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Evaluating population vulnerability to volcanic risk in a data scarcity context: The case of Goma city, Virunga volcanic province (DRCongo)

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ABSTRACT

Goma city, at the eastern border of DRCongo, is highly exposed to natural hazards, especially from Nyiragongo volcano, located directly North of it. In January 2002, the city centre of Goma was devastated by lava flows and several thousands of people were temporarily displaced. Defining and quantifying population vulnerability to natural hazards, and lava flow hazards in particular, is a crucial element to evaluate and manage the risk. This paper aims at assessing the vulnerability of the population facing volcanic hazards in Goma, and its spatial variation across the city, in order to support volcanic risk prevention and management at the local levels. In this data scarcity context, two parallel methodologies are tested based on data collected through a large-scale household survey: the Social Vulnerability Index (SoVI) as defined by Cutter et al. (2003) based on a statistical data reduction; the other using fewer significant indicators in order to develop an Operational Vulnerability Index (OVI). Results show that the spatial distribution of the vulnerability levels with both approaches is quite similar, but the construction of an OVI can help to communicate the message more easily to political authorities for risk management actions – e.g., to target neighborhoods where to develop priority prevention programs – but also in terms of spatial urban planning – e.g., to identify areas where to act. Population vulnerability assessment, together with the lava flow hazard invasion probability and population exposure, is one of the crucial steps towards the lava flow risk assessment.

1. Introduction

The area around the lakes Kivu and Tanganyika, along the borders between DR Congo, Rwanda and Burundi, is subject to various types of geohazards that endanger this densely populated area [1]. The Virunga volcanic chain, which stretches across the North Kivu province of the Democratic Republic of Congo (DRC) and northern Rwanda, has two active volcanoes, Nyiragongo and Nyamulagira, which permanently threaten the urban population of Goma (DRC) and Gisenyi (Rwanda) [2, 3]. In January 2002, the city centre of Goma was devastated by lava flows and several thousands of people were temporarily displaced.

Vulnerability corresponds to the characteristics and circumstances that make exposed elements susceptible to the impacts of hazards [4–9]. Defining and quantifying population vulnerability to natural hazards, and geo-hazards in particular, is a crucial element to evaluate and manage the risk. It is a specifically challenging research question in a context of developing country with a scarcity of data and high demographic dynamics. Such research question has already been addressed in other development contexts: Latin American and Asia [10–17], but only to a limited extent in sub-Saharan Africa [18–23].

Many studies on volcanic risk [24–32] only consider physical vulnerability of buildings or infrastructures. Indeed, the concept of

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vulnerability applied to volcanic risk is often restricted to the structural characteristics of building subjected to ash fallout or volcanic flows. This physical vulnerability is generally considered as binary for volcanic flows (i.e. no damage or complete damage) due to the ability of lava flows, pyroclastic density currents or debris avalanches to cause total destruction of any exposed element [33]. Only a few authors considered the vulnerability of people in their social and economic dimensions in the assessment of volcanic risk. At Vesuvius, Scandone et al. constrained the vulnerability of people to various volcanic hazards as the relative probability of death based on historical mortality estimates [34]. Aceves-Quesada et al. used a multi-criteria evaluation of a combination of data related to the exposed elements to assess vulnerability at Nevado de Toluca volcano in Mexico [35].

This paper aims at assessing the vulnerability of the population facing the impacts of volcanic eruptions in Goma, and its spatial variation across the city, in order to contribute to volcanic risk prevention and management at the local levels [36,37]. The objective of this paper is to present two different methods allowing to define context-specific social vulnerability indices. The main challenges of this research include the contextualization and operationalization of the concept of vulnerability [1] but also the lack of socio-demographic and statistical datasets to characterize the population. To fill the lack of reliable ancillary data, methodologies adapted to this particular constraint were developed. Databases were built to constitute the basis for the demographic characterization and the vulnerability spatial analysis. The presented vulnerability indices and maps constitute essential elements for an integrated assessment of volcanic risk in the city of Goma.

2. Contextualizing population vulnerability

Since the beginning of the millennium, risk assessment has been geared towards greater consideration of societal aspects [4,38–41]. Wisner even situates this tendency to reject the primacy of the hazard in the late 1980s [42]. As explained in Michellier et al., the concept of vulnerability was initially a question of assessing the impact of the hazard on assets, in terms of damage [1,41]. Then, progressively, it is not only the exposure of the stake that was considered, but also its own fragility and its ability to recover [41,43]. An in-depth analysis of hazards, through their magnitude, frequency, duration, mechanism and intensity, remains crucial to understand the risk that the population faces. But, as explained by Wisner et al., such knowledge is far from sufficient to calculate the actual level of risk and account for the distribution of the impact once the hazard happens [4]. Vulnerability analysis has become just as crucial as natural phenomena [4,6,44–47]. And for some authors, even more.

Vulnerability is a polysemic, multiscale and multidimensional concept [48–51]. As a result, many definitions of vulnerability have emerged in the past 30 years. They are influenced by different schools of thoughts, research traditions, and the different disciplines involved in its evaluation [41,49,50,52–55]. In their literature review, Thywissen and Birkmann both identify over 30 different definitions of vulnerability [50,55]. Birkmann also identifies three schools of thoughts from which the concept of vulnerability emerged [50]: one interested in research on development and poverty, another studying the reduction of hazards and disaster risks and finally a third on climate change, each studying vulnerability according to the specificity of its angle of approach. From this come more than a dozen conceptual models, all of which bring a specific added value to the analysis of vulnerability [5,42,49,50,52]. There is no scientific consensus about the definition of vulnerability, or the underlying conceptual models, or the factors that influence it [56,57].

According to several authors, a generic definition of vulnerability most appropriate to risk analyzes is that the vulnerability is “a propensity for damage or dysfunction of various exposed elements (assets, people, activities, functions, environment, systems) of a given territory and society” [4,5,7,43,58]. In other words, vulnerability characterizes the elements exposed directly or indirectly to the hazard, reflecting their own fragility.

Multiple and complex interpretations of vulnerability have led some authors to divide it into several dimensions: social, economic, environmental, institutional, physical, functional and so on [44,50,59]. Other authors, such as Brooks, delineate essentially two types of vulnerabilities [60]. First, there is the social vulnerability, which takes into account criteria such as poverty, social inequality, health, access to resources and basic infrastructures, and social status - which tend to increase or reduce the long-term impacts and capacity to recover of communities and individuals facing a hazard [44,56]. Second, the physical (or biophysical) vulnerability corresponds to the characteristics of the infrastructures exposed to the hazard that control the level of destruction and therefore the direct tangible impacts caused by the hazard [60].

Assessing social vulnerability is a challenge as it is a multi-dimension concept. Cutter et al. have developed a data-driven methodology which aims at quantifying the social vulnerability of a population through a complex index built on a wide range of socio-economic data [44]. Their first application was developed at the USA scale. Other studies applying strictly the same methodology of Cutter et al. have been developed in data-rich contexts, e.g. Greater Lisbon (Portugal [61]); Pacific coast of Oregon (US [62]); or Norway [63]. These studies argued that assessing social vulnerability in combination with hazard analysis was essential to develop context specific risk reduction strategies, or well-designed evacuation plans [64]. Similar social vulnerability assessments have been conducted in some developing countries, with fewer data available: in Indonesia, Siagian et al. developed social vulnerability profile to propose adapted disaster risk reduction strategies [16]. Other vulnerability assessment studies have been carried out on a larger scale, e.g. in the villages around the Merapi volcano in Indonesia [65], or in the city of Sao Paulo in Brazil [66], where the population is particularly vulnerable to flooding, or in the Mekong delta in Vietnam where households are threatened by coastal risks [67].

