



Assessment of physical vulnerability of buildings and analysis of landslide risk at the municipal scale: application to the Loures municipality, Portugal

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Abstract. This study offers a semi-quantitative assessment of the physical vulnerability of buildings to landslides in a Portuguese municipality (Loures), as well as the quantitative landslide risk analysis computed as the product of the landslide hazard by the vulnerability and the economic value of the buildings. The hazard was assessed by combining the spatiotemporal probability and the frequency–magnitude relationship of the landslides. The physical vulnerability assessment was based on an inquiry of a pool of European landslide experts and a sub-pool of landslide experts who know the study area, and the answers' variability was assessed with standard deviation. The average vulnerability of the basic geographic entities was compared by changing the map unit and applying the vulnerability to all the buildings of a test site, the inventory of which was listed on the field. The economic value was calculated using an adaptation of the Portuguese Tax Services approach, and the risk was computed for different landslide magnitudes and different spatiotemporal probabilities. As a rule, the vulnerability values given by the sub-pool of experts who know the study area are higher than those given by the European experts, namely for the high-magnitude landslides. The obtained vulnerabilities vary from 0.2 to 1 as a function of the structural building types and the landslide magnitude, and are maximal for 10 and 20 m landslide depths. However, the highest risk was found for the landslides that are 3 m deep, because these landslides combine a relatively high frequency in the Loures municipality with a substantial potential damage.

1 Introduction

Landslides are natural phenomena that can cause costly damage when occurring in or impacting constructed areas. Landslide risk analysis is used to estimate the risk of landslide hazard to individuals, populations, properties, or the environment (Fell et al., 2008; Corominas et al., 2014, 2015) and generally contains five main steps: (i) hazard identification, (ii) hazard assessment, (iii) inventory of elements at risk and exposure, (iv) vulnerability assessment, and (v) risk estimation. Landslide risk analysis is useful to locate the zones where the risk is highest, but it is a complex and time-consuming task, especially when the study is conducted at the municipal scale.

During the last three decades, the landslide risk (R) has been considered as the product of the landslide hazard (H), the vulnerability (V), and the value of the elements at risk (EV) (Varnes and the IAEG Commission on Landslides and other Mass-Movements, 1984; Michael-Leiba et al., 1999; Cardinali et al., 2002; Remondo et al., 2005; Uzielli et al., 2008; van Westen et al., 2008; Zêzere et al., 2008): $R = H \times V \times EV$, where R is the risk (annual loss of property value). Landslide hazard (H) is the probability of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon (Varnes and the IAEG Commission on Landslides and other Mass-Movements, 1984) having a given magnitude (Jaiswal et al., 2011a), which is typically measured with the landslide area or the landslide volume (Lee and Jones, 2004; Li et al., 2010). The vulnerability (V) concept is defined in physical terms as the “degree of loss” of a given element or set of elements at risk exposed to the occurrence of a landslide of a given

magnitude, expressed in a scale ranging from 0 (no loss) to 1 (total loss) (e.g. Varnes and the IAEG Commission on Landslides and other Mass-Movements, 1984; Remondo et al., 2008). The value of the elements at risk is the economic value (EV) of the elements at risk, which in this study correspond to the built environment.

Whereas the landslide susceptibility and the landslide hazard have been extensively studied in the last two decades, whether with heuristic, statistic-probabilistic, or deterministic methods (e.g. Fell et al., 2008; Corominas et al., 2014), less work has been done, for various reasons, on the spatial assessment of landslide vulnerability and on the assessment of the value of the elements at risk (e.g. Zêzere et al., 2007, 2008; Papathoma-Köhle et al., 2012a; Silva and Pereira, 2014).

First, for most types of landslide, very limited damage data are available (van Westen et al., 2005; Papathoma-Köhle et al., 2012a), which hamper the creation and validation of any reliable vulnerability model. Second, different physical mechanisms are associated with different types of landslides, which mean that the same elements at risk have different vulnerability to different types of landslides. Therefore, the method used for assessing rockfall vulnerability would not be directly transferable to the slow slide vulnerability assessment (Alexander, 2005; Papathoma-Köhle et al., 2011; Ciurean et al., 2013). Third, the vulnerability of the elements at risk depends on the landslide intensity, which is usually associated with the landslide velocity (Hungr, 1997; Lateltin et al., 2005) that may range from some millimetres per year to several metres per second (Cruden and Varnes, 1996).

Moreover, methods used to assess vulnerability should be selected according to the scope and the scale of the study, which influences the level of spatial detail requested (Papathoma-Köhle et al., 2011). A vulnerability study conducted at the municipal level typically implies the existence of a large number of elements at risk (e.g. buildings) and details about building characteristics and landslide damage. Due to this reason, landslide vulnerability assessment is usually performed in small study areas with a reduced number of exposed elements in order to ease the methodology demonstration (e.g. Uzielli et al., 2015).

Previous studies have attempted to assess the landslide vulnerability and to analyse the landslide risk. Some of them are qualitative, focusing on human lives (e.g. Santos, 2003) and in both buildings and human lives (Macquarie et al., 2004). Other physical vulnerability studies are semi-quantitative, assigning empirical weighting of a set of building resistance parameters to buildings exposed to landslides (e.g. Silva and Pereira, 2014), or applying vulnerability curves to buildings exposed to hydrometeorological hazards (e.g. Godfrey et al., 2015).

Quantitative vulnerability studies usually aim to estimate the physical vulnerability of buildings based on landslide intensity parameters (e.g. impact energy, average velocity) and resistance or susceptibility of the exposed elements

(e.g. structure type, construction material, maintenance state) (e.g. Uzielli et al., 2008, 2015; Li et al., 2010; Du et al., 2013; Peng et al., 2015). Most of the time, landslide intensity parameters can be quantified (e.g. landslide velocity), while proposed values for resistance or susceptibility of the exposed buildings are usually assigned based on expert opinion (Peng et al., 2015; Uzielli et al., 2015), which may increase the subjectivity and uncertainty of the vulnerability estimation. In addition, expert surveys can be used to estimate physical vulnerability using the standard deviation of the expert answers to measure the variability of the average vulnerability (Winter et al., 2014).

Physical vulnerability assessment has several sources of uncertainty that can be either epistemic or aleatory (Ciurean et al., 2013). Epistemic uncertainties can come from the use of proxies for the landslide intensity assessment (e.g. velocity, depth of affected material, volume), or from the characterization of elements at risk (e.g. structural-morphological characteristics, state of maintenance, strategic relevance), from the vulnerability model (e.g. selection of parameters, mathematic model, calculation limitations), or from expert judgement about building resistance parameters and landslide damaging potential (Ciurean et al., 2013). Aleatory uncertainties come from the spatial variability of parameters (e.g. landslide intensities, population density) (Ciurean et al., 2013). For instance, the position of the element at risk (e.g. a building) on the track of a landslide is a source of aleatory uncertainty as the damage would not be the same if it is located on the crown of the landslide or on its run-out zone (van Westen et al., 2005).

Some examples of non-site-specific studies on landslide risk to buildings are available in the technical literature (e.g. Michael-Leiba et al., 1999; Cardinali et al., 2002; Remondo et al., 2008; Uzielli et al., 2008; Zêzere et al., 2008; Jaiswal et al., 2010, 2011b; Uzielli et al., 2015). Despite the progress already made, major limitations persist on the reliable assessment of landslide frequency and magnitude (which are both critical for the hazard assessment), and on the quantification of the buildings' vulnerability, which is frequently based on expert opinion. This work aims to contribute to the fulfilling of a research gap on the physical vulnerability assessment based on expert opinion. The main purposes of the study are to develop and apply a method for building vulnerability assessment in a Portuguese municipality (Loures), and to analyse the landslide risk to buildings in this study area.

Following the previous work of Guillard and Zêzere (2012), the susceptibility of the slopes was modelled for deep-seated and shallow slides, and the hazard was assessed, considering the magnitude probability of the landslide area and the annual and multiannual spatiotemporal probability of landslides.

In this study, there are few records on building damage caused by landslides, which constitutes a drawback in the construction and validation of the vulnerability model. Due

to this reason, buildings' physical vulnerability assessment was based on expert judgment of a pool of European landslide experts. In addition, from this pool, we extracted a sub-pool constituted by experts that have been working in the study area, i.e. who have a deep knowledge of both the landslides and the built environment of the study area. With this methodology, we aimed to evaluate the variability of the expert judgments, comparing the answers from the pool of landslide European experts with the answers from the sub-pool of landslide experts who know the study area, assessing thus the epistemic uncertainty in buildings' vulnerability assessment and evaluating how vulnerability controls risk results.

The market economic value of the buildings was assessed per pixel and the buildings' landslide risk of the municipality of Loures was assessed for different spatiotemporal probabilities using pixel units in a GIS environment.

2 Study area

For various reasons we chose to analyse the risk of slides triggered by rainfall in the Loures municipality, near Lisbon. First, this municipality is prone to different natural hazards and in particular to landslides. Most of the landslides in the Loures municipality are rotational or translational and are triggered by rainfall (Zêzere et al., 2004, 2008). Landslides were classified according to the depth of slip surface in two groups: shallow slides (slip surface depth ≤ 1.5 m) and deep-seated slides (slip surface depth > 1.5 m). The landslide inventory includes 333 shallow slides (average area 961 m^2) and 353 deep-seated slides (average area 3806 m^2). Velocity of landslides is typically slow for shallow slides and very slow or extremely slow for deep-seated slides, according to Cruden and Varnes' (1996) classification. These landslides often affect buildings and roads with significant direct and indirect consequences. Out of 686 landslides (Fig. 1) inventoried by Guillard and Zêzere (2012), 462 occurred within 50 m of buildings and roads, and some of them had caused damage to a built environment in the past (Zêzere et al., 2008).

Second, Loures is adjacent to the city of Lisbon (Fig. 1), hence a large number of inhabitants, buildings, and infrastructures are exposed to landslide hazard; indeed, about 205 000 persons currently live in the Loures municipality (density around 1220 inhabitants per km^2), which is 6 % higher than in 2001 according to the National Institute of Statistics (INE, 2002, 2011). The mean age of the buildings is 37.5 years, 66.9 % of them with a structure of reinforced concrete, 30.6 % of masonry, 1.8 % of adobe, rammed earth, or loose stone, and 0.7 % of other materials (INE, 2011). The 32 495 buildings of the Loures municipality represent a total built-up area of 9.25 km^2 and the number of buildings, most of which were erected without taking into account the possibility of future landslide occurrence, increase every year. Indeed, according to the results obtained in the framework of

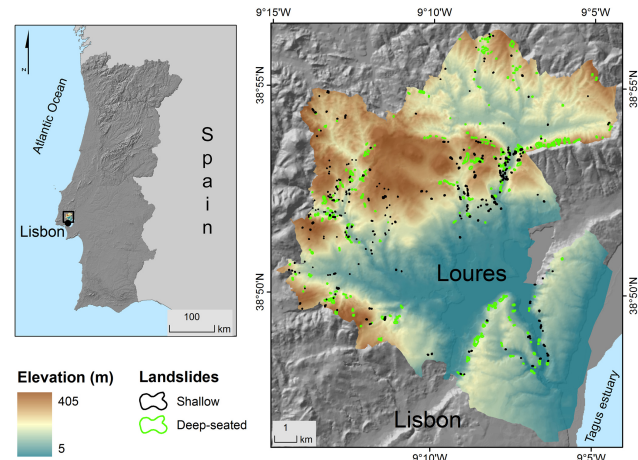


Figure 1. Loures municipality location, elevation, and location of the 686 inventoried landslides.

the new Master Plan for the Lisbon Metropolitan Area, the construction on potentially unstable slopes within the Loures municipality increased by 64 % between 1995 and 2007.

