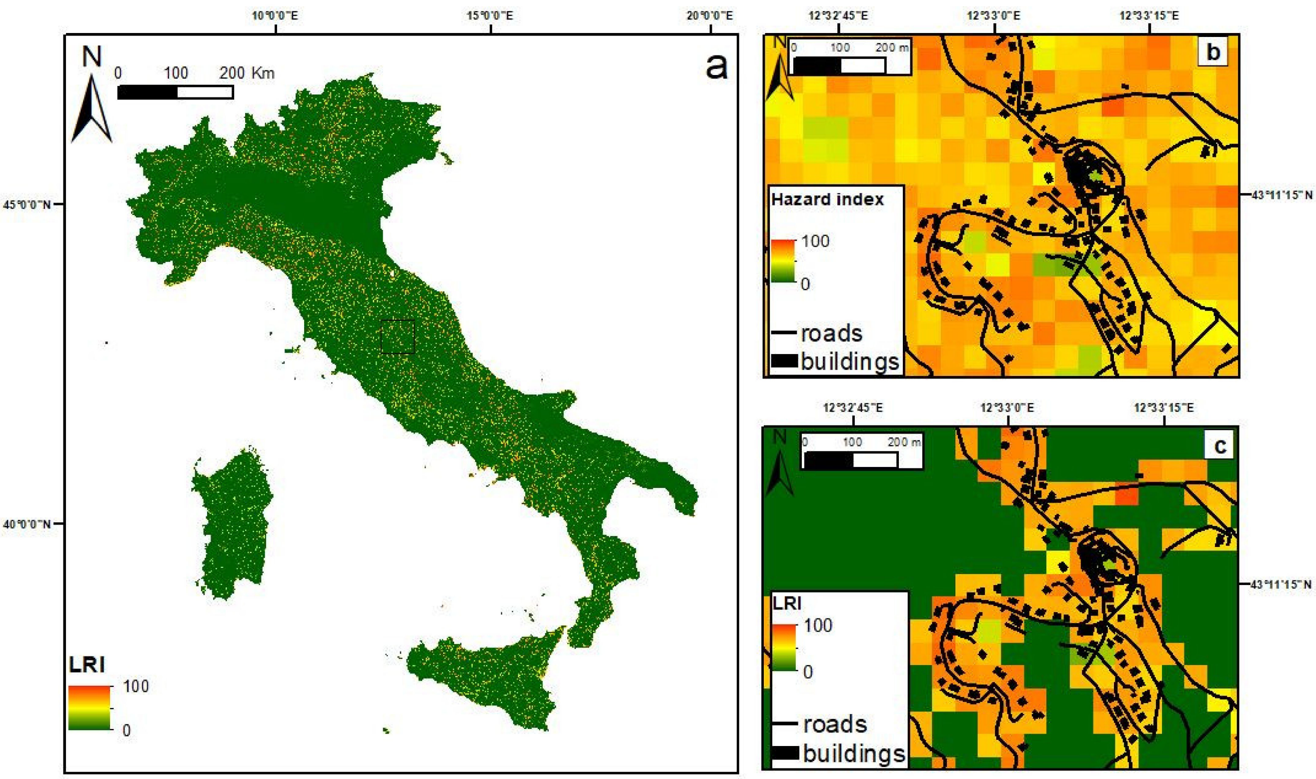

Figure 3. (**a**) Landslide Risk Index (LRI) map for the whole Italian territory; (**b**) Focus on hazard index map; (**c**) Focus on LRI map. Roads and buildings are from OpenStreetMap dataset.

LRI ranges from 0 to 100 and represents a spatially distributed indicator, which can be considered a basic element to be aggregated over larger spatial units in order to characterize them with respect to landslide risk. In this work, we derived from LRI two more indexes at municipal scale. The LRI raster and the shapefile of the borders of the Italian municipalities were overlaid in ArcMap and a "zonal statistics" was performed twice, using "mean" and "sum" to characterize each municipality with respect to two indexes named Average Landslide Risk (ALR) and Total Landslide Risk (TLR), respectively. The outcome of this operation represents the last step of the proposed procedure: the resulting indexes and a discussion about their interpretation are contained in the next section.

