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Integration of census data based vulnerability in landslide risk mapping - The case of Angra dos Reis, Rio de Janeiro, Brazil

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ABSTRACT

Landslide risk arises from the combination of hazard, the exposed population and their vulnerabilities. Whereas hazard depends on natural and anthropogenic factors that render the slopes susceptible to mass movements, vulnerability is related to community conditions that render it susceptible to the damaging effects. As disaster risk management (DRM) usually tends to focus on the physical aspects of the problem, it is common to neglect the level of vulnerability among exposed populations to landslide threats, a practice which may compromise the efficiency of DRM policies. This paper presents a method to evaluate vulnerability and combine it with hazard and exposure, using data sourced from the Brazilian Institute of Geography and Statistics (IBGE) census information and hazard mapping. The method includes procedures for spatial compatibilization of the three components, definition of values for each, and the manner by which they are combined. The method was applied to the municipality of Angra dos Reis in Rio de Janeiro State, Brazil. The results indicated that vulnerability has a significant influence on risk estimation and, hence, in the spatial distribution of risk levels – 66% of risk sectors had their ratings altered after consideration of this component, corresponding to 58% of the total area mapped, in which 58% of the population lives.

1. Introduction

Mass movement (translational and rotational slides, creeps, mudflows or debris flows and rock falls - [1] is one of the most frequent threats to which socioenvironmental disasters are related in Brazil [2], more frequent in the country's coastal regions and south-eastern inland areas [3,4]. According to a survey by the Integrated Disaster Information System [2] between 2009 and 2019 there were some 100 notifications of this type of disaster officially recognized by the Brazilian federal government. Noteworthy among mass movement associated disasters in Brazil is the event in the mountainous region of Rio de Janeiro state in January 2011, with the highest number of fatalities and affected people – 910 dead and 662 missing [5]. In this text, the term "landslide" is used to designate the different types of mass movements, focusing on those triggered by rainwater infiltration.

Disaster is considered a serious disruption of the functioning of a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability leading to human, material, economic and environmental losses and impacts. It is worthy of note that, as with "disaster", the other terms related to disaster risk followed the terminology conventions of the United Nations Office for Disaster Risk Reduction [6]. Risk is determined probabilistically as a function of hazard, exposure, vulnerability and capacity. The vulnerability of an element exposed to a hazard involves different aspects that determine the severity of the potential consequences if that element is affected by the relevant event. As observed in different research papers, vulnerability may be categorized in different dimensions: physical, economic, social, political, technological, ideological, cultural, educational, ecological, institutional, psychological, demographic and historical [7,8].

Landslide related disasters in Brazil bring to light a form of social organization conducive to inequality and land disputes, resulting in the fast-moving and haphazard settlement of disaster-prone land areas by poorer populations [9,10]. Disasters of this nature can be even more severe, because in addition to occupying landslide-prone areas, almost all of the exposed population is more vulnerable as a result of their socioeconomic circumstances and the poor-quality construction of their homes [11–13]. Depending on the level of vulnerability, the consequences of disasters brought about by landslide can be profound and extensive, ranging from death, homelessness and displacement through

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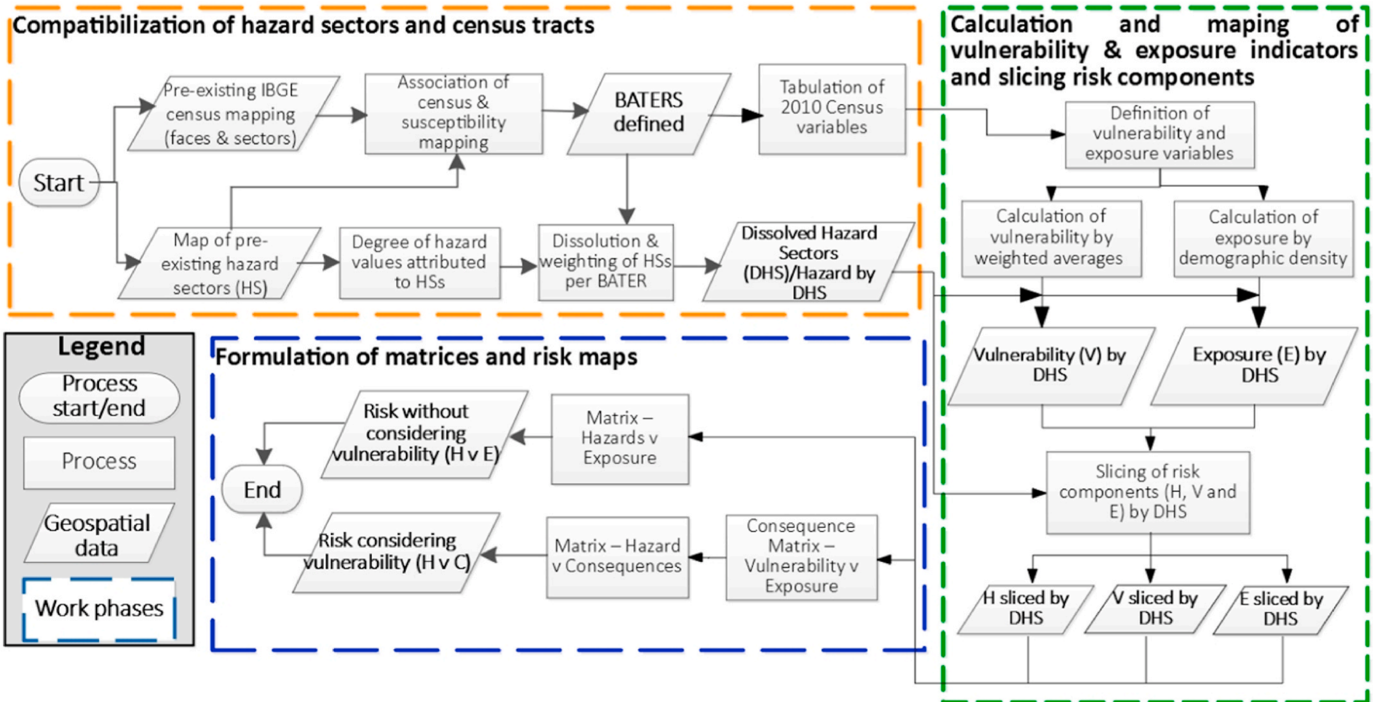

Fig. 1. Flowchart for formulation of risk maps.

social and psychological damage to material and economic losses [14]. Many authors [15–17] affirm that socio-spatial inequalities and precariousness among the population (access to sanitation, poor schooling, low income) contribute to determining levels of risk, constituting conditions of vulnerability to hazards. Certain research in Brazil also shows that this relationship also exists between social inequalities and the magnitude of socioenvironmental disasters, demonstrating that vulnerable conditions among the population aggravate, or even create, a disaster [18–20].

Therefore, in order to manage landslide disaster risks, those involved need to know that they arise from a combination of physical processes – landslides, in this case – and social processes exposing certain groups in society to the potentially damaging effects thereof. The nature of landslide disasters as detailed above highlights the need for an interdisciplinary approach to disaster risk as it emerges from this complex interrelationship between human and natural (hazardous processes) systems [15,21,22].

The inadequate approach to the problem explains the misdirected efforts to boost resilience by increasing physical resistance to impacts and remediating affected areas, while neglecting the multiple community vulnerability dimensions at the root of the problem. In the case of landslides in Brazil, the increased frequency, magnitude and territorial extension affected by mass-movement disasters, despite concentrated investments in engineering solutions, indicates that to reduce risks and disasters, not only structural actions are required, but also non-structural vulnerability reduction solutions [50,51]. This view is supported and institutionalized by the Sendai Framework [23] which, in its preamble, states that in order to prevent new disaster risks it is necessary to tackle the consequences of inequality and poverty and rapid, unplanned urbanization and inadequate land management. In effect, some authors [16,24–26] state that knowledge of vulnerability is necessary for a better understanding of the risks and, consequently, to improve formulation of public DRM policies. However, as noted by Ahmed and Kelman [27]; assessing vulnerability at a community scale taking into account the differences within local populations, difficulties in index construction and limitations in obtaining data is a challenging task.

Grounded in the National Civil Protection and Defence Policy, instituted in 2012 [28], one of the actions most encouraged by the Brazilian government over the last decade has been the formulation of instruments to subsidise the prevention of disasters associated to landslides, noteworthy among which is mapping – producing knowledge of risk components and enabling land areas to be zoned according to such components. The Sendai Framework [23], in turn, acknowledges that to understand the risks in all their dimensions and, therefore, manage risks more efficiently, one of the action priorities must be the compilation, use and dissemination of disaster risk information, including risk maps, to decision makers, the general public and communities at risk in an appropriate format by using, as applicable, geospatial information technology. Given all of the above, however, it should be noted that during the course of their work, those responsible for mapping should not confine themselves to observations regarding the physical aspects of the environment, but instead seek to expand their knowledge considering the different dimensions of vulnerabilities in the community in terms of landslide disasters.

