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Quantitative analysis of consequences to masonry buildings interacting with slow-moving landslide mechanisms: a case study

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Quantitative analysis of consequences to masonry buildings interacting with slow-moving landslide mechanisms: a case study. *Peduto D., Nicodemo G., Caraffa M., Gullà G. (2018)*

Abstract

Quantitative analysis of consequences (in terms of expected monetary losses) induced by slow-moving landslide mechanisms to buildings or infrastructure networks is a key step in the landslide risk management framework. It can influence risk mitigation policies as well as help authorities in charge of land management in addressing/prioritizing interventions or restoration works. This kind of analysis generally requires multidisciplinary approaches, which cannot disregard a thorough knowledge of landslide mechanisms, and rich datasets that are seldom available as testified by the limited number of examples in the scientific literature. With reference to the well-documented case study of Lungro town (Calabria region, southern Italy) – severely affected by slow-moving landslides of different types – the present paper proposes and implements a multi-step procedure for monetary loss forecasting associated with different landslide kinematic/damage scenarios. Procedures to typify landslide mechanisms and physical vulnerability analysis, previously tested in the same area, are here appropriately merged to derive both kinematic and damage scenarios to the exposed buildings. Then, the outcomes are combined with economic data in order to forecast monetary loss at municipal scale. The proposed method and the obtained results, once further validated, could stand as reference case for other urban areas in similar geo-environmental contexts in order to derive useful information on expected direct consequences unless slow-moving landslide risk mitigation measures are taken.

Keywords: landslide kinematic scenarios; damage scenarios; vulnerability curves; monetary loss; DInSAR.

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Introduction

The analysis of consequences is a key phase in landslide risk management (Fell et al. 2008). It aims at identifying and quantifying the elements exposed to landslide risk falling within a certain region, and understanding their response depending on given landslide intensities to assess the potential loss.

In case of slow-moving landslides, the main exposed elements are facilities such as buildings, roads, bridges, pipelines, etc. Indeed, these landslides generally produce significant economic losses, in medium to long time, to private citizens as well as to the public administrations in terms of damage recorded to the exposed elements.

The quantitative estimation of the consequences induced by slow-moving landslides requires the damage produced on structures to be quantified in term of monetary loss for the community (Fell et al. 2005). In this regards, estimative methods and tools turn out to be necessary in order to both assign a monetary value to affected facilities (single or groups of buildings, infrastructure, etc.) and evaluate the monetary loss (and complementary residual value) induced by the occurrence of a natural event. The value of elements at risk may be expressed through (Alexander 2005; Silva and Pereira 2014): *i)* the price or current value of the asset, or the cost of its replacing with a similar or identical asset; *ii)* the intrinsic value, which measures the importance and the irreplaceable character of the asset; *iii)* utilitarian value, which measures the usefulness of the asset. As for the buildings, which are the focus of this work, the monetary value can be assessed based on cadastral or market values (Remondo et al. 2008; Silva and Pereira 2014) or considering the (re)construction costs (Fuchs et al. 2007; Zêzere et al. 2008). The monetary losses can account for only the direct damage, or in addition, also for indirect and intangible economic consequences (Meyer et al. 2013).

As for the vulnerability of the exposed elements, its estimation is a difficult task because it depends on several factors related to both the intensity of the landslide (e.g. for slow-moving landslides, their kinematics and related displacements) and peculiar features of exposed facilities (structural and foundation typology, geometry, material properties, state of maintenance and adopted design codes). Therefore, its quantification entails a thorough knowledge on *i)* the landslide mechanisms, *ii)* the behavior of buildings located in the slow-moving landslide-affected area and *iii)* the monitoring of landslide intensity parameters as well (Fell et al. 2008; Mavrouli et al. 2014; Palmisano et al. 2016; Peduto et al. 2017a).

Currently, there are very few examples concerning the study of the consequences induced to buildings by slow-moving landslides following a quantitative approach. Guillard-Gonçalves et al. (2016) based buildings' physical vulnerability assessment on the expert judgment of a pool of landslide experts and assessed the market economic value of the buildings (per pixel units in a GIS environment) at municipal scale for a quantitative risk analysis. Pellicani et al. (2014) merged the results of a landslide susceptibility index map and four asset index maps (physical, social, economic and environmental) to generate the final landslide exposure map. Vranken et al. (2013) presented the quantitative economic assessment of the direct and indirect damage caused by slow-moving landslides in a study area located in Belgium, based on focus interviews with homeowners, civil servants, etc. Lu et al. (2014) provided a GIS-based landslide risk map with each pixel indicating the amount of expected loss in areas affected by slow-moving landslides in the Arno river Basin (Italy).

As shown recently by some authors (Bianchini et al. 2015; Cascini et al. 2013; Ferlisi et al. 2015; Gullà et al. 2017; Lu et al. 2014; Nicodemo et al. 2017; Peduto et al. 2016b, 2017a), the use of Synthetic Aperture Radar satellite data processed via Differential Interferometric (DInSAR) techniques provide displacement measurements of coherent benchmarks - with sub-centimeter accuracy (Nicodemo et al. 2017; Peduto et al. 2018) - that can be very useful to analyze the behavior of (a set of) buildings located in (or in proximity of) slow-moving landslide-affected areas, especially in densely built up areas where the implementation of only

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conventional geotechnical monitoring methods can be rather difficult (Gullà et al. 2017; Peduto et al. 2016a).

This paper proposes an innovative methodology for a quantitative consequence analysis in terms of the expected monetary loss associated with different damage scenarios to buildings at municipal scale. For this purpose, the results of *i)* slow-moving landslide characterization, developed via the joint use of geomorphological criteria, geotechnical and remote sensing (DInSAR) monitoring techniques (Gullà et al. 2017; Peduto et al. 2016a), *ii)* building vulnerability analysis derived from landslide kinematics and visual damage surveys (Nicodemo et al. 2017; Peduto et al. 2016b, 2017a) and *iii)* a quantitative estimation of the monetary value or (re)construction cost of the buildings within a municipal area are appropriately merged.

The procedure is applied to the urban area of Lungro, a small town in Calabria region (southern Italy), where damages of different severity have been recorded to buildings and roads interacting with several slow-moving landslide mechanisms as shown by previous works (Antronico et al. 2015; Gullà et al. 2017; Peduto et al. 2016a, 2017a) whose results represent the necessary background for the present study.

Methods

The adopted methodology (Fig. 1) consists of three cascading phases. In particular, Phase I pursues a threefold objective consisting of *i)* typifying the geometric and kinematic features of landslides mechanisms (Phase I.a), *ii)* the generation of a vulnerability curve for the selected building typology (i.e. masonry buildings for the study at hand) (Phase I.b) and *iii)* the assessment of the exposed element value (Phase I.c). The results achieved in Phase I.a are then used in Phase II to define possible kinematic scenarios (with respect to fixed periods), which, in turn, combined with the results provided in Phase I.b, are associated with the relevant building damage scenarios. Finally in Phase III, the latter are merged with the values of the

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exposed elements retrieved in Phase I.c in order to evaluate the expected monetary loss computed over the different periods considered for kinematic scenarios.

Phase I.a – Characterization of landslide mechanisms

Phase I.a concerns the geometric and kinematic characterization of the landslides. This is accomplished via the *"aPosteriori Integration Procedure"(aPosIn)* developed and thoroughly discussed by Gullà et al. (2017) to whom the reader can refer to get all details. In brief, the *aPosIn* procedure allows typifying landslides in a given area by assigning boundaries, types, involved soils, reference velocities, size (in term of length, width and depth of the slip-surface) to each mapped landslide. This is achieved via the combination of the results of different methods which are *i)* geological-geomorphological interpretation of multitemporal aerial photographs (GeoG), *ii)* conventional geotechnical monitoring (e.g. inclinometers and GPS) of landslide (deep and surface) displacements (Geot) and *iii)* satellite displacement monitoring data (Sat).