3. Results and Discussion

The TLR index (Figure 4) expresses for each mapping unit (municipalities in this study) the sum of the susceptibility values of all the cells with urbanized soil. Basically, this index cumulates for each administration the situations of interaction between spatial hazard and urbanized areas, expressing how much the development of the municipality has let hazardous areas to be "invaded" by constructions, infrastructure and services. In this regard, TLR could be used to describe the attention of an administration to harmonize the urban development with the main geomorphological hazard affecting its territory. Figure 4 shows that the Italian areas characterized by the highest TLR values are the Apennines (mainly the northern and central sectors), the isle of Sicily and, to a lesser extent, the eastern Alps. The drawback of this index is that it is sensitive to the extension of each aggregation unit: large municipalities have a greater chance than small ones to have a high TLR value, because of the higher number of pixels. For this reason, the value of the index does not have a fixed upper limit, and the value could theoretically tend to infinite, requiring particular attention for a correct interpretation. Indeed, when comparing different municipalities, a similarly high value of the index could be determined by many pixels with mid LRI values or by fewer pixels with higher LRI values. For this reason, the municipalities with the higher TLR index are large and densely urbanized municipalities. This result is not an artifact or a bias: the index effectively describes a recurring situation in some of the largest and most densely urbanized municipalities, which are exposed to a very high landslide risk in their territory because, during their urban expansion, they have had to cope with more hazardous areas than small municipalities. The highest values are found in the cities of Rome and Genova (both characterized by a very wide territory, densely populated and almost completely urbanized), and in the municipalities of Perugia, Gubbio and Messina, which are less populated but still have large portions of territory urbanized in hazardous areas (Figure 4). Nevertheless, TLR seems effective in highlighting the municipalities most affected by landslide risk, as the aforementioned territories correspond to areas where news about landslides continuously appear in newspapers and online blogs, as reported by [32]. In the last ten years, 4% of the landslide news catalogued and geotagged by their semantic engine is located in the aforementioned five municipalities with higher TLR values: in particular, 600 online news providers talked about landslides in Genova, 533 in Rome, and 235 in Messina.

Our results are further supported by the governmental data coming from ItaliaSicura web platform (http://mappa.italiasicura.gov.it/ last accessed on 31 May 2021), which collects the number of interventions and the economic resources allocated to mitigate hydrogeological risk in Italy. Rome is the Italian municipality with the highest number of interventions (64), likewise Genova has the highest total cost (about 378 m €) (however, it should be noted that data also include interventions for flood risk mitigation).

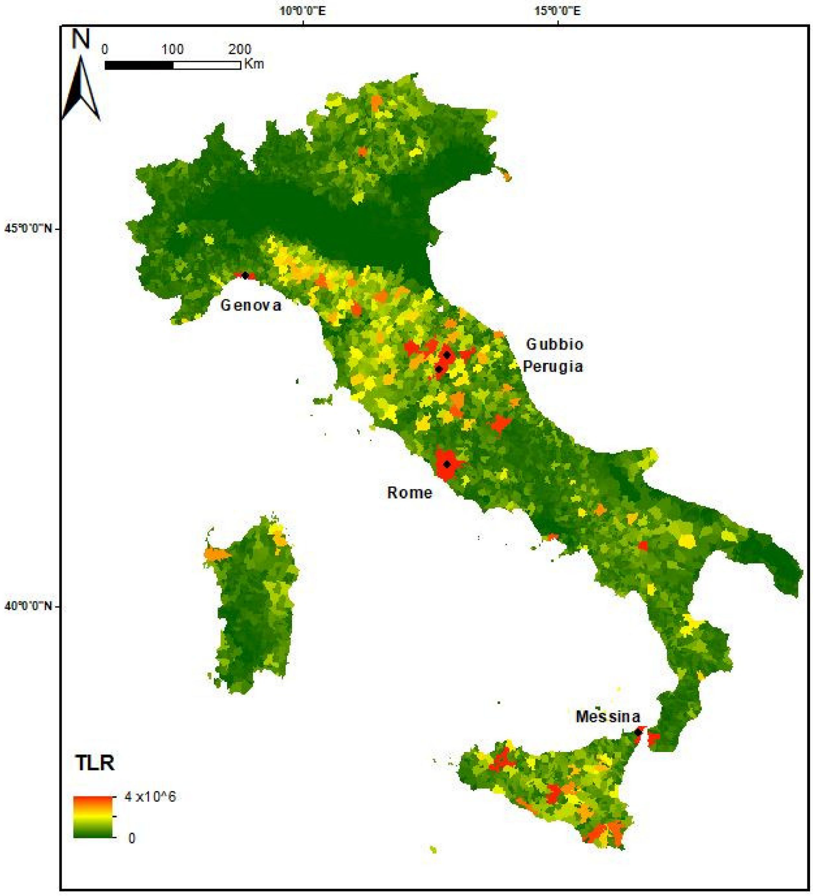

Figure 4. Characterization of the Italian municipalities with the Total Landslide Risk (TLR) index.

