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Assessing population exposure for landslide risk analysis using dasymetric cartography

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Abstract. Assessing how many people are exposed and where are they located is a crucial step in landslide risk management and emergency planning. Frequently the available population statistical data have no sufficient detail to an accurate assessment of the potential exposed people to a hazardous phenomenon, mainly if it occurs at the local scale, like landslides. The present study aims to apply the dasymetric cartography technic to improve population spatial resolution and to assess potential exposed population. An additionally objective is to compare the obtained results with a more common approach that uses basic census units in its better spatial resolution (BCU) as spatial units. Considering the Portuguese census data and a layer of residential building limits, whose area was used as ancillary information, the number of exposed inhabitants significantly differs between two approaches. Using BCU approach and considering the three highest landslide susceptible classes, people inhabitants are overestimated in 132 % (2539 inhabitants). Despite the associated uncertainties in a general cost-benefit analysis the presented methodology seems to be a reliable approach as first approximation to a more detailed estimation of exposed people. The approach based on dasymetric cartography allows an increasing of the spatial resolution of population over large areas and enable the use of detailed landslide susceptibility maps and thus improving the population assessment.

Keywords: people exposure, people spatial distribution, dasymetric, risk analysis, landslides

1 Introduction

In natural sciences, risk is function of the probability of occurrence of a hazard scenario and the related consequences that are expected on the exposed elements at risk (e.g. Varnes and IAEG, 1984; Fuchs et al. 2013). Lee and Jones (2004) consider risk as a “human-centred concept that is applied when human or things that human value were adversely impacted”. So, assessing exposed elements and their vulnerability are essential to risk analysis. However, the variety of potential exposed elements and their different characteristics (buildings, roads, people, etc.) leads to a complex and multi-level analysis, and because of that studies with more than one type of exposed elements are rare (e.g. Michael-Leiba et al., 2003; Keiler, 2004;

Promper and Glade, 2016). Nevertheless, exposure assessment and vulnerability of fixed elements in territory has received by scientific community a special attention in recent years, being specified the type and number of exposed elements and assessed their expected degree of loss (e.g. Galli and Guzzetti, 2007; Papathoma-Köhle et al., 2007, 2012; Petrucci and Gullà, 2010; Kappes et al., 2012; Silva and Pereira, 2014; Uzielli et al., 2014; Winter et al., 2014; Fuchs et al., 2015; Promper et al., 2015; Guillard-Gonçalves et al., 2016).

In social sciences many times the focus is placed on evaluate how communities and society in general can couple with a disaster event (e.g. Cutter et al., 2003; Kienberger et al., 2009; Mendes, 2009; Nathan et al., 2010). Other studies tried to evaluate relations between process occurrence and damages to people, calculating the probability of fatalities, their acceptability/tolerance or combining approaches to making f-N curves (e.g. HSE, 1992; Cruden and Fell, 1997; Evans, 1997; Guzzetti, 2000). Further studies have been evaluating the probability of people to be affected outside/inside an element (e.g. a house) that is hit by the hazardous phenomenon (e.g. Ragozin and Tikhvinsky, 2000; Bell and Glade, 2004; Kaynia et al., 2008). The abovementioned studies are generally based on historical data of hazard phenomena that affected population (e.g. Dai et al., 2002; Guzzetti et al., 2005). However, these historical databases are frequently insufficient and incomplete, which means that "probabilities" have been assumed frequently based on knowledge and judgement (Michael-Leiba et al., 2003).
For the analysis of such dynamic and "multi-faceted" topic as vulnerability, truly interdisciplinary research is necessary (Fuchs et al., 2011). In addition, different datasets of elements must to be taken into account (e.g. building structure and materials, number of inhabitants, infrastructures uses, traffic volume, among several others) to estimate direct and indirect costs within the quantitative risk analysis (e.g. Zêzere et al., 2007, 2008; Remondo et al., 2008; Corominas et al., 2014; Schwendtner et al., 2013). In other perspective the lack of interdisciplinary and multi-level approaches (e.g. regional/international, personal/political) can reduce the efficiency of adopted policies to avoid disasters (e.g. Xanthopoulos, 2007; Aubrecht et al., 2013).

Without underestimating the significance of know the probability of fatalities, which is extremely important for spatial management, the simple and accurate assessment of "how many people" is present at a certain time and space is crucial, for example, to manage people evacuation. To know where potential exposed population are is important but to know it with higher precision and accurately is mandatory to guarantee the efficiency of emergency plans and to reduce associated costs (e.g. Bhaduri et al., 2002; Sutton et al., 2003; Chen et al., 2004; Su et al., 2010; Freire and Aubrecht, 2012; Freire et al. 2012; Aubrecht et al., 2013). In fact according to Bhaduri et al. (2002) locating population at risk has to be the first step in saving lives.

As base of a complete risk assessment the location and number of exposed people, with a lower degree of uncertainty, is mandatory and demands a harmonization between the resolution of the hazard and detailed population data distribution. A higher resolution of population distribution is mainly need when the hazard has no extensive consequences, as in the case of landslides, where the processes are more selective and local damage related (Deichmann et al., 2011). Additionally, in larger study areas where diverse types of occupation can take place (urban, rural) significant differences on population density are expected. When the combination of these two situations occurs (local hazard and sparse population) it becomes even more important to know where the exposed people are located.