Phase I.b – Generation of vulnerability curves

The vulnerability of an exposed element (e.g. single building or a set of buildings) is herein defined (Corominas et al. 2014; Fell et al. 2008) as the expected degree of loss due to the occurrence of a landslide phenomenon (i.e. slow-moving in this case study) of given intensity. The "expected degree of loss" is linked to the expected reversible or irreversible damage on the exposed element that, in turn, relies on the repair/replacement costs needed to restore the suffered damage with respect to the value of the building (Fell et al. 2008; Peduto et al. 2017a; Pitilakis and Fotopoulou 2015).

In this work, vulnerability curves (Saeidi et al. 2012; Peduto et al. 2017a) are used in order to provide, for a given building structural typology (i.e. masonry buildings), a quantitative relationship between the expected average level of damage severity (μ_D) and the landslide intensity assumed as the differential settlement (Δ) suffered by the exposed building (Nicodemo et al. 2017; Peduto et al. 2016b, 2017a). In particular, following the procedure proposed by Peduto et al. (2017a) empirical data-driven vulnerability curves derive from three input data: building typology; damage scale; intensity parameter.

First, the exposed buildings are identified by intersecting - in GIS environment - the information gathered from the map of built-up area with the inventory map of landslides typified in Phase I.a; at this stage, reinforced concrete and masonry buildings are distinguished (the latter being the ones considered in the present study).

Then, a damage scale is defined. For the purpose of the present analysis, rankings based on damage interpretation of crack patterns exhibited by buildings façades, as the one proposed by Burland et al. (1977), particularly fit the level of details required by such a study carried out at municipal scale. According to the abovementioned classification based on the "ease of repair" of the visible damage (Burland et al. 2004), five damage severity levels affecting "aestethics" (negligible (D0), very slight (D1), slight (D2)), "serviceability" (moderate (D3) and severe (D4)) or "stability" (very severe (D5)) are distinguished. In this study, these damage severity levels are assigned to buildings during in-situ visual inspections using ad-hoc predisposed fact-sheets (Ferlisi et al. 2015; Nicodemo et al. 2017).

As for the differential settlement (Δ), it is computed as the maximum difference of the cumulative settlements (derived by multiplying the DInSAR velocity along the vertical direction for the observation period of the available SAR dataset) recorded by the DInSAR benchmarks within the building perimeter (Bianchini et al. 2015; Nicodemo et al. 2016, 2017; Peduto et al. 2015, 2016a,b, 2017a,b; Sanabria et al. 2014).

Starting from these input data, as shown by Peduto et al. (2016b, 2017a), fragility curves (Ferlisi et al. 2018; Mavrouli et al. 2014; Negulescu and Foerster 2010; Negulescu et al. 2014; Nicodemo et al. 2017) can be derived, thus providing the probabilities for the superstructure of reaching or exceeding a particular damage severity level (Di) for a fixed value of the differential settlement (Δ).

Then, for each Δ value, the average damage severity levels μ_D (Δ) can be computed by adapting the formula proposed by Pitilakis and Fotopoulou (2015):

$$\mu_D(\Delta) = \sum_{i=1}^{5} P_i \cdot d_i \quad (1)$$

where P_i is the discrete probability related to the damage severity level (D_i); d_i is an associated numerical index assumed as 1, 2, 3, 4, and 5 for D1, D2, D3, D4, and D5, respectively (Peduto et al. 2017a).

Finally, the vulnerability curve is modelled to obtain the vulnerability function according to the procedure proposed by Lagomarsino and Giovinazzi (2006):

$$\mu_D = a[b + tanh(c \cdot \Delta + d)] \quad (2)$$

being a, b, c and d four coefficients determined by fitting the empirical data $(\mu_D(\Delta), \Delta)$ - derived from Eq. (1) - using standard procedures (i.e. least mean square method).

Phase I.c - Value of the exposed elements

There is not a univocal method to determine the value of a building since it depends on several factors such as the aim of the study, the scale of the analysis and the available information. Anyhow, once these factors are set, it must be applicable to every investigated element and based on reliable and homogenous sources of information (Simonotti 2006).

The method adopted in the present study follows the criteria proposed by Lari et al. (2012) for quantitative earthquake and water-flow risk analysis in urbanized environments. The approach does not include the costs associated with indirect and intangible consequences.

The first step consists of collecting, for each building, a homogeneous dataset including the footprint area, the number of floors, the actual occupancy type (i.e. residential or non-residential), and the maintenance state/condition (i.e. poor, average, good, very good). This kind

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of data can be collected through a visual in situ survey or even utilizing Google Street View®, whether available.

Once collected these data in GIS environment, an estimation criterion is selected. As for the buildings with an established trade-market (i.e. residential buildings, shops, etc.), it is possible to refer to the *most likely market value*; whereas the remaining buildings, for which an established trade-market value is not available (this is the case of churches, public buildings and schools in the study area), the *most likely construction value* criterion can be utilized. The application of these estimation criteria requires, in addition to the abovementioned features of the exposed elements, the knowledge on the *market unitary prices (*v_{mup} expressed in €/m^2*)* and the *construction unitary costs (*v_{uc} expressed in €/m^3*)*, which are closely related to the analyzed study area. However, it is worth stressing that for small villages - such as the one analyzed in the present work - for which there is a limited trade-market, the market value of a building does not differ too much from its construction cost.

The market value V_m (expressed in €) can be determined for each building that has a destination use for which an effective trade market exists. If buildings composed by different apartments and commercial spaces are considered, this value equals the sum of the market value related to the residential part of the building $V_{m,res}$ (expressed in €) and the market value related to the non-residential part of the building V_{m,n_r} (expressed in €):

$$V_m = V_{m,res} + V_{m,n\_r} \tag{3}$$

The $V_{m,res}$ and V_{m,n_r} values can be evaluated, respectively, as following:

$$V_{m,res} = A_{res} \times v_{mup,res} \times c_i \tag{4}$$

$$V_{m,n\_r} = A_{n\_r} \times v_{mup,n\_r} \times c_i \tag{5}$$

wherein A_{res} and A_{n_r} represents the total area (expressed in m^2) of the portions of the building with, respectively, a residential or non-residential (i.e. commercial, stores, offices, boxes) use;

$v_{mup,res}$ and v_{mup,n_r} are the arithmetic averages between minimum and maximum values evaluated from the range of the market unitary prices (expressed in €/m^2) in the study area for, respectively, residential or non-residential use; c_i are correction coefficients of the market value of residential or non-residential portions of a building that depend on the building maintenance state. These latter coefficients (see Table 1) need to be evaluated for each homogeneous areas and occupancy types in a given municipality. Considering that, in the present study, the building maintenance state was classified - during in situ surveys - in four quality levels (i.e. very good, good, average and poor), the values of the correction coefficients (c_i) to be applied were the following: for the buildings with "very good" quality, c_{vg} was defined as the increase needed to obtain the maximum value of the market unitary price range in the study area with respect to the mean value; for the buildings with poor quality c_p was defined as the decrease needed to obtain the minimum value of the market unitary price range in the study area with respect to the mean value; the coefficients corresponding to the classes "good" (c_g) and "average" (c_a) derived from the previous ones according to the equations in Table 1, wherein x, y and z, respectively, represent the minimum, the maximum and the mean market unitary prices.

