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Estimation of exposed population to landslides and floods risk areas in Brazil, on an intra-urban scale

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A R T I C L E I N F O

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A B S T R A C T

The knowledge on population demographics and the living conditions in risk areas are crucial for risk management and disaster response. In Brazil, this information is not available yet on a national scale. With the goal of characterizing at risk populations, in the present article a methodology is proposed to associate demographic census data with risk areas for landslides and floods in Brazil. The unique source of information about the Brazilian population, available for the entire country, in intra-urban scale, is provided by the Population Census developed by the Brazilian Institute of Geography and Statistics. However, the association of census information with risk areas cannot be done in a direct and automated way, due to the different geometries between the risk areas and census tracts. Considering the need to associate data from distinct geometries, a new basemap was created, named Statistical Territorial Base of Risk. Its graphical delimitations incorporate information from the population census about the mapped risk areas. The proposed methodology was initially implemented in three pilot municipalities located in the state of Rio de Janeiro (Petrópolis, Teresópolis and Nova Friburgo). The results show the estimation of approximately 155.000 people exposed to the risk of landslides and/or floods in 1.357 risk areas. It also allowed for the identification of regions within those municipalities with the highest concentration of at-risk population. The availability of information on the conditions of exposure of populations residing in risk areas can subsides decision makers in the context of disaster risk management.

1. Introduction

The Brazilian social and economic development was characterized by different land use and occupation, revealing a heterogeneous spatial distribution of its population throughout the territory. This process, associated with the interannual climate variability, intrinsic in a country of continental dimensions, and a natural susceptibility of the terrain, contributes to the occurrence of disasters related to landslides and floods. Notwithstanding, in the last 20 years the number of disasters has been increased [11], due to the intensification of geodynamic, hydro-meteorological and climate events in many regions, or in reason of the increment of population living in risk areas. Almost 39.000 records of disasters related to droughts, floods, windstorms, landslides, tornados, hail, and frost were recorded in the period from 1991 to 2010 in Brazil, which resulted in 126,926,656 affected [11].

The major disasters in the country are due to floods, flash floods landslides, droughts and windstorms [11]. In the last decade, a significant number of disasters were registered in Brazil, with some of the occurrences considered to be events of the century. In 2008, the region of Itajai Valley, in the state of Santa Catarina, suffered significant economic and social losses due to intense rain, floods and multiple landslides, which ended in 135 deaths and thousands of affected in 60 cities [38] and a total estimated cost of over 5 billion Brazilian real (over 1.5 billion US dollars) [48]. In 2010, extreme weather events

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caused floods and flash floods in the states of Pernambuco, Alagoas and landslides in state of Rio de Janeiro, leading to hundreds of deaths, and around 12 million people affected, 6 million of which in the city of Rio de Janeiro only. In January 2011, the worst natural disaster ever recorded in Brazil took place, in the mountainous region of the state of Rio de Janeiro. There were over 900 confirmed fatalities, 300 missing and tens of thousands dislodged and left homeless after the disaster. The economic losses were estimated to be around 4.8 billion Brazilian real (over 1.4 billion US dollars) [49], with the destruction of houses and buildings and infrastructure due to the occurrence of floods and multiple landslides [2].

In spite of the undoubted evidence that disasters in Brazil have incurred very high human, socioeconomic and environmental costs, it is essential to establish disaster risk-reduction measures in order to reduce impacts. In this context, an important initiative is investing in monitoring and alerts of hazards, including better knowledge of the characteristics of at-risk populations and homes. In the past decade there has been an increasing consensus that the magnitude of a disaster is directly related to aspects of vulnerability and exposure of populations living in risk areas [9,17,30,42,44,46,47].

According to the Sendai Framework 2015–2030 it is a priority the understanding of disaster risk in all its dimensions of vulnerability, capacity, exposure of people and assets, hazard characteristics and the environment [40]. Vulnerability is a multi-dimensional concept and, despite various methods for its analysis [5,8,45,46], there is a general consensus of it is being the factor that determines the scale of impact of disasters. Another important aspect is the highly dynamic nature, in time and space, of the vulnerability concept [41,43]. Therefore, vulnerability involves the population characteristics as well as the different degrees of preparedness to deal with the materialization of risk, i.e. disasters. The United Nations Office for Disaster Risk Reduction [39] proposes a broader definition of vulnerability, characterizing it as "the conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards."

Particularly in Brazil, efforts have been expended to analyze vulnerability in different contexts, not necessarily focusing disasters [15,35]. However, the Population Census, produced by the Brazilian Institute of Geography and Statistics (IBGE) is the unique database available for the entire country, considering information at an intra-urban scale. Nonetheless, data from the census tracts were used by the mentioned references above as the smallest unit of analysis, although IBGE does generate data on a more detailed scale.

On the other hand, the more detailed data from the Population Census, such as those from the block faces, are not usually made available to the general public, although they are crucial to subsidize, for example, the evaluation of vulnerability of the population to disasters, since they are useful to be associated with areas of hydrological and geological risk. Thus, it is important to characterize vulnerability in the different steps of risk management and disaster response, including them in early warning systems - EWS. In this context, information about exposure and population's vulnerability has been used to subsidize risk analysis, either for planning emergency situations or early warnings [21]. In France, for example, vulnerability analysis is a part of the natural hazards prevention plan, whose information are incorporated with hydro-meteorological conditions and disseminated daily to the population. Also, in China, some population data, related to the more vulnerable segments, are included in the management and response to emergency plan, in order to support actions for mitigation and prevention. Additionally, information on impacts, intensity and potential losses are also included in warnings.

In Brazil, the institution responsible for monitoring and early warning is the National Center for Monitoring and Early Warning of Natural Disasters (CEMADEN), which belongs to the Ministry of Science, Technology, Innovation and Communication (MCTIC). This center, created in 2011, monitors almost 1.000 Brazilian municipalities at risk of landslides, floods and flash floods. Therefore, with the purpose of improving monitoring and early warning, it is essential to have access to systematized information about the Brazilian territory, which can then be incorporated in early warning systems, contributing to effective measures for prevention, mitigation and disaster response.

Thus, in the present study, a method is proposed to characterize exposed and vulnerable populations living in risk areas for landslides and floods in Brazil. For this reason, the numbers of people living at several risk areas were estimated, considering a detailed scale as well as ensuring homogeneity of data required. The proposed methodology, which includes two adjusted heterogeneous scales (mapped risk areas compatible with the territorial base of the Population Census, specifically census tract and block faces), was implemented to evaluate three municipalities of mountainous region of the state of Rio de Janeiro, Brazil.

2. Materials and methods

2.1. Study area

The studied area is located in the central part of the state of Rio de Janeiro, Brazil. It is included 14 municipalities [12], whose estimated population in 2016 was 825.834 inhabitants [25]. For the present paper, the three most affected cities of the 2011 disaster were analyzed: Petrópolis, Teresópolis and Nova Friburgo (Fig. 1).