In volcanic risk studies, although no more exclusive, the assessment of physical vulnerability (*i.e.* vulnerability of buildings) is an important step in risk assessment. Social vulnerability remains neglected, and when considered, it is not always in a spatially explicit and reproducible methodology. However, the social dimension of vulnerability is significant too and is probably even more relevant in context with large social inequalities, deficient volcanic risk management and limited social protection. Although quantifying the various dimensions of social vulnerability is very difficult, we here present a reproducible methodology adapted to a data-poor context to characterize the spatial variation of the social vulnerability of the population relative to volcanic risk and demonstrate its application for the city of Goma. Indeed, measuring the social vulnerability (*i.e.* the vulnerability of the population and exposed households) is key for understanding the risks associated with natural hazards and the potential long term impact of a disaster on a society, and for developing effective response capacities [4].

3. Materials and methods

3.1. Study area

The study was conducted at the scale of Goma, the capital city of North Kivu Province, home of about 775,000 people (Fig. 1). Over the past 25 years, in a context of very low economic development, Goma has been the scene of regional political instability and recurrent armed conflicts, pushing thousands of refugees to seek safety within its administrative boundaries [68,69]. This context makes the city particularly vulnerable. Moreover, it is exposed to the threat of lava flows and other volcanic hazards produced by Nyiragongo volcano, which last erupted in 2002 [68,70,71]. The two historical eruptions of Nyiragongo volcano occurred in 1977 and in 2002, the latter destroying about 10% of the city centre, killing more than a hundred people and impacting the economic activity of the whole region on the long term [72,73].

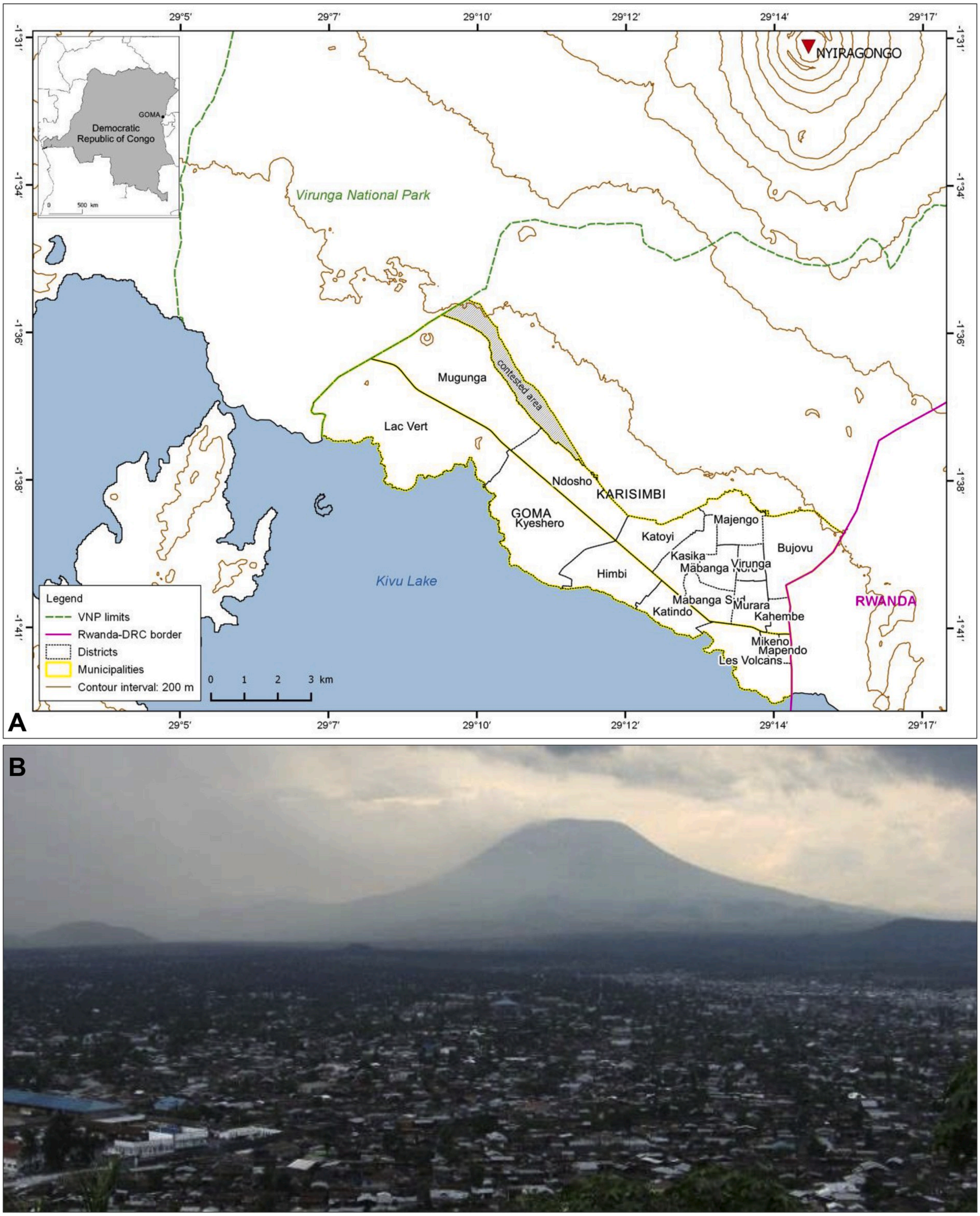

Fig. 1. (A) Map of Goma city (DRC) surrounded by the Kivu lake to the south, the Virunga National Park (VNP) to the west, the Nyiragongo volcano to the north, and Rwanda to the east; (B) Picture of Goma, at the foot of the Nyiragongo volcano.

One major limitation for assessing and managing volcanic risk in Goma city, but also in the region at large, is the very poor availability in ancillary data [1]. The methodology presented in this study was constructed to address this key constraint.

3.2. Defining vulnerability indicators

As explained in Michellier et al., we organised a Delphi survey based on the contributions of about 20 local and international experts, selected after the "2013 AVCoR conference" working group discussion, focusing on "vulnerability and risk assessment" [1]. The objective was to identify the main dimensions of vulnerability in the specific context of Goma as well as the appropriate and measurable parameters that could directly inform about each of these dimensions, as well as the methodology which could be implemented for the vulnerability and risk assessment at the household scale [1].

3.3. Morphological zones

As mentioned in the introduction, sources of second hand data to characterize the population were scarce and of limited quality [1]. To cope with this, we used a methodology combining remote sensing and demographic survey, in order to reach two distinct objectives: (1) to quantify the population number and characterize its spatial distribution within the studied city [74], and (2) to collect information on the key socio-economic characteristics of the population to be used to define a vulnerability index at neighborhood level.

Multispectral Pléiades satellite images pansharpened to 0.5 m resolution (dating from September and October 2014) and covering the whole urban area were visually analyzed to identify contrasted land use. On the basis of satellite imagery, field knowledge and field validation, zones corresponding to residential or "uninhabited" areas were delineated, these latter being identified to be surveyed separately (university campuses, football fields, schools, military camps, cemeteries, churches, administrations, businesses, health structures, public markets, etc.).