The aim of this article is to contribute to landslide risk management by proposing a method to combine hazard, exposure and vulnerability data – the latter two based on census information – to compile a landslide risk map, using as a case study the central area of the municipality of Angra dos Reis, Rio de Janeiro State, Brazil. This method involves spatial compatibilization between hazard sectors and census features, definition of risk -component values and use of matrices to obtain the combination between these aspects. The effect of including vulnerability in the results is assessed in comparison with the method that does not consider this risk component.

2. Landslide risk mapping in Brazil

Based on risk component concepts, there is a difference between hazard and risk maps. According to JTC-1 - Joint Technical Committee on Landslides and Engineered Slopes, formed by the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE), the International Association for Engineering Geology and Environment (IAEG) and the International Society For Rock Mechanics and Rock Engineering (ISRM), the landslide hazard map presents, based on a

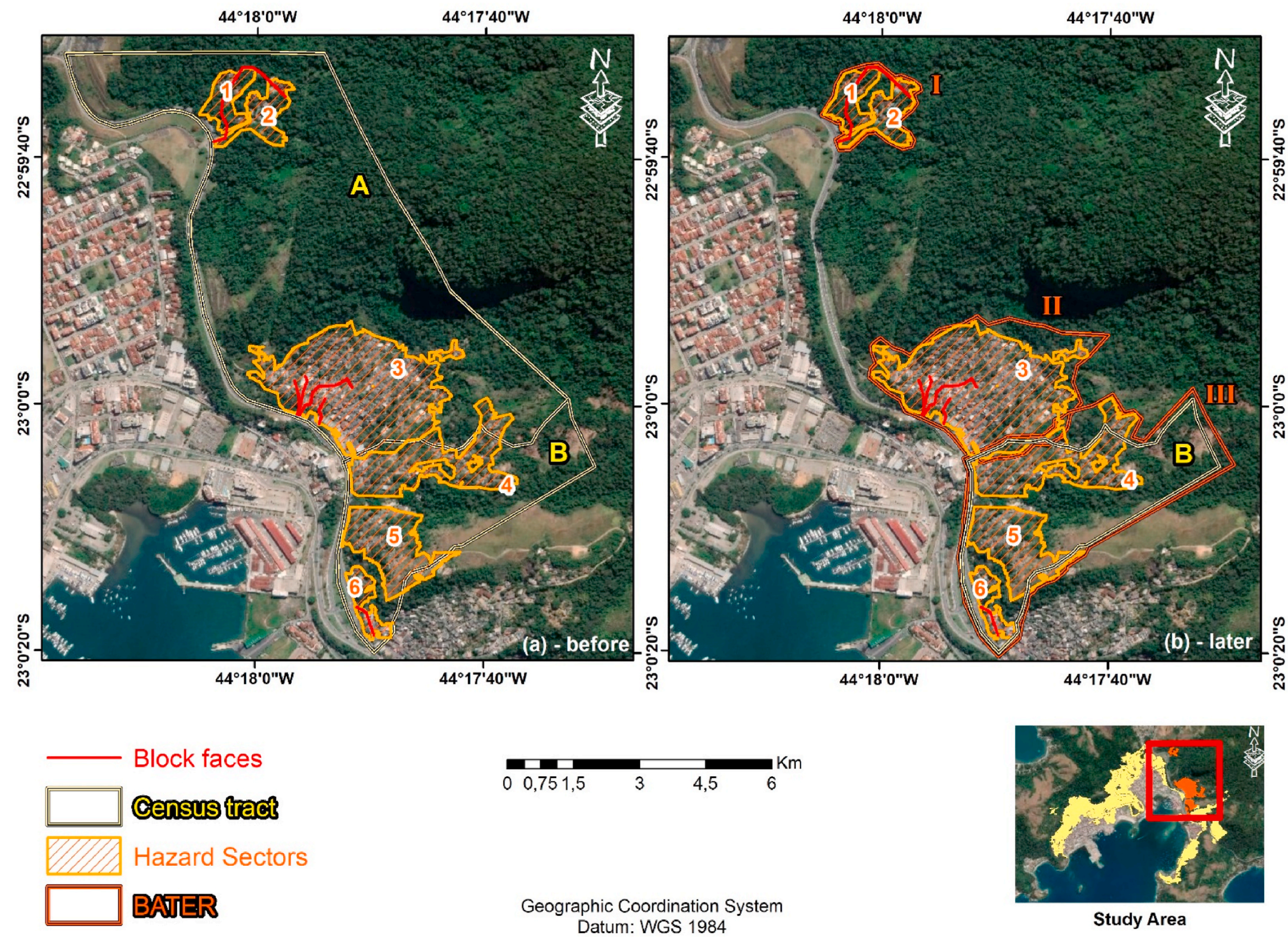

Fig. 2. Example - creation of BATERs in study area. (a) Block faces, census tracts and HS; (b) BATER polygons for the case presented in (a).

Table 1
Hazard grading.

Level	Value
Low	0–0.25
Medium	0.25001–0.5
High	0.50001–0.75
Very high	0.75001 a 1

Table 2
Exposure grading.

Level	Value (inhab/ha)	Normalized Value
Low	0–138.33	0–0.4
Medium	138.34–238.41	0.40001–0.7
High	238.42–485.6	0.70001–1.

qualitative or quantitative analysis, the spatial distribution of landslide occurrence probabilities in a study area, which may be separated by types and volumes involved [29]. According to this paper, the landslide risk map presents the results of associating the hazard map with the potential harmful effects in the respective areas. Vulnerability, in this case, is generally assessed empirically for life and property losses, varying from 0 to 1, and the authors acknowledge that more advanced methods are as yet unavailable.

Risk maps are relatively recent in Brazil, gaining momentum from the 1990s [30]. Until quite recently it was common in Brazil to find susceptibility or hazard maps erroneously being labelled as risk maps, as they did not include the components of exposure or, more frequently, vulnerability. When the vulnerability component was mentioned, reference was only made to the housing construction standard, as suggested by Brasil et al. [31]. Pereira et al. [32] present risk mapping of Portugal with municipalities as risk sectorization units, resulting from association of hazard, exposure and vulnerability data, this latter component characterized by thephysical conditions of the building features and estimated level of loss of buildings due to landslides.

In certain Brazilian municipalities, community vulnerabilities have recently been surveyed for compilation of landslide risk maps [33]. The methodologies adopted for these vulnerability surveys vary significantly between municipalities, as they are conducted by different authors, and were based on completion of forms with the communities or using census data from the Brazilian Geographical and Statistics Institute (IBGE), or a combination of both. It is important to highlight that the use of surveys based on demographic census data is limited, as the data disclosure unit in Brazil is the census tract [34], a spatial feature which does not necessarily coincide with the zones constituting susceptibility or hazard maps, making it difficult to combine the three risk components (hazard, exposure and vulnerability).

Use of census data to calculate vulnerability using factors such as school education level, age, income, basic sanitation, possession of a residence, etc., is extremely useful to socioenvironmental disaster risk management, as in addition to these variables providing significant

Table 3
Vulnerability dimensions, variables groups and their respective justifications (adapted and modified from Ref. [4].

Vulnerability Dimension	Variables Group	Justification for consideration of variables
Physical	Type of electricity supply Type of water supply Type of sanitary sewage Type of waste collection	Loss of sewage systems, water and communications constitute the potential losses in the event of a disaster. The loss of infrastructure may establish an insurmountable financial weight on small communities lacking in financial resources for reconstruction. The lack and precariousness of these infrastructures and access to potable water for populations may worsen in disaster and post-disaster situations [16,53,54] Less infrastructure indicates greater vulnerability
Social	Illiteracy among residents	Poor schooling levels limit the ability to access and understand information on the DRR and alerts or alarms. Higher levels of literacy indicate lesser vulnerability
	Dependence Ratio in relation to age	People of extreme ages are difficult to evacuate in areas where hazardous event occurrence is imminent. The elderly have reduced mobility, and parents lose time and money when crèches are affected. Dependent ages (<14 and >60) contribute to a higher level of vulnerability.
	Type of housing (house, apartment or villa)	The concentration of residences is an important factor in the dispersal and evacuation of people. When hazardous events are imminent and in the period immediately post-disaster, a configuration of residences with good neighbourhood cohabitation provides greater solidarity among residents. Better social cohesion indicates lower vulnerability
Economic	Type of housing property (own, rented, etc.)	People normally rent properties because they are temporary residents without the financial resources to acquire their own and, frequently, lack access to information on financial assistance during recovery. In more extreme cases, tenants have fewer options for shelter in the case of their home being affected. Residents of rented houses are more vulnerable
	Residents' income	Greater financial wealth enables an individual to better absorb and recover from losses due to his or her assets, insurance and social security networks. The higher the income the lower the vulnerability.

information on the exposed communities [18,35,36], census data are drawn from an existing, highly reliable database. The frequency of census data surveys, providing a temporal analysis and the experience and international recognition of IBGE, along with the uniformity of survey methodology and availability of data on all 5570 municipalities in Brazil, render the census data a precious source of information for risk management.