In these three cities, there was a rapid population growth from 1940 to 2010, especially from the 1970s onwards (Fig. 2). According to the IBGE data [24,25], in Teresópolis a growth rate of 123% was recorded between 1970 and 2010, followed by Nova Friburgo (101%) and Petrópolis (66%). This process was connected to the occupation of areas susceptible to geological and hydrological hazards, in steep slopes and floodplains, therefore, in areas of preservation. Although the three municipalities had the highest human development indexes (Nova Friburgo and Petrópolis 0.745 and Teresópolis 0.730) among the 14 of the mountainous region [25], the physical features of these cities, combined with an intense rainfall regime during the rainy season, and frequently inadequate land use and occupation patterns, lead to a scenario of high susceptibility to events that have the potential to be destructive, in particular related to landslides and flash floods [7,18,36]. Specifically in January 2011, it was observed that the urban and rural areas mostly affected by debris flow and flash floods were those on river banks, on declivities up to 30 degrees, at the hills base and in the lowest valley terrains [6].

Historically, the region had already presented various reports of disaster [20,22]. According to CEPED [11], in the period from 1991 to 2012, Petrópolis presented the highest number of deaths, especially due to landslides (Table 1). These numbers are, for the most part, related to emergency situations and public calamity decrees, and, therefore, do not take into account small occurrences within the cities. For the same period, 440 deaths were registered in Nova Friburgo, 209 in Petrópolis and 412 in Teresópolis [11].

Among the landslides that occur within the studied area, it is highlighted the debris flow, which correspond to a wide-spread hazardous phenomenon in mountainous terrain, that often occur simultaneously with floods [23]. After the January 2011 disaster, various studies were conducted to characterize the origin of these types of processes in the mountainous region of the state of Rio de Janeiro [14,19,33,34], showing that the extreme precipitation triggered the generalized debris flow.

Besides debris flow, landslides occur throughout the studied area. Avelar et al. [4] identified a total of 3.562 landslide scars, especially in Nova Friburgo, Teresópolis and Sumidouro, after January 2011. Coelho Neto et al. [13] concluded that thousands of landslide scars occurred in reason of heavy rainfall, lightning and rock fractures.

Therefore, the selected area is characterized by population growth in the last decades and by reports of recurrent landslides that impact the

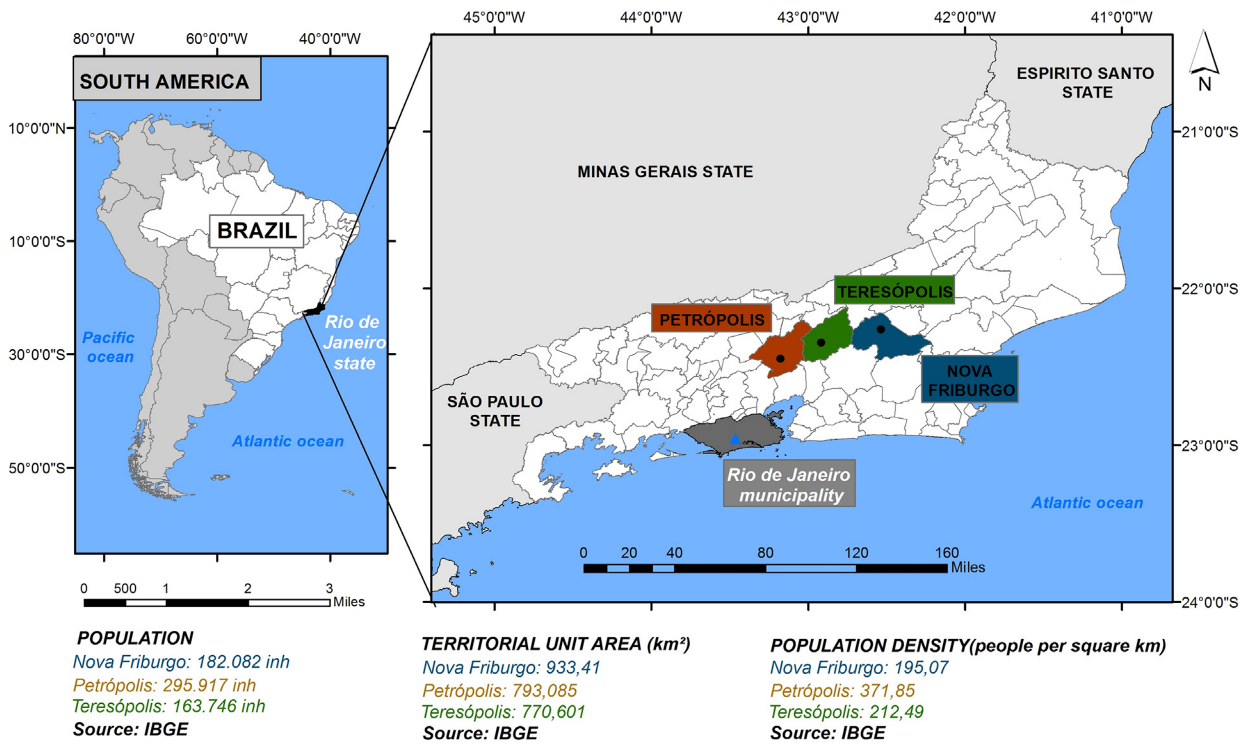

Fig. 1. Location of the municipalities selected for the study.

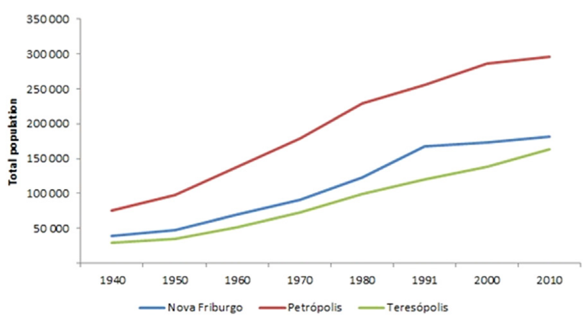

Fig. 2. Population growth from 1940 to 2010, in Nova Friburgo, Petrópolis and Teresópolis. Source: IBGE [24,25].

Table 1
Natural disaster reports, for the period of 1991–2012, associated with emergency situations and public calamity decrees.
Source: CEPED [11].

Municipality	Landslides	Flash floods	Floods	Total of reports	Total of victims
Nova Friburgo	1	4	1	6	440
Petrópolis	18	6	6	30	209
Teresópolis	6	4	5	15	412

population and infrastructure.

2.2. Population census databases

Since 1937, IBGE is the Institute responsible for the Brazilian Population Census, which survey is every 10 years obtained. The last census was made in 2010, when socioeconomic data from 5.565 Brazilian municipalities were collected.