The socio-economic characteristics of the population cannot be deduced from the satellite image, but the spatial distribution of these characteristics is often linked to the spatial organisation of the population [75]. More specifically, Dureau et al. mention that zoning the urban area in homogeneously built sectors is a relevant basis for a survey sample oriented towards studying the characteristics of a rapidly growing urban population [76].

Therefore, homogeneous areas were identified in the urbanized space, according to their buildings' size, density and canvas. As described in Michellier et al. [74], we worked in a Geographical Information System (GIS) environment on the city's satellite image to visually map these homogeneous 'morphological zones' (MZ). The MZ were subdivided in a number of polygons and identified by a unique MZ identifier. Several polygons, even spatially non-contiguous, but presenting similar characteristics, could be assigned to the same MZ, identified by a unique MZ code (Fig. 2).

3.4. Sample size and sampling plots

The sample of surveyed areas was stratified by municipalities, as this administrative unit is representative of the city functioning; the same number of plots were then attributed to each municipality.

To be statistically representative, i.e. to be considered representative of the studied population, the size of our sample was fixed at a minimum of 40 'plots' per municipality. A 'plot' is an area encompassing several households, the number of which depends on their spatial density. The 40 'plots' to be surveyed in each of the two municipalities (Goma and Karisimbi) were distributed randomly and proportionally to the area of each MZ. The plots were then manually delineated from the randomly distributed in a GIS environment at a scale of 1/1500, on the basis of linear urban elements visible on the satellite image, such as roads, gullies, rivers, etc. [74]. An additional sample of about 30 plots was randomly distributed in the northern part of the urbanized area, located in the Nyiragongo territory administrative unit. The exact number of

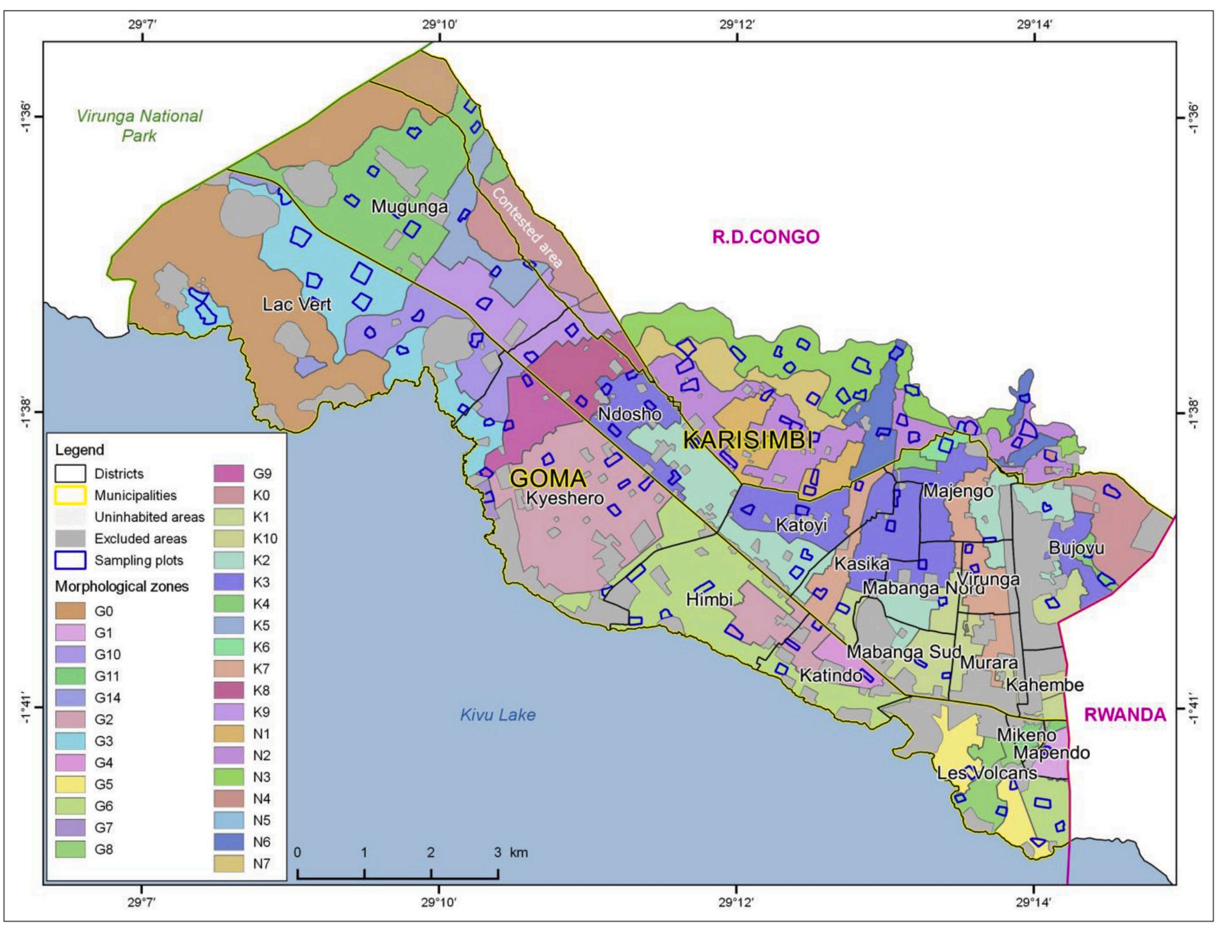

Fig. 2. Distribution of the sampling plots in the morphological zones of Goma; some of the colors might seem similar, but all these 31 morphological zones were distinguished based on the structure and the density of the buildings; this large number of categories is due to the fact that, as we have stratified our sample by municipalities, each municipality + Nyiragongo territory was considered separately (i.e. although some density and structure of buildings were similar, their code are different). The grey areas were not surveyed for the collection of demographic data as they were either areas with specific activities (business, schools, hotels, military camps, airport) or not inhabited areas (volcanic cones).

plots per municipality was slightly adapted compared to the target value, as field conditions enabled to document more plots, or as plots turned out to be unoccupied.

Our final sample in Goma included 115 plots (Table 1). In total, in a 2-month period (May–June 2015 – close period to the satellite images acquisition), a dozen of local interviewers were able to collect socio-demographic data from nearly 6500 people, from 1060 households, randomly selected by clusters of 10 per plot.

3.5. Household survey: creating demographic data

A questionnaire allowing to get the appropriate demographic baseline data and more specific information on the past disasters experience and risk perception of the population was developed. The questionnaire was first translated into Swahili – the main language used during the survey – to limit language misunderstandings, and a field test was organised. Once the final survey was validated, the local interviewers were trained in the delivery of the survey before the actual data collection phase. The survey was structured in four parts, allowing successively to register (A) household identification codes, (B) data over individual characteristics of each household member (sex, age, education, language, religion, activity, etc.), (C) information regarding the threats faced by the household (particularly its experience of geohazards), and (D) details about the housing and its equipment. Most of these data correspond to those considered relevant following the Delphi survey mentioned above.

3.6. Defining a context-specific vulnerability index

Although only sparse data were available at the beginning of the project, the vulnerability assessment could finally be based on a wide socio-economic database, comprising data at the individual and at the household level. Therefore, methodologies based on quantitative statistical analyses were explored. Two different approaches were chosen: the application of the data-driven Social Vulnerability Index (SoVI) developed by Cutter et al. (2003) and the development of a deductive Operational Vulnerability Index (OVI) based on a limited number of meaningful indicators (Fig. 3).