Since Equ. (3) considers the market value V_m as the sum of a term related to the residential portion of the single building ($V_{m,res}$) and another term related to different intended use V_{m,n_r} that have different unitary prices, when a building has two or more different non-residential spaces (i.e. commercial, stores, offices, boxes), an equal number of terms V_{m,n_r} must be added in Eq.(5).

The monetary value to be assigned to the buildings that cannot be evaluated through the market value criterion is the construction value V_c (€). This latter can be evaluated as:

$$V_c = v_{uc} \times ac \times A \times n_f \times h_i \qquad (6)$$

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wherein v_{uc} is the unitary construction value (€/m^3) according to the building typology; *ac* represent the actualization coefficient; A, n_f and h_i are, respectively, the footprint area, the number of the floors and the height of each storey of the building.

The unitary cost value v_{uc} can be taken from an appropriate list of construction costs (e.g. regional or national price list of construction works) available for the examined area and updated at the time of the analysis. Furthermore, the values should refer to the current use of the buildings and taking into account that a structure, whose present occupancy type is hospital/school/commercial with structural and functional characteristics that do not satisfy the requirements of these building categories, will be assigned a value estimated using the necessary costs to reconstruct the building matching those requirements. Indeed, this approach does not identify the real/current value of public buildings, but it accounts for the amount of money that the Public Administration should spend for their eventual reconstruction or restoration.

Phase II – Kinematic and damage scenarios

Phase II defines possible kinematic and damage scenarios based on the results obtained from Phases I.a and I.b. Three main steps are carried out: *i)* possible landslide kinematic scenarios referring to different time intervals are defined by exploiting the *aPosIn* procedure results (Gullà et al. 2017) in terms of the landslide velocity; *ii)* in each kinematic scenario the exposed building is assigned a value of Δ that can derive from either DInSAR data analysis - for buildings covered by at least two DInSAR coherent benchmarks - or the *aPosIn* procedure results in case of buildings where these benchmarks are lacking; *iii)* for each considered kinematic scenario, both the expected damage level (Di) and the corresponding degree of loss (d_{li}) are assessed.

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As for the kinematic scenarios (Phase I.a), for the case study at hand, they derive from the combination of “ordinary” and “critical” (i.e. from 3 to more than 10 times the “ordinary” values) velocities that Gullà et al. (2017) identified for each typified landslide by applying the *aPosIn* procedure. In particular, since Gullà et al. (2017), by analyzing the monitoring data (inclinometers, GPS and DInSAR), highlighted that landslides in Lungro area exhibit velocity values close to the “critical” value twice in 10-year monitoring period and “ordinary” values for the remaining time, it was prudently assumed that the landslides reach “critical” velocity values (“critical” scenario) for one year over five years and for two years over ten years. This suggested considering two main reference kinematic scenarios: the first one, in which the landslide is moving with an “ordinary” velocity; the second one (worst case scenario), where the phenomenon is moving with a velocity that, for a certain period, can reach “critical” values. These assumptions have led to define four scenarios (prediction over 5 and 10 years), whose kinematic features are summarized in Table 2. In scenarios 1 and 3, the landslides velocity remains equal to “ordinary” values throughout the entire periods considered; in the other two scenarios (i.e. 2 and 4) the phenomena reach “critical” values for limited periods.

As for the expected value of Δ, suffered by each building in each kinematic scenario, it is computed using the available monitoring data. In particular, for the buildings covered by DInSAR data (at least two coherent benchmarks), the expected differential settlements are computed as the difference between the maximum and the minimum cumulative vertical displacement, obtained multiplying the vertical component of the DInSAR velocity for the observation period (Peduto et al. 2017a, b). Being this velocity an annual displacement rate, its value is assumed corresponding to the “ordinary” value of the landslide in order to calculate the Δ value in “ordinary” conditions. As for the “critical” conditions, for each landslide, the DInSAR-derived “ordinary” velocities pertaining to each benchmark are multiplied for a coefficient assumed equal to the ratio between the “critical” and the “ordinary” velocity values

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provided by the *aPosIn* procedure (Gullà et al. 2017). Subsequently, the DInSAR-derived "critical" velocities pertaining to each PS are multiplied for the period of observation to compute the Δ value in "critical" conditions.

On the other hand, as for the buildings interacting with slow-moving landslides but not covered by DInSAR data, their velocity values are assumed equal to the velocity of the landslide on which they are located as provided by the *aPosIn* procedure (Phase I.a). Accordingly, the velocity of each building is multiplied for the time interval of the considered scenario to retrieve the absolute cumulative settlement suffered by the building. Then, in order to pass from the absolute to the differential settlements (Δ) associated with each building, examples available in classical geotechnical literature for foundations resting on sandy soils (like the geomaterials characterizing the landslide bodies in Lungro area) are referred to. In particular, the empirical correlation proposed by Bjerrum (1963) indicate that maximum differential settlements do not exceed the maximum absolute ones and the experience of Terzaghi and Peck (1948) suggests that maximum differential settlements should not exceed 75% of maximum settlements. Accordingly, the differential settlements are conservatively assumed as equal to absolute ones for buildings not covered by DInSAR data.

Finally, using the vulnerability function (derived in Phase I.b via Eq.2) both μ_{Di} and its corresponding numerical index d_i (associated with a damage level Di) are computed with reference to the value of Δ pertaining to a building in a given scenario. The degree of loss of building value (d_{li}) associated with each damage severity level Di is assumed as: 0.2, 0.4, 0.6, 0.8, 1, respectively for D1, D2, D3, D4 and D5.

Phase III - Expected monetary loss

Phase III concerns the computation of the expected monetary loss that should affect the entire municipality in each considered damage scenario, unless mitigation measures are implemented.

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In particular, the expected monetary loss (EML expressed in €) for each building is computed by multiplying the building monetary value (coinciding with either the correspondent market value V_m and/or construction value V_c) for the expected degree of loss (d_l) in a given scenario:

$$EML = d_l \times V_{m,c} \tag{11}$$

The study area

The urban area of Lungro municipality (Fig. 2a), located at 650 m a.s.l. in the southern Italian Apennines (Calabria region), was analyzed. As described by Antronico et al. (2015) and Gullà et al. (2017), the geological context mainly consists of Middle Pliocene–Pleistocene sediments. The urban area, affected by several slow-moving landslides with either active or dormant state of activity based on geomorphological criteria (Fig. 2a), includes the *Historic centre* with low-rise (2–3 floors) masonry buildings on shallow foundations, mainly made with pebbles, or erratic/irregular stones; two sub-zones (*Carmine* and *Lafcantino)* with both masonry and reinforced concrete buildings and *San Leonardo* area where reinforced concrete buildings up to 5–6 floors were built since the early 1950-60s. As for damage to facilities (e.g., buildings and roads), Antronico et al. (2013, 2015) and Gullà et al. (2017) highlighted, via visual inspections carried out in 2005-2011, that many buildings located in both the *Historic center* and in the new developed urban areas (*San Leonardo*) suffered from damages whose severity has increased over the time (see also Peduto et al. 2017a).

Results

Phase I.a

Slow-moving landslides (Fig. 2a) affecting Lungro urban area were typified by Gullà et al. (2017) according to the *aPosIn* procedure in six categories (see Table 3) using geomorphological criteria, (surface and deep) displacement monitoring data (Fig. 2b) provided

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by, respectively, 12 vertical inclinometers (measurements collected from 2006 to 2011 between depths of 25 and 80 m) and 9 GPS points (monitored from June 2006 till May 2011), as well as DInSAR data, processed according to the SAR tomographic analysis (Fornaro et al. 2009, 2014). The DInSAR dataset, whose spatial velocity distribution along the Line of Sight (LOS) sensor-target direction is shown in Figures 2c and 2d, consists of 35 ENVISAT images acquired on ascending orbit (from August 2003 to January 2010) as well as 39 COSMO-SkyMed images acquired on ascending orbit (from October 2012 to April 2014). For a cross-comparison between different measurement techniques (i.e. inclinometers and DInSAR data) available in Lungro area the reader can refer to Peduto et al. (2016a). A synthesis of typified landslide features is reported in Table 3 as provided by Gullà et al. (2017).

