UNIVERSIDADE DE LISBOA

Instituto de Geografia e Ordenamento do Território

Vulnerability Assessment and Landslide Risk Analysis. Application to the Loures Municipality, Portugal

Clémence Guillard-Gonçalves

Orientador: Prof. Doutor José Luís Gonçalves Moreira da Silva Zêzere

Tese especialmente elaborada para a obtenção do grau de Doutor em Geografia, especialidade de Geografia Física.

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Preamble

The three chapters of the thesis are the full contents of three papers which were published in different ISI indexed peer reviewed journals. That is why the written English (American English or UK English) may vary from one to the other. In order to ease the reading, the format was harmonised and figures and tables were renumbered.

My contribution to the three papers is:

- Chapter 1: *Guillard, C. and Zezere, J.: Landslide susceptibility assessment and validation in the framework of municipal planning in Portugal: the case of Loures Municipality., Environ. Manage., 50(4), 721–735, doi:10.1007/s00267-012-9921-7, 2012.*

The inventory of the 313 landslides coming from the interpretation of orthophotomaps and the inventory of the 70 landslides coming from the stereoscopical interpretation of aerial photographs were made by myself, as well as the differentiation of the depletion and accumulation zones, following the advice of José Luís Zêzere and an anonymous reviewer. I applied the Information Value Method, plotted the success and prediction rate curves and gathered the most susceptible zones which integrated the National Ecological Reserve. I interpreted and discussed the results together with my co-author.

- Chapter 2: *Guillard-Gonçalves, C., Cutter, S. L., Emrich, C. T. and Zêzere, J. L.: Application of Social Vulnerability Index (SoVI) and delineation of natural risk zones in Greater Lisbon, Portugal, J. Risk Res., 18(5), 651–674, doi:10.1080/13669877.2014.910689, 2015.*

I chose the study area, selected the 46 socioeconomic variables, ran the correlations, applied the Principal Component Analysis, selected and interpreted the principal components and mapped the SoVI following the advice of Susan Cutter and Chris Emrich. I elaborated the total susceptibility map, the risk zones map and the exposed population map on the advice of José Luís Zêzere. I elaborated the matrix for delineation or risk zones and I interpreted and discussed the results together with my co-authors.

- Chapter 3: *Guillard-Gonçalves, C., Zêzere, J. L., Pereira, S. and Garcia, R. A. C.: Assessment of physical vulnerability of buildings and analysis of landslide risk at the municipal scale – application to the Loures municipality, Portugal, Nat. Hazards Earth Syst. Sci., 16(2), 311–331, doi: 10.5194/nhess-16-311-2016, 2016.*

Following the advice of José Luís Zêzere, I elaborated a questionnaire, sent it to more than 300 European landslide experts and interpreted the answers. I listed all the buildings of the test site during field work. I created a map with the Location Coefficient based on the one of the Portuguese Tax Services. I applied the Information Value Method to the deep-seated slides inventory and I calculated the probability of occurrence of the deep-seated and shallow slides. I mapped the vulnerability, the standard deviation, the value of the buildings and the risk. I interpreted and discussed the results together with my co-authors.

Aknowlegments

I would like to thank all the persons who contributed to the realization of this work.

Among them, I specially thank my advisor the Professor José Luís Zêzere for his support, his recommendations and his availability.

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I thank the members of the RISKam team, and especially Susana Pereira, Ricardo Garcia, Sérgio Oliveira, Raquel Melo, Teresa Vaz, Cristina Henriques, Aldina Piedade and Jorge Rocha for their advice and friendship.

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Abstract

The present study aims to develop a method for assessing the landslide vulnerability at the municipal scale which supports the landslide risk analysis.

Three susceptibility assessments to deep-seated rotational and translational slides and to shallow slides in the Loures municipality are presented in the first chapter. A bivariate statistical method called Information Value Method was used to cross the 686 inventoried landslides with seven predisposing factors (slope angle and aspect, plan slope curvature, inverse of the topographic wetness index, geology, soil types and land use). The accuracy and the robustness of the models were assessed by success and prediction-rate curves. The 20.3% of the municipality where 70% of the future landslides should occur according to the susceptibility models were selected to be included in the National Ecological Reserve.

The second chapter presents a study of the social vulnerability of the 149 civil parishes of the Greater Lisbon. The method used is the Social Vulnerability Index (SoVI) method, which consists in selecting socioeconomics variables, removing the auto-correlated variables and applying a Principal Component Analysis (PCA). The seven principal components resulting from the PCA were interpreted and the SoVI values were classified based on standard deviation. The risk delimitation was effectuated by combining the SoVI map with the susceptibility maps of the main natural hazards which threaten the Greater Lisbon (earthquakes, floods, flash floods, landslides, tsunami, and coastal erosion). The exposition of the population was finally considered by combining the number and location of the residents with the risk zones map.

The third chapter shows a physical vulnerability assessment of the Loures municipality buildings for different landslide magnitudes. The average of the vulnerability attributed by a pool of European landslide experts and by a sub-pool of landslide experts who know the study area on the basis of the structural type of the buildings was used. The variability of the answers was assessed by standard deviation calculation. Then, the economic value of the buildings was assessed based on the Portuguese Tax Services approach. In addition, the landslide hazard was calculated by combining the landslides spatiotemporal probability and their frequency-magnitude relationship. Finally, the landslide hazard was combined with the vulnerability and the value of the buildings in order to obtain the landslide risk.

In the conclusion section, the social vulnerability and the physical vulnerability of the Loures municipality were combined twice. First, the considered social vulnerability was extracted from the second chapter results; its scale is the civil parish scale. Second, a new social vulnerability assessment was made at the basic geographic entity (BGRI) scale. Finally, the landslide risk was analysed considering the total vulnerability provided by the combination of the physical vulnerability and the new social vulnerability assessment, the landslide susceptibility, the exposition of the population and the economic value of the buildings.

Keywords: Landslide susceptibility, social vulnerability, physical vulnerability, landslide risk.

Résumé

La présente étude a pour but de développer une méthode d'évaluation de la vulnérabilité à l'échelle municipale qui servirait de base à une évaluation de risque de glissements de terrain.

Trois évaluations de la susceptibilité aux glissements de terrain plans et rotationnels profonds et aux glissements de terrain superficiels de la municipalité de Loures sont présentées dans le premier chapitre. Une méthode statistique bivariée appelée Méthode des Valeurs Informatives a été utilisée pour croiser les 686 glissements de terrain qui ont été inventoriés au sein de la municipalité de Loures avec sept facteurs de prédisposition (inclinaison et orientation des pentes, concavité/convexité des pentes, inverse du *topographic wetness index*, géologie, types de sols et occupation du sol). La justesse et la robustesse des modèles ont été évaluées par des courbes de réussite et de prévision. Les 20,3% de la municipalité où les 70% des futurs glissements devraient avoir lieu ont été sélectionnés pour intégrer la Réserve Écologique Nationale.

Le deuxième chapitre présente une évaluation de la vulnérabilité sociale au sein des 149 paroisses civiles de la Grande Lisbonne. La méthode utilisée est l'Indice de Vulnérabilité Sociale (SoVI), qui comprend une sélection de variables socioéconomiques, le retrait des variables corrélées et l'application d'une Analyse en Composantes Principales (ACP). Les sept composantes principales qui proviennent de l'ACP ont été interprétées et les valeurs de SoVI ont été classées sur la base des écarts types. La délimitation du risque a été effectuée en associant la carte de SoVI avec la carte de susceptibilité des principaux aléas naturels qui menacent la Grande Lisbonne (séismes, inondations, crues éclaires, mouvements de terrain, tsunami et érosion côtière). Enfin, l'exposition de la population a été prise en compte par la superposition du nombre d'habitants et de leur lieu de résidence avec la carte des zones de risque.

Le troisième chapitre montre une évaluation de la vulnérabilité physique des bâtiments de la municipalité de Loures associée à des glissements de terrain de différentes magnitudes. La moyenne de la vulnérabilité attribuée par un groupe d'experts européens et par un sous-groupes d'experts qui connaissent la zone d'étude et qui se base sur le type de structure des bâtiments a été utilisée. La variabilité des réponses a été évaluée par le calcul des écarts types. Puis, la valeur **éc**onomique des bâtiments a été calculée en se basant sur l'indice de calcul des Services de Taxes Portugais. De plus, l'aléa glissements de terrain a été associé à la vulnérabilité et à la valeur des bâtiments pour obtenir le risque de glissements de terrain.

Dans la section de conclusion, la vulnérabilité sociale et la vulnérabilité physique de la municipalité de Loures ont été réunies en considérant deux approches différentes. Lors de la première approche, la vulnérabilité sociale considérée a été extraite des résultats provenant du deuxième chapitre ; elle est à l'échelle de la paroisse civile. Lors de la deuxième approche, une nouvelle évaluation de la vulnérabilité sociale a été effectuée à l'échelle de l'entité géographique de base (BGRI). Finalement, le risque de glissements de terrain a été analysé considérant la vulnérabilité totale provenant de l'association de la vulnérabilité physique et de la nouvelle évaluation de la vulnérabilité sociale, de la susceptibilité aux glissements de terrain, de l'exposition de la population et de la valeur économique des bâtiments.

Mots-clefs : Susceptibilité aux glissements de terrain, vulnérabilité sociale, vulnérabilité physique, risque de glissements de terrain.

Resumo

A presente tese de doutoramento pretende aprofundar a avaliação da vulnerabilidade a deslizamentos e a análise do risco de deslizamentos à escala municipal. O risco é considerado como sendo o produto da perigosidade, da vulnerabilidade e do valor dos elementos em risco. A principal área de estudo corresponde ao município de Loures (169,3 km²), situado na região a norte de Lisboa (Portugal).

No primeiro capítulo é aplicada uma metodologia para avaliar a suscetibilidade a deslizamentos, numa perspetiva de aplicação prática ao nível municipal. A suscetibilidade a deslizamentos é a expressão da propensão da ocorrência do deslizamento numa área dada, com base em características do terreno, não considerando o período do retorno ou a probabilidade de ocorrência dos fenómenos de instabilidade. A sua avaliação é baseada no princípio que os deslizamentos futuros têm uma probabilidade de ocorrência mais elevada sob circunstâncias similares àquelas que determinaram a instabilidade passada e presente. Um inventário de 686 deslizamentos que ocorreram no município de Loures entre 1967 e 2004 foi elaborado a partir de três fontes: (1) 313 deslizamentos foram derivados da interpretação de ortofotomapas digitais pormenorizados (pixel = 0.5 m), combinados com a representação detalhada da elevação do terreno (curvas de nível espaçadas a cada 5 m); (2) 70 deslizamentos resultaram da leitura estereoscópica de fotografias aéreas obtidas em 1983 na sequência de um evento chuvoso intenso que desencadeou muitos deslizamentos na região a Norte de Lisboa; (3) 303 deslizamentos resultaram de um inventário efetuado em 1996 por Zêzere (1997) em duas zonas do município de Loures a partir de ortofotomapas e foram validados no terreno por trabalho de campo. O inventário total foi separado em três grupos para elaborar três modelos de suscetibilidade de acordo com os tipos de deslizamentos (rotacionais, translacionais profundos e translacionais superficiais). Para a avaliação da suscetibilidade a deslizamentos, assume-se que a distribuição espacial dos deslizamentos futuros pode ser prevista através de relações estatísticas entre os deslizamentos passados e um conjunto de fatores de predisposição da instabilidade geomorfológica; neste estudo, o declive, a exposição e a curvatura das vertentes, o inverso do *wetness index*, a geologia, os tipos de solo, e o uso do solo foram selecionados. A suscetibilidade é avaliada usando algoritmos baseados numa análise estatística bivariada (Método do Valor Informativo) sobre unidades de terreno de condição única, numa base matricial. A robustez e a exatidão dos modelos de suscetibilidade criados foram validadas pela construção de taxas de sucesso e de predição. A legislação que exige a avaliação da suscetibilidade a movimentos de massa em vertentes em Portugal a nível municipal é a Reserva Ecológica Nacional (REN). As zonas mais suscetíveis foram extraídas a partir dos três mapas de suscetibilidade, e os resultados obtidos permitem concluir que 70% dos futuros deslizamentos devem ocorrer em 20,3% da área total do município classificadas como mais suscetíveis a deslizamentos. Deste modo, a inclusão desta área mais suscetível na REN poderá potencialmente reduzir os danos resultantes de 70% dos futuros deslizamentos no município de Loures.

As metrópoles são altamente vulneráveis aos perigos, pela concentração de população, de infraestruturas críticas e de atividades económicas. Em Portugal, muitos serviços são centralizados na Grande Lisboa, onde 19% da população total vive em apenas 1,5% do território (1376 km^2). O segundo capítulo apresenta um estudo que tem como objetivo aprofundar a avaliação dos riscos naturais na Grande Lisboa, através de uma abordagem multirriscos. Em primeiro lugar foi avaliada a vulnerabilidade social das 149 freguesias da Grande Lisboa, onde se integram as 18 freguesias do município de Loures. Com efeito, a avaliação da vulnerabilidade das populações pode ajudar os responsáveis do planeamento da emergência a perceber quem é vulnerável a desastres naturais, para

que possam preparar uma evacuação realista e eficaz e procedimentos de resposta para os indivíduos expostos ao risco. O método de avaliação que foi utilizado e adaptado ao contexto português é o SoVI (Índice de Vulnerabilidade Social). Deste modo, numa primeira fase foram escolhidas 46 variáveis socioeconómicas, e 38 delas foram mantidas, depois de aplicar testes de auto-correlação. As 38 variáveis não-correlacionadas foram estandardizadas e uma Análise em Componentes Principais (ACP) foi aplicada, seguida de uma rotação Varimax. Sete fatores que resultaram da ACP e que explicam 79.5% da variância foram extraídos usando o critério de Kaiser. Cada fator foi interpretado e um sinal foi atribuído tendo em consideração se o fator é responsável pelo incremento ou pela diminuição da vulnerabilidade social. O SoVI foi calculado somando os fatores e foi mapeado utilizando uma classificação baseada na média e desvio padrão dos resultados obtidos. Doze das 149 freguesias da Grande Lisboa foram classificadas como tendo uma vulnerabilidade social muito elevada, e 24 como tendo uma vulnerabilidade social elevada. O mapa de SoVI foi combinado com o mapa de suscetibilidade a perigos que ameaçam a Grande Lisboa (sismos, cheias rápidas e progressivas, movimentos de vertentes, tsunami e erosão costeira), o qual foi baseado nos trabalhos elaborados no âmbito da revisão do Plano Regional de Ordenamento do Território da Área Metropolitana de Lisboa (PROT-AML). As zonas de risco foram traçadas a partir do cruzamento dos mapas de SoVI e de suscetibilidade total, permitindo assim destacar as áreas que necessitam de uma atenção especial em termos de planeamento de emergência. Vinte e duas freguesias da Grande Lisboa têm um risco muito alto, cujas 17 fazem parte do município de Lisboa, quatro do município de Loures e uma do município de Vila Franca de Xira. Finalmente, a população da Grande Lisboa foi considerada e combinada com o mapa das zonas de risco, dando informações sobre o número e a localização dos residentes expostos aos riscos naturais considerados.

O terceiro capítulo apresenta uma avaliação da vulnerabilidade física dos edifícios do município de Loures a deslizamentos. O risco de deslizamentos foi calculado como sendo o produto da perigosidade, da probabilidade de magnitude dos deslizamentos, da vulnerabilidade física e do valor económico dos edifícios. Em primeiro lugar, a perigosidade foi avaliada combinando a probabilidade espaciotemporal e a relação de frequência-magnitude dos deslizamentos. Dois modelos de suscetibilidade a deslizamentos profundos e superficiais foram obtidos pela aplicação do Método do Valor Informativo. As probabilidades anuais e plurianuais foram estimadas, fornecendo um modelo de perigosidade a deslizamentos. Em segundo lugar, uma avaliação da vulnerabilidade dos edifícios a deslizamentos foi desenvolvida e aplicada ao município de Loures, com base num inquérito feito a um grupo de peritos europeus em deslizamentos. O inquérito foi baseado em nove cenários de magnitudes e quatro tipos de estrutura de construção. Um subgrupo de peritos em deslizamentos que conhecem a área de estudo foi extraído do primeiro grupo de peritos europeus, e a variabilidade das respostas provenientes do primeiro grupo e do subgrupo foi avaliada com base no desvio padrão. Além disso, a vulnerabilidade média das entidades geográficas básicas (BGRI) foi comparada pela mudança da unidade de mapeamento e aplicando a vulnerabilidade a todos os edifícios de uma zona de teste que faz parte do município de Loures, cujo inventário foi efetuado através de trabalho de campo. Em seguida, o valor económico dos edifícios foi calculado usando uma adaptação da fórmula utilizada pelos Serviços Fiscais Portugueses. Finalmente, o risco anual e plurianual de deslizamentos foi calculado para os nove cenários de diferentes magnitudes de deslizamentos e as diferentes probabilidades espaciotemporais, multiplicando a perda potencial (Vulnerabilidade × Valor Econômico) pela probabilidade de perigo. Em regra, os valores de vulnerabilidade dados pelo subgrupo de peritos que conhecem a área de estudo são superiores aos indicados pelos peritos europeus, nomeadamente para os deslizamentos de grande magnitude. As vulnerabilidades obtidas variam de 0,2 a 1 em função dos tipos de estrutura de construção e da magnitude dos deslizamentos, e são máximas para deslizamentos de 10 e 20 metros de profundidade. No entanto, o risco anual mais

elevado foi encontrado para os deslizamentos de 3 metros de profundidade, com um valor máximo de 25,68 € por pixel de 5 metros, porque estes deslizamentos combinam uma frequência relativamente alta no concelho de Loures com um dano potencial substancial.

Na seção de conclusão, a vulnerabilidade social e a vulnerabilidade física do concelho de Loures foram combinadas através de duas abordagens. Na primeira abordagem, a vulnerabilidade social utilizada provem do segundo capítulo e respeita à escala da freguesia. Na segunda abordagem, uma nova avaliação da vulnerabilidade social foi feita à escala da BGRI. O risco de deslizamento foi finalmente analisado considerando a vulnerabilidade total obtida pela combinação da vulnerabilidade física e da nova avaliação da vulnerabilidade social à escala da BGRI, a suscetibilidade a deslizamentos, a exposição da população e o valor económico dos edifícios.

Em termos de aplicação, os modelos de suscetibilidade desenvolvidos no primeiro capítulo foram utilizados como base para a elaboração da REN no concelho de Loures. Isso significa que o município está ciente do perigo de deslizamentos. Além disso, exigências especiais em relação ao uso e transformação do solo (por exemplo, proibição de construção de habitação e de vias de comunicação) são aplicadas nas áreas que foram determinadas como sendo as mais perigosas pelos modelos de suscetibilidade e que integraram a REN. Os modelos de vulnerabilidade e de risco ainda não foram utilizados pelas partes interessadas, sendo certo que o mapeamento do risco proveniente do modelo de vulnerabilidade física desenvolvido no terceiro capítulo pode ser muito útil para as companhias de seguros, uma vez que considera em detalhe o valor económico dos edifícios. A proteção civil poderá estar mais interessada pelo modelo de vulnerabilidade total desenvolvido na secção de conclusão, para efeitos de planeamento de emergência. De facto, esta avaliação de vulnerabilidade fornece a localização da população mais vulnerável em grande escala, cruzada com os edifícios que têm uma alta vulnerabilidade física a deslizamentos de diferentes magnitudes.

Palavras-chave: Suscetibilidade a deslizamentos, vulnerabilidade social, vulnerabilidade física, risco de deslizamentos.

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Introduction

0. Introduction

Landslides affect exposed populations worldwide, causing damage, fatalities and injuries. In Portugal, their magnitude has been rarely high enough to cause injuries, although the DISASTER database lists 239 fatalities occurred in the period 1865-2010 (Pereira et al., 2015; Zêzere et al., 2014). In addition, landslides are quite frequent and have been responsible for damage on roads and buildings. These losses and the ensuing disruption of activities make landslides a major geomorphologic hazard in Portugal. Damage caused by landslides can be reduced with adequate policies and practices. For that, it is mandatory to assess landslide hazard and vulnerability to analyse the landslide risk in order to manage it.

0.1. The landslide disaster system

The term landslide refers to a downslope movement of soil, debris, rock, and/or organic materials driven by gravitational forces (Cruden, 1991; Highland and Bobrowsky, 2008). To better understand the effects that landslides may induce, they are usually classified by: (1) the type of movement (fall, topple, slide, spread, flow and slope deformation); (2) the type of affected material (e.g. rock, soil, earth, debris); and (3) the velocity of the moved material (which ranges from some millimetres per year to some metres per second) (Varnes, 1978; Cruden and Varnes, 1996; Hungr et al., 2013). The predisposing conditions and triggering mechanisms of slope failures are also important factors which must be considered for the landslides understanding. The triggering mechanism is usually associated to a natural event (e.g. rainfall, earthquake, snowmelt; stream erosion) but can also come from human activities (e.g. excavation during road building, excessive loading of a slope) (Highland and Bobrowsky, 2008). It also can be a combination of both, as it happened in Amadora (a municipality of the Greater Lisbon) in January 2010, when a large landslide triggered by rainfall affected a highway (A9 - CREL) embankment, the overloading of which having jeopardised its drainage and stability (TVI24, 2010). This huge landslide caused direct losses: some electricity poles were toppled (Fig. 0.1) and 600,000 m^3 of material had to be removed from the highway (Fig. 0.2) (Diario de Notícias 2010); as well as indirect losses: the affected part of the highway was not usable by drivers during three weeks in both directions and the highway remained partially closed in one direction during three more weeks (RTP Noticias 2010). The costs generated whether by the deposition removal or by the lack of money coming from the toll that was not paid during all this period were very elevated, and the drivers who used to travel by this highway lost time and money because of the deviation paths.

The consequences of a landslide can be diverse according to the landslide magnitude and the vulnerability and value of the exposed elements (also called elements at risk). The assessment of the potential damage (e.g. injuries, fatalities, destruction of buildings or infrastructures, loss of activity) that landslides can produce on a set of elements at risk is named landslide risk analysis (Bell and Glade, 2004). Analysing landslide risk means to define the risk (what could happen?), to calculate the frequency of the hazard (when could it happen?), to determine which are the elements at risk (who is threatened?), to evaluate the consequences (what is the intensity of the hazard? how vulnerable are the elements at risk?), and to assess the involved costs (Fell et al., 2005). Landslide risk analysis is the first step to assess the risk, which implies to fix a limit of risk acceptation. Then, risk assessment allows to manage the landslide risk, which implies the reduction of the risk through policies, procedures and practices (Bell and Glade, 2004; Fannin et al., 2005).

Fig. 0.1 - Damage caused by the landslide on the CREL embankment. *Source: Sérgio Cruz de Oliveira, CEG, IGOT, Universidade de Lisboa, 24/01/2010*

The landslide hazard, which is the spatial and temporal probability of a landslide occurrence, is usually the first step for a landslide risk analysis. Then, the vulnerability and the value of the elements at risk which are exposed to landslides have to be assessed, because the landslide risk is generally considered as the product of the landslide hazard, the vulnerability of the elements at risk and their values (e.g. Varnes and the International Association of Engineering Geology Commission on Landslides and Other Mass Movements, 1984; Cardinali et al., 2002; Uzielli et al., 2008). These concepts and their assessment are developed in the next subsections.

Fig. 0.2 - CREL interrupted by the landslide. *Source: Sérgio Cruz de Oliveira, CEG, IGOT, Universidade de Lisboa, 24/01/2010*

0.2. Landslide hazard

The landslide hazard expresses the probability of occurrence of a potentially damaging landslide event within a given area and in a given period of time (Varnes and the International Association of Engineering Geology Commission on Landslides and Other Mass Movements, 1984; Guzzetti et al., 1999; Glade, 2001). In addition, the landslide hazard assessment must include information on landslide types and magnitudes (Guzzetti et al., 1999; Bell and Glade, 2004; Jaiswal et al., 2010). Landslide magnitude refers to the intensity and potential destructiveness of a landslide (Guzzetti et al., 1999). The landslide destructiveness can be measured by the characteristics of the landslide, like the landslide area (Guthrie and Evans, 2007) or the landslide volume (Evans et al., 2007), or by the consequences generated by the landslide, like the number of fatalities (Guzzetti, 2000).

The assessment of the landslide hazard is based on the assessment of the susceptibility of the slopes. Indeed, the susceptibility assessment refers to the spatial probability of the landslides based on the local terrain conditions (Soeters and van Westen, 1996; Glade, 2001; Zêzere, 2002). Landslide susceptibility assessment at the basin scale as well as at the municipal scale is based on the assumption that future landslide have higher probability to occur under the same conditions that led to past landslides (Varnes and the International Association of Engineering Geology Commission on Landslides and Other Mass Movements, 1984; Soeters and van Westen, 1996; Zêzere et al., 2004a; Guzzetti, 2005). Therefore, a complete inventory of the past landslides must be listed in order to combine the distribution of these landslides with the spatial patterns of the predisposing factors for slope instability (Zêzere et al., 2004b; Chacón et al., 2006). The landslide inventory records the location and the type of the landslide, as well as the date of occurrence, when this is known (Malamud et al., 2004). It can be carried out from various sources, like the stereoscopically examination of aerial photographs, or by the examination of orthophoto maps combined with the accurate topography. Field investigation is useful to validate slope movements seen on the photographs or orthophoto maps and to map the fresh landslides which are more recent than the photographs and therefore do not appear in them.

The inventory of the landslides must be combined with a set of slope instability predisposing factors for landslide susceptibility assessment. For an assessment at the municipal scale, the critical data regarding predisposing factors include slope angle and slope aspect, lithology, geological structure, faults, soil types, geomorphologic units, land use types, land use changes and hydrological components (van Westen et al., 2008; Pereira, 2010). Nevertheless, the set of factors can be limited and must be coherent and logical (Zêzere et al. 2008a).

The methods used for the susceptibility assessment can be statistic, heuristic or deterministic (Corominas et al., 2014; Dai et al., 2002; Guzzetti et al., 2006). The statistical models have the advantages (1) to be easily applicable at the municipal scale unlike the deterministic models which require detailed knowledge regarding the unstable slope characteristics (e.g shear resistance parameters, unstable soil thickness); and (2) to be objective, unlike the heuristic models which are subjective and the quality of which depends on the experience of the expert, especially for the attribution of weighted values (Soeters and van Westen, 1996; Pereira, 2010). The accuracy and the robustness of the statistical models can be validated by success and prediction-rate curves (Chung and Fabbri, 2003; Guzzetti et al., 2006), which allow to know the goodness of fit of the susceptibility model and the predictive power of the susceptibility model, respectively (Chung and Fabbri, 2003).

Then the temporal component must be considered and combined with the susceptibility assessment in order to assess the landslide hazard. For that, the probability of landslide occurrence can be determined by using landslide records. Alternatively, the probability of the landslide triggering event can be used (Glade, 2001).

Landslide magnitude and frequency have to be considered during the landslide hazard assessment (Guzzetti et al., 2005). The magnitude of a landslide event can be measured by the total number, total area and/or total volume of landslide in a landslide event (Malamud et al., 2004; Oliveira, 2012). Frequency-magnitude curves are necessary for a correct understanding and characterisation of municipal or regional landslide hazard (Guthrie et al., 2007) and can be obtained by multiplying the probability distribution by the total number of landslides in the event (Malamud et al., 2004).

The landslide hazard assessment implies several uncertainties which must be considered when using the landslide hazard map. First, it is based on the assumption that future landslides have a higher probability to occur under the same conditions that generated the past landslides; but if slope instability conditions change, because of human intervention on slopes or because of climate change, for example, the magnitude of the landslides should increase. Second, the inventory of landslides used as a base for the susceptibility assessment is always incomplete, because the areas of depletion and accumulation of the landslides are not always visible for various reasons, particularly in the forested, ploughed or recently urbanised areas or regarding old or inactive slope movements which disappeared from the landscape due to erosion or vegetation growth (Guzzetti et al., 1999). Moreover, the quality of the landslide inventory depends not only on the freshness of the landslides and on the absence of alterations of the land use, but it depends also on the quality and the scale of the photographs, on the morphological and geological complexity of the considered area and on the degree of experience of the expert who mapped the landslides (Varnes and the International Association of Engineering Geology Commission on Landslides and Other Mass Movements, 1984).

The landslide hazard map is useful to town and country planning stakeholders because it allows them to take decisions regarding the use of the areas where most of the future landslides should occur. They can therefore adopt preventive measures, as the prohibition of building dwellings, roads, infrastructures or other types of constructions on the most hazardous areas. Indeed, planning control is one of the effective and economical way to reduce landslide losses, because if the local governments remove or convert the buildings and infrastructures that are on unstable areas, or discourage or regulate new development on these areas, the risk would be reduced at source (Dai et al., 2002). The stakeholders can also adopt protective measures, as the development of engineering work in potentially unstable slopes where elements at risk need to be protected, by correcting the underlying unstable slope or controlling the landslide movement, for example (Dai et al., 2002). However, these solutions are costly and are not always practicable, namely when the landslide magnitude is very high. In already developed hazardous areas, a possible solution is the introduction of a monitoring and warning system to evacuate preventively the residents prior meteorological events prone to trigger landslides, but it is only possible on the places that are already known as unstable.

For civil protection, the hazard assessment is important, but the assessment of the vulnerability of the elements at risk is also useful to know which part of the population is more at risk. In relation to hazard assessment, vulnerability assessment to natural hazards in general and to landslide hazard in particular is a new field of research and the number of studies focusing on vulnerability assessment is limited (Fuchs, 2009; Papathoma-Köhle et al., 2012). For Zêzere and co-authors, landslide vulnerability is probably the most difficult term to represent quantitatively within landslide risk analysis (Zêzere et al. 2008b). Landslide vulnerability understanding and assessment are therefore a crucial path for assessing the landslide risk (Ding et al., 2012; Fotopoulou et al., 2013), but they are not easy tasks.

0.3. Vulnerability and losses due to natural disasters

0.3.1. Different facets of vulnerability

Geographers have a long-standing interest in natural hazards and vulnerability research since the work of Gilbert F. White who submitted his pioneering thesis on flood hazards and flood plain management to the University of Chicago in 1942 (Fuchs et al., 2011). Nevertheless, the term "vulnerability" is used in several disciplines, which makes it a quite fuzzy term because of the different definitions and conceptual models that are used (Alcántara-Ayala, 2002; Fuchs et al., 2011). Indeed, Thywissen (2006) listed 22 definitions of risk and 36 definitions of vulnerability to natural disasters, which emerged between 1983 and 2005.

Most of the definitions of vulnerability to natural disasters agree to state that the vulnerability is multi-dimensional (vulnerability has several facets: e.g. physical, social, economic, environmental, institutional), dynamic (vulnerability changes over time), intrinsic of any community, scale-dependant (vulnerability can be expressed at different scales from human or household to country resolution) and site-specific (each study area might need its own approach) (Thywissen, 2006).

For the United Nations, the term "vulnerability" refers to the conditions which make a community susceptible to the impact of hazards, the conditions being determined by physical, social, economical and environmental factors or processes (UNISDR, 2009). This makes it a term with different facets, which should be all considered to make a complete vulnerability assessment. In practice, it is rarely the case. Indeed, authors usually focus on one facet of the vulnerability according to their background.

Engineers are more often interested in the physical vulnerability (also called structural vulnerability) of the buildings. The physical vulnerability can be assessed by considering different scenarios and by calculating the likelihood of occurrence of specific process scenarios (Fuchs, 2009). Vulnerability curves are often used to assess the physical vulnerability of a type of element at risk (e.g. reinforced concrete buildings), indicating the interaction between the intensity of the hazard and the type of element at risk (Corominas et al., 2014).

Not only the built environment factors are important in terms of natural disaster outcome, but also the social factors (Zahran et al., 2008); this work is in general done by sociologists who assess the social vulnerability of the population. For Cutter and co-authors (2008), social vulnerability is linked to the inherent characteristics of social systems that create potential for harm. It exists before the occurrence of a disaster and is function of the exposure of the element at risk and sensitivity of system (Cutter, 1996; Cutter et al., 2008). To assess the social vulnerability of a population, social scientists collect and explore a set of socioeconomic factors in order to know which part of the population would have more difficulty to recover from a natural disaster, and which part would be less vulnerable and more able to cope with stress or change (Fuchs, 2009).

Economists focus on the economic vulnerability. Guillaumont (2009) developed an Economic Vulnerability Index (EVI) which measures the likelihood that a country's economic development process is hindered by the occurrence of exogenous unforeseen events, often called external shocks, and which come from the occurrence of a natural disaster (e.g. earthquake, volcanic eruption, flood) or trade or exchange-related shocks (e.g. slumps in external demand, world commodity prices instability, international fluctuations of interest rates) (Guillaumont, 2009). This index has been used by the United Nations to measure the vulnerability of the least developed countries.

According to Tapsell and co-authors (2010), the vulnerability to natural disasters has other facets. Indeed, additionally to social, physical and economic vulnerabilities are the organizational, cultural, systemic, territorial and institutional vulnerabilities (Tapsell et al., 2010). Another facet is the functional vulnerability, which characterises the potential damage that activities and functions may suffer. It depends on the damage caused on goods, persons and secondary functions as well as the capacity the society can restore the activity (Léone et al., 1996). Gleyze and Reghezza proposed a method to assess the functional vulnerability of the transport networks to a 100-year flood in Ile-de-France (Gleyze and Reghezza, 2007).

0.3.2. Potential losses

The potential losses or consequences of a natural disaster are often defined as a product of the vulnerability and the value of the elements at risk (Julião et al., 2009; Silva and Pereira, 2014; van Westen et al., 2005). Potential losses can be diverse according to the different types of hazards and of elements at risk, and according to the facet of the vulnerability which is considered. The losses can be whether direct when they result from the effects of elements at risk (e.g. injuries, structural damages to buildings or infrastructures), or indirect when they result from the consequences of this destruction (Eidsvig et al., 2014). Figure 0.3 lists some of the direct and indirect losses which can result from natural disasters. Direct losses belonging to social and physical vulnerabilities are more frequently evaluated (in red in Fig. 0.3). For instance, some authors, as Fuchs and co-authors (2007) and Akbas and co-authors (2009), assessed the vulnerability of buildings to debris flows by defining the vulnerability as the ratio between the loss and the individual reconstruction value, which was calculated for each building on function of its type and size. The obtained ratios were coupled to the corresponding deposition height and the vulnerability was plotted in function of the intensity of the debris flows, represented by their height. Some authors assess the indirect losses, as Eidsvig and co-authors (2014), who proposed a model to assess the relative socioeconomic vulnerability to landslides at the local or regional scale by indicators representing the degree of preparedness, effectiveness of the response and capacity to recover from the damage caused by landslides. Nevertheless, indirect losses are more difficult to assess than direct losses, and are therefore less considered than direct losses (Gall et al., 2011). The lack of consideration of direct and indirect losses is responsible for under-estimation of the risk, which is by definition the product of the hazard by the potential losses.

	Human - social	Physical	Economic	Cultural Environmental
Direct losses	• Fatalities • Injuries • Loss of income or employment • Homelessness	• Structural damage or collapse to buildings • Non-structural damage and damage to contents • Structural damage infrastructure	• Interruption of business due to damage to buildings and infrastructure • Loss of productive workforce through fatalities, injuries and relief efforts • Capital costs of response and relief	• Sedimentation • Pollution • Endangered species • Destruction of ecological zones • Destruction of cultural heritage
Indirect losses	• Diseases • Permanent disability • Psychological impact • Loss of social cohesion due to disruption of community • Political unrest	• Progressive deterioration of damaged buildings and infrastructure which are not repaired	• Economic losses due to short term disruption of activities • Long term economic losses • insurance losses weaken-ing the insurance market • Less investments • Capital costs of repair • Reduction in tourism	• Loss of biodiversity • Loss of cultural diversity

Fig. 0.3 - Overview of types of loss resulting from natural hazards. *Source: van Westen and Kingma, 2009*

Besides the diverse vulnerability facets and the difficulty associated to the assessment of all the potential losses, the absence of clear goals for risk and vulnerability reduction is an issue in the development of vulnerability and risk indicators. The development of tools for the vulnerability assessment aims at filling the gaps between the theoretical concepts of vulnerability and the decisions that the stakeholders have to take (Birkmann, 2007).