The territorial unit of registration control for data collection in the census is named census tract. It is formed by adjacent areas and inserted into to the political-administrative borders, considering urban and rural legal definitions [28]. The urban areas of 2010 Population Census was made possible by associating residences to the block faces. Each block is generally a well-defined rectangular area in an urban zone, limited by streets and/or roads. However, it can have an irregular shape and be limited by elements such as railroads, rivers or declivities. The block face is one of the sides of the block, and may or may not contain residences. Nevertheless, for the purpose of disseminate the Census results, the smallest territorial unit used is the census tract [26,27,44]. The information from data collected from the block faces are not available for general public, because of restrictions related to statistical confidentiality. On the other hand, the information provided within the scope of the block faces can be utilized for the elaboration of specifically territorial segments, such as to characterize the population living in disaster risk areas. However, the use of the block faces to achieve territorial units smaller than the census tracts should only be done following a detailed analysis of the database, since not all block faces contain data associated with the graphic base. Thus, in these cases, the census tract remains the smallest territorial unit with available data. Each census tract presents a myriad of information about population and housing, gathered by personal interview surveys. For the present paper only data from urban areas were used, that is, areas within the urban perimeter as defined by municipal law. Another territorial limit included in the census is the subnormal agglomerates (AGSN), which is an assortment of, at least, 51 low income residences, distributed in a disordered and/or dense way, most of them lacking in essential public services [28,29].

2.3. Mapping risk areas

Mapping areas of geodynamic and hydrological risk constitutes the second information base needed for the proposed methodology in this paper. Risk areas are defined as the ones susceptible to the occurrence of natural or induced processes or phenomena that cause accidents. People who reside in these risk areas are vulnerable to physical injury, and subject to losses and human or material damages. These areas are represented by polygons in the geographical boundaries of a site, and are determined by signs of soil movement observed in the area, such as signs of soil movement (step abatement), cracks in houses, inclined poles or trees, erosion at the bases of slopes, length of slopes, and others [16]. Risk areas can also be delimited from other environmental parameters, such as geology, slope, geotechnics, vegetation and natural drainage [37].

The risk areas of Nova Friburgo was mapped by the Geological Survey of Brazil (CPRM), in the context of the Municipal Plan for Risk Reduction (PMRR), in the year 2007; and also in 2012 for the emergency action to determine areas of high and very high risk of landslides and floods. In the context of this last mapping, two risk levels were defined, in which there were strong indications that, without intervention, it would be perfectly possible (high risk) or highly likely (very high risk) that destructive events would occur during episodes of intense and prolonged rain [16]. On the other hand, the mapping of risk areas in the municipalities of Petrópolis and Teresópolis, for years 2003 and 2007 respectively, were made in the context of the Municipal Plan for Risk Reduction. In these cases, to determine risk sectors, four risk levels were attributed, considering the likelihood that destabilization processes would occur, varying from a low to a very high probability of occurrence [1,37].

In both cases, emergency action and PMRR, there was no data collection concerning the population living in risk areas. That is, in the emergency action conducted by CPRM, estimation was made on the number of residences in risk areas, based on observations from the field, and considering an average of four people per home. Regarding PMRR, the quantification of risk areas took into account the visible conditions of structures, instead of the number of people in each family and their living conditions.

2.4. Definition of the statistical territorial base of risk (BATER)

The above-mentioned databases have different characteristics, since they were established for different purposes; thus, there is no direct spatial correspondence between them. The link between the census information and risk areas cannot be made directly and automatically, due to the geometrical differences between both block faces. There could be several combinations when associating a block face or a census tract with a risk area. For example, a census tract could contain several risk areas and/or parts of various risk areas (see Fig. 3a); or still, a risk polygon may constitute a smaller area than a census tract (see Fig. 3b).

Considering the premise above, to associate census data with the risk areas it was necessary to create a new territorial base in order to associate both geometries, which was then named Statistical Territorial Base of Risk (BATER). BATER constitutes a territorial generalization, since an exact intersection between both original polygons was not possible. Therefore, the data generated from the "BATERs" do not quantitatively represent the population residing in risk areas, but offer an estimate for the population living in these areas.

After evaluating the spatial distribution of the various geometrical faces required to define the limits of BATER, the premises, operational construction procedures, and basic attributes of the new database were established.

The graphical delimitation of each BATER was initially established by analyzing the occupation density and the building standards in risk areas, taking into account the census tracts or block faces and the associated data. This analysis was made by visual interpretation, observing the spatial context of the risk area and the census limits, as well as following the premises below:

a) BATER should primarily be the smallest possible area resulting from the intersection of the risk area and the census tracts or block face. Considering the statistical confidentiality, each BATER should contain at least 5 homes and 20 residents.
b) Each census tract or block face and each risk area should belong to only one BATER, hence avoiding a recount of at-risk populations.
c) Concerning to risk areas localized in subnormal agglomerates, the full extent of these areas were considered as a BATER, once, by definition, these areas concentrate residences in vulnerable conditions. This generalization was assumed because of the similarities between the occupation pattern and topographical characteristics of the risk area polygon with the ones of the remaining area of the subnormal agglomerates.
d) In cases where the block face surpassed the boundaries of the risk area, the density and 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.
e) When two or more nearest risk areas presented both density and building standards similar, these were merged in a single BATER.
f) Specifically regarding flood risk areas, the block faces on both sides of a street or a body of water were taken into consideration, because in a disaster the whole area would be affected.
g) Regarding to landslide risk areas, the characteristics of topography, such as the degree, shape and direction of slope were considered to define the BATER limits.
h) The different risk levels of the mapped areas were not taken into account, due to the lack of homogeneous criteria to define risk levels, since the mappings come from different data sources.

BATERs were also created for situations that do not follow the above criteria, although in such cases an association of data was not possible. As an example, there is the case of various small risk area polygons, with few homes, within a census tract. The census tract would then contain a larger amount of people, not necessarily residing in risk areas, which could lead to an overestimation of the population effectively exposed to risks.

Regarding the operational procedures to develop the BATER, Quantum Gis 1.8 and ArcGIS 10.2 software solutions were used. With these software products a supervised interpretation took place, utilizing high definition satellite imagery and Digital Elevation Models (DEMs) available on Google Earth, as well as the identification of housing and topographical patterns, based on the risk areas and census tract or block face.

Simultaneously to the delimitation of BATER, a table of attributes was generated, containing specific information to each polygon, such as geocodes, data sources, numbers, accuracy and specific observations (Table 2).

The accuracy, estimated through interpretation of high resolution satellite imagery, was classified according to the following classes: **great**, when 90–100% of housing in the block face or census tract were located inside risk area polygons; **good**, when 60–90% of housing in the block face or census tract were located inside risk area polygons; and **regular**, when 60% or less of housing in the block face or census tract were located inside risk area polygons. The percentages above were defined by specialists in geodynamics, cartography and social sciences.

In the second phase, housing and residents data, made available in census tracts or block faces in the IBGE 2010 Population Census, was associated with the BATER polygons, utilizing the spatial join technique of the ArcGis 10.2 platform. Within the universe of over 600 variables made available by the Census, 183 were selected to characterize residents, such as age, gender, literacy, etc., and 135 chosen to characterize housing, such as access to basic services like electricity, sanitation, water, and waste collection, in the context of monitoring an early warning. The database generated from the presented methodology has the potential to characterize the population in different aspects. In the present article a characterization was proposed, whose selected variables have been used in studies of vulnerability in disasters, which are detailed in item 3.2.