3. Methodology for combining the risk components

The methodology for formulation of the risk maps associated to landslides was structured in three major phases (Fig. 1): compatibilization between hazard sectors (HS) and census features; calculation and mapping of risk component indicators (hazard, exposure and vulnerability); and construction of the matrices which define the levels of risk and compilation of the risk maps.

3.1. Compatibilization between hazard sectors and census tracts – creation of BATERs

The census features map for the municipality is comprised of census sectors (polygons) and block faces (lines which represent to the sides of a block). In addition to census sectors – polygons that serve as a basis for collation and disclosure of demographic census results in Brazil – after the 2010 census a new data collection unit was created by IBGE, enabling better detailing of the statistical variables gathered – the block face, which represents one face of a square providing aggregated census data from hoses located therein [37]. The block-face datasets covered by a census sector are equivalent to the data gathered therefrom. Block-faces data are still not publicly disclosed - this type of feature involves smaller areas, which may lead to identification of interviewees, and that would compromise statistical confidentiality.

Providing more spatially detailed census data, there is still the difficulty of spatially comparing census data with data on landslide hazards for formulation of the risk map. This difficulty is brought about by the census features (census tract or block faces) not necessarily coinciding with the landslide hazard data, requiring a spatial adjustment to achieve compatibilization. Hence, the link between the census information and HS cannot be made directly and automatically.

This inconsistency is illustrated by the example in Fig. 2a, showing census tract A, involving hazard sectors (HSs) 1, 2 & 3 and the block faces available in those places, and census tract B, with HSs 4, 5 & 6. If the data were associated using only the census tracts, this could lead to an error if they were considered uniformly for HSs 1 and 2 and hazard sector 3, as these may present significantly different sociodemographic characteristics, and the use of block faces may be more convenient. Given that it is not possible to use an automated process to associate hazard and census data maps, as this requires interpretation of the features, the methodology described by IBGE and Assis Dias et al. [39] was used, by which a new land base is created to associate both geometries with an end to associating the census data to hazard sectors more adherent to census features: the Statistical Territorial Base of Risk (BATER). Fig. 2b presents this compatibilization. HSs 1 and 2 were grouped in a single BATER polygon to obtain the block face statistics making up these hazard sectors. HS 3 is in another polygon of the BATER, which will take on the statistics from the block faces contained therein. This avoids generalization of data for different sociodemographic situations (ecological fallacy – [40]. Block faces, as disaggregated data from the census tracts that contain them, therefore enable better compatibilization between the hazard maps and census data. BATERs were generated in line with the following principles determined by IBGE and Assis Dias et al. [39]; p. 452):

- "BATER should primarily be the smallest possible area resulting from the intersection of the" HS "and the census tracts or block face. Considering the statistical confidentiality, each BATER should contain at least 5 homes and 20 residents" to make census data available;
- "In cases where the block face surpassed the boundaries of the" hazard sector, "the density and" building standards "were used as a criterion for generalization. That is, if the block face had both density and building standards similar, the BATER would include the full length of the block face";
- "When two or more nearest" hazard sector "presented density and building standards similar, these were merged into a single BATER."

The BATERs were produced by vectorization on ArcGIS 10.2

Table 4
Vulnerability grading.

Level	Value
Low	0–0.4
Medium	0.40001–0.7
High	0.70001–1

Consequence Matrix (V x E)		Vulnerability (V)		
		Low	Medium	High
Exposure (E)	Low	Low	Medium	Medium
	Medium	Low	High	Very High
	High	Medium	High	Very High

Fig. 3. Consequence matrix.

Risk Matrix (C x H)		Hazard (H)			
		Low	Medium	High	Very High
Consequences (C)	Low	Low	Low	Medium	Medium
	Medium	Low	Medium	High	High
	High	Medium	High	Very High	Very High
	Very High	Medium	High	Very High	Very High

Fig. 4. Risk Matrix (Hazard Vs. consequences).

software, inputting IBGE census data (tracts and block faces), optical sensor images available on the ArcGIS basemap and digital elevation models. A table of correspondence was created between each BATER and the census features contained therein, enabling tabulation of the 2010 Census variables.

3.2. Calculations and mapping of risk component indicators

3.2.1. Hazard

As a BATER may contain more than one HS, those contained therein should be diverted in the BATER polygon, to form what is denominated as a dissolved hazard sector (DHS). These are the new spatial units for risk component mapping and, for each, statistics are generated to calculate the exposure and vulnerability components. Dissolution of the hazard sectors forming each DHS is achieved by a spatial moving average of the levels of hazard in the HSs (Equation (1)), applied in the ArcGIS 10.2 GIS environment. The numerical value of the level of hazard in a HS is based on the HS hazard map prior to dilution (Fig. 8), with the values 0.25, 0.50, 0.75 and 1.0 attributed to the low, medium, high and very high levels respectively, as proposed by Coelho Netto et al. [41]. The level of hazard is then calculated for each DHS, assuming a value from 0 to 1, and the closer to 1, the higher the probability of a landslide occurring.

$$\text{DHS Level of Hazard} = \sum_{i=1}^{i=n} \frac{\text{Area of HSi*Level of Hazard}}{\text{Total HSi areas in BATER}} \tag{1}$$

where.

n: amount of sectors comprising a DHS.

The hazard component was sliced in intervals as proposed by Coelho Netto et al. [41] in the hazard map on which this study is based (Table 1).

3.2.2. Exposure

With a view to better planning of DRR actions by public administrators, it is proposed that exposure should be characterized by the number of residents per land area unit, i.e. by demographic density [42], although other variables are also used for exposure, such as roads and constructions [32,43]. After the DHSs are defined, the area of each polygon is calculated and, based on census data, the number of residents per DHS, thereby obtaining the demographic density. Using ArcGIS 10.2, the level of exposure was calculated according to Equation (2).

$$\text{Demographic Density by DHS} = \frac{\text{Total residents per DHS}}{\text{DHS area}} \tag{2}$$

To classify the exposure data and maintain coherence between data from the three components, it was necessary to normalize the demographic density values on a scale of 0–1, as per Equation (3). The exposure component was then sliced in the same manner as for vulnerability, i.e. low level from 0 to 0.4, medium level from 0.40001 to 0.7, and high level from 0.70001 to 1 (Table 2).

$$\textit{Normalized exposure} = \frac{V_x - V_{min}}{V_{max} - V_{min}} \tag{3}$$

where

V_x: the observed value;
V_{min}: the minimum value for the variable;
V_{max}: the maximum value for the variable.

Risk Matrix (E x H)		Hazard (H)			
		Low	Medium	High	Very High
Exposure (E)	Low	Low	Medium	High	Very High
	Medium	Low	Medium	High	Very High
	High	Medium	High	Very High	Very High

Fig. 5. Risk matrix (hazard Vs. Exposure).