0.4. The assessment of vulnerability

The vulnerability assessment is certainly useful for disaster risk reduction and promoting an exchange of information, as aims the Americas Project (Birkmann, 2007; Cardona, 2005), or for improving disaster preparedness and preventing losses, as aims the Hotspots Project by creating indicators regarding the frequency of the hazards and the foreseeable economic or human impacts at a global scale (Birkmann, 2007; Léone, 2007). Ideally, it should also assist policy makers in identifying investments priorities (e.g. prevention and mitigation measures) to reduce risk, to identify national risk-management capacities and to evaluate the effects of policies and investments on risk management, and to gauge a country's relative position and follow its evolution over time (Birkmann, 2007).

Some global approaches aim to compare disaster risk between countries exposed to selected natural hazards, as it is the case of the Disaster Risk Index (DRI), which measures the mortality by assessing the relative vulnerability, which is the ratio of the number of persons killed by the number of exposed persons (UNDP/BCPR 2004; Birkmann 2007). The DRI was used to identify the countries which most need prevention and development (Peduzzi et al., 2009). Another index of structural vulnerability to climate change was developed to assess the environmental vulnerability of the least developed countries which are facing environmental shocks resulting from climate change (e.g. droughts, floods, storms and rise of sea level), in order to allocate adaptation funds (Guillaumont and Simonet, 2011).

0.4.1. Vulnerability representation

Birkmann (2006. p.11) noted that "we are still dealing with a paradox: we aim to measure vulnerability, yet we cannot define it precisely". Vulnerability can be measured either on a metric scale or a non-numerical scale (Glade, 2003) and is represented by different ways.

One of them is the elaboration of an index which combine various indicators. The index elaboration is usually used to assess social vulnerability (e.g. Social Vulnerability Index (SoVI) which was established by Cutter and co-authors (2003)), economic vulnerability (e.g. Economic Vulnerability Index (EVI), established by Guillaumont (2009)), human vulnerability (e.g. Disaster Risk Index (DRI), established by UNDP/BCPR (2004)) or environmental vulnerability (e.g. Index of Structural Vulnerability to Climate Change, established by Guillaumont and Simonet (2011)).

Physical vulnerability is more often expressed through vulnerability functions (e.g. Fuchs et al., 2007) which represent the interactions between the damaging event and the elements at risk through curves expressing the possible resistance of the elements to an impact (Li et al., 2010; Puissant et al., 2013). In the case of the landslide vulnerability , the vulnerability functions are usually used for detailed assessments (1:5000-1:10000) (Puissant et al., 2013). An example of application is the study of Papathoma-Köhle and co-authors (2012), who measured the degree of loss of buildings in function of the debris flow intensity, represented by the height of the debris deposit.

Fragility curves are another way to represent physical vulnerability by providing the probability for a type of elements at risk to reach or to exceed a specific damage state under a given hazard intensity (Blong, 2003). For example, in the case of earthquakes, for which the fragility curves have been frequently used, they express the level of damage to a building given, for example, the amplitude of ground shaking (Douglas, 2007). Although less used for landslides than for earthquakes (Douglas, 2007), some authors use them, as Fotopoulou and co-authors (2013), who expressed the level of damage caused by permanent cumulative ground displacement at the foundation level on reinforced concrete buildings. According to Lateltin and co-authors (2005), more research is needed because a lot of uncertainties remain in the calculation of fragility curves according to different landslide intensities.

Finally, the relation between hazard intensity and degree of damage can also be given in a vulnerability table or matrix, especially when the hazard intensity has no intermediate values (e.g. the Modified Mercalli Intensity for earthquake hazard). Léone and co-authors (1996) established vulnerability matrices to assess the structural damage on elements at risk to landslides. Similar matrices can be used to assess the corporal and functional vulnerabilities (Léone, 1996).

Most of the scientific studies assessing the vulnerability of the populations to natural hazards examine either the social vulnerability or the physical vulnerability of the elements at risk, which are discussed in the following subsections.

0.4.2. Social vulnerability to natural hazards

Social vulnerability characterises the inequalities which define the predisposition of social groups in the context of a disaster (Hewitt, 1997; Susman et al., 1983). The concept of social vulnerability is complex (Ciurean et al., 2013); indeed, it is itself a multi-faceted entity and authors use this term with different meanings (Tapsell et al., 2010). Therefore, fundamental differences exist between the main types of social vulnerability to natural hazards assessment approaches; some of them are based on intangible losses assessments and others are based on the underlying socioeconomic factors that are responsible for vulnerability in a society (Ciurean et al., 2013). If physical vulnerability is usually considered as hazard-dependant (Papathoma-Köhle et al., 2011), a unique social vulnerability assessment is often combined with different natural hazards assessments (e.g. Cutter et al., 2010; Chen et al., 2014).

Social vulnerability is commonly measured by indexes which are based on a set of socioeconomic indicators (e.g. age, gender, disability) which can either be weighted (by expert judgement, analytic hierarchy, Principal Component Analysis (PCA), factor analysis or multiple regression models) or not (if all indicators are assumed to have an equal significance). The indicators are then combined, often by an additive combination when the factors are independent or by a multiplicative combination when the utility of one factor depends on another factor, or even by an association of both additive and multiplicative combinations (SafeLand, 2012). The obtained social vulnerability can then be combined with susceptibility or hazard assessments in order to locate the risk to different natural disasters (e.g. Cutter et al., 2000).

In attempting to define social vulnerability, a new concept of resilience emerged and evolved (Tapsell et al., 2010). As the social vulnerability concept, the concept of resilience has many definitions. Klein and co-authors (2003) made a literature review of the resilience concepts. The authors noted that the Resilience Alliance defines the resilience of social-ecological systems by considering three dimensions: (1) the amount of disturbance a system can absorb still remaining within the same state; (2) the degree to which the system is capable of self-organisation; (3) the degree to which the system can build and increase the capacity for learning and adaptation. This comprehensive interpretation of the resilience became the basis of a scientific background paper, which refers to resilience as the "flip side" of vulnerability. A later interpretation defines the resilience as a component of the vulnerability, along with exposure and sensitivity. It is also the interpretation of different authors, as Pelling (2003). According to the United Nations, resilience is the "ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in timely and efficiently manner, including through the preservation and restoration of its essential basic structures and functions" (UNISDR, 2009). Berkes (2007) believes that resilience thinking helps the providing of an all-hazard approach and avoid the division that is often made between social and physical vulnerability.

0.4.3. Physical vulnerability of elements at risk to landslides

Physical vulnerability is a functional relationship between process magnitude, the impacts on structural elements at risk and exposed values (Fuchs, 2009). Regarding the built environment, vulnerability is related to the fragility of physical structures and is defined as the expected degree of loss resulting from the impact of a certain event on the elements at risk. Its assessment requires the evaluation of different parameters and factors such as type of element at risk, resistance, and implemented protective measures (i.e. local structural protection) (Fuchs, 2009).

In physical geography and in engineering geology, most of the studies consider the vulnerability to a hazardous event of a given magnitude as being the degree of loss of elements at risk expressed in a scale ranging from 0 (no loss) to 1 (total loss) (e.g. Varnes & the International Association of Engineering Geology Commission on Landslides and Other Mass Movements 1984; Hufschmidt et al. 2005; Chacón et al. 2006; Uzielli et al. 2008; Zêzere et al. 2008b; Fuchs et al. 2011; Uzielli et al. 2014). From this definition emerged a wide range of vulnerability assessment models, each study addressing vulnerability in a different way (Papathoma-Köhle et al., 2011). These different models partly depend on the different scales of the vulnerability assessment (Puissant et al., 2013), and on the purpose for which the vulnerability assessment method was created.

There are few studies focusing on vulnerability assessment to landslides and other gravitational hazards comparing to other types of hazards according to Hollenstein (2005), which registered more than 1000 vulnerability assessments for earthquakes, more than 100 vulnerability assessments for wind events and only 20 or less for gravitational hazards (Hollenstein, 2005). For this author, this must be due to the fact that the gravitational hazards are usually accurately delimited, therefore the stakeholders simply avoid the potentially affected areas. In addition, the institutions that manage the risk do not seem to need empirical models because they think having sufficient empirical knowledge. However, assessment of the physical vulnerability to landslides is useful to assess the potential losses that can be caused by landslides and the associated risk. Several ways exist to measure the physical vulnerability to landslides (van Westen and Kingma, 2009). The first one consists of collection and analysis of the registered damage in recent historical events. This method is particularly used for relatively frequent events such as floods or earthquakes, which normally affect many buildings of the same type, allowing thus the elaboration of vulnerability curves by correlating the magnitude of the event and the degree of damage. Recent approaches have been made regarding the assessment of physical vulnerability to landslides on the base of observed damages. For example, Galli and Guzzetti (2007) assessed the physical vulnerability of buildings and roads to landslides in Umbria, Italy. They considered 103 slides and slide-earth flows which caused damage to roads and buildings in 90 sites in Umbria, and they established a relation between the area of the landslides and the vulnerability of the roads and the buildings by observing the consequences of the landslides. The minimum and maximum vulnerability thresholds were plotted for each type of element at risk (buildings, major roads and secondary roads) and were used to map expected vulnerability of the elements at risk. The results of the study show that when the landslide area increases, the amount of damage also increases, as well as the vulnerability of the elements at risk.

When there is not enough available information regarding the caused damage, the physical vulnerability can be measured through expert opinions. For example, landslide experts can give their opinion on the potential damage that can be caused to a specific type of elements at risk by a landslide that has a certain magnitude, and the vulnerability assessment would be based on their answers. This method is time-consuming because numerous experts must be interviewed to obtain results with a lower subjectivity.

Analytical methods study the behaviour of structures based on engineering criteria, computer simulation programs helping for modelling the behaviour of buildings (e.g. Huang et al. 2011). These methods have been more used for earthquakes than for landslides.

Geography is an interdisciplinary field of research which allows to make progress in the mitigation and adaption to natural hazards by analysing the multi-faceted characteristics of the vulnerability (Fuchs et al., 2011). Some studies focus only on one aspect of the vulnerability, while others focus on different facets of the vulnerability and propose a combination of these assessments. Some of the studies which have the ambition to assess several facets of the vulnerability to landslides are presented in the next subsection.

0.4.4. Studies which combine social and physical vulnerability to landslides

Léone was one of the pioneer in the assessment of vulnerability to landslides. He proposed a method to assess the corporal (for people), structural (for material goods) and functional (for activities) sides of the vulnerability to landslides and presented them in matrices (Léone, 1996).

Before him, Lavigne and Thouret (1994) proposed a method to assess the vulnerability to lahars on the Merapi Volcano (Java, Indonesia). They aimed to assess: (1) the vulnerability of the populations, by assessing the density of the resident populations and by studying the demographical evolution and socio-demographical previsions; (2) the vulnerability and the value of the movable and immovable goods by assessing the density and the quality of the buildings, their resistance to the lahars and the repair and reconstruction costs; and (3) the vulnerability and value of the infrastructures and economic activities by making an inventory of the exposed infrastructures and by assessing the value of the agricultural crops and the costs of the potential damage.

More recently, Shrestha (2005) proposed a method to assess the socioeconomic and physical vulnerabilities to landslides and floods in Putalibazaar municipality, Nepal. Total vulnerability was assessed by combining the physical and socioeconomic vulnerabilities which are functions of the hazard, the physical exposition indicators (number of households, total population, agricultural land area and road length), and the capacity of adaptation indicators (e.g. accessibility, health, communication). Perception of disaster by the population and by governmental and nongovernmental organisations was also assessed by questionnaires. The author concluded that in the study area, the risk is increasing because the exposition increases, namely through settlement expansion and roads constructions. Moreover, the hazard tends to increase as well.

Alexander (2005) proposed a method based on the vulnerability of buildings, structures, human lives and socioeconomic activities. The methodology can be used at three levels: single asset method (vulnerability is assessed for each element at risk within the hazard zone), summed assets method (vulnerability is assessed as the average vulnerability of the elements at risk within the hazard zone), and generalised assets method (a global vulnerability level of all the elements at risk present in the hazard zone is heuristically estimated).

Puissant and co-authors (2006) created an index to assess the potential damage which can be caused by landslides. The index is called Potential Damage Index (PDI), and was elaborated in order to assess the potential physical injuries, structural and functional damage, and socioeconomic effects at a scale from 1:10,000 to 1:100,000. This index has been used as a base in other studies: for example, Carlier and co-authors (2016) used it to assess the direct and indirect consequences of landslides in the Upper Guil catchement, an area of the PACA region in France, and also assessed the social and institutional vulnerabilities through questionnaires, interviews and mind-maps dealing with risk perception, mitigation measures and confidence in the actors of risk management.

Recently, Murillo-Garcia and co-authors (2015) proposed a method to assess the vulnerability to landslides by combining the exposure level of the population and the infrastructures, the sensitivity of the population and its lack of resilience. The exposure is calculated from data regarding population and hazard, the sensitivity of the population is composed by social indicators (e.g. population density, youngest and oldest population, female population, indigenous population), and the lack of resilience is composed by indicators dealing with incomes, economically active population, health insurance and road characteristics. The combination of the different facets of the vulnerability considered in this study is interesting, though the physical vulnerability of the buildings is not assessed and the possible application of the vulnerability assessment is not clearly defined.

0.5. Presentation of the work done in the present thesis

According to Papathoma-Köhle and co-authors (2011), before developing a methodology for vulnerability assessment, the aim of the assessment and its end-users should be identified. Indeed, a tool for decision making about town and country planning or emergency planning would not be the same, and the choice of the end-users also influences the scale of the assessment, which can be local, regional or national (Papathoma-Köhle et al., 2011).

How assessing the vulnerability of a municipality to landslides and how integrating the vulnerability assessment into a landslide risk analysis?

The main aim of the present study is to develop a method of vulnerability assessment which includes the social and the physical facets of the vulnerability, and which is applicable at the municipal scale in the Portuguese municipalities. The second aim is to use the vulnerability assessment to support the landslide risk analysis. Finally, the developed method should be useful to spatial planning, civil protection and insurance stakeholders.

A large number of methodologies developed for vulnerability assessment are difficult to implement because of the unavailability of data. In addition, the achievement of relevant data is frequently time-consuming due to extensive field work. The present study aims to be easily and readily applicable in others Portuguese municipalities for which an inventory of the past landslides has been listed.

Following this Introduction, the present study is composed by three chapters and by a conclusion section. The organisation of the tasks of each chapter and their relations are presented in Figure 0.4.

The first chapter presents a susceptibility assessment to deep-seated rotational and translational slides and to shallow slides in the Loures municipality. A bivariate statistical method was used. The accuracy and the robustness of the models were assessed by success and prediction-rate curves. The probability magnitude curves of deep-seated and shallow landslides were constructed. The 20.3% of the area where at least 70% of the future landslides should occur, according to the susceptibility models, were selected to be included in the National Ecological Reserve (NER), which is the legislation that demands the evaluation of the landslide susceptibility in Portugal. Thus, the application of adequate prevention and protection measures in the 20.3% of the total area which are the most susceptible should allow the reduction of the damage which could be caused by 70% of the future landslides.

The second chapter shows a study of the social vulnerability of the 149 civil parishes of the Greater Lisbon. The method used is the Social Vulnerability Index (SoVI) method, which consists in: (1) a selection of variables which represent the social vulnerability of the

Greater Lisbon population and which were chosen according to the availability of the data at the civil parish scale; (2) a selection of the non-correlated variables; (3) a Principal Component Analysis (PCA); (4) the interpretation of the principal components resulting from the PCA; (5) the calculation and mapping of the SoVI values. The SoVI map was then combined with the susceptibility maps of the main natural hazards which threaten the Greater Lisbon (earthquakes, floods, flash floods, landslides, tsunami, and coastal erosion), allowing thus the delimitation of risk zones. The resident population exposition was finally considered by combining the number and the residential location of the inhabitants with the map of the risk zones delimitation.

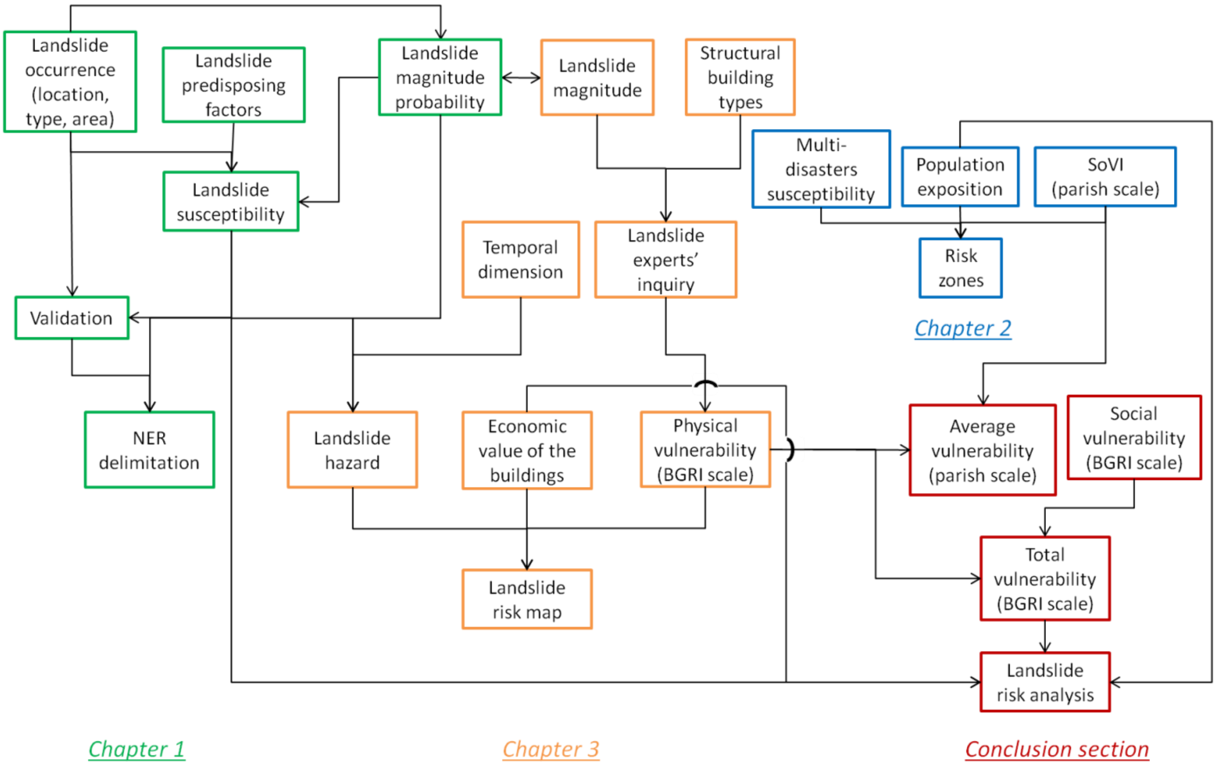

Fig. 0.4 - Organization of the study

The third chapter presents an assessment of the physical vulnerability of the Loures municipality buildings for different landslide magnitude scenarios. The vulnerability was obtained by calculating the average vulnerability attributed by a pool of European landslide experts and by a sub-pool of landslide experts who know the study area. The variability of the answers was assessed by calculating the standard deviations. The average vulnerability, based on the structural type of the buildings, was calculated at the basic geographic entity (BGRI) level. Each building of a test site within the Loures municipality was identified and the vulnerability was allocated for each building in this test zone, allowing thus the comparison with the average vulnerability per BGRI and assessing the effect of this approximation. Then, the economic value of the buildings was assessed on the base of the Portuguese Tax Services approach. Finally, the landslide hazard was calculated by combining the landslides spatiotemporal probability and their frequency-magnitude relationship, and was then combined with the vulnerability and the value of the buildings in order to obtain the landslide risk.

In the conclusion section, the social vulnerability and the physical vulnerability of the Loures municipality were combined through two approaches. In the first approach, the used social vulnerability was the one which was assessed in the second chapter at the civil parish scale, whereas in the second approach, a new social vulnerability assessment was made at the BGRI scale. The landslide risk was finally analysed considering the total vulnerability provided by the combination of the physical vulnerability and the new social vulnerability assessment, the landslide susceptibility, the exposition of the population and the value of the elements at risk (Fig. 0.4).

The study area is the Loures municipality in the first and the third chapters, and is the Greater Lisbon in the second chapter. The choice of the Loures municipality for principal study area was driven by four reasons: (1) Loures municipality is prone to landslides; (2) data about landslides and types and location of elements at risk were available for this study area; (3) this municipality is next to Lisbon, the capital of Portugal, and has been experiencing an increasing urbanization pressure; (4) the stakeholders of the municipality are conscious that there is a need of natural risk reduction in the municipality. The study provided in the first chapter was used as a base to elaborate the report for the Loures municipality authorities which defines the delimitation of the areas prone to landslides that must be included in the NER. The choice of the Greater Lisbon as study area in the second chapter was made because it was not possible to apply the SoVI in the Loures municipality only for the reasons that there are no sufficient data at the BGRI scale and there are too few civil parishes in the Loures municipality. Indeed, the SoVI method is based on a PCA, which requires at least 100 spatial units to give satisfying results (Garson, 2008), and the Loures municipality has only 18 civil parishes. This is why the study area was extended to the Greater Lisbon, which gathers 149 civil parishes and which includes the Loures municipality. This change in the study area generated a need for some adaptations, hence the study developed in the conclusion section.

0.6. References

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Chapter 1

Landslide susceptibility assessment and validation in the framework of municipal planning in Portugal: The case of Loures Municipality

Chapter 1 is the full content of the following published paper:

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1. Landslide susceptibility assessment and validation in the framework of municipal planning in Portugal: The case of Loures Municipality

Abstract. The legislation that demands the evaluation of landslide susceptibility in Portugal at the municipal level is the National Ecological Reserve (NER). A methodology for the evaluation of landslide susceptibility to be used in municipal planning is applied in Loures Municipality (169.3 km²) located north of Lisbon (Portugal). A landslide inventory was made for the whole area interpreting ortophotomaps and aerial photographs and using standard geomorphologic techniques in field work. It consists of 686 polygons, each polygon representing a rotational, a deep translational or a shallow translational slide, and is integrated into a GIS database. Landslide susceptibility is evaluated using algorithms based on statistical/probabilistic analysis (Information Value Method) over unique-condition terrain units in a raster basis. Three susceptibility models are elaborated independently according to the type of slide (rotational, deep translational, shallow translational). The landslide susceptibility maps are prepared by sorting all pixels according to the pixel susceptibility value in descending order. The robustness and accuracy of the landslide susceptibility models are evaluated by prediction-rate curves, which are used for the quantitative interpretation of the landslide susceptibility maps. Unstable slopes that have to be included into the National Ecological Reserve are extracted from the three susceptibility maps following the general rules to draw the NER that state that the area to be included in the NER should guarantee the inclusion of at least 70% of the landslides identified in the landslide inventory. The obtained results allow us to conclude that 70% of the future landslides should occur in these areas, classified as most susceptible to landslides corresponding to 20.3% of the total area of Municipality. Thus, the consideration of these 20.3% as regards prevention and protection of landslide risk could potentially reduce damage resulting from 70% of future landslides in the Loures Municipality.

Keywords: Landslides, Susceptibility, Prediction-Rates, National Ecological Reserve, Municipal Planning.

1.1. Introduction

Landslides are natural phenomena which may produce deaths and injuries and direct and indirect economic losses. It is thus important to take them into account within town and country planning in order to reduce their consequences. Landslide susceptibility assessment allows for the identification of slopes for which failure probability is high and to consequently make prevention and protection decisions accordingly.

In the framework of the European Soil Thematic Strategy, the directive on the protection and sustainable use of soil recognizes landslide risk as being a soil threat which requires specific strategies in terms of assessment and management (Günther and others 2008). A two tier study is proposed; as there does not exist any landslide inventory for all of Europe, a qualitative zonation based on topographic, lithologic and soil information will be carried out. In the areas defined as susceptible in this first study, a quantitative inventory-based evaluation of landslide susceptibility will follow, adopting statistical assessment techniques.

In Europe, only four countries (France, Italy, Sweden and Switzerland) have an officially recognized Landslide Risk Assessment Methodology (RAM) (Malet and Maquaire 2008). Nine other countries have official RAMs in development, four countries have RAMs used by research institutes or private engineering offices (this is the case of Portugal) and seven countries have no specific landslide RAM (ibid.).

Despite the lack of official RAM in Portugal, the landslide prone areas have to be integrated into the National Ecological Reserve (NER) at the municipal level. The NER is a biophysical structure which integrates all the areas that need a special protection because of their value and ecological sensitivity, or because of their exposure and susceptibility to natural hazards. It was created by decree nº321/83 and was reviewed several times, in particular in 1990, 2006 and 2008. It aims to contribute to the sustainable use of the territory, and its main objectives are: (1) protection of natural resources, especially water and soil; (2) prevention and reduction of the effects of natural phenomena (among others, effects of landslides); (3) contribution to the connectivity and ecological coherence of the Nature Conservation Network; (4) contribution to the realization of the priorities of the Territorial Agenda of the European Union in the ecological field and in trans-European management of natural risks (Decree n.º166/2008, Chapter 1, Article 2). The new jurisdictional regime of the NER, established in 2008, clarifies the typologies of the areas that should be integrated in the NER, establishing the criteria for its delimitation, designating the respective functions and identifying the uses and actions that are admitted in them. It specifies that the operative level is municipal. In areas classified as NER, the uses and actions of public or private initiative, like (a) operations of land division, (b) urban development, (c) road works, (d) cuts and landfills, (e) destruction of the vegetation cover, are forbidden (Decree n.º166/2008). Therefore, integration of susceptible slopes into the NER aims to reduce damages generated by slope instability.

According to Soeters and van Westen (1996), landslide susceptibility is the expression of the propensity of landslide occurrence in a given area, on the basis of terrain characteristics, by not considering the return period or the probability of occurrence of the instability phenomena. Evaluation of landslide susceptibility at the municipal level is based on the principle that future landslides have a higher likelihood of occurring under conditions similar to those which caused past slope instability (Varnes and others 1984; Soeters and van Westen 1996; Guzzetti and others 1999; Zêzere and others 2004a; Guzzetti 2005). Therefore, the landslide susceptibility may be assessed by combining the spatial distribution of past landslides with the spatial patterns of the relevant predisposing factors of slope instability (Carrara and others 1998; Zêzere and others 2004b; Chacón and others 2006). The obtained landslide susceptibility map provides a classification of the study area only in terms of “spatial probability” (Soeters and van Westen 1996; Guzzetti and others 2005a; Chacón and others 2006).

It is therefore necessary to first construct an inventory of the landslides which have occurred in the study area and to note the characteristics of the affected slopes. Traditionally, landslides have been mapped through interpretation of aerial-photographs and more recently by exploring digital ortophotomaps. In addition, landslides are usually confirmed by field work using standard geomorphologic techniques (Soeters and van Westen 1996; Chacón and others 2006; Zêzere and others 2009).

The landslide susceptibility assessment can be made using deterministic, heuristic or statistical approaches (Soeters and van Westen 1996; Dai and others 2002; Guzzetti and others 2006; Günther and others 2008). The statistical approach has been widely used in the last 20 years by quantifying the relationship between predisposing factors and landslides in an objective way through mathematical algorithms. Different types of slope movements may have distinct spatial incidence normally associated with different thresholds conditions regarding landslide preparatory factors (Carrara and others 1992). This constraint may be solved by assessing the landslide susceptibility independently for each type of landslide (Zêzere 2002).

The validation of robustness and accuracy of the landslide susceptibility models is possible by computing success-rate and prediction-rate curves (Chung and Fabbri 2003; Zêzere and others 2004a; Guzzetti and others 2006). The success-rate curve checks the goodness of fit of the susceptibility model by assessing if the landslides which were used to build the model are correctly classified within those zones having a high susceptibility. The prediction-rate curve is more effective for validation because it checks the predictive power of the susceptibility model by verifying if landslides independent of those used to build the model are correctly classified within susceptible slopes (Chung and Fabbri 2003).

The main objective of the present study is to select the potentially unstable slopes that should integrate the National Ecological Reserve (NER) and must be restricted for development purposes according to the Portuguese law. Therefore, we evaluate and map the landslide susceptibility of a Municipality located in the Metropolitan Area of Lisbon by using a bi-variate statistical method, and creating three landslide prediction models for three different types of landslide. Finally, we identify the main exposed elements which are within the NER, and which have therefore high landslide risk.

1.2. Study area

The study was performed in the Loures Municipality, located north of Lisbon. The test site is 169.3 km² in size and its elevation ranges from 0 to 405 meters (see Fig. 1.1).

The Loures Municipality is underlain by sedimentary and volcanic rocks dating from the Upper Jurassic to the Quaternary. These rocks are tectonically deformed in a large monocline dipping (5 to 25°) south and southeast. Differential erosion was prevalent during the Quaternary allowing for the formation of a hilly landscape (Zêzere and others 2008a). Such a landscape includes structural landforms (e.g. *cuestas*) and large erosive depressions like the Loures basin located in the central part of the county (Fig. 1.1).

The tectonic framework of the Lisbon region, where the Loures Municipality is located, is responsible for a moderate seismicity (Vilanova and Fonseca 2007). The Lisbon area has suffered in the past the effect of earthquakes, that caused extensive damage (e.g. in 1344, 1531, 1755, 1909) (Moreira 1985; Carvalho and others 2008). Despite this, the available information regarding earthquake-induced landslides in Portugal is scarce and little historical descriptions can be found (Vaz and Zêzere 2011). In addition, the last strong earthquake affecting the study area occurred in 1909, making difficult the field recognition of the triggered landslides.

The climate of the study area is typically Mediterranean. The rainfall regime is highly variable at both the inter-seasonal and the inter-annual scales (Zêzere and others 1999, 2005). The mean annual precipitation (MAP) is 730 mm. Summer months are typically dry and rainfall concentrates in the period lasting from October to March (78% of the total amount; 72% of the total rainy days). The rainfall is the triggering factor of the large majority of landslides occurred in the study area.

Slope instability in the study area is characterized by the prevalence of slides of shallow translational, deep translational and rotational subtypes (Zêzere and others 1999, 2005). Shallow translational slides are small landslides (usually < 600 m^2) affecting loose soil material (colluvium) covering impermeable marls and clays (Zêzere and others 2005). They concentrate on steep valley hill slopes. Deep translational slides typically affect the bedrock (e.g. limestone, marl and clay). The planar slip surface is structurally controlled and such landslides are constrained to slopes that follow the dip of the strata. Rotational slides develop along curved rupture surfaces in the most homogeneous clay formations present in the study area. The study area has also been affected by small debris flows and rock falls. Nevertheless, these landslides were not considered in the present study as they are too few to model and validate slope instability conditions.

The Municipality of Loures is located contiguous to Lisbon and has a population of approximately 205,000 inhabitants (National Institute of Statistics (INE) 2011). This area was particularly interesting to analyze because, belonging to the metropolitan zone of Lisbon, its number of inhabitants is growing annually. In addition, the pressure of urban growth has been responsible for significant land use changes in the last 50 years, namely a decrease in agricultural and pasturing activities, and the expansion of building and road construction (Zêzere and others 1999). This past urban development did not take into account the existence of landslide prone areas in the study area. Therefore, the number of exposed elements has been increased, and consequently the risk, also has increased. Indeed, according to preliminary results obtained in the framework of the new Land Use Plan for the Lisbon Metropolitan Area (PROT-AML), the construction on unstable slopes within the Loures Municipality increased by 64% between 1995 and 2007.

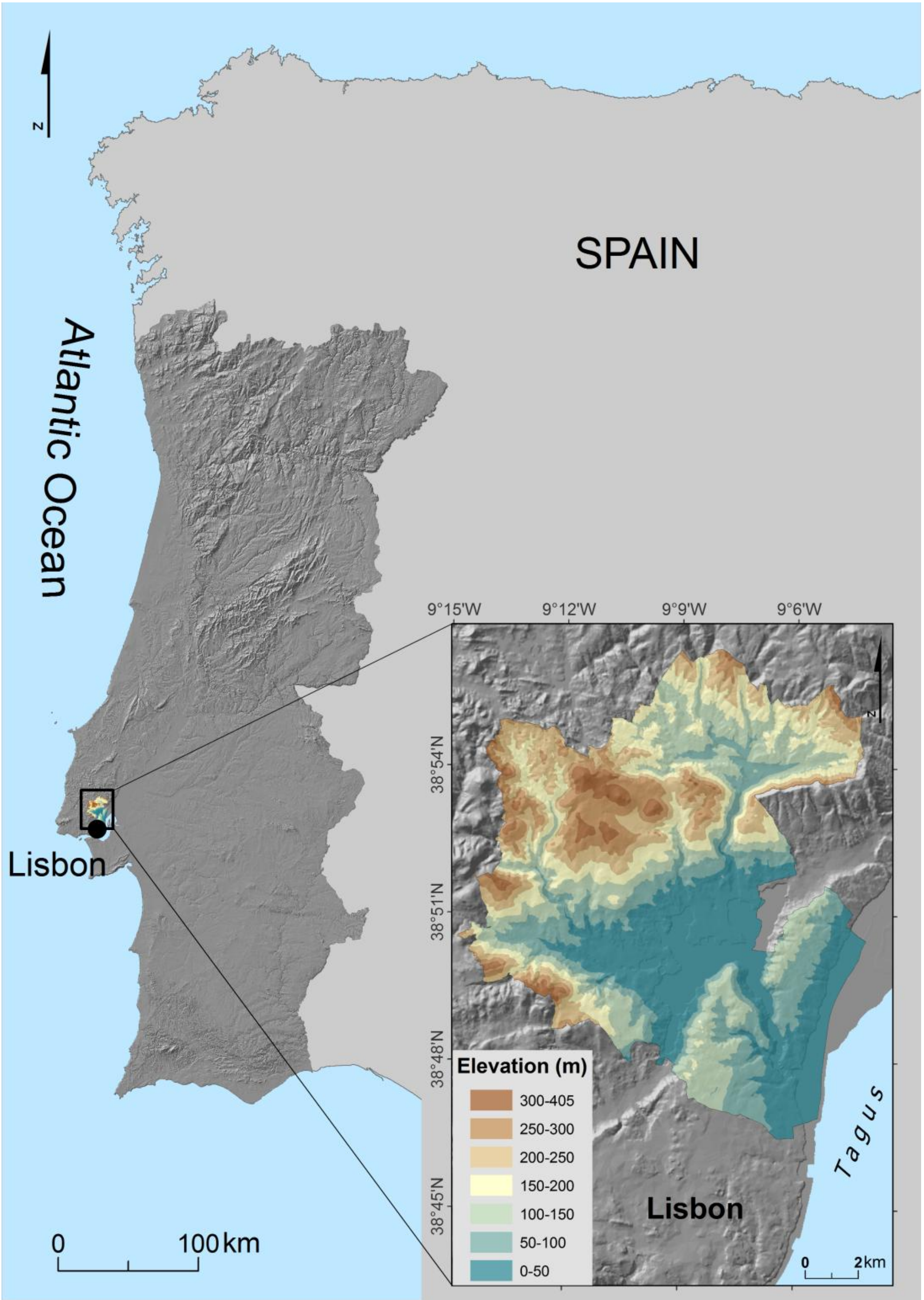

Fig. 1.1 - Geographic situation and elevation of Loures Municipality

1.3. Data and methods

1.3.1. Landslide inventory and probability of landslide area

The landslide inventory was constructed collecting data from three different sources. The first source is an inventory going back to 1996 which was made from aerial photographs interpretation and validated by intensive field work in two test areas within Loures Municipality (Fanhões-Trancão, 18.7 km² and Lousa-Pinheiro de Loures, 28.6 km²) (Zêzere and others 1999). It contains 303 landslides represented by polygons and corresponding to 0.71 km² of unstable area. Only 147 of them could be dated.

The second source is the interpretation of aerial photographs covering most of the Municipality. The photos were taken at the 1:15,000 scale, in December 1983, after a particularly intense rainfall episode occurred in 18 November 1983 which was responsible for an event of major slope instability (Zêzere and others 1999). They allowed us to identify 70 landslides stereoscopically, which correspond to 0.26 km² of unstable area.