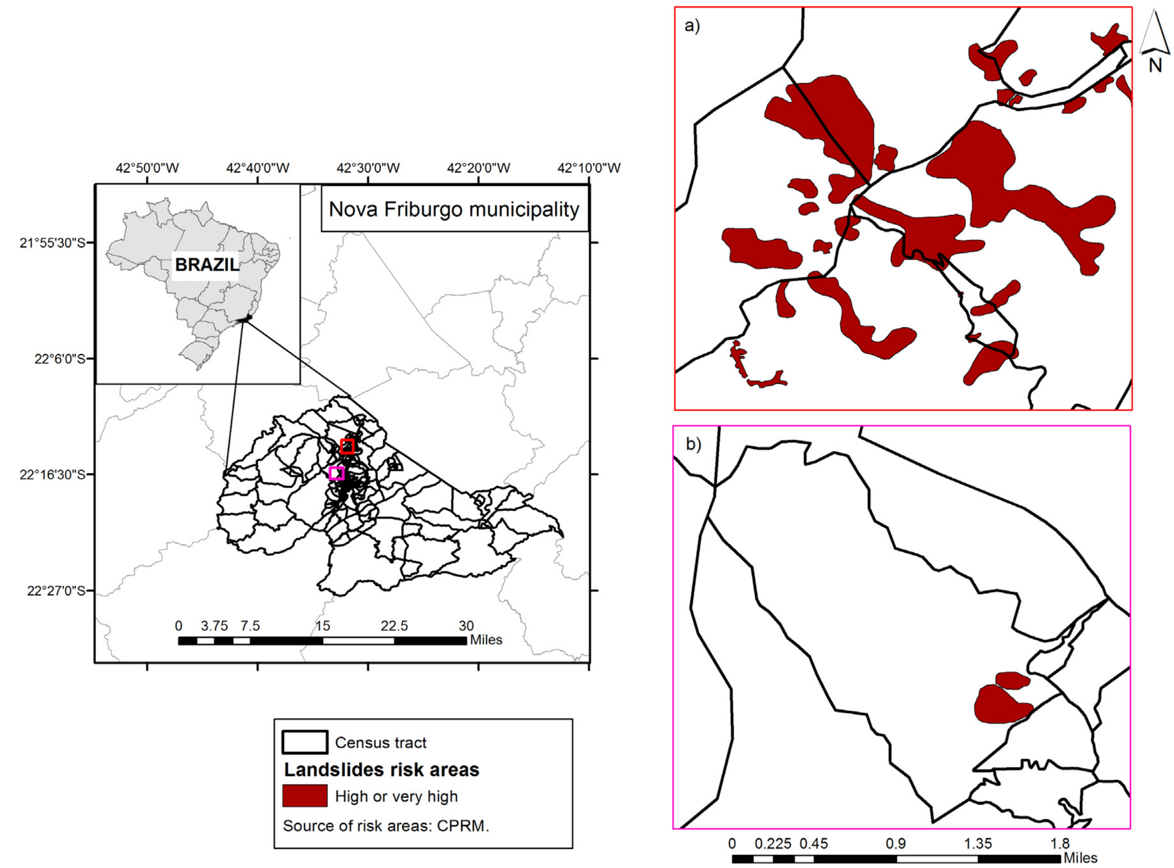

Fig. 3. Illustrative examples of (a, in the red square) census tract containing various risk areas and/or parts of various risk areas, (b, in the magenta square) risk polygon with a smaller area than a census tract in the city of Nova Friburgo. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
BATER Attributes.

Attribute	Description
BATER Geocode	A unique identifier of each BATER created, 11 digits long, composed by the federation unit codes (UF), the municipality code and the BATERs number. The UF and city codes are those officially adopted by IBGE.
Origin	Refers to the census origin information in each BATER, which could be a census tract or block face.
Num	Refers to the number of risk areas in each BATER.
Accuracy	Refers to how much the risk area coincides with the actual inhabited area of the census tract or block face.
Observations	Observations considered relevant to the BATER delimitation.

Table 3
Number of risk areas and BATERs polygons in the municipalities of Nova Friburgo, Petrópolis and Teresópolis.

Municipality	*Number of risk areas*			*Territorial extension (km²) of risk areas*	*Number of BATERs polygons*
	Landslide risk areas	*Flood risk areas*	*Landslide and flood risk areas*		
Nova Friburgo	652	1	20	23.3	125
Petrópolis	557	8	0	6	97
Teresópolis	113	6	0	1.18	70
Total	1.322	15	20	30.48	292

3. Results and discussion

3.1. Analysis of the proposed methodology

It is important to highlight that the proposed methodology can be extrapolated to estimate all exposed populations throughout the Brazilian territory, as long as mappings of disaster risk areas are made available. The present work focuses on the results of application in 3 out of the 14 cities of the mountainous region of Rio de Janeiro State, Brazil, with the goal of evaluating the methodology and its potentials and limitations.

The municipalities of Nova Friburgo, Petropolis and Teresopolis contain 1.357 mapped risk areas, distributed within the municipal territories. From the spatial distribution of the risk areas and considering the census limits, 292 BATER polygons were created. In Table 3, specific information about the number of risk areas is presented, considering types of disasters and number of BATERs polygons for each city, as well as total area and population.

Considering the three municipalities, 76% of BATERs polygons data came from block faces, and the remaining 24% from census tracts. It should be noted that the data from block faces contains the highest possible degree of detail at the census level. These data base represents the more detailed information to be associated with risk areas, since previously only the census data used for association with risk areas were originated by information at municipal level or census tracts.

The accuracy was classified as regular in 61% of BATERs polygons, followed by accuracies good (35%) and optimum (4%). This is a result of the mapped risk areas being associated mainly with landslides (97.4%); therefore, these areas are characterized by small polygons, with an average area of 0.03 km^2 in Nova Friburgo, 0.01 km^2 in Petrópolis and 0.006 km^2 in Teresópolis. On the other hand, the risk areas associated with hydrological processes represented only 2.6% of the areas mapped, but with larger areas, equal to 0.07 km^2, 0.02 km^2