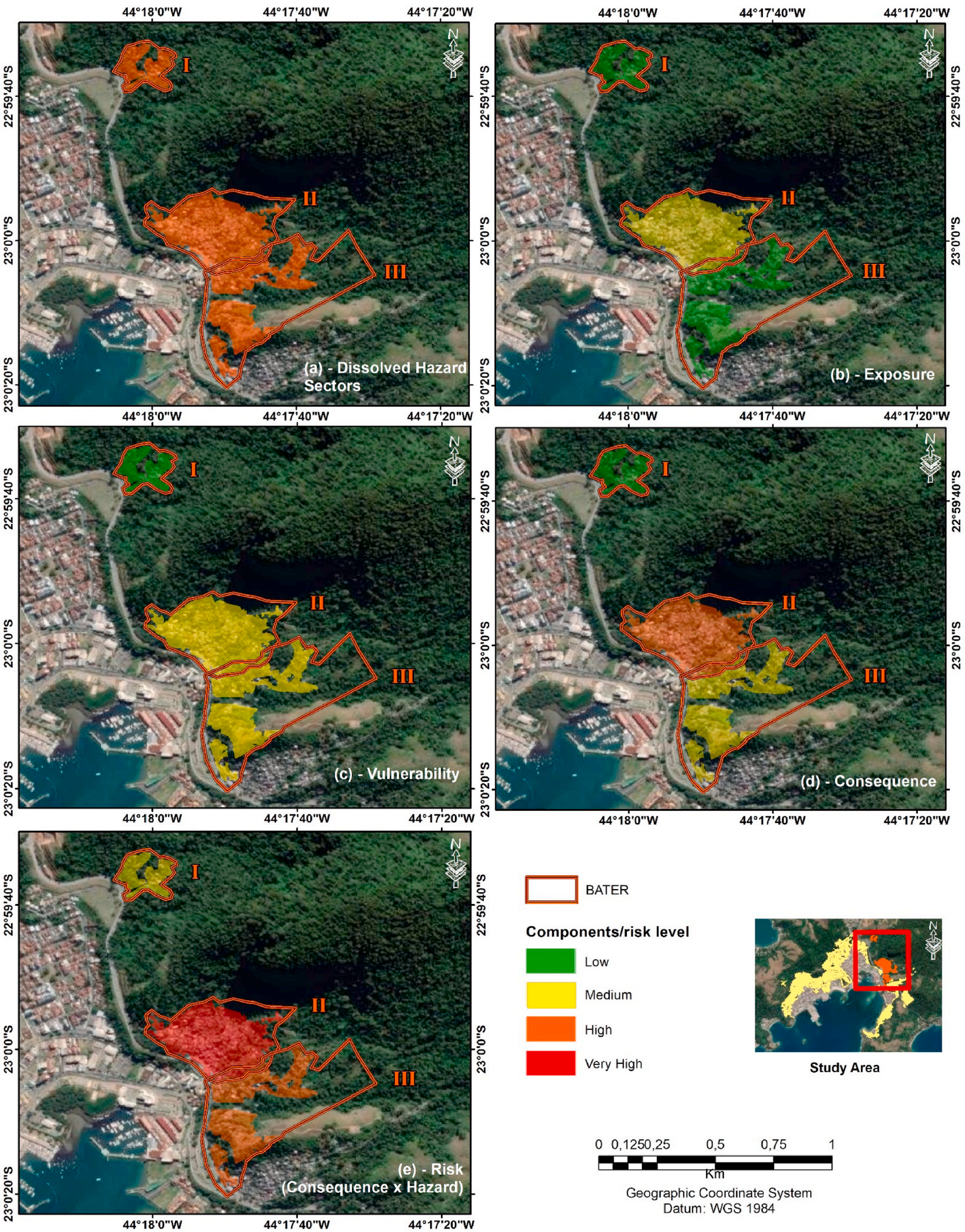

Fig. 6. Example - Method application maps: (a) Dissolved hazard sectors; (b) Exposure; (c) Vulnerability; (d) Consequence matrix; (e) Risk matrix (consequence x hazard).

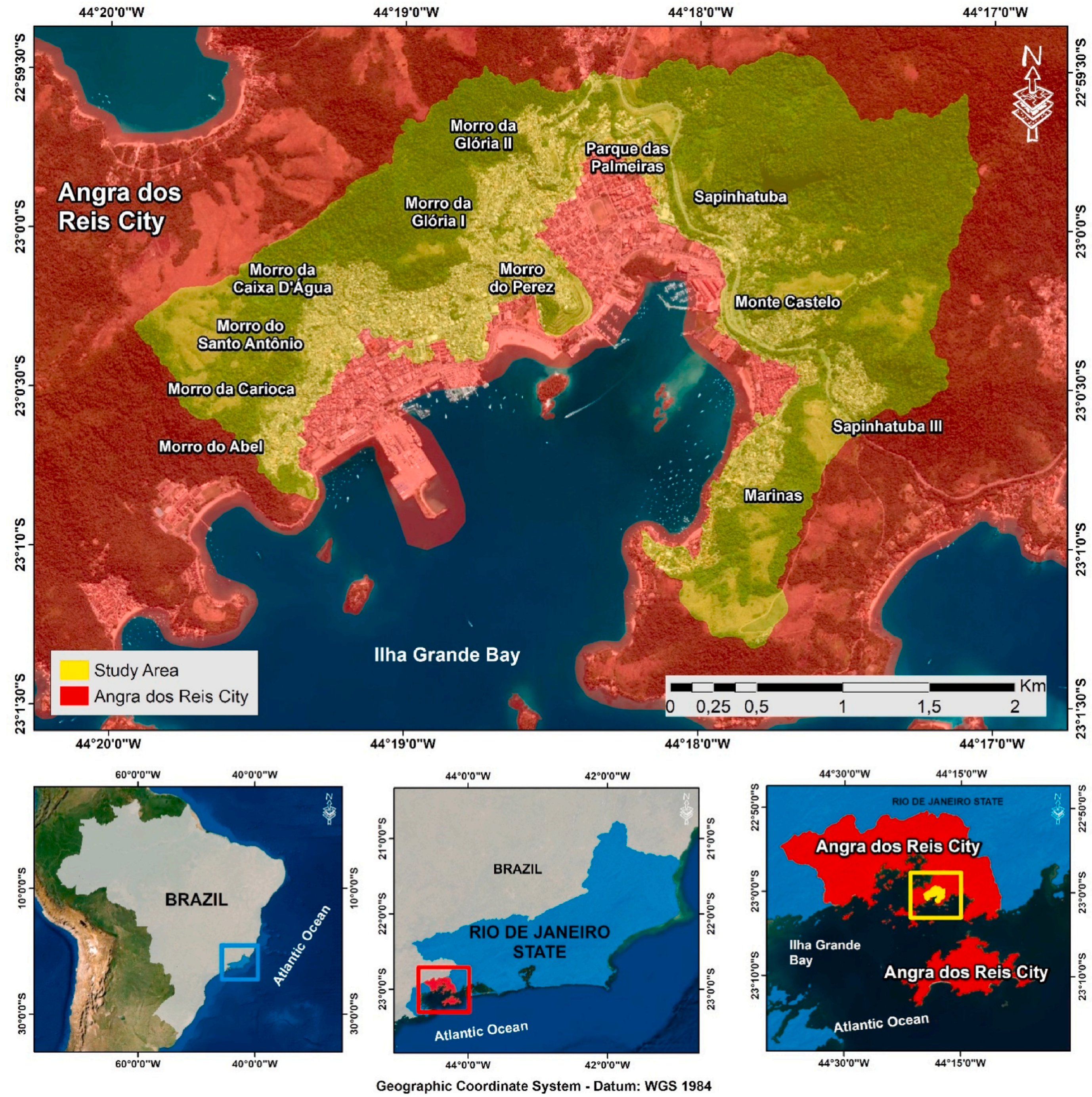

Fig. 7. Delimitation and location of study area.

3.2.3. *Vulnerability*

Vulnerability was defined in three dimensions: physical; economic; social, following the typologies presented by Wilches-Chaux [7]. From the 2010 census data, 47 variables were chosen and grouped into the following themes, referred to herein as variables groups: electricity, water, sanitary sewage, waste collection, illiteracy, dependence ratio, type of housing, ownership of housing and income. Within each group, the variables received scores from 0 to 1, and the closer to 1, the higher the contribution to vulnerability. Definition of the scores for each variable was based upon the discussions in Cutter et al. [36]; Bollin and Hidajat [44] and Almeida [18] on the influence of different variables in increased vulnerability among exposed populations. Table 3 shows the variables groups used, the dimensions into which these groups are classified and the respective justifications for their consideration.

With the exception of the illiteracy and dependence ratio groups, the variables are expressed in number of domiciles or residents. Three equations were used to arrive at the vulnerability value. Firstly, the vulnerability value is calculated for each group of variables then the value for each dimension by arithmetic mean of the groups, and finally the vulnerability value for the Dissolved Hazard Sector (DHS) by arithmetic mean of the dimensions, as shown in equations (3)–(5).