The third source is the interpretation of detailed geo-referenced digital ortophotomaps of the entire Loures Municipality (pixel = 0.5 m). These ortophotomaps, dating back to 2004, were combined with the accurate topography (contour lines spaced every 5 m) for photo interpretation. Landslides were located at the 1:2,000 scale. The photographic characteristics for landslides identification were the following (Soeters and van Westen 1996): (1) light-toned scarp, associated with small, slightly curved lineaments, (2) oval or elongated depressions, (3) coarse surface texture, contrasting with smooth surroundings, (4) anomaly in valley morphology, often with lobate form and flow pattern on body, (5) light-toned elongated areas at crown of mass movement or on body, and (6) denuded areas showing light tones, often with linear pattern in direction of movement. Moreover, the presence of consolidation walls was a sign of the presence of a landslide. The obtained landslide inventory has 313 polygons, corresponding to 0.73 km² of unstable area.

The final inventory, constructed by adding these three inventories, comprises 686 slides, representing 1.7 km², that is to say 1% of the municipal area.

From the geomorphological point of view, the final landslide inventory is enough representative of the landslide spatial incidence in the Municipality although it is certainly incomplete. Indeed, the morphological signs of landslides may disappear a few months after landslide occurrence by the human action associated to cultivation or development purposes.

In a first step, each landslide was mapped as a polygon, representing the surface of moved material. In a second step, each landslide polygon was split in two parts representing the landslide depletion and accumulation zones. The landslide typology was specified according to the geometry (rotational slides and translational slides) and depth of the slip surface (shallow slides and deep slides). The threshold of 1.5 m for the depth of slip surface was used to distinguish between deep and shallow slides, following the proposition of Zêzere and others (2008a) for the Lisbon region.

Dependence of landslide probability densities on landslide area was estimated using the probability density function proposed by Malamud and others (2004), considering two landslide groups: shallow and deep landslides - deep landslides comprising rotational and translational slides. We also assessed the probability of landslide size, which is a proxy for landslide magnitude (Guzzetti and others 2005b).

1.3.2. Landslide predisposing factors

The landslide predisposing factors are used as independent variables for the elaboration of the landslide susceptibility maps. Their choice was made according to their physical meaning and the availability of data.
Contour lines at every 5 meters allowed the construction of a digital elevation model (DEM), of which four of the seven independent variables were extracted. Within each variable, the values which have the same characteristics are gathered to form a class, each variable having a specific number of classes. The imperfections arising from the DEM elaboration were corrected by a hydrological function of analysis of the SIG, which finds the "wells" (the places where altitude is very low and which are surrounded by a high-altitude field) caused by the transformation of the TIN into raster, and fills them by replacing their altitude with the value of the closest, lowest altitude. The seven variables used for this study and their physical meanings are:

- Slope angle, which is directly related to the physical properties of the landslides under the force of gravity. Moreover, the instability of the rock and soil theoretically tends to increase with the slope angle. This is checked easily in Table 1.1 where IV values increase with the slope angle.

- Slope aspect, which could be related to the weather and climate, where south-facing slopes receive more sunlight than those that are north-facing. However, the altitude of Loures is not large enough for this to be relevant. As the general geological structure is characterized by a monocline dipping to south and southeast, the south-facing slopes in Loures correspond to the dip slopes, and are more susceptible than the others to deep translational slides (see Table 1.1).

- Plan slope curvature, which is the curvature of the surface perpendicular to the slope direction, and is related to the superficial and sub-superficial runoff flow, which converges when the slope is concave and diverges when it is convex. Theoretically, straight slopes do not influence the water flow.

- Inverse of Topographic Wetness Index (ITWI), which is an index that qualifies the moisture retention, the soil water content and the surface saturation zones (Lopes da Fonseca 2005). It is calculated as follows for each pixel:

$$\mathrm{ITWI} = \frac{\tan \beta}{a}$$

where: a is the specific catchment area, i.e. the upslope area per unit width of contour (m^2), and β is the slope steepness, i.e. the maximal rate of elevation change in gravitational f ield, ranging from 0° to 90°; geometrically it is an angle between the horizontal plane and tangential to the surface plane (degrees).

- Geology, which characterizes, indirectly, the mechanical properties of the rocks. Therefore, this variable is a proxy of the shear strength of terrains which directly controls the stability state of slopes.

- Soil types, which characterize, indirectly, the mechanical properties of the soil and are particularly important for the study of shallow landslides. The soil types benefited from the United Nations' Food and Agriculture Organization (FAO) classification, except the *Brown vertisols* class.

- Land use, because, on the one hand, the anthropogenic activity can be a factor affecting landslides (Varnes and others 1984; Soeters and van Westen 1996; van Westen and others 2008). However, on the other hand, the slopes where the vegetation is dense and deeply rooted tend to be more stable than those where it is short or absent.

Each variable is represented in raster and the selected size of a pixel is five meters for each thematic layer, which is in accordance with the detail of cartographic information. For generating the slope curvature, the precision of the DEM was degraded so that the representation is more realistic; in this case, the size of a pixel is twenty-five meters. Then it was crossed with a raster of the study area to return to pixels of five meters.

Classes within each thematic layer are described in Table 1.1.

Table 1.1 - Thematic layers and Information Value scores of variables considering the modeling groups of landslide types. More significant results are highlighted in bold.

Thematic layer Class	**Class ID**	**Number of pixels**	**Rota-tional slides IV**	**Deep transla-tional slides IV**	**Shallow transla-tional slides IV**
Slope angle					
[0 - 5[	1	2469554	-2.934	-1.940	-2.682
[5 - 10[	2	2014058	-1.130	-0.142	-0.666
[10 – 15[	3	1099793	0.154	0.516	0.041
[15 - 20[	4	559885	1.035	**0.938**	0.782
[20 - 25[	5	317099	1.493	0.839	1.365
[25 - 30[	6	173792	1.643	0.756	1.681

[30 - 35[	7	77930	**1.853**	0.783	**2.032**
[35 - 40[	8	26466	**1.990**	**0.906**	**2.298**
≥ 40	9	11924	**2.222**	**1.078**	**2.487**
Slope aspect					
Flat	1	1102194	-3.550	-2.847	-4.501
N	2	479050	**1.347**	0.054	0.104
NE	3	691717	0.009	-0.235	0.066
E	4	881006	-0.201	-0.236	0.286
SE	5	979464	-1.059	-0.224	-0.396
S	6	971188	-1.966	**0.413**	-0.092
SW	7	727071	-0.895	**0.977**	-0.098
W	8	514038	0.492	-0.518	**1.009**
NW	9	404773	**1.516**	0.104	**0.521**
Slope curvature					
Concave	1	82512	**0.484**	**0.228**	**0.361**
Flat	2	94037	-0.999	-0.756	-0.764
Convex	3	93440	0.083	**0.269**	0.142
Inverse of Topographic Wetness Index					
0	1	1289719	-2.698	-2.540	-2.617
]0-0.0001]	2	284088	-0.845	-0.862	-1.165
]0.0001-0.001]	3	1284086	-0.235	**0.061**	-0.310
]0.001-0.01]	4	3057971	**0.319**	**0.372**	**0.370**
]0.01-0.149]	5	812029	**0.468**	-0.140	**0.369**
Geology					
Basalt and volcanic tuff (Neo-Cretaceous)	1	1621788	-0.750	0.543	0.451
Alluvium (Quaternary)	2	964620	-1.545	-4.843	-0.883
Compact limestone (upper Cenomanian)	3	159772	0.089	-0.069	**0.715**
Terrace deposit (Quaternary)	4	148664	-2.800	-4.900	-4.600
Volcanic intrusion	5	116980	**1.333**	-4.900	0.183
Sand and sandstone (Miocene)	6	640180	-0.088	-4.900	-0.601
Clay (Miocene)	7	78444	-1.378	-4.900	0.702
Limestone (Miocene)	8	380372	-0.914	-4.900	-1.045
Sandstone and marl (Tithonian)	9	507176	-0.664	-4.900	-4.511
Marl and limestone (Tithonian)	10	386900	0.544	**0.954**	-1.140
Conglomerate, sandstone and clay (Paleogene)	11	491380	0.306	-4.900	-0.776
Limestone (Paleogene)	12	22808	-2.800	-4.900	-4.600
Marl and marly limestone (Albian - Cenomanian)	13	589264	**1.306**	**1.566**	**1.146**
Sandstone, conglomerate and siltstone (Berriasian)	14	139640	-0.480	-4.900	-0.753
Limestone, marl and dolomite (Barremian - Aptian)	15	203728	0.471	-4.900	-0.044

Sandstone, conglomerate and siltstone (Hauterivian - Barremian)	16	147756	0.369	-4.900	-0.091
Marl, sandstone and limestone (Valanginian - Hauterivian)	17	53968	-2.800	-4.900	-0.661
Sandstone, siltstone and limestone (Tithonian - Berriasian)	18	69248	-1.068	-4.900	0.227
Limestone, sandstone and siltstone (Hauterivian - Barremian)	19	50764	-2.718	-4.900	-4.600
Soil type					
Fluvisols	1	153936	-1.760	-1.493	-1.138
Bare rock	2	4624	0.825	-5.800	-1.700
Solonchaks	3	53311	-1.241	-5.800	-1.700
Brown vertisols	4	1158	-2.100	**4.311**	**1.060**
Vertisols	5	287734	-0.740	-0.092	0.587
Leptosols	6	74766	-1.061	0.703	-0.523
Kastanozems	7	9747	**1.890**	-5.800	**0.956**
Cambisols	8	298821	-0.701	-0.101	-0.261
Luvisols	9	128082	-0.025	0.044	0.307
Calcisols	10	451374	**0.901**	0.514	0.296
Social area	11	229817	-2.071	-5.711	-1.691
Land use					
Cultivated areas	1	319886	**0.226**	-0.243	-0.234
Built areas	2	514955	-1.403	-0.765	-1.087
Forested areas	3	102829	-0.510	-1.816	-0.559
Water course	4	18144	-5.600	-1.900	-3.300
Dense shrubs	5	464459	**0.850**	**0.938**	**0.946**
Empty spaces in construction	6	4295	-5.600	-1.900	**0.356**
Empty spaces without construction	7	147381	-2.164	-1.900	-3.275
Extractive industry	8	4125	-5.600	-1.900	-3.300
Alluvium (Quaternary)	9	8154	-5.600	-1.900	-3.300
Industries	10	109141	-5.563	-1.900	-3.300

1.3.3. Modeling strategy

The 686 inventoried landslides were divided into three groups according to the type of landslide. The first set comprises 292 rotational slides (Fig. 1.2.a), the second one contains 61 deep translational slides (Fig. 1.2.b) and the third consists of 333 shallow translational slides (Fig. 1.2.c).

We wondered whether it was better to consider the depletion area of landslides or to model landslide susceptibility with the complete landslide affected area. Indeed, on the one hand, it might seem more rigorous from the scientific point of view to consider only the depletion areas for modeling landslide susceptibility. But on the other hand, in doing so, landslide damage might take place in areas that would be themselves not susceptible to failure but that would be impacted by landslide coming from upslope. Consequently, if predisposing factors of total (i.e. depletion + accumulation) landslide areas are equal or very similar to those of the depletion areas, we can model with total areas, and the landslide susceptibility map expresses the likelihood of an area to be involved in the rupture zone or accumulation zone of a landslide. This proposition is in accordance with the statement of Chung and Fabbri (2005), who recommend to model with the total landslide areas when their spatial signatures are not significantly different from the ones of the depletion areas.

To evaluate the accuracy of a landslide susceptibility model, this needs to be validated in an independent way, i.e. with a sample of landslides which was not used to construct the model. Therefore, we split the landslides of each type into two groups. Ideally, the landslide partition should be based on a temporal criterion. Although the absolute age of most slope movements is unknown, the (relative) temporal component of the landslide inventory could support a partition using the year 1996 as the temporal threshold. This option would allow to obtain modeling and validation landslide groups equivalent in number and landslide affected area for both rotational slides and shallow translational slides. However, 56 of the 61 deep translational slides occurred before 1996, and only 5 were mapped from the ortophotomaps dating back to 2004. These two groups being too different to permit an accurate validation, we chose to split the three landslide sets with a random criterion, into two groups of equal dimension (Fig. 1.2). Three landslide susceptibility models were elaborated using only the landslides of the first groups, represented in black in Figure 1.2 and called modeling groups. The second groups are the validation groups and they are represented in grey in Figure 1.2.

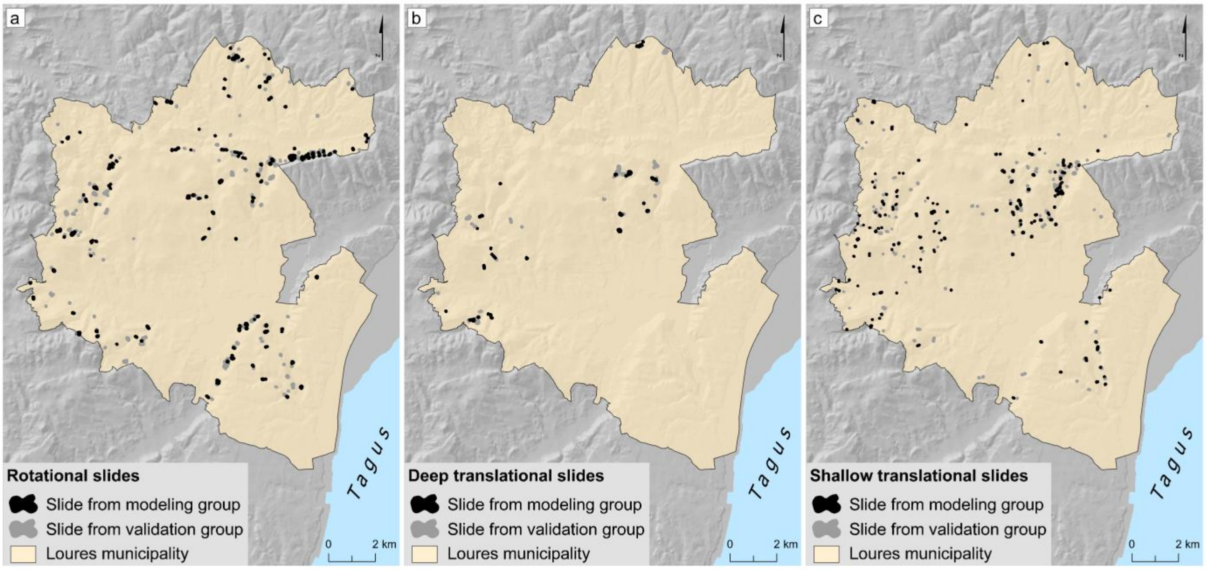

Fig. 1.2 - Landslide inventories of rotational slides (a), deep translational slides (b), and shallow translational slides (c); to facilitate visualization landslides areas were magnified.

The Information Value (IV) Method was used to assess quantitatively the landslide susceptibility independently for each type of landslide. Accordingly, the weighting of each class within each variable is given by Eq. (1) (Yin and Yan 1988):

$$IVi = \ln\left(\frac{Si/Ni}{S/N}\right) \qquad (1)$$

where: Si = the number of pixels with landslides belonging to modeling group and the presence of variable *Xi*

Ni = the number of pixels with variable *Xi*

S = the total number of pixels with landslides belonging to modeling group

N = the total number of pixels

S/N is the *a priori* probability. It is the probability for each pixel to have a landslide without considering predisposing factors.

Si/Ni is the conditional probability. It is the probability to have a landslide given the presence of variable *Xi*.

Negative *IVi* means that the presence of the variable is favorable to slope stability. Positive *IVi* indicates a relevant relationship between the presence of the variable and landslide distribution**;** the higher the score, the stronger the relationship (Yan 1988). *IVi* equal zero means no clear relationship between variable and landslide occurrence.

The classes of each variable not containing any landslide have a conditioned probability equal to zero. In this case, *IVi* cannot be obtained because of log transformation, and therefore the *IVi* was forced to be equal to the decimal value lower than the lowest *IVi* within the variable.

The susceptibility map is then obtained by the sum of the *IVi* of each variable present in each pixel (Eq. (2)).

$$IVj = \sum_{i=1}^{m} Xji\, IVi \qquad (2)$$

where: m is the number of variables and Xji is either 0 if the variable is not present in the pixel j, or 1 if the variable is present.

The information value of each class of the seven variables was calculated three times using the landslide modeling groups, first considering the rotational slides, then considering the deep translational slides, and finally considering the shallow translational slides. Thus, three landslide susceptibility maps were elaborated, one for each type of landslide.

Landslides of the validation groups were inserted into the above mentioned susceptibility models and three prediction-rate curves were computed, one for each landslide type set. Their Areas Under Curves (AUC) were calculated in order to quantify the global quality of each prediction model; higher is his value, better is the model (Bi and Bennett 2003; Garcia and others 2007; Pereira 2010). The AUC is computed using Eq. (3).

$$AUC = \sum \left[(x_{i+1} - x_i) \frac{y_{i+1} + y_i}{2} \right] \qquad (3)$$

where x gets the percentage of study area predicted as susceptible by descending order and y the percentage of correctly classified landslide area belonging to the validation group.

1.3.4. NER delimitation

According to the National Commission of the National Ecological Reserve (CNREN 2010), the slopes classified as being most susceptible by the Information Value Method must integrate the NER. The general rules to draw the NER concerning slope instability at the municipal level state that the area to be included in the NER should guarantee the inclusion of at least 70% of the landslides identified in the landslide inventory. This criterion was applied to the three landslide susceptibility models and the union of the obtained areas is selected to integrate the NER.

Finally, the exposed elements of the Loures Municipality are crossed with the obtained NER in order to identify buildings and roads that would not be allowed according to the NER law. All types of building and main roads (motorways, national roads and municipal roads) are considered, using raster with pixels of 1 meter for cross-tabulation.

1.4. Results and discussion

In order to assess probability of landslide area in the Loures Municipality, we decided to aggregate rotational slides and deep translational slides (deep landslides) because of the low number of cases (61) of the latter landslide type. Furthermore, these two types of slope movements have similar mean affected areas and may be described by the same probability density function. The probability of landslide area was also assessed for the shallow translational slide set (shallow landslides) and results are shown in Figure 1.3. Curves represented in Figure 1.3.a correspond to the expected probability for a deep or a shallow landslide according to its size. The left axis represents the probability that a slide will have an area smaller than a given size, and the right axis shows the probability that its area will exceed this given size (Guzzetti and others 2005b). The size of shallow landslides is not very high compared to deep landslides. Indeed, Figure 1.3.a shows that half of the shallow landslides have an area lower than 600 m^2, whereas half of the deep landslides have an area lower than 2,500 m^2. Moreover, the probability of landslide area to be higher than 1000 m^2 is about 0.32 and 0.83 for shallow landslides and deep landslides, respectively. Considering that landslide size is a proxy for landslide magnitude, these results confirm that magnitude of shallow landslides is lower than magnitude of deep landslides (Zêzere and others 2008b). Figure 1.3.b shows the probability densities of deep (grey diamonds), shallow (black triangles) and total (white circles) landslide areas. Their distribution is in agreement with the probability density function described by Malamud and others (2004) which is represented by a black line in Figure 1.3.b. The general trend of deep landslides to have an area larger than the one of shallow landslides is also visible on this graph.

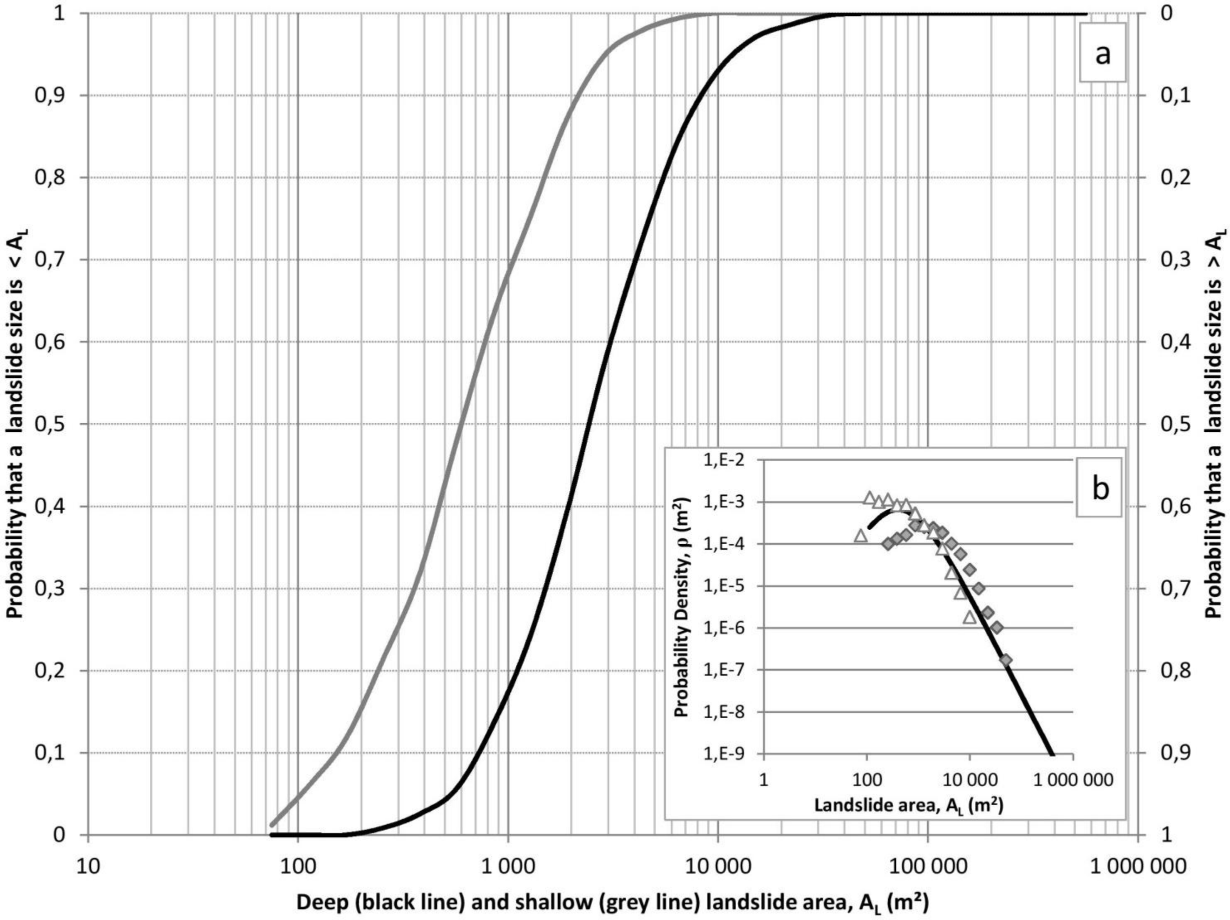

Fig. 1.3 - Probability of landslide area (a) and probability densities (b) for deep and shallow landslides in the Loures Municipality

For each landslide type (rotational slides, deep translational slides and shallow translational slides), we calculated the fraction of landslide depletion areas and total landside areas in each class of each predisposing factor. Figure 1.4 shows the obtained results for the slope angle factor and the geological factor. Stable slope areas are also represented by a double line, which permit to better understand the importance of each class in relation to the total slopes area. We observe that the three landslide types have different spatial signatures, although some classes are important for the total set of landslides, as is the case of geological class 13 (Fig. 1.4.b), that corresponds to marl and marly limestone (Albian – Cenomanian age). For each type of landslide, the depletion area curve is very similar to the curve representing the total landside area. We chose to show in Figure 1.4 only two factors (slope angle and geology being the most significant in terms of the physics of landslides) but the depletion area and total landslide area curves are very similar for the seven predisposing factors. Therefore, we chose to model landslide susceptibility with the total areas of the landslides.

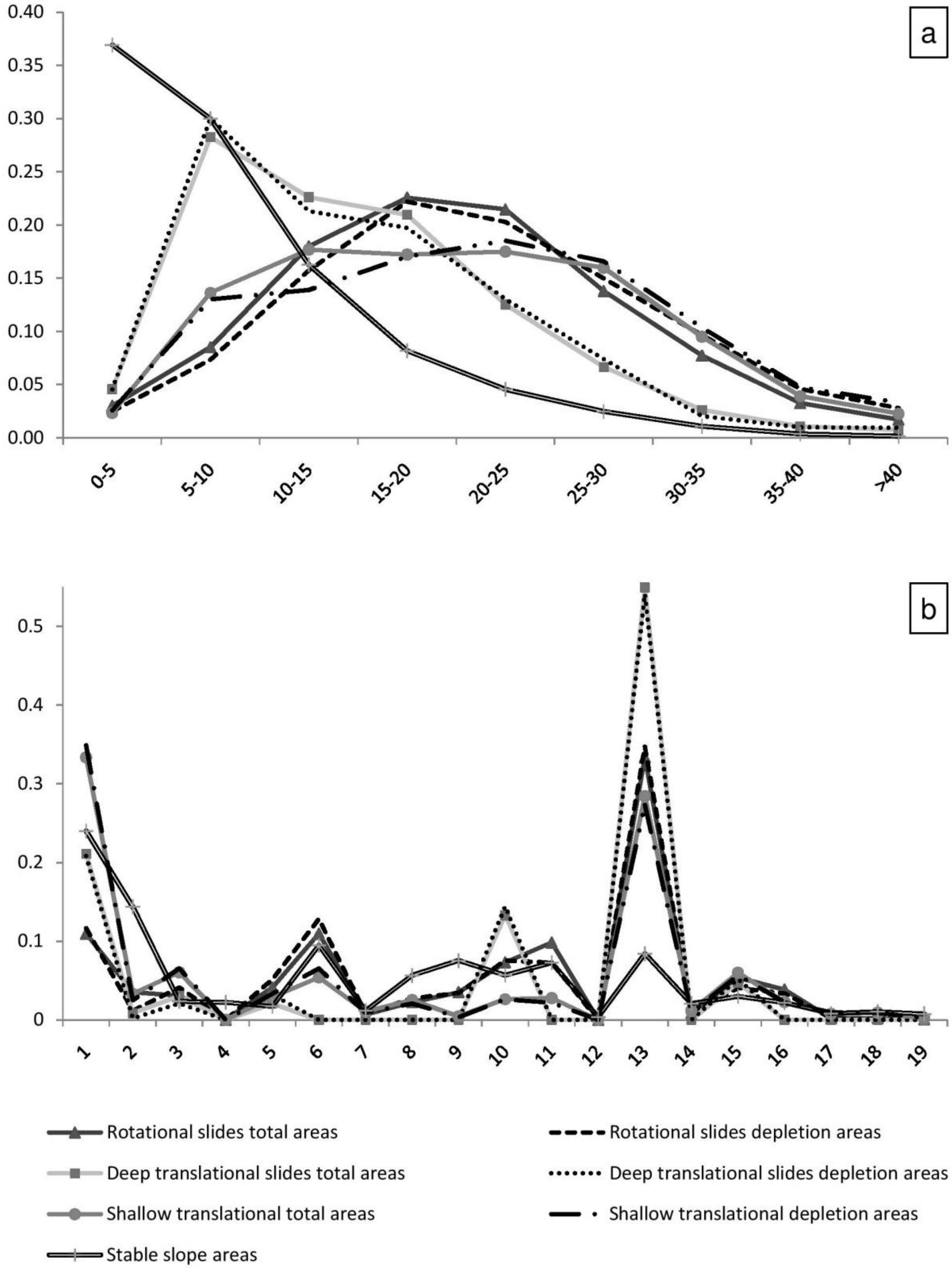

Fig. 1.4 - Fraction of landslide depletion area and total affected area in each class of slope angle factor (º) (a) and in each class of geological factor (see Table 1.1. for signification) (b)

The total affected area of landslides belonging to three landslide modeling groups (one for each landslide type) was cross-tabulated with each predisposing factor in order to compute the IV scores summarized in Table 1.1. According to the obtained results, the ideal conditions for landslide occurrence in the study area are: a concave slope (or convex in the case of deep translational slides) oriented to North, West or Northwest (for rotational and shallow translational slides), and South or Southwest (for deep translational slides) with a gradient above 15°, an inverse of the wetness index above 0.001, a geology containing marl and marly limestone of Albian – Cenomanian age, soils being brown vertisols or kastanozems and covered by dense shrubs (see Table 1.1).

Figure 1.5 shows the three prediction-rate curves obtained inserting the landslides of the validation groups into the susceptibility models created with the landslides of modeling groups. The IV aggregate scores obtained for each pixel were classified in decreasing order and were distributed in four classes so that the zones where susceptibility is the highest can be easily located. AUC values of the three prediction-rate curves are high (from 0.872 to 0.891; see Fig. 1.5) attesting that predictive models are robust. For example, within the 5% of the total study area classified as more susceptible by the three predictive models we found 48%, 51% and 44%, respectively, of rotational slides, deep translational slides and shallow translational slides belonging to landslide validation group.

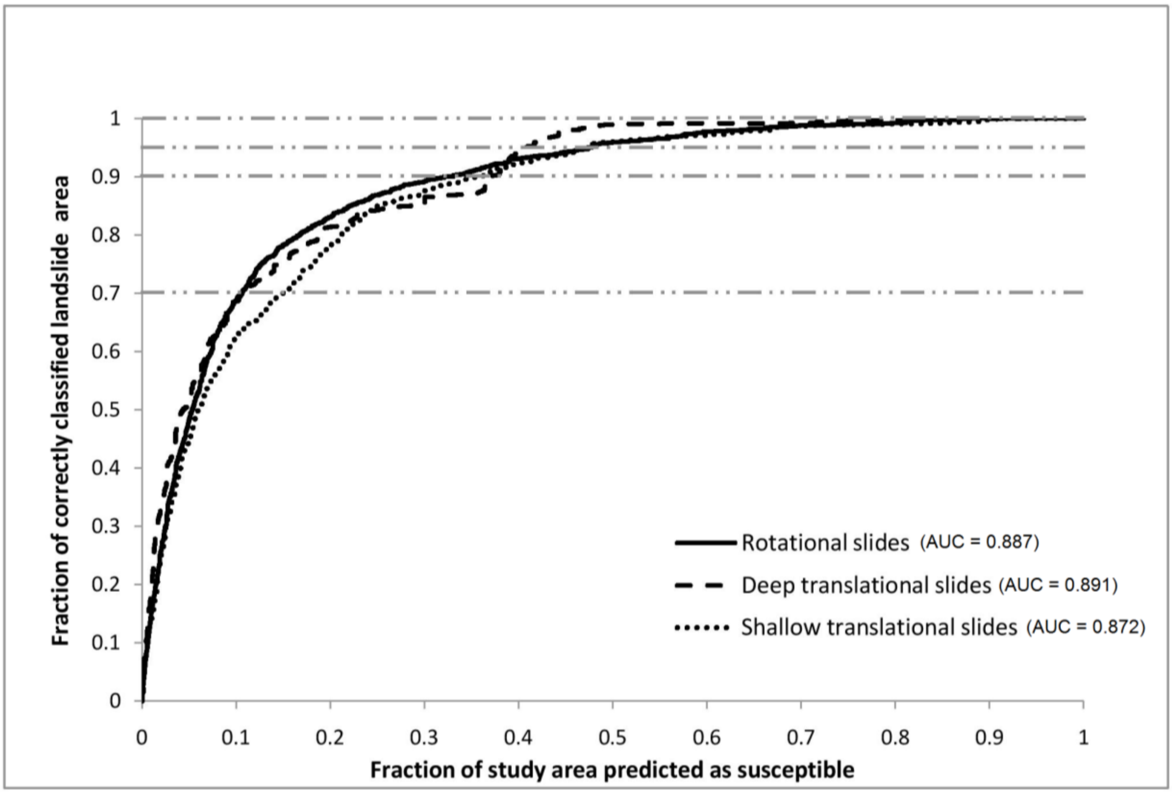

Fig. 1.5 - Prediction-rate curves corresponding to landslide susceptibility models

Table 1.2 - Summary of landslide susceptibility models for the Loures Municipality

Susceptibility class of rotational slides model	Area (pixels)	% of study area	Predictive capacity (%)	Predictive capacity / % of study area
I	716877	10.7	70	6.567
II	1443910	21.5	20	0.932
III	1023718	15.2	5	0.328
IV	3540552	52.6	5	0.095

Susceptibility class of deep translational slides model	Area (pixels)	% of study area	Predictive capacity (%)	Predictive capacity / % of study area
I	706345	10.5	70	6.665
II	1785980	26.6	20	0.753
III	213940	3.20	5	1.572
IV	4018792	59.8	5	0.084

Susceptibility class of shallow translational slides model	Area (pixels)	% of study area	Predictive capacity (%)	Predictive capacity / % of study area
I	1001759	14.9	70	4.699
II	1385835	20.6	20	0.971
III	814009	12.1	5	0.413
IV	3523454	52.4	5	0.095

For each landslide susceptibility model, the susceptibility classes were defined in function of the landslide predictive capacity according to the following rules (Fig. 1.5, Table 1.2): Class I (high susceptibility) includes the area of Loures Municipality with the highest IV scores that validate 70% of landslide validation group. Class II (moderate susceptibility) comprises the surface that validate the following 20% of landslide validation group (aggregate 90%); Class III (low susceptibility) represents the area that validate the following 5% of landslide validation group (aggregate 95%); and Class IV (very low susceptibility) comprises the remaining study area that validate the last 5% of landslides belonging to validation group.

The landslide susceptibility maps are shown in Figure 1.6. According to the susceptibility models, 70% of future rotational slides, deep translational slides and shallow translational slides should occur within 10.7%, 10.5% and 14.9% of the total area, respectively (Table 1.2). The union of those three areas, which are the classes I of landslide susceptibility models (Fig. 1.6) represents 34.3 km² (20.3% of the Loures Municipality area) and is the base of the NER elaboration. Indeed, the NER was constructed generalizing this 34.3 km² area: smaller than 1000 m² isolated areas classified as NER were reclassified as no-NER, and vice versa. The generalized NER, shown in Figure 1.7, is rather compact, which facilitates its exploitation in terms of territorial management. Thus, appropriate measures (e.g. land division and urban development prohibition) taken in this zone, which constitute 20.3% of the surface of Loures, would make it possible to potentially avoid approximately 70% of the damage caused by future landslides. Nevertheless, it is up to the competent authorities of the Municipality to consider a larger area to be included in the NER; but the territorial management costs increase would be higher than the additional proportion of unstable area considered.

We crossed the NER and the exposed elements of Loures Municipality and a small example is shown in Figure 1.8. About 235,900 m^2 of roads (124,590 m^2 of motorways, 56,050 m^2 of national roads and 55,260 m^2 of municipal roads) and 114,040 m^2 of buildings (it means 2,638 buildings) are in the NER. In fact, the total built area of Loures Municipality being 9.3 km^2, the area of buildings situated within the NER corresponds to 2.06% of total built area. Moreover, the area of motorways located within the NER corresponds to 5.71% of total motorways area of Loures, the area of national roads within the NER corresponds 6.55% of total Loures national roads area, and the area of municipal roads within the NER corresponds to 10.36% of total Loures municipal roads area.