Potential affected people are usually assessed based on inhomogeneous spatial units from census data, which mainly indicates night-time population distribution (e.g. Freire and Aubrecht, 2012; Aubrecht et al., 2013; Fraser et al., 2014). For this reason some authors tried to evaluate the population fluctuation (daily, seasonal, historical) to accurate their exposed people counting (e.g. Keiler, 2004; Keiler et al., 2005; Freire and Aubrecht, 2012; Schwendtner et al., 2013). Aubrecht et al. (2010) provided a detailed approach, in a 13 km^2 area, adding to a high resolution land cover map information about building eight (as proxy of building capacity) and building use (residential, public, commercial, others). Freire et al. (2012) used also a 3D building model to define how many people needs to be evacuated due to a tsunami, in a 2.5 km^2 estuarine area in Lisbon. Fuchs et al. (2015) assessed exposure to several hazard phenomena in Austria based on unusual detailed property data information, as for example height, net area, configuration, main use, for individual floors as well population per building. Although, quite detailed methods for disaggregation of people and counting of how many people are exposed to a hazard have already been tested, the need of high detailed information does not allow its widespread use in areas of hundreds of km^2. On the other hand, in some cases, as in Portugal, due to privacy policies, the best source of population data (e.g. census) are always aggregated which distort reality. Even in small units as Basic Census Unit (BCU) homogeneity is not always achieved; in these cases the assumption of homogeneity leads to an error that is greater as greater are the diversity of uses (e.g. residential, commercial, agricultural). In the best cases BCU corresponds to the city block (in urban areas) but can have a huge dispersion in sparsely populated rural areas, which constrains a more accurate assessment of the number and precise location of people exposed. Even if the data were collected individually an aggregation is done which implies that is assumed a uniform distribution of population inside the aggregation unit, i.e. population could be distorted (e.g. Fisher and Langford, 1996; Su et al., 2010). In addition people can be concentrated in specific places within a BCU. Distribute population inside these units is a major goal of this work. For this purpose an increasing of population data resolution is needed.

Although the objective is to obtain a finer spatial distribution of the population, different methods and data can be used, mainly when considering different scale approaches (Aubrecht et al. 2013). The adopted methodology and obtained results are dependent on the type and quality of the input data used as ancillary information to disaggregate data (Su et al., 2010). In fact on global scales (from world to regional scale), the base to disaggregate general information is frequently a land use map or an accessibility map that allow to spatially distinguish population between urban and rural areas (e.g. Eicher and Brewer, 2001; Mennis and Hultgren, 2006; Reibel and Agrawal, 2007; Langford, 2007; Langford et al., 2008; Gallego, 2010; Steinnocher et al., 2011). The drawback of these approaches is the limited spatial resolution of the land use map that leads to over or underestimate population in sparsely populated areas (Steinnocher et al., 2011; Aubrecht et al. 2013).

On local scales (municipality to parish), due to a detail of input data, it is possible to consider urban systems, with finer grid cells and taking into account other parameters as weighting factors like built-up areas, roads typology or population fluctuation (e.g. Keiler, 2004; Reibel and Bugalino, 2005; Freire and Aubrecht, 2012; Fuchs et al., 2013).

In this framework, the major aim of this work is to present a methodology to assess population exposed to landslides increasing the population resolution over large areas, based on a detailed landslide susceptibility map (pixel 5 m), the national official statistics, and a simple building limits layer. This can be considered as an intermediate, and quickly approach between coarser assessment (e.g. parish level) and local time-consuming detailed approaches. Additionally, the differences on people exposure are assessed by comparing a more traditional approach (considering population per statistical unit) and using a dasymetric distribution of population by building. The present study is applied on the Alenquer river basin which is located in the North of Lisbon region (Portugal). In the last decades the urban sprawl and better accessibilities in turn off Lisbon metropolitan area led to an occupation of former agricultural areas which are landslide prone areas.

2 Study area

The study area is the Alenquer river basin (120 km^2), which is located north of Lisbon (Fig. 1). The elevation ranges from 20 to 375 meters and the major landforms are hills and fluvial valleys, which are strongly controlled by differences in resistance and plasticity of the bedrock, such as sandy-marl (particularly prone to rotational landslides), sandstone and limestone. Field work and aerial photo interpretation allow identifying and mapping 136 rotational slides (0.98 landslides/km^2) that generated a total unstable area of 663,508 m^2 (0.56 % of the study area).

Concerning human occupation, the study area has 15,253 inhabitants (Census 2011) that area mainly concentrated in the Alenquer village located in the SE sector of study area.)The population is also present in scattered small “villages”, where agriculture is the dominant activity. Cadastral cartography and field work allows to identify over 6,889 residential buildings that were considered in this work. Considering the Basic Census Unit (BCU), that is the highest Census spatial resolution available for population data, the area is covered by 676 BCU with huge ranging surfaces (minimum: 280 m^2; mean: 176,100 m^2; maximum: 4,4 km^2). The mean BCU population is 26 inhabitants (not considering the 10 % BCU that have no inhabitants) and the maximum population per BCU is 357 inhabitants.

3 Data and methodology

The most detailed public information about population available in Portugal comes from national census Basic Census Unit (BCU), which smaller territorial units correspond to city blocks. However, these units are inhomogeneous in space, and consequently in number of buildings and inhabitants, namely in rural areas or transition areas between urban and rural.

The assessment of spatial distribution of population considering a conventional statistical terrain unit (BCU) and a dasymetric population distribution follows three main steps (Fig. 2):

(i) the landslide susceptibility assessment for two spatial units (pixels and BCU);

(ii) the evaluation of population density considering two different spatial entities (BCU and target zones within BCU);

(iii) the calculation of potential exposed inhabitants per landslide susceptibility class based on spatial entities referred in (ii).