Third, a study on the susceptibility of slopes to landslides was previously conducted in this municipality (Guillard and Zêzere, 2012). Therefore, we intend to complete the risk analysis for buildings in this study area.

Finally, a social vulnerability assessment was conducted for the greater Lisbon area (Guillard-Gonçalves et al., 2015), which opens up an avenue for a future study that combines these two dimensions of the vulnerability.

Additional information about the study area can be found in Guillard and Zêzere (2012).

3 Data and methods

The frequency–magnitude relationship of the inventoried landslides was established, plotting the probability of a landslide area. The susceptibility of deep-seated and shallow landslides was assessed by a bivariate statistical method and has been mapped. The annual and multiannual spatiotemporal probabilities were estimated, providing a landslide hazard model. Then, the physical vulnerability was assessed by analysing the answers to a questionnaire that had been sent to a pool and a sub-pool of landslide experts. The vulnerability map was based on statistical mapping units for the whole study area, and based on fieldwork building inventory for a test site included in the study area. Next, the market economic value of the buildings was calculated. Finally, the landslide risk (R) was computed by multiplying the potential loss ($V \times EV$) by the hazard probability (H).

3.1 Frequency–magnitude of the landslides, susceptibility and hazard

3.1.1 Frequency–magnitude relationship

In order to complete the assessment of the landslide hazard and risk, we needed to establish a relationship between the magnitude of the landslides and their frequency. Ideally a landslide hazard model should incorporate not only the spatiotemporal probability of occurrence of the landslides, but also the landslide magnitude (Guzzetti et al., 1999; Cardinali et al., 2002). A landslide with a depth of 20 m can cause severe damage, but its frequency in the study area is much lower than a 1 m deep landslide. Which magnitude of landslide would present the highest risk for the Loures municipality?

Assuming that future landslides would have similar characteristics to the past ones, we considered the 686 landslides inventoried inside the Loures municipality. A curve representing the probability of a landslide versus its area was computed in the same way as Malamud et al. (2004) and Guillard and Zêzere (2012) for the deep-seated and shallow landslides of the Loures municipality. In this study, the landslides were considered all together (deep-seated and shallow rotational and translational slides) in order to know the probability associated with each scenario.

In addition, we linked the depth of the slide slip surface to the slide area and the height of accumulated material to the slide area. The relationship between the depth (d) and the area (A_L) of landslide used in this study is statistically based, and was established by Garcia (2012) ($A_L = 706 \times d$). The proximity of Garcia's study area from the Loures municipality and similarities in terms of landslide types and volumes were the main reasons for the choice of this relationship. As there is no established relationship between the height of accumulated material and the slide area, or between the height of accumulated material and the depth of the slide, we considered that the height-to-depth ratio is 0.5. This is an assumed relationship with significant uncertainty that can be an important source of bias, but which is based on landslides studied in the field whose depth is known (Zêzere et al., 1999).

3.1.2 Annual and multiannual spatiotemporal probabilities

The temporal probability has to be associated with the spatial probability in order to determine the spatiotemporal probability, which is part of the landslide hazard. First of all, the spatial probability of a shallow and a deep landslide occurrence was assessed by constructing two susceptibility maps. The susceptibility was mapped using a bivariate statistical method called the information value method (Yin and Yan, 1988). The first model represents the susceptibility of the slopes to shallow landslide occurrence, published in a previ-

ous study (Guillard and Zêzere, 2012). The total area of the shallow landslides is 319 975 m². The second model represents the susceptibility of the slopes to deep-seated landslide occurrence, and was built and validated by the joining of the 292 deep-seated rotational slides and the 61 deep-seated translational slides inventoried in the Loures municipality (Guillard and Zêzere, 2012). The total area of the deep-seated slides is 1 343 525 m². These two models provided two landslide susceptibility maps in a raster format with a pixel size of 5 × 5 m. Each map contains four landslide susceptibility classes that were defined by taking the predictive capacity of the model into account. Additional details on the landslide susceptibility assessment in the study area can be found in Guillard and Zêzere (2012).

The spatiotemporal values for shallow and deep-seated landslides were then calculated for each susceptibility class by dividing the product of the total affected area and the predictive capacity by the area of the class (Zêzere et al., 2004). As the inventoried landslides occurred from 1967 to 2004, we managed to calculate the hazard values for the next 38 years, and to deduce the 1-, 10-, 25-, and 50-year probability values.

3.2 Physical vulnerability of the buildings

Most of the landslides in the study area are slow (shallow slides), very slow, or extremely slow (deep-seated slides); therefore inhabitants' lives are unlikely to be endangered. However, buildings, roads, and infrastructures may suffer damage, thus generating relevant costs, both direct and indirect. That is why the vulnerability assessment is focused on the study of buildings, for which some data are available. Buildings were classified by structural elements and construction material (Table 1). Nevertheless, only direct costs are considered in the current study, due to scarcity of data.

3.2.1 Vulnerability matrix

In order to predict damage caused by landslides it is important to know the building resistance capacity. As the data related to the foundation properties of each building are not available for a large study area, such as a region or a municipality, mainly because of the huge number of elements at risk, other elements of buildings like age, structure type, and number of floors are generally used to assess the building resistance capacity (Douglas, 2007).

In contrast to social vulnerability, which is a measure of the sensitivity of a population to hazards and its ability to respond to and to recover from the hazards' impacts (Cutter and Finch, 2008), physical vulnerability is related to a specific scenario (Uzielli et al., 2008; Papathoma-Köhle et al., 2011). That is why we focused on rotational slides for which we considered nine magnitude scenarios: five scenarios in which the building location is on the body of the slide, assuming different depths of the slip surface (1, 3, 5, 10, and 20 m); and four scenarios in which the building loca-

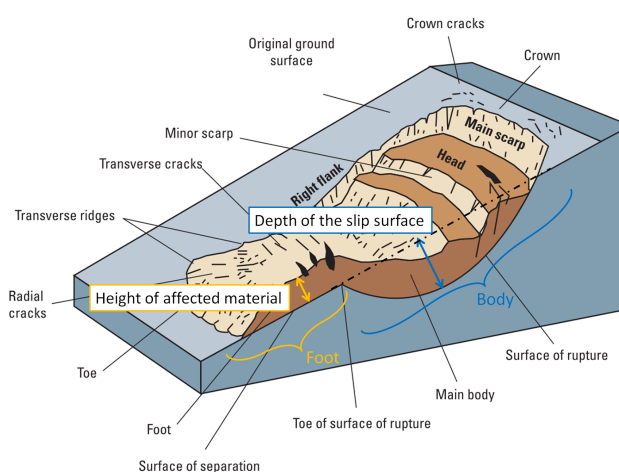
Table 1. Structural building types in the Loures municipality (National Institute of Statistics, Census 2011, INE, 2011).

Structural building type	Structural elements and construction material	Number of buildings	%
SBT1	Wood or metal (light structures)	221	0.7
SBT2	Adobe, rammed earth, or loose stone walls	577	1.8
SBT3	Brick or stone masonry walls	9947	30.6
SBT4	Masonry walls confined with reinforced concrete	21 750	66.9
Total		32 495	100.0

tion is on the foot of the slide, assuming different heights of affected material (0.5, 1, 3, and 5 m) (Fig. 2). The maximum values considered for both the depth of the slip surface and the height of affected material were defined, taking the largest landslides inventoried in the study area into consideration (Zêzere, 2002; Zêzere et al., 2008). The remaining scenarios use standard values considered in landslide classifications (e.g. Záruba and Mencl, 1982). A building situated on the landslide body may suffer vertical and lateral displacements, whereas a building situated on the landslide foot may support dynamic pressures against the walls, and may be buried (Glade et al., 2005; van Westen et al., 2005; Léone, 2007).

Existing relationships between building damage patterns and height of affected material for debris flows (e.g. Papathoma-Köhle et al., 2012b) cannot be applied to the study area, as landslide types and velocities are not comparable. In this study, the landslide slip surface depth and the accumulated material height were used as proxies for landslide destructive capacity because of the following reasons. Landslides affecting the study area have generally slow, very slow, or extremely slow velocities, and in these circumstances, the landslide velocity is not the most appropriate parameter to assess the landslide destructive capacity. Moreover, there is no instrumental data about the velocity of each landslide. On the other hand, without relevant differences regarding landslide velocity, the depth of the slip surface is significant as a proxy for landslide destructiveness, namely through the comparison with the depth of the building foundation. In addition, it was possible to find a statistic relationship between the landslide slip surface depth and the landslide area, which is an accurate landslide morphometric parameter that is available in the landslide inventory.

A study realized at a local scale enables the landslide vulnerability to be assessed with a quantitative method, relying on expert judgment, damage records, or statistical analysis (Ciurean et al., 2013). Nevertheless, for a study at a municipal or regional scale, the physical vulnerability assessment is usually done by a semi-quantitative or a qualitative method, and is often based on historical records (Dai et al., 2002) and on expert judgments (Sterlacchini et al., 2007), and is largely subjective (Léone et al., 1996; Uzielli et al., 2008; Silva and

**Figure 2.** Rotational slide body and foot (adapted from Highland and Bobrowsky, 2008).

Pereira, 2014). In this work, we decided to ask the opinion of a pool of experts. A questionnaire was formulated and sent to more than 300 international experts on landslides and other natural risks who have worked with landslides in the past.

The experts were asked to fill in the questionnaire in which they attributed, on four structural types of buildings (Table 1), the corresponding potential damage caused by landslides of different magnitudes (Table 2); the magnitudes of the landslides were associated with the depth of the slip surface and with the height of the affected material. The experts provided 36 answers, corresponding to each situation (Supplement 1).

Fifty-two experts completed the questionnaire and their answers were used to obtain an average value of physical vulnerability for each type of building, for location within the landslide body and the landslide foot, and for each landslide magnitude. Each damage class was associated with the corresponding upper bound of its corresponding physical vulnerability, thus adopting a conservative approach (Table 2). We were also able to assess the variability of the obtained results by calculating and mapping the standard deviation of the answers. This vulnerability assessment exercise was repeated, keeping only a sub-pool with the answers of the 14 landslide experts who know the landslides and the buildings

Table 2. Damage level of buildings.