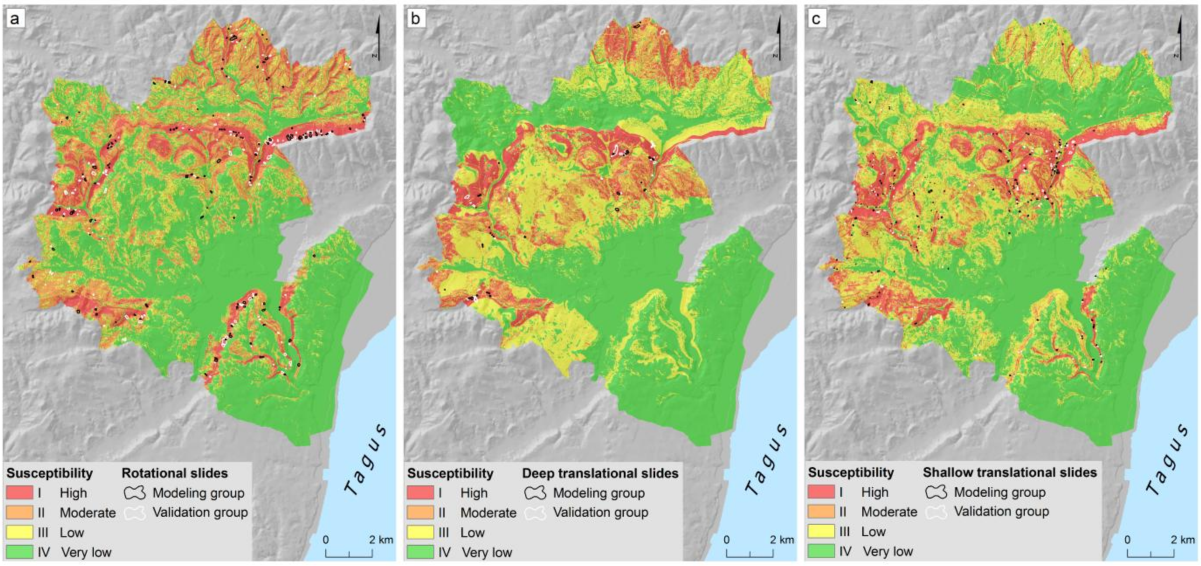

Fig. 1.6 - Landslide susceptibility maps of rotational slides (a), deep translational slides (b), and shallow translational slides (c)

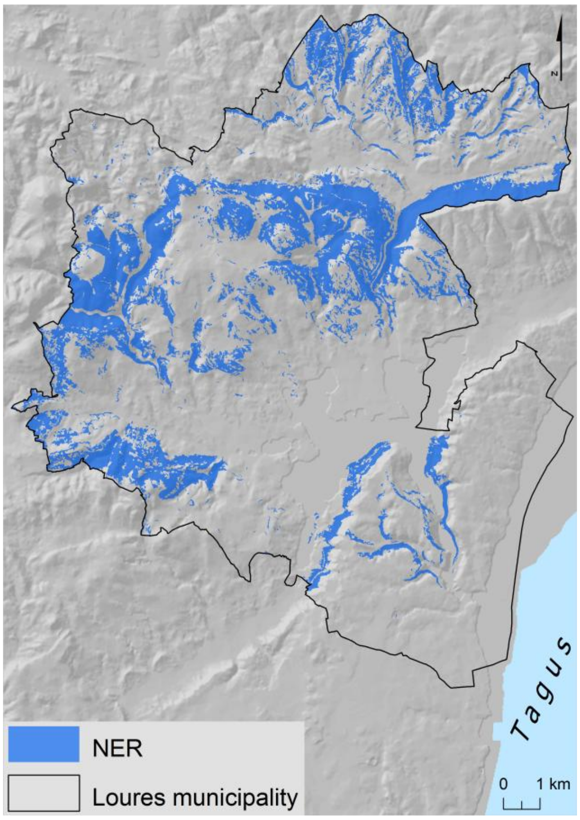

Fig. 1.7 – National Ecological Reserve (NER)

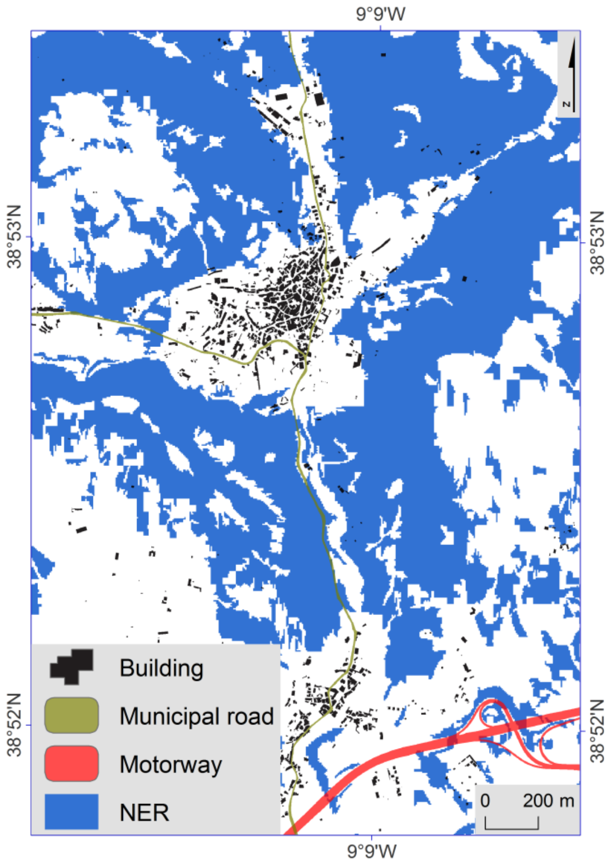

Fig. 1.8 – Example of exposed elements (buildings and roads) distribution and relation with the NER

1.5. Conclusions

In order to decrease the impact of landslides on people, structures and infrastructures, it is necessary to evaluate landslide susceptibility. The National Ecological Reserve (NER) extracted from the obtained susceptibility maps allows the authorities dealing with town and country planning to make good decisions about urban development on those zones identified as being susceptible to landslide occurrence.

A general methodology for landslide susceptibility assessment was applied in a Municipality in the area north of Lisbon. Landslide susceptibility was evaluated assuming that future landslides can be predicted by statistical relationships between past landslides and the spatial data set of the landslide predisposing factors. Thus, landslide susceptibility was assessed independently for three types of slope movements using the Information Value Method, with the superposition of seven thematic layers and an inventory including 686 landslides (292 rotational slides, 61 deep translational slides and 333 shallow translational slides).

Validations of the landside susceptibility models were made splitting randomly the rotational, deep translational and shallow translational slide inventories into two roughly equivalent groups. Prediction images were constructed using the landslides of the first groups (modeling groups), and prediction-rate curves were computed comparing the second landslide groups (validation groups) with the predicted results.

The high Area Under Curves (AUC) values attest that the predictive models obtained are robust, and the quality of the obtained susceptibility maps is very high. For each landslide susceptibility model, four susceptibility classes were defined in function of the landslide predictive capacity.

The NER was obtained using a union procedure of the class I extracted from the three susceptibility models and generalizing the obtained area, excluding areas lower than 1000 m^2 for the sake of a town and country planning application.

The generalized NER is rather compact, which facilitates its exploitation in terms of territorial management. Thus, appropriate measures (e.g. land division and urban development prohibition) taken in this zone, which constitute 20.3% of the surface of Loures, would make it possible to potentially avoid approximately 70% of the damage caused by future landslides. Within this approach, 30% of future landslides should occur outside the NER. Furthermore, a highly unusual and infrequent earthquake and/or a high-intensity rainfall may trigger landslides in areas considered free of landslides. Therefore, site investigations are recommended for urban development projects to be implemented in all potentially dangerous slopes.

The obtained NER was crossed with the exposed roads and buildings which permit to identify what elements are most exposed to slope instability and not according to the existing law. It is not possible to relocate the complete set of buildings and roads within dangerous slopes because of the very high financial costs associated. Also, the extensive engineering works in potentially unstable slopes is not a viable solution because of the high costs involved. Therefore, the landslide prone areas that are currently occupied by buildings and roads should be managed by the Municipal Civil Protection Department, namely through preventive evacuation during high intensity rainfall periods that can be anticipated 24 to 72 hours prior the event using state of the art meteorological models (e.g. WRF model). Nevertheless, population evacuation is neither a simple social process nor a low cost action, and false alarms should be avoided.

In future, the obtained landslide susceptibility maps can be used to assess the risk of landslides triggered by rainfall in the Loures Municipality. Indeed, the landslide hazard can be evaluated integrating triggering information in the modeling procedure. Moreover, the in deep evaluation of vulnerability and value of exposed elements will permit the estimation of potential losses, which, crossed with the hazard, would give the landslide risk analysis.

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Chapter 2

Application of Social Vulnerability Index (SoVI) and delineation of natural risk zones in Greater Lisbon, Portugal

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2. Application of Social Vulnerability Index (SoVI) and delineation of natural risk zones in Greater Lisbon, Portugal

Abstract. Social Vulnerability Index (SoVI) was applied to Greater Lisbon (Portugal). Based on the concepts used for the SoVI assessments in the U.S., forty-six variables representing social vulnerability of the 149 civil parishes of Greater Lisbon were chosen. Thirty-eight variables were selected after application of correlation tests. They were standardized, and a Principal Component Analysis and a Varimax rotation were applied to them. Seven factors were extracted using the Kaiser criterion, which explain 79.5% of the variance, and the SoVI scores were then mapped using a Standard Deviation classification. Twelve of the 149 civil parishes of Greater Lisbon have a very high social vulnerability and twenty-four of them have a high social vulnerability. The map of SoVI was then integrated with susceptibility maps of earthquakes, floods, flash floods, landslides, tsunami and coastal erosion, delineating thus risk zones. Twenty-two civil parishes of Greater Lisbon have a very high risk; among them, seventeen belong to Lisbon Municipality, four belong to Loures Municipality and one belongs to Vila Franca de Xira Municipality. Finally, exposed population was considered and combined with risk zones map in order to assess the number of people being potentially exposed to risk and their location.

Keywords: Natural hazards; social vulnerability; susceptibility maps; risk zones; Greater Lisbon; SoVI; multi-hazard maps; regional scale

2.1. Introduction

Due to their important densities of population and activities, metropolises are highly vulnerable to hazards. In Portugal, many services are centralized in Lisbon and its region, where 19% of the population lives on only 1.5% of the territory. As a global city, the capital and the largest city of Portugal, Lisbon was built near the Tagus estuary and the Atlantic Ocean, which were valuable assets of its development. However, they can also cause misfortune when they trigger floods or tsunami, which consequences may be catastrophic, as in November 1967, when flash floods killed more than 500 inhabitants on the Lisbon region (Quaresma and Zêzere 2012), or in 1755, when the earthquake and the triggered tsunami caused from 30,000 to 60,000 fatalities (Fuchs, K. 2009). How can we better understand the distribution of disaster risk and vulnerability in urban areas?

Firstly, studying hazards, which are, according to ISO (2009, pp.6), "sources of potential harm", and according to UNISDR (2009, pp.17), “dangerous phenomena, substances, human activities or conditions that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage", or assessing susceptibility, which is, according to Guzzetti and coauthors (2005), a spatial probability of a hazard, may highlight the areas that require a special attention in terms of spatial planning. For instance, landslide susceptibility assessment and prohibition to build on the susceptible areas could minimize the impact of landslides on houses and roads, and avoid destruction which occurred in the Metropolitan Area of Lisbon – e.g. in February 1979, January 1996, January 2001 and March 2010, when several houses and roads were disrupted (Zêzere and Trigo 2011).

Secondly, assessment of populations' vulnerability could help emergency managers to understand who is vulnerable to natural hazards so that they can prepare realistic and effective evacuation and response procedures for individuals (Wood et al. 2010). Vulnerability to natural disasters is approached in different ways depending on the disciplines. Indeed, sociologists, interested in social vulnerability, try to assess the difficulty a population would have to recover from a natural disaster and its ability to cope with stress or change, based on the exploration of a set of socio-economic factors (Allen 2003, cited by Fuchs, S. 2009); engineers more often consider the vulnerability in terms of likelihood of occurrence of specific process scenarios, and associated impacts on the build environment, whereas economists are interested in assessing the economic vulnerability (Fuchs, S. 2009). ISO defines vulnerability as "intrinsic probabilities of something resulting in susceptibility to a risk source that can lead to an event with a consequence" (ISO 2009, pp.8), and UNISDR as "the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard" (UNISDR 2009, pp.30). Vulnerability is linked with resilience, but because an important number of different definitions exists, the relationship between the concepts of vulnerability and resilience is not clear and depends on how the two terms are defined (Manyena 2006). In her study, the author examined different definitions and concluded that "two views have emerged: one sees disaster resilience and vulnerability as factors of each other, while the other sees them more as separate entities" (Manyena 2006, pp 443). Moreover, she affirmed that many definitions showed that resilience was not the opposite of vulnerability, as that was often perceived. In the same sense, Cutter and coauthors (2008) propose that resilience and vulnerability are overlapped so that they are not totally mutually exclusive, nor totally mutually inclusive.

Finally, risk is the product of hazard, vulnerability and value of the elements at risk (Varnes et al. 1984). According to UNISDR (2009), risk is "the combination of the probability of an event and its negative consequences" (UNISDR 2009, pp. 25), and according to Randolph, risk is "the probable degree of injury and damage likely to occur from exposure of people and property to the hazard over a specific time period" (Randolph 2004, pp 201). He also affirms that "risk analysis involves combining (or overlaying as maps) assessment of relative hazard, exposure, and vulnerability, as well as analyzing the probability of occurrence" (Ibid.). These definitions are rather complete, but in practice, it is very difficult to assess the risk of a region threatened by several natural hazards and where millions of elements are exposed. A large number of studies assess the susceptibility to one kind of hazard, as it is the case of the study conducted by Guillard and Zêzere (2012) which focused on the landslide susceptibility assessment in Loures, municipality of Greater Lisbon. Other studies are based on the vulnerability assessment and include a susceptibility assessment, as Burton and Cutter (2008) did, studying the social vulnerability of Sacramento-San Joaquin Delta Area (California) with the Social Vulnerability Index (SoVI) and combining the vulnerability with the flood exposure due to levee failure, calling the resulting map "place vulnerability" map. In terms of multi-hazard studies, Tate and coauthors (2010) combined the studies of social vulnerability and economic loss assessments of Charleston County, South Carolina, and the multi-hazard frequency of this county into a multi-hazard of place vulnerability map. Regarding the studies on social vulnerability to disasters that were conducted previously in Portugal, Ribeiro (2006) proposed a model based on eighteen variables (six socio-structural, six socio-urban and six socio-cultural variables) and applied it to two civil parish of the Lisbon Municipality, collecting information interviewing a sample of resident population. The used variables, based on the literature, are similar with the ones considered by Cutter and coauthors (2003), and the result is presented in a table with five classes, most of the population having a medium-high (45.3%) or medium (52.8%) social vulnerability. However, the assessed social vulnerability was not mapped, and the framework for analysis on the degree of social vulnerability being empirical, its reproducibility is reduced. In terms of application of social vulnerability in Portugal using the SoVI created by Cutter and coauthors (2003), a previous study has been done by Mendes (2009). The study area is the Centre Region of Portugal, and the resolution is the municipality. The method is well applied; 13 factors explain 78.8% of the variance. The analysis presents however a small drawback: indeed, the total number of considered municipalities is 78, and the result of the PCA may not be satisfactory according to Hatcher (1994, cited by Garson 2008), who recommended a minimum number of cases above 100 or a number of cases above five times the number of variables for performing factor analyses. The number of variables of the considered study being 50, the number of cases should have been bigger than 100. In a latter work, Mendes and coauthors (2011) present a classification of social vulnerability for the complete municipalities of Portugal, based on the prior definition and assessment of criticality and support capacity.

The main purpose of this study is to go further into the natural risk analysis on the Greater Lisbon area, using a multi-hazard approach. First, social vulnerability was assessed, using the method elaborated by Cutter and coauthors (2003), exploiting socio-economical variables to calculate a social vulnerability score (SoVI score) for each civil parish of Greater Lisbon. This method offers the advantage of being compatible with a multi-hazard analysis, and of being able to be applied at regional scale, by using data provided by censuses from National Institute of Statistics of Portugal, called INE (Instituto Nacional de Estatística). The resulting SoVI map was combined with the susceptibility maps created by Ramos and coauthors (2010) in the framework of the revision of the PROT-AML (*Plano Regional do Ordenamento do Território da Área Metropolitana de Lisboa*, i.e. Regional Plan for Spatial Planning for the Metropolitan Area of Lisbon), thus providing the delineation of risk zones. At last, the population of Greater Lisbon was considered and combined with the risk zones map, thus giving information about the number and the location of Greater Lisbon residents being exposed to the considered natural risks.

2.2. Data and methods

2.2.1. Study area

The study area is Greater Lisbon. It is a sub-region (NUTS III) of the Metropolitan Area of Lisbon (NUTS II) (Fig. 2.1.a and 2.1.b), and is composed by nine municipalities (LAU-1), subdivided into 149 civil parishes (LAU-2) (Fig. 2.1.c). The area of Greater Lisbon is 1376 km^2 and corresponds to 1.5% of Portugal area. The number of inhabitants in Greater Lisbon was 1,947,261 in 2001, which corresponds to 18.8% of the inhabitants in Portugal. This number increases year by year: in 2011, there were 2,042,477 inhabitants, corresponding to 19.3% of the inhabitants of Portugal (INE 2002; 2012). It is also the sub-region of Portugal where the commuting movements are the most intense: according to the INE (2012), 197,328 people get into Greater Lisbon and 53,729 people - i.e. 2.7% of Greater Lisbon resident population, leave Greater Lisbon daily to work or to study.

2.2.2. Data sources

The data used for the social vulnerability assessment was provided by the National Institute of Statistics of Portugal (INE) or was calculated from data collected by the INE. The 2011 Census data was not fully accessible when this study began. Therefore, we used data from the 2001 Census. Even though there is more available data at the municipality level than at the civil parish level, it was not so difficult to get data from 2001. Most of it was available in the statistical database on the INE website, and in a publication of the 2001 Population Census of Lisbon. Information related to the number of pharmacies per civil parish came from CESAP (Carta de Equipamentos e Serviços de Apoio à População, INE 2004) which was also provided by the INE.

Greater Lisbon is prone to different hazard types that should have a meteorological origin (e.g. floods, flash floods, storms, heat waves), or geodynamical origin (earthquakes, tsunami, landslides, coastal erosion). These hazards may evolve into disasters with important consequences on the population.

2.2.3. Difficulties in adapting the SoVI concepts

The social vulnerability assessment is based on the study in which Cutter and coauthors (2003) created the Social Vulnerability Index (SoVI). Cutter and coauthors created SoVI within the context of the United States, which limits its applicability in other national contexts; that is why SoVI was readapted not only to reflect data available from INE and Census sources, but also to suit the societal context of Greater Lisbon. For instance, the variables related to the “Race and Ethnicity” concept in the studies assessing social vulnerability in the U.S. are percentages of (1) African-American people, (2) Native American people, (3) Asian or Hawaiian Islanders and (4) Hispanic people. These variables had to be adapted considering the minorities living in Portugal, and among them, the ones that may suffer discrimination.

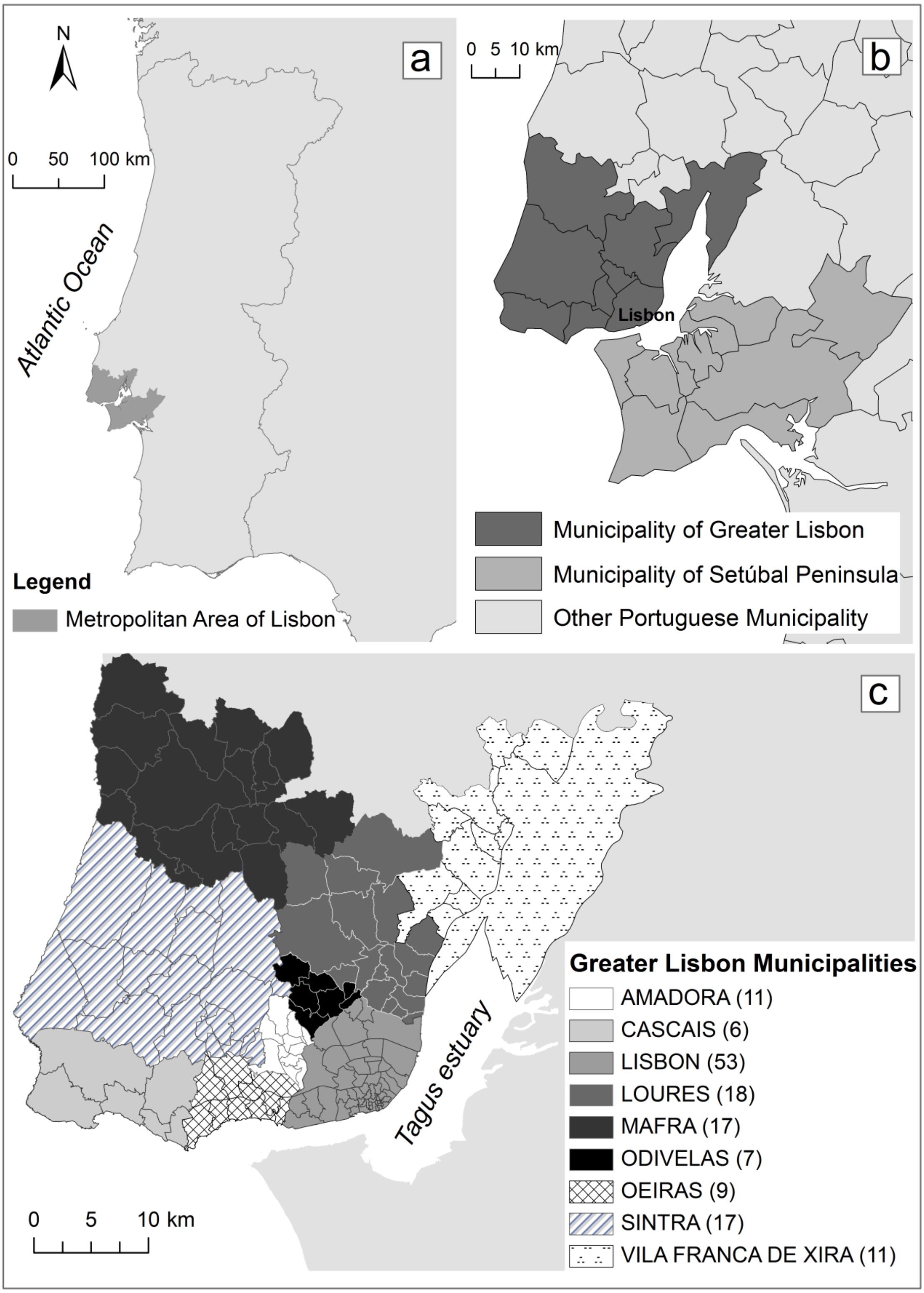

Fig. 2.1 - Situation of Metropolitan Area of Lisbon (a) and of Greater Lisbon (b). Municipalities of Greater Lisbon (c). In Fig. 2.1.c legend, the numbers in parentheses are numbers of civil parishes in 2001.

In terms of minorities, Machado wrote that ethnicity became more important when contrasts of a minority with the society where it was set were more pronounced (Machado 1992). In his study, he represented all the minorities coming from Portuguese-speaking African countries, from India and from Europe on a graph composed by the two following axes: social contrast (defined by, inter alia, residential location, age structure and schooling levels) represented by the vertical axis, and cultural contrast (defined by, inter alia, religious, linguistic, racial and matrimonial dimensions) represented by the horizontal axis. He did not determined minorities with a "strong ethnicity" in Portugal, i.e. with both a high social contrast and a high cultural contrast, even if Guineans and Cape Verdeans had a stronger ethnicity than the other minorities. In terms of discrimination in Portugal, Carrilho and Figueiredo (2007) conducted a study in order to assess discrimination based on racial or ethnic origin, color or nationality, and concluded that the comparative analysis of different information sources highlights disparities between the various nationalities but does not offer evidence about the existence of ethnic discrimination (Carrilho and Figueiredo 2007). However, Marques claimed that "Portugal does not seem to constitute an exception regarding racist attitudes and behaviors in Europe" (Marques, J.F 2007, pp.13); and he added that the main victims of the racism of the Portuguese are African immigrants and Roma population (Marques, J.F 2007). More recently, the Portuguese newspaper "Público" published an article entitled "ONU draws a picture of discrimination and "subtle racism" in Portugal", explaining that persons of African origin living in Portugal are victims of exclusion and marginalization, are underrepresented in political and institutional decision making processes, do not have equal access to education, public services and employment, are discriminated by the justice system, and are victims of racial discrimination and violence by police (Henriques 2012). Finally, Rosário and coauthors (2011) studied racism in Portugal from four discussions groups composed by adults with different social, professional and educational characteristics living in the Metropolitan Area of Lisbon, and concluded that among the participants is a rampant belief that racism in Portugal has legitimately increased in response to the increasing criminality and unemployment, and the perception that foreigners receive more help from the government than Portuguese. The minorities more discriminated by the participants of the study are the Africans, the Brazilians and the Roma populations. Other minorities (e.g. Indians, Asians, Eastern Europeans and Muslims) also suffer discrimination by some participants, for various reasons (for example, people from African and Roma populations are seen like potential sources of physical threats, whereas Indians and Chinese are considered as an economic threat) (Rosário et al. 2011). It was not possible to create a variable representing the Roma populations because no data about Roma populations was available at the civil parish level. However, proportion of people having an African nationality and proportion of residents born in Africa were considered. In order to take into account the other minorities, variables representing all foreigners were also considered.

Regarding the "Socioeconomic Status" concept, the variables used in the original SoVI study (percentage of the population living below poverty level; per capita income) were absent from the INE Census data. Therefore, other variables were used. Some of these variables are related to wealth and standards of living, like the average amount paid to rent a conventional dwelling, or the proportion of overcrowded living quarters; others are related to development, like proportions of private households living without electric installation, toilet installation, sewerage installation or bath or shower installation. The last variable is related to social level and is the proportion of professionals socially more valued. Socioprofessional groups and working population economic activities classification were used in the “Occupation” concept, distinguishing the groups of workers who would be particularly affected after a disaster (population employed in farming, fishing, mining, forestry and population employed in tourism).

Finally, it was difficult to find variables corresponding to the “Medical services & access” concept. Indeed, some variables are available at the municipal level (e.g. the number of physicians per 1000 inhabitants), but only one was available at the civil parish level, which is the number of pharmacies per civil parish, and from which was calculated the number of pharmacies per 1000 inhabitants.

The variables extracted or calculated from the INE data and corresponding to the original SoVI concepts are listed in Table 2.1. An extensive number of variables was selected (forty-six), expecting however to be reduced after analyzing the relationships between candidate variables using a correlation matrix; that is why some variables being quite similar, as the 7th, the 8th and the 9th, or the 42nd and the 44th, were kept.

2.2.4. SoVI calculation

To eliminate redundant information, it was necessary to analyze the relationships between candidate variables using a correlation matrix. Most of the data were not normally distributed, so a Kendall’s tau-b correlation was preferred to Pearson correlation. In addition, Kendall’s tau-b correlation matrix was the one that best summed up the information of the three matrices created by Pearson, Spearman and Kendall’s tau-b correlations. Variables having an important Tau value, i.e. higher than 0.7 or lower than -0.7, were examined. When two highly correlated variables were representing the same aspect of social vulnerability, one of the two variables was removed (for example, QNOBASIC was removed because of its high correlation with QNOBATHSH and QNOFLWC). Sometimes, even though the correlation between two variables was high, the two variables were kept because they represent different data, as is the case for QAFRBORN and QFORNAT. Finally, these eight variables were removed: QNOBASIC, QPOP65O, QUNDER4, Q5-14, QCVLBR, QUNIVST, QDISNOECO, QDISEXTR. The SoVI was created from the thirty-eight remaining variables.

The same methodology that Cutter and coauthors (Cutter et al. 2003) used to create SoVI was applied: The thirty-eight variables were standardized in order to permit a comparison of their values. Principal Components Analysis (PCA) was then applied to the standardized variables, and the principal components were extracted with the Kaiser Criterion - i.e. the components having an eigenvalue higher than one were kept. A Varimax rotation was applied, simplifying thus the interpretation of the components because, after a Varimax rotation, each original variable tends to be associated with one component, and each component represents only a small number of variables, which allows more independency between the components (Abdi 2003; Cutter et al. 2003).

Table 2.1 - Description of the variables chosen to create SoVI for Greater Lisbon. All of them come from the Census 2001 made by the INE, except PHARM1000 that comes from a study conducted by the INE in 2002.

Concept	No.	Name	Variable description
Socioeconomic status	1	AVMORTG	Average mortgage charge resulting from dwelling purchase (€)
	2	AVRENT	Average monthly amount paid for renting a conventional dwelling (€)
	3	QPROFVAL	Proportion of professionals socially more valued (Senior officers of the public administration, leaders and senior officers of companies, and Specialists of the intellectual and scientific professions)
	4	QNOELEC	Proportion of private households in housing units without electrical installation
	5	QNOSEW	Proportion of housing units without sewerage installation
	6	QNOBATHSH	Proportion of housing units without bath or shower installation
	7	QNOWC	Proportion of resident population in housing units without private toilet installation
	8	QNOWCBUIL	Proportion of resident population in housing units without toilet installation in the building (shared toilet)
	9	QNOFLWC	Proportion of resident population in housing units without flush toilet installation
	10	QNOBASIC	Proportion of housing units without at least one basic infrastructure (electricity, sanitary installation, piped water, bath or shower facilities)
	11	QOVERCROW	Proportion of overcrowded living quarters
Gender	12	QFEMALE	Proportion of female population
Race and Ethnicity	13	QAFRBORN	Proportion of population born in Africa
	14	QAFRNAT	Proportion of population with an African nationality
	15	QABRBORN	Proportion of population born abroad (out of Portugal)
	16	QFORNAT	Proportion of population with a foreign nationality
	17	QPSL	Proportion of population whose Portuguese is not its first language
	18	CHPROPFOR	Change in the proportion of resident population with a foreign nationality between 1991 and 2001
Age	19	QPOP65O	Proportion of resident population aged 65 and over
	20	QUNDER4	Proportion of resident population aged 4 and below
	21	Q5-14	Proportion of resident population aged 5 to 14
	22	Q15-19	Proportion of resident population aged 15 to 19
	23	MEDAGE	Mean age (Years) of resident population
Employment loss	24	QUNEMPL	Ratio of unemployed population and labor force
	25	QEMPLRATE	Ratio of employed population Employment rate ((Employed population/ Resident population with 15 and more years old)*100)
Rural/Urban	26	QSOLEAGRI	Proportion of sole agricultural holders

	27	POPDEN	Population density
Renters	28	QRENTER	Proportion of rented or sub-rented conventional dwellings
Occupation	29	QAGRIEXTR	Proportion of population employed in farming, fishing, mining, forestry
	30	QTOURISM	Proportion of population employed in tourism
	31	QCVLBR	Activity rate
	32	QFEMLBR	Female activity rate
Family structure	33	QMONOFAM	Proportion of single parent family nuclei
	34	PPUNIT	Average number of people per household
Education	35	QSCHLEAV	Proportion of school leavers (resident population aged between 10 and 15 years old who left school without attaining lower secondary education)
	36	QUNIVST	Proportion of university students
	37	QNOTALPH	Illiteracy rate
Population Growth	38	POPCHANGE	Change in the resident population between 1991 and 2001
	39	POP5OUTM	Proportion of resident population that, 5 years before, inhabited outside municipality
Medical services and access	40	PHAR1000	Number of pharmacies for 1000 inhabitants (in 2002)
Social dependency (dependency ratio)	41	QDEPEND	Total dependency ratio
Special needs populations	42	QDISAB	Proportion of disabled persons (auditory, visual, motor or mental disability, or cerebral paralysis)
	43	QDISNOECO	Proportion of persons that are disabled and unemployed or without economic activity
	44	QHIGHDIS	Proportion of persons with a disability degree above 60% (the disability degree having been attributed by a health authority constituted for this purpose)
	45	QDISEXTR	Proportion of persons that are disabled and are under 4 or above 65 years old
	46	QDISABLF	Proportion of labor force permanently disabled for work

In order to understand the meaning of the generated independent components, all the significant variables - i.e. variables that have a correlation value higher than 0.5 or lower than -0.5, were extracted from the rotated component matrix. These variables are called drivers of the components. The spatial distribution, value and sign of the drivers allowed us to interpret the components’ meanings, to name them accordingly, and to determine whether they positively or negatively influence social vulnerability. A positive sign was attributed to components that increase social vulnerability; a negative sign was attributed to components that decrease social vulnerability; an absolute value was attributed to components that had both positive and negative implications for social vulnerability. SoVI was then calculated by summing the values of each component for each civil parish, considering their attributed sign. The additive combination of the indicators is suitable in this case because all factors have an equal contribution to the SoVI. Moreover, the reduction of one factor can be compensated by increasing the value of another factor, whereas a multiplicative combination would be more suitable if the utility of one factor depended on another factor (SafeLand 2012), which is not the case here, the factors being independent. Standard Deviation classification was used to map the SoVI scores, which were divided into five classes. This classification emphasizes the extremes, i.e. the very vulnerable civil parishes and the ones that have a very low vulnerability in relation to the others, what can be useful to the decision makers in order to focus the efforts on the most vulnerable civil parishes.

2.2.5. Susceptibility maps and total susceptibility

Earthquake, flood, flash flood, landslide, tsunami and coastal erosion susceptibility maps created by Ramos and coauthors (2010) for the Metropolitan Area of Lisbon were considered. These maps were made in the framework of the revision of the PROT-AML. PROT (i.e. Regional Plan for Spatial Planning) defines the territorial development regional strategies, integrating the options established at the national level, and considering the local development municipal strategies. The Portuguese Government determined the elaboration of the PROT-AML by Resolution of the Council of Ministers no. 21/89. The PROT-AML was approved by Resolution of the Council of Ministers no. 68/2002, and its modification was deliberated by Resolution of the Council of Ministers no.92/2008 (CCDR-LVT 2012). The necessity of its modification was justified, among other reasons, by the options about the location of big transports infrastructures, namely the constructions of the New Airport, the high-speed rail network, the third bridge over the Tagus River in Lisbon and two new logistic platforms. The implementation of guidelines concerning natural and anthropogenic risk areas is included into the modification of the PROT-AML (Resolution of the Council of Ministers no.92/2008, paragraph 2-*b*)*v*)), helping so the stakeholders to chose a relatively safe location for these constructions. Towards this end, Ramos and coauthors (2010) created susceptibility maps for the natural hazards threatening the AML as following: The earthquake susceptibility map was created on the base of three criteria: i) maximal intensities isoseismal lines, based on historical seismicity; ii) peak ground acceleration (PGA), according to the PGA distribution for a 475 years return period (Montilla and Casado 2002); iii) local effects producing amplification of seismic hazard, namely unconsolidated sedimentary geological formations, sedimentary geological formations subjected to liquefaction, and a 100 meters band around the active faults. The areas susceptible to flood and flash flood were delimited: i) considering the Water Law (Lei da Água, Law No. 58/2005, article 4, paragraph ggg) for the Tagus Valley, using the water height reached by the February 1979 flood, which was the worst recorded flood of the 20th century; ii) for the remaining valley bottoms, using the information contained in the Plans of Hydrographic Basin of the West and Sado Rivers, complemented by geomorphological analysis of valley floors, namely the individualization of floodplains from geology and topography at the 1:25,000 scale. To map the landslide susceptibility, Zêzere and coauthors (2008), defined critical thresholds for slope instability based on several scientific studies conducted in the region and on the existing rocks types that were validated by field surveys. The critical slope thresholds used to map the susceptibility to landslide were defined as following: i) from 10º for the surface deposits and plastic sedimentary rocks; ii) from 15º for the detrital sedimentary rocks and for slate and schist; iii) from 20º for the volcanic rocks; iv) from 25º for the remaining rocks. The tsunami susceptibility map was based on the simulation model of the tsunami triggered by the 1755 earthquake provided by Viana-Baptista and coauthors (2006). The model considered six- meter high waves coming from the SW, a fifteen meters reference run-up, and local effects, namely: i) type of coastal zone (beach, cliff); ii) geometry of the coastline and its relation to the most likely spread of wave(s) (SW); iii) altimetry of coastal area and its relation to the height of the tsunami waves; and iv) presence, layout and geometry of obstacles that canalize the wave propagation. Coastal erosion susceptibility was classified as high or moderate according to the following criteria: i) geomorphologic dynamic described in the literature (Marques, F.M.S.F. 1997; Neves, 2004); ii) characterization of the coastal zone in the Coastline Development Plans of Alcobaça-Mafra, Sintra-Sado and Cidadela-São Julião da Barra; iii) for the cliffs: lithology types and their mechanical resistance and inclination of the layers and their geometry in relation to the coastline exposition; and iv) critical points identified by the Institute of Water and photo interpretation.

Each susceptibility map was cross-tabulated with the SoVI map. Pixels of five meters were chosen for cross-tabulation, illustrating what proportion of the civil parishes is susceptible to one or several hazards, and what proportion of the civil parishes’ coastal strips is susceptible to coastal erosion.

To synthesize information on susceptibility to all natural hazards at the civil parish level, the proportions of the susceptibility areas to all hazards were summed in each civil parish, based on the study of Ramos and coauthors (2010). The moderately susceptible areas were not considered, respecting so the choice that was made in the PROT-AML. The result was mapped according to the same classification as the SoVI map, which is the Standard Deviation classification.

2.2.6. Delineation of risk zones and exposed population

A matrix gathering information about social vulnerability classes and about susceptibility to all hazards classes was created. A risk map was delineated on the basis of this matrix, highlighting the civil parishes having both a high social vulnerability and a high susceptibility to hazards in relation to the other civil parishes of Greater Lisbon. This model combines the social vulnerability and the total susceptibility without weighting them, considering that they have an equal weight into the risk zones.