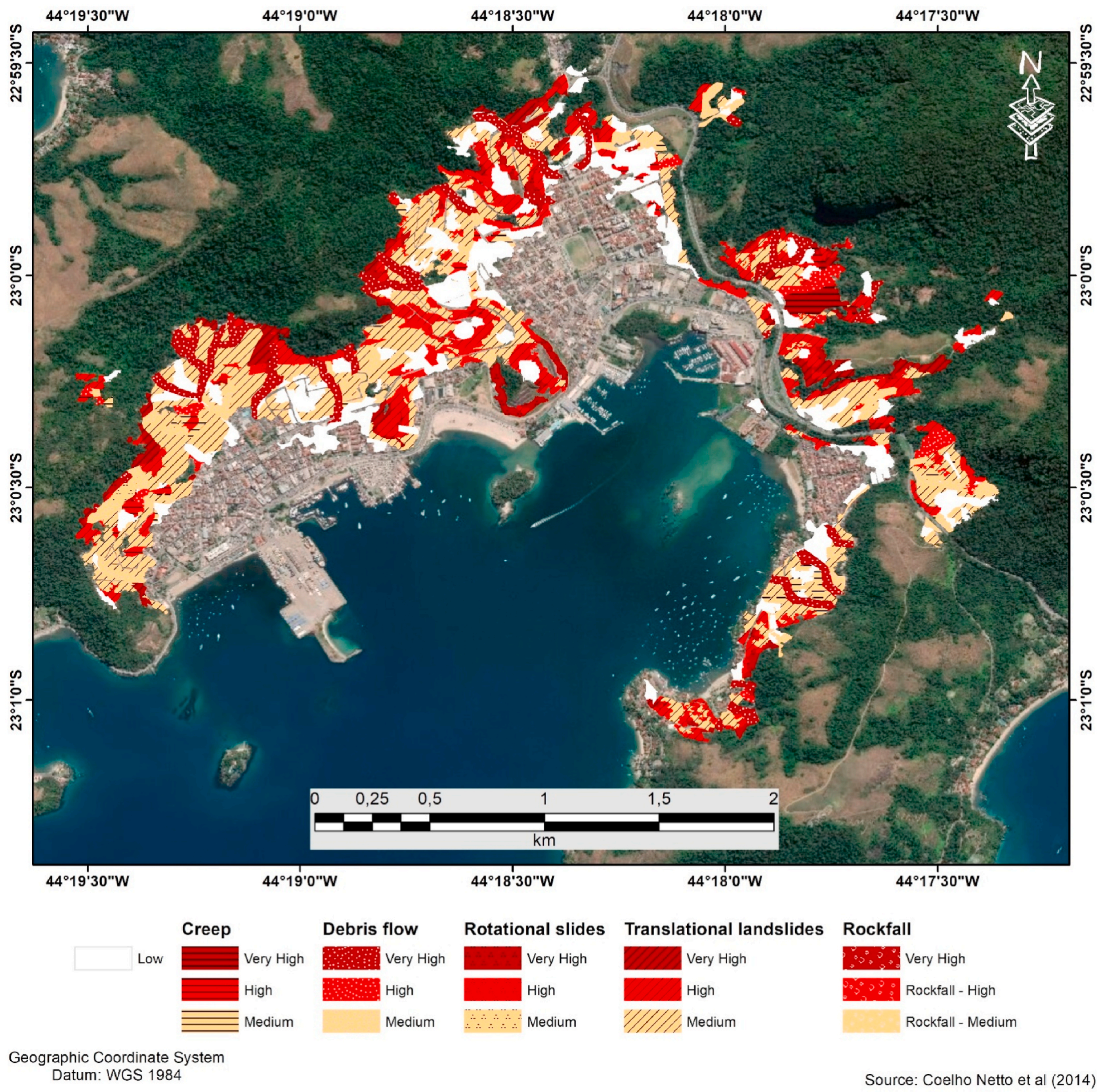

Fig. 8. Study area hazard map.

$$\text{Vulnerability of Variables Group} = \sum_{i=1}^{i=j} \frac{\text{Value of Censo 2010 variable in DHS*score}}{\text{Sum of residences or residents in HS}} \tag{4}$$

$$\text{Vulnerability of Dimension} = \frac{\sum_{i=1}^{i=m} \text{Value of variables group vulnerability}}{\sum_{i=1}^{i=n} \text{groups of variables}} \tag{5}$$

$$\text{Vulnerability} = \frac{\sum_{i=1}^{i=p} \text{Value of vulnerability of dimension}}{\text{number of dimensions}} \tag{6}$$

where.

j: number of variables; m: number of groups of variables; p: number

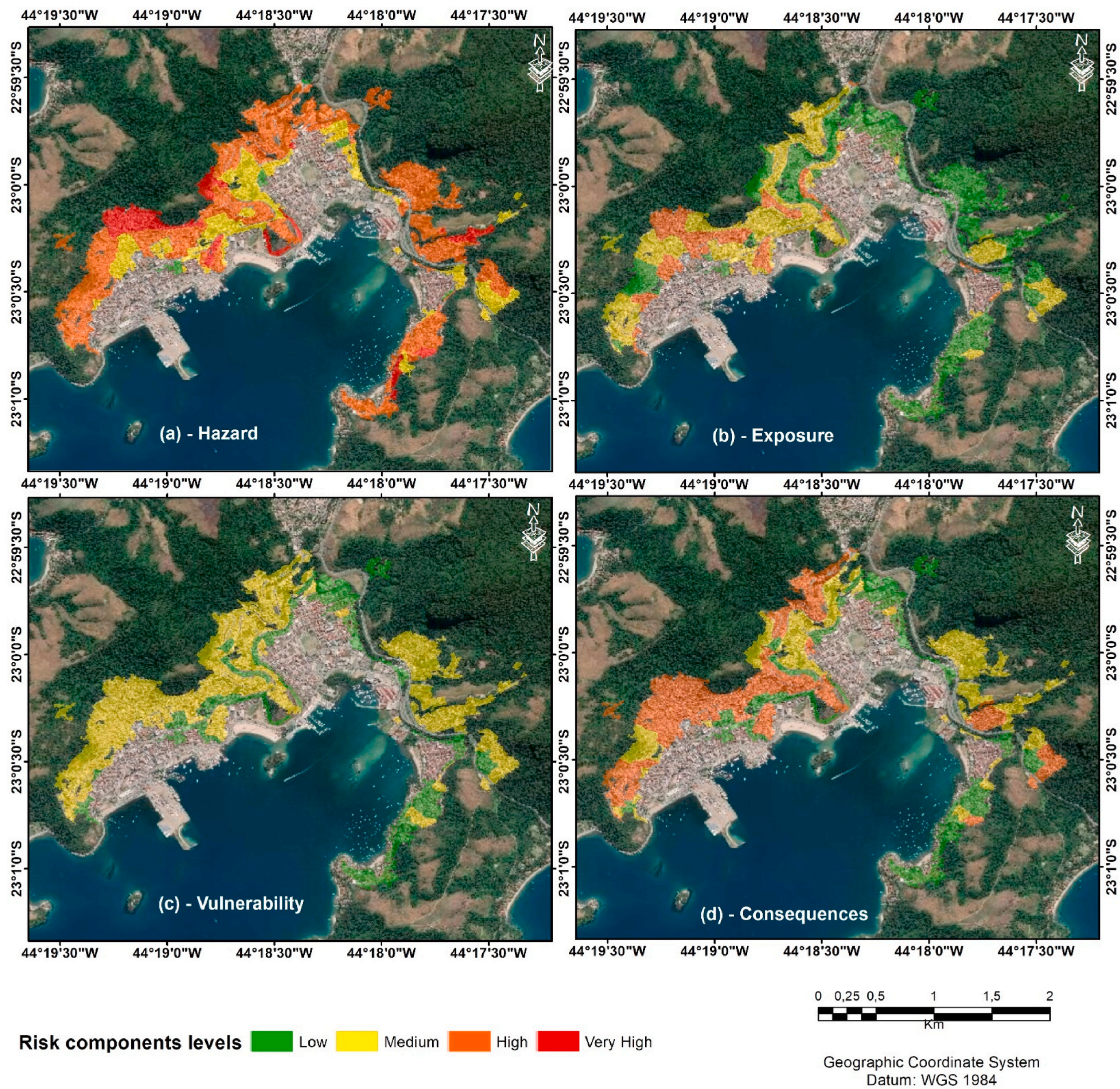

Fig. 9. Study area maps: (a) Hazard. (b) Exposure; (c) Vulnerability; (d) consequences.

of dimensions.

The vulnerability component was sliced at intervals manipulated by the authors, as observed in other studies, such as Bollin and Hidajat [44] – Table 4.

3.3. Formulation of risk component matrices

In line with one of the recognized risk analysis methods [45], also used in analysis of disaster risks associated to landslides by certain authors (e.g. Ref. [46,47], two matrices were formulated to arrive at the final risk indicator. The first cross-references data on exposure and vulnerability, creating consequence values, and the second cross-references this latter (consequences) with the hazard values.