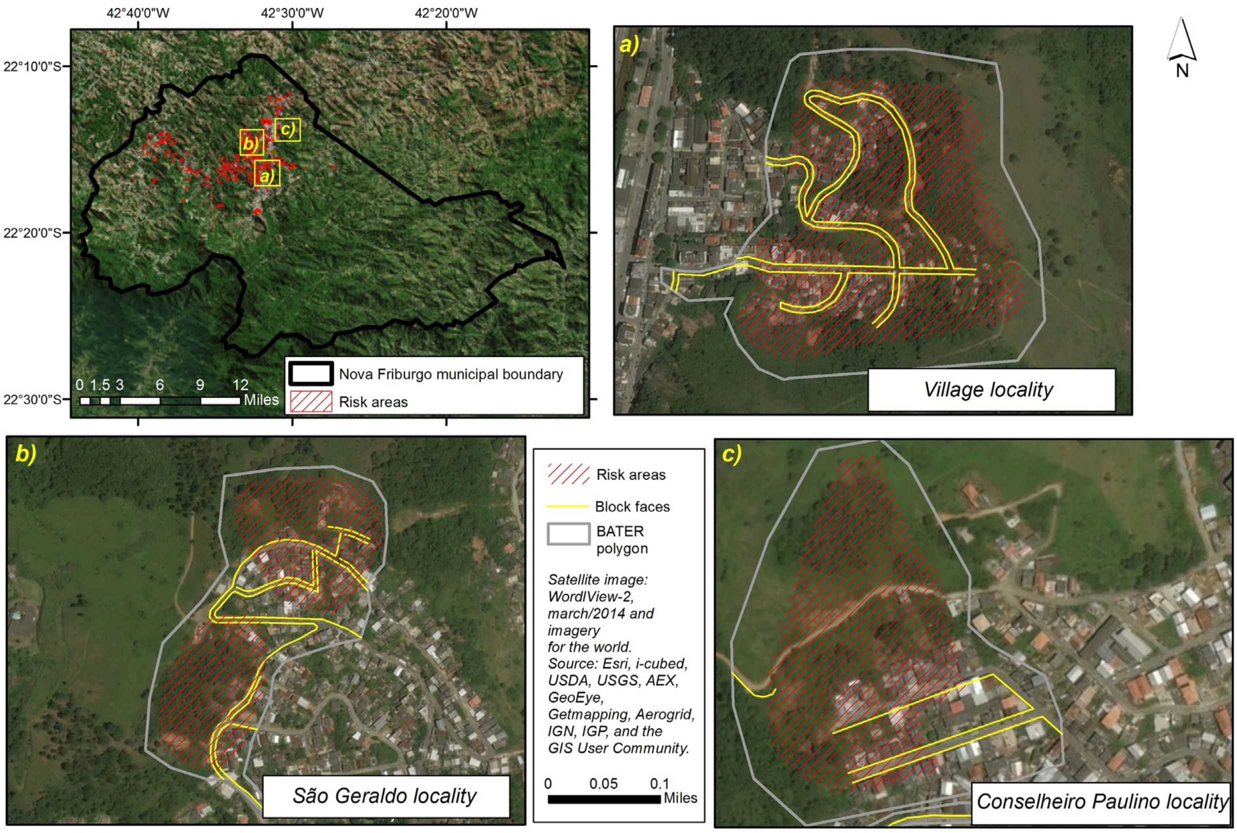

Fig. 4. Examples of three accuracy classification cases from localities within the city of Nova Friburgo.

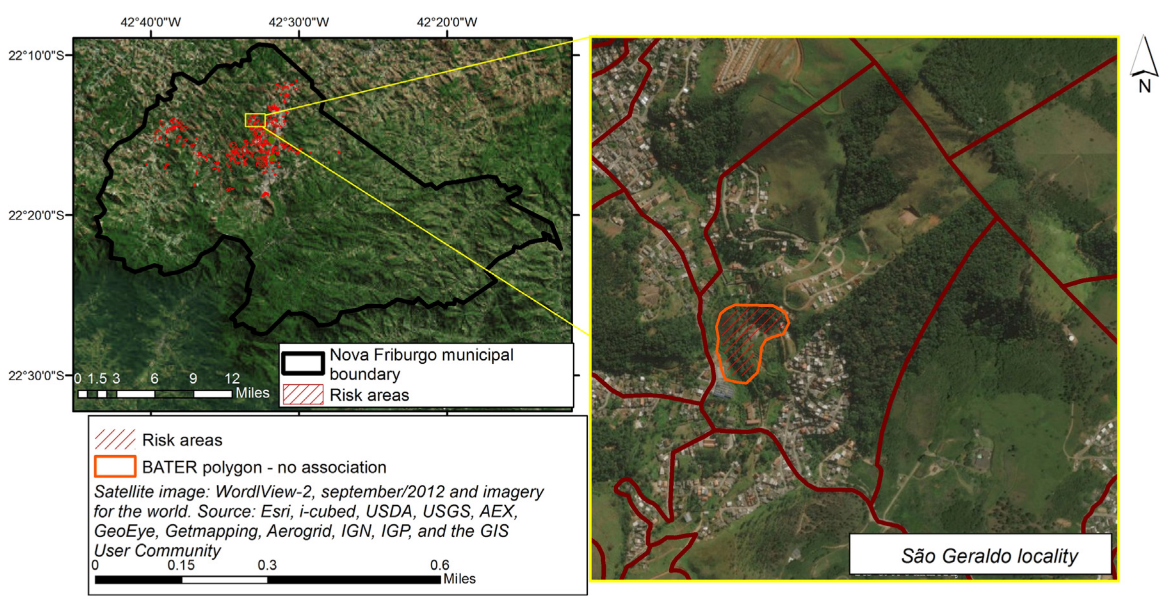

Fig. 5. Example of the situation with no data association, in the locality of São Geraldo, Nova Friburgo.

and 0.08 km^2 in Nova Friburgo, Petrópolis and Teresópolis, respectively.

Fig. 4 presents three examples of BATERs from the municipality of Nova Friburgo, containing the accuracy classification. Specifically, Fig. 3a shows optimum accuracy for the BATER polygon associated with census data from block faces for mapped risk areas in the "Village" locality. It should be emphasized that in the present context, the term locality does not exclusively characterize a neighborhood. In this case, all the data coming from the block faces refer to the population at risk. Fig. 3b presents the good accuracy, in which most of the homes located in the block faces also belonged to the mapped risk areas in the "São Geraldo" locality, with most people in this BATER polygon inhabiting risk areas. Finally, Fig. 3c shows one example of regular accuracy, a case for which few block faces were available to estimate exposed population in the mapped risk areas of the "Conselheiro Paulino" locality; however, in this case, it was possible to consider the block faces nearby, due to a similar home construction pattern and the spatial context of susceptibility to landslides. Consequently, in this instance, the surrounding population can also be considered exposed, because of the topographical characteristics observed. Hence, in this case, it was

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considered that the association of data helped characterize not only the population residing in risk areas, but also in the adjacent areas. It is important to highlight that when mass movement processes occur in a generalized way within a territory, their impacts are not limited to the risk area polygons. Therefore, in evaluating the methodology, it was considered viable to include the population residing near these areas, since in the case of a disaster they would also be exposed to risk. Besides, from a visual interpretation of satellite imagery, it was observed that the conditions and location of residences presented a similar distribution to those effectively located inside the mapped risk area polygons, either it in risk areas, block faces and census tracts.

In cases where, from the analysis of visual interpretation, a possible association was identified that could lead to overestimation or underestimation of the population at risk, it was decided not to associate the census data. Fig. 5 presents an example in which a mapped risk area, in the locality of São Geraldo, Nova Friburgo, did not have its data associated. In this case, the risk area represented only 3% of the entire sector area.