3.1 Landslide susceptibility

Landslide susceptibility was assessed on a pixel base by the application of the Information Value method (Yin and Yan, 1988), which is a Bayesian bivariate statistical model that has been shown to be suitable for landslides susceptibility assessment (e.g. Piedade et al., 2011; Guillard and Zêzere, 2011, Pereira et al., 2012; Oliveira et al., 2015 and references therein) being recommended as a method for data-driven landslide susceptibility assessment worldwide (Corominas et al., 2014). Landslide inventory was based on field work and interpretation of aerial proto interpretation with 0.5 m resolution. The landslide database includes only deep rotational slides (rupture surface deeper than 3m) was divided in two independent groups, one for modelling landslide susceptibility, and other for independent validation of landslide susceptibility models based on a temporal criteria. The landslide modelling group includes all the rotational slides that occurred until the regional landslide event of march 2010 (Zêzere and Trigo, 2011) (104 cases) and the landslide validation group includes all the rotational slides that occurred during that landslide event (32 cases).

Six landslides predisposing factors were use as independent variables: slope, lithology, land use, inverse of wetness index, morphostructural units, soil type. Lithology, soil type and land use were based on national official cartography at 1:25 000 scale. The slope and the inverse of wetness index were derived from a digital elevation model (DEM) built on a 5 m contours topographical map. The morphostructural units map was obtained by combining the aspect map derived from the DEM with information on dipping direction of lithological layers obtained from geological maps and field work.

The susceptibility model was further validated using success and prediction rate curves (Chung and Fabbri, 2003, 2008) and calculating the area under the curve (AUC) (Sweets, 1988).

The final susceptibility model was made with a 5 m resolution and was classified using five quantile classes, i.e. each landslide susceptibility class includes 20 % of the study area. In a subsequent step the classified pixel-based landslide susceptibility map was overlaid to the BCU map (vector structure), and the landslide susceptibility classification attributed to each BCU was defined according to the majority landslide susceptibility class represented in the BCU.

3.2 Population exposure

The potential exposed population to landslide risk was assessed using two approaches: (1) considering the population presented within each BCU; and (2) distributing population d by the residential buildings within each BCU using dasymetric cartography.

Dasymetric cartography is a classic approach (Wright, 1936) that has been recently recovered as analytical tool based on Geo graphical Information Systems (e.g. Eicher and Brewer, 2001; Mennis and Hultgren, 2006). The dasymetric cartography use ancillary information to turn into a finer resolution coarser input data. A set of target zones should be defined and then based on areal interpolation or other weighting algorithms disaggregate data, estimating, for example, population in a set of smaller units based on a known amount of population for the global unit (e.g. Flowerdew and Green, 1992; Langford and Unwin, 1994; Mennis, 2003; Wu et al., 2008; Su et al., 2010; Tapp, 2010; Holt et al., 2013). In this work the dasymetric approach was anticipated by a binary analysis over residential building/not residential building areas (Fig. 3).

Thus, the first step is the definition of target zones. In this work a layer with the limits of residential buildings was used. Maantay and Maroko (2009), compared three different disaggregation methods, and identified the cadastral-based one (tax lot) as the best approach to a realistic population distribution/location. By overlaying BCU and buildings layer (both in a vector structure) it is possible to identify in each statistical unit the potentially inhabited places (target zones).

Considering the target zones and the BCU, the population density was calculated. To compare the obtained results within BCU and target zones, density maps were classified accordingly to standard deviation method.

The second step is the weighting of each target zone (Eq. 1), i.e. the importance of each building (W_{tzi}) inside a specific BCU:

$$W_{tzi} = w_{j1} \times w_{j2} \times \ldots \times w_{jn} \qquad (1)$$

where w_j are the parameters used as proxies to weight each target zone, as for example, for each building polygon the surface, number of residential floors, number of bedrooms, occupation rate, among others.

In the present work once the available data in Census (2011) is aggregate at BCU level and the ancillary cadastral information (building) has only the outline of each individual house just one weighting parameter was considered, the area of the building.

The third step is the dasymetric distribution of the population in each polygon of target zones (P_{tzi}) as show in Eq. 2 (adapted from Su et al., 2010):

$$P_{tzi} = \frac{P_t \times W_{tzi}}{\sum_{i=1}^{n} W_{tzi}} \qquad (2)$$

where W_{tzi} is the weight of each target zone in the BCU and P_t is total population in the BCU. This procedure is applied independently to all BCU to distribute the population among the buildings present in each terrain unit. After disaggregation the total number of inhabitants per BCU is maintained.

The last step is the assessment of the number of people exposed in each susceptibility class. In the case of BCU as terrain units, the assessment is direct because each BCU is classified within a single landslide susceptibility class (Sect. 3.1). In the case of target zones (buildings) as terrain units, each building can be covered by more than one landslide susceptibility class. In these cases it was necessary to convert the target zones from vector to a grid structure, coincident with the 5 m resolution susceptibility map. The population in each building is then equally distributed among the pixels that compose that building. For example, a 100 m2 building (converted in 4 pixels of 5 per 5 meters) that has 8 inhabitants will have in the final population distribution 2 inhabitants in each pixel.

4 Results

Figure 4 show the obtained landslide susceptibility maps applied in a pixel based map (a) and in a BCU vector structure based map (b) according to the dominant susceptibility class inside each BCU. The visual agreement between both maps is evident although the homogenization of the susceptibility classes per BCU leads to an increase of about 8% of the area classified with very high susceptibility. However, if the three highest susceptible classes are combined their overall representation remains equal to the pixel map model (60 % of the total study area).

The validation of the landslide susceptibility map (pixel unit) presents acceptable results with a 0.76 AUC for the success rate curve and 0.78 AUC for the independent validation with the prediction rate curve.