Consequence and risk matrices are shown in Figs. 3 and 4. As it is common to find studies which estimate risk based on the combination between only the hazard and exposure components, and not considering vulnerability, a matrix combining only the two former components was developed (Fig. 5) for comparison with the method proposed herein.

3.4. Example of method application

By way of an example, Fig. 6 shows the results of each phase of application of the risk calculation method for the section shown in Fig. 2. These six HS (Fig. 2a and b) were broken down into three DHS (I, II and III) resulting in different hazard values (Eq. (1)): 0.54, 0.73 and 0.75, all high hazard level (Table 1 – Fig. 6a). The demographic densities (Eq. (2)) of DHS I, II & III are: 17.96 inhab/ha, 72.42 and 59.29, which are low, medium and low exposure levels respectively, (Table 3 – Fig. 6b). The vulnerability values (Eq. (5)) are 0.32, 0.43 and 0.45 for DHS I, II & III: low, medium and medium vulnerability levels, respectively (Table 4

Table 5
Distribution of number of DHS, area and population by hazard, exposure and vulnerability levels.

Map/Component	Level	Number of DHSs	Area (ha)	% Area	Population	% Population
Hazard	Low	6	3.20	1.6	571	2.0
	Medium	37	46.11	23.5	7467	25.8
	High	56	124.55	63.4	17,301	59.9
	Very High	12	22.67	11.5	3,56	12.3
	Total	111	196.53	100	28,889	100
Exposure	Low	45	94.46	48.1	7102	24.6
	Medium	44	73.82	37.6	13,999	48.4
	High	22	28.24	14.4	7798	27
	Total	111	196.53	100	28,899	100
Vulnerability	Low	45	56.93	29	6169	21
	Medium	66	139.60	71	22,73	79
	High	0	0	0	0	0
	Total	111	196.53	100	28,899	100
Consequences	Low	39	53.06	27	5018	17.4
	Medium	26	60.12	30.6	5822	20.1
	High	46	83.34	42.4	18,059	62.5
	Very High	0	0	0	0	0
	Total	111	196.53	100	28,889	100

– Fig. 6c). Based on these results, the consequence level (Fig. 3) is low, high, medium (Fig. 6d). Finally, combining consequence and hazard (Fig. 4), the risk levels (Fig. 6e) are medium, very high and high.

4. Study area

The area studied in this research is the central region of Angra dos Reis, a municipality in the south of Rio de Janeiro State, Brazil (Fig. 7). The area is characterized by urban sprawl on slopes susceptible to landslides triggered by heavy rainfall. One of the deadliest events to date was triggered by 440 mm of rainfall in the space of 36 h between 4 p.m. on December 30, 2009 and 6 a.m. on January 1, 2010 [41], claiming the lives of 53 people, including 22 in the study area. After the 2010 disaster, the area was included in a landslide hazard map, delimited by the 10 m level downstream and the summit line upstream [41], considering the local catchment, finalized in 2012. The total area is 646.2 ha, of which 196.53 ha are populated, with 29,899 inhabitants [34].

Angra dos Reis has natural physical and anthropogenic aspects which contribute to its susceptibility to landslides. The climate is tropical and humid, with average rainfall of 1886 mm, most of which falling with more frequency during the summer period (December to March).

The local geomorphology has formed some floodplains in the municipal area, with escarpments very close to the sea and a predominance of medium slopes with declivity between 20 and 35°. In general, the geological-geotechnical conditions are characterized by folds and faults, thin residual soils, colluvials and rock blocks. Recurring landslides observed include landslides, rock-roll and rockfall, debris flow and creep [41].

A hazard map for the study area was formulated in 2012 using quantitative and qualitative processes, through map algebra, supported by laboratory and field work, considering the relations between the hydrogeomorphology (drainage efficiency index, slope, slope position classification), geological-geotechnical aspects (rocky outcrop; landfill; colluvium; fluvial-marine deposite; thick saprolite; shallow saprolite and lithology – granite and orthogneiss), vegetation and land use to subsequently stipulate landslide processes (translational landslide, rotational landslide, creep, debris flow and rockfall) which may come to occur and their respective level of probability (low, medium, high or very high), with defined zoning formed by a set of polygons on the map, as referred to by Coelho Netto et al. [41]. Based on the understanding that there is no risk without exposure, the hazard map was revised so that only the inhabited area (196.53 ha) would be considered in this study (Fig. 8).

The hazard map validation was based on the inventory of residual landslide scars from the 2010 disaster referred to previously. Some 36 scars were identified, distributed according to the HS hazard level as follows: 47.2% at a very high level, 36.1% at a high level, 11.1% at medium level and 5.6% at low level.

In relation to its socio-spatial evolution, the municipality is marked by a background of fast population growth and conflicts between different coexisting groups (large industrial and tourism enterprises and residents of different social classes). In addition to its unequal development, Angra dos Reis presents problems in terms of environmental conditions (e.g. landslides, pollution and flooding), land ownership issues and deficient urban infrastructure. These factors, along with a scarcity of flat areas suitable for occupation, have resulted in expansion onto slope areas susceptible to landslides, primarily among more socioeconomically vulnerable sections of the population, in some cases leading to the formation of favelas (Brazilian community of largely unregulated housing construction, often on hillsides and with a predominantly low-income population). This combination of land susceptible to hazardous events such as landslides and a vulnerable population is very common in Latin America and many other parts of the world [9, 48].

There is a need for the municipal public administrators of Angra dos Reis to pay attention to such factors, as along with this process of slope occupation there has been a historical development of vulnerabilization of the population forced to occupy these unsuitable areas. In these kind of locations, some social needs are neglected by government authorities and disasters ultimately evince a composite of social and environmental injustice [9,49]. This situation escalates the need to investigate the vulnerability component in risk estimation in the region.

5. Results and discussion

5.1. Hazard, exposure, vulnerability and risk maps

As previously stated, the HSs were formulated using previous hazard mapping [41], and needed to undergo an adjustment process to enable spatial compatibilization between the risk components, as explained in sections 3.1 and 3.2.1. The level of hazard is spatialized in the map in Fig. 9a showing the dissolved hazard sectors (DHS). Table 5 provides a statistical summary of the number of DHSs, population and territorial area by level of hazard, and it is possible to observe a larger area with a high level, demonstrating the severity of this type of threat in the study area. Based on interpretation of the images, it is noted that the more upstream portion of the study area comprises DHSs with the higher levels (high and very high). It is important to note this configuration, as in these areas it is more difficult to undertake response actions due to access issues.

