Assessment of risk scenarios to support landslide studies

Giovanna Capparelli$^{(1)*}$, **Pasquale Versace**$^{(1)}$, **Danilo Spina**$^{(1)}$

1) University of Calabria, Department of Computer Engineering, Modeling, Electronics and Systems (DIMES), Ponte Pietro Bucci, cubo 41/B – 87036 Rende, Italy

Abstract The definition of risk scenarios that are as reliable and detailed as possible is a primary objective to increase the effectiveness of civil protection actions in the alert phases, together with adequate self-protection actions. In the workflow that characterizes integrated emergency management systems, risk scenarios are an essential element for connecting the information coming from the early warning systems and the actions at responding to the need of safeguard human life. Nowadays, the availability of high-resolution terrain data allows access to an almost precise knowledge of the territory, forgetting purely topographical approaches whose application over a vast domain has proven impractical or misleading. This translates into new potential in the definition of event scenarios and risk scenarios. In reality, alongside highly advanced pre-announcement and monitoring systems, there are often barely outlined event scenarios and mostly qualitative risk scenarios, and therefore lacking the effectiveness they should and could have. To achieve a level of detail that effectively supports the activities in the intervention phase, it is necessary to aim, even more decisively, towards a quantitative analysis of the risk deriving from hydrogeological phenomena. Event scenarios, as is known, describe the phenomena that can occur, quantitatively define their magnitude, locate the vulnerable areas, i.e. those that can be affected by the event. Landslide phenomena, for example, are distinguished by kinematics, the type and size of the material involved, the speed of movement, the impact energy.

The risk scenarios, therefore, describe the foreseeable effects of the events identified and described by the event scenarios on the exposed elements. In general, in risk analysis, vulnerability is considered invariant or, in any case, is only assessed quickly, whereas it is almost always decisive in defining the level of risk to which a vulnerable area is subject.

In this work we propose a simplified vulnerability assessment method for people exposed to fast moving landslides. The procedure is very flexible because it can be developed at different levels of detail and at different spatial scales depending on the size of the objects involved. The proposed approach has some similarities with other methods used in the vulnerability assessment to other natural risks, as earthquake and floods and, therefore, it can be adopted for multi-risk analyses. Referring to a case study, it shows the advantages and potential of the approach for a high-resolution landscape mapping at reach scale to support landslides studies.

Keywords risk assessment, vulnerability index, integrated approach, non-structural measures

Introduction

Risk scenarios describe the foreseeable effects of events identified and outlined by event scenarios on exposed elements. Various models for the quantitative assessment of risk have been proposed in the literature. Generally, the factors determining risk depend on the severity of the phenomenon (magnitude), the extent of exposed elements, and their ability to withstand the event (vulnerability). A key element is the definition of vulnerability to natural risks, expressed on a scale from 0 (no damage) to 1 (total loss). In technical literature, the concept has many connotations depending on the research perspective (Dow, 1992; Cutter, 1996). There are three fundamental principles in vulnerability research: "Vulnerability as hazard exposure" - the identification of conditions that make people or places vulnerable to extreme natural events (Burton, Kates, and White, 1993; Anderson, 2000); "Vulnerability as social response" - the assumption that vulnerability is a social condition, measuring social resistance to events, resilience, and recovery (Blaikie et al., 1994); "Vulnerability of places" - the integration of exposure and social resilience with a specific focus on particular places or regions (Kasperson and Turner, 1995).

Similarly, it has been widely recognized that vulnerability can have three dimensions. Economic, referring to potential economic damage as a risk to production, distribution, and consumption (Comfort et al., 1999). Social vulnerability recognizes the vulnerability of individuals, emphasizing their coping ability. Social vulnerability is related to various characteristics of human beings (Blaikie et al., 1994). The ecological dimension of vulnerability acknowledges ecosystem or environmental fragility. According to Williams & Kaputska (2000), vulnerability can be seen as the "inability of an ecosystem to tolerate stress factors over time and space," emphasizing the importance of understanding how different types of natural environments cope or adapt differently. Cutter et al. (2000) has integrated various elements contributing to the overall vulnerability of places, referred to as the "Hazard of place model of Vulnerability."