When evaluating population densities the use of different spatial units (BCU and BCU built-up area) shows, as expected, considerable differences (Fig. 5). In fact, if a common approach is adopted and BCU are classified accordingly to their overall area (population density per BCU area), density values (mean: 0.002 inhabitants/m2; SD: 0.003) are around one order of magnitude lower when compared with results obtained considering only the built-up area (population density per BCU residential building area) (mean: 0.011 inhabitants/m2; SD: 0.009). Additionally Fig. 5 shows that whereas in high building density terrain units (blue outline squares example), the registered population density hierarchy remains similar in maps (a) and (b); in rural terrain units (red outline squares example) differences can be considerable (more than two standard deviations in the presented example).

This is important in areas as the study case where the majority of BCU (73 %) have a residential built-up area under 20 %, which means that the use of total BCU area underestimate the population density.

Figure 6 shows the obtained results for the three highest landslide susceptible classes considering the population presented within each BCU (approach 1) and distributed by the residential buildings using dasymetric cartography (approach 2). It is clear that the number of exposed inhabitants considerably change depending on the method used to estimate population. The approach 1 systematically generates a higher number of inhabitants (4465, 29% of total inhabitants) in the considered landslide susceptibility classes when compared with approach 2 (1926, 13% of total inhabitants). The difference is equivalent to 132%, which means that 2539 inhabitants are overestimated when using approach 1. prone areas.

5 Discussion and conclusion

In this work, two different approaches were used to evaluate people exposed to landslide hazard in a test site located north of Lisbon (Portugal). The consideration of the total population per BCU, not accounting the building environment (approach 1) implies the generalization of the landslide susceptibility map from the raster structure to the BCU terrain unit. On contrary, the approach 2 that considers target zones (buildings) within each BCU enable the use of the original landslide susceptibility map with a 5m pixel.

In fact, surely part of the difference of 132% of exposed population from approach 2 to approach 1 is due to the generalization process of landslide susceptibility by BCU, which can generate an over- or underestimation of the total area of each susceptibility class. As a consequence, the classification of the same building can be very diverse in the two produced landslide susceptibility maps (pixel-based and BCU-based) (Fig. 7). In some few cases a building located in a very high susceptibility class in the pixel-based map is classified as very low susceptibility in the BCVU-based map, due to large spatial expression of that class within the BCU terrain unit (Fig. 7b'). In the majority of cases, a building located in a very low susceptibility class in the pixel-based map is classified as very high susceptibility in the BCVU-based map (Fig. 7a'), thus overestimating the exposure to landslide hazard.

The use of the majority class, as classification method, in the BCU susceptibility map is a source of error that tends to overestimate exposure of buildings and indirectly exposure of inhabitants. An analysis should be done to the previous classification of the susceptibility map (in pixel structure) to ensure that the obtained differences are not due to the considerable changing area of the landslide susceptibility classes. However, independently of the previous tests this kind of approach has always a huge degree of generalization once it assumes that all spatial units are homogeneous in terms of landslide susceptibility.

The approach 2 does not require the generalization of landslide susceptibility and this is a major advantage of the method. The approach 2 is a user-friendly methodology that allows improving the accuracy of population spatial distribution and the evaluation of the number of inhabitants exposed to a hazardous phenomenon. Besides the abovementioned advantage, the use of dasymetric approach for the population distribution reveals two additional advantages: (i) the increasing of population resolution which allows a more detailed evaluation of the number of inhabitants potentially affected by a hazardous event; and (ii) the location of people is confined to a territory (buildings) that present physical limits (not administrative) that can be easily recognized by those responsible for civil protection planning and emergency management, which is not the case when the analysis is performed in a grid cell-based map.

However, some uncertainties related to the dasymetric population distribution are present, generally associated to three main assumptions that have to be adopted: (i) the building area was considered as the only proxy of the number of people inhabiting per building; (ii) people inside buildings have a homogeneous distribution; and (iii) people are inside the buildings.

In fact, equal building areas can have different number of bedrooms, different number of floors or floors with different uses (e.g. residential or commercial) and consequently a potentially different number of inhabitants, which is probably the major cause of uncertainty of the present study. However, in this study, 96% of the buildings are in the same class considering the number of floors (1-2), and buildings with higher number of floors are located in urban areas where the size of the BCU is smaller and homogeneous. Therefore we are confident that the achieved overall population distribution values are representative of the reality in the study area. This approach, even considering some uncertainties related to people distribution inside buildings, particularly in the more susceptible zones is definitely closer to reality than when considering the total population coming from BCU (the finest public population information available), once the susceptibility in BCU units is far from homogeneity.

The homogeneous distribution of people inside the buildings is another source of uncertainty not explored in this study due to lack of data. Additionally the temporal component of people mobility inside each building, for example, day or night, was not considered. Moreover, the available population data do not take into account the daily fluctuation to work, school or other activities outdoor. Nonetheless, in this specific area daily or seasonal fluctuations are not significant, as for example in Lisbon (Freire and Aubrecht, 2012).

Although the existing uncertainty in this work due to people are considered to be at home, Pereira et al. (2015) found that, in Portugal in the period 1865-2010, the majority of landslide fatalities occurred with people indoor (60%) whereas 40% occurred outdoors or inside a transportation vehicle.

Lastly, despite we have obtained good results, these may still be improved if other ancillary information is available, as the number of floors per building, floating population (day/night, summer/winter, employment), transport data, among several others, to better characterize the population distribution.

From the point of view of a general cost-benefit analysis, the Census data (available and free of charge in Portugal) and the digital maps with building limits (available or easily acquirable by digital image interpretation), as ancillary information to dasymetric mapping approach prove to be a good option to increase population distribution resolution at the regional/municipal scale and it can be considered as a first approach to better identify locals where future detailed surveys should be developed. Additionally it allows fast, partial (per BCU) or global, upgrades every time new information is provided about population, buildings or landslide susceptibility.