Risk areas located in rural sectors were also not considered in the methodology, since the collection of data of these sectors is obtained in the scope of rural census; thus, the data association was not undertaken in these areas. Therefore, 60 BATERs polygons were created that, although delimited and including 115 risk areas, do not include associated data. Thus, from the total of risk areas mapped, around 8% do not have associated data, and, consequently, do not allow an estimation of at-risk population.

The city of Nova Friburgo contains the highest number of mapped risk areas (673) concentrated in the urban area. Approximately 97% of them are related to landslides, whilst the remaining 3% are risk areas related to both hydrological processes and landslides. For this city, 125 BATERs polygons were generated, of which 98 met the accuracy criteria and had data associated to them, the majority of which came from block face (86%), allowing estimation of exposed population in 597 risk areas. Each BATER polygon includes, on average, 4 risk areas.

Petrópolis had 565 risk areas mapped, distributed across the Southern region of the municipality, around the urban area, with 98% of these areas associated with the risk of landslides. The remainder is related to the risk of flooding in the central area, along the Quitandinha River. Of the 86 BATER polygons created and viable for association, about 77% had data associated from block faces, and 23% from census tracts. As a result, it was possible to estimate at-risk population in 550 risk areas, of which 117 are distributed within 7 BATERs polygons that belong to areas of subnormal agglomerates.

The lowest number of mapped risk areas was observed in the city of Teresópolis, of which 113 were related to mass movement risks, and 6 to flooding risks. 70 BATERs polygons were created for the city, which 20 ones were associated with subnormal agglomerates, while for 22 of them association of data was not possible. The mapped areas were restricted to small zones, leading the risk area polygons to have a very small average area, 0.006 km^2. In this case, there was a direct effect on the accuracy level of the information generated, with around 94% of created polygons classified as of regular accuracy, while in the other municipalities analyzed this percentage was about 50%. However, as discussed previously, after analyzing each risk area it was considered viable to associate data and estimate the at-risk population in 95 risk areas, since the spatial context of these areas and their surroundings presented similar characteristics. Also, in the case of disasters, more areas than those effectively mapped have the potential to be impacted. As an example, in Fig. 6 it is possible to observe 2 risk areas mapped along slopes in the locality of Santa Cecilia, but it is notable that the bases of the slopes were not marked as risk areas. From the analysis of satellite imagery and understanding about mass movement processes, it could be inferred that in the occurrence of landslides, the slope bases would also have the potential to be impacted. That is, the resident population in this area could also be considered exposed to risk. Therefore, the block face located at the slope base was utilized to estimate the exposed population, although it was not included in the original mapped risk area.

An important highlight should be made concerning the creation of BATERs polygons, as well as the quality of the data association, which both depend on the criteria used to map the risk areas. It was observed that mappings with delimitation of small polygons generated a higher occurrence of regular accuracy information. In such cases, the risk areas were mapped considering only event occurrence points, not included in the conditions of the surrounding area. It should be noted that each case was individually evaluated and that in situations where it was possible to infer that the population of the surrounding area was also exposed to risk, the data from those areas were associated.

3.2. Characterization of the exposed population

In order to characterize the population in the mountainous region of Rio de Janeiro in the context of monitoring and early warning, the estimates of population living within risk areas in the cities of Nova Friburgo, Petrópolis and Teresópolis were 19%, 24% and 30% of the total population in each municipality, respectively (Fig. 7). Considering the total population exposed to disaster risk in all three cities, 91% were living in areas of mass movement risks and the remaining 9% in areas of flood risks.

In Fig. 8, the spatial distribution of the exposed population concentration is presented at an intra-urban scale, estimated from data associated in BATER polygons. The natural breaks of classification method from ArcGis was considered, when the class intervals were derived by the analyst from the data analysis. In this case, the natural breaks can be observed from the results of the frequency histogram.

The areas concentrated up to 2.6%, on average, of the exposed population in each one of the three cities. However, localities within the cities with a high concentration of exposed population were observed with percentages superior to 10% of the total at-risk population in Teresópolis and Nova Friburgo.

In Teresópolis, the high exposure rate mentioned above was identified in risk areas for landslides in the locality of São Pedro, one of the most populous in the city, with exposed residents concentrated on slopes with a history of landslide recurrence and in homes of subnormal agglomerates (AGSN) conditions. It is important to point out, in this locality, the risk areas are located at the AGSN Lama Fria, Rosário, Perpétuo Socorro and Morro do Pimentel. Two other locations with high concentrations of exposure to flood risks are Agriões and Várzea, especially in the vicinity of the Avenues Feliciano Sodré, Lúcio Meira and Tenente Luis Meireles Street, which are important connection paths in the city and for mobility, which raises the number of people exposed to risk even more at certain times of day. Other city localities, especially the AGSNs Vale da Revolta and Jardim Meudom (in Jardim Meudom neighborhood), Durvalino (Meudom neighborhood), Quinta Lebrão (in neighborhood of the same name), Morro Paineiras (in Vila Muqui), and Tiro na Cascata do Guarani, are characterized by their high concentration of population exposed to high risk of landslides. It is also noted that these localities are characterized by the recurrence of landslide events during times of continuous and intense rainfall.

In Nova Friburgo, the risk areas in the localities Barroso and Olaria concentrate over 10% of the total exposed population in the city. Also, this region deserves special attention due to its exposure to risks related with severe processes, such as debris flow and rockfall. Furthermore, in this context, highlights should be given to the risk areas at Córrego Dantas locality, where there is population exposed to a very high risk of landslides and mudflow. This was one of the most devastated region in the disaster of 2011, when the serious debris flow led to the movement of materials along the drainage channel. Regarding population exposure to landslides, highlighted also are risk areas at the locations Alta Floresta, Conselheiro Paulino, Conquista and Campo do Coelho.

Concerning to the concentration of people exposed to risk of landslides in the city of Petrópolis, highlighted are the AGSNs Morro do