Phase I.b

As for Phase I.b, the results of an extensive building damage survey carried out in October 2015 are available for the study area (see Figure 3a and Peduto et al. 2016b, 2017a). These data were used by Peduto et al. (2017a) to generate both fragility (Fig. 3b) and vulnerability (Fig.3c) curves for single buildings located in landslide-affected areas. In particular, both curves were generated focusing on 37 masonry structures covered by at least two DInSAR benchmarks in both ENVISAT and COSMO-SkyMed datasets as this building typology exhibited all the different damage levels (i.e. from D1 to D5) considered in the analysis. This sample of masonry buildings constitutes a group of similar elements that can be representative of the "typical masonry buildings" that are present in the urban area of Lungro because they share key features such as period of construction, structural and foundation typology, number of floors and footprint area. For these buildings, differential settlements (Δ) were computed (see section "Phase I.b – Generation of vulnerability curves" in "Methods") and related to the surveyed damage severity level to generate both fragility and vulnerability curves (Peduto et al. 2017a). These latter (Fig. 3c) resulted from fitting the empirical data - obtained from Eq. (1) - using Eq.

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(2), wherein the corresponding fitting coefficients are equal to (Peduto et al. 2017a): a = 2.6745; b = 0.8695; c = 0.4810; d = -1.3310.

Phase I.c

The monetary value of exposed (or likely to be exposed) elements was preliminarily evaluated for all the buildings (no. 521 in total) within the Lungro urban area according to the *most likely market or construction* criteria.

The market unitary prices (in €/m^2) used in this study are provided by the Italian Institute Osservatorio del Mercato Immobiliare (OMI, http://www.agenziaentrate.gov.it). In particular, the OMI database divides Lungro municipality in two homogeneous areas, R1 (rural) and B1 (urban), with only 6 of the 521 analyzed buildings that are in the R1 zone (Fig. 4a). For the case at hand, Table 4 shows the minimum, maximum and mean market unitary prices v_{mup} (OMI database) jointly with the "c_i" values evaluated - according to the formulas shown in Table 1 - for the two homogeneous areas. With reference to the construction value (V_c) of public buildings - for which in Lungro area an established trade-market value is not available – the value derived using Eq. (6), assuming as unitary construction value v_{cu} the costs published by the Engineering Association of the nearby town of Catanzaro (namely "Ordine degli Ingegneri di Catanzaro", https://ordineingegneri.cz.it). These costs refer to 2011, thus an actualization coefficient (*ac*) was applied equal to 1.04 based on data provided by the Italian Institute for Statistics (ISTAT).

In this analysis, some structures (Fig.4c) such as the *Eparchia Cathedral* (antique and particular construction), as well as the municipal stadium and the cemetery, which are very different from the surrounding buildings, should have been evaluated through a more appropriate and articulated method that is out of the scope of this paper; accordingly, they were not considered.

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The values of the buildings in Lungro urban area are shown in Figure 4b (in terms of the number of buildings belonging to different monetary value intervals) and Figure 4c, considering their spatial distribution. The analysis of the obtained monetary values highlights that most of the buildings are included into the monetary range < 250,000 € and within the interval 250,000-500,000 € (Figs. 4b and 4c); moreover, it seems that the parameter that mostly influence the monetary value is the footprint area. This is probably due to: *i)* a similar number of floors of the buildings, *ii)* the OMI distinction of the urban area in just two zones. Indeed, the only buildings that present a value higher than 500,000 € are public buildings (different estimation criterion) and few, more recent, residential buildings that have four or more floors.

Phase II

Following the procedure previously described (see "Phase II–Kinematic and damage scenarios" in "Methods"), the differential settlements (Δ) pertaining to each exposed masonry building (no. 78) included in landslide-affected areas were computed for the four considered kinematic scenarios (see Figs. 5a-d).

Then, the expected damage levels Di and the associated degree of loss (d_{li}) were evaluated using the vulnerability curve (Fig. 3c). Figures 6a-d show the maps of the expected damage to masonry buildings in the *Historic centre* of Lungro.

Phase III

The expected monetary losses (EML) associated to each considered masonry building in each damage scenario are reported in Figures 7a-d, jointly with the percentages of value loss and residual monetary values with respect to the total monetary value estimated by taking into account 78 masonry buildings interacting with slow-moving landslides in Lungro area. This total monetary value, assessed considering the market unitary prices and unitary cost referred

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to 2015 is equal to 32,742,841 € (see Fig.4c). Figures 7a-d clearly show the major economic losses recorded in the scenarios 2 and 4 (52% of the total value in scenario 2 and 61% in scenario 4) for which the higher velocity values due to the "critical" conditions of the landslides induce more damages to the buildings and, consequently, higher economic losses during the reference time interval (i.e. respectively 5 and 10 years). As for scenarios 1 and 3, where the kinematics of the landslides is assumed to exhibit "ordinary" conditions, the economic losses are lower due to the absence of "critical" condition (33% of the total aggregate value in the scenario 1 and 47% in the scenario 3).

Discussion and Conclusion

The selection of appropriate risk mitigation strategies depends on several factors among which economic issues such as the monetary loss associated with repair/reconstruction costs as well as decrease in value of properties exposed to landslide risk often play a key role. Thus, a quantitative analysis of consequences in terms of physical vulnerability and related costs turns out to be fundamental in a decision process. This kind of analysis concerning slow-moving landslides affecting urban areas is still limited in the scientific literature. In this regard, the present study aimed to provide an original contribution following a multidisciplinary approach encompassing geological/geomorphological criteria, geotechnical and remote sensing monitoring data analysis for the characterization of the involved landslide mechanisms (landslide typifying). These data together with empirical vulnerability curves - derived from DInSAR data and damage surveys to buildings at the municipal scale - allowed deriving four possible damage scenarios for masonry buildings referring to different time spans characterized by various combination of landslide kinematic conditions. The obtained results show that, as expected, the occurrence of "critical" velocity conditions for the scenarios 2 and 4 (Fig. 6b and 6d) induce significant and widespread increases of the damage severity levels on structures,

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over the same time interval, if compared with the "ordinary" scenarios 1 and 3, respectively (Figs. 6a and Figs. 6c). For instance, the number of buildings that may exhibit D4 and D5 damage severity levels passes from 39% out of the total in scenario 1 to 68% in scenario 2. Similarly, they pass from 63% in scenario 3 to 77% in scenario 4. Moreover, when only the time interval increases buildings appear more damaged passing from scenario 1 to scenario 3 (Figs. 6a,c), as well as from scenario 2 compared to scenario 4 (Figs. 6b,d).

The combination of information on expected damage level – and its associated degree of loss d_{li} – with market value or (re)construction costs allowed highlighting that in Lungro urban area the direct consequences induced by landslides (in term of economic losses) may range from 33% (after 5 years in scenario 1) up to even 61% (after 10 years in scenario 4) of the current total value of the analyzed sample of 78 exposed masonry buildings (Figs. 7a-d).

It is worth stressing that the present analysis is to be considered as a preliminary and conservative test of the proposed procedure given *i)* the scale of the analysis (i.e. municipal), *ii)* the expedite character of the available data on damage surveys (visual and limited to building facades) related to a fixed date and not directly referring to the settlement monitoring period, *iii)* the impossibility of accounting for effects induced on buildings by settlements occurred when no monitoring data were available, and *iv)* the simplified assumption concerning the kinematic scenarios. Moreover, market value and (re)construction costs, when used for forecasting purposes, should be multiplied for a coefficient taking into account the possible fluctuations of unitary costs/values within the considered periods (i.e. 5 and 10 years); however this is out of the scope of this work.