The level of exposure is spatialized on the map (Fig. 9b). By

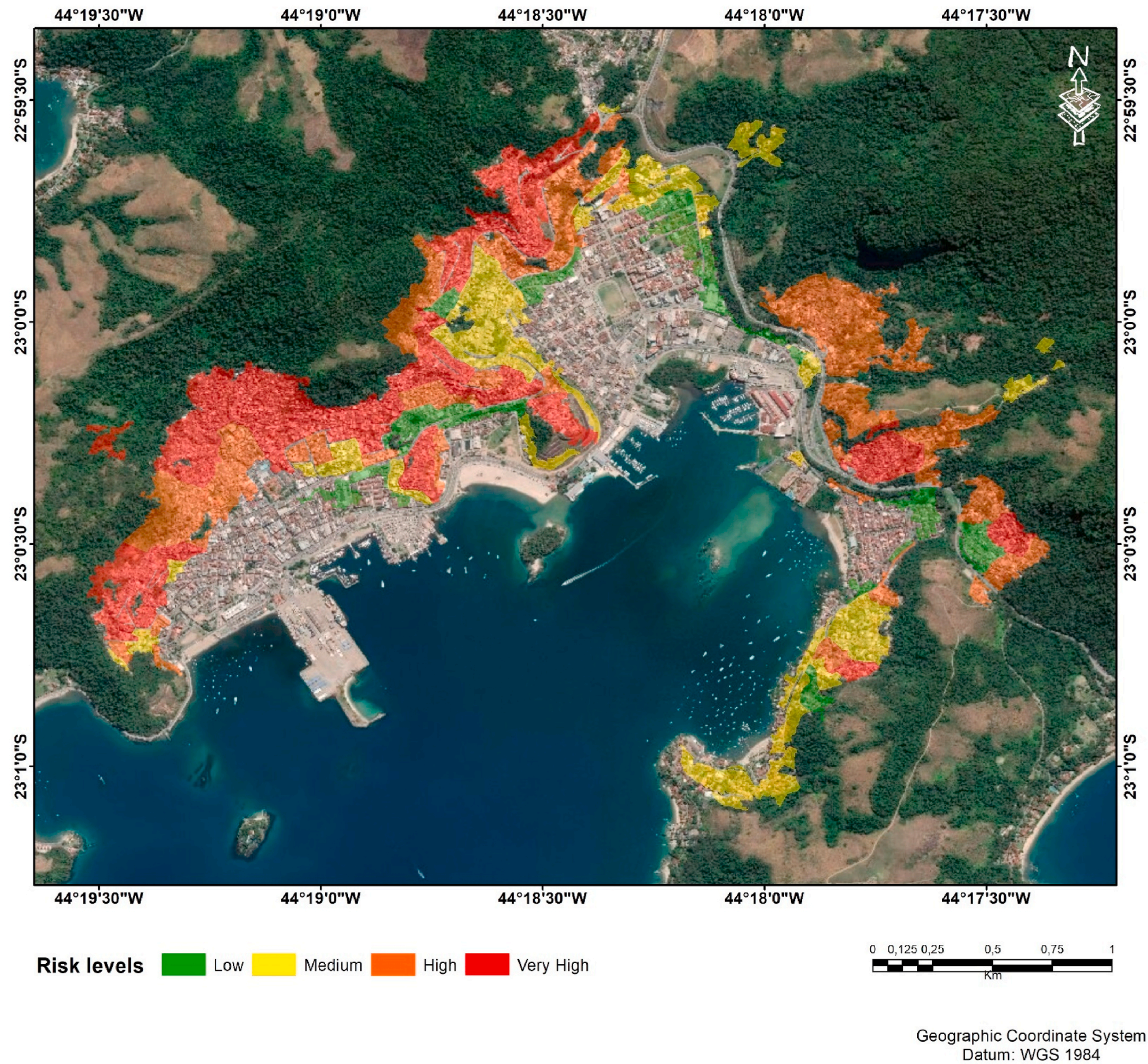

Fig. 10. Risk map related to landslides based on the hazard, exposure and vulnerability components.

Table 6
Distribution of number of DHS, area and population by risk level - including vulnerability.

Level of risk	No. of DHS	Area (ha)	% Area	Population	% Population
Low	22	22.44	11.4%	2827	9.8%
Medium	28	43.50	22.1%	4142	14.3%
High	30	63.29	32.2%	7518	26,0%
Very high	31	67.28	34.2%	14,412	49.9%
Total	111	196.53	100	28,899	100

associating the interpretation of these results with aerial images available via the software, photographs of study area locations viewed on Google Street View and direct site observations, it is verified that areas with the highest level of exposure are those with poorer quality standards of house and surrounding-area construction (spacing between buildings, alignment in relation to streets). Table 5 demonstrates that the DHSs with high levels of exposure house 27% of the population, a cause for concern as more densely populated areas present more risk management challenges.

The level of vulnerability is spatialized on the map (Fig. 9c) and its statistical summary shown in Table 5. Analysis of photographs and site observations reveal that DHSs with greater vulnerability (medium level), where 79% of the population lives, have the worst construction standards.

The consequence map (Fig. 9d) shows potential damage in hazard areas. Despite there being no DHS at very high level, 62.5% of the population reside in sectors where the potential consequences are high, demonstrating the principal requirement, for measures to reduce vulnerabilities and exposure.

Fig. 10 shows the risk map resulting from the combination of the three risk components - hazard, exposure and vulnerability, while

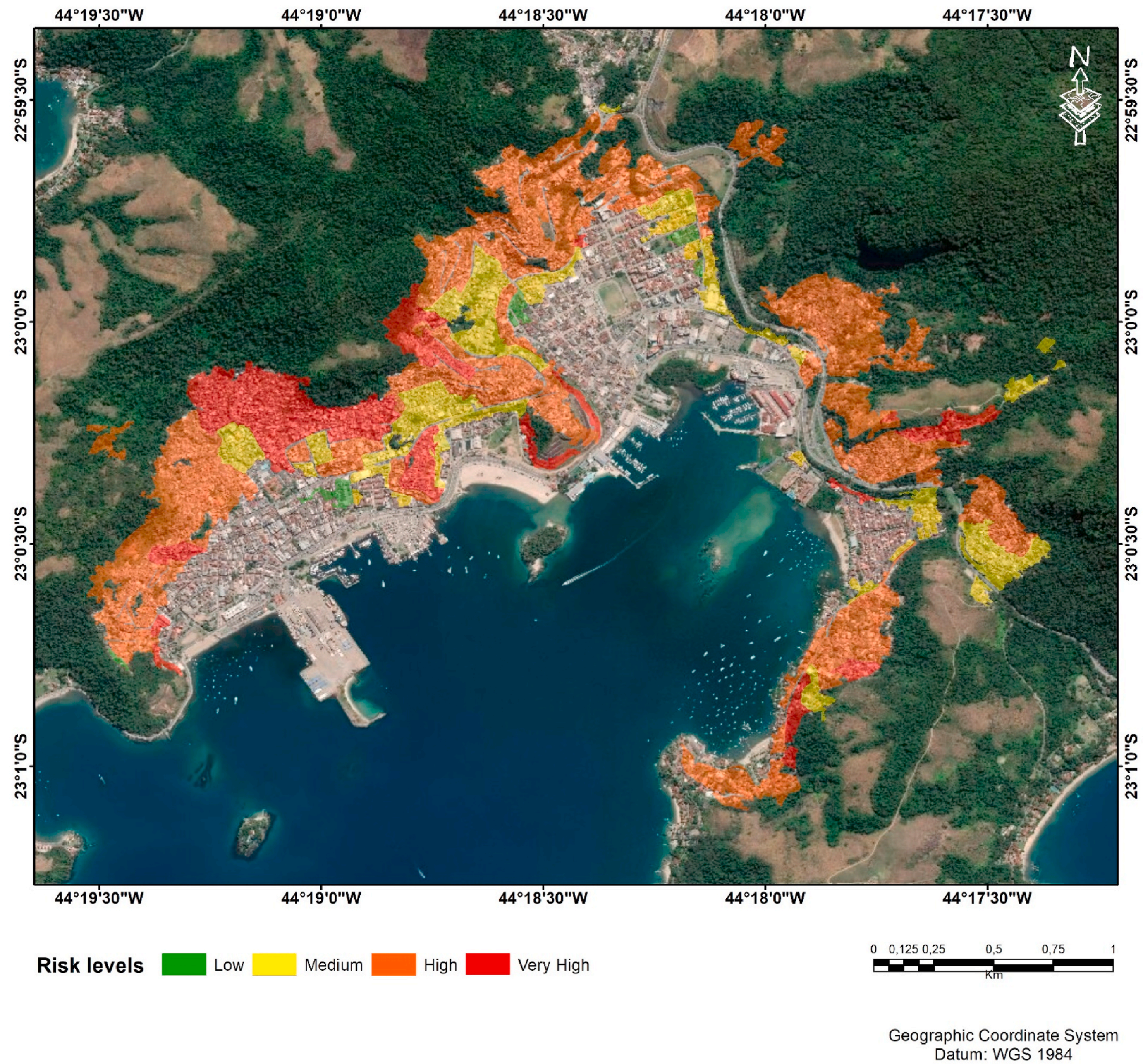

Fig. 11. Landslide risk map based only on hazard and exposure.

Table 6 carries a statistical summary of the amount of DHSs, population and territorial area by level of risk.

As the study area is significantly densely populated, primarily upstream, with high and very high levels of hazard in many DHSs, there are high and very high levels of risk in areas where 75,9% of the population resides, independent of the construction standard. On the other hand, it is observed that most DHS with low and medium levels of risk are in the more downstream section of the study area, with a better standard of construction.

5.2. *Comparisons – risk map with and without vulnerabilities*

A map was formulated combining only the hazard and exposure components (Fig. 11) given that, as previously stated, it is a common though erroneous or limited practice for administrators to disregard vulnerability in risk estimation. As one of the study aims, this map is compared to Fig. 10 risk map to evaluate the effects of this practice. Based on comparison of these two maps, a further map can be produced representing the effect of including the vulnerability component in altering the level of risk for each DHS against the map which only considers the hazard and exposure components (Fig. 12).