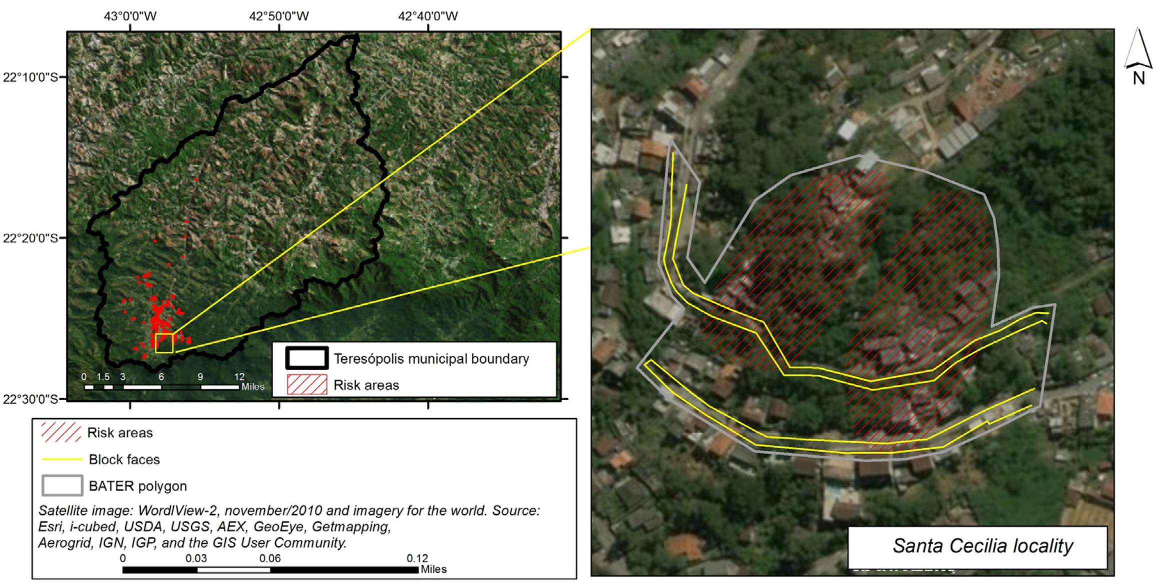
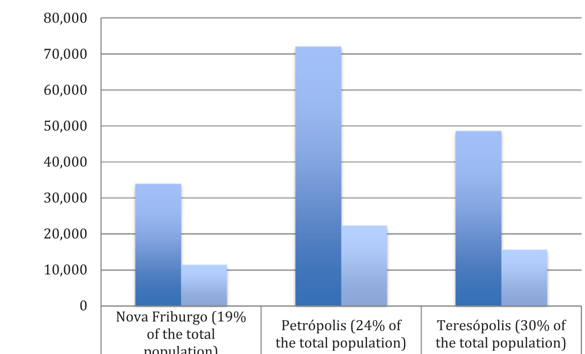


Fig. 6. Example of information considered of regular accuracy, for the location Santa Cecilia in the city of Teresópolis.



	Nova Friburgo (19% of the total population)	Petrópolis (24% of the total population)	Teresópolis (30% of the total population)
Residents	33,930	72,070	48,591
Households	11,453	22,298	15,659

Fig. 7. Estimate of exposed residents and homes in risk areas, by municipality.

Neylor (Retiro neighborhood), Veridiano Felix (on Saudade Road), Cantinho da Esperança and Comunidade Unidos Venceremos (at Quarteirão neighborhood), Rua dos Ferroviários (at Morro da Oficina), Alto Independência (at Independência), as well as the neighborhoods Alto da Serra and Floresta. These risk areas are characterized by occupations on high declivity slopes that are frequently affected by landslides, especially in the neighborhoods closest to the central region, like Independência, Alto da Serra and Floresta. A concentration of population exposed to flood risks was identified in the central region, related to the possibility of overflow in the Quitandinha River, which crosses an important transit road in the city.

Among residents exposed to risk in the cities evaluated, 52% were female and 48% were male. Around 20% of the at-risk population was composed of children and the elderly, considered to be the most vulnerable age groups for disasters, since they require special care, due to their higher dependency for autonomous locomotion and lower resistance to wounds, as pointed out by Wisner et al. [46]. Considering the different coping levels for each age group, Liu et al. [31] pointed out that, contrary to most adults, children would not be capable of reacting adequately when faced with the materialization of risk. Similarly, elderly people tend to present more difficulty for autonomous locomotion, requiring assistance in case of emergency. Besides, these age groups tend to remain more time at home; thus, are more exposed to risk. In Fig. 9, details about gender and age in each municipality are presented.

Considering the cities of Petrópolis and Teresópolis, an estimated 26% and 70% of at-risk populations were living in AGSNs, respectively. In these areas the precarious conditions of homes, regarding access to basic services, are highlighted (Fig. 10).

In Petrópolis, approximately 54% of homes located in AGSN risk areas did not have water, while in Teresópolis half of the homes at-risk did not have adequate sanitation, indicating the precariousness of exposure conditions in these areas. Concerning to landslide risks, for example, attention should be given to homes without sanitation and water supply. These aspects can reveal the precarious conditions of residences and contribute to better understanding of the human interventions that favor the occurrence of landslides, and increase exposure. This was highlighted by CARVALHO et al. [10], ARMESTO [3], MIRANDOLA and MACEDO [32], which emphasized that inadequate sanitation and the presence of septic systems in risk areas are anthropogenic factors that favor the occurrence of landslides. Besides accelerating slope erosion, they can saturate the soil and increase the likelihood of landslides. On the other hand, no risk areas in AGSNs were identified in the city of Nova Friburgo. Additionally, it was observed that 28% exposed homes in this city did not have access to adequate sanitation while 23% had no water supply.

It is highlighted that, in general terms, Nova Friburgo presented the highest number of risk areas mapped, totalizing half of the risk areas analyzed, as well as the greater territorial concentration (in km^2) of risk areas for all three cities. However, Petrópolis and Teresópolis concentrated the higher number of people exposed and in worse conditions of exposure. This result reveals that a quantitative analysis, if limited to the number of risk area polygons in a given city, for example to define priorities, can lead to an erroneous interpretation of vulnerability in the region being studied. So, the methodology adopted can be used to guide public policy on a national scale. Furthermore, the spatial information about population exposure at the intra-urban scale helps to identify areas of special attention for risk management and natural disaster response, especially in the context of monitoring an early warning. Thus, the methodology presented, associated with knowledge of geodynamic or hydrologic processes as well as the monitoring of intensity and duration of rainfall, it could assist the identification of the most critical areas inside a city. It is essential for immediate action by civil defense, during and after a disaster.