Furthermore, the presented analysis is site-specific and referred to a quite limited number of masonry buildings (i.e. the ones for which the vulnerability curve was available). In this regard, since the paper present the results of a still ongoing research, by enlarging the sample of

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analyzed buildings it will be possible to extend the analysis also to reinforced concrete structures (for which specific vulnerability curves are necessary) and distinguish them according to *i)* the foundation typology, *ii)* the different landslide mechanisms, *iii)* the position of the buildings within the landslide body in order to take into account all the factors that preside over damage occurrence. In this way, it will be possible to typify a set of geotechnical-structural (i.e. building-foundation-landslide mechanism) scenarios for which coupled/uncoupled geotechnical-structural analyses will provide numerical fragility/vulnerability curves at the scale of the single building.

Notwithstanding all the mentioned limitations, the proposed integrated approach, once further validated, could represent a valuable tool for providing a synoptic view of expected direct consequences at the municipal scale. It could address knowledge deepening and more accurate and detailed analyses and investigations just in the portions of the built-up area (or just on the buildings) where the highest economic losses (or unacceptable losses) are expected. Accordingly, this information could play a key role in supporting decision makers on whether reducing building vulnerability via building repairs or setting up active landslide stabilization works, thus addressing the selection of most appropriate strategies for risk mitigation.

Finally, it is worth mentioning the potential exportability of this approach to several villages (e.g. Borrelli et al. 2018; Ferlisi et al. 2015, 2017; Gullà et al. 2018; Nicodemo et al. 2017) with similar geo-hydro-mechanical contexts and urban fabric that are widespread in the southern Italian Apennines.

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Hydrological Protection, National Research Council of Italy (IRPI – CNR) on "*Attività di ricerca mirate ad approfondire le conoscenze sulla tipizzazione di movimenti franosi a cinematica lenta e sulla vulnerabilità di strutture e infrastrutture che con essi interagiscono anche mediante l'impiego di tecniche innovative di monitoraggio satellitare e da terra*". It is also part of the *Commessa TA.P05.012* ''*Tipizzazione di eventi naturali e antropici ad elevato impatto sociale ed economico''* of the CNR Department *''Scienze del sistema Terra e Tecnologie per l'Ambiente*'', and was partially funded by the PRIN2015 Project "Innovative monitoring and design strategies for sustainable landslide risk mitigation". The research is also framed within the Research Contract between IREA-CNR and the Department of Civil Engineering of the University of Salerno on "*Analisi geotecniche finalizzate alla caratterizzazione di fenomeni franosi a cinematica lenta e all'analisi della vulnerabilità di edifici e infrastrutture con essi interagenti in aree dell'Appennino Meridionale*".

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Table 1. Formulas for computing the "c_i" correction coefficients used to evaluate the market value V_m of buildings with different maintenance state.

Correction coefficients	Building maintenance state (quality)			
	very good (c_{vg})	good (c_g)	average (c_a)	poor (c_p)
c_i	$y/_z$	$c_{vg} - \frac{c_{vg} - c_p}{3}$	$c_p + \frac{c_{vg} - c_p}{3}$	$x/_z$

Table 2. Kinematic characteristics of typified slow-moving landslides adopted for each considered scenario in the Lungro study area.

Kinematic scenario	Time interval (year)	Kinematic characteristics of landslide
1	5	The landslide velocity is assumed equal to the "ordinary" value for each year of the considered time interval.
2	5	The landslide velocity reaches the "critical" value for 1 year within the time interval and it is assumed equal to the "ordinary" value for the remaining 4 years.
3	10	The landslide velocity is assumed equal to the "ordinary" value for each year of the considered time interval.
4	10	The landslide velocity reaches the "critical" value for 2 years within the time interval and it is assumed equal to the "ordinary" value for the remaining 8 years.

Table 3. Main features of the typified landslides in Lungro urban area resulting from the *aPosIn* procedure (modified from Gullà et al. 2017).

Typified landslide	Width (W) [m]	Length (L) [m]	L/W	Depth [m]	Velocity [cm/year]		Involved soil	Kinematic type
					ordinary	critical		
T_A1	25-100	≤ 180	≤ 2.5	about 6	2-4	> 200	detritic-colluvial covers	Complex landslide
T_A2	15-100	≥ 80	> 2.5	about 10	5-7	> 20		
T_B1	90-260	130-550	< 2.5	10-20	0.5-5	> 80	deeply weathered and chaotic phyllites	Complex landslide
T_B2	80-220	>300	≥ 2.5	10-16	4-20	> 100		
T_C	830	1500	1.8	20-30	0.5-5	> 40	deeply weathered and chaotic phyllites	Landslide zone

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T_D	100-250	350-550	2.2-3.2	20-30 /10-15	0.2-0.5	2-5	weathered and chaotic phyllites	Slide

Table 4. Values of correction coefficients "c_i" of the average market values for the buildings of Lungro urban area according to their maintenance state, occupancy type and homogeneous area.

Homogeneous area	Occupancy type	v_{mup} (€/m^2)			Correction coefficients "c_i" Building maintenance state (quality)			
		min	mean	max	poor (c_p)	average (c_a)	good (c_g)	very good (c_{vg})
B1	Residential	395	468	540	0.85	0.95	1.05	1.15
	Commercial	560	720	880	0.80	0.90	1.10	1.20
	Stores	240	303	365	0.80	0.90	1.10	1.20
	Office	470	580	690	0.80	0.90	1.10	1.20
	Box	240	293	345	0.80	0.90	1.10	1.20
R1	Residential / commercial	200	248	295	0.80	0.90	1.10	1.20

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List of Figure captions

Fig. 1. Flowchart of the adopted methodology.

Fig. 2. The Lungro study area: a) Geological sketch and landslide inventory map (modified from Gullà et al. 2017); b) map of typified landslides with surface (GPS) and deep (inclinometers) monitoring benchmarks (modified from Gullà et al. 2017); distribution of DInSAR benchmarks over the study area referring to c) ENVISAT data on ascending orbit for the period 2003–2010 and d) COSMO-SkyMed data on ascending orbit for the period 2012–2014 (modified from Peduto et al. 2017a).

Fig. 3. a) Map of surveyed buildings in Lungro urban area distinguished according to the recorded damage severity levels (modified from Peduto et al. 2017a) with some examples of observed crack patterns for both reinforced concrete and masonry buildings; b) empirical fragility and c) vulnerability curves for masonry buildings in Lungro urban area (modified from Peduto et al. 2017a).

Fig. 4. Values of the building located in Lungro urban area: a) homogeneous areas (OMI database); b) number of buildings belonging to different monetary value intervals and c) their spatial distribution.

Fig. 5. Expected differential settlements of buildings located in landslide-affected areas for each considered kinematic scenarios: a) scenario 1; b) scenario 2; c) scenario 3; d) scenario 4.

Fig. 6. Expected damage severity levels on masonry buildings located in Lungro *Historic center* for each considered kinematic scenarios: a) scenario 1; b) scenario 2; c) scenario 3; d) scenario 4.

Fig. 7. Expected monetary loss induced to masonry buildings located in Lungro *Historic center* for each considered kinematic scenario: a) scenario 1; b) scenario 2; c) scenario 3; d) scenario 4.