The results in Table 7 indicate that, considering the study area as a whole, there was no significant change in the percentage of the population exposed to high and very high risk (79.3%), but there was a considerable reduction in population in DHS which was previously very high, dropping by almost half (7086 inhabitants), and almost a doubling of the population in the DHS that are classified as high (15,837 inhabitants). Moreover, a significant alteration is observed in the spatial distribution of levels of risk. It is noted that the majority of DHSs whose levels of risk were reduced in one or two classes are those farther downstream, and therefore those with better housing construction quality. For the upstream section, where the level of risk was high or

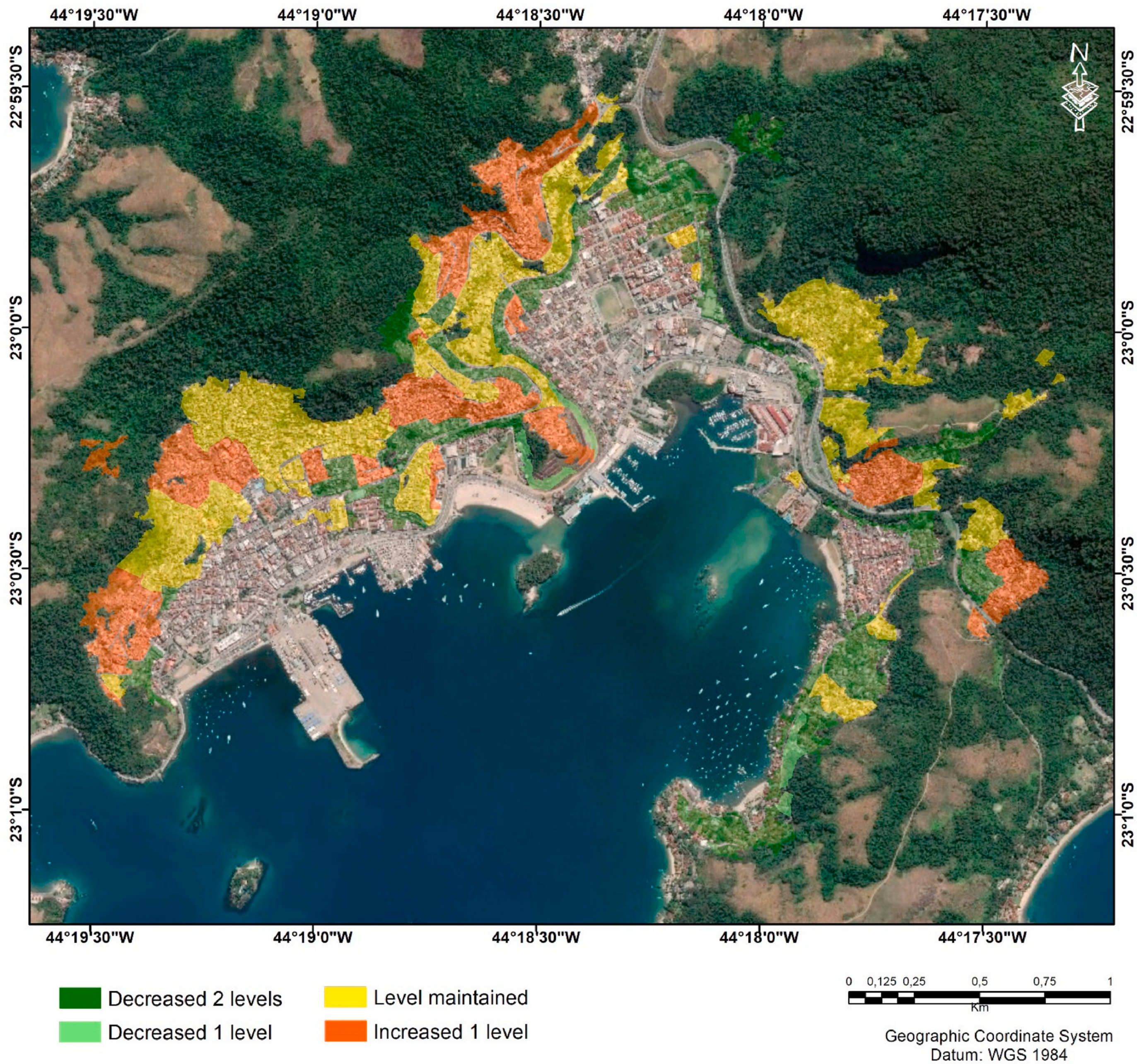

Fig. 12. Map of landslide level of risk changes due to inclusion of the vulnerability component in the risk estimate.

Table 7
Distribution of DHS quantity, area and population by risk level - not including vulnerability.

Level of risk	No. of DHS	Area (ha)	% Area	Population	% Population
Low	5	2.99	1.5%	430	1.5%
Medium	32	39.09	19.9%	5546	19.2%
High	51	119.05	60.6%	15,837	54.8%
Very high	23	35.39	18%	7086	24.5%
Total	111	196.53	100	28,899	100

very high, the level was maintained or increased with the inclusion of vulnerability. It is worth mentioning that a few DHSs with poor construction standards or in favelas lowered the level of risk. Fig. 13 presents the number of DHS level of risk changes on considering the vulnerability component. It is noted that there were more changes in the levels of risk (73 DHSs) than those which remained the same (38 DHSs), testifying to the influence of vulnerability. The 73 DHSs correspond to 66% of the number of risk sectors, 58% of the population and 58% of the study area It is also confirmed that including vulnerability decreased, by some 1,000, the number of study area inhabitants facing a high and very high level of risk, when compared to the method which does not include it, equivalent to a 3,4% decrease.

6. Conclusions and future scopes

Given the concept of risk and the awareness that risk results from a combination of physical and social processes, it is necessary to consider the vulnerability of the exposed population when estimating landslide risks to be used by different institutions in all steps of landslide risk management, as agencies of civil protection and defence, spatial planning and engineering works. This consideration, however, poses a

	Risk level with vulnerability (H x E x V)											
	Low			Medium			High			Very high		
Risk level without vulnerability (H x E)	Qty DHSs	Area (Ha)	Population	Qty DHSs	Area (Ha)	Population	Qty DHSs	Area (Ha)	Population	Qty DHSs	Area (Ha)	Population
Low	3	1.99	224	2	1	206	0	0	0	0	0	0
Medium	19	20.45	2603	5	8.84	966	8	9.80	1,977	0	0	0
High	0	0	0	18	29.81	2,798	16	46.65	4,841	17	42.59	8,198
Very high	0	0	0	3	3.85	172	6	6.85	700	14	24.70	6,214
Total	22	22.44	2,827	28	43.51	4,142	30	63.30	7,518	31	67.28	14,412

	decreased 2 levels			decreased 1 level			Level maintained			increased 1 Level		
Total by quantities of levels changed	Qty DHSs	Area (Ha)	Population	Qty DHSs	Area (Ha)	Population	Qty DHSs	Area (Ha)	Population	Qty DHSs	Area (Ha)	Population
	3	3.85	172	43	57.11	6,101	38	82.17	12,245	27	53.38	10,381
	Quantity of changed DHS = 73 (66%) Area of changed DHS = 114.35 Ha (58%) Population in changed DHS = 16,654 (58%)											

Fig. 13. Number of sectors with level of risk altered due to inclusion of the vulnerability component.

significant challenge. If there is yet to be a consensus on hazard estimation, this difficulty is much greater in the case of vulnerability due to the incipient nature of studies with that aim and scarcity of data to make it possible. At the same time, society needs to urgently progress studies along these lines, given that processes rendering the population vulnerable have been responsible for an unequal distribution of landslide disaster impacts for the same level of hazard, demonstrating how consideration of the vulnerability component enables more efficient risk management.

This paper contributes to the proposal of a risk estimation method considering the vulnerability of the exposed population using census data, with its inherent advantage of being commonly obtained during census compilation. The use of this method contributes to advances in the mapping process, as it enables spatial combination between census and hazard data to obtain the risk map. There is, however, a limitation in not presenting certain important specific data which should be considered in vulnerability estimation such as, for example, the existence of a risk management institution, emergency shelters, early warning system, and education for risk reduction in the location analyzed.

The application of the method which considers the three risk components – hazard, exposure and vulnerability - showed that consideration of vulnerability, even when there is no significant spatial variation in the study area, brought about a significant change in the spatial distribution of the level of risk compared to results from the method which includes only the hazard and exposure elements, leading to alterations of 66% in levels of risk where 58% of the population lives. These findings corroborate the necessity of including vulnerability in risk estimation. It should also be highlighted that the possibility of obtaining an awareness of vulnerabilities in exposed communities enables a better understanding of the risk and assists in planning risk management actions with a more holistic and, therefore, more efficient view.

Based on what was observed, it is perceived that there is very significant potential for close interaction between the census body and risk management for effective reduction of landslide disasters, provided not only by the provision of more spatially detailed data, but also tailoring the census to include specific data which more fully express the different dimensions of vulnerability in the population exposed to this hazard.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2020.101884.

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