	Damage class	Physical vulnerability	Damage level of buildings (based on Alexander, 1986; AGS, 2000; Tinti et al., 2011; Garcia, 2012)
1	Negligible damage	[0; 0.2]	No significant damage – slight accumulation of material causing aesthetic damage (dirt, chipping paint, etc.)
2	Slight damage]0.2; 0.4]	No structural damage – minor repairable damage: chipping of plaster, slight cracks, damage to doors and windows
3	Significant damage]0.4; 0.6]	No structural damage – major damage requiring complex repair: displacement or partial collapse of walls or panels without compromising structural integrity, highly developed cracks. Evacuation required.
4	Severe damage]0.6; 0.8]	Structural damage that can affect the stability of the building: out-of-plane failure or collapse of masonry, partial collapse of floors, severe cracking or collapse of sections of structure due to settlement. Immediate evacuation; demolition of the element may be required.
5	Very severe damage]0.8; 1]	Heavy damage seriously compromising the structural integrity: partial or total collapse of the building. Imperative and immediate evacuation and complete demolition.

of the study area, and the results obtained by the two different groups of experts were compared.

3.2.2 Vulnerability based on statistical mapping units

A geodatabase containing information about elements at risk was provided by the Loures municipality. Buildings of the municipality were compared with the most recent high-resolution images of the Loures municipality provided by the World Imagery File ESRI (2014) and buildings in ruins were excluded. However, the only data provided and used by this geodatabase are the geographical location of the buildings. In order to obtain more information about the buildings, like their structure, age, or functionality, we used data from the census of the INE. We chose, as a mapping unit, the smallest statistical unit, which is the Geographic Basis for Information Reference subsection (BGRI). The BGRI units are the basic geographic entities used for the 2011 census operations, which divide each basic administrative unit (which is the civil parish) into sections and subsections. The BGRI subsections are territorial units, whether built-up or not, which represent a block in urban areas, a locality or part of a locality in rural areas, or residual areas which may or may not have dwellings (INE, 2011). Their boundaries were defined by the INE, and the statistical information was also collected by the INE. The 3061 BGRI subsections of the Loures municipality used for the 2011 census were used in this study.

The buildings of the study area were classified into four structural types, corresponding to the data which are avail-

able for the whole area at the BGRI subsection scale, considering their structural elements and construction materials (Table 1). It should be noted that although the information provided at the BGRI subsection scale includes the number of structural types of buildings, no information was provided on the structural type of each individual building.

Therefore, the number of buildings pertaining to each structural building type class (from SBT1 to SBT4, see Table 1) is known for each BGRI, although the association of this information with each building polygon cannot be made directly. As the physical vulnerability of buildings was established for each structural building type, the vulnerability of the buildings was assessed for each BGRI subsection by calculating a weighting average, which takes into account the number of buildings of each structural building type within the BGRI (Eq. 1):

$$V_i = \frac{\sum_j V(\text{SBT}_j) \times N(\text{SBT}_j)}{\sum N(\text{SBT})}, \quad (1)$$

where V_i is the vulnerability of the BGRI subsection to a landslide magnitude i , $V(\text{SBT}_j)$ is the vulnerability of the structural building type j and $N(\text{SBT}_j)$ is the number of buildings with a structural building type j .

Then, the average vulnerability was assigned to all the buildings of the BGRI subsection. This limitation of the study in which the value of vulnerability is the same for all the buildings of a BGRI comes from limited data. However, the average number of buildings per BGRI in the Loures municipality is 11, and most of the BGRI units have a large

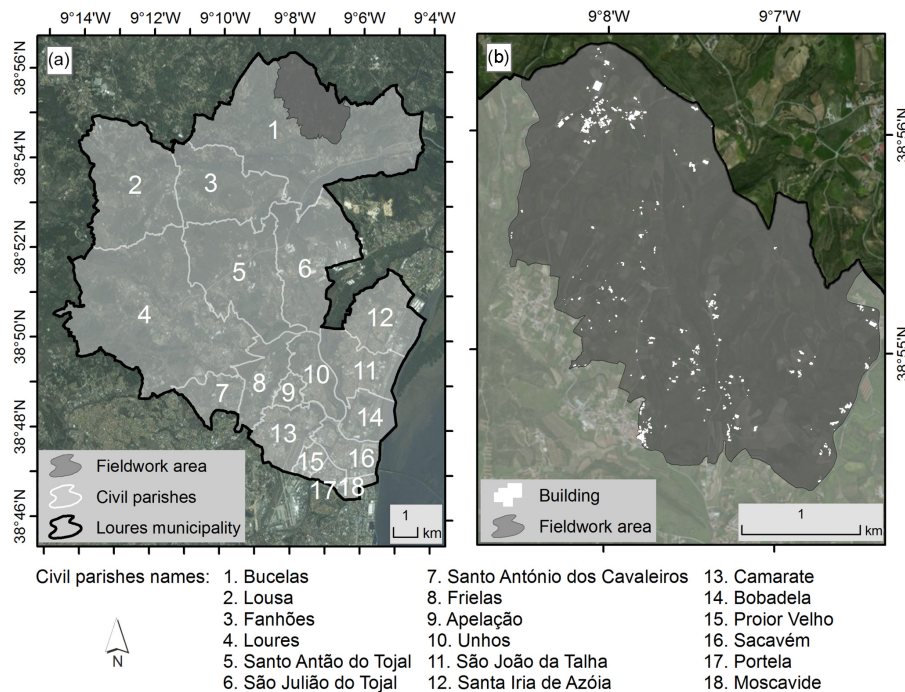


Figure 3. (a) Civil parishes of the Loures municipality and location of the fieldwork area; (b) buildings of the fieldwork area.

number of buildings belonging to the same structural building type (56 % of the BGRI have only one structural building type and 30 % have two structural building types). This means that the generalized vulnerability attributed to the BGRI buildings is in most cases quite close to what it would be for a vulnerability assessment made building by building.

The standard deviations of the answers given by the experts represent the variability of the vulnerability values and were calculated and mapped for each scenario and for each structural building type.

3.2.3 Vulnerability based on fieldwork building inventory

The above-mentioned vulnerability assessment approach based on statistical mapping units has the advantage of being time-saving, in contrast to a study that considers each building of the study area, as Silva and Pereira (2014) did for the Santa Marta de Penaguião municipality. In order to assess the accuracy of this approach, we selected a test site inside the Loures municipality to develop fieldwork, where the structural building type was inventoried for each individual building. The choice of the test site was made because of its proneness to landslides. The test site is located in the northern part of the Bucelas civil parish, has an area of 6.71 km², and has 782 buildings (Fig. 3). Physical vulnerability of the test site was assessed using the same vulnerability matrix referred to in Sect. 3.2.1, but the vulnerability was attributed to each single building instead of being calculated per BGRI. With this

approach, we evaluated the influence of the mapping unit in the final results of buildings' physical vulnerability.

3.3 Economic value of the buildings

The economic value (EV) of the buildings has been calculated using the same equation as Silva and Pereira (2014) (Eq. 2):

$$EV = ACC \times TA \times FC \times LC \times AC, \quad (2)$$

where EV is the market economic value, ACC is the average cost of construction, TA is the total area, FC is the functionality coefficient, LC is the location coefficient, and AC is the age coefficient. The ACC is established by the Portuguese government (Decree Number 1456/2009) and expresses the costs associated with the construction of buildings. It was fixed at 603 EUR m⁻² for the year 2011. As ACC is expressed per square metre, it had to be multiplied by the TA, which was calculated by multiplying the buildings area, provided by the Loures municipality geodatabase, by the average number of storeys in each BGRI subsection. The FC is related to the function of the buildings (residential, store or storages are the main functions of the Loures municipality buildings), also provided by the BGRI subsection data, and the coefficients were defined by the Portuguese Tax Services (Dec.-Law Number 287/2003 of 12 November), ranging from 0.35 (storage buildings) to 1.2 (buildings that have a commercial use). The AC values are also classified by Portuguese Tax Services (Law Number 64-A/2008 of 31 December), ranging from 0.40 (buildings older than 60 years) to 1

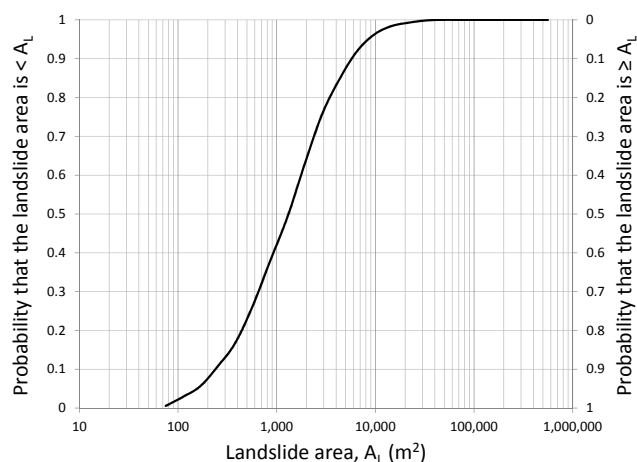


Figure 4. Probability of landslide area in the Loures municipality (based on the work done by Guillard and Zêzere, 2012).

(building less than 2 years old). The information about number of buildings per function and building age was obtained from BGRI data. The weighted average values were calculated for each BGRI for both coefficients and assigned to the buildings. LC is determined by the Portuguese Tax Services according to property market and accessibility (Law Number 64-B/2011 of 30 December). At the national level, the LC values range from 0.4 to 3.5; in the Loures municipality, the LC values vary between 0.85 for the rural areas and 2.25 for the zones of the Moscavide and Sacavém civil parishes (Fig. 3), which are located near Lisbon and have a better accessibility and proximity to social facilities and public transport.

The economic value per pixel (EV_{pix}) was calculated from the EV value obtained for each building. Indeed, as the landslide hazard was calculated at a pixel base, we needed to obtain an economic value per pixel to calculate the risk. The EV_{pix} value was obtained by dividing the EV value by the area of the building and multiplying it by 25, which is the pixel area in square metres.

3.4 Landslide risk

The buildings shape files were converted into raster files with a pixel size of 5×5 m. Then, the risk was computed according to Eq. 3, based on Varnes and the IAEG Commission on Landslides and other Mass-Movements (1984):

$$R_{ij} = H_i \times P_j \times PV_j \times EV_{\text{pix}}, \quad (3)$$

where R is the risk, H is the spatiotemporal probability, P is the magnitude probability, PV is the physical vulnerability, and EV_{pix} is the economic value per pixel. The index i takes the values of 1, 10, 25, and 50 years; the index j takes the values of 1, 3, 5, 10, and 20 m for the slip surface depth, and 0.5, 1, 3, and 5 m for the accumulated material height. The multiplication of the last two terms (the physical vulner-

Table 3. Magnitude probability of slides according to their slip surface depth in the Loures municipality.