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Figure_1

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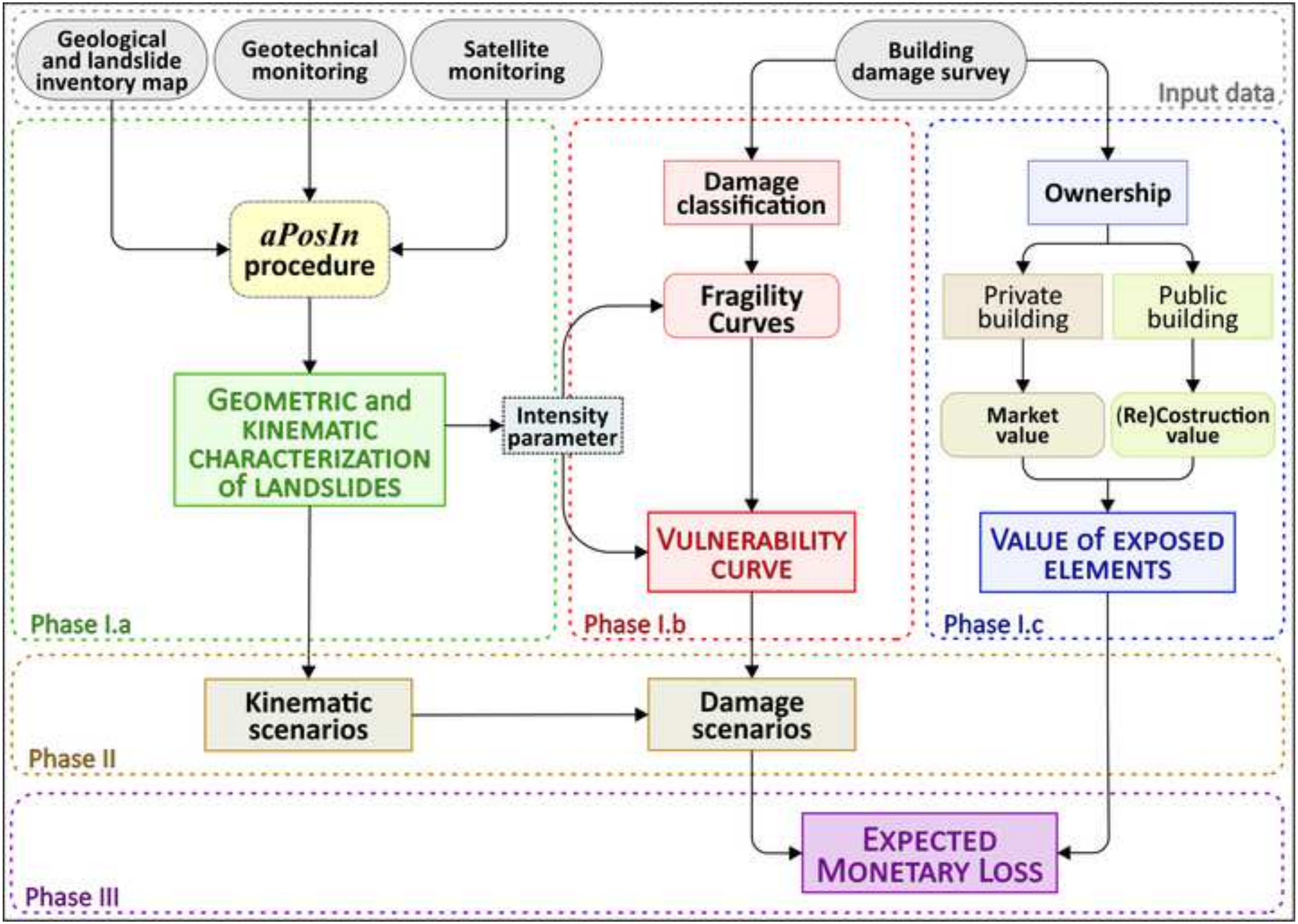

Figure_2

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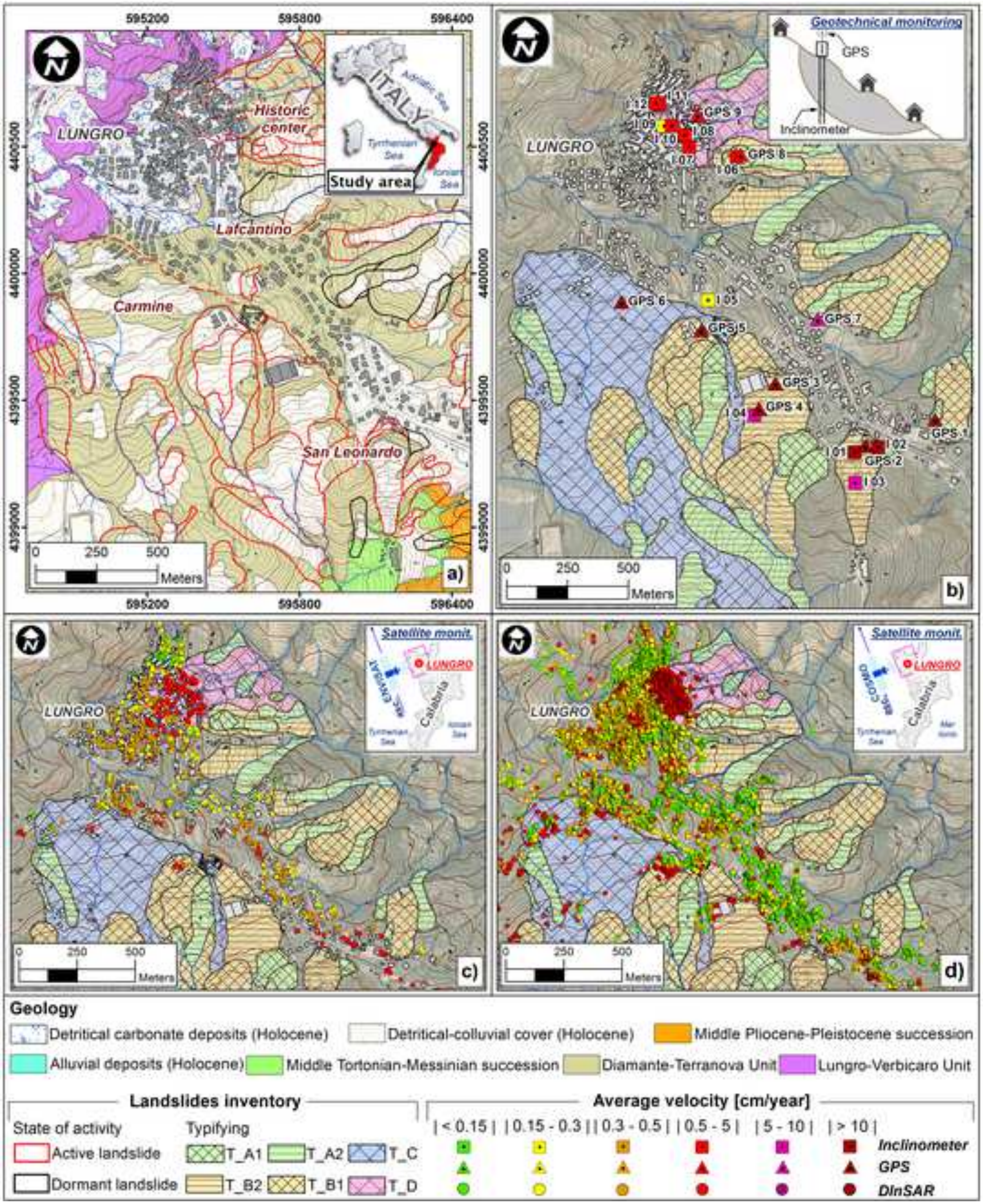