ALR index characterizes each municipality with the mean value of hazard found in correspondence of anthropic elements (Figure 5a). This index expresses, for each municipality, how hazardous is the portion of the territory where buildings, infrastructure and other services have been located. The values of the index range from 0 (minimum value) to 100 (maximum value): low values mean that the local administration has been cautious in planning urban development avoiding landslide risk, while high values are associated with municipalities where a consistent percentage of the urban structure has been built in hazardous areas, resulting in a relevant level of risk. It should be stressed that this does not necessarily mean that urban expansion has been recklessly planned: landslide hazard is so widespread in Italy that sometimes a municipality could be almost entirely interested by a relevant level of hazard posed by landslides or other geohazards (e.g., flood or volcanic activity). Nevertheless, also in such cases, ALR is an indicator that can be used to highlight situations where landslide risk is a very serious issue and should be carefully evaluated before further planning activities, or in the perspective of considering mitigation strategies. From a mathematical point of view, the value of ALR is independent from the areal extension of each municipality. However, a close investigation on the distribution of the values (Figure 5b) reveals that the highest values are found in small municipalities, most of them renowned international holiday destinations located by the sea, in rocky coasts (Positano, Amalfi, Capri, and Portofino, to name a few). We do not consider this outcome as a bias, and we explain it with a concurrence of factors of different nature. Firstly, in correspondence of many rocky and high-cliff coasts, the susceptibility to rockfalls presents very high values. Secondly, the territory of these municipalities is very steep and traditionally managed with the terracing method. This could be an effective method to cope with landslide hazard, but several studies highlighted that currently the loss of farmed land and the lack of maintenance seem to have recently increased the landslide hazard in these areas [56–58]. Thirdly, in the touristic locations with very high real estate value, the building of houses, accommodation facilities, infrastructure and services has been more intense than elsewhere. It has been driven mainly by market law and, especially in the last decades of the last century, not adequately counterbalanced by countermeasures concerning landslide hazard or environmental protection. This effect is particularly exacerbated in small municipalities, because the territory that can be used for urban expansion is limited and causes a severe competition between economic interests (urban expansion to support tourism and investments on the real estate market) and geomorphological processes. This is particularly alarming because small municipalities usually have scarce resources (both in terms of funds and manpower) to effectively face emergencies or to manage in-house risk mitigation strategies.