Author contribution

R.A.C. Garcia and S.C. Oliveira performed field work for landslide inventory and cartography data base validation. Cartographical and statistical input data, susceptibility modelling and dasymetric cartography adaptation were done by R.A.C. Garcia that prepared the manuscript with contributions from all co-authors (that supervised all the work development)

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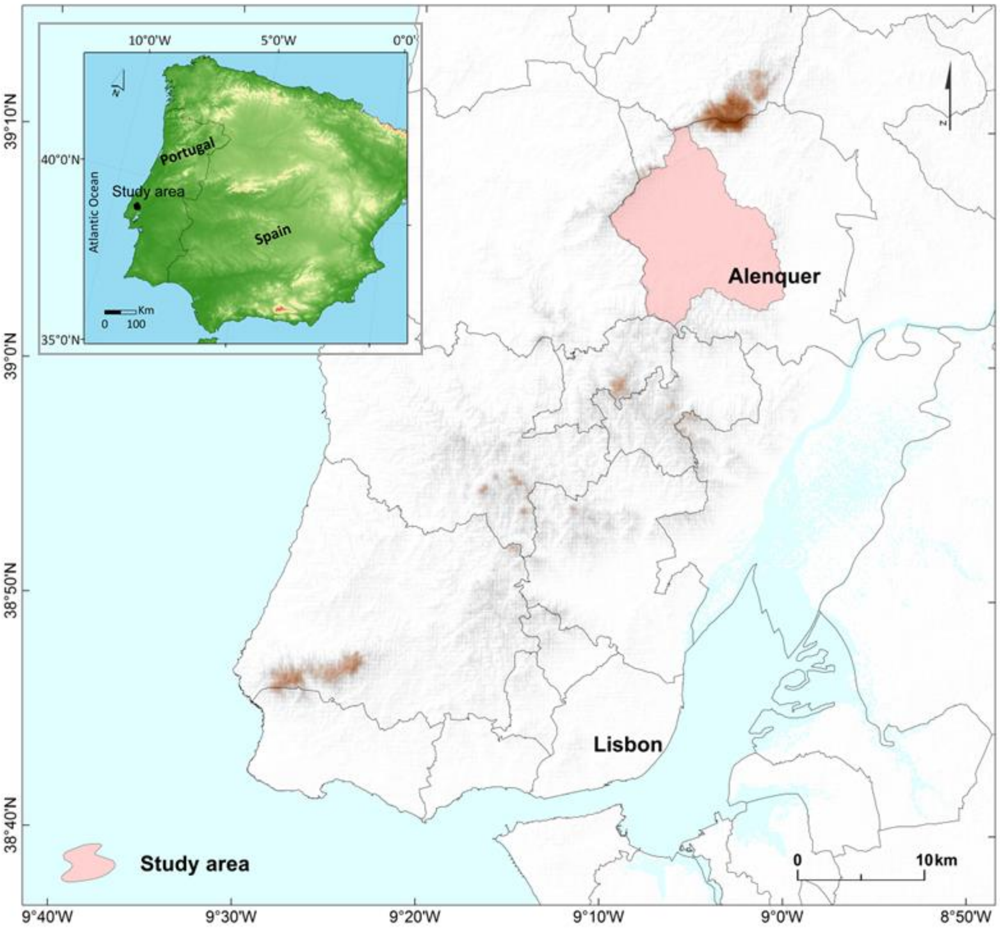

Figure 1: Location of Alenquer study area.

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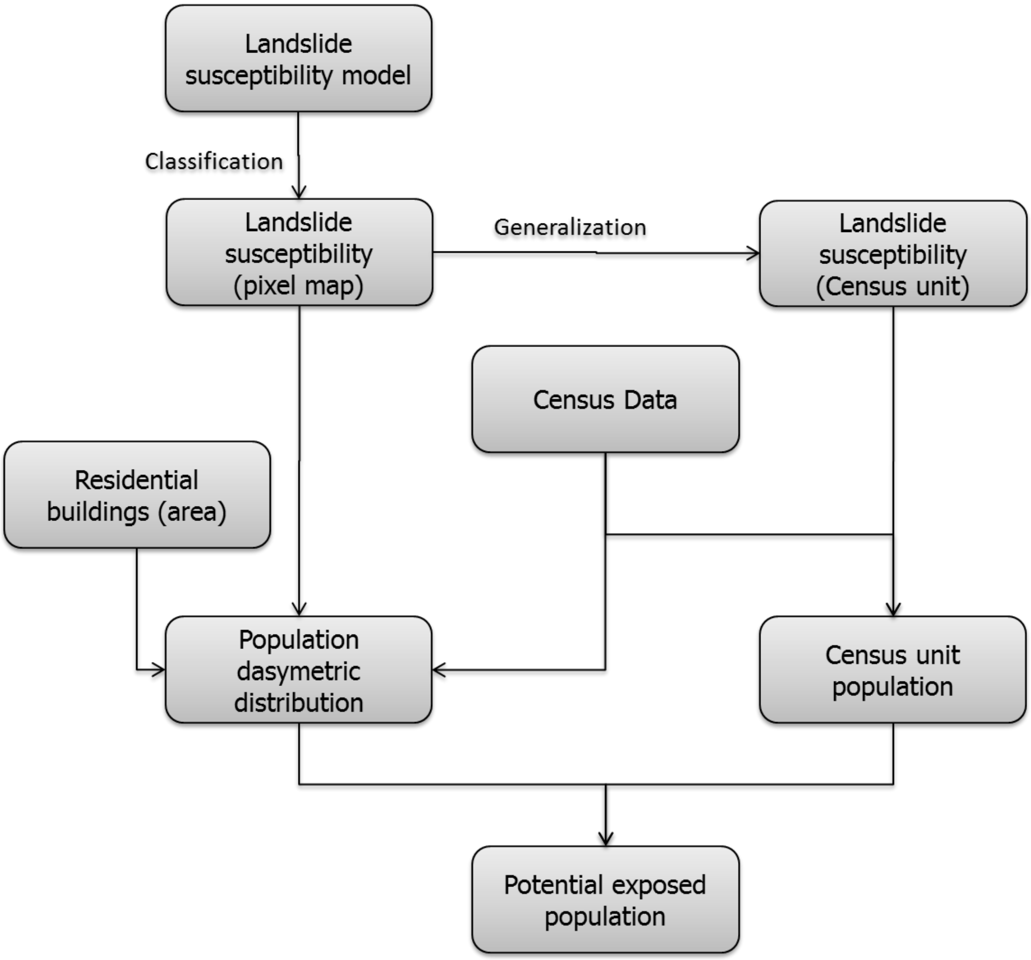