Slip surface depth (m)	Landslide area (m ²)	Probability
1	706	0.57
3	2119	0.34
5	3532	0.19
10	7064	0.07
20	14 127	0.02

Table 4. Magnitude probability of slides according to the height of their accumulated material in the Loures municipality.

Accumulated material height (m)	Corresponding slip surface depth (m)	Landslide area (m ²)	Probability
0.5	1	706	0.57
1	2	1413	0.48
3	6	4238	0.16
5	10	7064	0.07

ability and the economic value) represents the potential loss for the buildings.

Annual spatiotemporal probability was considered (i.e. index $i = 1$ year) to calculate the landslide risk values for a year with different probabilities of occurrence according to the different landslide magnitude values. Box plots were computed to compare the effect of the landslide magnitude on the landslide risk. Then, the probability of occurrence was fixed (index $j = 10$ m deep) and the risk was calculated for different spatiotemporal probabilities.

4 Results

4.1 Frequency–magnitude of the landslides, susceptibility and hazard

The probability of the different landslide magnitudes was assessed using the curve shown in Fig. 4. The landslide area was used as a proxy for both the depth of landslide slip surface and the height of affected material in the landslide foot; the results are summarized in Tables 3 and 4. The corresponding slide areas range from 706 to 14 127 m². When a landslide occurs in the Loures municipality, the probability that this landslide has a slip surface depth higher than 1 m is 0.57; the probability that this landslide has a slip surface depth higher than 20 m is 0.02. In general terms, the probability of landslides decreases when their magnitude increases, which obeys the universal rule governing natural processes, and which is consistent with the results previously obtained by Guillard and Zêzere (2012) for this study area.

Table 5. Probability of occurrence of deep-seated landslides in 1, 10, 25, and 50 years in the Loures municipality.

Susceptibility class	Area (no. of pixels)	Predictive capacity	1-year probability	10-year probability	25-year probability	50-year probability
Very high	468 814	0.5	1.51×10^{-3}	1.51×10^{-2}	3.77×10^{-2}	7.54×10^{-2}
High	647 436	0.25	5.46×10^{-4}	5.46×10^{-3}	1.37×10^{-2}	2.73×10^{-2}
Low	1 246 342	0.15	1.70×10^{-4}	1.70×10^{-3}	4.26×10^{-3}	8.51×10^{-3}
Very low	4 362 465	0.1	3.24×10^{-5}	3.24×10^{-4}	8.10×10^{-4}	1.62×10^{-3}

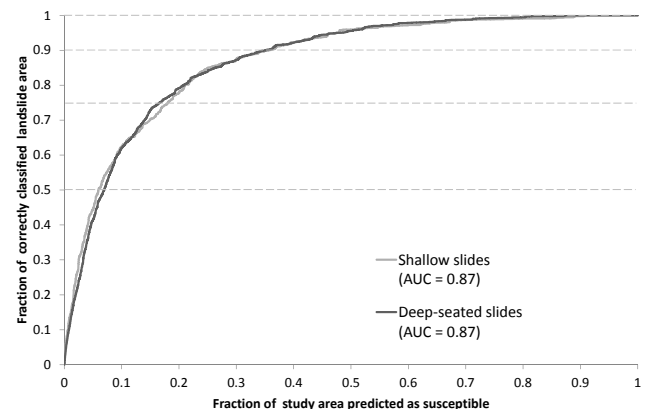
Table 6. Probability of occurrence of superficial landslides in 1, 10, 25, and 50 years in the Loures municipality.

Susceptibility class	Area (no. of pixels)	Predictive capacity	1-year probability	10-year probability	25-year probability	50-year probability
Very high	400 890	0.5	4.20×10^{-4}	4.20×10^{-3}	1.05×10^{-2}	2.10×10^{-2}
High	810 140	0.25	1.04×10^{-4}	1.04×10^{-3}	2.60×10^{-3}	5.20×10^{-3}
Low	1 176 564	0.15	4.29×10^{-5}	4.29×10^{-4}	1.07×10^{-3}	2.15×10^{-3}
Very low	4 337 463	0.1	7.77×10^{-6}	7.77×10^{-5}	1.94×10^{-4}	3.88×10^{-4}

The deep-seated and shallow landslide susceptibility models were validated based on the random partition of the landslide inventories in two groups: the modelling group and the validation group. The modelling group was used to weight the classes of each landslide-predisposing factor and to build the landslide susceptibility models, whereas the validation group was crossed with the susceptibility results for their independent validation. The prediction-rate curves show the robustness of the models (Fig. 5): the area under curve (AUC) value is 0.87 for both models, which attests to the robustness of the models.

The landslide susceptibility maps are shown in Fig. 6, with the landslides used for computing and for validating the models. In a previous work (Guillard and Zêzere, 2012), the conditional probability of both the landslide depletion areas and the landslide total areas were calculated for each class of each landslide predisposing factor, for shallow slides and deep-seated slides in the study area. The obtained results are very similar and we chose to model landslide susceptibility with the landslide total areas. Therefore, landslide susceptibility maps express the likelihood of an area to be involved in the rupture zone or the accumulation zone of a landslide (Guillard and Zêzere, 2012). The separation of the classes was done using the fraction of correctly classified landslide area (Fig. 5, and “predictive capacity” in Tables 5 and 6). Therefore, 50 % of future landslides should occur in the “very high” susceptibility classes, which represent only 7 and 6 % of the total area for the deep-seated and shallow landslides, respectively. Moreover, 25 % of future landslides should occur in the “high” susceptibility classes, which represent only 10 and 12 % of the total area for the deep-seated and shallow landslides, respectively.

Tables 5 and 6 show the probabilities of a pixel within a susceptibility class to be affected by a deep-seated (Table 5)

**Figure 5.** Prediction-rate curves and area under the curve (AUC) of landslide susceptibility models in the Loures municipality (based on the work done by Guillard and Zêzere, 2012).

or shallow (Table 6) slide, for different time periods (1, 10, 25, and 50 years). Probabilities of the total area to be affected by landslides in the future were calculated, as well as the area of the class and the class predictive capacity, as explained in Sect. 3.1.2. They can be calculated for any time period from the 1-year probabilities, but we selected 10, 25, and 50 years, which are significant time periods considering that stakeholders have to make choices that will have repercussions for decades. Indeed, even if a pixel within the high susceptibility class only has a probability of 5.46×10^{-4} (that is, a 1 in 1832 chance) of being affected by a deep-seated slide during the next year, it has a probability of 2.73×10^{-2} (that is, a 1 in 37 chance) of being affected by a deep-seated slide during the next 50 years (Table 5). Moreover, each pixel within the very high susceptibility class has a probability of

Table 7. Average vulnerability (Avg. vuln.) and standard deviation (SD) for each structural building type located on a landslide body (cf. Table 1 for building type).

		Landslide body: depth of slip surface									
		1 m		3 m		5 m		10 m		20 m	
		Avg. vuln.	SD	Avg. vuln.	SD	Avg. vuln.	SD	Avg. vuln.	SD	Avg. vuln.	SD
Pool of European experts (52)	SBT1	0.60	0.24	0.73	0.21	0.84	0.18	0.90	0.19	0.90	0.20
	SBT2	0.57	0.23	0.72	0.20	0.85	0.17	0.92	0.14	0.91	0.17
	SBT3	0.46	0.22	0.60	0.22	0.76	0.18	0.88	0.18	0.91	0.18
	SBT4	0.35	0.20	0.48	0.18	0.66	0.19	0.80	0.18	0.86	0.19
Sub-pool of study area experts (14)	SBT1	0.64	0.19	0.84	0.14	0.96	0.09	1.00	0.00	1.00	0.00
	SBT2	0.59	0.15	0.77	0.15	0.96	0.09	1.00	0.00	1.00	0.00
	SBT3	0.43	0.15	0.66	0.15	0.86	0.12	0.99	0.05	1.00	0.00
	SBT4	0.30	0.10	0.50	0.13	0.71	0.15	0.91	0.13	0.99	0.05

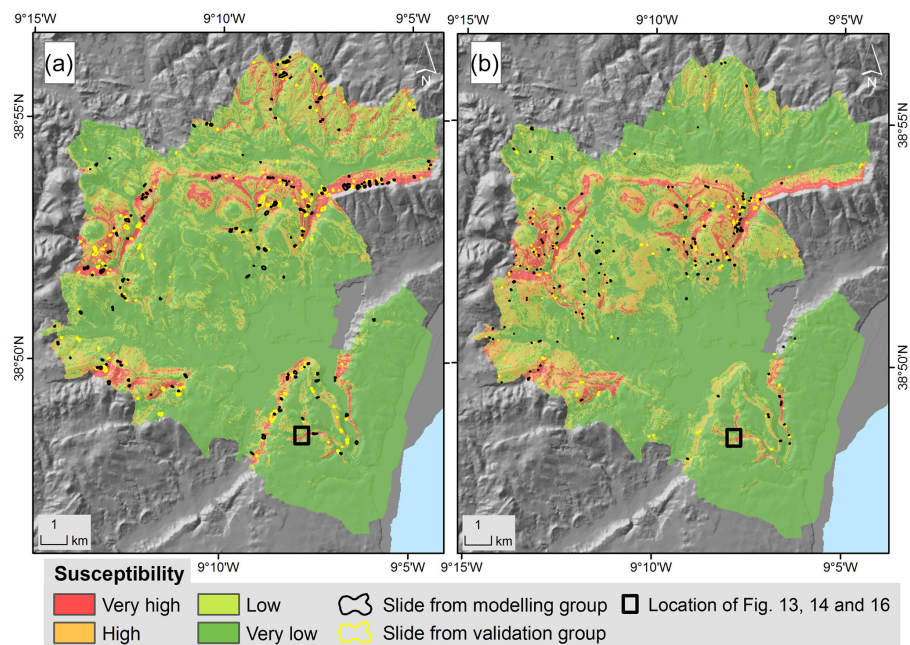


Figure 6. Landslide susceptibility maps in the Loures municipality for (a) deep-seated slides, (b) shallow slides (based on the work done by Guillard and Zêzere, 2012).

7.54×10^{-2} (that is, a 1 in 13 chance) of being affected by a deep-seated slide during the next 50 years.

4.2 Physical vulnerability of the buildings

Out of 52 questionnaires completed by the experts who have a research background or some experience in the landslide field, 30 came from Portuguese experts, 14 of whom have been doing research on landslides in the area north of Lisbon. As the damage level asked about in the questionnaire is a proxy for the physical vulnerability, the damage values provided by the experts, comprised between 1 and 5, were con-

verted into vulnerability values, comprised between 0 and 1 (see Table 2).