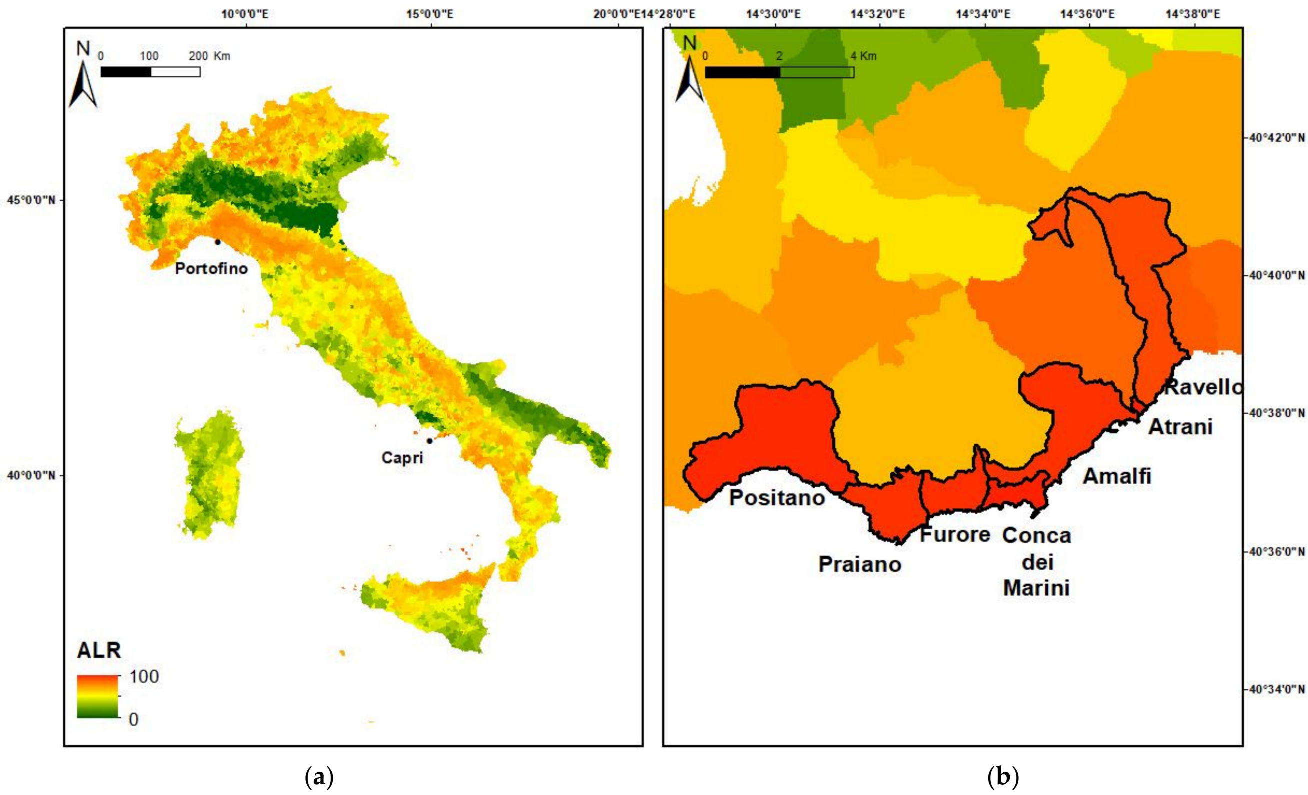

Figure 5. (**a**) Characterization of the Italian municipalities with the Average Landslide Risk (ALR) index; (**b**) Focus on the Amalfi Coast, where seven municipalities are ranked among the 10 Italian municipalities with the highest ALR value.

Our findings are in accordance with the evidence resulting from the governmental WebGIS platform presented by [12]: in most of the high-ALR municipalities highlighted in Figure 5 (especially Positano, Amalfi, Conca dei Marini), a high number of buildings are built in areas classified as landslide hazard areas according to Italian laws. For example, at least 90% of Amalfi buildings are located in hazardous areas.

The combined use of ALR and TLR indexes can be useful in gaining preliminary insights on the landslide risk of municipalities. Starting from the LRI index, which is defined at the pixel level, the same principle could be applied to other spatial units and ALR and TLR could be calculated for administrative subdivision of different level (e.g., provinces or districts) or for geographical areas (e.g., basins). It should be stressed that the proposed indexes are environmental indicators and, by definition, are conceived to simplify a complex phenomenon to aid an easy understanding also for non-experts. As a consequence, we acknowledge that the proposed indexes are an oversimplification of reality and cannot substitute a thorough quantitative risk assessment. The main utility of the indexes lies in the fact that a nation-wide quantitative landslide risk assessment is still far from being accomplished for Italy; thus, the proposed indexes can be used to explain, at scales ranging from the local to the national, the severity of the phenomenon, and to evaluate how the administrations have dealt with landslide hazards when planning urban expansion and associated services.

One of the most important requirements for indicators is the possibility to be easily updated. Concerning LRI, the updating procedure can be accomplished in GIS environment whenever updated input data (susceptibility and soil sealing maps) are available. Soil sealing is a dynamic anthropogenic process, and an updated nation-wide map is officially released every year, thus allowing for a yearly update of LRI to account for variations in urban expansion. Conversely, susceptibility is traditionally considered a quasi-static element and a constant update of this element is not expected. However, the index could be updated if a nation-wide susceptibility map is released and deemed more accurate than the one used in this work. E.g., a susceptibility map considering also the runout of landslides would be particularly indicated to thoroughly consider the interactions between hillslope processes and elements at risk. Indeed, we acknowledge that one of the main limitations of the present work is the absence of a method to explicitly include the landslide runout in the model. Unfortunately, complex modeling techniques are required to assess the post-failure displacement of landslides [59,60] and the travel distance is correlated to lithological and morphological factors [61]. For these reasons, a model accounting for landslide runout at the scale of this work ($3*10^6$ km^2) has not been proposed yet; even the latest attempts to include landslide runout in susceptibility assessments are limited to few case studies with limited extension [62,63].

Once LRI is updated, the derivation of TLR and ALR at municipal level can be also accomplished easily in a GIS system. This procedure could be carried out using the last update of the shapefile representing the Italian municipalities, which is also updated every year to account for small variations mainly consisting of the merging of very small and scarcely populated municipalities.

4. Conclusions

A nation-wide quantitative landslide risk assessment is not yet feasible in Italy (301,304 km^2) because of the lack of homogeneous, complete and detailed data. In this work we partially fill this gap by proposing a set of indicators to characterize landslide risk. Indicators are simple numerical indexes widely used in environmental studies by scientists and governmental agencies to simplify and describe complex phenomena. By definition, indicators should be simple and easy to measure, update and understand.