Figure 2: General methodological work flow.

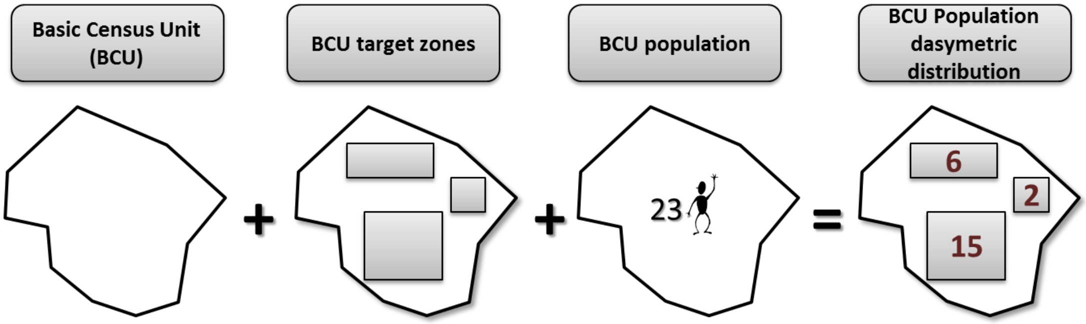


Figure 3: Schematic dasymetric evaluation of population based on target zone area

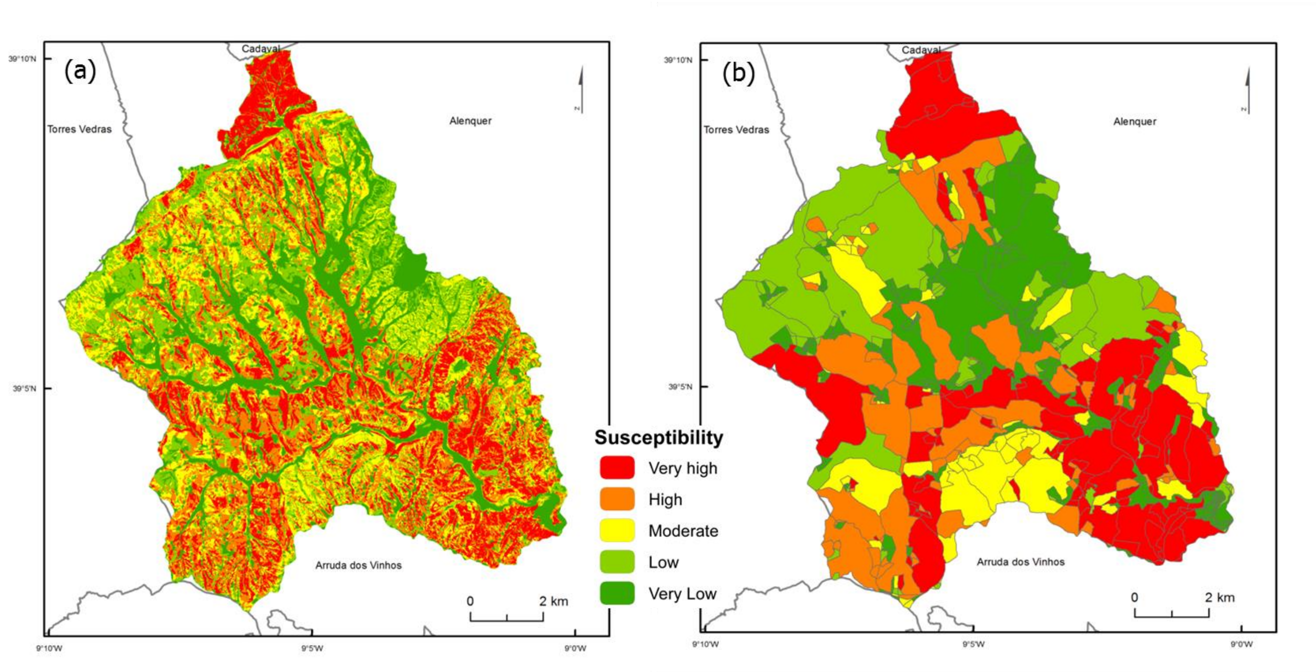


Figure 4: Rotational slides susceptibility maps in Alenquer study area: (a) pixel unit, (b) Basic Census Unit.