The new definition of vulnerability, apart from minor oscillations as indicated, remains fundamentally unchanged at the United Nations until the most recent formulation (UNISDR, 2016), where it is clearly emphasized that vulnerability is a context and a factor that, in relation to hazards, contributes to risk. To cite a few, vulnerability represents: "Conditions determined by physical, social, economic, and environmental factors or processes that increase the community's susceptibility to the impact of hazards (UNISDR, 2005)"; "The characteristics and circumstances of a community that make it susceptible to the damaging effects of a hazard (UNISDR, 2009)." The ability to measure vulnerability is an essential prerequisite for reducing the risk of disasters and for adaptation strategies, but it requires the capacity to identify and better understand the various vulnerabilities that largely determine the risk.

The complexity of the vulnerability concept itself requires the reduction of potentially collected data to a series of important indicators and criteria that facilitate the estimation of vulnerability. The World Conference on Disaster Reduction (WCDR) held in Kobe, Japan, in 2005, emphasized the need to develop vulnerability indicators. The final document of the WCDR, the Hyogo Framework for Action 2005–2015 (UN, 2005), emphasizes that it is important to: "develop systems of disaster risk and vulnerability indicators at the national and sub-national levels that allow decision-makers to assess the impact of disasters on social, economic, and environmental conditions and to disseminate the results to decision-makers, the public, and the at-risk population" (UN, 2005, p. 9).

The following describes the methodological criteria for the quantitative identification of risk scenarios, considering people as the sole element at risk. From an existing literature analysis, the main factors contributing to the vulnerability of individuals and the methods used for quantitative assessment have been identified.

From the analysis of the developed survey, a procedure called EVIL (Evaluation of Vulnerability to Inundations and Landslides) has been defined, which was applied to a case study "Frana di Gimigliano," producing the vulnerability map and the risk scenarios map. The following provides a detailed description of the EVIL procedure, in its version dedicated to landslide phenomena, and the application to the Gimigliano case study.

Description of the EVIL method for landslide risk assessment

Object Identification

The object is defined as the minimum territorial element of reference: for it, intrinsic characteristics (position, geometric features, conditions of occupants, etc.) and contextual conditions (event characteristics, environmental conditions, etc.) are considered constant.

The level of detail intended in the analysis influences the choice of objects for which to define the risk index and the attributes that will be used for its estimation. With fixed times and available resources, the smaller the scale of the investigation, the larger the size of the objects considered, and the lower the level of detail of the result. Conversely, the larger the scale of the investigation, the smaller the size of the identified objects, and the greater the achievable level of detail. Developing at the maximum expected level of detail, the objects considered as the minimum unit of reference can belong to one of the following categories: Buildings (residential, productive, commercial, directional/tertiary, tourist/receptive, services, etc.); Short stretches of roads and railway network (highways, main rural roads, secondary rural roads, urban arterial roads, neighborhood urban roads, and local roads); Individual portions of open spaces (paved areas in general, including sidewalks, parking lots, courtyards; urban green areas and agricultural green areas, pastures, wooded areas, uncultivated areas, etc.).

Estimation of Vulnerability Index

The Vulnerability Index (IVI), expressed for each of the objects into which the territory is divided, is assessed using several factors, Fi (i= 1, 2, ... , m), which indicate the main elements contributing to determining the vulnerability of an individual object. In the EVIL procedure for landslides, m is assumed to be 4. Its value is given by:

$$IVI = \sum_i F_i W_i \qquad [1]$$

Where Wi is the weight of factor Fi and is between 0 and 1. It must also be:

$$\sum_i W_i = 1 \qquad [2]$$

For the estimation of Fi, certain attributes Aij (j= 1, .., ni) are used to characterize it. The value of Fi is given by:

$$F_i = \sum_i V(A_{ij}) w_{ij} \qquad [3]$$

Where V(Aij) is the value of attribute Aij, which is between 0 and 1, wij is the weight of attribute Aij, and it can also take values between 0 and 1. Additionally, it must be:

$$\sum_i w_{ij} = 1 \qquad [4]$$

Therefore, both Fi and IVI are bounded between 0 and 1. For the estimation of V(Aij), EVIL uses the following criteria: V(Aij) is a discrete variable that can take only a limited number of values predetermined by the class to which the attribute belongs; the assignment of an attribute to a class is based on indicators that can be numerical when there is a procedure to measure them or descriptive when there are no concrete procedures applicable for their measurement. In the case of numerical indicators, a rule is defined for each attribute that allows, based on the values assumed by the indicators, to assign Aij to a class and consequently assign the corresponding value to V(Aij) for that class. In the case of descriptive indicators, each class is characterized by a concise description that uniquely places the analyzed indicator in a specific class and assigns the attribute the corresponding value.

If an object is affected by multiple phenomena, this calculation must be repeated for each potentially harmful phenomenon to the occupants of that object. The vulnerability of the object, in this case, will be the maximum calculated vulnerability. The factors, attributes, indicators, and assignment criteria that characterize the EVIL method for landslides are listed below.

The four considered factors are: F1: Event characteristics, F2: Characteristics of people, F3: Position, and F4: Possibility of escape and rescue.

For each category of objects (buildings, roads and railway network, open spaces), these factors do not change even though their weights may differ. However, within each category of objects, the attributes that define these factors are slightly different. The weights assigned to the various factors are reported in Tab. 1

Table 1 List of factors and their respective weights.

Fattore F_i		Valore peso W_i
Event characteristics	F1	0,35
Characteristics of people	F2	0,2
Position	F3	0,35
Possibility of escape and rescue	F4	0,1

Estimation of the Crowding Index

The estimation of the crowding index assumes that the population affected by landslide events is the one present in the at-risk areas at the time of the event and is referred to as PP (present population). PP is divided into two components: RP (resident population present) and NRP (non-resident population present). Documents provided by ISTAT (ISTAT, is the National Institute of Statistics and is a public research body. It has been present in the country since 1926 and is the main producer of official statistics to support citizens and public decision-makers), allow for the estimation of PR (resident population) broken down and divided at the level of census sections. From this, RP and NRP can be estimated:

$$\begin{cases} RP = \alpha\, PR \ \ (0 \leq \alpha \leq 1) \\ NRP = \beta\, PR \ \ (\beta \geq 0) \end{cases}$$

Therefore:

$$PP = (\alpha + \beta)\, PR$$

Usually, α=1 and β=0, so PP=PR. However, in some cases, PP and PR can be different, for example, in summer in large cities, PP < PR, in tourist areas PP > PR.

At the time of the event, PP can be in buildings (PPE), on the streets (PPS), in open areas (PPA), or in other spaces different from the previous ones (special categories: railway, hospitals, schools, barracks). For example, people (PPF) on trains in the vulnerable area and at the station can be considered. PPE, PPS, PPA are usually expressed as fractions of PP; PPF is expressed as the number of people. The distribution of the population can take different configurations depending on the period in which the event occurs, for example:

A. Average daytime configuration, in which a substantial part of the population is expected to be inside a building (home, workplace, commercial activity, school, etc.). The remaining part will be distributed outside a building, moving between various buildings by car, train, or on foot. B. Nighttime configuration, in which a majority percentage of the population (compared to configuration A) will be inside their homes, and only a small fraction will be outside. C. Special event configuration, in which a representative configuration of presence in the area is proposed, including the resident population PR, the population on the railway network PPF, and also non-resident people PNR (this extraordinary presence may be due to events, attractions, tourism, etc.).