Firstly, a spatially distributed landslide risk index (LRI) was obtained combining state-of-the-art nation-wide susceptibility maps and a soil sealing map released in the framework of a governmental monitoring program of the urban expansion. While the former account for hazardous areas, the latter indicates if anthropic elements could be exposed; their spatial overlapping defines the relevance of the degree of risk.

LRI was then aggregated at the municipal scale to define the average landslide risk index (ALR) and the total landslide risk index (TLR), expressing respectively how hazardous the areas occupied by settlements or infrastructure are, and how serious the overall risk level in each municipality is. ALR and TLR proposed in this work are simple to update and can be adapted to various contexts and scales; in this test they were applied at the municipal level because municipalities are the key administrative subdivisions involved in urban development, land planning and risk mitigation strategies. The proposed indexes cannot substitute a detailed quantitative risk assessment, nevertheless they can provide a preliminary outlook on the spatial distribution of landslide risk at a national scale, and they can be used to evaluate how cautionary each municipality has been in planning its development to deal with the geomorphological hazards threatening its territory.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Varnes, D. *Landslide Hazard Zonation: A Review of Principles and Practice*; UNESCO: Paris, France, 1984.
2. Fell, R.; Ho, K.K.S.; Lacasse, S.; Leroi, E. A framework for landslide risk assessment and management. *Int. Conf. Landslide Risk Manag. Vanc. Can.* **2005**, *31*, 3–25.
3. Van Westen, C.J.; van Asch, T.W.J.; Soeters, R. Landslide hazard and risk zonation—Why is it still so difficult? *Bull. Eng. Geol. Environ.* **2006**, *65*, 167–184. [CrossRef]
4. Remondo, J.; Bonachea, J.; Cendrero, A. A statistical approach to landslide risk modelling at basin scale: From landslide susceptibility to quantitative risk assessment. *Landslides* **2005**, *2*, 321–328. [CrossRef]
5. Hungr, O. A Review of Landslide Hazard and Risk Assessment Methodology. In *Landslides and Engineered Slopes. Experience, Theory and Practice*; Aversa, S., Cascini, L., Picarelli, L., Scavia, C., Eds.; CRC Press: Boca Raton, FL, USA, 2018; pp. 3–27, ISBN 978-1-315-37500-7.
6. Huang, J.; Griffiths, D.V. Gordon Fenton Quantitative Risk Assessment of Individual Landslides. In Proceedings of the 7th International Symposium on Geotechnical Safety and Risk (ISGSR), Taipei, Taiwan, 11–13 December 2019; pp. 45–54.
7. Guo, Z.; Chen, L.; Yin, K.; Shrestha, D.P.; Zhang, L. Quantitative risk assessment of slow-moving landslides from the viewpoint of decision-making: A case study of the Three Gorges Reservoir in China. *Eng. Geol.* **2020**, *273*, 105667. [CrossRef]
8. Catani, F.; Casagli, N.; Ermini, L.; Righini, G.; Menduni, G. Landslide hazard and risk mapping at catchment scale in the Arno River basin. *Landslides* **2005**, *2*, 329–342. [CrossRef]
9. Lu, P.; Catani, F.; Tofani, V.; Casagli, N. Quantitative hazard and risk assessment for slow-moving landslides from Persistent Scatterer Interferometry. *Landslides* **2014**, *11*, 685–696. [CrossRef]
10. Pereira, S.; Santos, P.P.; Zêzere, J.L.; Tavares, A.O.; Garcia, R.A.C.; Oliveira, S.C. A landslide risk index for municipal land use planning in Portugal. *Sci. Total Environ.* **2020**, *735*, 139463. [CrossRef]
11. Dilley, M.; Chen, R.S.; Deichmann, U.; Lerner-Lam, A.; Arnold, M.; Agwe, J.; Buys, P.; Kjekstad, O.; Lyon, B.; Yetman, G. *Natural Disaster Hotspots: A Global Risk Analysis*; Disaster Risk Management Series; World Bank Publications: Washington, DC, USA, 2005; Volume 5, pp. 1–132.
12. Iadanza, C.; Trigila, A.; Starace, P.; Dragoni, A.; Biondo, T.; Roccisano, M. IdroGEO: A Collaborative Web Mapping Application Based on REST API Services and Open Data on Landslides and Floods in Italy. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 89. [CrossRef]
13. Tiranti, D.; Nicolò, G.; Gaeta, A.R. Shallow landslides predisposing and triggering factors in developing a regional early warning system. *Landslides* **2019**, *16*, 235–251. [CrossRef]
14. Donnini, M.; Modica, M.; Salvati, P.; Marchesini, I.; Rossi, M.; Guzzetti, F.; Zoboli, R. Economic landslide susceptibility under a socio-economic perspective: An application to Umbria Region (Central Italy). *Rev. Reg. Res.* **2020**, *40*, 159–188. [CrossRef]
15. Manzo, G.; Tofani, V.; Segoni, S.; Battistini, A.; Catani, F. GIS techniques for regional-scale landslide susceptibility assessment: The Sicily (Italy) case study. *Int. J. Geogr. Inf. Sci.* **2013**, *27*, 1433–1452. [CrossRef]
16. Segoni, S.; Lagomarsino, D.; Fanti, R.; Moretti, S.; Casagli, N. Integration of rainfall thresholds and susceptibility maps in the Emilia Romagna (Italy) regional-scale landslide warning system. *Landslides* **2015**, *12*, 773–785. [CrossRef]
17. Piacentini, D.; Troiani, F.; Soldati, M.; Notarnicola, C.; Savelli, D.; Schneiderbauer, S.; Strada, C. Statistical analysis for assessing shallow-landslide susceptibility in South Tyrol (south-eastern Alps, Italy). *Geomorphology* **2012**, *151–152*, 196–206. [CrossRef]
18. Trigila, A.; Frattini, P.; Casagli, N.; Catani, F.; Crosta, G.; Esposito, C.; Iadanza, C.; Lagomarsino, D.; Mugnozza, G.S.; Segoni, S.; et al. Landslide Susceptibility Mapping at National Scale: The Italian Case Study. In *Landslide Science and Practice: Volume 1: Landslide Inventory and Susceptibility and Hazard Zoning*; Margottini, C., Canuti, P., Sassa, K., Eds.; Springer: Berlin/Heidelberg, Germany, 2013; pp. 287–295, ISBN 978-3-642-31325-7.
19. Munafò, M. *Consumo di Suolo, Dinamiche Territoriali e Servizi Ecosistemici*; SNPA: Rome, Italy, 2019; p. 224.
20. Guillard-Gonçalves, C.; Cutter, S.L.; Emrich, C.T.; Zêzere, J.L. Application of Social Vulnerability Index (SoVI) and delineation of natural risk zones in Greater Lisbon, Portugal. *J. Risk Res.* **2015**, *18*, 651–674. [CrossRef]