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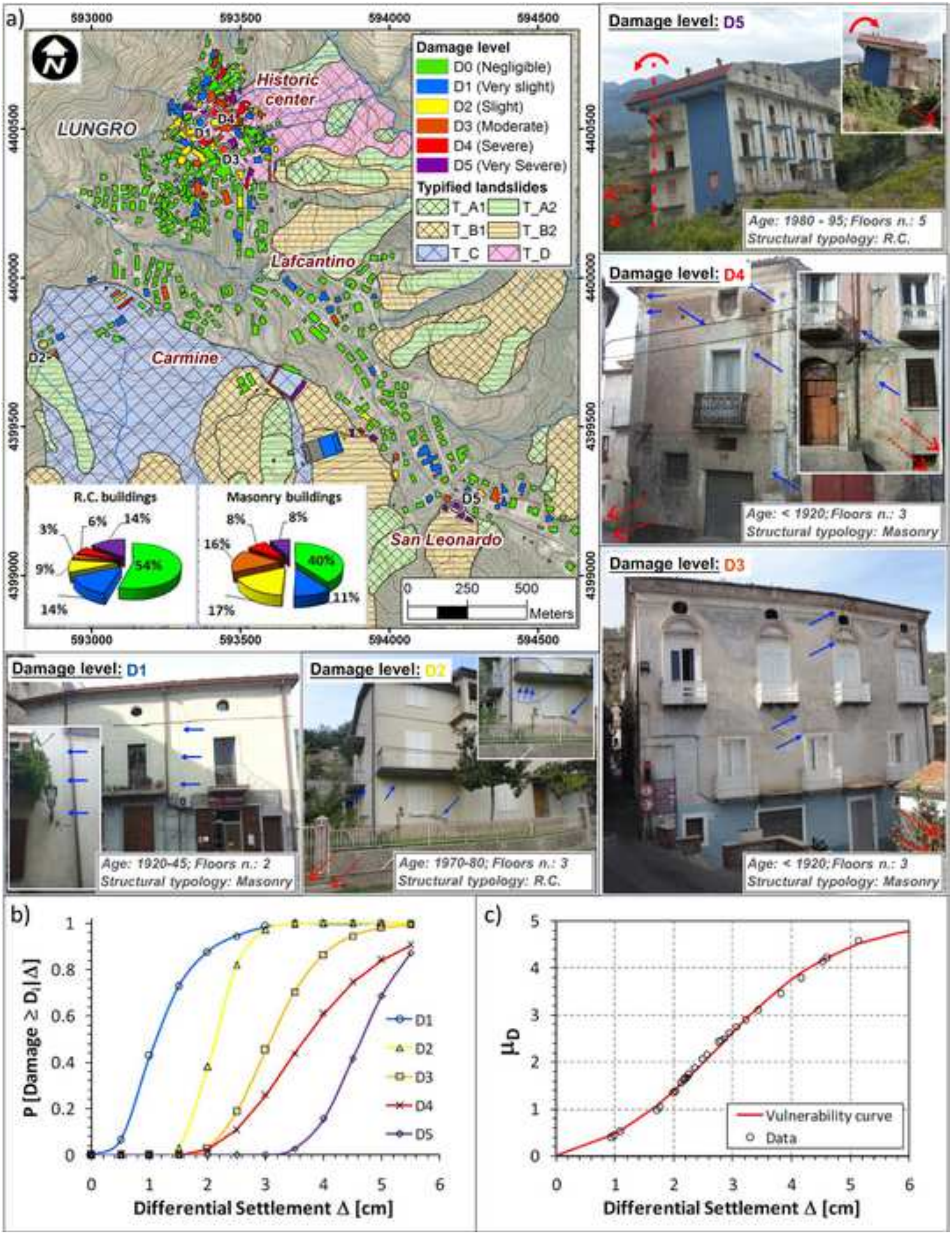

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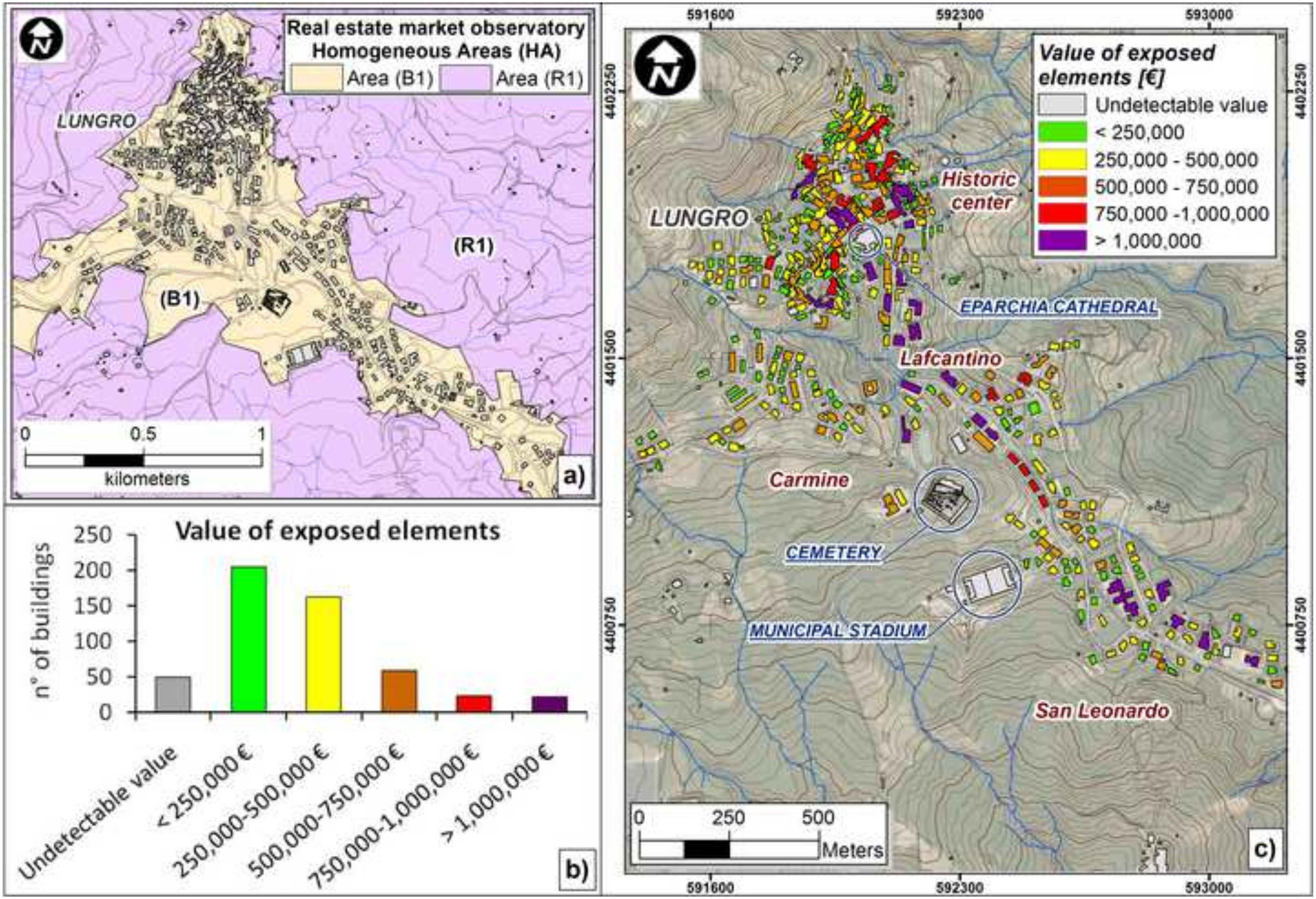