Calculation of the Risk Index

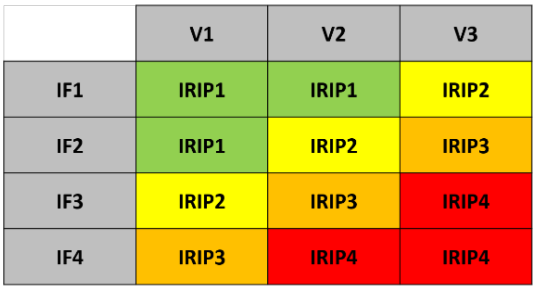
The calculation of the risk index divides the Vulnerability Index (IVI) into three classes:

V1 (Moderate Vulnerability): per 0<IVI≤0.5
V2 (Medium Vulnerability): per 0.5<IVI≤0.75
V3 (High Vulnerability): per 0.75<IVI≤1

The number of occupants for each object has been discretized as follows:

IF1 – Modest Crowding: 0 – 5 people
IF2 – Medium Crowding: 5 – 10 people
IF3 – High Crowding: 10 – 15 people
IF4 – Very High Crowding: >15 people

The vulnerability and crowding classes have been set considering the values found for different objects in the specific case, providing a sufficient representation of the various classes. Once the three vulnerability classes and the four crowding classes are defined, the Risk Index for People's Safety (IRIP) is calculated using the following matrix (Fig. 1):



	V1	V2	V3
IF1	IRIP1	IRIP1	IRIP2
IF2	IRIP1	IRIP2	IRIP3
IF3	IRIP2	IRIP3	IRIP4
IF4	IRIP3	IRIP4	IRIP4

Figure 1 Index Risk Matrix for People's Safety (IRIP)

Application

Identification of risk scenario for the study case.

The procedure was applied for the landslides occurred in Gimigliano village, in Calabria region, South of Italy (Fig. 2). The resident population amounts to 3035 inhabitants as of January 1, 2022 (source: ISTAT), with 1682 residing in the central area, while the remaining residents are distributed among the near zones. From a morphological perspective, the municipality has a predominantly hilly terrain (about 40%) and mountainous terrain (about 60%).

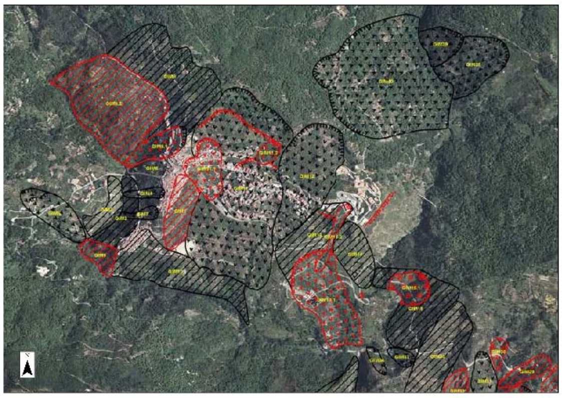


Figure 2: Inventory map of unstable inhabited centers, Municipality of Gimigliano - Calabria Region - Italy. Source: Extract basin plan for the iderogological structure (Legislative Decree 180/98) - Regional Basin Authority - Department of Public Works and Water

The entire territory of Gimigliano is affected by numerous landslide phenomena, characterized not only by different mechanisms but also by different states, distributions, and styles of activity. This is a consequence of an extremely complex geological framework involving lithological units that have undergone various deformation phases.

Among all instability phenomena affecting the territory, the attention has been focused on the landslide, which involves the recently developed inhabited center. A detailed geomorphological study (MUTO, 2012b) revealed a highly complex situation, characterized by the presence of minor landslide movements that overlap and, in the central part, cover the main landslide. Some of these phenomena are characterized by a complex and sometimes composite kinematic style.

The main landslide extends for a width of about 800 meters and a length of about 1,300 meters, ranging between elevations of 820m and 420m. It features a pronounced main scarp, a well-defined right flank, and a less evident left flank, partly overlapped or covered by other landslide phenomena.

The mid-upper portion of the slope is affected by minor landslides showing translational sliding kinematics and, in some cases, rotational components. Other landslide phenomena exhibit complex kinematics. The estimated depth is greater than 20 meters in the central part, showing signs of slow activity and deformation.