The population of Greater Lisbon is also an important factor that should be considered in terms of risk analysis. Indeed, people are the "elements at risk" within a territory that first need to be protected. Population of Greater Lisbon was mapped, giving a global idea of what parts of the civil parishes are most populated. For that, the exposed population on the civil parish subsections (i.e. subsections created by the INE and used to divide the civil parishes) was represented by dots, each dot standing for 100 inhabitants.

2.3. Results and discussions

2.3.1. SoVI components

Seven components were generated by PCA and selected by the Kaiser Criterion, explaining 79.5% of the variance. They are listed in Table 2.2, with their drivers and the correlation value of the drivers in parentheses.

The first component was named "Urban, Age (elderly) and Gender (female)". It has fifteen drivers and explains 27.0% of the variance. Its representation on a map allowed us to see that the historic center of Lisbon was highly vulnerable. The drivers MEDAGE, QDEPEND, QDISAB and QHIGHDIS loading positively and QEMPLRATE, Q15-19 and QFEMLBR loading negatively show that this factor is related to elderly people. QFEMALE and QMONOFAM loading positively are indicators of the number of women (even though QMONOFAM is the proportion of single parent family, there are more of these families headed by a woman than by a man). POPDEN and QRENTER are related to urbanity. The historic center of Lisbon being a touristic place, it explains why QTOURISM loads positively. It also suffers a population decline, represented by POPCHANGE loading negatively. This component contributing to increase the social vulnerability, a positive sign was attributed to it.

The second component was named "Development and Education". The nine drivers load positively. Most of them represent a low development (absence of sewerage, WC, bathroom or shower). This component also includes the proportion of illiterate people, and is linked with variables representing presence of agriculture. In fact, Greater Lisbon is heterogeneous in terms of urbanization, comprising very urbanized areas, less urbanized areas and rural areas; the contrast existing between these different areas explains the presence of variables linked to agriculture in this component. This factor, which represents 21.8% of the variance, and to which a positive sign was attributed, highlights a strong relationship between rural zones, low educational level and poor building conditions.

The third component was named "Nationality and Ethnicity". The five drivers load positively. They are related to African residents and to foreign nationalities and residents born abroad. It represents 13.3% of the variance and a positive sign was attributed to it.

The fourth component, representing 6.9% of the variance, was named "Wealth and Mobility". It has six drivers, among them only the one representing the proportion of overcrowded living quarters loads negatively. Variables representing wealth and standards of living are highly correlated with this component, and POP5OUTM represents mobility. The proportion of people for whom Portuguese is not the first language is correlated with this component. On the map representing this component, five zones of Greater Lisbon have an elevated or very elevated score.

Table 2.2 - Components, drivers and signs attributed to the components to calculate the SoVI

Component No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Component name	Urban, Age (elderly) and Gender (female)	Development and Education	Nationality and Ethnicity	Wealth and Mobility	Early school leavers and Health deficiency	Disabled Laborers	Medical access
Sign	+	+	+	-	| |	+	+
Drivers and their correlation values	MEDAGE (.918) QEMPLRATE (-.899) PPUNIT (-.891) QDEPEND (.834) QFEMALE (.820) POPCHANGE (-.819) QRENTER (.807) QMONOFAM (.760) Q15-19 (-.700) QFEMLBR (-.650) QDISAB (.627) POPDEN (.618) QHIGHDIS (.601) QTOURISM (.574) POP5OUTM (-.503)	QNOSEW (.915) QNOWC (.892) QAGRIEXTR (.858) QSOLEAGRI (.782) QNOELEC (.767) QNOTALPH (.719) QNOWCBUIL (.590) QNOFLWC (.589) QNOBATHSH (.541)	QFORNAT (.953) QAFRNAT (.861) QABRBORN (.856) CHPROPFOR (.837) QAFRBORN (.816)	AVMORTG (.836) QPSL (.666) AVRENT (.645) QOVERCROW (-.637) POP5OUTM (.595) QPROFVAL(.515)	QSCHLEAV (.747) QHIGHDIS (-.648) QDISAB (-.528)	QDISABLF (.763)	PHAR1000 (-.617)

The comparison of this map and the map of each driver allowed us to understand why these zones have an elevated score (for instance, the civil parishes of the Southwest coast, and more specifically the parishes of Cascais Municipality named Cascais and Estoril, have an elevated or very elevated score because of the combination of elevated average mortgage and renting, elevated proportion of professionals socially more valued, elevated proportion of resident population that, 5 years before, inhabited outside of the municipality, low proportion of overcrowded living quarters and very elevated proportion of population for whom Portuguese in not the first language; observing these results, we can assume that rich, mobile and foreign people live there. Tending to decrease social vulnerability, a negative sign was attributed to this component.

The fifth component has three drivers and represents 4.8% of the variance. It was named “Early school leavers and Health deficiency” because its drivers are the early school leavers (loading positively) and the proportions of disabled and highly disabled people (loading negatively). An absolute value was attributed to this component because all the drivers tend to increase social vulnerability and they load in an opposite way.

The sixth component represents 2.8% of the variance and was named “Disabled Laborers” because of its only driver. A positive sign was attributed to this component.

The seventh and last component was named “Medical access”. It represents 2.8% of the variance, and its only driver is the number of pharmacies per 1000 inhabitants. Tending to decrease social vulnerability and loading negatively, a positive sign was attributed to this component.

2.3.2. SoVI map

Summing the scores of all these components according to their attributed signs resulted in a SoVI representation for Greater Lisbon. SoVI was classified by the Standard Deviation (Std. Dev.) method, highlighting the civil parishes having high (i.e. between 0.5 and 1.5 Std. Dev.; mapped in orange) or very high (i.e. above 1.5 Std. Dev.; mapped in red) SoVI scores. Parishes having low (i.e. between -1.5 and -0.5 Std. Dev.) or very low (i.e. under -1.5 Std. Dev.) SoVI scores are mapped in shades of blue (Fig. 2.2).

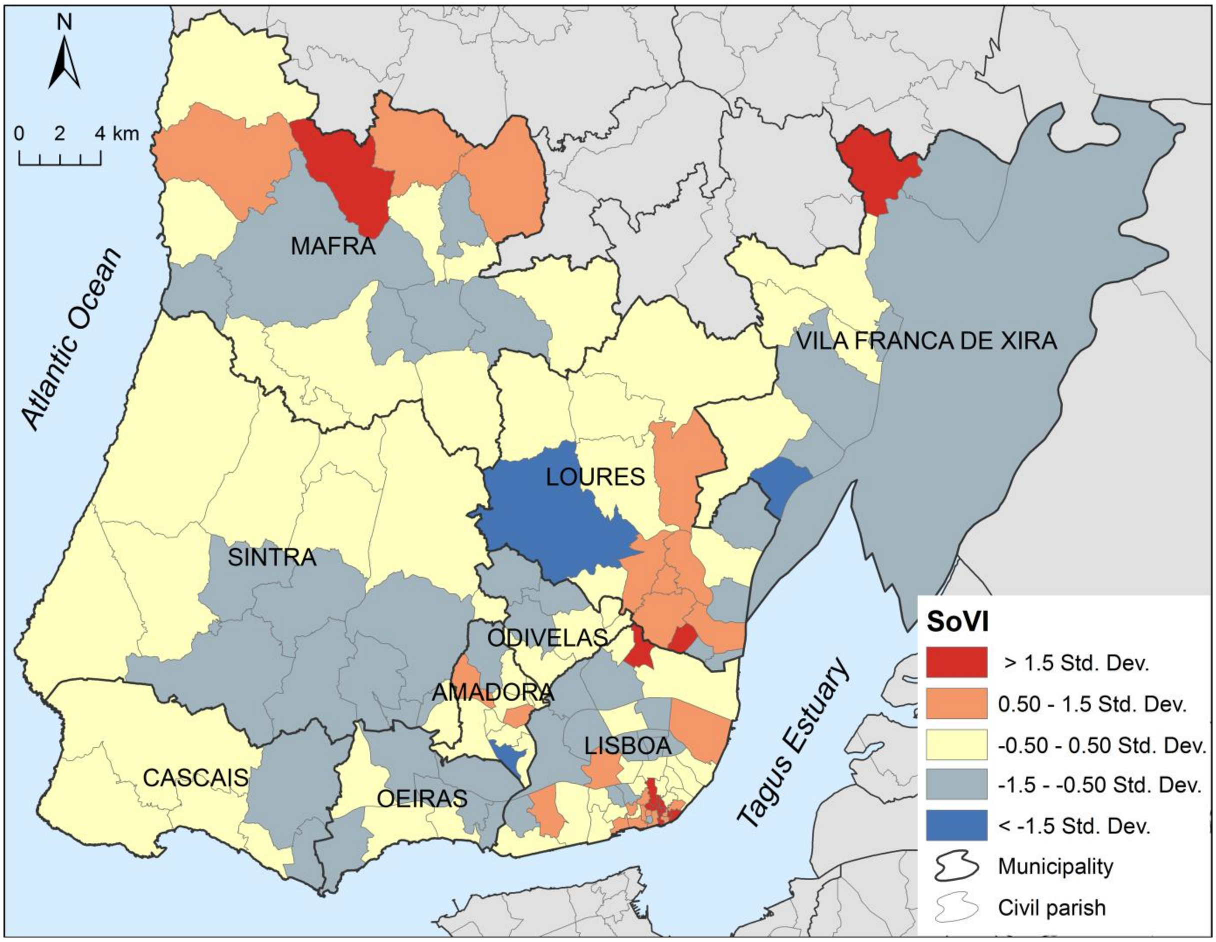

Fig. 2.2- Greater Lisbon SoVI map (data from Census 2001)

Twelve civil parishes belonging to four of the nine municipalities of Greater Lisbon have a very high SoVI score. Among them, nine belong to Lisbon Municipality. Most of these nine civil parishes have a high proportion of urban, female and elderly people, a high proportion of disabled labor force and low medical access, in relation to the other civil parishes of Greater Lisbon. Some of them have a high proportion of school leavers and people suffering health deficiency, and some have a relatively high proportion of foreigners. Prior Velho, the civil parish of Loures Municipality that has a very high SoVI score, has a high proportion of African residents and residents from other foreign countries, a relatively high illiteracy rate and a relatively high proportion of housing units of which infrastructure is underdeveloped. Sobral da Abelheira, the civil parish of Mafra Municipality that has a very high SoVI score, has also a high proportion of housing units of which infrastructure is underdeveloped, and among its population, a high illiteracy rate, a high proportion of early school leavers and of people suffering health deficiency, and a relatively high proportion of residents whose wealth may be low. Cachoeiras, belonging to Vila Franca de Xira, has a very high SoVI score because of its high proportion of labor force permanently disabled for work, its relatively high illiteracy rate, its relatively high proportion of housing units with underdeveloped infrastructure and its high proportion of disabled people.

Twenty-four civil parishes belonging to four municipalities have a high SoVI score. Among them, thirteen belong to Lisbon Municipality, six to Loures Municipality, three to Mafra Municipality and two to Amadora Municipality.

Forty-eight civil parishes belonging to the nine municipalities of Greater Lisbon have a low SoVI score. Only three civil parishes have a very low SoVI score, which are Loures (civil parish of Loures municipality), Alfragide (belonging to Amadora Municipality) and Póvoa de Santa Iria (civil parish of Vila Franca de Xira Municipality).

A large quantity of the vulnerable civil parishes belongs to Lisbon Municipality and in particular to the historic center of the city. But the Lisbon Municipality also has a large number of civil parishes (53) in relation to the others. Nevertheless, Lisbon is the municipality that has the largest proportion of civil parishes with a high or very high SoVI score (41%). Then, Loures Municipality is the second most socially vulnerable, because 38.9% of its civil parishes have a high or very high SoVI score. The third one is Mafra Municipality, with 23.7% of its civil parishes having a high or very high social vulnerability.

The SoVI was assessed at the regional scale, and its resolution was the civil parish; indeed, being the smallest administrative unit in Portugal, it offers an assessment having both a high spatial resolution (higher than the municipality resolution) and a high quality data (better than the sections or subsection of the INE, for which little information about population is provided). These choices influence the SoVI map, which may be different if the scale were larger or smaller, and if the resolution were different. Moreover, as the SoVI metric is comparative, the SoVI map would change if the study area was bigger or smaller. For example, the aggregation of other municipalities in the current study area could generate modifications in the classification of the civil parishes SoVI - a civil parish currently in the "very elevated class" may change to the "elevated class" if the new cases are added, in others words if the study area changes.

2.3.3. Susceptibility maps and total susceptibility map

Earthquake, flood, flash flood, landslide, tsunami and coastal erosion susceptibility maps of Greater Lisbon were combined with the SoVI map, of which classes are the same than the ones shown on Figure 2.2, but which were qualitatively renamed (Fig. 2.3).

Cross-tabulation of the susceptibility maps with the SoVI map provided the areas and percentages of Greater Lisbon being both highly (or very highly) socially vulnerable and highly (or very highly) susceptible to hazards, percentages of Greater Lisbon territory being: 4.7% for earthquakes, 0.03% for floods, 0.91% for flash floods, 2.1% for landslides and 0.29% for tsunami, and the percentage of the coastal area of Greater Lisbon that is highly susceptible to coastal erosion and highly or very highly socially vulnerable being 1.44%.

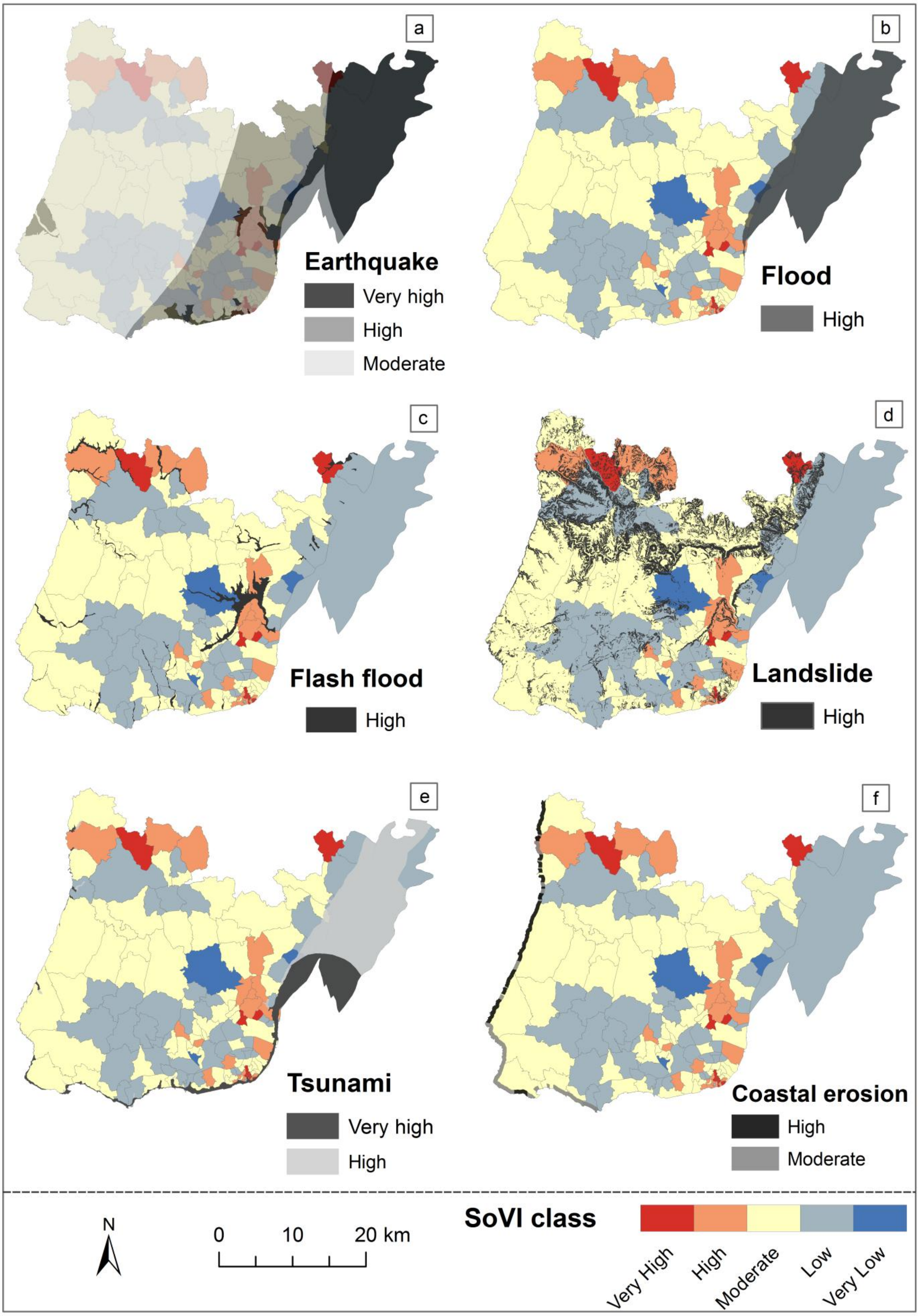

Fig. 2.3 - Greater Lisbon susceptibility maps and SoVI map (data from Census 2001)

Proportions of civil parishes being highly or very highly susceptible to earthquakes, floods, flash floods, landslides, tsunami and coastal erosion were calculated and were added together in each civil parish in order to represent the susceptibility of the civil parishes to all hazards (Fig. 2.4). The twelve civil parishes that have a very high total susceptibility are on the east and northeast (six of them belong to Vila Franca de Xira and one belongs to Loures Municipality) and some of the southeast (the remaining five belong to Lisbon Municipality). The ones of Vila Franca de Xira and Loures Municipalities are very highly susceptible to earthquakes, and highly susceptible to floods and highly or very highly susceptible to tsunami. Moreover, some of them are also susceptible to landslides and to flash floods. The civil parishes of Lisbon Municipality are very highly or highly susceptible to earthquakes, highly susceptible to landslides and very highly susceptible to tsunami. The western half of Greater Lisbon has a low or very low total susceptibility due to its moderate susceptibility to earthquakes and to the absence of susceptibility to floods and tsunami. The only exception is Carvoeira, civil parish of Mafra Municipality, which has a moderate total susceptibility because of a relatively big part of its territory being highly susceptible to flash floods and landslides, and a small part of its territory being susceptible to tsunami and coastal erosion.

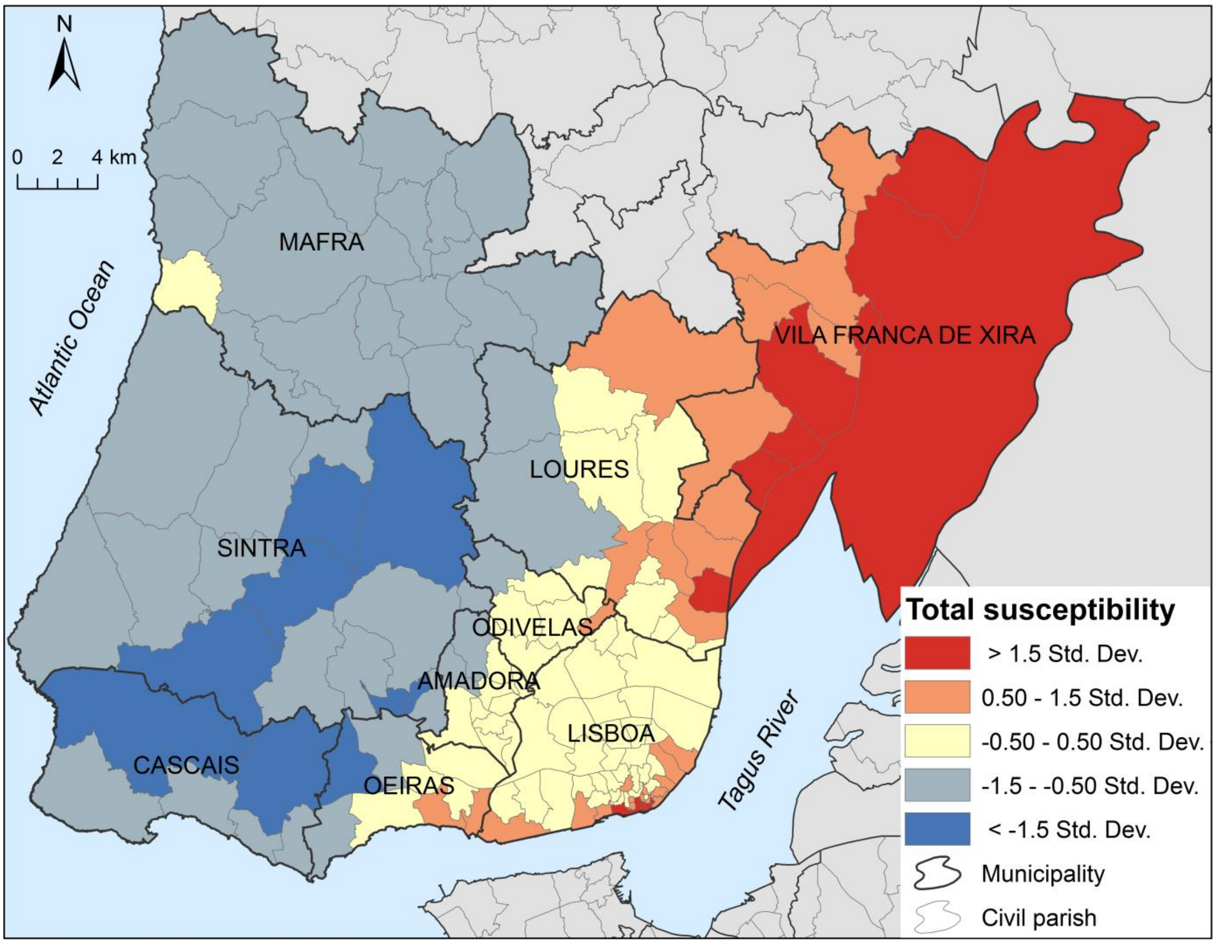

Fig. 2.4 - Greater Lisbon susceptibility to all dangerous phenomena

This model provides a global vision of the repartition of the hazards in Greater Lisbon and could therefore be used as a basis to take decisions in terms of natural hazards reduction policy - for instance it could be used to manage the repartition of the funds for the prevention of natural disasters among the Greater Lisbon civil parishes.

2.3.4. Delineation of risk zones and exposed population

The matrix gathering information about social vulnerability and about hazards susceptibility was made from the classes of total susceptibility map (Fig. 2.4) and of SoVI map (Fig. 2.2), which were numbered from one to five beginning by the "Very High" classes (i.e. the ones with the values above 1.5 Std. Dev.) and ending to the "Very Low" ones (i.e. the ones with the values below -1.5 Std. Dev.). The matrix is shown in Table 2.3.

Table 2.3 - Matrix for delineation of risk zones

+		Susceptibility class				
		Very High -1	High -2	Mode-rate -3	Low -4	Very Low -5
Vulnerability class	Very High-1	2	3	4	5	6
	High-2	3	4	5	6	7
	Moderate-3	4	5	6	7	8
	Low-4	5	6	7	8	9
	Very Low-5	6	7	8	9	10

The numbers of the classes were added together and the resulting numbers were used to create a map of risk zones. As the SoVI map and the total susceptibility map, the risk zones were classified into five classes (Table 2.3 and Fig. 2.5). The civil parishes within the very high risk zone are twenty-two; among them, seventeen belong to Lisbon Municipality, four belong to Loures Municipality and one belongs to Vila Franca de Xira Municipality.

The trend coming from the total susceptibility map (Fig. 2.4) is still present, showing the eastern part of Greater Lisbon with a high risk, and the western part with a low risk, except for Sobral da Abelheira, the civil parish of Mafra Municipality that has a high risk due to its very high SoVI score.

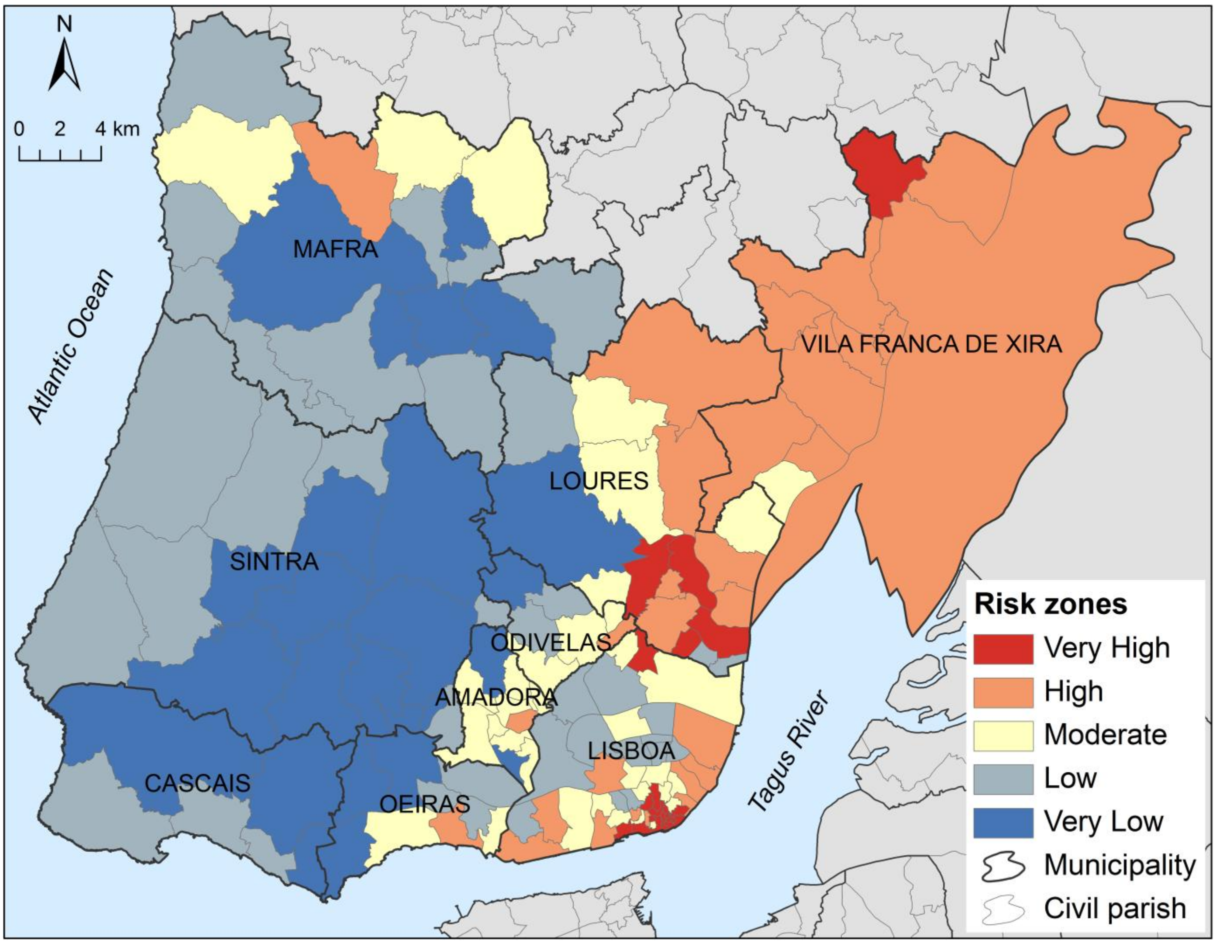

Fig. 2.5 - Greater Lisbon risk zones (SoVI based on Census 2001)

Population exposure is shown in Figure 2.6, each point representing 100 inhabitants. This model shows the population of Greater Lisbon during the night and the weekend, knowing that during the week day, the total population of Greater Lisbon rises by 7.3% because of the commuting movements and has a different distribution.

Lisbon Municipality is densely populated, except on the west side, where is the large Monsanto forested park, on the northeast, where the airport is built, in the middle, where is the University, and along the shoreline. The civil parishes close to Lisbon Municipality are also densely populated, mainly the ones of Amadora Municipality and of the southeast of Sintra Municipality, which are served by the A16 and A37 highways. The surroundings of the A1 highway, which runs through Vila Franca de Xira Municipality from north to southwest, are also densely populated, as well as the south part of Greater Lisbon, situated between the A5 highway and the waterfront.

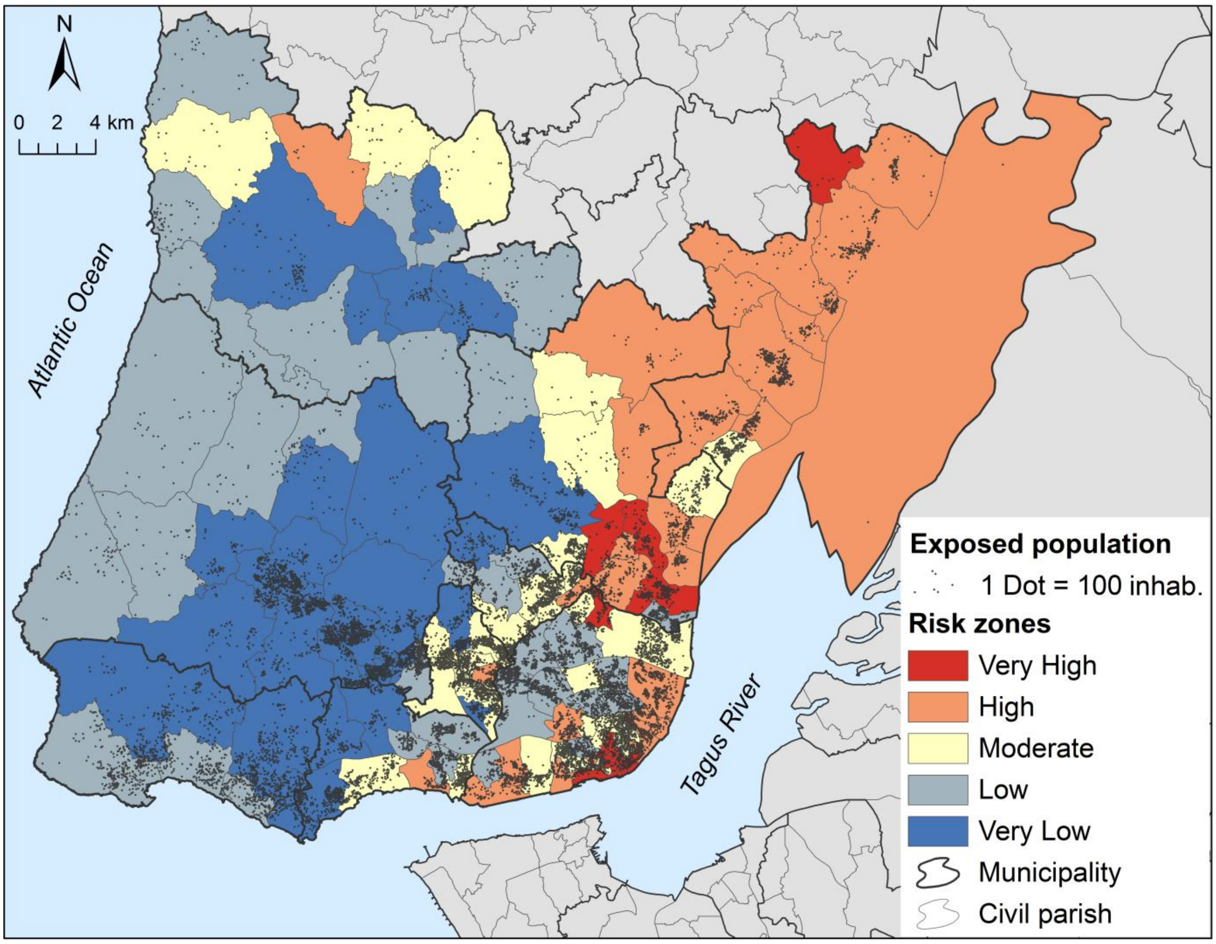

Fig. 2.6 - Greater Lisbon exposed population to risk (SoVI based on Census 2001)

Among the civil parishes having a very high risk, the most densely populated are the ones of Lisbon Municipality; then, the ones in the south of Loures Municipality are quite densely populated. In terms of priority, the stakeholders may then focus their attention on the civil parishes of Lisbon Municipality, Loures Municipality, Vila Franca de Xira Municipality and Amadora Municipality that have a high risk and that are densely populated, before considering the one of Vila Franca de Xira which has a high risk but a relatively low population density. Indeed, even if they are less susceptible to hazards and their populations are less socially vulnerable, the number of inhabitants, which is part of the exposure component of the risk analysis in the Randolph (2004) definition, is so important, that the risk is also important. For the same reason, the civil parishes having a moderate or low risk and a high population density may then be taken into account by stakeholders.

The map shown in Figure 2.6 provides a global vision of the natural risk prone areas and of the potentially affected population. For that reason, it could help the decision makers to implement strategies in order to reduce the social and economical consequences of natural disasters in Greater Lisbon and the emergency managers to prepare realistic and effective evacuation and response procedures for individuals.

2.4. Conclusions

Lisbon and its region are prone to several natural disasters. Being the capital and the largest city of Portugal, many buildings, infrastructures and economic activities are concentrated in Lisbon and its region, where about two million people live. For these reasons, the analysis of natural risks can help the stakeholders to make good decisions in terms of spatial planning.

Social vulnerability was assessed with the Social Vulnerability Index (SoVI) at the civil parish level. Based on thirty-eight variables grouped into seven components, the social vulnerability assessment must be interpreted on two different levels: the SoVI map provides the most socially vulnerable civil parishes (Fig. 2.2), and the attribute table of the SoVI shapefile provides detailed information about the components and the drivers, allowing us to understand the social vulnerability of each civil parish. These tools could be useful for the stakeholders, allowing them to take into account what makes the populations vulnerable and to adapt the prevention and protection measures to the analyzed vulnerability. For instance, the civil parishes being vulnerable because of their high illiteracy rate must have prevention systems understandable by illiterate people.

The obtained SoVI map was combined with the total susceptibility map, which was elaborated from the sum of the percentages of civil parish area susceptible to earthquakes, floods, flash floods, landslides, tsunami, and coastal erosion. The susceptibility analysis must also be read on two different levels, the first one being the total susceptibility map which can be used to detect the most susceptible civil parishes of Greater Lisbon (Fig. 2.4), and the second one is the individual maps built for each dangerous phenomenon (Fig. 2.3), which can be used to know what kind of dangerous process threats the civil parishes. This study provides a global vision of the risk zones in Greater Lisbon; however, studies at a larger scale are required for urban planning.

A matrix gathering information about social vulnerability and total susceptibility was the base of the elaboration of a risk zones map. Finally, exposed population was considered and combined with the risk zones map in order to have an idea of how many people are potentially exposed to risk and of where these people live.

The definition of risk zones as it was done in the present study, i.e. crossing SoVI and hazard susceptibility classes, as well as the superposition of population exposure and risk zones are innovative methodologies in the field of vulnerability assessment and natural risks analysis. These innovative methodological approaches may have impacts on public policies being a support for social policy, helping the stakeholders to focus on the most vulnerable civil parishes and to mitigate their vulnerabilities, caring about its different aspects (vulnerabilities induced by poverty or lack of education cannot be treated the same manner than the ones induced by age or disabilities). In addition, the obtained results may also have an impact on spatial planning and emergency management, helping the stakeholders to mitigate the potential consequences resulting from natural hazardous phenomena by building new infrastructures in areas where risk is low and applying prevention measures and protecting the population where risk and population density are high.

Vulnerability of the buildings and infrastructures was not taken into account in this study. It could be assessed in a future work, but it would be a difficult task, because of the large number of elements at risk in Greater Lisbon, their different physical resistance properties, and their diverse reactions to the different hazards.

A major drawback of this work is that the analysis is based on 2001 Census data, and the recently available 2011 Census has shown major demographic and sociocultural changes in Greater Lisbon, where a municipality like Mafra increased its population by almost 30%. However, all the newer data required for constructing SoVI were not yet available when the analysis was performed. In addition, variable concerning medical services and access are not included in the Census data and it was available only for 2001. Anyway, we intend to explore the Census 2011 data in a future paper to assess change in social vulnerability based on a comparison with the obtained results.

Moreover, a combination of the maps of the principal components coming from the PCA and of the susceptibility maps could be interesting in terms of analysis of the relationships between the socio-economic conditions of the residents and the safety of their place of residence. At last, an economic assessment of the damage and a study of the return period or the probability of the hazards would make possible the analysis of the natural risk of Greater Lisbon.