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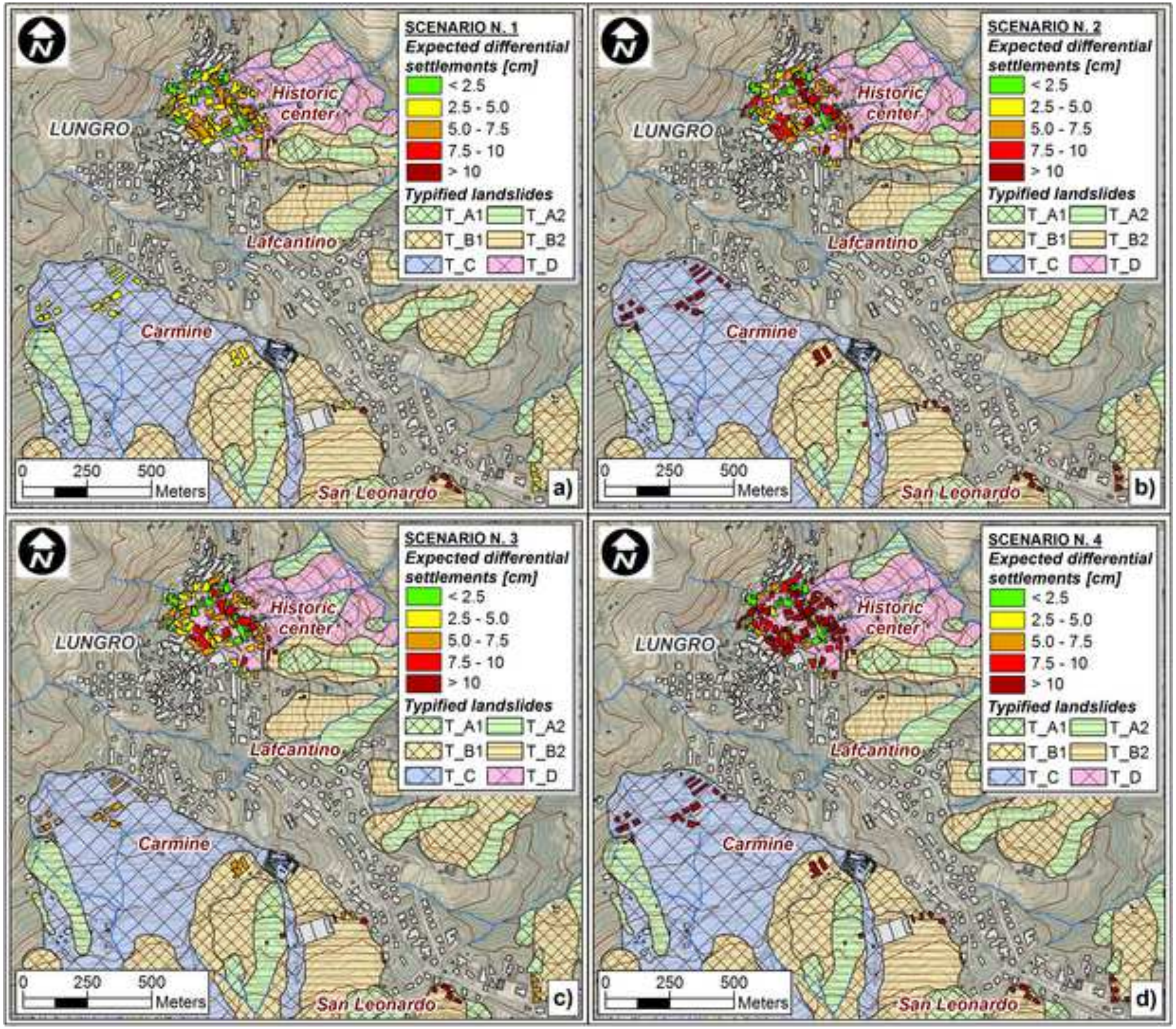

Figure_6

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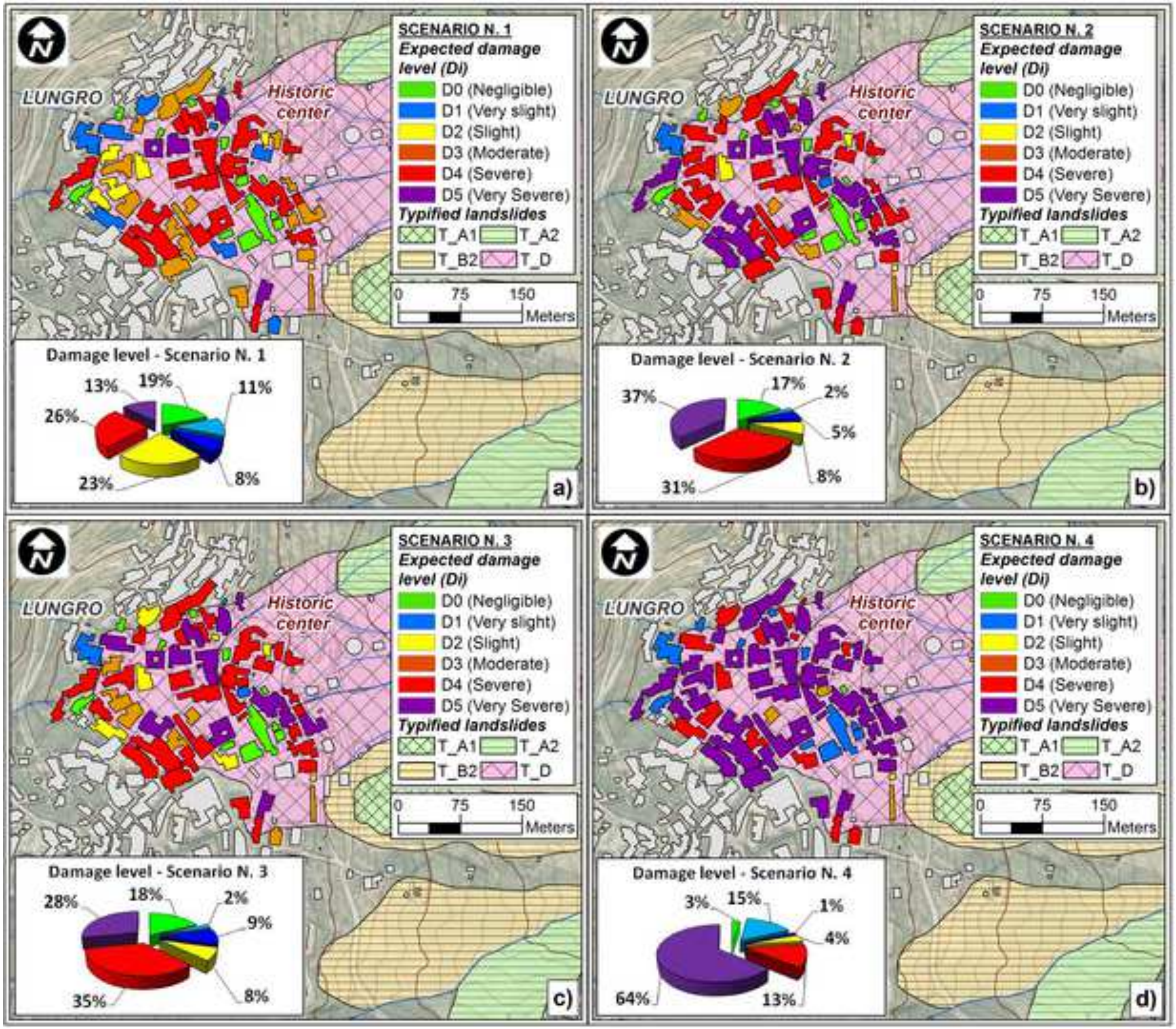

Figure_7

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