The movement is active with speeds falling within slow movements. The depth data, although the landslide body consists of a heterogeneous mass, indicate the existence of a single sliding surface for the main Gimigliano landslide. Almost the entire inhabited center is affected by this complex and articulated system of landslide phenomena, showing more or less evident signs on structures.

For developing the analysis of the degree of vulnerability and risk in the territory, a deep-seated phenomenon has been considered as a large unitary accumulation with a single sliding surface set at a depth of over 50 m. It exhibits characteristics of rock sliding, with a constant activity distribution; five superficial phenomena; two fast superficial flows; a phenomenon identified as rock collapse and/or debris avalanches.

For the application of the method, after identifying and selecting the phenomena to be addressed, their intensity was evaluated—their capacity to cause damage to property and people—through a geomorphological approach (PON LEWIS). Each phenomenon was characterized with the attributes listed in Tab. 2.

Table 2 Attributes necessary for estimating the intensity of landslide phenomena

Field	Content
Code	Progressive numeric unique identifier of the event
Typology	Indication of the type of landslide movement
Activity	Indication of the landslide activity status
Area	Surface affected by the instability expressed in m2
Depth	Estimation of the thickness of the displaced mass
Volume	Estimation of the volume of material involved in the movement
Crown	Crown length
Landslide face	Length of the landslide front
Intensity	Estimation of landslide intensity
Speed	Estimation of landslide speed
Frequency	Estimate of the probable frequency of the landslide

Once the phenomena have been characterized, the geometric severity index is estimated. For lateral spreading, debris flows and/or earth flows, complex landslides, and rock slides, the geometric severity index is estimated based on the landslide surface area (SUP), crown length (COR), landslide front length (FRO), thickness (SPE), and the volume of material involved in the movement (VOL). For rockfalls and/or topples, the dimensions of the fallen or potentially mobilizable blocks are evaluated (DIM).

After determining and classifying the parameters, the geometric severity index is assessed for each landslide by intersecting the five parameters (SUP+COR+FRO+SPE+VOL). The geometric severity index is divided into five classes ranging from very low to very high. The intensity of a landslide defines the impact of the event on the territory, categorizing it into three intensity classes (low, medium, and high).

For landslides latu sensu, the intensity (INF) is evaluated by combining the geometric severity index (ISG) with the speed of the mapped landslide phenomena. In the case of rockfalls and/or topples, for the intensity estimate (INR), the combination of the dimensions of the fallen blocks with the speed is carried out.

The proposed scheme has been applied to individual identified phenomena, which have been considered as possible scenarios. Material involved, type of movement, activity status, surface area, maximum depth of the sliding surface, crown length, and front length were evaluated. The estimation of landslide volume was performed using geological cross-sections of individual landslide bodies. The speed of deep landslides and superficial landslides was derived by assessing the results of inclinometer readings, surface topographic monitoring, and data from satellite interferometry. For rockfalls/debris avalanches and fast superficial flows, the classification of CRUDEN & VARNES (1996) was used.

Once the individual attributes were evaluated and classified, it was possible to calculate the geometric severity index (ISG) first and then the intensity (INF/INR) of the phenomena.

Identification of the Objects

The identified objects belong to one of the following categories: buildings, roads/railway network, and open spaces. For this case study, the objects have been primarily identified based on cartographic data, using information represented on the map at a scale of 1:5000 (CTR).

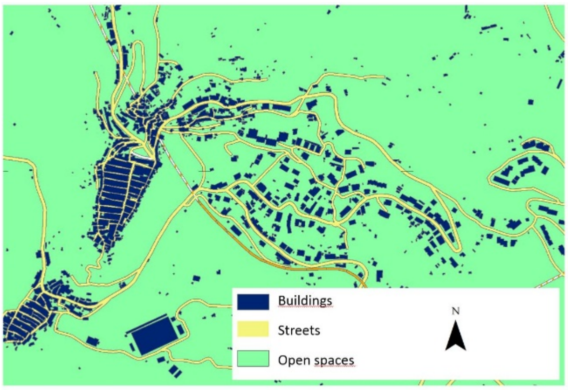


Figure 3 – objects identified in the study area, grouped by category.