The physical vulnerability of buildings was assessed twice, first with the total landslide expert answers and second with the sub-pool of landslide experts who have been working in the study area. The vulnerability averages of the two groups of experts are presented in Tables 7 and 8, along with the standard deviation for each scenario, which was calculated in order to evaluate the variability of the answers through the differences between the experts' answers. The vulnerability averages were used to calculate the vulnerability of each BGRI subsection. These averages range from 0.25

Table 8. Average vulnerability and standard deviation for each structural building type located on a landslide foot (cf. Table 1 for building type).

		Landslide foot: height of accumulated material							
		0.5 m		1 m		3 m		5 m	
		Avg. vuln.	SD	Avg. vuln.	SD	Avg. vuln.	SD	Avg. vuln.	SD
Pool of European experts (52)	SBT1	0.45	0.22	0.61	0.20	0.85	0.17	0.94	0.12
	SBT2	0.38	0.23	0.53	0.21	0.78	0.18	0.93	0.12
	SBT3	0.30	0.18	0.40	0.22	0.66	0.17	0.83	0.17
	SBT4	0.25	0.16	0.31	0.19	0.54	0.19	0.72	0.20
Sub-pool of study area experts (14)	SBT1	0.39	0.18	0.56	0.22	0.86	0.15	0.97	0.07
	SBT2	0.29	0.15	0.49	0.17	0.81	0.12	0.97	0.07
	SBT3	0.24	0.09	0.39	0.15	0.71	0.15	0.90	0.13
	SBT4	0.20	0.00	0.27	0.10	0.53	0.10	0.79	0.15

(for a SBT4 building on a 0.5 m high landslide foot) to 0.94 (for a SBT1 building on a 5 m high landslide foot) regarding the European expert answers, and from 0.20 (for a SBT4 building on a 0.5 m high landslide foot) to 1 (for a SBT1 building on a 5 m high landslide foot) regarding the answers of the sub-pool of experts. As expected, the vulnerability of the buildings increases with the landslide magnitude, and is lowest for SBT4 and SBT3. The standard deviation ranges from 0.12 (for SBT1 and SBT2 buildings located on a 5 m high landslide foot) to 0.24 (for a SBT1 building located on a 1 m deep landslide body) regarding the European expert answers, and from 0 (several times) to 0.22 (for a SBT1 building on a 1 m high landslide foot) regarding the answers of the sub-pool of experts.

The vulnerability assessment provided by the sub-pool of experts who know the study area has a larger scope than the European landslide experts. Indeed, according to the study area experts, the low-magnitude landslides (landslides that are 1 m deep for the SBT3 and SBT4 buildings, and 0.5 and 1 m high of accumulated material landslides for all the structural building types) cause less damage than according to the European experts, and the high-magnitude landslides cause more damage than according to the European experts (Tables 7 and 8). Moreover, the standard deviation values of the study area experts' answers are typically lower than the standard deviation values of the European experts' answers (Tables 7 and 8), which indicates the consistency of the answers given by the study area experts.

In each BGRI subsection, the average vulnerability was calculated, taking into account the number of buildings belonging to each structural building type. Then, the average vulnerability given by the sub-pool of study area experts was attributed to each building included into the BGRI subsection in order to obtain more explicit maps (Figs. 7 and 8). The average vulnerabilities of the Loures municipality buildings associated with the landslides that are 1, 3, 5, 10, and 20 m deep

are 0.34, 0.55, 0.75, 0.92, and 0.97, respectively; the average vulnerabilities of the Loures municipality buildings associated with the landslides which have a height of accumulated material of 0.5, 1, 3, and 5 m are 0.21, 0.31, 0.58, and 0.81, respectively. The standard deviation of the BGRI subsection vulnerability was also represented in shades of blue in Figs. 7 and 8. As a rule, the standard deviation decreases as the landslide magnitude increases.

As expected, the average vulnerability depends on the structural building type, and increases with the landslide magnitude. However, when the magnitude is maximum – which is for a landslide 10 m or 20 m deep – all the buildings have maximum vulnerability ($PV > 0.8$ see Fig. 7d and e, and Table 7), independently of their structural building type. This means that the structure type may play a role when the landslide magnitude is low, but all the buildings have the same (maximum) vulnerability when the landslide magnitude reaches a certain level of potential damage. The variability in the expected damage to buildings among the study area experts is higher for damage generated by low-magnitude landslides (e.g. landslides 1 m deep, and landslides with a 0.5 to 1 m high of accumulated material) on SBT1, SBT2, and SBT3. This can be explained by the fact that the landslide experts have more facilities to assess the vulnerability to the high-magnitude landslides, which have a high potential for damage, than to the low-magnitude landslides, for which the potential for damage is more difficult to determine. The maps shown in Figs. 7 and 8 enable the location of the buildings and their vulnerabilities to be identified according to different landslide magnitudes, but they also highlight the uncertainty associated with the attributed vulnerabilities.

The vulnerability of the test site buildings inventoried during fieldwork (Fig. 3) is presented in Figs. 9 and 10 for locations in the landslide body and the landslide foot, respectively. As each building has its own vulnerability, the results are more accurate than when an average value is calculated

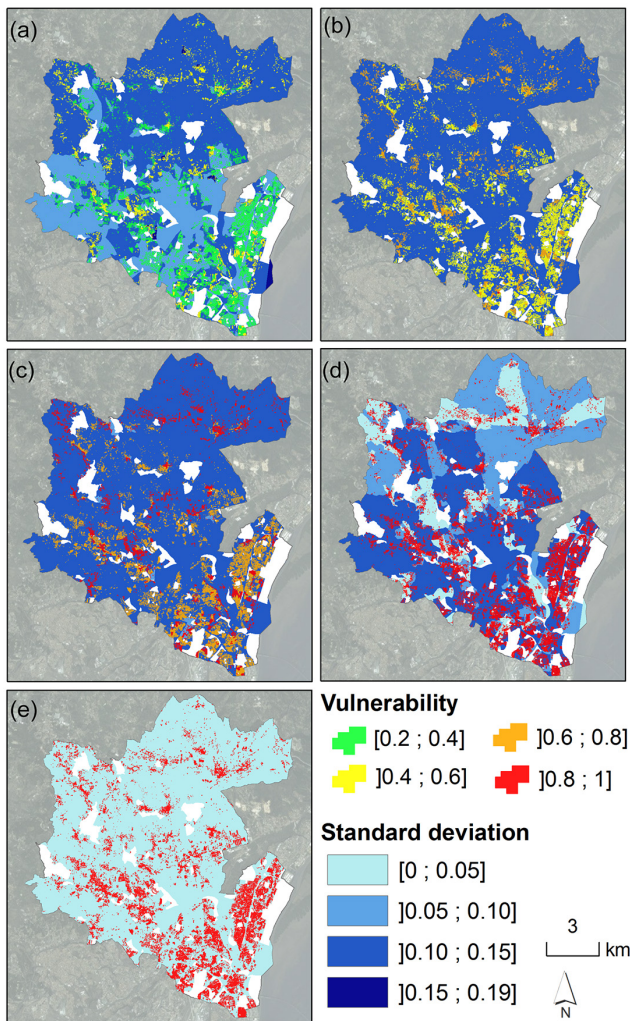


Figure 7. Average building vulnerability and standard deviation per BGRI subsection for buildings located on a landslide body, for a slip surface depth of (a) 1 m, (b) 3 m, (c) 5 m, (d) 10 m, and (e) 20 m. White polygons are BGRI subsections without buildings.

for all the buildings of the BGRI subsection. However, the comparison of building vulnerability expressed in Figs. 9 and 10 with the corresponding area at the BGRI subsection level shows that global results are similar. In order to obtain a more accurate comparison, the box plots of the vulnerability values obtained by both vulnerability approaches for the test site are shown in Fig. 11. Indeed, Fig. 11 enables the comparison of vulnerability values of the test site buildings inventoried by fieldwork (in grey) with the vulnerability values of the buildings of the BGRI subsections (in black). In each case, the range of the vulnerability values obtained by fieldwork is wider than the one obtained by the BGRI subsections calculations. This can be explained by the fact that the data obtained by fieldwork are much more detailed because the buildings were considered one by one; therefore the results are less generalized. Moreover, for each scenario,

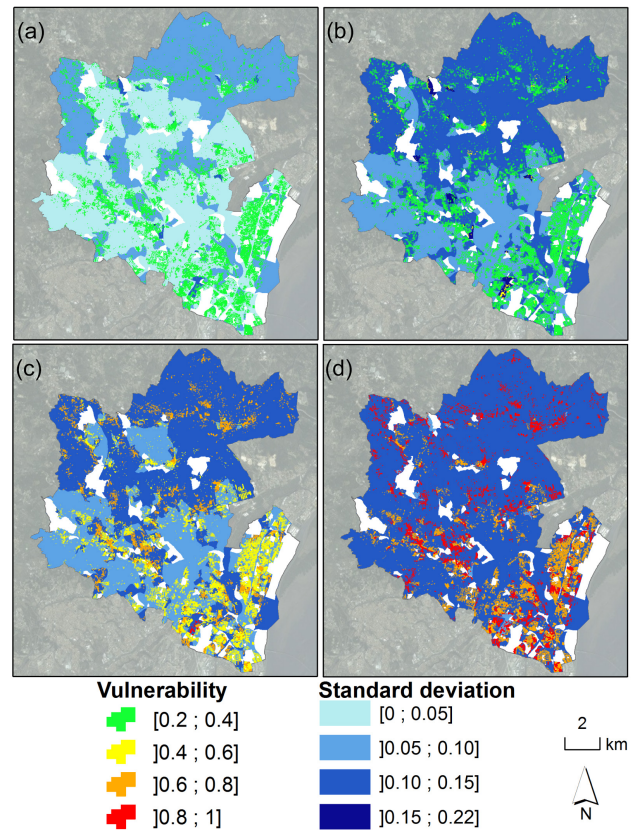


Figure 8. Average building vulnerability and standard deviation per BGRI subsection, for buildings located on a landslide foot with an affected material height of (a) 0.5 m, (b) 1 m, (c) 3 m, and (d) 5 m. White polygons are BGRI subsections without buildings.

the median of the fieldwork data is the same (or almost the same in the case of the landslides that are 10 m deep) as the one calculated from BGRI subsections data, which validates the accuracy of the vulnerability values obtained by calculations in the BGRI subsections. The vulnerability assessment procedure based on BGRI subsection mapping units is much less time-consuming than the fieldwork procedure and can easily be applied to other areas, because the data are available in the census. As the obtained results are satisfactory, we recommend the application of the first approach at the municipal level.