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Chapter 3

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

Chapter 3 is the full content of the following published paper:

Guillard-Gonçalves, C., Zêzere, J. L., Pereira, S. and Garcia, R. A. C.: Assessment of physical vulnerability of buildings and analysis of landslide risk at the municipal scale – application to the Loures municipality, Portugal, Nat. Hazards Earth Syst. Sci., 16(2), 311–331, doi: 10.5194/nhess-16-311-2016, 2016.

3. Assessment of physical vulnerability of buildings and analysis of landslide risk at the municipal scale. Application to the Loures municipality, Portugal.

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 spatio-temporal 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 knowing the study area, which 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 spatio-temporal probabilities. As a rule, the vulnerability values given by the sub-pool of experts knowing 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 3 m deep landslides, because these landslides combine a relatively high frequency in the Loures municipality with a substantial potential damage.

3.1. 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 to individuals, populations, properties or the environment from landslide hazard (Fell et al., 2008; Corominas et al., 2014; Corominas et al., 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 × V × 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 (Guzzetti et al. 2005; 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 (EV) is the economic value 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 rock fall vulnerability would not be directly transferable to the slow slide vulnerability assessment (Alexander, 2005; Papathoma-Köhle, 2011; Ciurean et al., 2013). Third, the vulnerability of the elements at risk depends on the landslide intensity, which is usually associated to the landslide velocity (Hungr, 1997; Lateltin, 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 damages. 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 hydro-meteorological hazards (e.g. Godfrey et al., 2015).

Quantitative vulnerability studies usually aim to estimate physical vulnerability for 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; Li et al., 2010; Du et al., 2013; Peng et al., 2015; Uzielli 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 not site-specific studies on landslide risk for buildings are available in the technical literature (e.g Michael-Leiba et al., 1999; Cardinal 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 fulfil 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 for 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 spatio-temporal probability of landslides.

In this study, there are few records about building damages 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. having a deep knowledge on 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 coming from the pool of landslide European experts with the answers coming from the sub-pool of landslide experts who know the study area, assessing thus the epistemic uncertainty on 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 spatio-temporal probabilities using pixel units in a GIS environment.

3.2. 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 3,806 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. 3.1) inventoried by Guillard and Zezere (2012), 462 occurred within 50 metres from buildings and roads and some of them produced damage to built environment in the past (Zêzere et al. 2008).

Second, Loures is adjacent to the city of Lisbon (Fig. 3.1) 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 1,220 inhabitants per km^2), which is 6% higher than in 2001 according to the National Institute of Statistics (INE, 2001; INE, 2011). The mean age of the buildings is 37.5 years, 66.9% of them having a structure in reinforced concrete, 30.6% in masonry, 1.8% in adobe, rummed earth or loose stone, and 0.7 in other materials (INE, 2011).

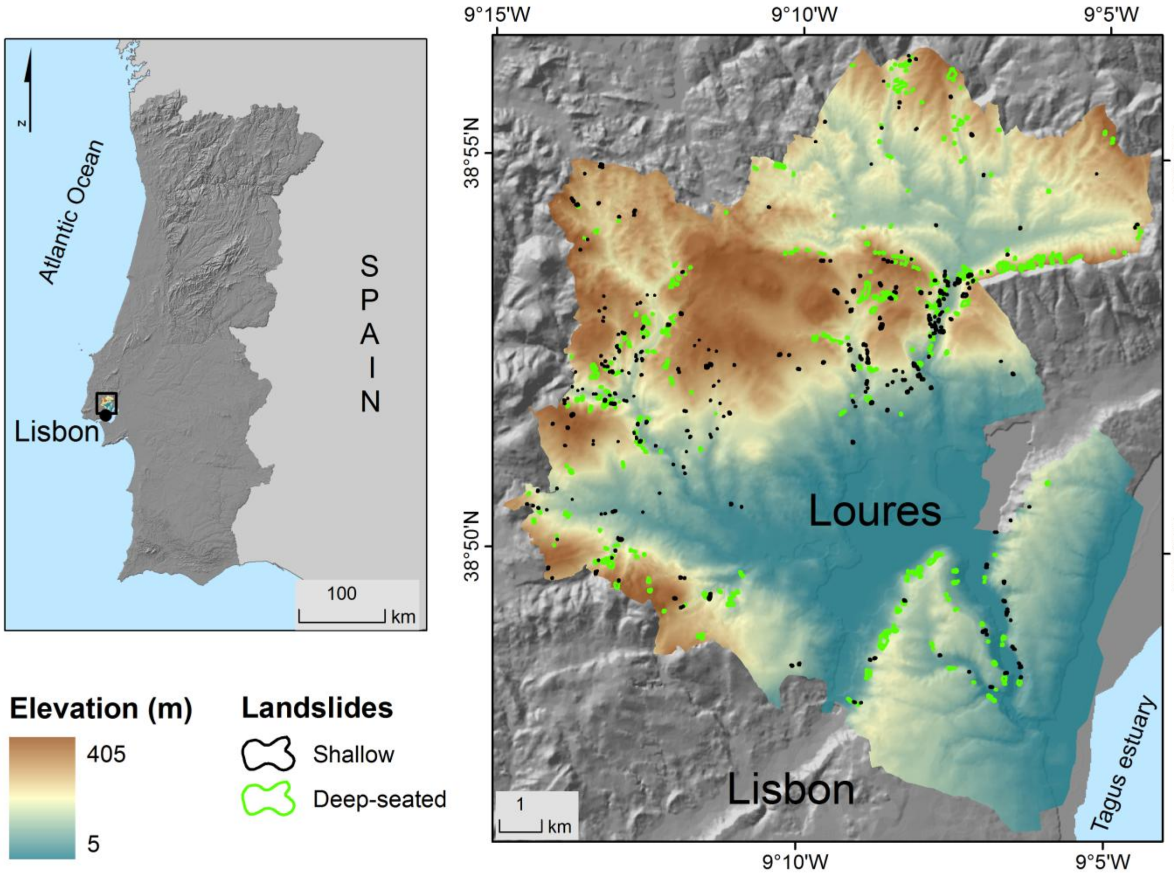

Fig. 3.1 - Loures municipality location, elevation and location of the 686 inventoried landslides

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 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 Zezere, 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 Zezere (2012).

3.3. 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 bi-variate statistical method and has been mapped. The annual and multiannual spatio-temporal 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 × EV) by the hazard probability (H).

3.3.1. Frequency-Magnitude of the landslides, susceptibility and hazard

3.3.1.1. 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 spatio-temporal 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 Zezere (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 to 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).

3.3.1.2. Annual and multiannual spatio-temporal probabilities

The temporal probability has to be associated to the spatial probability in order to determine the spatio-temporal probability, which is part of the landslide hazard. First of all, the spatial probability of a shallow and a deep landslide occurrence was assessed constructing two susceptibility maps. The susceptibility was mapped using a bi-variate statistical method called Information Value Method (Yin and Yan, 1988). The first model represents the susceptibility of the slopes to shallow landslide occurrence, published in a previous study (Guillard and Zezere, 2012). The total area of the shallow landslides is 319,975 m^2. The second model represents the susceptibility of the slopes to deep-seated landslide occurrence, and was built and validated by the union of the 292 deep-seated rotational slides and the 61 deep-seated translational slides inventoried in the Loures municipality (Guillard and Zezere, 2012). The total area of the deep-seated slides is 1,343,525 m^2. 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 taking into account the predictive capacity of the model. Additional details on the landslide susceptibility assessment in the study area can be found in Guillard and Zezere (2012).

The spatio-temporal 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 year, 10 years, 25 years and 50 years probability values.

3.3.2. 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' life is 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 3.1). Nevertheless, only direct costs are considered in the current study, due to scarcity of data.

Table 3.1 - Structural building types in the Loures municipality (National Institute of Statistics, Census 2011)

Structural building type	Structural elements and construction material	Number of buildings	%
SBT1	Wood or metal (light structures)	221	0.7
SBT2	Adobe, rummed earth or loose stone walls	577	1.8
SBT3	Brick or stone masonry walls	9,947	30.6
SBT4	Masonry walls confined with reinforced concrete	21,750	66.9
Total		32,495	100.0

3.3.2.1. 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 location is on the foot of the slide assuming different heights of affected material (0.5, 1, 3 and 5 m) (Fig. 3.2). The maximum values considered for both the depth of the slip surface and the height of affected material were defined taking into consideration the largest landslides inventoried in the study area (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).

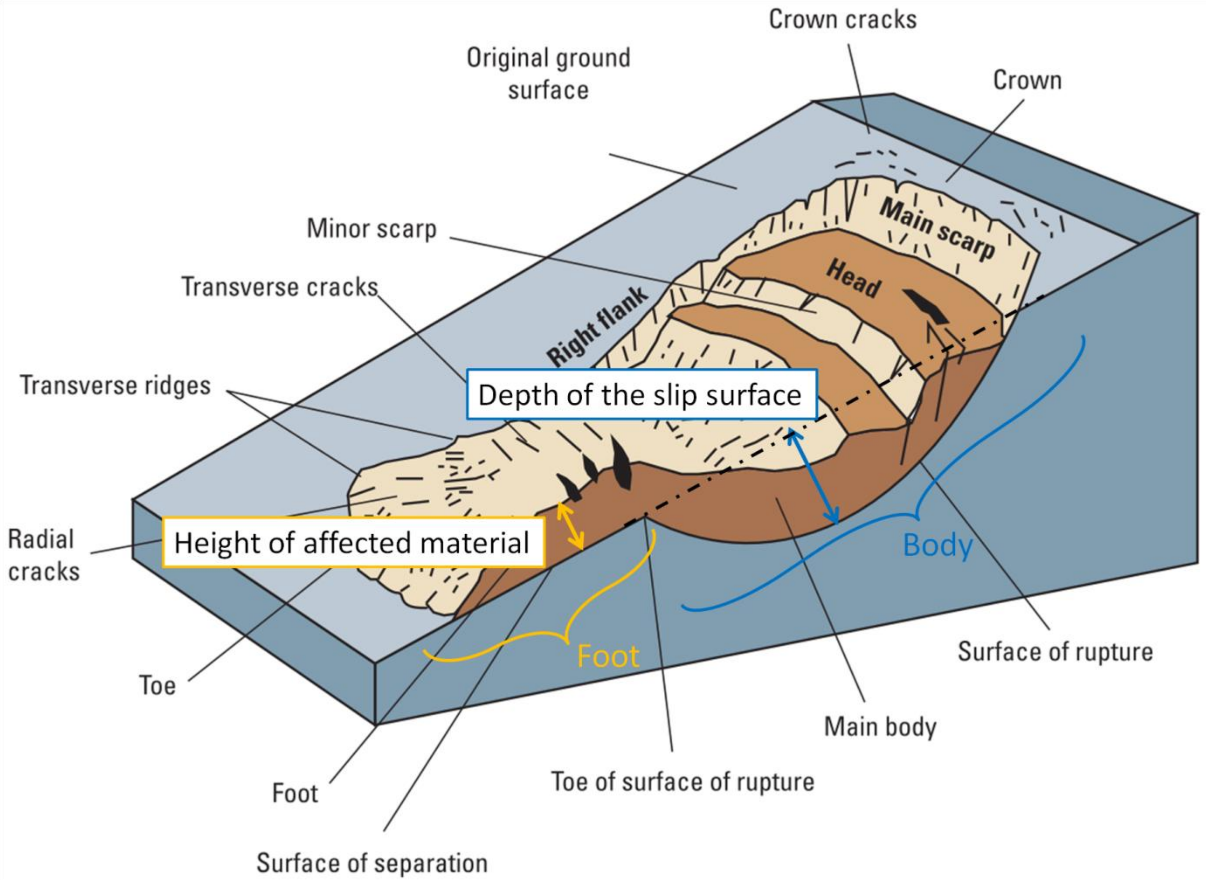

Fig. 3.2 - Rotational slide body and foot (adapted from Highland and Bobrowsky, 2008)

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.

Table 3.2 - Damage level on buildings

Damage class		Physical Vulnerability	Damage level on 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 originating aesthetic damages (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.

A study realized at a local scale enables assessing the landslide vulnerability 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 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 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 3.1), the corresponding potential damage caused by landslides of different magnitudes (Table 3.2); 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 (Annex 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 to the corresponding upper bound of its corresponding physical vulnerability, thus adopting a conservative approach (Table 3.2). 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 of the study area, and the results obtained by the two different groups of experts were compared.

3.3.2.2. 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 mapping unit, the smallest statistical unit, which is the "Geographic Basis for Information Reference" subsection (BGRI). The BGRI 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 3,061 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 available for the whole area at the BGRI-subsection scale, considering their structural elements and construction materials (Table 3.1). 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 3.1) 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 making a weighting average, which takes into account the number of buildings of each structural building type within the BGRI (Equation 1).

$$\mathrm{Vi} = \frac{\sum_{j} \mathrm{V(SBTj)} \times \mathrm{N(SBTj)}}{\sum \mathrm{N(SBT)}} \quad (1)$$

where Vi is the vulnerability of the BGRI-subsection for a landslide magnitude i, V(SBTj) is the vulnerability of the structural building type j and N(SBTj) 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 have a large 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.

3.3.2.3. Vulnerability based on fieldwork building inventory

The above-mentioned vulnerability assessment approach based on statistical mapping units has the advantage to be 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 and has an area of 6.71 km^2 and 782 buildings (Fig. 3.3). Physical vulnerability of the test site was assessed using the same vulnerability matrix referred 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.

3.3.3. Economic value of the buildings

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

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

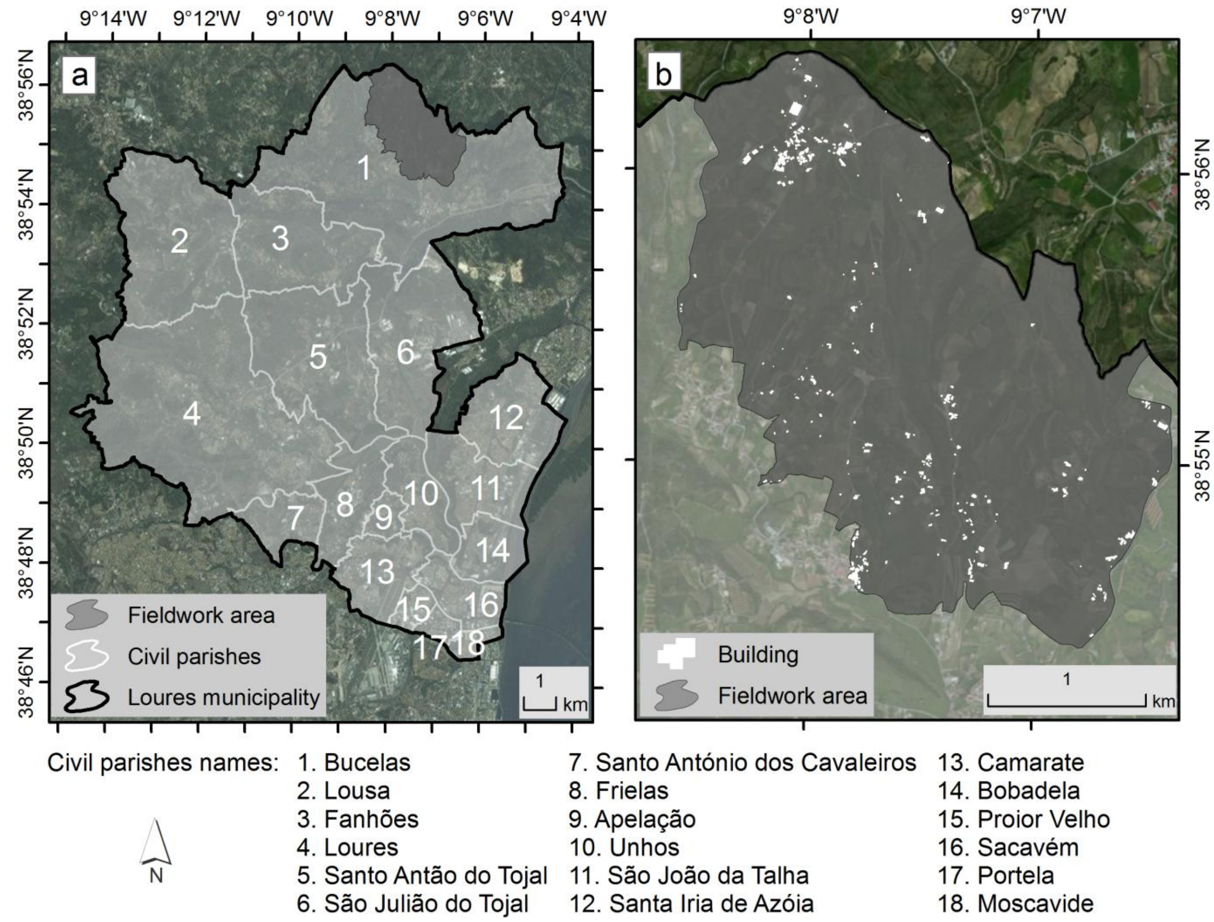

Fig. 3.3 - a. Civil parishes of the Loures municipality and location of the fieldwork area; b. buildings of the fieldwork area

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 €/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 November 12) 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 December 31) ranging from 0.40 (buildings older than 60 years) to 1 (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 December 30). 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. 3.3), which are located near Lisbon and have a better accessibility and proximity to social facilities and public transports.

The Economic Value per pixel (EVpix) 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 EVpix 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.

3.3.4. Landslide risk

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

$$R_{ij} = H_i \times P_j \times PV_j \times EVpix \qquad (3)$$

where R is the risk, H is the spatio-temporal probability, P is the magnitude probability, PV is the physical vulnerability, and EVpix is the economic value per pixel. The index i takes the values of 1 year, 10 years, 25 years and 50 years; the index j takes the values of 1 m, 3 m, 5 m, 10 m, 20 m for the slip surface depth, and 0.5 m, 1 m, 3 m and 5 m for the accumulated material height. The multiplication of the last two terms (the physical vulnerability and the economic value) represents the potential loss for the buildings.

Annual spatio-temporal 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 spatio-temporal probabilities.

3.4. Results

3.4.1. Frequency-magnitude of the landslides, susceptibility and hazard

The probability of the different landslide magnitudes was assessed using the curve shown in Fig. 3.4. 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 Table 3.3 and Table 3.4. The corresponding slide areas range from 706 m^2 to 14,127 m^2. 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 to the universal rule governing natural processes, and which is consistent with the results previously obtained by Guillard and Zezere (2012) for this study area.

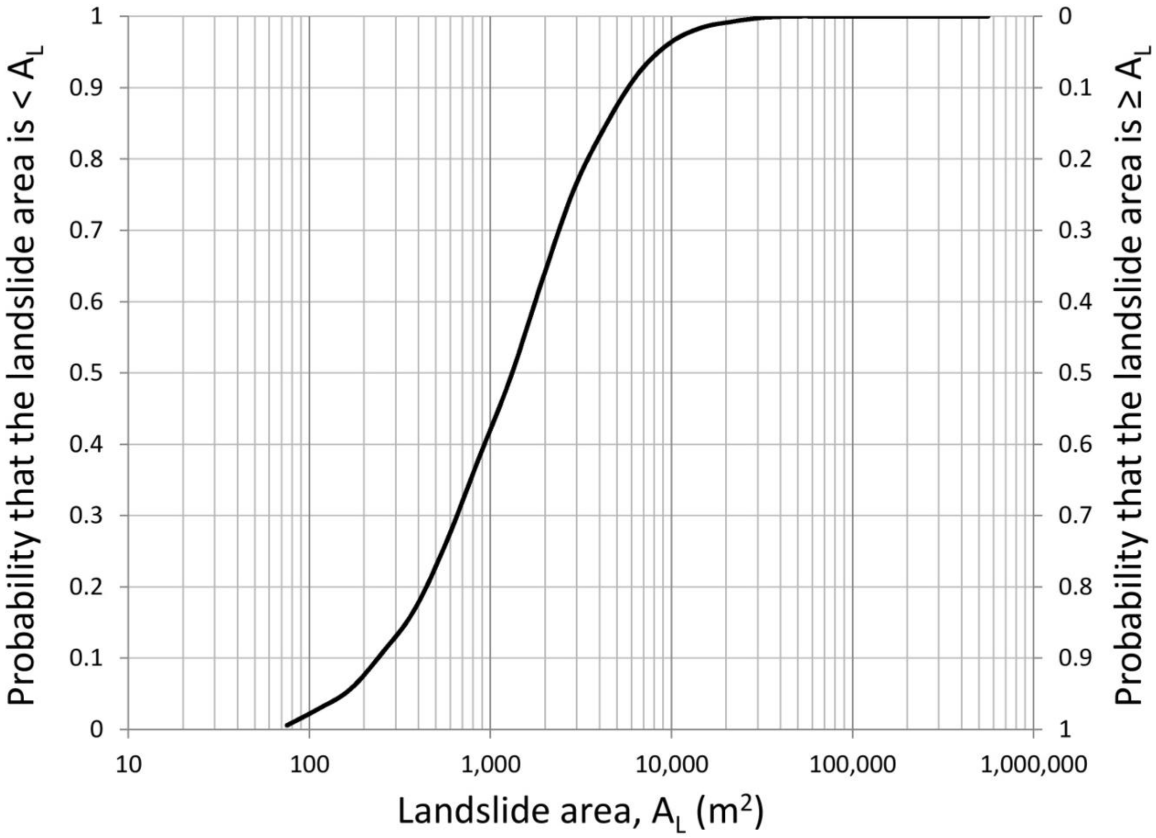

Fig. 3.4 - Probability of landslide area in the Loures municipality (based on the work done by Guillard and Zezere, 2012)

Table 3.3 - 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	2,119	0.34
5	3,532	0.19
10	7,064	0.07
20	14,127	0.02

Table 3.4 - 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	1,413	0.48
3	6	4,238	0.16
5	10	7,064	0.07

The deep-seated and shallow landslides susceptibility models were validated based on the random partition of the landslide inventories in two groups: modelling group and 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. 3.5): the Area Under Curve (AUC) value is 0.87 for both models, which attests the robustness of the models.

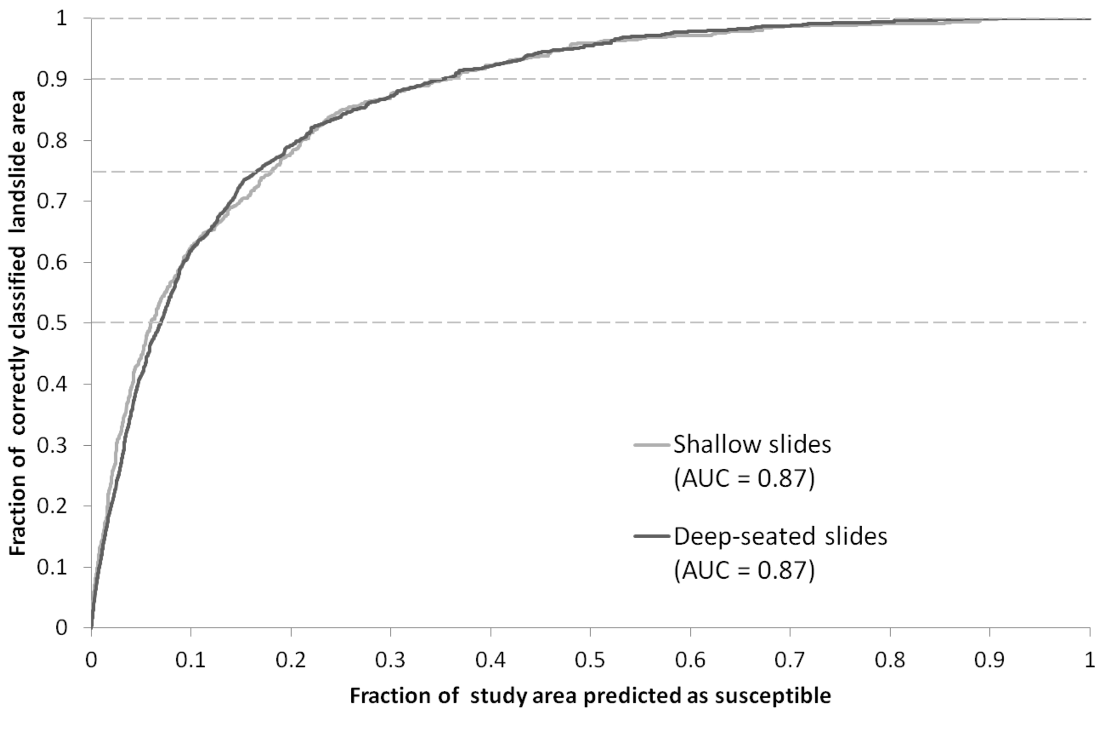

Fig. 3.5- Prediction-rate curves and area under the curve (AUC) of landslide susceptibility models in the Loures municipality (based on the work done by Guillard and Zezere, 2012)

The landslide susceptibility maps are shown in Fig. 3.6, 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. 3.5, and "predictive capacity" in Table 3.5 and Table 3.6). Therefore, 50% of the 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 the 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.

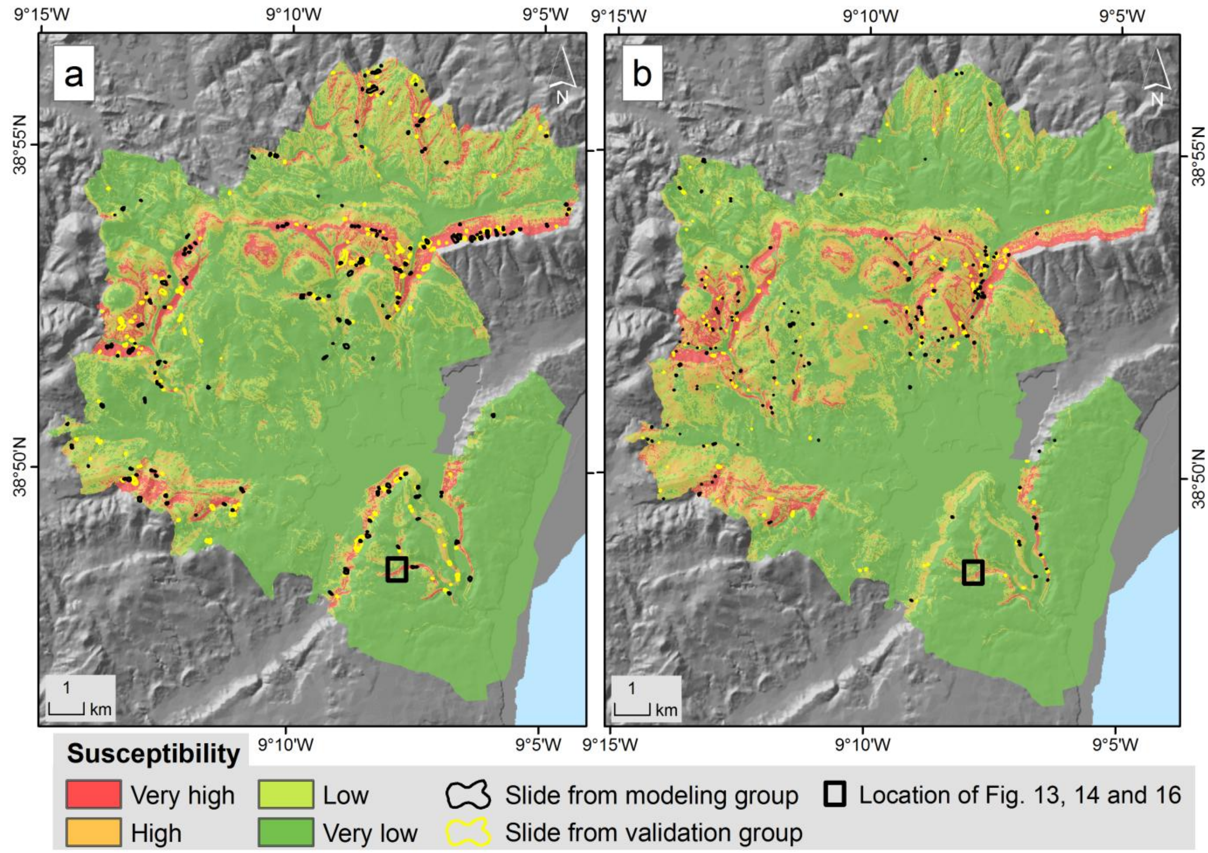

Fig. 3.6 - Landslide susceptibility maps in the Loures municipality for: a. deep-seated slides, b. shallow slides (based on the work done by Guillard and Zezere, 2012)

Table 3.5 and Table 3.6 show the probabilities of a pixel within a susceptibility class to be affected by a deep-seated (Table 3.5) or shallow (Table 3.6) slide, for different time periods (1 year, 10 years, 25 years and 50 years). Probabilities were calculated from the total area to be affected by landslides in the future, 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 has only a probability of 5.46×10^{-4} (that is 1 chance in 1832) to be affected by a deep-seated slide during the next year, it has a probability of 2.73×10^{-2} (that is 1 chance in 37) to be affected by a deep-seated slide during the next 50 years (Table 3.5). Moreover, each pixel within the “Very high” susceptibility class has a probability of 7.54×10^{-2} (that is 1 chance in 13) to be affected by a deep-seated slide during the next 50 years.

Table 3.5 - Probability of occurrence of deep-seated landslides in 1 year, 10, 25 and 50 years in the Loures municipality

Susceptibility class	Area (no. of pixels)	Predictive capacity	1 year probability	10 years probability	25 years probability	50 years 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 3.6 - Probability of occurrence of superficial landslides in 1 year, 10, 25 and 50 years in the Loures municipality

Susceptibility class	Area (no. of pixels)	Predictive capacity	1 year probability	10 years probability	25 years probability	50 years 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}

3.4.2. 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 in the questionnaire is a proxy for the physical vulnerability, the damage values provided by the experts, comprised between 1 and 5, were converted into vulnerability values, comprised between 0 and 1 (see Table 3.2).

Table 3.7 - Average vulnerability and standard deviation for each structural building type located on landslide body (cf. Table 3.1 for building type)

		Landslide body: depth of slip surface									
		1 m		3 m		5 m		10 m		20 m	
		Avg. Vuln.	*Std Dev*	*Avg. Vuln.*	*Std Dev*	*Avg. Vuln.*	*Std Dev*	*Avg. Vuln.*	*Std Dev*	*Avg. Vuln.*	*Std Dev*
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

The physical vulnerability of buildings was assessed twice, first with the total landslide expert answers and second with the sub-pool of landslide experts that have been working in the study area. The vulnerability averages of the two groups of experts are presented in Table 3.7 and Table 3.8, 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 (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.

Table 3.8 - Average vulnerability and standard deviation for each structural building type located on landslide foot (cf. Table 3.1 for building type)

		Landslide foot: height of accumulated material							
		0.5 m		1 m		3 m		5 m	
		Avg. Vuln.	Std Dev	Avg. Vuln.	Std Dev	Avg. Vuln.	Std Dev	Avg. Vuln.	Std Dev
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

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 (1 m deep landslides for the SBT3 and SBT4 buildings, and 0.5 m and 1 m high of accumulated material landslides for all the structural building types) produce less damage than according to the European experts, and the high magnitude landslides produce more damage than according to the European experts (Table 3.7 and Table 3.8). Moreover, the standard deviation values of the study area experts answers are typically lower than the standard deviation values of the European experts answers (Table 3.7 and Table 3.8), 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 (Fig. 3.7 and Fig. 3.8). The average vulnerabilities of the Loures municipality buildings associated with the 1 m, 3 m, 5 m, 10 m and 20 m deep landslides 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 m, 1 m, 3 m 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 Fig. 3.7 and Fig. 3.8. As a rule, the standard deviation decreases as the landslide magnitude increases.

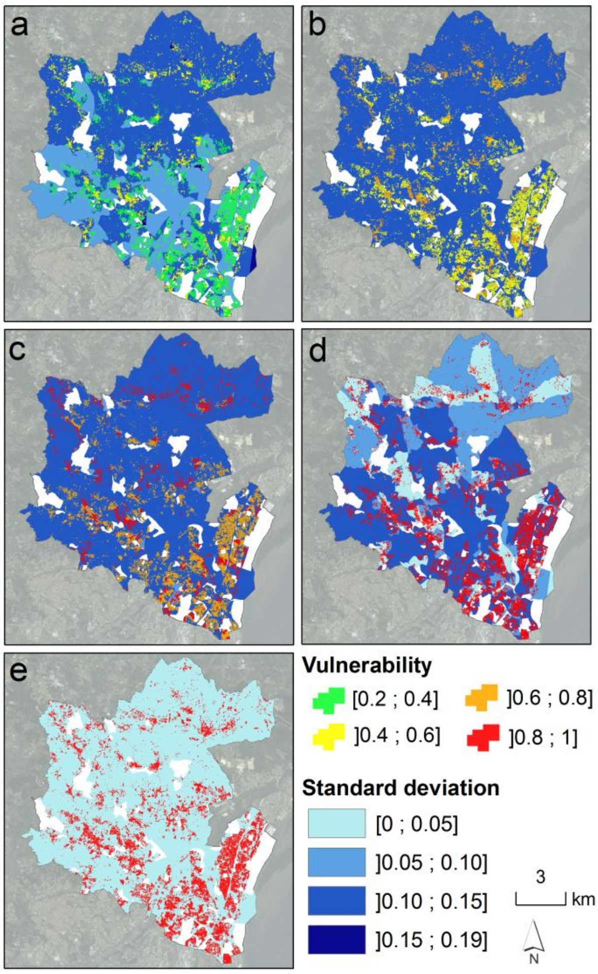

Fig. 3.7 - Average building vulnerability and standard deviation per BGRI-subsection for buildings located on landslide body, for a slip surface depth of: a. 1 metre; b. 3 metres; c. 5 metres; d. 10 metres; and e. 20 metres. White polygons are BGRI-subsections without buildings

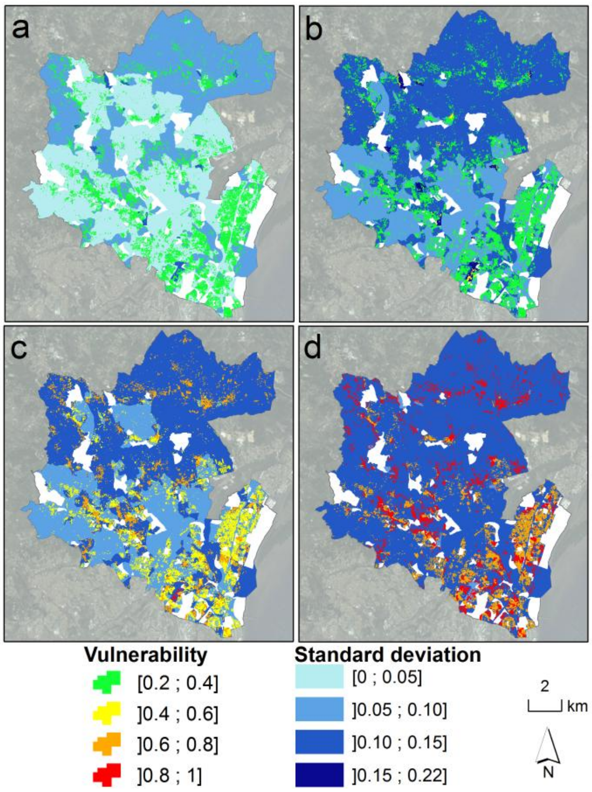

Fig. 3.8 - Average building vulnerability and standard deviation per BGRI-subsection, for buildings located on landslide foot having an affected material height of: a. 0.5 metre; b. 1 metre; c. 3 metres; and d. 5 metres. White polygons are BGRI-subsections without buildings

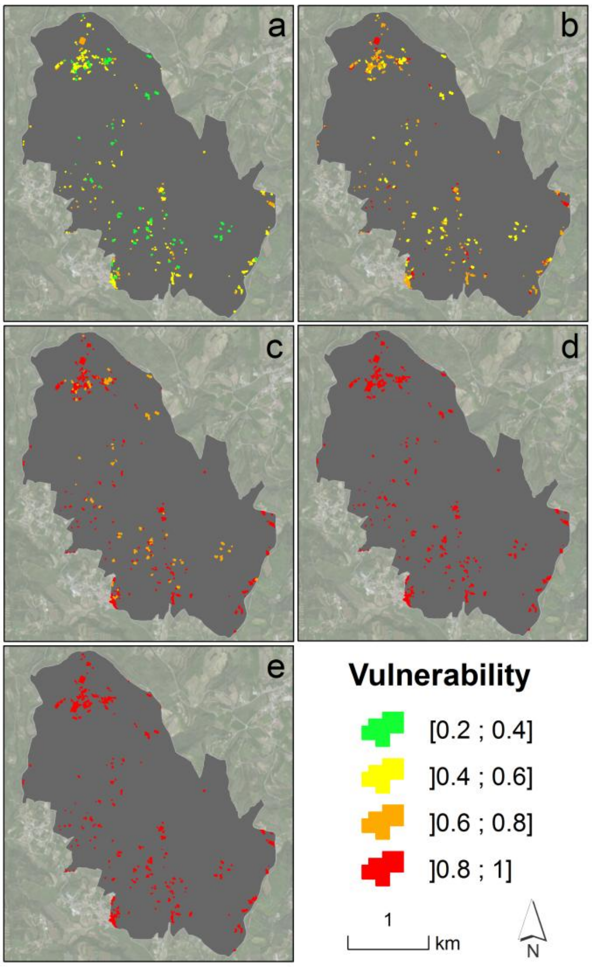

Fig. 3.9 - Vulnerability of buildings inventoried in the fieldwork area, being on landslide body having a slip surface depth of: a. 1 m; b. 3 m; c. 5 m; d. 10 m; and e. 20 m

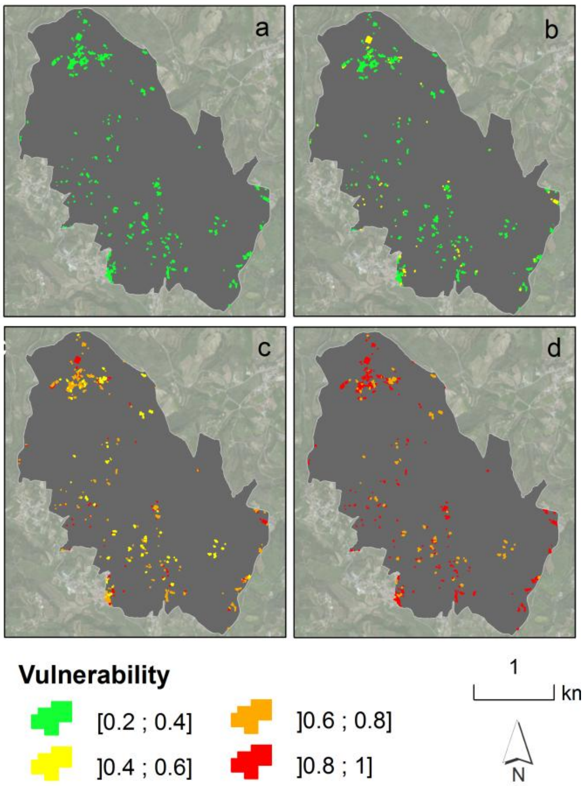

Fig. 3.10 - Vulnerability of buildings inventoried in the fieldwork area, being on landslide foot having an affected material height of: a. 0.5 m; b. 1 m; c. 3 m; and d. 5 m

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 10 m or a 20 m deep landslide, all the buildings have maximum vulnerability (PV > 0.8 see Fig. 3.7.d and 3.7.e, and Table 3.7), 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 about the expected damage on buildings among the study area experts is higher for damage generated by low magnitude landslides (e.g. 1 m deep landslides, and landslides with a 0.5 m 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 facility in assessing 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 Fig. 3.7 and Fig. 3.8 enable to identify the location of the buildings and their vulnerabilities according to different landslide magnitudes, but also highlight the uncertainty associated to the attributed vulnerabilities.