Assessment of Vulnerability Index

The Vulnerability Index (IVI) was assessed using the factors (Fi) outlined in the EVIL procedure. For each object category (buildings, roads/railway network, open spaces), the following factors were considered: F1 Event Characteristics, F2 People Characteristics, F3 Location, and F4 Escape and Rescue Possibility.

The vulnerability index was calculated for buildings using the attribute values listed below. Additionally, this calculation was repeated for various identified landslide phenomena.

The IVI is calculated by applying the procedure described above, summarized by the mathematical expression number 1. Below are the attributes used for each factor (Tab. 3).

Table 3 Attributes used for the estimation of the four factors.

Fattore	Attributo
F1 - Event characteristics	Intensity of the event
F2 - Characteristics of people Position	Age
	Physical conditions
F3 - Possibility of escape and rescue Event characteristics	Relative position
	Degree of protection
F4 - Characteristics of people	Length of the escape route
	Extension of the area involved
	Effectiveness of the warning system

After calculating the IVI value for each object and for each phenomenon included in the reference event scenarios, each object was assigned the maximum vulnerability value obtained. An example of the spatial distribution of the vulnerability index for the buildings category is shown in Fig. 4.

Estimation of Crowding Index

The crowding index (IF) was calculated as explained, particularly for risk calculation, considering the average daytime crowding configuration A as an example. In this configuration, the total population present coincides with both the resident population (PR) and the population on the railway network (PPF). In this setup, a significant portion of the population is expected to be inside a building (home, workplace, commercial activity, school, etc.). The remaining part will be distributed outside a building, moving between various buildings by car, train, or on foot. The distribution of the crowding index (IF) for the buildings category is shown in Fig. 4.

Risk Index Estimation

Once the three vulnerability classes and four crowding classes were defined, the risk index for people's safety (IRIP) was calculated. Fig. 4 illustrates the distribution of the risk index for the buildings category.. .