The first step in the development of a vulnerability index is to aggregate individuals' socio-economic data at the household level (Fig. 3). Eight variables were defined from the individuals' database, and transformed into a household average or ratio. Considered as potentially meaningful based on expert elicitation and our field knowledge, these variables were then merged with 14 household variables to form a single household level database comprising 22 variables related to the concept of vulnerability (Table 2).

These 22 variables were then extrapolated at the level of the sampling plots assuming a homogeneous population as:

$$V_i = \sum_{m=1}^{M} \left(\frac{I_m}{I_i} V_m \right)$$

where $\mathbf{V_i}$ is the value of a given variable at the level of the plot, **M** is the number of surveyed households in the plot, $\mathbf{I_m}$ is the number of individuals living in the household **m**, $\mathbf{I_i}$ is the total number of individuals living in the surveyed households and $\mathbf{V_m}$ is the value of the given variable at the level of the household.

The variables at the level of the sampling plot were subsequently converted to z-scores. Following this step, the two approaches become different.

3.7. The social vulnerability index (SoVI)

In order to assess the SoVI, Z-scores of all variables are used as input in a Principal Component Analysis (PCA; [77]), performed with the SPSS software. The rational of such PCA approach is to identify the major dimensions of vulnerability by grouping the information of correlated variables into few Principal Components. A varimax rotation was applied to enhance the interpretation of the component matrix. Principal components (PCs) with an eigenvalue larger than one were retained for the construction of the SoVI.

The sums of the PC scores were aggregated at the level of the MZ as:

$$W_Z = \sum_{i=1}^{I} \left(\frac{J_i}{P_i} \left(\sum_{k=1}^{K} a_k W_k \right) \right)$$

where **I** is the number of sampling plots in a MZ, **Ji** is the number of inhabitants living in a sampling plot, **Pi** is the total number of people living in the sampling plots of the MZ, **K** the number of retained PCs (eigenvalue $>$ 1), $\mathbf{a_k}$ a positive or negative sign depending on the interpretation of the PC with respect to the vulnerability, $\mathbf{W_k}$ the score of the PC **j** in the plot, and **Wz** the sum of the retained PC scores in a MZ. This Wz result was then normalized to a 0–1 scale to define the SoVI for each MZ.

3.8. The Operational Vulnerability Index (OVI)

The selection of variables included in the OVI was based on the PCA. We first identified the significant variables. Then we selected the variables according to two main criteria: (1) a single variable selected from each PC, and (2) the relevance of the variable to the vulnerability assessment. This corresponds to the variable whose reliability and interpretation appears to be the most consistent with the PC, the experts' opinion and the vulnerability literature. The values used to calculate the OVI are the average values standardized in z-scores at the plot scale; in other words, they are the same values as those used as inputs in the PCA. Then, we aggregated them, weighting them by the size of the plot, at the scale of the morphological zones. The objective of the OVI is to build a meaningful vulnerability index capturing the different dimensions of vulnerability with a parsimonious selection of indicators, in order to facilitate the understanding, reproducibility and update of the data collection.

4. Results

4.1. Results of the PCA

The results of the PCA on the 22 input variables, including the explained (cumulative) variance, the main variables loading on each retained component and the sign of the component in terms of its contribution to vulnerability are provided in Table 3. Variables linked to education and economic levels of the households are the main categories highlighted by the PCAs.

The PCA results in 6 PCs with an eigenvalue above 1, accounting for 70% of the total variance of the entire dataset. These 6 PCs are related to a total of 18 variables:

Those retained in PC 1 explain 32% of the variance of the dataset, and group variables related to the household's physical and economic resources and its economic resources including the income,

Table 1
Number of sampling plots, individuals and households surveyed to collect socio-economic data in each municipality of Goma.

	Municipality	Total number of sampling plots	Total number of surveyed households	Total number of surveyed individuals
GOMA	Goma	42	364	2.329
	Karisimbi	44	400	2.412
	Nyiragongo	29	296	1.731
	TOTAL	115	1060	6472

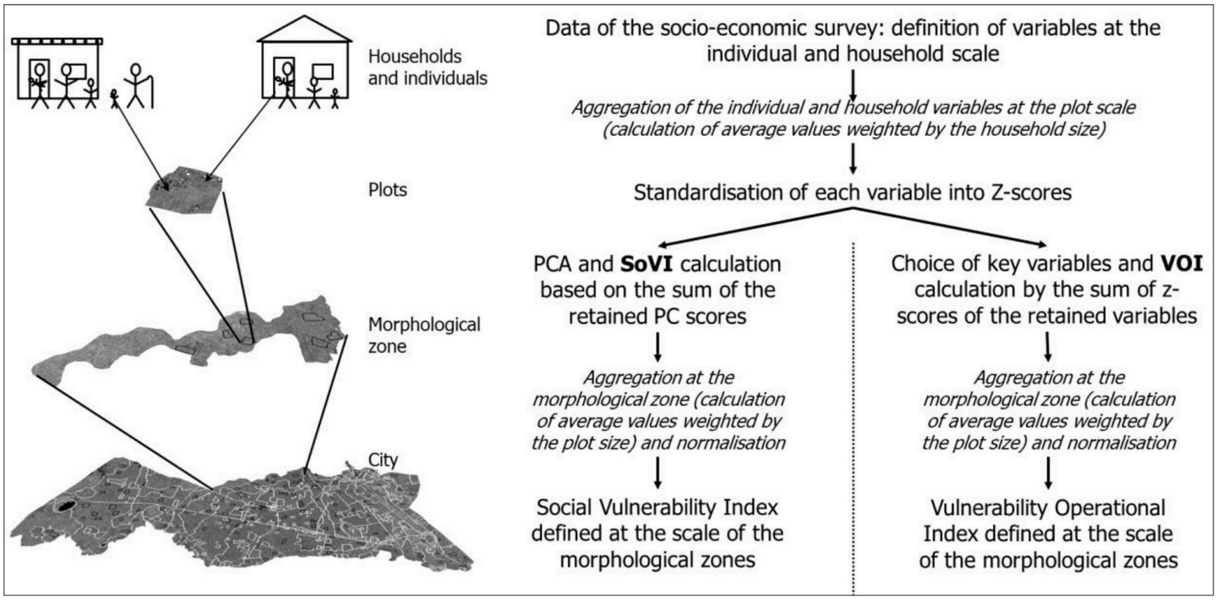

Fig. 3. Illustration of the methodology and the different levels considered in the development of, on the one hand, a Principal Component Analysis (PCA) leading to the Social Vulnerability Index (SoVI) and, on the other hand, the Operational Vulnerability Index (OVI).

material assets, and housing characteristics: an high economic level contributes to lowering the vulnerability of the household [78].

The level of education and the proportion of individuals who have attended school are summarized in PC 2, being associated with variables that represent means of communication within the household (owning a radio and a mobile phone). Households with low levels of education and few means of communication are more vulnerable [67]. This PC explains more than 10% of the variance of the dataset.

PC 3 groups two parameters related to household structure and resources: the total number of individuals in the household and the proportion of economically active individuals in the household. Large households with low activity rate are characterized by high vulnerability [18]. This PC 3 explains 10.5% of the variance of the dataset.