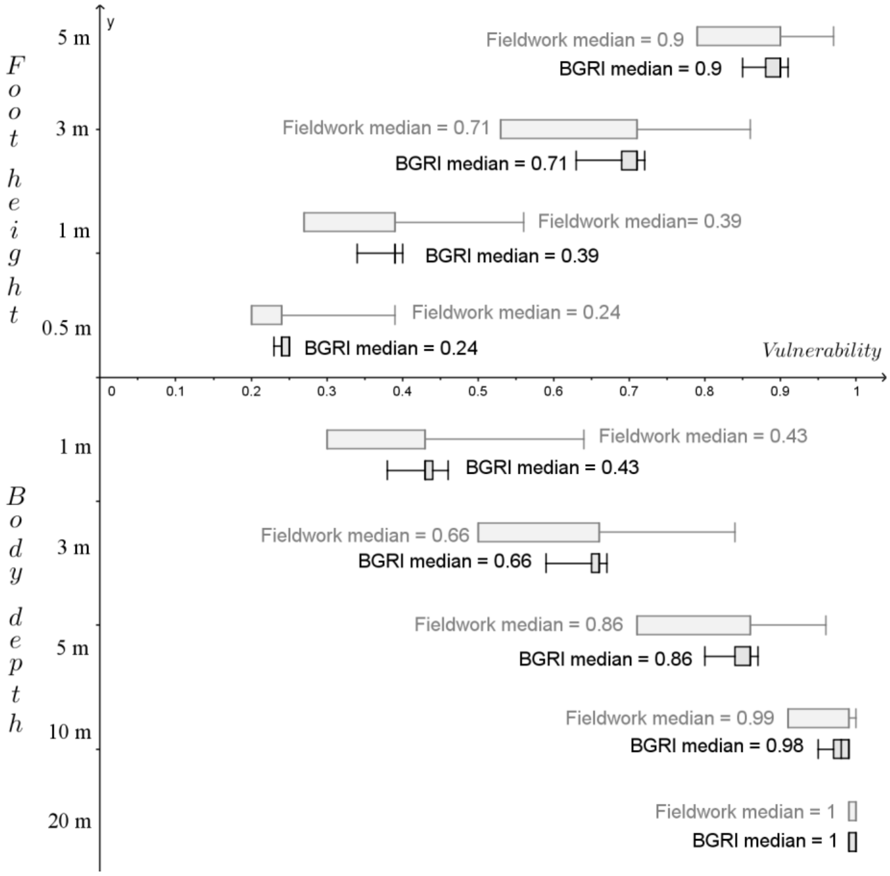

Fig. 3.11 - Box plots of the vulnerability of the test site buildings for each scenario, for the buildings inventoried by fieldwork (in grey) and for the buildings of the BGRI-subsections (in black)

The vulnerability of the test site buildings inventoried during fieldwork (Fig. 3.3) is presented in Fig. 3.9 and Fig. 3.10 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 for all the buildings of the BGRI-subsection. However, the comparison of building vulnerability expressed in Fig. 3.9 and Fig. 3.10 with the corresponding area at the BGRI-subsection level shows that global results are similar. In order to have a more accurate comparison, the box plots of the vulnerability values obtained by both vulnerability approaches for the test site are shown in Fig. 3.11. Indeed, Fig. 3.11 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, the median of the fieldwork data is the same (or almost the same in the case of the 10 m deep landslides) 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 unit 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.

3.4.3. Economic value of the buildings

The economic value of the buildings was calculated using the Equation 2. We found that 3,417 buildings have an economic value above 100,000 € per pixel (which corresponds to 4,000 €/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 Sacavém (Fig. 3.3 and Fig. 3.12). 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.

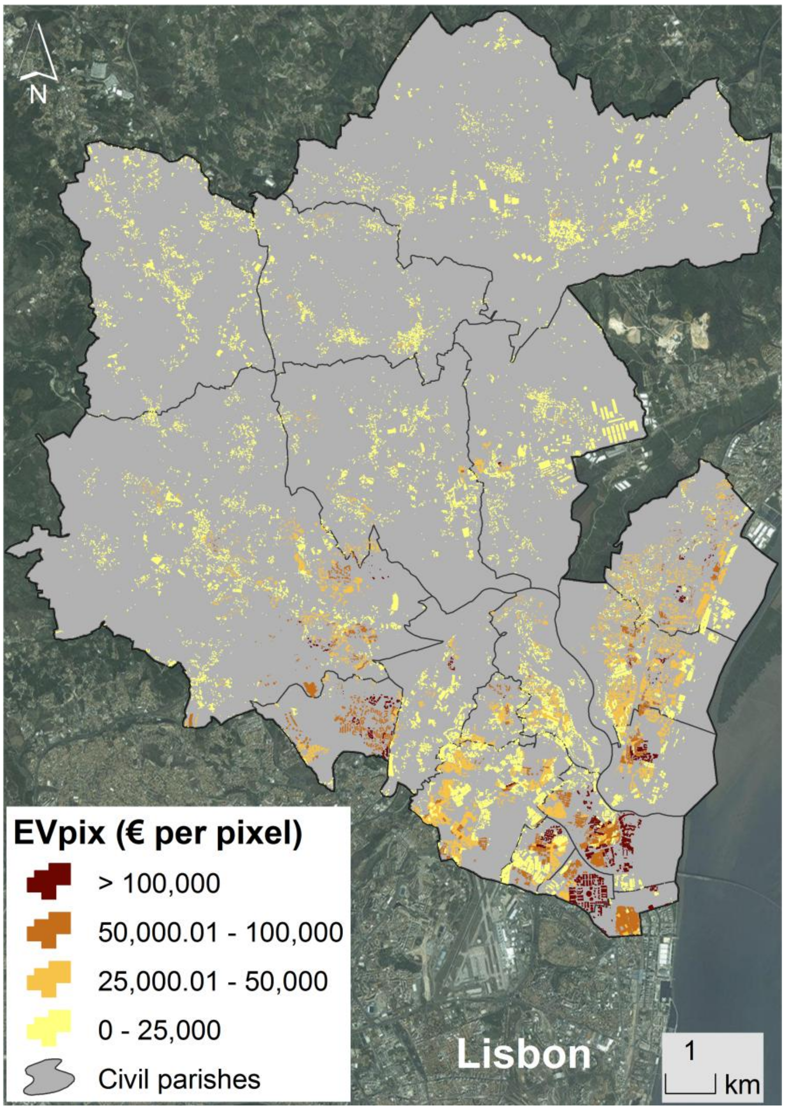

Fig. 3.12 - Economic value of buildings per 5 m pixel in the Loures municipality

3.4.4. Landslide risk

Figures 3.13 and 3.14 illustrate the risk for buildings according to the spatio-temporal landslide probability, the landslide magnitude and the building vulnerability and value. The buildings have been transformed into raster in order to multiply the potential losses associated to 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 vector is 9.25 km^2, and the total area of the buildings in raster is 9.00 km^2. The 0.25 km^2 which were lost during the transformation from vector to raster represent only 2.7% of the total area of the buildings, thus, even if the transformation changes slightly the shape of the buildings, their surface is almost the same, what has little influence on the risk estimates. Figures 3.13 and 3.14 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.

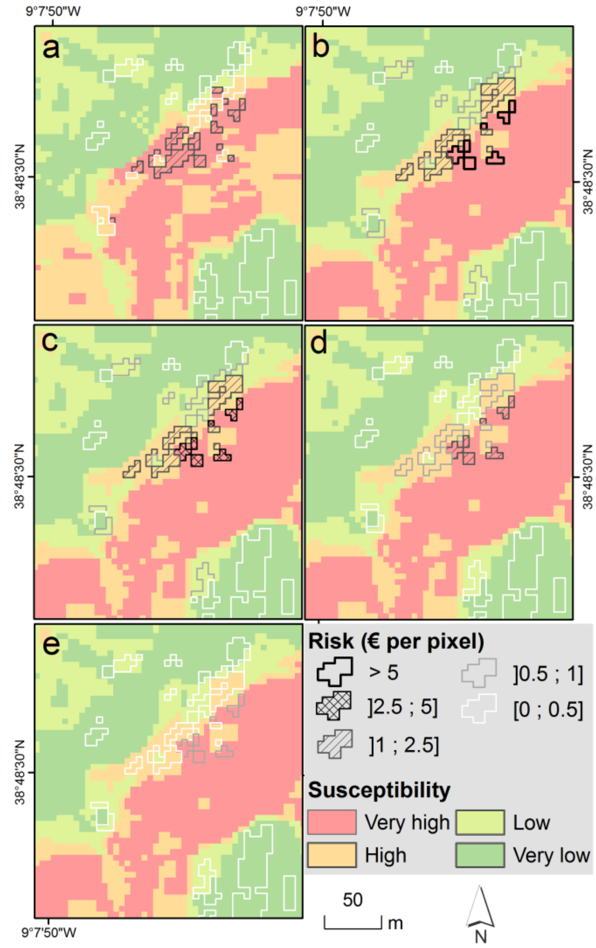

Fig. 3.13 - Detail of annual risk for buildings of the Loures municipality located on a landslide body, for a: a. 1 m; b. 3 m; c. 5 m; d. 10 m; and e. 20 m slip surface depth. Pixel size: 5 m. For location, see Fig. 3.6.

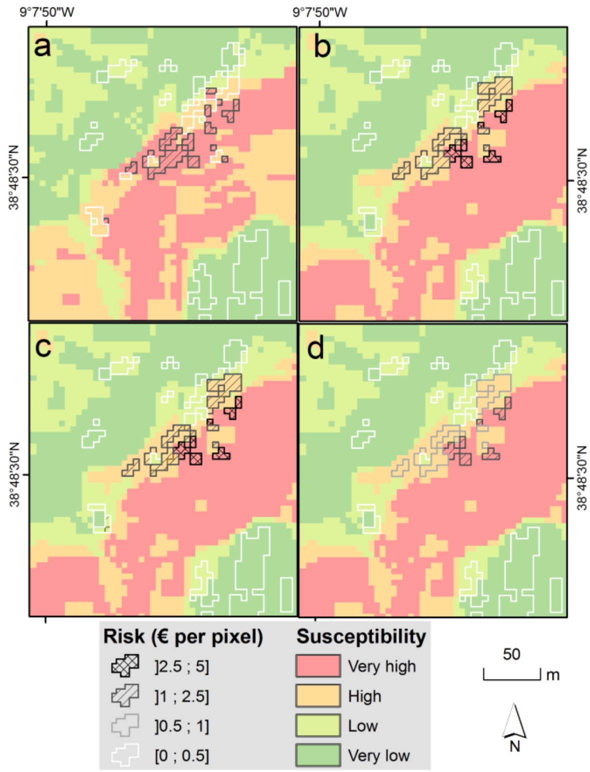

Fig. 3.14 - Detail of annual risk for buildings of the Loures municipality located on a landslide foot, for a: a. 0.5 m; b. 1 m; c. 3 m; d. 5 m high of affected material. Pixel size: 5 m. For location, see Fig. 3.6.

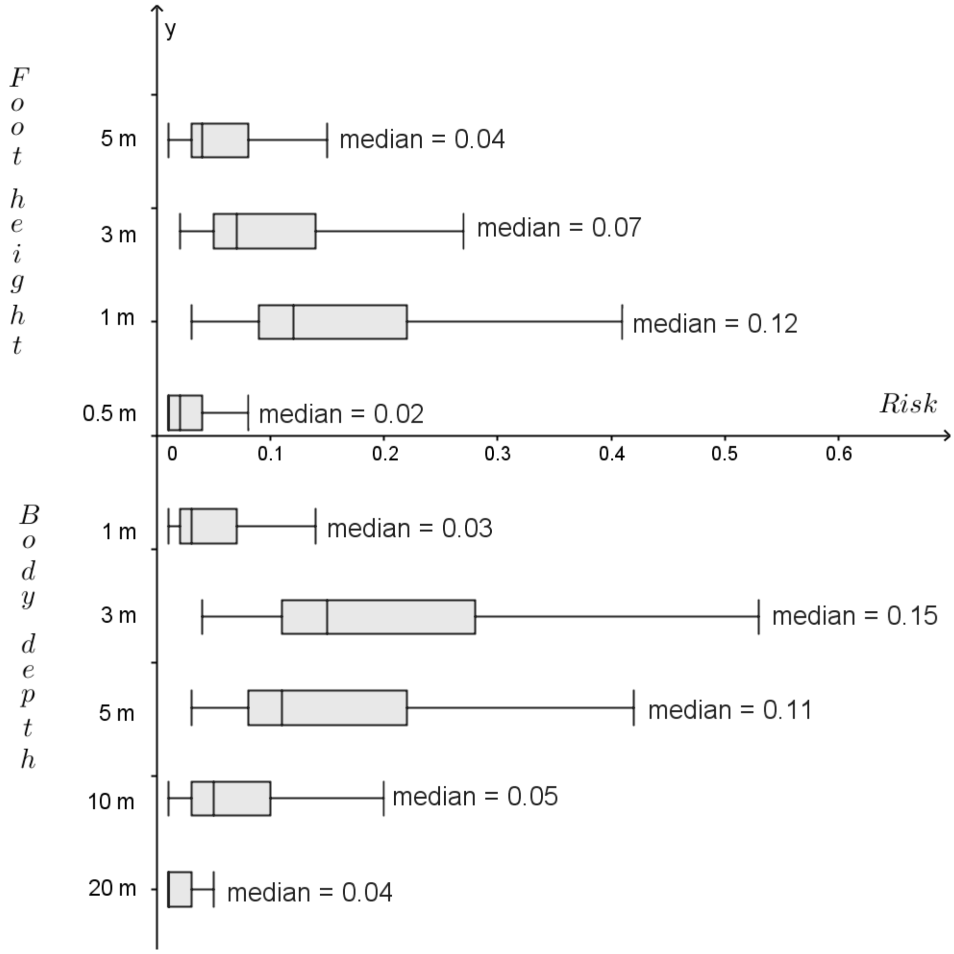

Fig. 3.15 - Box plots of the risk for the buildings per 5 m pixel, for each scenario. Outliers are not shown. The maximum outlier values are: 8.35 (Foot height: 5 m), 12.81 (Foot height: 3 m), 19.58 (Foot height: 1 m), 5.46 (Foot height: 0.5 m), 8.2 (Body depth: 1 m), 25.68 (Body depth: 3 m), 20.38 (Body depth: 5 m), 9.62 (Body depth: 10 m) and 2.99 (Body depth: 20 m).

The box plots of the risk values were plotted for each scenario in order to compare them (Fig. 3.15). Outliers have been considered, but their values are too high to be shown on this figure (the maximum value is 25.68 € per pixel, for a 3 m deep slide). Figure 3.15 and Table 3.9 show that the maximum values of risk correspond to 3 m deep landslides, for which 741 pixels buildings (that is 0.2% of the buildings of the Loures municipality) have a risk above 5 € per pixel, and for which there is an annual risk of 96,693 € for the Loures municipality, that is 109 € per hectare of buildings (Table 3.9). Indeed, these landslides are the ones which combine a relatively high frequency in the Loures municipality (magnitude probability = 0.34, cf. Table 3.3) with a substantial potential damage (the median vulnerability value associated to them is 0.66, cf. Fig. 3.11). 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 having a depth of 20 m or more in the Loures municipality is 0.02 (cf. Fig. 3.4 and Table 3.3). Therefore, despite the high median vulnerability associated to these landslides (1, cf. Fig. 3.11) the risk associated to them is quite low (the median value is 0.04, cf. Fig. 3.15).

Table 3.9 - Landslide risk per civil parish. Vulnerability data obtained with a sub-pool of landslide experts knowing the study area.

				Body depth: 1m		Body depth: 3m		Body depth: 5m		Body depth: 10m		Body depth: 20m	
Civil parish Id (cf. Fig.3.3.a)	Civil parish name	Civil parish area (ha)	Area of buildings (ha)	Total risk (€)	€/ha of buildings	Total risk (€)	€/ha of buildings	Total risk (€)	€/ha of buildings	Total risk (€)	€/ha of buildings	Total risk (€)	€/ha 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	Sto Antão 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	Sto 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	Sta 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	16934	886	23158	26	96693	109	74293	84	33078	37	8946	10
-	Loures municipality with vulnerability data from the pool of the 52 landslide European experts			26871	30	92581	105	67389	76	28642	32	7551	9
-	Difference (%)			-16.0		4.3		9.3		13.4		15.6	

The risk was calculated for each civil parish for the five scenarios considering the different landslide body depths (1 m, 3 m, 5 m, 10 m and 20 m). The risk in euros per hectare of buildings was also calculated for each civil parish (Table 3.9). The maximum annual risk value was computed for the Loures civil parish (16,310 euros), and the maximum value of risk per area of buildings was obtained for the Santo António dos Cavaleiros civil parish (246 €/ha). The Loures civil parish has the highest number of buildings within the municipality and it has also the highest risk values for the five scenarios summarized in Table 3.9. 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 the Table 3.9 show the annual risk values for the municipality obtained using the average vulnerability given by the pool of landslide European 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 (1 m deep landslides), the study area experts gave lower vulnerabilities for the SBT3 and SBT4 buildings than the European experts (Table 3.7); these buildings represent 97.5% of all the buildings of the Loures municipality (Table 3.1) 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 imply a generalized higher risk for the municipality.

Finally, the risk was calculated considering different time periods. Figure 3.16 shows the risk to 10 m deep landslides in a part of the Loures municipality, for 1 year, 10 years, 25 years and 50 years. In this zone where the zoom was carried out, the annual risk is between 1 and 5 € per pixel in the "Very high" susceptibility zones, and below 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 20 € per pixel for "High" and "Very high" susceptibility zones and between 5 and 20 € per pixel for "Low" susceptibility zones.

3.5. 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 ~1500 m^2 resulted in negligible to significant damages to buildings corresponding to a vulnerability of 0.6 or less, whereas landslides larger than ~7000 m^2 produced significant to very severe damages corresponding to a 0.6 or higher vulnerability, 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 high 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 metres 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.

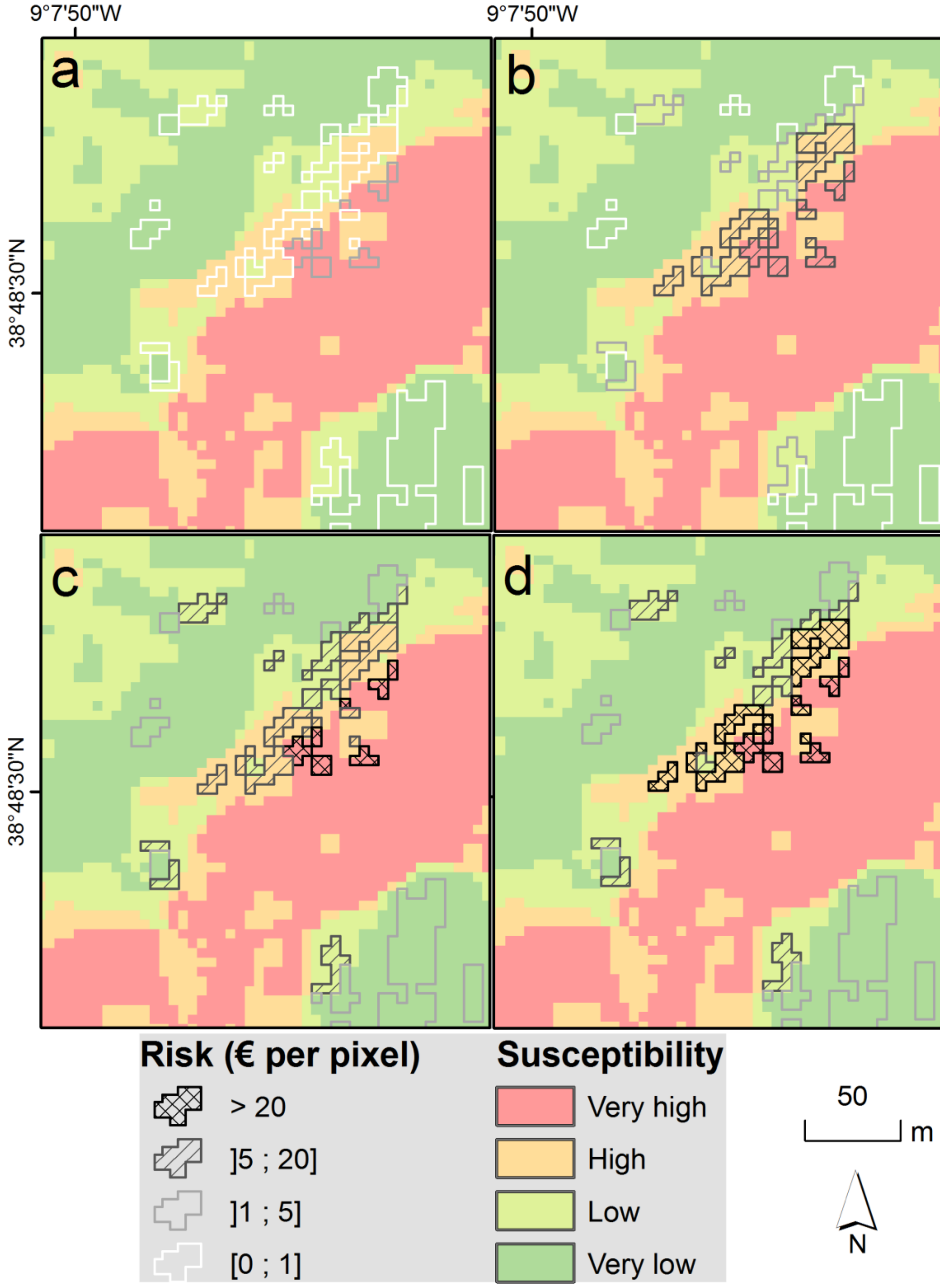

Fig. 3.16 - Detail of multiannual risk for buildings of the Loures municipality located on a landslide body with a 10 metres-deep slip surface, for a hazard of: a. 1 year, b. 10 years, c. 25 years, d. 50 years. Pixel size: 5 m. For location, see Fig. 3.6.

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

If we consider that the sub-pool experts have a more accurate opinion on 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 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 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 way. 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 part of the experts expressed the potential damage as maximum, and the other as medium, the average values provide a not too conservative model, but neither too low in terms of expected potential damage, and this is what the authors were seeking.

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 having similar landslide types and built environment in 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 spatio-temporal 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 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 spatio-temporal 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 have a complete landslide inventory. From this point of view, the hazard was underestimated. In addition, changes in the frequency of occurrence of landslides associated to 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 had 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 of 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 nowadays, without taking into account the urban expansion, which is a factor of element at risk exposure, and is thus responsible for risk increasing.

3.6. Concluding remarks

An assessment of buildings vulnerability to landslides, based on a nine magnitude scenarios inquiry of 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 3 m deep landslides, with a maximum value of 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 5 m, 10 m or 20 m deep landslides 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 an accurate planning. The landslides that have a low magnitude being more frequent, the risk they imply has to be considered for the short term planning, whereas the risk implied by high magnitude landslides has to be considered for the 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 Zezere (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 × 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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3.8. Annex

Annex 1. Matrix of the experts questionnaire

	Landslide body (rotational slide): Depth of the slip surface (m)					Landslide foot: Height of affected material (m)			
	1	3	5	10	20	0.5	1	3	5
STB1									
STB2									
STB3									
STB4									

Note: complete with a potential damage between 1 (negligible damage) and 5 (very severe damage).

Structural building type	Structural elements and construction material
SBT1	Wood or metal (light structures)
SBT2	Adobe, rummed earth or loose stone walls
SBT3	Brick or stone masonry walls
SBT4	Masonry walls confined with reinforced concrete

Potential damage class	Damage level on buildings (based on Alexander, 1986; AGS, 2000; Tinti et al., 2011; Garcia 2012)
1: Negligible damage	No significant damage - slight accumulation of material originating aesthetic damages (dirt, chipping paint, etc.)
2: Slight damage	No structural damage - minor repairable damage: chipping of plaster, slight cracks, damage to doors and windows
3: Significant damage	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	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	Heavy damage seriously compromising the structural integrity: partial or total collapse of the building. Imperative and immediate evacuation and complete demolition.

Conclusion

4. Conclusion of the thesis

The main objective of this thesis was to assess the vulnerability of the elements at risk within the Loures municipality and to include this assessment in a landslide risk analysis.

In the first chapter, the susceptibility of the Loures municipality to landslides was assessed by a bi-variate statistical method. In the second chapter, the social vulnerability of the Greater Lisbon was assessed by the Social Vulnerability Index (SoVI) method developed by Cutter and co-authors (2003) and adapted to the Portuguese context. An assessment of the physical vulnerability of the buildings of the Loures municipality and an analysis of the landslide risk considering direct losses for buildings is presented in the third chapter.

As two facets of the vulnerability were studied separately in the second and the third chapters, a last study gathering these results seemed interesting in terms of assessment of what has been called "combined vulnerability" or "total vulnerability". Indeed, the second chapter shows the civil parishes where the residents are the most vulnerable to natural hazards, and the third chapter shows the Geographic Basis for Information Reference (BGRI) subsections (basic geographic entities) where the buildings are the most vulnerable to landslides. That is why the study conducted and exposed along this conclusion section aimed to combine the social and physical vulnerabilities, in order to locate the areas within the Loures municipality where the total vulnerability (which is the consideration of the social vulnerability and the physical vulnerability) is the highest, and to analyse the landslide risk in these areas. Other facets of the vulnerability (like functional vulnerability) were not considered in the total vulnerability.

The combination of social vulnerability to natural hazard with the physical vulnerability of buildings to landslides is an innovative part of this study. A combination of these two facets of vulnerability has rarely been carried out. A study was done by Barros and co-authors (2015) in the frame of the tsunami risk assessment, though the authors seemed to mix the concept of vulnerability with the concept of risk by including in their vulnerability composite index a factor of what they called morphological vulnerability (which is similar to susceptibility, i.e. a part of the hazard, and not the vulnerability) and a factor of tax (which is relative to the values of the elements at risk, and not to their vulnerability). The study of Zahran and co-authors (2008) shows, using multiple regression analyses, the links that may exist between the natural environment, the built environment and the social vulnerability on the one hand, and on the other, the victims of floods; nevertheless, the latter authors do not provide any conclusions about individuals harmed by flooding (Zahran et al., 2008), and do not offer the spatial interpretation of vulnerability.

The combination of the social vulnerability and the physical vulnerability of the buildings of Loures municipality was carried out and the results are exposed in this conclusion section. This combination was conducted by two different approaches. In the first approach, the social vulnerability which was combined with the physical vulnerability was extracted from the results exposed in the second chapter, and the mapping unit is the civil parish. This combination of the vulnerability was named “average vulnerability”. In the second approach, the social vulnerability was assessed with a different method and a different mapping unit: the mapping unit in this case is the BGRI subsection, which is the one which was used for the assessment of the physical vulnerability of the buildings in the third chapter, in order to have a location of the total vulnerability more precise. In this approach the social vulnerability assessed at the BGRI scale was then combined with the physical vulnerability presented in the third chapter. In this second approach, the combination of the two facets of the vulnerability was named “total vulnerability”. Finally, the landslide risk was analysed at the BGRI scale considering the total vulnerability, which is the most precise in terms of vulnerability location.

4.1. Data and methods

The combination between the two facets of the vulnerability was made using two different approaches. With the first approach, the combination was made by calculating the average of the physical vulnerability (originally at the BGRI scale) and the social vulnerability (originally at the civil parish scale). Then with the second approach, a social vulnerability assessment was made at the BGRI scale, and the combination of the two facets of the vulnerability was made by crossing the classes of the new vulnerability assessment with the classes of the physical vulnerability at the BGRI scale. Finally, the 3 metres-deep landslide risk was analysed and mapped using the vulnerability obtained with the second approach.

4.1.1. Average of the physical vulnerability and the social vulnerability

In the second chapter SoVI values were calculated for the civil parishes of the Greater Lisbon, through an adaptation to the Portuguese context of the method developed by Cutter and co-authors (2003). From this work, the SoVI values of the civil parishes located within the Loures municipality were extracted. The minimum SoVI value in Loures is -5.84, and the maximum value is 7.06. The SoVI values were scaled and converted into values between 0 and 1, where -5.84 becomes 0 and 7.06 becomes 1. The scaled SoVI value of each civil parish was considered unchanged and representative for the complete set of BGRI that constitutes the parish.

The physical vulnerability values ranging from 0 to 1, which were attributed to the buildings in relation to the type of material of their structure in the third chapter, were considered.

Then, the average vulnerability resulting from the social vulnerability on the one hand and from the physical vulnerability of the buildings on the other hand was calculated for each BGRI (Eq. 1):

$$Average\ Vulnerability = \frac{Social\ vulnerability + Physical\ vulnerability}{2} \qquad (1)$$

This first approach of the combination of the two facets of the vulnerability presents the following issue: the mapping unit of the social vulnerability (the civil parish) is very large in relation to the mapping unit of the physical vulnerability (the BGRI). As a consequence, the results given by this combination are quite generalised.

In order to refine these results, the social vulnerability was assessed again, but this time using the BGRI as mapping unit. Then, a combination of this 'new social vulnerability' with the physical social vulnerability exposed in the third chapter was carried out, providing thus the second approach of the two facets of the vulnerability combination.

4.1.2. Assessment of the social vulnerability at the BGRI scale and its combination with the physical vulnerability

4.1.2.1. Assessment of the social vulnerability at the BGRI scale

The social vulnerability was calculated at the BGRI scale. As it was not possible to use the SoVI method mainly because of the scarcity of the data at the BGRI scale, the social vulnerability was here defined as the average of the sensitivity of the population and its lack of resilience (adapted from Murillo-Garcia and co-authors (2015)), as shown in the Eq. 2.

$$Social\ vulnerability = \frac{Sensitivity + Lack\ of\ Resilience}{2} \qquad (2)$$

The social vulnerability indicators used in this study were adapted from those proposed by Murillo-Garcia and co-authors (2015), who assessed the vulnerability of the indigenous population of Pahuatlán-Puebla (Mexico) to landslides, and by Rufat and co-authors (2015), who conducted a study gathering 67 published papers about social vulnerability assessments to floods between 2000 and 2013. The social vulnerability indicators that were chosen to compute the sensitivity and the lack of resilience of the Loures municipality were obtained from the National Institute of Statistics (INE) census at the BGRI level. Relative to the Murillo-Garcia and co-authors (2015) formulas, only the sensitivity and lack of resilience of the population were considered as parts of the vulnerability, excluding thus the population exposition to the landslides, which is considered later in the study as a part of the risk. Moreover, the average of the indicators was considered (and not the power of their multiplication, as Murillo-Garcia and co-authors (2015) did) in order to have values of sensitivity, lack of resilience and social vulnerability ranging between 0 and 1, 0 being the minimum and 1 the maximum. Some of the indicators were adapted; for instance, the "road" indicator of the lack of resilience formula of Murillo-Garcia and co-authors (2015) was replaced by the "reclassified location coefficient (RLC)" indicator, calculated from the location coefficient that the Portuguese Tax Services use to characterise the property market and the accessibility of the buildings (Law Number 64-B/2011 of 30 December). The location coefficient values of the Loures municipality range from 0.85 (the worst localisation in terms of accessibility) to 2.25 (the best localisation). They were reclassified and converted into values ranging from 0 to 1, 0 corresponding to the 2.25 location coefficient value and 1 to the 0.85 location coefficient value.

In total, ten indicators were used to quantify the social vulnerability at the BGRI scale, five for the sensitivity (Eq. 3) and five for the lack of resilience (Eq. 4).

$$Sensitivity = \frac{DP+YP+OP+FP+IP}{5} \qquad (3)$$

where:

DP = Population density; YP = Population younger than 13 years old; OP = Population older than 64 years old; FP = Female population; IP = Illiterate population

The indicator characterising the population with physical limitation, present in the sensitivity formula of the study of Murillo-Garcia and co-authors (2015), was not used because it was not listed by the INE at the BGRI scale, and the indigenous population indicator, also present in Murillo-Garcia and co-authors (2015), was not used because it does not concern the Portuguese context.

$$\text{Lack of Resilience} = \frac{\text{WA+UNEMP+NDEV+RDW+RLC}}{5} \qquad (4)$$

where:

WA = Persons without financial activity; UNEMP = Unemployed population; NDEV = Dwellings without water, WC, sewer or bathroom; RDW = % Rented dwellings; RLC = Reclassified location coefficient

The income population indicator and the population with access to the national health insurance indicator present in the lack of resilience formula of Murillo-Garcia and co-authors (2015) were replaced by the WA, UNEMP, NDEV and RDW indicators, which are proxies for some of the social vulnerability indicators considered by Rufat and co-authors (2015) (e.g. wealth, employment, non-home ownership), because of their absence from the INE census.