21. de Almeida, L.Q.; Welle, T.; Birkmann, J. Disaster risk indicators in Brazil: A proposal based on the world risk index. *Int. J. Disaster Risk Reduct.* **2016**, *17*, 251–272. [CrossRef]
22. Munafò, M.; Salvati, L.; Zitti, M. Estimating soil sealing rate at national level—Italy as a case study. *Ecol. Indic.* **2013**, *26*, 137–140. [CrossRef]
23. Bosellini, A. Outline of the Geology of Italy. In *Landscapes and Landforms of Italy*; Soldati, M., Marchetti, M., Eds.; Springer International Publishing: Cham, Switzerland, 2017; pp. 21–27.
24. Dal Piaz, G.V.; Bistacchi, A.; Massironi, M. Geological outline of the Alps. *Episodes* **2003**, *26*, 175–180. [CrossRef]
25. Vezzani, L.; Festa, A.; Ghisetti, F.C. *Geology and Tectonic Evolution of the Central-Southern Apennines, Italy*; Geological Society of America: Boulder, CO, USA, 2010. [CrossRef]
26. Scisciani, V.; Tavarnelli, E.; Calamita, F. The interaction of extensional and contractional deformations in the outer zones of the Central Apennines, Italy. *J. Struct. Geol.* **2002**, *24*, 1647–1658. [CrossRef]
27. Boccaletti, M.; Corti, G.; Martelli, L. Recent and active tectonics of the external zone of the Northern Apennines (Italy). *Int. J. Earth Sci.* **2011**, *100*, 1331–1348. [CrossRef]
28. Pinna, M. Contributo alla classificazione del clima d'Italia. *Riv. Geogr. Ital.* **1970**, *77*, 129–152.
29. Alpert, P.; Ben-Gai, T.; Baharad, A.; Benjamini, Y.; Yekutieli, D.; Colacino, M.; Diodato, L.; Ramis, C.; Homar, V.; Romero, R.; et al. The paradoxical increase of Mediterranean extreme daily rainfall in spite of decrease in total values. *Geophys. Res. Lett.* **2002**, *29*, 31-1–31-4. [CrossRef]
30. Libertino, A.; Ganora, D.; Claps, P. Technical note: Space–time analysis of rainfall extremes in Italy: Clues from a reconciled dataset. *Hydrol. Earth Syst. Sci.* **2018**, *22*, 2705–2715. [CrossRef]
31. Gariano, S.L.; Guzzetti, F. Landslides in a changing climate. *Earth-Sci. Rev.* **2016**, *162*, 227–252. [CrossRef]
32. Battistini, A.; Segoni, S.; Manzo, G.; Catani, F.; Casagli, N. Web data mining for automatic inventory of geohazards at national scale. *Appl. Geogr.* **2013**, *43*, 147–158. [CrossRef]
33. Battistini, A.; Rosi, A.; Segoni, S.; Lagomarsino, D.; Catani, F.; Casagli, N. Validation of landslide hazard models using a semantic engine on online news. *Appl. Geogr.* **2017**, *82*, 59–65. [CrossRef]
34. Calvello, M.; Pecoraro, G. FraneItalia: A catalog of recent Italian landslides. *Geoenviron. Disasters* **2018**, *5*, 13. [CrossRef]
35. Trigila, A. *Rapporto Sulle Frane in Italia: Il Progetto IFFI: Metodologia, Risultati e Rapporti Regionali*; APAT: Rome, Italy, 2007; ISBN 88-448-0310-0.
36. Trigila, A.; Iadanza, C.; Spizzichino, D. Quality assessment of the Italian Landslide Inventory using GIS processing. *Landslides* **2010**, *7*, 455–470. [CrossRef]
37. Herrera, G.; Mateos, R.M.; García-Davalillo, J.C.; Grandjean, G.; Poyiadji, E.; Maftei, R.; Filipciuc, T.-C.; Jemec Auflič, M.; Jež, J.; Podolszki, L.; et al. Landslide databases in the Geological Surveys of Europe. *Landslides* **2018**, *15*, 359–379. [CrossRef]