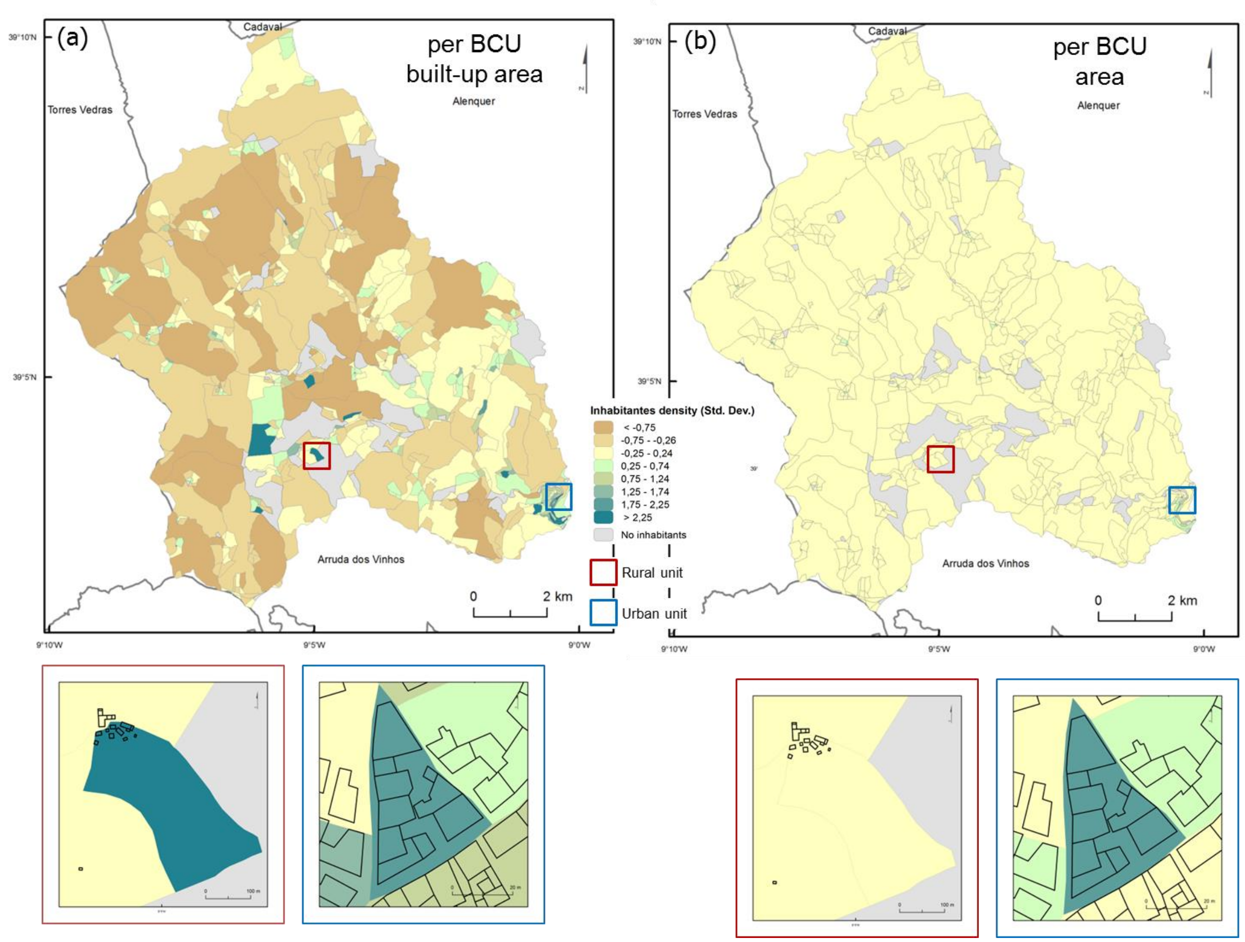
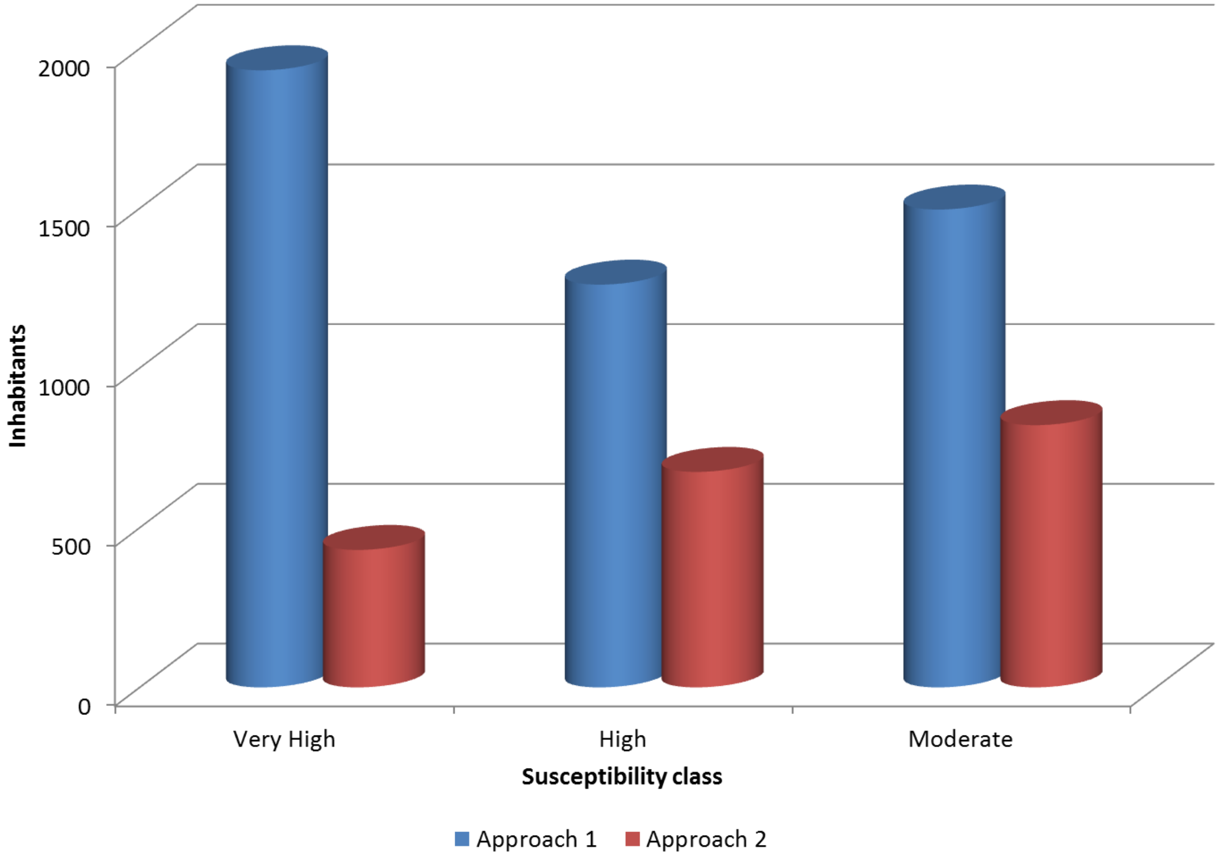