PC 4 represents 6.3% of the variance and focus on the perception of a risk (based on the question: *do you feel your household is in danger?*) and the experience of a past geological disaster. These two variables are highly correlated meaning that past experience leads to a strong feeling of risk perception (i.e. people who have experienced a past disaster express the feeling that their household is in danger). We consider that households that feel threatened or have already experienced a disaster have a lower vulnerability because they are a priori better prepared [79].

Factors representing household structure are included in PC 5 which explains 5.8% of the variance. It results in high vulnerability for dependent households (e.g., with a high rate of old persons or single-parent household), and the households counting mainly women [19].

Finally, only one economic variable (owning a motorcycle) is included in PC 6 (4.6% of the variance). The motorcycle is an essential transport vehicle in the city; it is used as a revenue generating activity; it facilitates commercial exchanges, etc.. The proposed interpretation is that it goes in the direction of reducing vulnerability [19].

The representation of the spatial distribution of the 6 PCs separately gives insights into the influence of each PC in the spatial pattern of the vulnerability assessment (Fig. 4). Indeed, it shows that the PC 1 has a higher importance in Les Volcans districts – which is among the richest neighborhood of the city –; PC 2, related to education, is more homogeneously high across the districts included in the administrative limits of the city (except Mugunga and Lac Vert districts) highlighting lower educated population at the outskirt of the city; PC 3 (household resources) presents higher values in Goma municipality; Risk perception and past disasters experience (PC 4) is stronger in the areas affected by the 2002 lava flow; PC 5 (household structure) highlighting more dependent households is more important in the western and northern outskirts of the urbanized area; and the additional economic factor symbolized by owning a motorcycle (PC 6) has a lower weight in Goma municipality.

Based on the output of the PCA and according to the formula presented in sections 3.6 and 3.7, the vulnerability indexes for each morphological zone can be calculated based on the aggregated value of the different sampling plots. This enables to map the spatial variation of the vulnerability indexes across Goma. For both indices (SoVI and OVI), a 9-class equal intervals scale was used to allow comparisons between the two maps. Neighborhoods with high vulnerability (i.e. dark orange color in Fig. 5 and Fig. 6) can be interpreted to be areas hosting more socio-economically fragile population, with lower assets, education and experience of their local environment, making them less able to face and recover from a disaster.

4.2. A high social vulnerability index in the outlying areas of the city

The **SoVI** (Fig. 5) presents a gradient from the city centre to the outskirts. It is distributed along a gradient of increasing social vulnerability from south-east to north-northwest, ranging from central residential neighborhoods to semi-rural and newly-built neighborhoods. The population living in Les Volcans district, situated along the lake shore along the Rwanda border, has economic and educational characteristics that give it a very low level of social vulnerability (i.e. light orange). This district corresponds to the old European quarter of the colonial city: it is made up of large plots, on which are located spacious houses, equipped with water and electricity, and whose occupants own a large range of material assets. This district Les Volcans is however cut in two parts by an area of greater vulnerability, which corresponds to the area that had been impacted by one of the lava flows of the 2002 volcanic eruption. Housing construction materials and/or the economic level of households that have resettled in this devastated part of the city

Table 2
Variables defined in the vulnerability study. For each variable, the assumed relationship between the variable and the household vulnerability is based on expert's opinion following the Delphi approach.

Variable	*Abbreviation*	*Description*	*Link with vulnerability*
Number of individuals living in the household	NUMIND	Total number of individuals living in the household on a daily basis	+
Proportion of dependent individuals living in the household	PROPDEP	Number of individuals living in the household and dependent on another individual compared to the total number of persons living in the household. An individual is considered as dependent if its age is smaller than 16 years or larger than 65 years.	+
Maximum residence time in the city of Goma of an individual living in the household	MAXRESTIME	Maximum residence time (in years) in the city of Goma of an individual living in the household	-
Proportion of individuals living in the household and with an age above three that have been or are currently going to school..	PROPSCH	Number of individuals living in the household and going to school (all level) compared to the total number of persons living in the household	-
Basic education followed by an individual in the household	BASEDUC	Boolean variable identifying if at least one individual living in the household acquired a basic education level (*i.e.* at least secondary school)	-
Maximum number of languages spoken by an individual living in the household	MAXLAN		-
Proportion of individuals living in the household that declared to be economically active (*i.e.* being part of the active population)	PROPACT		-
Household monthly income per person	INCOMEP	Household monthly income per person (*i.e.* total monthly household income divided by the number of individuals living in the household).	-
Household with less than two independent people	<2INDEP	Boolean variable identifying if less than two independent people (*i.e.* age between 16 and 65) are living in the household. This variable identifies single-parent households or households consisted only of dependent individuals.	+
Proportion of woman living in the household	PROPWOMAN	Number of individuals living in the household and being a woman compared to the total number of persons living in the household	+
Threat of hazard	THRHAZARD	Boolean variable identifying if the household was threatened by a hazard in the past.	-
Experience of hazard	EXPHAZARD	Boolean variable identifying if the household experienced a hazard in the past.	-
House with an economically costly wall material	WALL	Boolean variable identifying houses with an economically costly wall material (*i.e.* bricks, stones, concrete or cement).	-
House with an economically costly roof material	ROOF	Boolean variable identifying houses with an economically costly roof material (*i.e.* roof tiles, asbestos cement, galvanised metal sheet or concrete).	-
House with an economically costly floor material	FLOOR	Boolean variable identifying houses with an economically costly floor material (*i.e.* floor tiles, stones, concrete or cement).	-
Household possessing at least one radio	RADIO		-
Household possessing at least one mobile phone	MOBPHONE		-
Household possessing at least one multimedia device (*i.e.* television, computer of DVD-player)	MULTIMEDIA		-
Household possessing at least one bicycle	BICYCLE		-
Household possessing at least one moto	MOTO		-
Household possessing at least one car	CAR		-
House area	HOUSEAREA	Measured width x measured length	-

do not have the same characteristics as the older parts.

At the extreme opposite, the social vulnerability map highlights three poles of very high social vulnerability (i.e. dark orange, in the districts of Lac Vert, Mugunga (north), and Bujovu). These areas, although scattered at the edge of the city, have similar characteristics. These are semi-rural areas, whose population has maintained an agriculture-based lifestyle, with houses in wood, and low monthly incomes (less than 100 US $ per month; PC 1, Fig. 4).

Much of Mugunga district, as well as the northern area beyond the administrative boundaries of Goma city, in Nyiragongo territory, are characterized by their recent development, due to an influx of displaced population fleeing rural insecurity. As mentioned above, this population is poor (low monthly income, few material assets) and has a low level of education, making it particularly vulnerable.

Lac vert district presents also very high level of vulnerability. Following the 2002 eruption, some of the affected population had resettled in this district [80]: the authorities had parceled out a part of

Table 3
Results and interpretation of the PCA for Goma.