4.3 Economic value of the buildings

The economic value of the buildings was calculated using Eq. (2). We found that 3417 buildings have an economic value above EUR 100 000 per pixel (which corresponds to 4000 EUR m⁻²), that is 3 % of the buildings of the whole municipality. Most of them are located in the southern half of the Loures municipality (near Lisbon), which is more urbanized than its northern half, and presents the highest concentration in the civil parishes of Portela, Moscavide, and

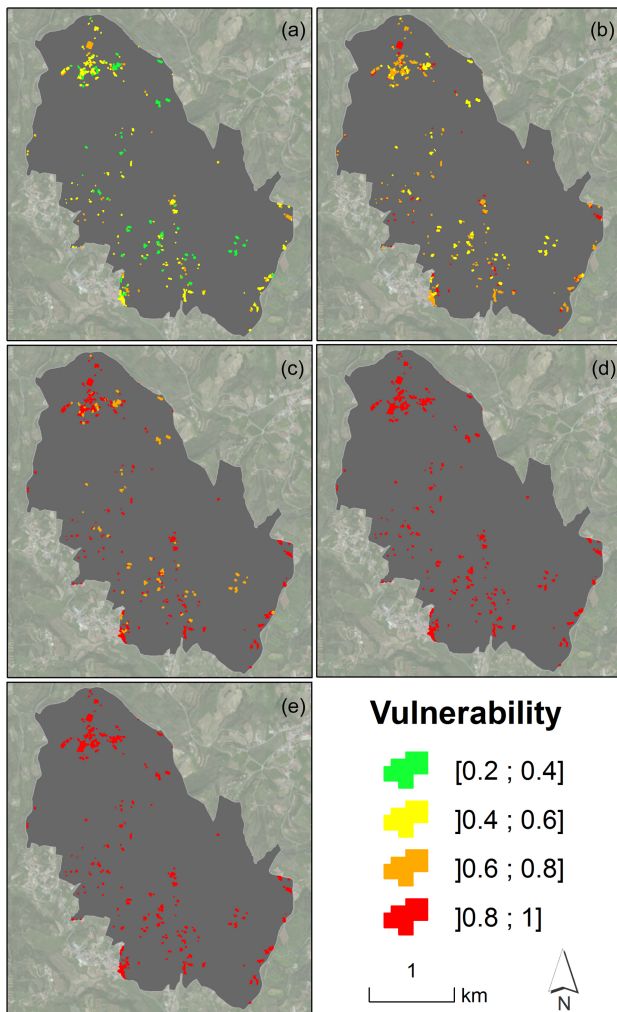


Figure 9. Vulnerability of buildings inventoried in the fieldwork area, located on a landslide body with a slip surface depth of (a) 1 m, (b) 3 m, (c) 5 m, (d) 10 m, and (e) 20 m.

Sacavém (Figs. 3 and 12). The civil parishes of Santo António dos Cavaleiros, Loures, Santa Iria de Azóia, São João da Talha, and Bobadela also have high economic value buildings. Most of them are recent residential and industrial buildings located near social facilities.

4.4 Landslide risk

Figures 13 and 14 illustrate the risk for buildings according to the spatiotemporal landslide probability, the landslide magnitude, and the building vulnerability and value. The buildings have been transformed into a raster in order to multiply the potential losses associated with the buildings by the hazard values. The value of risk is the value per pixel, and each pixel has an area of 25 m^2 . The total area of the buildings in the vector is 9.25 km^2 , and the total area of the buildings in the raster is 9.00 km^2 . The 0.25 km^2 which was lost during

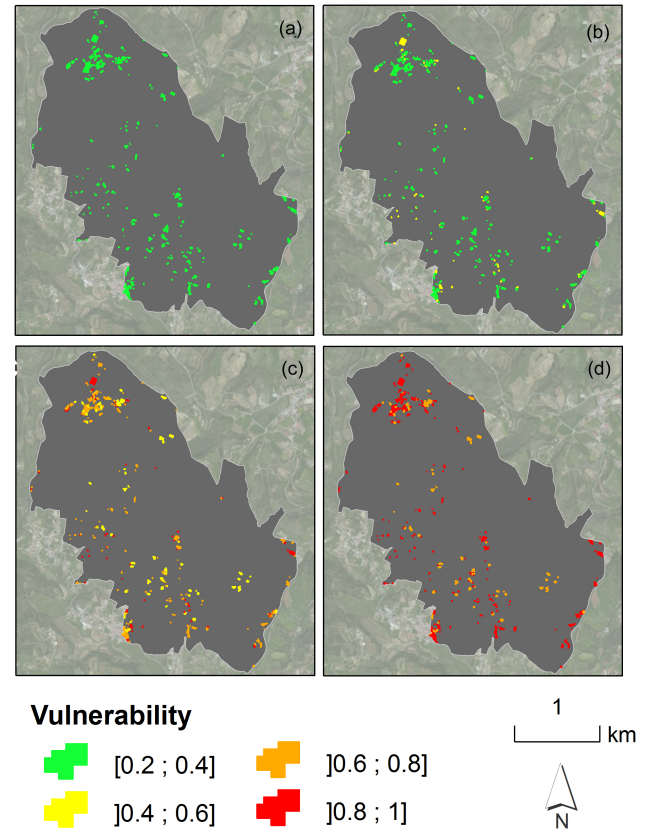


Figure 10. Vulnerability of buildings inventoried in the fieldwork area, located on a landslide foot with an affected material height of (a) 0.5 m, (b) 1 m, (c) 3 m, and (d) 5 m.

the transformation from the vector to the raster only represent 2.7 % of the total area of the buildings; thus, even if the transformation changes the shape of the buildings slightly, their surface is almost the same, which has little influence on the risk estimates. Figures 13 and 14 show that the risk values are closely related to the landslide susceptibility values. As the buildings have similar economic values, the ones that were constructed in high or very high susceptibility zones have a higher risk in comparison to the ones constructed in the “low” or “very low” susceptibility zones.

The box plots of the risk values were plotted for each scenario in order to compare them (Fig. 15). Outliers have been considered, but their values are too high to be shown on this figure (the maximum value is EUR 25.68 per pixel, for a 3 m deep slide). Figure 15 and Table 9 show that the maximum values of risk correspond to landslides that are 3 m deep, for which 741 pixels buildings (that is 0.2 % of the buildings of the Loures municipality) have a risk above EUR 5 per pixel, and for which there is an annual risk of EUR 96 693 for the Loures municipality, that is EUR 109 per hectare of buildings (Table 9). Indeed, these landslides are the ones which combine a relatively high frequency in the Loures municipality (magnitude probability = 0.34, cf. Table 3) with a substantial

Table 9. Landslide risk per civil parish. Vulnerability data obtained with a sub-pool of landslide experts who know the study area.

Civil parish ID (cf. Fig. 3a)	Civil parish name	Civil parish area (ha)	Area of buildings (ha)	Body depth: 1 m		Body depth: 3 m		Body depth: 5 m		Body depth: 10 m		Body depth: 20 m	
				Total risk (EUR)	EUR ha ⁻¹ of buildings	Total risk (EUR)	EUR ha ⁻¹ of buildings	Total risk (EUR)	EUR ha ⁻¹ of buildings	Total risk (EUR)	EUR ha ⁻¹ of buildings	Total risk (EUR)	EUR ha ⁻¹ of buildings
1	Bucelas	3397	66	772	12	6671	101	4856	73	2004	30	467	7
2	Lousa	1653	46	1150	25	4349	96	3236	71	1364	30	347	8
3	Fanhões	1162	25	832	34	3112	126	2354	95	1024	41	286	12
4	Loures	3300	141	4778	34	16310	115	12404	88	5456	39	1501	11
5	São António do T.	1513	45	866	19	2702	60	2053	46	890	20	235	5
6	São Julião do T.	1328	56	695	12	2411	43	1817	32	772	14	164	3
7	São António dos C.	363	23	2265	97	5730	246	4521	194	2109	91	627	27
8	Frielas	556	25	299	12	2802	110	2225	87	1020	40	286	11
9	Apelação	140	12	382	32	1494	124	1163	97	523	44	146	12
10	Unhos	451	39	705	18	4698	121	3653	94	1652	42	457	12
11	S João da T.	652	83	1413	17	6546	79	5033	61	2249	27	566	7
12	Sia Iria de A.	756	87	1502	17	7077	82	5538	64	2494	29	653	8
13	Camarate	566	83	2025	24	9653	117	7341	89	3237	39	860	10
14	Bobadela	382	25	592	24	2534	101	1960	78	875	35	230	9
15	Prior Velho	131	35	662	19	2769	80	2134	61	966	28	258	7
16	Sacavém	379	51	1950	39	8465	167	6681	132	3075	61	889	18
17	Portela	102	21	1126	53	4594	217	3617	171	1684	80	488	23
18	Moscavide	102	22	1144	51	4775	213	3708	165	1685	75	489	22
–	Loures municipality	16 934	886	23 158	26	96 693	109	74 293	84	33 078	37	8946	10
–	Loures municipality with vulnerability data from the pool of the 52 landslide European experts			26 871	30	92 581	105	67 389	76	28 642	32	7551	9
–	Difference (%)			–16.0		4.3		9.3		13.4		15.6	

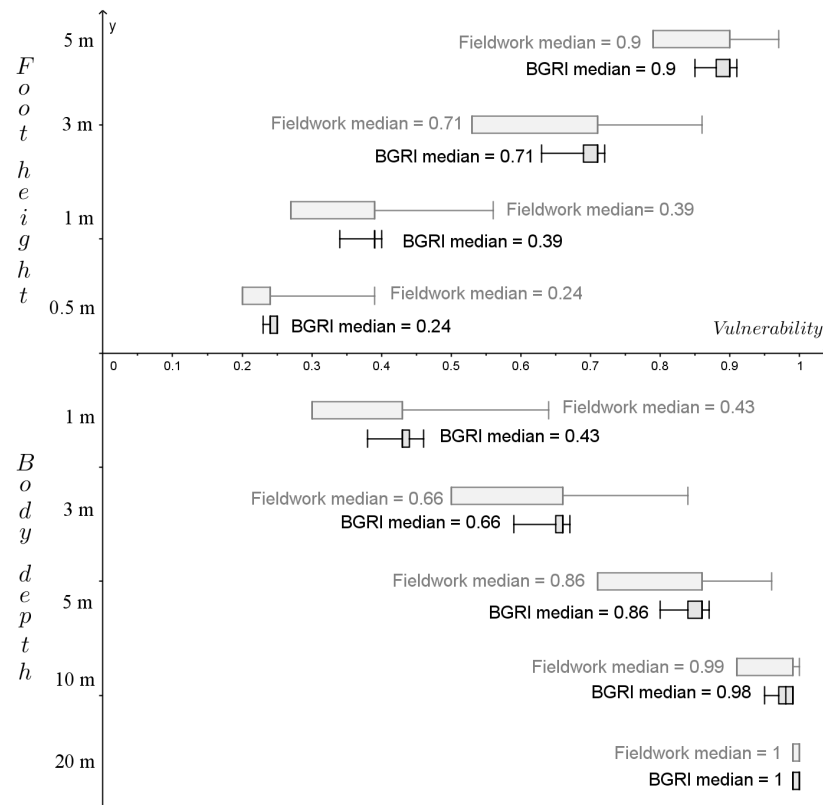


Figure 11. Box plots of the vulnerability of the test site buildings for each scenario, for the buildings inventoried by fieldwork (in grey) and for the buildings of the BGRI subsections (in black).