Figure 5: Population density in Alenquer study area: (a) per BCU built-up area, (b) per BCU overall area. To facilitate visualization, the classification of target zones in map (a) was extended to the complete BCU



5 **Figure 6: Potential exposed population in Alenquer study area considering BCU population (Approach 1) and BCU population per building (Approach 2).**

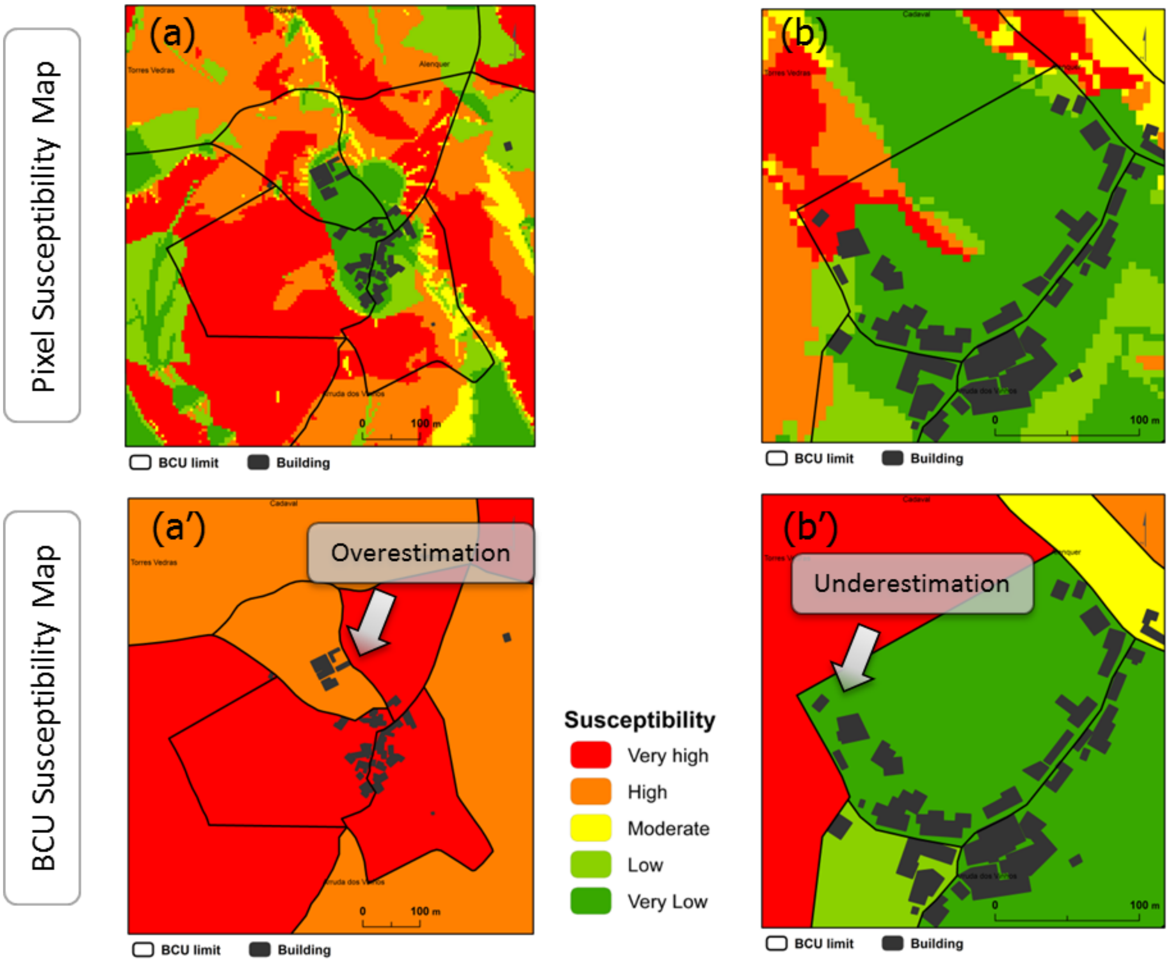


Figure 7: Examples of over- and underestimation of exposed buildings in Alenquer study area considering a pixel susceptibility map or a BCU susceptibility map.