	Var. (%)	Cum. Var. (%)	Eig.	Main interpretation	Representative variables and loadings	Sign
PC 1	32,3	32,3	7,1	Economic factors and household resources	INCOMEP (0,84) WALL (0,83) HOUSEAREA (0,79) CAR (0,74) MULTIMEDIA (0,72) BICYCLE (0,64) FLOOR (0,61)	–
PC 2	10,7	43,0	2,4	Education and communication	MOBILE (0,81) BASEDUC (0,80) PROPSCH (0,80) RADIO (0,62)	–
PC 3	10,5	53,6	2,3	Household resources and structure	NUMIND (0,75) PROPACT (−0,87)	+
PC 4	6,3	59,9	1,4	Risk perception and past disasters experience	EXPHAZARD (0,81) THRHAZARD (0,75)	–
PC 5	5,8	65.7	1,3	Household structure	<2INDEP (0,69) PROPWOMAN (0,65)	+
PC 6	4,6	70.3	1,0	Economic factor	MOTO (0,78)	–

this district to accommodate the families who had lost everything during the 2002 eruption. Since this disaster, these households might have remained at a low economic level (Fig. 4). But more obviously, this area is home of the refugee camps set up in 1994 following the genocide of the Tutsis in Rwanda. Part of this extremely poor population has definitively settled in this part of Goma city.

Apart from these extremes, the rest of the city has a medium level of social vulnerability, which is difficult to characterize at the first sight, as such values depend on various parameters. For example, based on our field knowledge and discussions with the municipalities' authority, the districts of Mapendo and Kahembe include the poorest populations of the city. However, their level of social vulnerability appears to be low (Fig. 5). According to the detailed analysis of each PC, this could be explained by the low proportion of dependent individuals and women in each household, the high level of geological hazards threat perception and the increased economic capacity strengthened by the motorcycle ownership. Another example: the western part of Kyeshero district has the highest number of people who have experienced a geological hazard (PC 4; Fig. 4); this population is probably aware and disturbed in its daily activities by the *mazuku* (*i.e.* local areas where CO_2 is accumulated up to lethal level; [81]. Associated with a difficult household economic situation and a low level of education, western Kyeshero however stands out as a medium to very high vulnerable area. If a high level of risk awareness should reduce vulnerability, in this case this is not reflected in the final index. In the end, the gradients of PC 1 and PC 2 are dominant in the final index.

4.3. The Operational Vulnerability Index: similar trend but additional value

The OVI (Fig. 6) was produced and mapped based on a specific equation taking into account only few relevant variables, selected based on each PC, as followed:

OVI = - (Average household income + Proportion of educated individuals + Proportion of active individuals in the household + Proportion of women in the household + feeling threatened by geological hazards)

Comparing both maps, the spatial trends are very similar although the level of vulnerability seems overall lower with the OVI. Les Volcans district remains the least vulnerable, while the northeast and northwest outskirt neighborhood are the most vulnerable areas.

Some differences can nevertheless be highlighted. Semi-rural morphological zones, located in the Lac Vert district, have an OVI lower than the SoVI. Relying on the average income of the household or the proportion of education and active individuals (as it is the case with the OVI) makes the household less vulnerable, than including the maximum education level – which remains low in this area –, and the household structure – high number of individuals –, which are tend to increase the SoVI value of these neighborhood. The Himbi and Katindo districts, identified as neighborhoods with a wealthy population, have a lower OVI than their SoVI. In contrast, those in Mapendo and Kahembe have a level of vulnerability (represented by the OVI), which is in line with the extreme living conditions of the inhabitants of these neighborhoods.

5. Discussion

5.1. Vulnerability to the lava flow hazard

The population of Goma is subject to different kinds of volcanic hazards, among which lava flow hazard is one of the most destructive. When such an event occurs, as it was the case in 1977 and in 2002, it strikes different parts of the city, and affect each household at risk differently. Although human fatalities and injuries due to lava flows are limited, some people might die as a consequence of reckless behaviour due to poor hazard awareness (e.g. as it was the case in 2002, when people crossed the lava flow while its temperature was still extremely high, or when some unaware people went to a petrol station near the lava flow to collect gasoline and it exploded; [72,73,82]).

Lava flows generally cause complete destruction of physical assets and infrastructure along its path [83], which can significantly impact the daily life of people living in the surroundings of volcanoes. This means that people living in the lava-affected areas lost their house, their land and belongings, but also that the economic activities and social services of the city were majorly disrupted for several weeks, due to interruptions of major road axes and massive displacement of population. The mapping of social vulnerability does not aim at identifying which area or population will suffer the greatest direct impact, as this is mainly controlled by the spatial distribution of the lava flow. Rather, we consider that the assessment of social vulnerability will inform on the short- and long-term impacts of such a volcanic hazard on people livelihood, i.e. on their capacity to cope with the consequence of direct (house destruction) and indirect impacts, such as temporary evacuation, decreased economic activities, interrupted transport networks. Indeed, depending on its level of social vulnerability, the population will bear the impact of the disaster with varying degrees of intensity; e.g. means and assets could enable the household to take more adequate protection or preparedness actions and recover from endured losses; knowledge of their environment could help the household to adopt the appropriate reaction in case of emergency. Assessing the vulnerability of the population has the objective to give a picture of the spatial contrast in the long-term impact such a hazard could have on the population and to identify the part of the population and neighborhood that will require more support to recover.

5.2. Assessing vulnerability in a data scarcity context

Strictly speaking, vulnerability cannot be measured because it does not correspond to an observable phenomenon [50,56,84]. However, by using representative variables and an adapted methodology, we can evaluate it. Indicators are a possible approach for making theoretical concepts operational [56]. A vulnerability index, whether social or operational, characterizes the vulnerability of the population according to various parameters reflecting its socio-economic status. Indices may