potential damage (the median vulnerability value associated with them is 0.66; cf. Fig. 11). More frequent landslides have a lower magnitude and are less destructive, whereas the ones which have a higher magnitude have a very low frequency; for example, the annual probability of a landslide with a depth of 20 m or more in the Loures municipality is 0.02 (cf. Fig. 4 and Table 3). Therefore, despite the high median vulnerability associated with these landslides (1; cf. Fig. 11), the risk associated with them is quite low (the median value is 0.04; cf. Fig. 15). The risk was calculated for each civil parish for the five scenarios considering the different landslide body depths (1, 3, 5, 10, and 20 m). The risk in euros per hectare of buildings was also calculated for each civil parish (Table 9). The maximum annual risk value was computed for the Loures civil parish (EUR 16 310), and the maximum value of risk per area of buildings was obtained for the Santo António dos Cavaleiros civil parish (246 EUR ha⁻¹). The Loures civil parish has the highest number of buildings within the municipality and it also has the highest risk values for the five scenarios summarized in Table 9. The Sacavém and Camarate civil parishes also have a high risk, which can be explained by the high economic value of their built environment.

The last two lines of Table 9 show the annual risk values for the municipality obtained using the average vulnerabil-

ity given by the pool of European landslide experts and the differences for risk values obtained with the average vulnerability given by the sub-pool of study area experts. For low-magnitude landslides (landslides that are 1 m deep), the study area experts gave lower vulnerabilities for the SBT3 and SBT4 buildings than the European experts (Table 7); these buildings represent 97.5 % of all the buildings of the Loures municipality (Table 1) and their low vulnerability implies a lower risk at the municipality scale. For high-magnitude landslides, the study area experts gave higher vulnerabilities for any structural building types than the European experts, which implies a generalized higher risk for the municipality.

Finally, the risk was calculated considering different time periods. Figure 16 shows the risk to landslides that are 10 m deep in a part of the Loures municipality, for 1, 10, 25, and 50 years. In this zone which was zoomed in on, the annual risk is between EUR 1 and 5 per pixel in the very high susceptibility zones, and below EUR 1 per pixel in the rest of the zoomed area. However, the risk increases when we consider longer periods of time; for instance, for a 50-year period, risk values are above EUR 20 per pixel for high and very high susceptibility zones and between EUR 5 and 20 per pixel for low susceptibility zones.

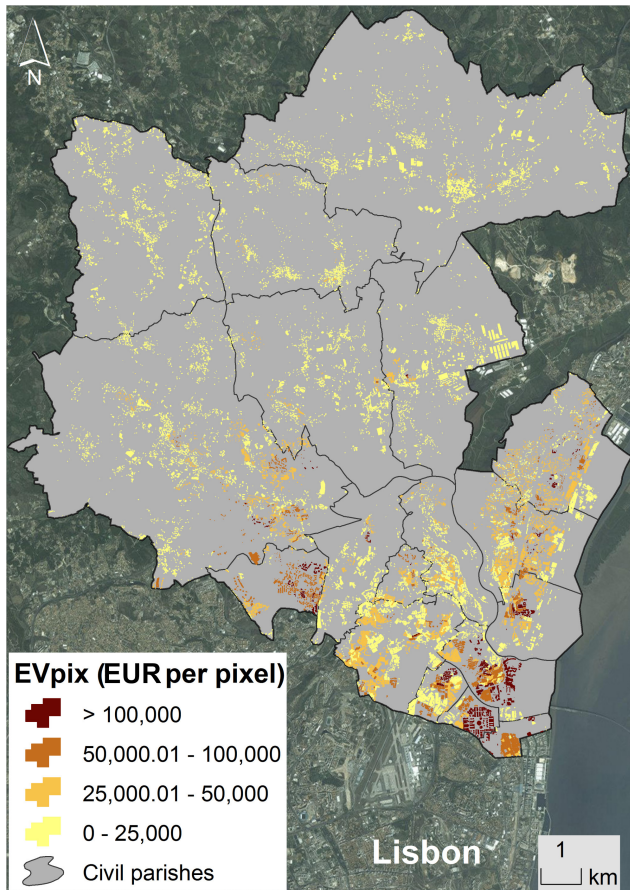


Figure 12. Economic value of buildings per 5 m pixel in the Loures municipality.

5 Discussion

The vulnerability values obtained in this study are in agreement with the ones found in the literature. Indeed, we found that in general, landslides smaller than $\sim 1500 \text{ m}^2$ resulted in negligible to significant damage to buildings, corresponding to a vulnerability of 0.6 or less, whereas landslides larger than $\sim 7000 \text{ m}^2$ produced significant to very severe damage, corresponding to a vulnerability of 0.6 or higher, which is in agreement with the results found by Galli and Guzzetti (2007). Moreover, in terms of accumulated material height, the landslides that have a 5 m depth of accumulated material, produce an average damage for the four structural building types corresponding to a vulnerability of 0.91. For comparison, the vulnerability curves computed by Papathoma-Köhle et al. (2012b) using a Weibull distribution show that debris flows produce a total destruction (vulnerability = 1) when the accumulated material reaches 3.5 m high. Considering that the debris flows' intensity is increased by their velocity, it is understandable that their potential for damage is higher than the potential for damage of the slow landslides considered in the present study.

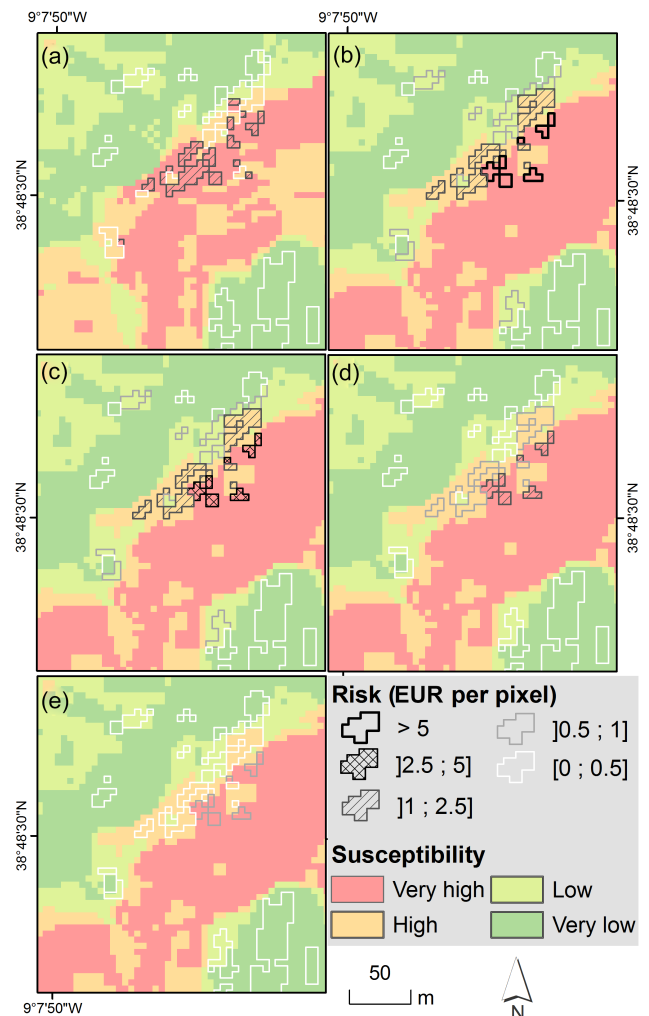


Figure 13. Detail of annual risk for buildings of the Loures municipality located on a landslide body, for a slip surface depth of (a) 1 m, (b) 3 m, (c) 5 m, (d) 10 m, and (e) 20 m. Pixel size: 5 m. For location, see Fig. 6.

The answers obtained by the sub-pool of experts with a deep knowledge of the landslides and built environment of the study area have low standard deviation; they are more consistent than the answers obtained by the whole European experts pool, given that they know the typical landslide characteristics in the study area (e.g. landslide velocity, affected material, height of landslide scarps) as well as the characteristics of the built environment that may influence the physical vulnerability (e.g. age, state of conservation, construction materials) better, and are better able to assess the degree of loss produced by the impact of landslides. This shows that the vulnerability is in part a site-specificity parameter, and it has to be taken into account during vulnerability assessment by a questionnaire.

The standard deviation tends to be higher for lower magnitude landslides, for which the potential damage is more

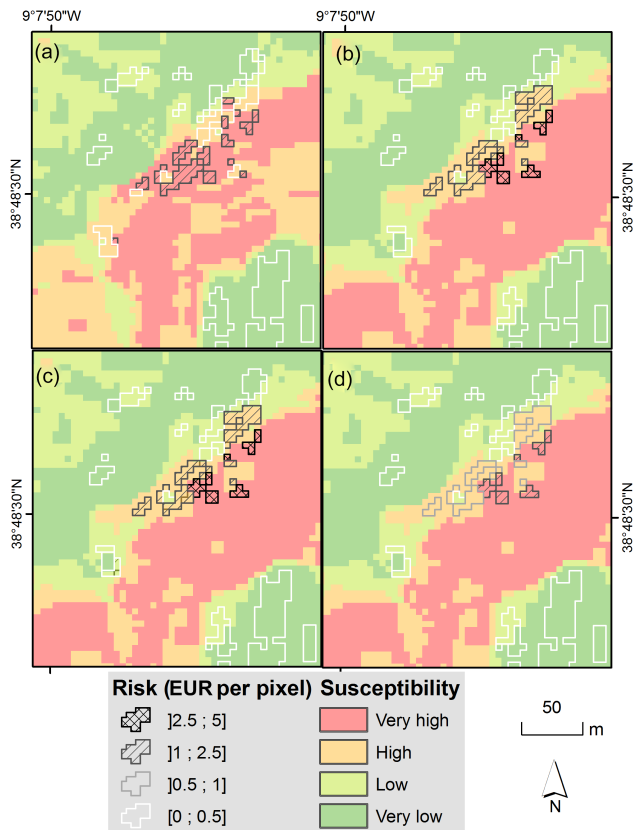


Figure 14. Detail of annual risk for buildings of the Loures municipality located on a landslide foot, for affected material that is (a) 0.5 m, (b) 1 m, (c) 3 m, and (d) 5 m high. Pixel size: 5 m. For location, see Fig. 6.

difficult to assess than for the higher magnitude landslides, which are considered as highly destructive by the large majority of experts within the sub-pool of experts. Implications of high standard deviation for final risk calculation may be relevant. For example, assessing the risk for a SBT1 building, with a value of EUR 100,000, affected by a landslide with 0.5 m high accumulated material located in the highest landslide susceptibility class, the annual risk is EUR 33.6 considering the average vulnerability. However, the risk may range between EUR 18 and 49 considering the standard deviation value, which means a difference of 46 % to the average value.