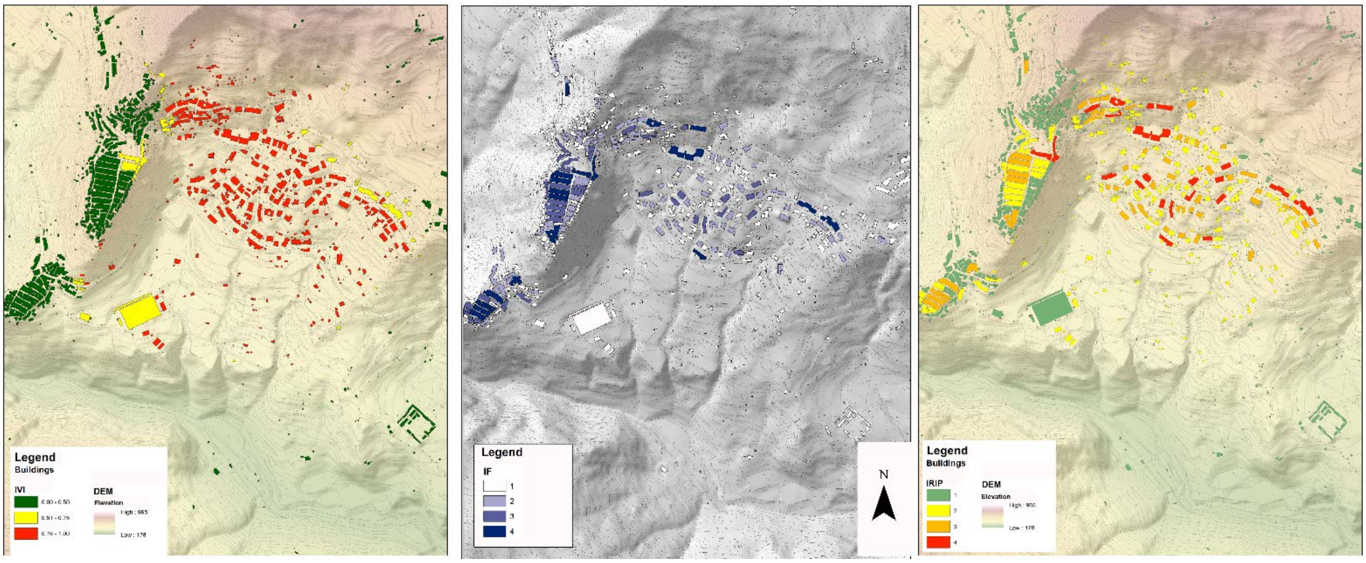


Figure 4 distribution of the vulnerability index (maximum), the IF crowding index and the risk index for the safety of people (IRIP) for the "buildings" object category"

Conclusion

Risk scenarios are strongly connected to the level of detail in the event scenarios. Moreover, for the estimation of various indicators contributing to the cascading assessment of attributes and their related factors, different types of data can be utilized. In some cases, this involves simply consulting existing databases (ISTAT), in others, it requires the development of activities for consulting and interpreting existing documents (thematic cartography, technical documents), and in still others, it involves the development of targeted investigations and studies (specific surveys and studies). Therefore, where detailed information is available, the EVIL procedure can be applied for the construction of the corresponding risk scenario. The procedure described is a preliminary application for the construction of risk scenarios. This procedure, or rather, the EVIL method, as described, is subjected of further future developments. Even the logical framework for assessing the vulnerability index is largely similar, the update involves some of the indicators incorporated into the methodology with the aim of using indicators based on an objective and scientifically grounded assessment.

Acknowledgements.

These are a preliminary results of long work into research carried out with great dedication by the late Prof. Emeritus Pasquale Versace, to whom we would like to extend our heartfelt thanks for the path taken so far.

References

Anderson, M. B. (2000). Vulnerability to Disaster and Sustainable Development: A General Framework for Assessing Vulnerability.Pp. 11–25 in R. Pielke, Jr. and R. Pielke Sr., eds.Storms (Vol. 1). London: Routledge

Blaikie, P., T. Cannon, I. Davis, and B. Wisner. (1994). At Risk: Natural Hazards, People's Vulnerability, and Disasters. London: Routled

Burton, I., R. W. Kates, and G. F. White. (1993). The Environment as Hazard (2nd ed.). New York: Guildford

Cutter, S. L. (1996). Vulnerability to Environmental Hazards. Progress in Human Geography 20(4), 529–39

Dow, K. (1992). Exploring Differences in Our Common Future(s): The Meaning of Vulnerability to Global Environmental Change. Geoforum 23(3), 417–36

ISTAT. https://www.istat.it/it/censimenti/popolazione-e-abitazioni

ISTAT. https://www.istat.it/it/benessere-e-sostenibilit%C3%A0/la-misurazione-del-benessere-(bes)/il-rapporto-istat-sul-bes

Landslides Types and Processes. Cruden D.M., Varnes D. J. (1996) Landslides: Investigation and Mitigation. Transportation Research Board Special Report 247. Turner A.K. & Schuster R.L.(Eds.). National Academy Press, WA, 36-75

MUTO F. (2012b) - "Studi ed indagini geologiche, geotecniche, idrologiche ed idrauliche nel Comune di Gimigliano" - Codice Intervento CZ/3862/1/008 - A-G4 - Indagine Geomorfologica.

MUTO F. (2015) – "PON LEWIS, Deliverable WP 1.1– Linee guida per l'identificazione di scenari di rischio/Parte seconda". Resp. Scientifico Prof. Pasquale Versace

R. E. Kasperson, and B. L. Turner, eds. (1995). Regions at Risk: Comparisons of Threatened Environments. Tokyo: United Nations University Press

UN/ISDR (International Strategy for Disaster Reduction) (2004) Living with Risk: A Global Review of Disaster Reduction Initiatives, Geneva: UN Publications