38. Budetta, P. Landslide hazard assessment of the Cilento rocky coasts (Southern Italy). *Int. J. Geol.* **2013**, *7*, 1–8.
39. Sacchini, A.; Faccini, F.; Ferraris, F.; Firpo, M.; Angelini, S. Large-scale landslide and deep-seated gravitational slope deformation of the Upper Scrivia Valley (Northern Apennine, Italy). *J. Maps* **2016**, *12*, 344–358. [CrossRef]
40. Pellicani, R.; Argentiero, I.; Spilotro, G. GIS-based predictive models for regional-scale landslide susceptibility assessment and risk mapping along road corridors. *Nat. Hazards Risk* **2017**, *8*, 1012–1033. [CrossRef]
41. Fell, R.; Corominas, J.; Bonnard, C.; Cascini, L.; Leroi, E.; Savage, W.Z. Guidelines for landslide susceptibility, hazard and risk zoning for land-use planning. *Eng. Geol.* **2008**, *102*, 99–111. [CrossRef]
42. Cervi, F.; Berti, M.; Borgatti, L.; Ronchetti, F.; Manenti, F.; Corsini, A. Comparing predictive capability of statistical and deterministic methods for landslide susceptibility mapping: A case study in the northern Apennines (Reggio Emilia Province, Italy). *Landslides* **2010**, *7*, 433–444. [CrossRef]
43. Conforti, M.; Robustelli, G.; Muto, F.; Critelli, S. Application and validation of bivariate GIS-based landslide susceptibility assessment for the Vitravo river catchment (Calabria, south Italy). *Nat. Hazards* **2012**, *61*, 127–141. [CrossRef]
44. Zizioli, D.; Meisina, C.; Valentino, R.; Montrasio, L. Comparison between different approaches to modeling shallow landslide susceptibility: A case history in Oltrepo Pavese, Northern Italy. *Nat. Hazards Earth Syst. Sci.* **2013**, *13*, 559–573. [CrossRef]
45. Segoni, S.; Tofani, V.; Lagomarsino, D.; Moretti, S. Landslide susceptibility of the Prato–Pistoia–Lucca provinces, Tuscany, Italy. *J. Maps* **2016**, *12*, 401–406. [CrossRef]
46. Segoni, S.; Pappafico, G.; Luti, T.; Catani, F. Landslide susceptibility assessment in complex geological settings: Sensitivity to geological information and insights on its parameterization. *Landslides* **2020**, *17*, 2443–2453. [CrossRef]
47. Esposito, G.; Carabella, C.; Paglia, G.; Miccadei, E. Relationships between Morphostructural/Geological Framework and Landslide Types: Historical Landslides in the Hilly Piedmont Area of Abruzzo Region (Central Italy). *Land* **2021**, *10*, 287. [CrossRef]
48. Lagomarsino, D.; Tofani, V.; Segoni, S.; Catani, F.; Casagli, N. A tool for classification and regression using random forest methodology: Applications to landslide susceptibility mapping and soil thickness modeling. *Environ. Modeling Assess.* **2017**, *22*, 201–214. [CrossRef]
49. Catani, F.; Lagomarsino, D.; Segoni, S.; Tofani, V. Landslide susceptibility estimation by random forests technique: Sensitivity and scaling issues. *Nat. Hazards Earth Syst. Sci.* **2013**, *13*, 2815–2831. [CrossRef]
50. Lee, S. Current and future status of GIS-based landslide susceptibility mapping: A literature review. *Korean J. Remote Sens.* **2019**, *35*, 179–193.