If we consider that the sub-pool experts have a more accurate opinion of the building vulnerability to landslides in the Loures municipality, we can state that the pool of European landslide experts overestimated the low-magnitude landslides and underestimated the high-magnitude landslides. Regarding the vulnerability assessment by the European landslide experts, most of them merely completed the questionnaire, but some of them expressed doubts that arose while filling in the questionnaire or made some comments. Whenever necessary, emails were exchanged before the experts

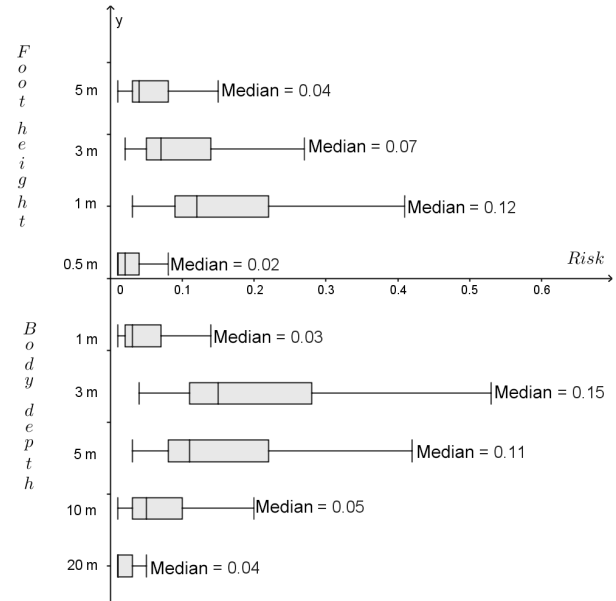


Figure 15. Box plots of the risk for the buildings per 5 m pixel, for each scenario. Outliers are not shown. The maximum outlier values are 8.35 (foot height: 5 m), 12.81 (foot height: 3 m), 19.58 (foot height: 1 m), 5.46 (foot height: 0.5 m), 8.2 (body depth: 1 m), 25.68 (body depth: 3 m), 20.38 (body depth: 5 m), 9.62 (body depth: 10 m), and 2.99 (body depth: 20 m).

completed the questionnaire. Most of the experts who had doubts expressed that it was difficult to assess the potential damage caused by a landslide to a building based only on the depth of the landslide slip surface or the height of accumulated material. Additionally, the structure of the building and its position on the landslide body or foot were referred as major concerns. However, it was not useful to give them more detailed information about the building position or about the characteristics of the landslides (e.g. the velocity of the landslide, the type of affected material, the height of the scarp) as they requested, because such information was not available for the complete landslide inventory and the aim of this study is to assess the vulnerability of the buildings of a whole municipality in a systematic fashion. One adopted solution was to consider the worst case scenario for the potential damage assessment; i.e. the height of the scarp is slightly smaller than the depth of the slip surface; the building is partly within the body and partly outside (on the scarp); the foot is perpendicular to length of the building; and the building is well within the foot, not simply touched by it. This model is quite conservative in that in more favourable situations, damage would logically be lower. But as some of the experts expressed the potential damage as maximum, and the others as medium, the average values provide a model that is not too conservative, but not too low either in terms of expected potential damage, and this is what the authors were seeking.

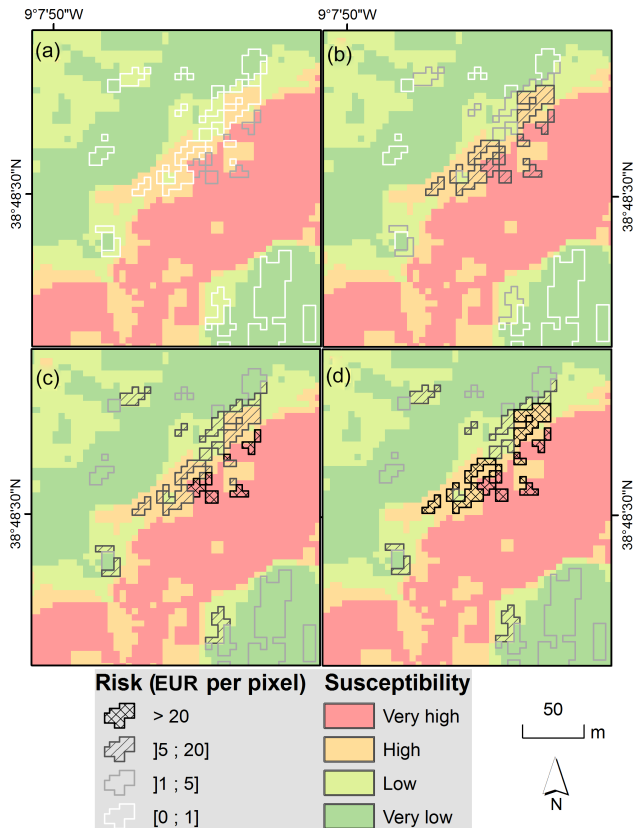


Figure 16. Detail of multiannual risk for buildings of the Loures municipality located on a landslide body with a 10 m deep slip surface, for a hazard of (a) 1 year, (b) 10 years, (c) 25 years, and (d) 50 years. Pixel size: 5 m. For location, see Fig. 6.

Regarding the representation of the buildings' vulnerability at the municipal scale, the vulnerability approach based on statistical mapping units is satisfactory. This approach is time-saving and provides correct results when the structural building types within the BGRI subsections are homogeneous. In the BGRI subsections where the structural building types are very heterogeneous, it is useful to take time to identify the structural building type of each building, by fieldwork.

The vulnerability assessment developed in this study has three main advantages: first, the method can be applied to the buildings of the whole Loures municipality despite its huge number (more than 30 000) and the few data available for these buildings; second, the variability of results can be assessed by calculating the standard deviation of the attributed vulnerabilities; third, the vulnerability assessment method developed in this study was applied to the Loures municipality, but it can be reproduced in another municipality or a region with similar landslide types and built environment in a reasonable time.

However, the risk analysis presented here has some limitations and drawbacks involving both the hazard assessment

and the potential damage assessment. In relation to the hazard assessment, the spatiotemporal probabilities were overestimated as they were calculated on the landslide areas as a whole. Therefore, the risk calculated for a building constructed on a landslide body on the one hand, or on a landslide foot on the other hand was also amplified because the potential damage was assessed separately for the body and the foot. In addition, the spatiotemporal probabilities were calculated on the basis of the total areas of the inventoried landslides, considering that the 686 landslides of the Loures municipality were the only ones that occurred from 1967 (first landslides inventoried and dated) until 2004 (date of the orthophoto maps used to complete the inventory); in reality, it is obvious that the real total affected area is larger because we could not have inventoried all the landslides that occurred in the Loures municipality during this period. An annual inventory of the whole municipality and extensive fieldwork from 1967 to 2004 could be the solution to obtain a complete landslide inventory. From this point of view, the hazard was underestimated. In addition, changes in the frequency of occurrence of landslides associated with climate change increase the uncertainty of probabilities computed for 10, 25, and 50 years.

In relation to the potential damage assessment, the element at risk values were underestimated. Indeed, the value of the contents inside the buildings was not considered as they were not known. Moreover, indirect costs linked to the function of the building are difficult to quantify and were not considered in this study, although they play an important role in a complete risk analysis. Some examples of these indirect costs would be the costs linked to the temporary or definitive resettling of families whose house has been destroyed by a landslide, as well as the eventual additional costs of transportation if their resettled home is farther from their work place. Another example of indirect costs is the capital lost by the cessation of activity in case an industry or an office were destroyed or damaged by a landslide. Last but not least, it would be even worse if the destroyed building was a strategic building such as a hospital or a school; the vital and sensitive role of these kinds of buildings was not considered in this study, which is another limitation.

The risk analysis is based on the assumption that future landslides will have similar characteristics to the past ones; however, if the landslide preparatory and triggering conditions change (e.g. due to climate change or direct human interference on slopes), the number of landslides and their magnitude would increase, as would the associated damage, and that would have to be considered.

Finally, the risk is underestimated for the scenarios of 10, 25, or 50 years, because it was calculated for the buildings that exist presently, without taking the urban expansion into account, which is a factor of element at risk exposure, and is thus responsible for an increasing risk.

6 Concluding remarks

An assessment of buildings' vulnerability to landslides, based on an inquiry of nine magnitude scenarios by a pool and a sub-pool of landslide experts, was developed and applied to Loures, a municipality within the greater Lisbon area. The obtained vulnerabilities vary from 0.2 to 1 as a function of the structural building types and increase with the landslide magnitude, being maximal for a 10 m or a 20 m deep landslide. The annual and multiannual landslide risk has also been computed for the nine magnitude scenarios; the maximum annual risk occurs for the landslides that are 3 m deep, with a maximum value of EUR 25.68 per 5 m pixel.

For the other magnitude scenarios, risk values are low, but they should not be confused with the potential loss values. Indeed, the risk values of the landslides that are 5, 10, or 20 m deep are low because the magnitude probabilities of these landslides are low; nevertheless, when these landslides occur, they produce severe or very severe damages to the buildings.

The analysis of the landslide risk for the buildings of the Loures municipality enables the stakeholders to focus on the buildings for which the landslide vulnerability and the landslide risk are high. All the magnitude scenarios must be taken into account for accurate planning. The landslides that have a low-magnitude being more frequent, the risk they imply has to be considered for short-term planning, whereas the risk implied by high-magnitude landslides has to be considered for long-term planning.

Landslide risk analysis performed in this work may be very useful for insurance companies, which are interested in risk values for buildings, but it may not be so useful for end users dealing with spatial planning and civil protection. Indeed, for spatial planning stakeholders, it is crucial to know where future landslides will occur in order to select the safest zones for development purposes. Therefore, a validated landslide susceptibility assessment, as the one which was presented by Guillard and Zêzere (2012), is a very useful tool for spatial planning, which can be improved with additional data on landslide magnitude and landslide frequency. On the other hand, the civil protection stakeholders need to know the landslide risk for buildings that have a vital or strategic role (e.g. hospitals, schools), but also the location of the population that need to be protected, including the most vulnerable groups of people. Therefore, the landslide hazard assessment and mapping is not enough for civil protection and should be complemented by the assessment of the specific risk (hazard \times vulnerability), namely for critical structures and infrastructures, which might be more useful and less time-consuming than the complete risk analysis for the complete built environment.

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