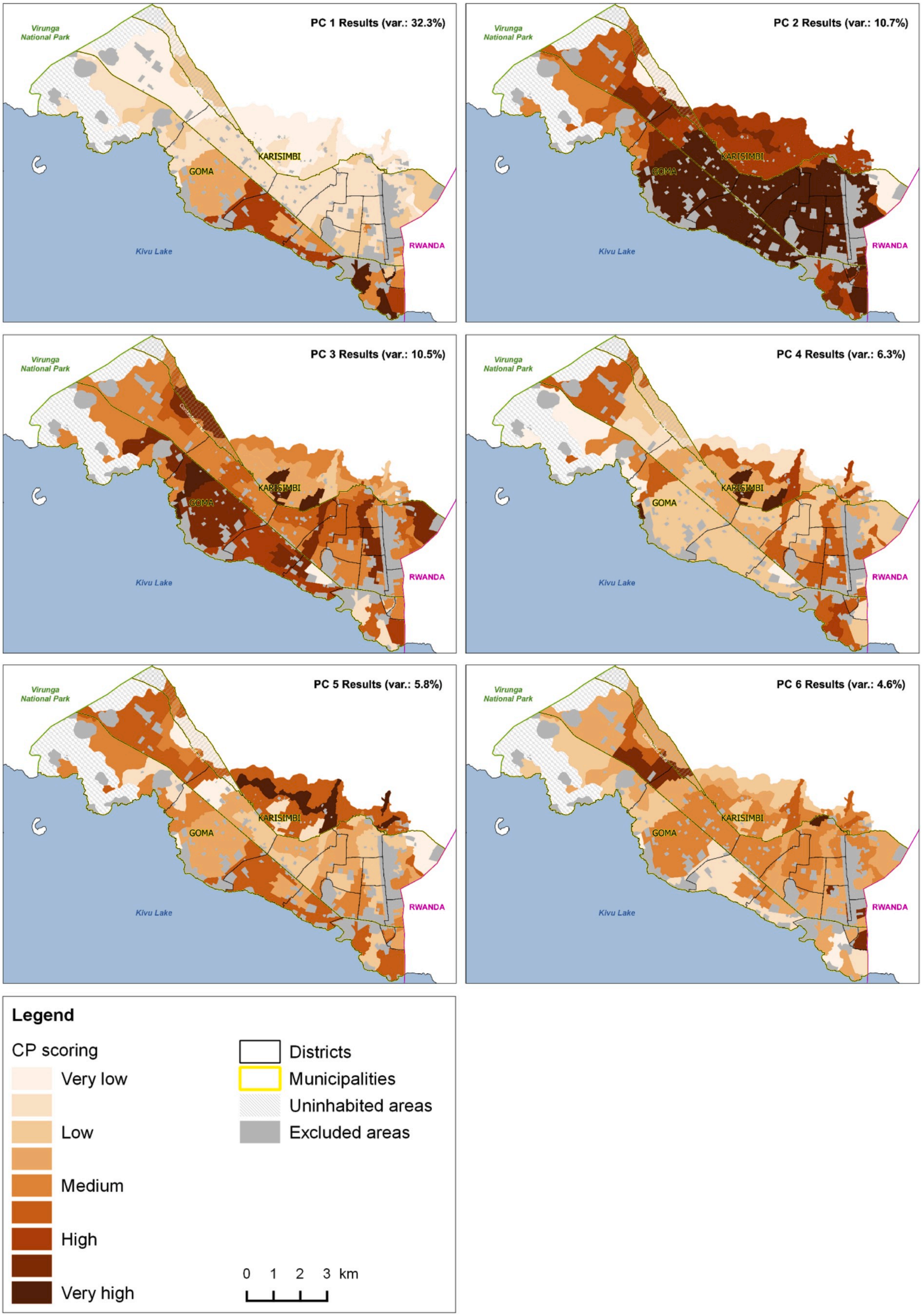

Fig. 4. Spatial representations of the PC 1 to 6.

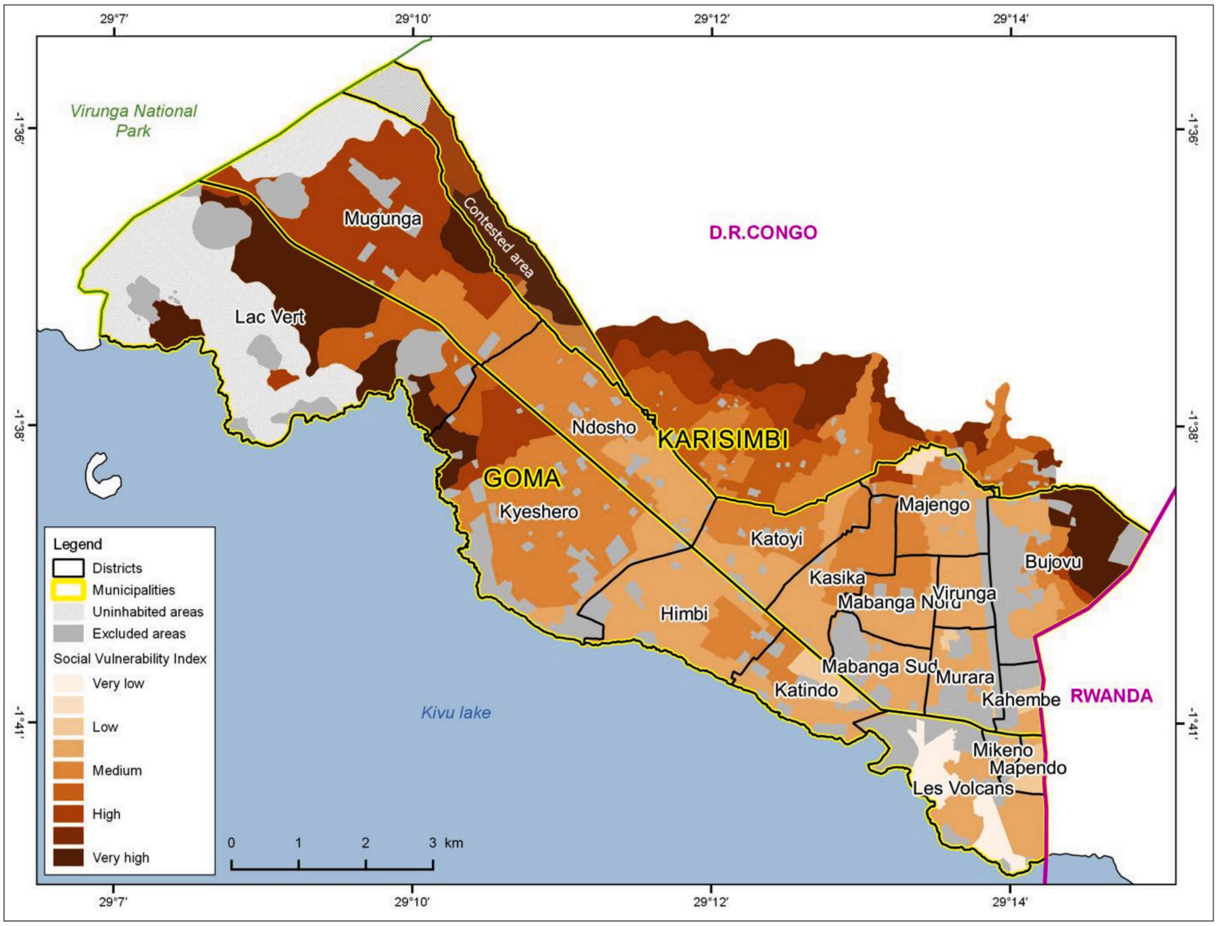

Fig. 5. Social vulnerability index map of Goma.

be useful for capturing a complex reality in simple terms and allowing comparisons across spatial and temporal scales. Nevertheless, attempts to develop vulnerability indices were met with many criticisms, mainly focusing on the fact that the methodologies applied are often neither presented in a transparent manner nor scientifically validated or relevant to disaster risk reduction policies [42,56,85]. Vigilance must be maintained because, in providing summary information, there is a risk that these indicators may not accurately reflect the intended situations or processes [86].

At the beginning of this study, and after evidence of the scarcity of existing and/or reliable data, we first considered assessing the population vulnerability by developing a semi-quantitative approach. Based on a combination of remote sensing, large-scale field campaigns and detailed knowledge of the research environment [74], a descriptive statistical analysis of the data collected led us to the conclusion that the newly collected database was sufficiently wide ranging and of a quality that was recently unequalled in the region.

5.3. *Measuring the social vulnerability*

Following, although the qualitative approach remained the basis for our data selection and allowed us a better understanding of the research environment, the wide range of collected data enabled us to move towards a widely recognized vulnerability index: the SoVI, as defined by Cutter et al. [44]. Indeed, such a methodology has already been used in many different contexts for evaluations at various scales [16,61–67,87–90].

The statistical analysis underlying SoVI has the advantage of highlighting links that are not always obvious between certain variables. From this derives the major criticism that we can formulate with regard to the SoVI: it is above all a technique for reducing the number of data in a statistical analysis taking into account the variables that influence vulnerability. In other words, what emerges is information on the most correlated variables in the set of preselected variables. Therefore, it should be kept in mind that even variables not included in the main PCs may be relevant for vulnerability assessment.

The technique therefore allows a spatial ranking of the city's districts according to their level of vulnerability. However, the SoVI does not allow to understand at first sight what governs vulnerability. This is another limitation of the approach proposed by Cutter et al. [44]: it is difficult to explain in a simple way which variables are important in the social vulnerability index and how the social vulnerability index was formed in detail.