All the indicators used in the Eq. 2, Eq. 3 and Eq. 4 range from 0 to 1, 1 characterising the maximum vulnerability. The social vulnerability values range therefore also between 0 and 1.

4.1.2.2. Combination of the new social vulnerability assessment with the physical vulnerability at the BGRI scale

As it was carried out for the SoVI classes in the second chapter, the new social vulnerability coming from the average of the sensitivity and the lack of resilience was classified into five classes using a standard deviation classification. The social vulnerability values and their class values are presented in Table 4.1.

Table 4.1- Classification of social vulnerability calculated at the BGRI scale

Social vulnerability value and level			**Value of the class**
≤ - 1.5 Std. Dev.	]0 ; 0.24]	Very low	1
]-1.5 Std. Dev ; -0.5 Std. Dev]	]0.24 ; 0.38]	Low	2
]-0.5 Std. Dev ; 0.5 Std. Dev]	]0.38 ; 0.53]	Medium	3
]0.5 Std. Dev ; 1.5 Std. Dev]	]0.53 ; 0.67]	High	4
> 1.5 Std. Dev	]0.67 ; 1]	Very high	5

On the other hand, the physical vulnerability values, which were attributed to the buildings in relation to the type of material of their structure in the third chapter, were classified into four classes as it was done in the third chapter. The classes and their attributed value are shown in Table 4.2. The values of the classes range from 2 to 5, 5 being the value of the very high physical vulnerability and 2 being the value of the low physical vulnerability. In this case, there are no physical vulnerability values between 0 and 0.2 (very low physical vulnerability), and this is why the classification begins at 2 and not at 1.

Table 4.2 - Classification of physical vulnerability calculated at the BGRI scale

Physical vulnerability value and level		**Value of the class**
[0.2 ; 0.4]	Low	2
]0.4 ; 0.6]	Medium	3
]0.6 ; 0.8]	High	4
]0.8 ; 1]	Very high	5

The classes of the social vulnerability (Table 4.1) and the physical vulnerability (Table 4.2) were then crossed by adding their values. The physical vulnerability values and the social vulnerability values representing a so different reality, it seemed better to combine them by crossing their classes than to calculate their average. The results are shown in Table 4.3.

Table 4.3 - Crossing of the social vulnerability values and the physical vulnerability values

+	Very high social vuln. (class 5)	High social vuln. (class 4)	Medium social vuln. (class 3)	Low social vuln. (class 2)	Very low social vuln. (class 1)
Very high physical vulnerability (class 5)	10	9	8	7	6
High physical vulnerability (class 4)	9	8	7	6	5
Medium physical vulnerability (class 3)	8	7	6	5	4
Low physical vulnerability (class 2)	7	6	5	4	3

The total vulnerability resulting from Table 4.3 was classified into four classes, from the low to the very high total vulnerability (see Table 4.4). Here again, the classes of total vulnerability range from low to very high, in order to follow the physical vulnerability classification.

Table 4.4 - Classification of the total vulnerability

Total vulnerability value	**Total vulnerability class**
3 and 4	Low
5 and 6	Medium
7 and 8	High
9 and 10	Very high

The total vulnerability values were mapped for each scenario of landslide magnitude (see chapter 3), and the maps are shown in the results subsection.

4.1.3. Landslide risk analysis

The landslide risk is defined as the product of the landslide hazard, the vulnerability and the elements at risk (Varnes and the International Association of Engineering Geology Commission on Landslides and Other Mass Movements, 1984; Cardinali et al., 2002; Remondo et al., 2004; Zêzere et al., 2008).

In the case of this study, the landslide risk was analysed and shown in a table crossing the deep-seated landslides hazard, the total vulnerability and the elements at risk, as it was made in the study of Koks and co-authors (2015). In the present study two types of elements at risk were considered: the first one is the population and the second one is the built environment. That is why the landslide risk is presented in two tables in the results subsection, the first one considering the exposition of the resident population, and the second one considering the economic value of the buildings.

In order to assess the exposition of the population, the resident population of each BGRI provided by the census of the INE was considered. Because the number of residents per building was not available, the resident population per BGRI was distributed into each residential building of the BGRI by dasymetric mapping in function of the area of each building (Garcia, 2012), in order to estimate the number of residents in each susceptibility class and in each total vulnerability class.

Regarding the economic value of all the buildings of the Loures municipality (not only the residential buildings economic value), the economic values calculated in the third chapter were used.

The two tables representing the 3 metres-deep landslide risk are shown in the results subsection; the value of 3 metres-deep landslide was chosen because it was shown in the third chapter that these landslides are the ones which generate the highest risk values.

4.2. Results

4.2.1. Combination of the physical vulnerability at the BGRI scale and the social vulnerability at the civil parish scale

The SoVI values of the Loures municipality civil parishes were converted into values between 0 and 1 in order to calculate the average vulnerability (Table 4.5). The new set of social vulnerability values has a mean of 0.53 and a standard deviation of 0.22. The map of the civil parishes of the Loures municipality is represented on Figure 3.3, in the third chapter.

Table 4.5 - Original and converted SoVI values

Civil parish name	Original SoVI value	Converted SoVI value
1. Bucelas	0.1	0.46
2. Lousa	1.9	0.6
3. Fanhões	1.21	0.55
4. Loures	-5.84	0
5. Santo Antão do Tojal	1.43	0.56
6. São Julião do Tojal	3.5	0.72
7. Santo António dos Cavaleiros	0.56	0.5
8. Frielas	2.4	0.64
9. Apelação	3.84	0.75
10. Unhos	3.4	0.72
11. São João da Talha	0.28	0.47
12. Santa Iria de Azóia	-1.56	0.33
13. Camarate	2.56	0.65
14. Bobadela	-1.22	0.36
15. Prior Velho	7.06	1
16. Sacavém	2.54	0.65
17. Portela	-2.97	0.22
18. Moscavide	-1.45	0.34

The averages of the physical vulnerability values and the converted SoVI values of the Loures municipality were calculated for the nine different landslide magnitude scenarios described in the third chapter. The average vulnerability for residents living in buildings potentially affected by a landslide body was mapped and was shown in Figure 4.1, while Figure 4.2 shows the average vulnerability for residents living in buildings potentially affected by a landslide foot. The classification of the average vulnerability is identical to the classification of the physical vulnerability in the third chapter.

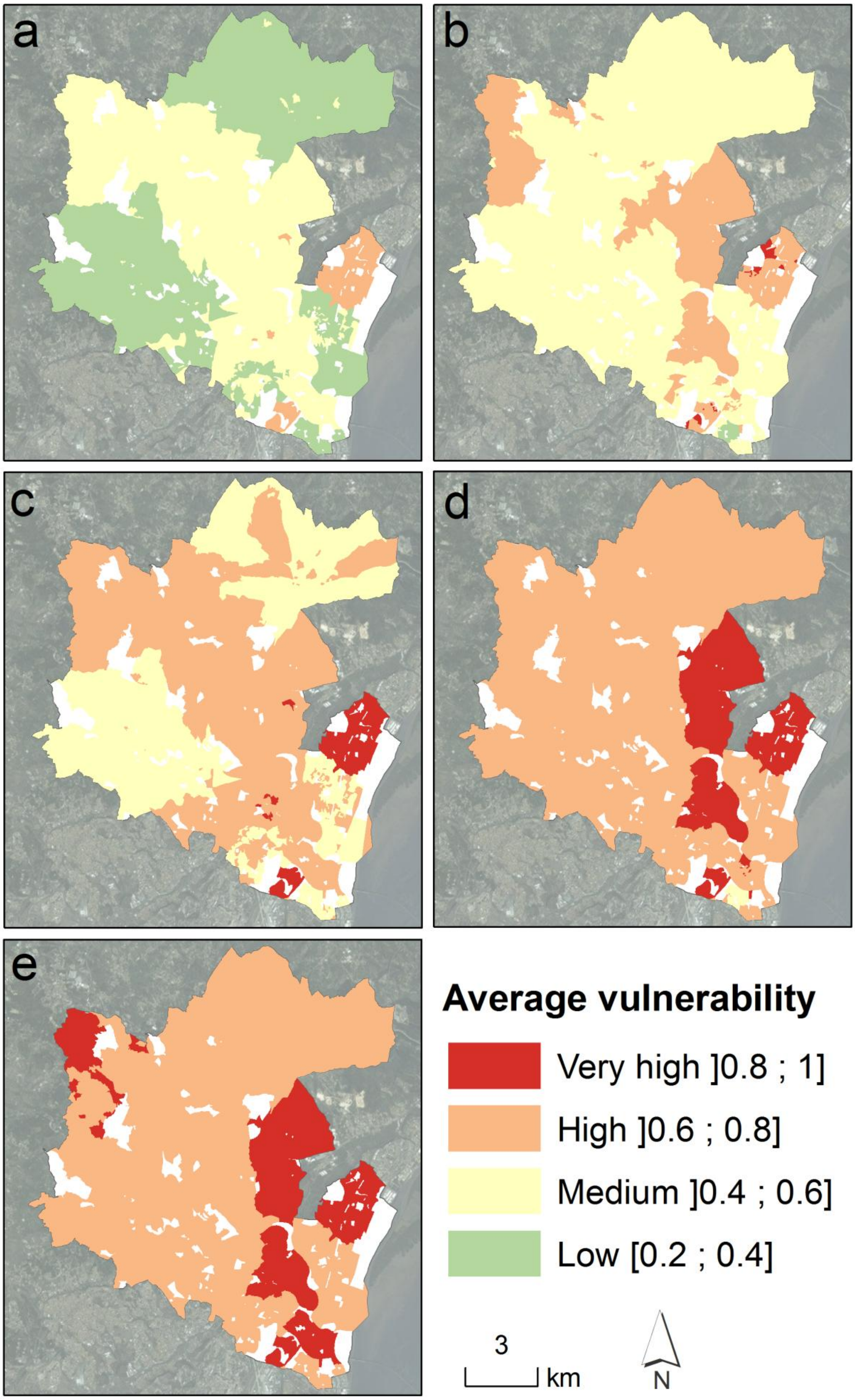

Fig. 4.1 - Average vulnerability for residents living in buildings potentially affected by a landslide body, for a slip surface depth of (a) 1 m, (b) 3 m, (c) 5 m, (d) 10 m, and (e) 20 m. White polygons are BGRI subsections without buildings.

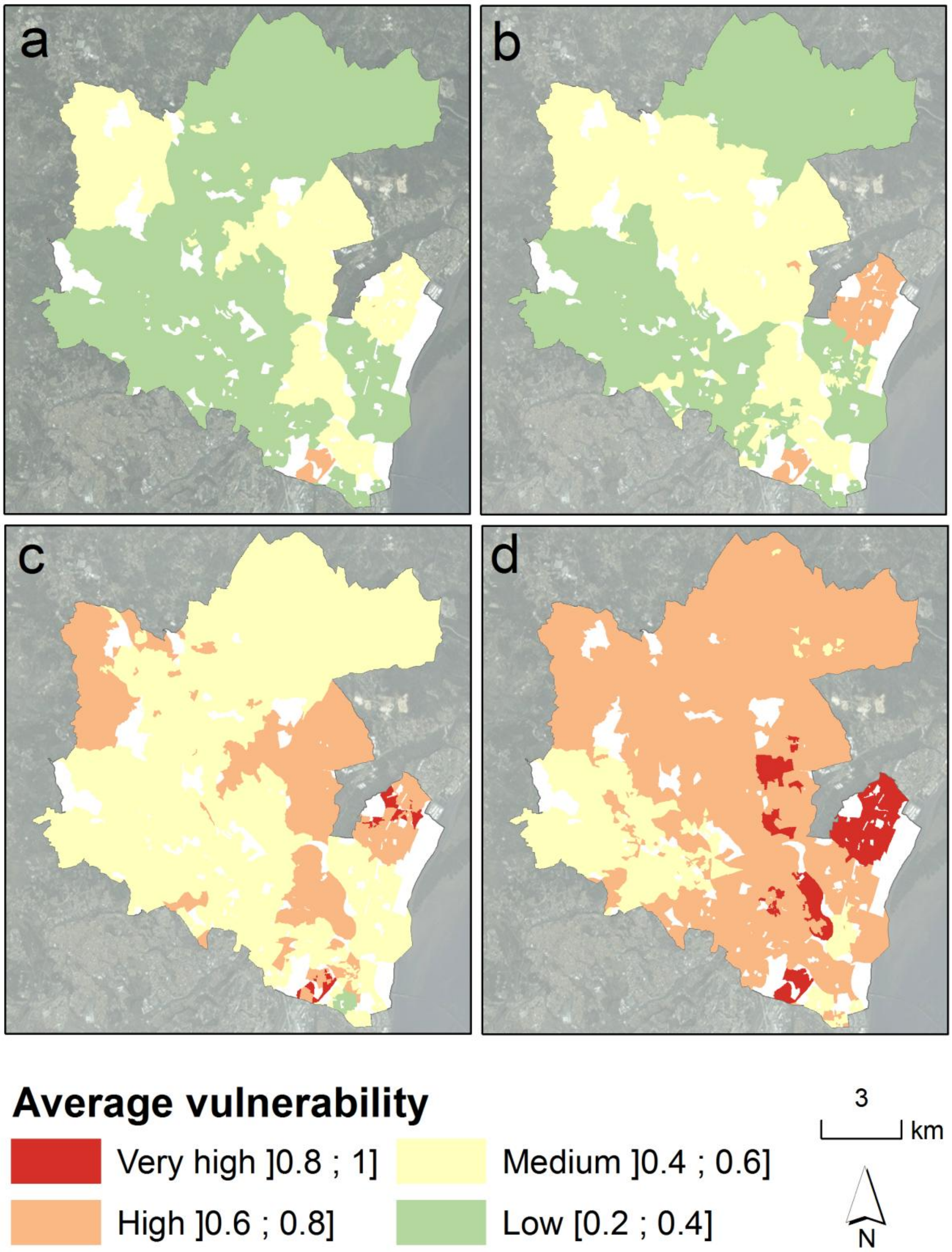

Fig. 4.2 - Average vulnerability for residents living in buildings potentially affected by a landslide foot with an affected material height of (a) 0.5 m, (b) 1 m, (c) 3 m, and (d) 5 m. White polygons are BGRI subsections without buildings.

As expected, the average vulnerability increases as the magnitude of the landslides increases (Fig. 4.1 and Fig. 4.2).

As a rule, the social vulnerability tends to generate a reducing effect on the values of average vulnerability; for instance, the physical vulnerability of the whole built environment of the Loures municipality is maximum (between 0.8 and 1) for the buildings potentially affected by a landslide body, for a slip surface depth of 10 and 20 m (Fig. 3.7.d and 3.7.e presented in the third chapter), whereas the average vulnerability of these buildings is between 0.6 and 1. The comparison of the physical vulnerability maps (Fig. 3.7 and Fig. 3.8 presented in the third chapter) and of the SoVI map (Fig. 2.2 presented in the second chapter) with the average vulnerability maps (Fig. 4.1 and Fig. 4.2) allows to understand the variation of the average vulnerability values. Indeed, to follow with the example of the buildings potentially affected by a landslide body for a slip surface depth of 10 and 20 m, the civil parishes of São Julião do Tojal and of Prior Velho have a very high average vulnerability because of their high SoVI values, whereas the civil parish of Santa Iria de Azóia has low SoVI values (cf. Fig. 2.2 presented in the second chapter), and therefore, its very high average vulnerability is due to the very high physical vulnerability of their buildings (which is closer to 1 than to 0.8).

The high average vulnerability values are present in the nine magnitude scenarios. The very high vulnerability values begin to appear for at least 3 metres-deep landslides and for at least 3 metres high of affected material on landslide foot. The areas classified as highly and very highly vulnerable increase when the landslide magnitude increases (Fig. 4.1 and 4.2).

The average vulnerability maps provide quite generalised information, because of the civil parish scale of the SoVI values. That is why a second approach of the combination of social vulnerability and physical vulnerability was done, using new approach for the social vulnerability that was assessed at the BGRI scale.

4.2.2. Assessment of the social vulnerability at the BGRI scale and its combination with the physical vulnerability at the BGRI scale

The social vulnerability was assessed at the BGRI scale. This assessment was based on the average of the sensitivity and the lack of resilience, themselves based on ten indicators provided by the INE census and by the Portuguese Tax Services (Law Number 64-B/2011 of 30 December). The social vulnerability has values between 0 (in the BGRI subsections where there is no resident) and 0.91, with a mean of 0.45 and a standard deviation of 0.15.

In terms of values of the combined vulnerability approaches, the total vulnerability (provided by the second approach) offers similarities with the average vulnerability (provided by the first approach). Indeed, most of the residents living in buildings potentially affected by a landslide body have a low or medium vulnerability to 1 metre-deep landslides, a medium, high and in some cases a very high vulnerability to 3 and 5 metres-deep landslides, and a high and very high vulnerability to 10 and 20 metres-deep landslides, in both approaches (Fig. 4.1 and Fig. 4.3). The same applies to the residents living in buildings potentially affected by a landslide foot: most of them have a low or a medium and in some cases a high vulnerability to 0.5 and 1 metre-high of affected material landslides, a medium or a high vulnerability to 3 metres-high of affected material landslides, and a medium, a high or a very high vulnerability to 5 metres-high of affected material landslides (Fig. 4.2 and Fig. 4.4).

Regarding the vulnerability for residents living in buildings potentially affected by a landslide body, only the south of the São Julião do Tojal civil parish is classified as "very high" in the total vulnerability maps (Fig. 4.3.c, 4.3.d and 4.3.e), whereas the whole civil parish was classified as "very high" for the average vulnerability (Fig. 4.1.d and 4.1.e). The same occurs for residents living in buildings potentially affected by a landslide foot within the Santa Iria de Azóia civil parish, which was entirely classified as very vulnerable in the first approach (Fig. 4.2.d) and for which only a small part of it was classified as very vulnerable in the second approach (Fig. 4.4.d). These findings show that even though fewer indicators were used for the second social vulnerability assessment than in the SoVI assessment, the second approach is more detailed in terms of location and therefore provides more precise results than the first approach.

4.2.3. Landslide risk analysis

The risk analysis associated to 3 metres-deep landslides for the resident population and for the built environment within the Loures municipality is presented in Table 4.6 and Table 4.7, respectively. In Table 4.6, the exposition of the population is characterised by the number and percentage of residents per class of landslide susceptibility. The share of the residents per class of total vulnerability is also shown by the percentage of total vulnerability, in each susceptibility class. In Table 4.7, the economic value of the buildings and the percentage of buildings per susceptibility class are shown, as well as the share of economic value of the buildings, which is represented by its percentage of total vulnerability, in each landslide susceptibility class. There is also an "error" column in each table, which comes from buildings which have been identified by the Municipal Master Plan (Direcção de Projecto do Plano Director Municipal, or DPPDM) but which have not been recorded in the BGRI by the INE (they are situated in the white zones of the Fig. 4.3); that is why the vulnerability could not be calculated in these BGRI subsections. The error caused by this lack of data has not a high influence on the total results, as the proportion of missing data is almost negligible in the case of the resident population (0.071%) and quite low in the case of the buildings (2.050%).

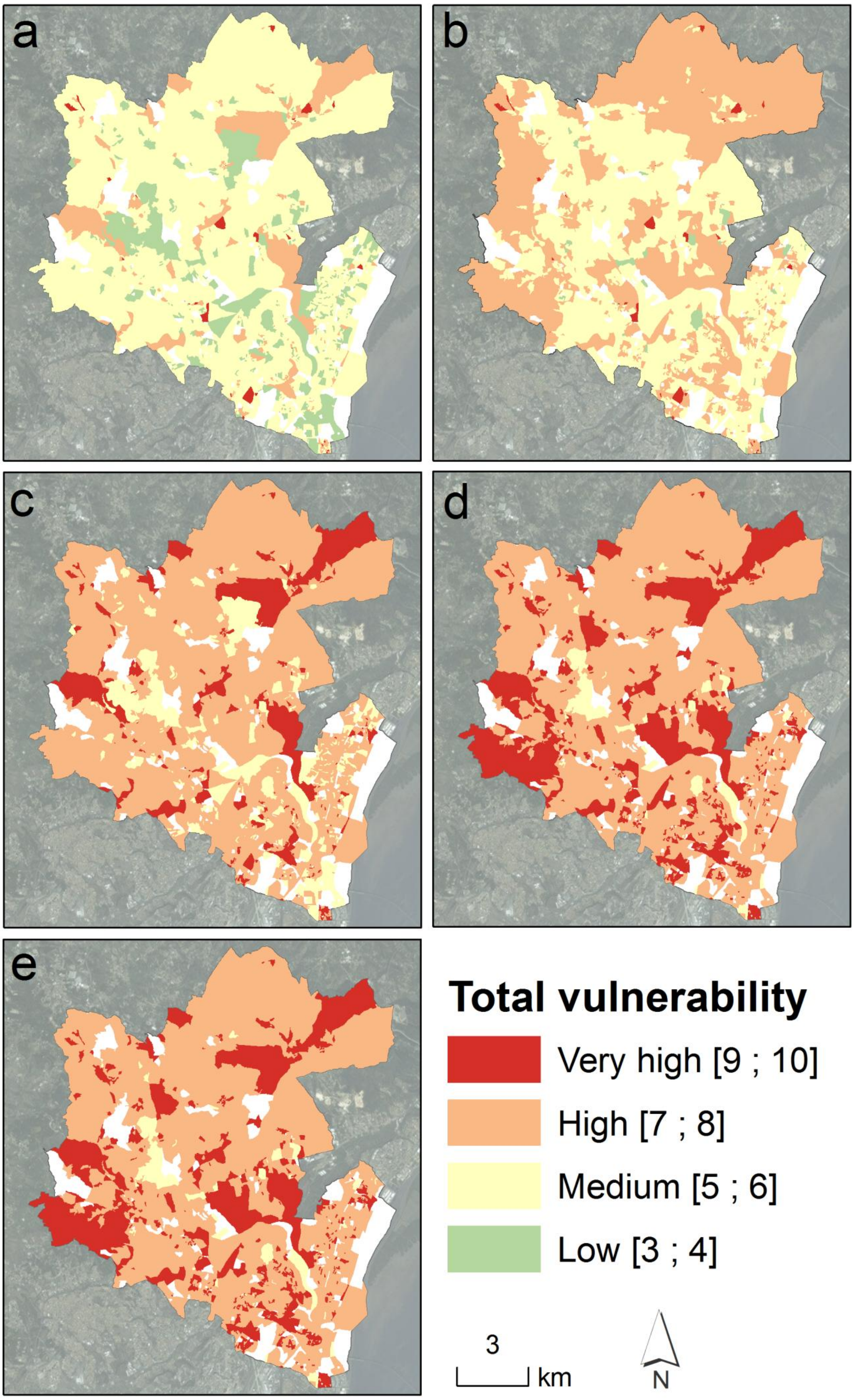

Fig. 4.3 - Total vulnerability for residents living in buildings potentially affected by a landslide body, for a slip surface depth of (a) 1 m, (b) 3 m, (c) 5 m, (d) 10 m, and (e) 20 m. White polygons are BGRI subsections without buildings.

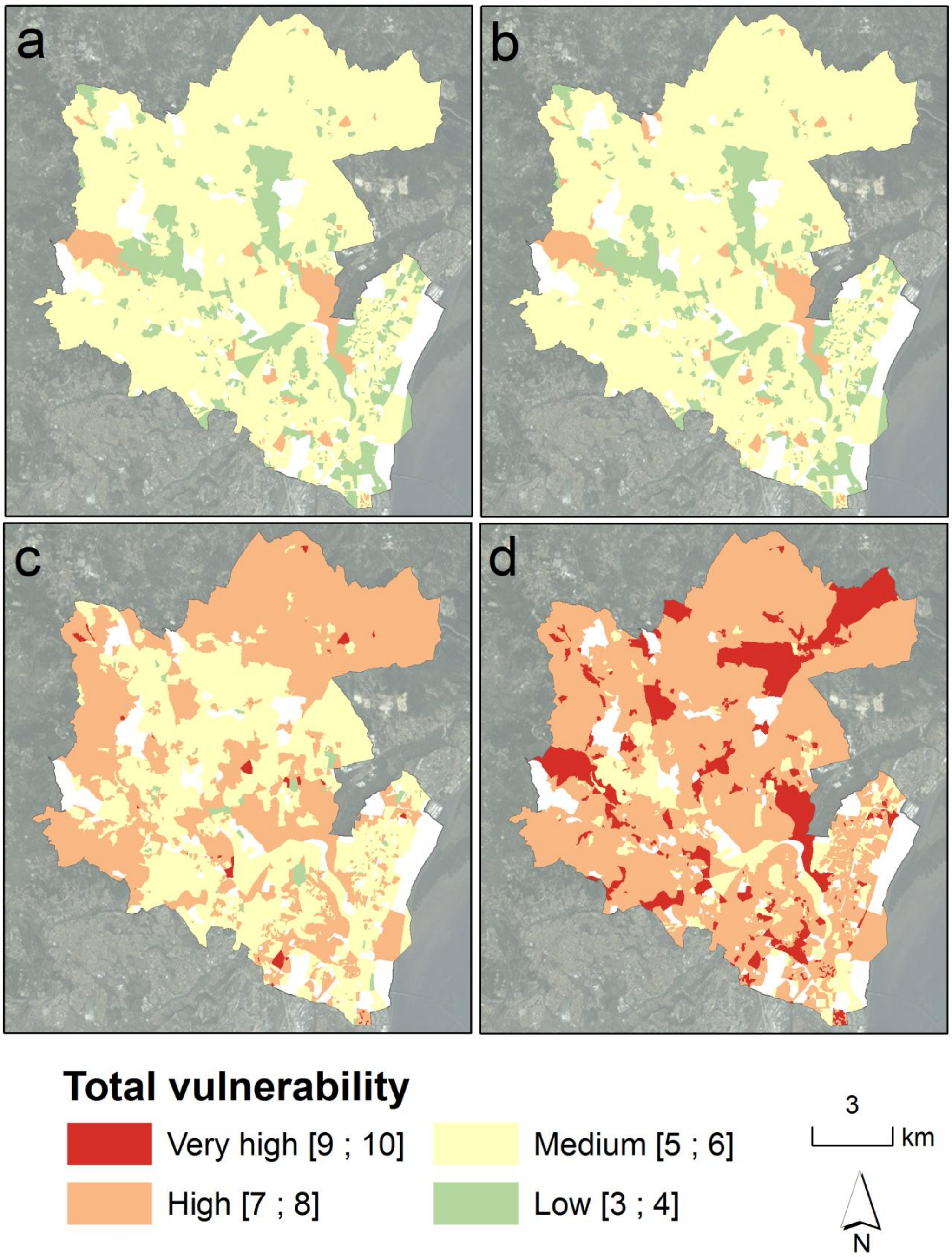

Fig. 4.4 - Total vulnerability for residents living in buildings potentially affected by a landslide foot with an affected material height of (a) 0.5 m, (b) 1 m, (c) 3 m, and (d) 5 m. White polygons are BGRI subsections without buildings.

Table 4.6 - Landslide risk analysis for the resident population, considering the total vulnerability for 3 metres-deep landslides (cf. Fig. 4.3.b); adapted from Koks and co-authors (2015)

Deep-seated landslide susceptibility class	**Area of the landslide susceptibility class**		**Resident population**		**Share of resident population per total vulnerability class**				
	Total (km^2)	%	Total	%	Very high	High	Medium	Low	*Error*
I. Very high	11.71	6.97	391	0.2	0	0.140	0.059	0	*0*
II. High	16.15	9.61	768	0.7	0	0.329	0.374	0	*0*
III. Low	31.16	18.53	8492	4.3	0.013	1.922	2.361	0.002	*0*
IV. Very low	109.10	64.89	187343	94.8	0.737	41.147	52.778	0.070	*0.071*
Total	168.13	100	197614	100	0.750	43.537	55.570	0.072	*0.071*

Table 4.7 - Landslide risk analysis for the buildings, considering the total vulnerability for 3 metres-deep landslides (cf. Fig. 4.3.b); adapted from Koks and co-authors (2015)

Deep-seated landslide susceptibility class	**Area of the landslide susceptibility class**		**Economic value of the buildings**		**Share of economic value of the buildings per total vulnerability class**				
	Total (km^2)	%	Total (M€)	% of buildings	Very high	High	Medium	Low	*Error*
I. Very high	11.71	6.97	34.79	0.47	0	0.136	0.055	0	*0*
II. High	16.15	9.61	111.38	1.48	0.002	0.324	0.281	0.001	*0*
III. Low	31.16	18.53	680.83	6.48	0.033	1.887	1.768	0.031	*0.007*
IV. Very low	109.10	64.89	17450.21	91.57	3.239	36.714	52.832	0.646	*2.042*
Total	168.13	100	18277.21	100	3.274	39.061	54.936	0.678	*2.050*

Considering the total vulnerability to 3 metres-deep landslides, the classes 1 (very high) and 4 (low) have a small area in relation to the classes 2 (high) and 3 (medium), as it can be seen in the Fig. 4.3.b. That is why the vast majority of the population (93.893%) resides in the classes 2 and 3 (respectively high and medium total vulnerability classes). Among these classes 2 and 3, the majority of the population resides in the very low landslide susceptibility class, which represents 64.89% of the Loures municipality. Its risk is thus not elevated, in comparison to the 0.902% residents who are living in high and very high landslide susceptibility classes. Similar observations can be done for the economic value of the buildings. Indeed, the majority of the built environment (93.997%) is located within the total vulnerability classes 2 and 3, and most of the buildings are located within the very low landslide susceptibility class. The risk is the highest for the 1.95% of the buildings which are located within the high and very high susceptibility classes (the total economic value of which being EUR 146,170,000) and among them, for the ones which are located within the most vulnerable classes (0.798% of the total economic value of the buildings are located within a high or very high susceptibility class and has a total vulnerability medium or higher).

4.3. Discussion

In comparison to the social vulnerability values resulting from the study of Murillo-Garcia and co-authors (2015), the social vulnerability which was assessed at the BGRI scale in the present study is on average lower. This can be explained by the fact that Murillo-Garcia and co-authors (2015) considered the exposition of the population as a part of the vulnerability. Moreover, the original formulas were adapted and the indicators are not always the same. Finally, the context is different, essentially by the absence of indigenous population in the Loures context.

The results coming from the risk analysis are comparable with the ones coming from the study of Koks and co-authors (2015). In terms of the residents exposition (Table 4.6), the residents of the Loures municipality seem to be on average as exposed to landslides as the residents of the Greater Rotterdam are exposed to floods: indeed, 16.58% of the Loures residents live in the high and very high susceptible classes where 75% of the future landslides should occur, while 16.96% of the Rotterdam residents live in the two highest susceptibility classes where the flood can reach at least 200 cm. Nevertheless, regarding the 3 metres-deep landslide risk, Loures residents are less vulnerable to these landslides than Rotterdam residents are vulnerable to floods: 0.469% of the Loures residents live in areas that are both very highly susceptible or highly susceptible to landslides and evidence a high or a very high total vulnerability, while 17.55% of the Rotterdam residents live in areas which are both susceptible to at least 200 cm floods and considered as highly vulnerable by Koks and co-authors (2015). The two main reasons that explain this difference are: (1) Koks and co-authors (2015) used only social vulnerability and the classification they used is relative (they used a standard deviation classification); (2) in the present study, the risk was analysed for 3 metres-deep landslides; in this case, the physical vulnerability is quite low, and consequently, the areas of high or very high total vulnerability are small in extension. If the risk were analysed for a landslide magnitude of at least 5 metres deep applying the present method, the percentage of residents living in areas with a high or a very high vulnerability would substantially increase because the areas of these classes would also increase with the landslide magnitude (cf. Fig. 4.3).

Regarding the economic value of the buildings (Table 4.7), the share of the economic values tends to follow the trends of the share of resident population shown in Table 4.6. This is mainly due to the fact that the distribution of the residential buildings (which were used in Table 4.6) is fairly homogeneous among the total built environment (which was used in Table 4.7).

The method which was used in the present study to assess the social vulnerability at the BGRI scale has the advantage to be applicable to any Portuguese municipality in a minimum of time, because the data used was provided by the INE and from the Portuguese Tax Services and are available at the BGRI scale for the entire country. Moreover, the risk analysis presented here for 3 metres-deep landslides can be reproduced for any of the other landslide magnitudes for which the physical vulnerability was assessed. Finally, the risk analyses are summarised in tables which enable a quick interpretation of the findings.

However, the present study has several limitations; one of them is that the results were not validated, as it occurs in most of the geospatial modelling studies which tend to focus on the construction, mapping and analysis of quantitative factors (Rufat et al., 2015). The lack of consequences data record after landslide occurrences in the Loures municipality hampers the validation of vulnerability and risk findings. Moreover, in terms of indicators used for assessing the social vulnerability at the BGRI scale, demographic characteristics, socio-economic status, neighbourhood quality of life and land tenure were considered in this study using the indicators which were available at the BGRI scale; nevertheless, Rufat and co-authors (2015) consider that indicators relative to the health, the coping capacity and the risk perception are also important for a complete social vulnerability assessment, and these indicators were not available in the INE census at the BGRI scale. Another limitation is that the model of social vulnerability provides results for the resident population, which must be close to the reality during the night-time; but during the daytime the population is not the same and the INE does not provide detailed data (e.g. age, employment) about the population which is present in the Loures municipality during the daytime. An estimate could be found with a spatio-temporal model of the population distribution which uses population mobility statistics, as the one of Freire and co-authors (2011). The population which is present in the Loures municipality during the daytime could be assessed in a future work. Finally, the repartition of the residents per buildings was not known and was therefore estimated by a dasymetric distribution, which is an approximation of the reality adding therefore a supplementary uncertainty.

4.4. Final considerations

The objectives of the present thesis were to elaborate a methodology of vulnerability assessment to landslides at the municipal scale, and to analyse the landslide risk, taking in consideration the vulnerability assessment. First, the susceptibility of the slopes of the Loures municipality to deep and shallow slides was assessed and validated (cf. first chapter). Then, the physical vulnerability of the buildings of the Loures municipality to nine magnitude landslide scenarios was assessed on the base of an inquiry which was filled up by a pool of landslides experts and by a sub-pool of landslide experts who know the study area (cf. third chapter). The comparison of the answers given by the pool of experts and by the sub-pool and the analysis of the standard deviations of the vulnerabilities were useful to interpret the vulnerability values and to assess their accuracy. The landslide risk was mapped, resulting from the multiplication of the landslide hazard, the physical vulnerability of the buildings and their economic values. Moreover, the social vulnerability was assessed by the SoVI method at the civil parish scale (cf. second chapter) and by another method adapted from Murillo-Garcia and co-authors (2015) at the BGRI scale (cf. conclusion section). Both social vulnerability assessments were combined with the physical vulnerability which was assessed in the third chapter, and the landslide risk for residents and for the buildings was analysed by crossing the exposition of the residents and the economic values of the buildings with the susceptibility of the slopes. The total vulnerability, which is a combination of the physical and social vulnerabilities at the BGRI scale was also considered in this work.

To summarise the findings, the landslide risk is maximum for the 3 metres-deep landslides; indeed, these landslides combine a relatively high frequency with a substantial potential damage. Moreover, 75% of the future deep-seated landslides should occur in 16.58% of the study area, according to the deep-seated susceptibility model (very high and high susceptibility classes). This area gathers 0.9% of the resident population (the 0.469% of the Loures population who live in this area are highly vulnerable to 3 metres-deep landslides and the remaining 0.433% have a medium vulnerability) and 1.95% of the buildings, the economic value of which being EUR 146,170,000.

In terms of application, the susceptibility models developed in the first chapter were used as a basis for the elaboration of the National Ecological Reserve (NER) in the Loures municipality. This means that the municipality is aware of the landslide hazard. Moreover, special conditions in relation to the use and the transformation of the land (e.g. prohibition of building housing, channels of communication, etc.) are applied in the areas which were determined as being the most hazardous by the susceptibility models and which are now part of the NER. The vulnerability and risk models have not been used yet by stakeholders even though the risk mapping coming from the physical vulnerability model developed in the third chapter would be useful for assurance companies because of the consideration of the economic value of the buildings. Civil protection would be more interested by the total vulnerability developed in the conclusion section. Indeed, this vulnerability assessment provides the location of the more vulnerable population at a large scale crossed with the buildings which have a high physical vulnerability to different landslide magnitudes.

4.5. References

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