51. Shano, L.; Raghuvanshi, T.K.; Meten, M. Landslide susceptibility evaluation and hazard zonation techniques—A review. *Geoenviron. Disasters* **2020**, *7*, 1–19. [CrossRef]
52. Prokop, G.; Jobstmann, H.; Schönbauer, A. *Overview on Best Practices for Limiting Soil Sealing and Mitigating Its Effects in EU-27*; European Communities: Brussels, Belgium, 2011.
53. Munafò, M.; Assennato, F.; Congedo, L.; Luti, T.; Marinosci, I.; Monti, G.; Riitano, N.; Sallustio, L.; Strollo, A.; Tombolini, I. *Il Consumo di Suolo in Italia*; Rapporti ISPRA n.218/2015; ISPRA: Roma, Italy, 2015; p. 90.
54. Luti, T.; Segoni, S.; Catani, F.; Munafò, M.; Casagli, N. Integration of Remotely Sensed Soil Sealing Data in Landslide Susceptibility Mapping. *Remote Sens.* **2020**, *12*, 1486. [CrossRef]
55. Hartlen, J.; Viberg, L. General report: Evaluation of landslide hazard. In Proceedings of the International Symposium on Landslides, Lausanne, Switzerland, 10–15 July 1988; pp. 1037–1057.
56. Di Napoli, M.; Carotenuto, F.; Cevasco, A.; Confuorto, P.; Di Martire, D.; Firpo, M.; Pepe, G.; Raso, E.; Calcaterra, D. Machine learning ensemble modelling as a tool to improve landslide susceptibility mapping reliability. *Landslides* **2020**, *17*, 1897–1914. [CrossRef]
57. Tarolli, P.; Preti, F.; Romano, N. Terraced landscapes: From an old best practice to a potential hazard for soil degradation due to land abandonment. *Anthropocene* **2014**, *6*, 10–25. [CrossRef]
58. Savo, V.; Salvati, L.; Caneva, G. In-between soil erosion and sustainable land management: Climate aridity and vegetation in a traditional agro-forest system (Costiera Amalfitana, Southern Italy). *Int. J. Sustain. Dev. World Ecol.* **2016**, *23*, 423–432. [CrossRef]
59. Stamatopoulos, C.A.; Di, B. Analytical and approximate expressions predicting post-failure landslide displacement using the multi-block model and energy methods. *Landslides* **2015**, *12*, 1207–1213. [CrossRef]
60. Firmansyah, S.; Feranie, S.; Tohari, A.; Latief, F.D.E. Prediction of landslide run-out distance based on slope stability analysis and center of mass approach. In Proceedings of the International Symposium on Geophysical Issues PEDISGI, Badung, Indonesia, 8–10 June 2015; Volume 29.
61. Guo, D.; Hamada, M.; He, C.; Wang, Y.; Zou, Y. An empirical model for landslide travel distance prediction in Wenchuan earthquake area. *Landslides* **2014**, *11*, 281–291. [CrossRef]
62. Mergili, M.; Schwarz, L.; Kociu, A. Combining release and runout in statistical landslide susceptibility modeling. *Landslides* **2019**, *16*, 2151–2165. [CrossRef]
63. Napoli, M.D.; Martire, D.D.; Bausilio, G.; Calcaterra, D.; Confuorto, P.; Firpo, M.; Pepe, G.; Cevasco, A. Rainfall-induced shallow landslide detachment, transit and runout susceptibility mapping by integrating machine learning techniques and GIS-based approaches. *Water* **2021**, *13*, 488. [CrossRef]