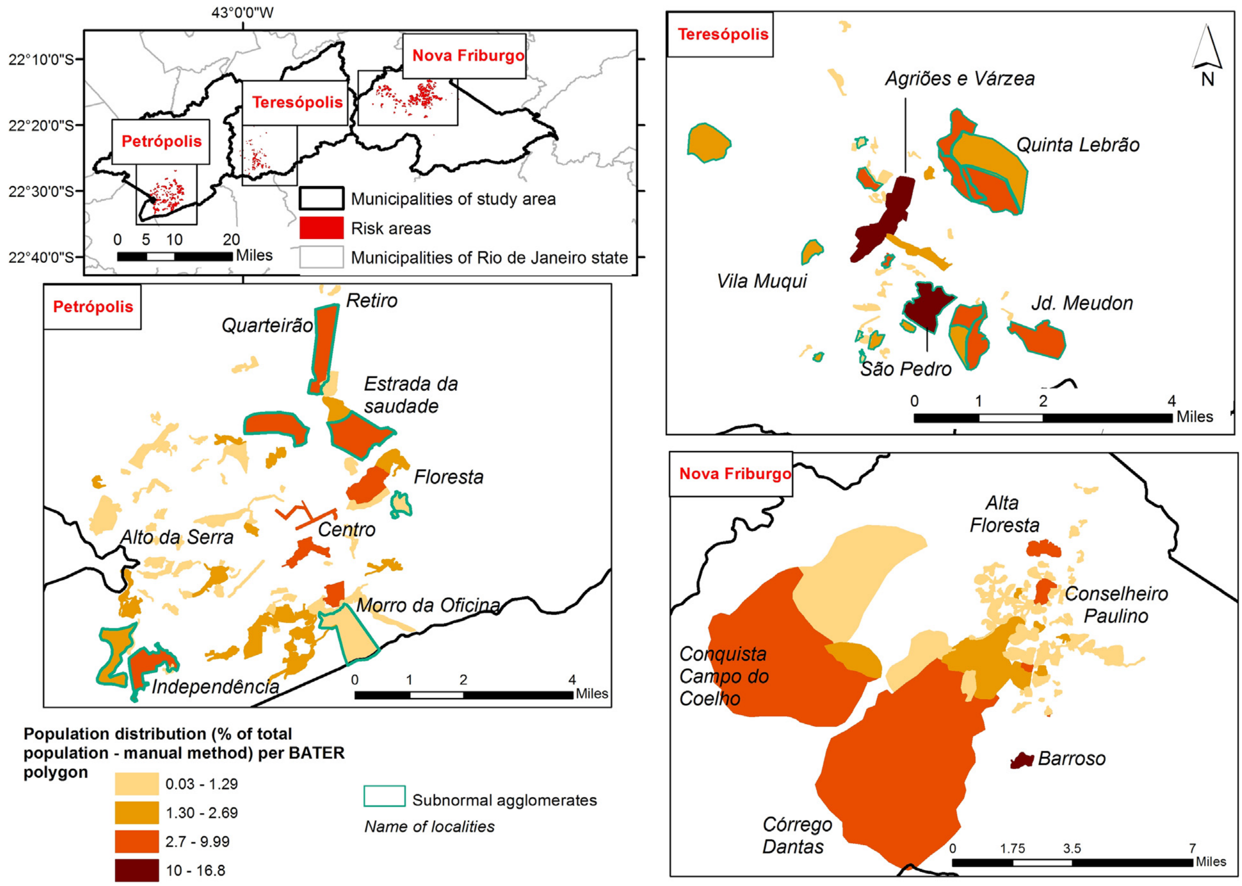
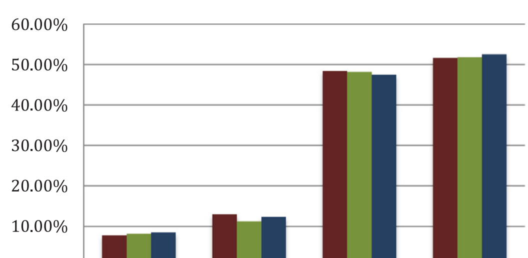


Fig. 8. Spatial distribution of exposed population estimated for the cities of Petrópolis, Teresópolis and Nova Friburgo.



	Children	Elderly	Male	Female
Nova Friburgo	7.78%	12.99%	48.40%	51.60%
Petrópolis	8.19%	11.24%	48.20%	51.80%
Teresópolis	8.50%	12.33%	47.48%	52.52%

Fig. 9. Distribution of at-risk population per gender and age of the cities analyzed.

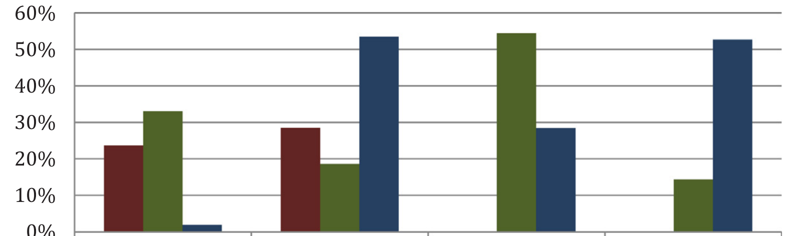
4. Conclusions

The methodology presented in this study generated unprecedented results, helping to identify people in areas susceptible to disasters in three municipalities of the mountainous region of Rio de Janeiro State, Brazil, which are considered critical due to the high recurrence of natural disasters. The main finding of the study was the estimation of population living within risk areas at Nova Friburgo, Petrópolis and Teresópolis, which were 19%, 24% and 30% of the total population in each municipality, respectively.

The positive aspect of the methodology is the association of census data directly from block faces, that allows a significant information gain about the exposed population at an intra-urban scale, even though it is an estimate. The accuracy classification obtained was mostly regular, it enabled the analysis of conditions in the regions surrounding risk areas, by associating data from these areas with the ones from the actual risk areas. It could be highlighted as a negative aspect the dependence on the quality of the risk mapping undertaken in the country, especially in regards to the accuracy of risk area delimitation.

It is also mentioned that another positive aspect of the methodology is that the results showed the detailed conditions of at-risk populations in the cities being studied, which could contribute to risk management actions and disaster response. That is, preventive actions could be directed towards different profiles of the population residing in risk areas, including campaigns and educational materials aimed at specific age groups, and simulation exercises in schools or communities, considering attributes of children, teenagers and adults. This kind of information could integrate national databases on exposed population and subsidize risk management actions and disaster response. In the context of monitoring systems, early warning alerts could include information about areas of special attention for on the ground action, taking into account the concentration of vulnerable groups such as children and the elderly. Additionally, in response actions, it could assist to prioritize the removal of these subsets of people in the event of a disaster, as well as identify areas with the highest concentration of people exposed. This kind of information can be essential to improve monitoring and early warning capacity in operational centers, such as CEMADEN. Contingency plans could also be made more efficient if including information regarding age profiles of the population, supporting the removal of residents and the setting up of temporary shelters.

Notably, the developed methodology can be replicated to evaluate other cities critical to disasters in the country, since census data is already widely produced for all cities of Brazil, ensuring the possibility of using a low-cost methodology and optimizing the returns from public resources already invested on the Population Census. Additionally, with the updating of census data it would be possible to monitor the



	no watter supply - not included AGSN	inadequate sanitary sewage - not included AGSN	no watter supply - AGSN	inadequate sanitary Sewage - AGSN
Nova Friburgo	24%	29%	0%	0%
Petrópolis	33%	19%	54%	14%
Teresópolis	2%	54%	28%	53%

Fig. 10. Home conditions in subnormal agglomerates (AGSNs) and in the remaining risk areas within the cities analyzed.

evolution of exposed population characteristics over time. On the other hand, the updating of the Population Census every 10 years is not ideal to analyze the dynamics of risk areas, revealing the need to update information in smaller intervals, for example through the development of quick count methodologies in between each Census.

With the goal of widening the analysis, accounting for other critical cities in terms of disaster occurrence, efforts are underway to apply the methodology to the remaining critical and priority cities throughout the country in order to disseminate data and publish the results in a national report, as well as to develop a vulnerability index, that would allow an integrated analysis of exposed population characteristics, for example, education level, *per capita* income, gender of householder, access to water supply, garbage collection, all attributes that can influence vulnerability to disasters.

Finally, the analysis of the positive and negative aspects evidenced the viability of the application of the methodology to other critical municipalities to disasters in Brazil. Also, it could be adapted for other countries with similar databases.

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