Another difficulty is that the social vulnerability assessment does not allow the uncertainty of the index to be assessed or validated. There is therefore no established model for the social vulnerability assessment. On the one hand, this leaves a great freedom in the choice of variables and the way they are associated (e.g., with or without weighting of the different PCs, in particular); and on the other hand, it creates a great subjectivity in all the choices made throughout the process. As Tate points out [91], at each stage, choices must be made between several options, all legitimate.

5.4. *The added value of the OVI*

If the additional value of our approach was to take into account the specific context (e.g., through the type of collected data and the selected variables) in which this study was carried out [1], the SoVI intended to aggregate a large variability of variables to highlight the different dimensions of social vulnerability. It then translates as followed: low

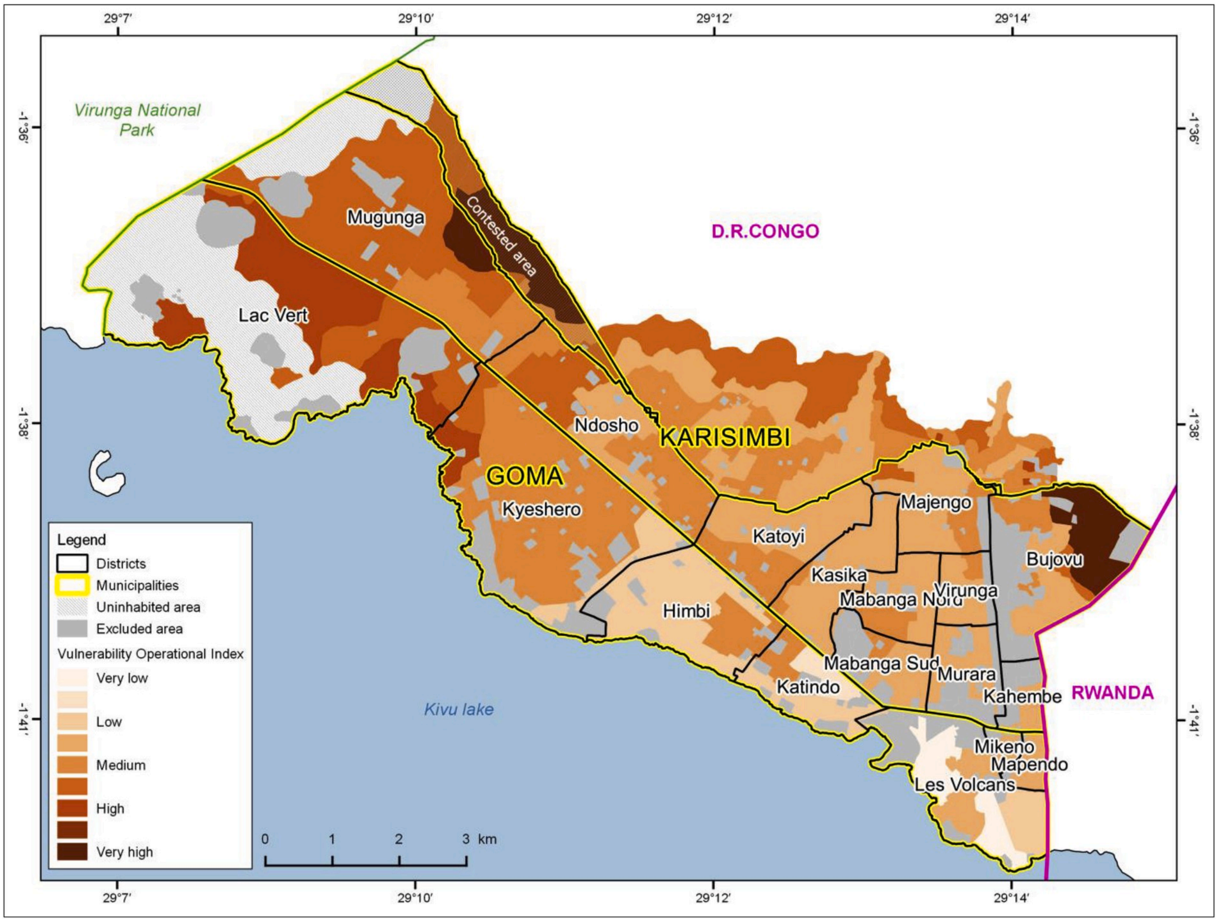

Fig. 6. Operational Vulnerability Index map of Goma.

social vulnerability highlights households for which the consequences of a hazard would be lower, *i.e.* households that, over the long term, have the capacity to cope with and recover from the impact of a crisis. This information can be useful to local authorities and DRR institutions, NGOs and the international community in order to provide adapted prevention programs and/or to better target assistance to the population following a crisis.

The limitations of this type of inductive approach (i.e., difficulty in identifying the key determinants factors and subjectivity in the construction of this index) has led us to develop an alternative vulnerability index, based on a deductive method.

The underlying reasons for the development of the OVI are multiple. Foremost, it is not always possible to implement the SoVI methodology, due to the difficulty, in some contexts, of having access to data in the required sufficient quantity and quality. The OVI is thus based on a much more limited number of variables. Moreover, the objective of such an approach is to create a vulnerability index which (1) is adapted to the field context, (2) has an operational value based on an easy-to-reproduce methodology and clearly identified contextualized variables, and (3) is easy to understand and adopt by less experienced researchers. As vulnerability is known to vary not only spatially but also over time, a reproducible method is essential to enable transversal analysis of the social vulnerability of each neighborhood. However, to be representative of the studied context, the vulnerability assessment should be reassessed after major shock occurring in the community, such as a large disaster or a refugee crisis, as unfortunately regularly happening in Goma.

Finally, beyond the scientific aspect, the construction of an OVI can help to communicate the message more easily to political authorities, in terms of risk management – e.g., to target neighborhoods where to develop priority prevention programs – but also in terms of spatial urban planning – e.g., to identify areas in which to act.

6. Conclusion

By developing a social vulnerability index, as defined by Cutter et al. [44], based on data from an unprecedented socio-economic survey (i.e., collection of qualitative and consistent data for the entire study area), we provide a first answer to our research question aimed at assessing the vulnerability of the population of Goma city. Despite some limitations, this first result puts our social vulnerability assessment on an equal benchmark with similar studies conducted around the world, in very different environments, particularly in terms of data accessibility and reliability. In addition, guided by the need to use an easy and operational method, we have developed an operational vulnerability index specific to urban areas of the study region, and to Goma in particular. This allows us to provide a second answer to our research question, which is based on a choice of appropriate variables and a detailed urban socio-economic study. If this methodology can also be criticized, it allows an easier identification of the role played by each of the variables taken into account since their number is limited and their combination very simple. As such, the obvious bias of being largely based on field knowledge is in fact a source of strength, because it brings statistical analysis closer to a reality that is crucial to integrate.

As conclusion, both methods have their own strengths and the spatial patterns in the produced indexes are very similar. Although this type of approaches cannot be validated as such, the most crucial is to be able to identify the parameters that control their spatial variations in order to develop targeted policies. Knowledge of the study context is essential at all stages of vulnerability assessment. Together with the lava flow invasion probability and the population exposure, the vulnerability assessment is one of the cornerstones towards the lava flow risk assessment.

Declaration of competing interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2019.101460.

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